Cold Tests of the Superconducting Coils for the Stellarator W7-X

Juergen Baldzuhn, Hartmut Ehmler, Laurent Genini, Kerstan Hertel, Alf Hoelting, Carlo Sborchia,
Thierry Schild

Abstract—**A new plasma fusion experiment, Wendelstein 7-X (W7-X), is built in the Max-Planck Institute for Plasma Physics in Greifswald (IPP), Germany. This experiment employs superconducting coils, allowing for plasma discharges up to 30 minutes duration. W7-X will be an “optimised” stellarator with respect to plasma transport and stability. The W7-X magnet consists of 70 individual coils in a toroidal arrangement. Each coil of W7-X is thoroughly tested before installation in a cryogenic test facility at the Commissariat a l’Energie Atomique (CEA) in Saclay, France. The tests are essential, because no access is foreseen to the magnetic system during the entire operation period of W7-X. The test procedure will be described briefly, and some test results will be presented.**

Index Terms—**Fusion magnets, stellarator, superconducting coils tests.**

I. INTRODUCTION

IN this chapter, we give a brief description of the W7-X magnetic field system [1]. The magnet system of W7-X will consist of 70 individual superconducting coils, 50 of them are non-planar and 20 planar. W7-X will have the shape of a pentagon, with five identical modules. It will be, together with the Japanese stellarator “Large Helical Device” (LHD) [2], the largest stellarator in the world. One of the most important peculiarities of W7-X will be the so-called “optimised” magnetic field configuration, which is one reason for the complicated coil shape.

Fig. 1 shows schematically a part of the magnet system. All coils are supported by central supports, keeping them in place and bearing the magnetic forces during operation. The support structures, all coils, busbars and helium supply lines will be situated under vacuum between the inner plasma vessel and the outer cryostat vessel. Ports between the plasma vessel and the outer cryostat skin will be used for plasma diagnostics, plasma heating, vacuum pumping, and as feed-through for cables and cooling tubes.

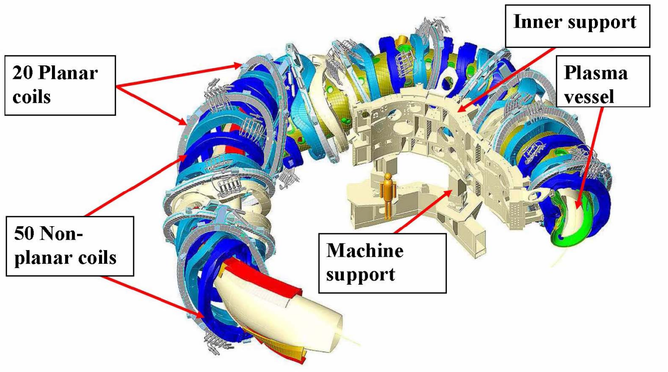

Fig. 1. Sketch of the W7-X magnet system. Shown is the outer plasma surface in the plasma vessel, some of the non-planar and planar coils, and some of the mechanical support structures.

Each coil consists of 6 double-layers of a Cable-In Conduit-Conductor (CICC) NbTi superconductor cable. The double-layers are connected in series by interlayer joints. The entire winding pack and the connection area of the CICC cables are embedded by a mixture of quartz sand and epoxy in a casing made of stainless steel 1.4429 (316LN). The interlayer joints reach out of the connection area, their surfaces are isolated by glass-fibre sleeves glued with epoxy and covered with a layer of conductive paint. Both, casing and winding, are cooled independently from each other by supercritical helium, the winding package by the CICC and the casing by independent stainless steel tubes on the surface.

Ten coils of the same type are connected in series. Thus it is guaranteed that in each module exactly the same magnetic field topology is realised. This is essential for the stellarator “optimisation”, as described below. Only this symmetry between the modules can guarantee a balanced power load to the plasma facing wall and diagnostic components. Due to the high inductivity of the coil series, high-voltage will be induced during a rapid current ramp-down; hence the coils have to be high-voltage proof. To reduce the maximum high-voltage as far as possible, a Nickel dump resistor is chosen [3]. The resulting current decay time constant is a compromise between a minimised high-voltage during the current discharge, and a maximum hot-spot temperature (130 K are assumed as uncritical) and helium pressure in the coil cable after a quench.

No time limitation is imposed to the discharge length in a stellarator, because no current drive mechanism is required (in opposite to a tokamak, as for instance ITER will be). In W7-X, the maximum discharge length will nevertheless be limited to about 30 minutes. This limit is dominated by technical reasons, for instance by the power load to the plasma facing

---

Manuscript received August 24, 2007.

J. Baldzuhn, H. Ehmler, K. Hertel and A. Hoelting are with the Max-Planck Institut fuer Plasmaphysik, IPP, EURATOM Assoc., 17491 Greifswald, Germany (corresponding author phone: 0049-3834-882534; fax: 0049-3834-882509; e-mail: baldzuhn@ipp.mpg.de, hartmut.ehmler@ipp.mpg.de, kerstan.hertel@ipp.mpg.de, alf.hoelting@ipp.mpg.de).

L. Genini, T. Schild are with the Commissariat a l’Energie Atomique CEA, CEA/DSM/DAPNIA, Centre de Saclay, 91191 Gif-sur-Yvette, France (e-mail: genini@dapnia.cea.fr, schild@dapnia.cea.fr).

C. Sborchia is with the ITER International Team Cadarache, 13108 St. Paul-lez-Durance, France (e-mail: carlo.sborchia@iter.org).

components, the cooling capacity for the plasma heating devices etc.

W7-X will have a modular coil system. This has the advantage that in the case of repair or maintenance, the relatively small coils can be removed from the machine, substituting coils can be installed, and the plasma operation can be continued. That concept has the additional advantage of relatively small magnetic forces between the coils, and the smaller modular coils are technically more feasible than one large coil. Such a large helical coil system is realised for LHD.

In parallel to the long experimental Wendelstein stellarator line, which started in the early 1960's with W1-A, theoretical calculations and numerical simulations were performed to investigate the potential of the stellarator magnetic field for the "optimum confinement" of a fusion relevant plasma [4]. For the "optimisation", one considered the technical feasibility of the coil design, the expectations for the power load to the vessel wall, and lots of other aspects. Major criteria through that process were the minimisation of particle and energy losses from the plasma, a maximum of stability against plasma oscillations, a minimisation of parasitic currents in the plasma, and good confinement of high energetic particles which result from the nuclear fusion reaction. But also technical aspects were taken into account, like for instance magnetic resilience of the configuration against external magnetic perturbations or coil imperfections.

Spontaneous equilibrium currents flowing parallel to the magnetic field lines, which appear in all fusion relevant plasmas, will also be minimised due to the "optimisation". These currents will lead to an unwanted shift of the entire plasma column, they will directly enhance plasma losses, and they will drive instabilities. The W7-X "optimisation" will reduce unwanted plasma particle drifts and losses. Those drifts are induced, for example, by the magnetic field gradient (grad-B) which results from the toroidal curvature. The W7-X magnetic field is tailored in such a manner, that those drifting particle populations will be shifted away from the W7-X pentagon "corners" where grad-B is large. They will be located in the straight parts where grad-B is small. Thus, the overall drift rate, and the losses, of these particles will strongly be minimised.

II. THE COIL TEST PROCEDURE

The W7-X coils are subject to a comprehensive coil test procedure [5]. Each individual coil [6] is carried from the manufacturers, either the Babcock Noell company BNG (Zeitz, Germany) for the non-planar coils, or from TESLA (England) for the planar coils to CEA, Saclay. There, two cryostats with a diameter of about 5 m allow for vacuum and cryogenic tests. Each cryostat can accept two coils. In the test hall, enough space is available to work on 6 coils simultaneously under air. A well trained test crew is responsible to carry out the entire test procedure and to provide the test result documentation, according to a well defined test procedure.

After an incoming visual inspection, all cables and sensors are tested for integrity. The electrical resistance of the winding is measured by application of 10 A, short-circuits can be detected by an AC electronic measurement of the complex impedance between 0.1 Hz and 100 kHz. Under air, a first DC high-voltage test is performed to investigate the coil insulation between winding pack and casing.

Then the coil sensors are cabled and two coils are installed together in one cryostat. After another DC-test under vacuum and a helium leak test, the coils are cooled down during about 10 days to the operating temperature of 5 K. When the coils reach this temperature, the nominal current of 17.6 kA is applied to the coil, and the sensor behaviour is investigated, the hydraulic flow impedance of winding and casing as well as the interlayer joint resistances are measured. The current can be applied only to one coil in one cryostat simultaneously, hence the coils are tested in the magnetic self-field. If stationary conditions can be maintained under nominal conditions, the coils are warmed up in steps of 0.1 K, just below the expected quench temperature. Then a fast current discharge is performed. For some coils, a temperature quench is performed by increasing the temperature up to the quench point. After the current test, another high-voltage DC and an AC-test are performed to check whether the insulation is still undamaged and no short-circuits developed.

Finally the coils are warmed up, and the DC high-voltage test is repeated under air to exclude cracks in the insulation due to mechanical stresses from the cool-down or the electric current test. If all tests are finished successfully, the coils are carried to IPP. There, Paschen-tests are performed. These are high-voltage DC-tests where the background gas pressure is varied between 10^{-4} mbar and 1000 mbar. Focus is on the pressure range around 1-10 mbar, the Paschen-minimum for discharges in air. The Paschen-tests turned out as a very sensitive means to investigate the coil insulation, and any defects can be localised easily by observation of the discharges with video cameras.

III. COIL TEST STATUS AND RESULTS

Almost all coils have been manufactured in the meantime. It is envisaged to terminate the planar coil production by end 2007, the non-planar coil production by beginning of 2008. With the strived test rate, the coil tests should be finished by spring 2009. Due to the very stringent time schedule for the W7-X assembly, it is planned to test some coils in the cryogenic test facility in the Forschungszentrum Karlsruhe (FZK) in parallel to CEA. The TOSKA test facility [7] is being upgraded to accept up to three coils simultaneously. A new test crew is educated during the tests at CEA. Several parts of the old TOSKA hardware have to be modernised, and a new control electronics and data acquisition system will be established.

The first coil test at CEA started in June 2003, after the test facility itself was checked thoroughly using the DEMO coil. The DEMO coil is a non-planar prototype with almost identical parameters to the non-planar W7-X coils, however slightly deviating properties of the CICC cable, the mechanical set-up and some geometrical measures. The DEMO properties were very well known, because it was carefully tested in FZK before. Thus, the behaviour of the CEA test facility could be examined in advance, and the details of the test procedure could be revised before the first W7-X coil entered the process. The test duration for the first W7-X coil was about 6 months, to assure that all measurement data were recorded correctly, and that the coil handling procedure was safe and reliable.

One test cycle takes about 8-9 weeks. Such a cycle includes the test of two coils in one cryostat. As two cryostats are available, and because a lot of preparation and finishing work can be done outside the cryostats in parallel, a test rate of about 18-20 coils/year can be realised. This does not include additional Paschen-tests or leak tests, which are performed at IPP. Up to now (July 2007), tests were performed on 22 different non-planar and 7 planar coils. After these tests, 19 non-planar and 5 planar coils could be delivered to IPP and could be accepted (corresponding to a success rate of 83%). The rest went back to the manufacturer because of design changes, repair or reinforcement. Between 2003 and now, 20 test cycles could be performed. Hence, one would expect 40 tested coils in the meantime. However, two test cycles were done with single coils only. For 4 individual coils, so far, an unsuccessful test had to be repeated. Two coils had to be re-tested three times before they succeeded.

In the meantime, 14 temperature quench tests have been performed, both on planar and non-planar coils. During the superconductor production, quality control checks were performed on samples of individual strands and strand bundles, by measuring the critical and the quench temperatures. From those measured values, one can extrapolate to the expected coil quench temperatures in the self-field. A very good agreement could be observed between those expectations and the quench temperatures of the coils evaluated at CEA. In fact, the measured coil quench temperatures are systematically about 0.1 – 0.2 K higher than the extrapolated temperatures. This convinced us of the good superconductor cable quality, and that no degradation or persisting damage happened to the conductor during the manufacture process. We measure typically a quench temperature between 6.2 K and 6.5 K for the non-planar, and 7.4 K and 7.7 K for the planar coils. The higher quench temperatures for the planar coils are due to the fact that the magnetic field strength is smaller at the location of the high field side layer, because the planar coils (max. magnetic field strength 2.5 T in the self-field) are slightly larger than the non-planar (max. magnetic field strength 5.2 T in the self-field).

One striking feature is the good agreement of the temporal development of the resistive voltage prior to the quenches, in comparison of all non-planar coils, as shown in fig. 2. The compensated voltages increase from 0.18 s (roughly the moment of the quench initiation) up to 0.38 s (the moment when the measurement electronics saturates at 1 V), with a temporal scatter of only about 40 ms up to the moment when electronic saturation is reached. This indicates a high reproducibility of the cable performance and quality, independent from the coil type. A certain scatter of the curves is expected, nevertheless, because the magnetic field distribution along the high field layer is different for the different five coil types because of the differing coil shapes. A very good reproducibility is observed as well for the temporal development of the pressure increases after the quench, and the increases of the casing and winding temperatures. Hence we conclude that not only the electric characteristics of the conductor are good, but also the hydraulic and mechanical properties of the cable.

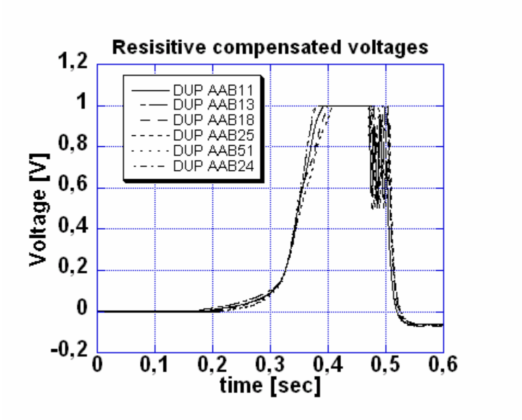

Fig 2. Temporal development of the compensated resistive voltage (y-axis) during a quench. Compared are time traces of 6 non-planar coils. All curves match at a compensated voltage of 0.2 V. The coil names are indicated in the inlet box.

During coil production and testing, several systematic flaws could be identified. The most frequent and severe drawbacks are summarised briefly. The first are high-voltage insulation problems, leading to discharges during DC tests. At the beginning of the test phase it was discovered that the original quench-detection-wires were not high-voltage proof. On all coils, the old cables had to be removed and replaced. As it was impossible to remove some of the old cables inside the epoxy embedding of the winding pack, particular connectors had to be designed to allow for a high-voltage proof connection between old and new cables. The new cabling arrangement and the connectors work now very well. Several current leaks appeared on the coils themselves. In most cases, the hand-made epoxy sleeves insulation failed. Sometimes the sleeves were obviously too dry or bubbles of air were enclosed. This can only be overcome by reinforcement and reparation of each individual current leak, each time that problem occurs. The Paschen-tests are here an extremely helpful means in localising the current leaks.

Another problem arose from flux residuals, which remained after the soldering of copper stripes to the stainless steel cooling tubes on the coil casing. The copper stripes improve the thermal contact to the coil casing. The remnant chlorides destroyed the steel tubes within some months by corrosion and produced helium leaks to the vacuum. That problem could be overcome by replacing the old tubes and by pre-tinning the new tubes before installation, such that any flux residuals can now be removed easily and reliably.

During the manufacture of the non-planar coils of type 1 and 5, the responsible sub-contractor ABB (Augsburg, Germany) realised, that several CICC cables of neighbouring double-layers come very close to each other in the connection area. Already in the early stage of winding package production, three short circuits were detected at those critical points, but those could be repaired straight forward because of the good accessibility. The other 17 coils of these two types seemed good. However, on one coil of type 5 a short circuit was detected after the current test in CEA. Fortunately, the winding package was still undamaged during the high-current test. But the coil failed during the final high-voltage AC test (performed with much smaller current). The subsequent RCL measurement clearly indicated then a short circuit between two double-layers, see Fig. 3 (RCL = simultaneous measurement of the resistance R, capacity C, and/or inductance L as a function of the frequency). The observed shift of the resonant frequency is typical for a short circuit between double layers, as confirmed by experiments with other winding packages, where artificial short circuits were applied. That coil was sent back to ABB, where the epoxy embedding was opened with precision sand-blasting tools, to dig out the critical location. In fact, it was discovered that less than 1 mm insulation remained between the adjacent cables. The remaining insulation between these cables was burnt.

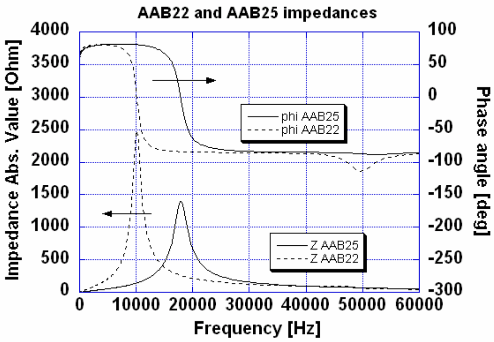

Fig. 3. Spectral impedance measurement of the coil complex impedance, with the absolute value of Z (left y-axis) and the U-I phase angle (right y-axis). The x-axis shows the frequency. The dotted curves show the values for coil AAB22 (no short-circuit), the solid line for coil AAB25 (with a short circuit). The resonance shift from 10 kHz to 18 kHz due to the short circuit is quite obvious.

The defect was repaired by opening the gap between the cables up to about 1.5 mm, using the sand-blaster and a dentist's drilling tool. Then the cable surfaces were wetted with epoxy, the epoxy layer was removed, then it was wetted again with epoxy and the gap between the cables was filled with NOMEX® plates of appropriate thickness. Remaining gaps and holes were filled with glass fibre pieces, finally the hole in the embedding was filled up with filler pieces and epoxy, then the coil surface was closed with laminates. Great care was taken not to move or bend the CICC cables in order to widen the gap. Extremely critical was the condition, that the quench detection wires parallel to the CICC cables should not be damaged. After the repair, DC and AC high-voltage tests were repeated to assure a successful repair.

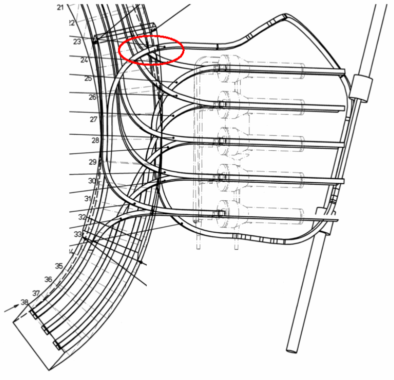

Fig 4. Sketch of the CICC cross-over region in the connection area of the non-planar coils type 5. The critical location with the hazard of a short circuit is marked with an ellipse. On the right-hand side, the interlayer joints (dashed lines) and the tail-ends can be seen, the winding package (left hand) is shown only partly.

The remaining coils of type 1 and 5, which had not yet been tested but were suspected to show the same problem, were opened and repaired as well. After that procedure, all coils of type and 1 will be tested with a quench at CEA, in addition 10 current cycles will be performed to investigate the behaviour of the winding package under current stress. Fig 4 shows a sketch of the geometrical situation in the connection area of the coils of type 5.

Systematic problems arise from the interaction between the test facility and the coils. The first are high-voltage failures during the DC-tests, even if the coil itself and the test facility alone are obviously high-voltage proof. The reasons are still unclear, at the moment, but we suspect a combination of ground loops, and locally trapped background gas reservoirs somewhere in the facility in the insulation vacuum, maybe at locations with insufficient pumping efficiency (the test facility is not Paschen-tight). The ground loops are opened when the coil is electrically disconnected, the remnant gas background is reduced when the coil's helium cooling is disconnected, or when the coil is taken out of the facility. Investigations of that effect continue, for instance by installation of video cameras at different locations during the high-voltage tests.

Another interaction problem are helium leaks, obviously caused by a mechanical mismatch between the complicated coils and the installations in the facility. Those effects are investigated now in detail by installation of small local leak test chambers, around the critical flanges, joints or connectors. This technique does not avoid the leaks, but it allows for a very efficient and fast localisation of possible leaks and their repair, before the installation of the coils into the large cryostat tank has to be done. Inside the cryostat, the leak search would take much longer.

Severe problems were caused spring 2006 by a damaged non-return valve close to the compressors in the helium liquefier. Oil penetrated into the "clean" pipes of the liquefier, destroyed the helium turbine and polluted all helium tubes. The entire cryogenic installation had to be dismantled, and the oil residuals had to be washed out with alcohol. That procedure could be finished successfully in the same year.

IV. CONCLUSION

We are optimistic that the most severe coil manufacture problems have been solved in the meantime, and that the production can be finished straightforward. Hence, all coils should be manufactured by spring 2008. With the envisaged coil test rate, combined in CEA and FZK, the test and acceptance procedure should be finished by spring 2009. This will be right in time for the W7-X assembly time schedule.

REFERENCES

[1] G. Grieger et al, *Phys. Fluids B*, vol. 4, p. 2081, 1992.
[2] O. Motojima et al, *Nucl. Fusion*, vol. 43, p. 1674-1683, 2003.
[3] T. Moennich, T. Rummel, *IEEE Trans. Appl. Supercond.*, vol. 16, p. 1741, 2006.
[4] J. Nührenberg, *Europhys. News*, p. 216, Nov./Dec. 1998.
[5] C. Sborchia et al, *IEEE Trans. Appl. Supercond.*, vol. 16, p. 848, 2006.
H. Scheller et al, *IEEE Trans. Appl. Supercond.*, vol. 16, p. 759, 2006.
J. Baldzuhn et al, *IEEE Trans. Appl. Supercond.*, vol. 16, p. 763, 2006.
[6] Technische Spezifikation fuer das Nichtplanare Spulensystem des W7-X Experimentes, IPP Technical Document, No.: AAB-S0003.1
[7] A. Ulbricht et al, *Fusion Eng. Design*, vol. 73, p.189, 2005.