Fabrication of the Superconducting Coils for WENDELSTEIN 7-X

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Abstract: The Max Planck Institute of Plasmaphysics is constructing the stellarator fusion experiment WENDELSTEIN 7-X (W7-X) at the branch institute in Greifswald. W7-X continues the line of stellarator experiments at IPP. To allow for steady state operation W7-X has a superconducting coil system with 50 non-planar and 20 planar coils. The coil system is grouped into five equal modules, each consisting of two mirrored symmetrical half modules. The half modules are assembled from five different non-planar coils, two planar coils and a sector of the coil support structure. All cryogenic parts are thermally protected by a cryostat. The magnet system has been ordered from the European industry. Production of the coils is well under way with the first two non-planar coils already delivered to the test facility CEA at Saclay. The focus of this paper is placed upon the fabrication state of the coil system.

1. INTRODUCTION

W7-X is based upon the experiences of the former stellarator experiment W-AS at IPP. There are two main differences to the former experiments - the coil system has a larger size and is superconducting. A DEMO coil which is a prototype of a non-planar coil was built and successfully tested under cryogenic conditions in 1999 [1]. The prototype demonstrated not only that the specified properties could be met, but also verified the design and basic technologies for production of the superconductor and coils.

2. THE W7-X COIL SYSTEM

The coil system of W7-X enclosing the plasma consists of 50 non-planar coils and 20 planar coils. The coils will be fixed on a central support ring and braced with each other. The coils are arranged toroidally within five equal modules. Each of the modules consist of two mirrored symmetrical half modules. The coil system of one half module consists of 5 different non-planar coils and 2 different planar coils (Fig. 1). The entire coil system is protected by a cryostat containing the ports, the plasma vessel, the thermal insulation as well as the outer vessel. The coils are cooled via circulating supercritical helium both through the void of a cable-in-conduit conductor and through tubes which pass around the casing. The coils are designed for a life cycle of 15 years, 50 cool downs, 50 quenches and 5000 full current changes. [2]

The non-planar coils were ordered at a consortium formed by Babcock Noell Nuclear GmbH and Ansaldo Superconduttori S.p.A. The planar coils were ordered at TESLA Engineering Ltd.. Both coil manufacturers ordered the superconductor at the consortium Vacuumschmelze GmbH (VAC) and Europa Metalli S.p.A. (EM).

All coils will be subjected to an acceptance test under nominal conditions at the cryogenic test facilities of CEA in Saclay (France).

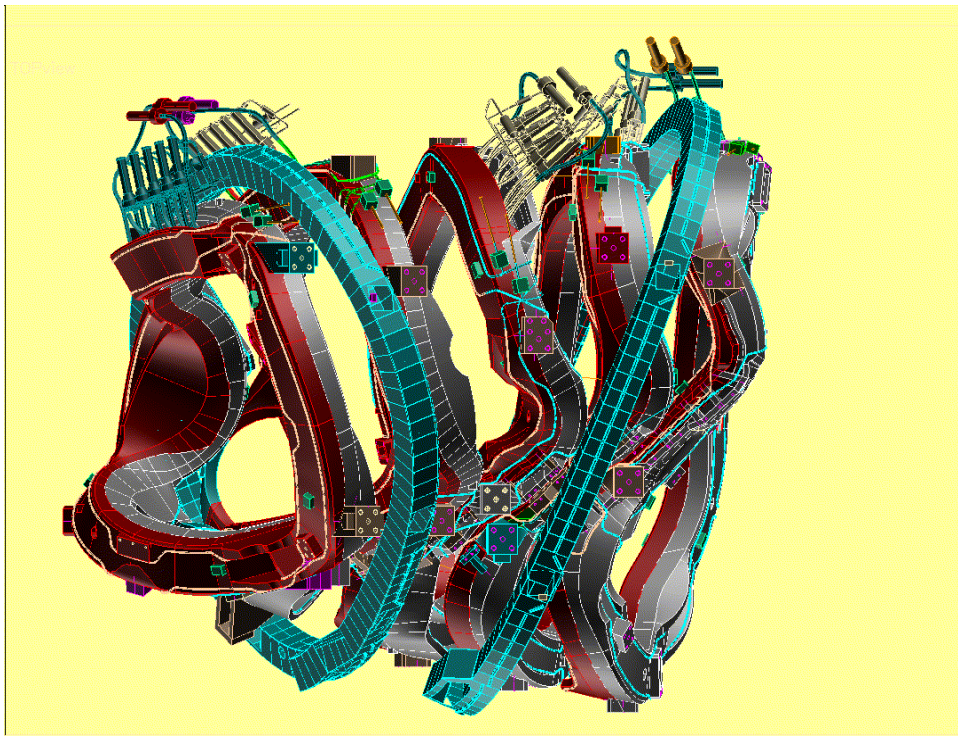

Fig. 1 Half module of W 7-X coil system (without plasma vessel, cryostat and support structure)

3. PRODUCTION OF SUPERCONDUCTOR

The W7-X coils utilise a special cable-in-conduit conductor. This conductor has two main differences as compared to the conductor of the DEMO coil: an increased number of strands (243 instead of 192) and an enlarged Cu/NbTi ratio of 2.7. Due to this increased number of strands the W7-X conductor has a slightly larger outer dimensions of 16x16 mm². Figure 2 and 3 depict cross sections of a strand and W7-X conductor respectively.

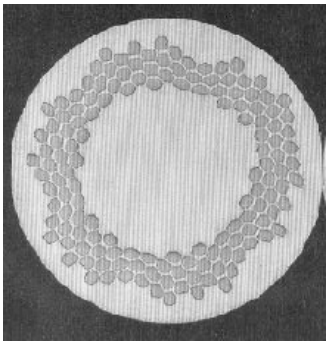

Fig. 2 Cross section of a strand

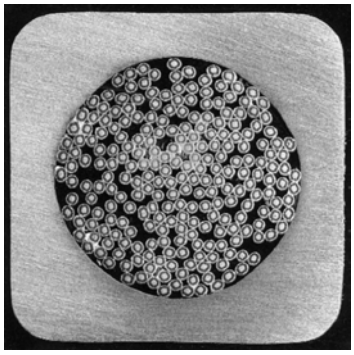

Fig. 3 Cross section of the conductor

The consortium VAC/EM experienced great difficulties in meeting the required tolerances whereby resulting in more than one year of delay. Enlarged tolerances for outer dimensions, void fraction and mass flow had to agree in order to proceed with the series production.
By August 2003 the number of co-extruded conductor lengths stood at 270 (from a total of 360).

4. PRODUCTION OF NON-PLANAR COILS

The production of the non planar coils takes place in different locations and is structured as follows:

1. The companies ABB Augsburg (Germany) and Ansaldo Superconduttori (Italy) are manufacturing the winding packs using very precise winding forms. Winding starts with the innermost double layer on the high field side and proceeds in radial direction. This procedure simplifies the application of the necessary moulding forces and press forces (see figure 4).

Fig. 4 Winding work at ABB (Germany) by courtesy of ABB

   The connection of the double layers by special low resistance joints and the mounting of quench detection wires is performed before the winding pack is impregnated. The geometrical accuracy, helium tightness and correct insulation are checked on each winding pack. At this point in time 12 winding packs are ready with a further 7 winding packs under process. IPP inspectors monitor all steps of the manufacturing processes.
2. The winding packs are embedded in stainless steel casings which are cast as half-shells at Österby Gjuteri AB in Sweden. As of the end of August 2003, 15 casings are available and 50 half shells under process. The general geometrical tolerance for the outer shape of the casings is ± 5 mm which is reduced to ± 2mm in special areas. Prior to delivery of the casings the material properties and the geometrical shape are measured and the half shells are inspected by x-ray and dye penetrant tests.
3. The coil assembly takes place in Zeitz (Germany) at a Babcock Noell Magnettechnik GmbH site with the following productional steps:
   - mounting of the winding packs into the encasings
   - welding of the casing half shells and of support pieces
   - embedding of the coils using glass and epoxy resin
   - final machining of all high precision surfaces and holes for fixation according the measuring marks on the winding pack
   - application of the copper cooling shield on the casing surface
     Roughly 150 copper stripes (20 mm wide) are welded around the casing and soldered to the 4 cooling pipes.
   - instrumentation of the coil with 7 temperature sensors and 2 strain gauges
   - final work acceptance tests e.g. geometrical measuring, electrical tests, flow tests, leak test. Figure 5 shows the first type 3 coil prior to delivery to CEA.

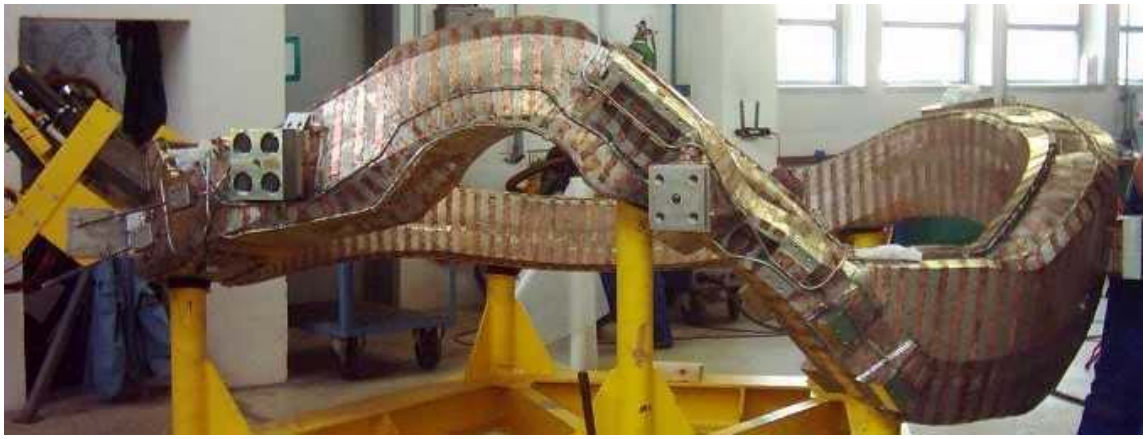

Fig. 5 Non-planar Coil prior to delivery

4. The final acceptance test takes place at cryogenic temperatures and nominal current at CEA in Saclay. The first coil is already installed in the cryostat and is undergoing cooling. A subsequent coil is being prepared for the test.

All manufacturing processes are monitored by IPP inspectors. The first two coils are ready and have been delivered to CEA in Saclay in June and July of 2003. The main features of the non-planar coils are explained in Table 1.

	Non- planar coils	**Planar coils**
number of differently shaped types	5	2
winding pack	108 turns in 6 double layers; hydraulically connected in parallel	36 turns, three double layers hydraulically connected in parallel
casings	cast stainless steel	welded and bolted steel plates
weight	approx. 5.5 tons per coil	approx. 3 tons per coil
dimension	≈ 3.5 m x 2.5 m x 1.5 m	≈ 4 m diameter
nominal current	17.6 kA at 4 K	16 kA at 4 K
nominal he-pressure	up to 20 bar	up to 20 bar
nominal insulation voltage	6 kV dc	4 kV dc

Table 1 Main features of non-planar and planar coils

5. PRODUCTION OF PLANAR COILS

Tesla Ltd., Storrington is producing the planar coils. The coils are wound on a rotating winding form. The casings for the planar coils are made from plate material and joined by screws. After cutting and bending of the stainless steel plates these plates will be arranged to quarter sections. The screw holes and threads are drilled into the quarter sections. After that, the quarter sections will be disassembled and the inner and outer rings will be welded together. For cooling of the encasing the casing is covered with copper plates. To avoid eddy currents during a rapid shutdown the copper stripes are segmented into stripes. One cooling loop around the circumference is sufficient to cool the encasing. Table 1 shows the main features of the planar coils.

By end of August 2003 12 winding packs have been impregnated, two casings are ready and the first coil is mechanically completed. The delivery of the first coil is expected by end of

September 2003 with a delay of more than 3 years. IPP inspectors monitor all steps of fabrication.

6. SUMMARY

The non-planar as well as planar coils for W7-X are in an advanced state of production. The first coils delivered met the stringent requirements of the technical specification with minor deviations especially within the casings. Delivery of the coils has been significantly delayed due to a series of difficulties experienced during the qualification of the superconductor as well as during winding and assembly. Following testing of the coils at nominal conditions the assembly of W7-X will start in Spring 2004.

References

[1] R.Heller, W.Maurer, A.Ulbricht, F.Wüchner, G.Zahn, I.Schoenewolf, Final test report for the Wendelstein 7-X demonstration coil, Karlsruhe, 2000

[2] M. Wanner, Status of WENDELSTEIN 7-X construction, Nuclear Fusion **43** (2003) p. 416-424