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Design, Production and QA Test Results of the NbTi CIC Conductors for the W7-X Magnet System

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Abstract: The magnet system of the W7-X Stellarator consists of 50 non-planar and 20 planar coils. The superconductors for both types have the same design, which is a Cable-in-Conduit (CIC) conductor of 243 NbTi strands. Namely the non-planar coils asked for a conductor, which can be easily wound to a complex shape, but has high mechanical strength to resist the large magnetic forces acting during magnet operation. This has been achieved by jacketing the cable into an Aluminium conduit by a co-extrusion process. The used 6063 Aluminium alloy is very soft in the extruded state, but gets high strength properties after winding during a precipitation hardening treatment at about 160°C. The production of the needed 390 conductor lengths (including spares) and the related QA tests are nearly completed and a large number of coils are fabricated. Some of them were already subjected to a cold test at CEA Saclay, where the conductor behaved as expected from short sample measurements.

1. Introduction

The magnet system of the W7-X stellarator consists of 50 non-planar coils and 20 planar coils, which are arranged in a toroidal configuration around the plasma vessel. The system has a 5-fold symmetry and is divided into 10 half sectors. Consequently there are 5 differently shaped non-planar and 2 planar coils per half sector, which are assembled around a half sector of the plasma vessel and the related thermal shield (see Fig. 1).

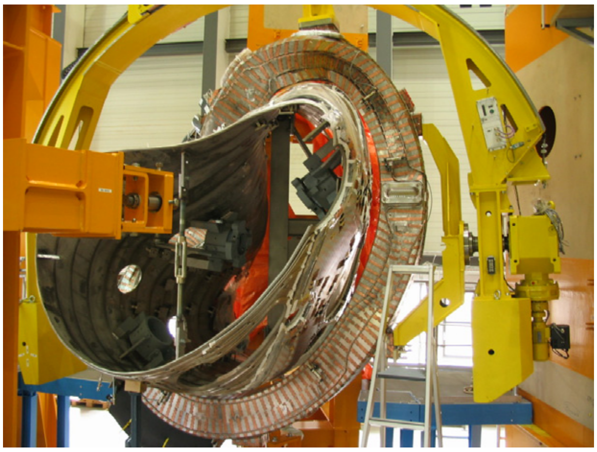

Fig.1: Assembly of one non-planar coil with a plasma vessel sector and its thermal shield at IPP.

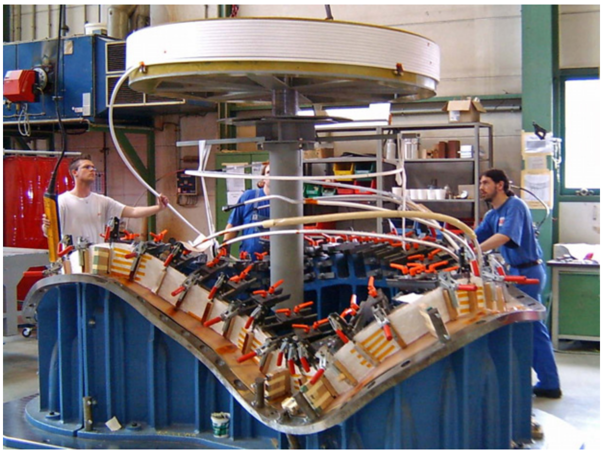

Fig.2: Winding into the complex shape of a non-planar coil at ABB works, Neusäß, Germany

The non-planar coils are wound in 6 double layers while the planar coils have 3 double layers, which are insulated and impregnated with epoxy resin to form the winding packs. Those are embedded in stiff stainless steel cases [1]. For both types of coils identical cable-in-conduit conductors are used being the main topic of this paper. A final acceptance test is being performed on all coils at liquid helium temperature including a quench originated by rising the helium temperature.

The current status of the project is that almost all conductors needed have been produced, about 90 % of the winding packs are completed, about 60 % are embedded in the cases and about 10 % have been tested at CEA Saclay successfully.

2. Design of the conductor

The specified characteristics of the W7-X conductor are listed in Table 1. An important requirement on the conductor was that it must be easy to wind the complex shaped coils with (almost) no spring back. On the other hand the conductor has to have high mechanical strength at operation. To meet these contradictory requirements the use of a cable-in-conduit conductor was proposed in an industrial study in 1989, consisting of a cable of NbTi strands in a jacket of precipitation hardening aluminium alloy. This type of conductor was then developed by IPP in collaboration with the Forschungszentrum Karlsruhe and industry, including the tests of several model coils and one prototype coil [2].

Table 1: Characteristics of the W7-X conductor

Strand diameter	0.57 mm
Ic (6 T/4,2 K)	> 150 A
Cu:NbTi	2.7 ± 0.2
Cabling law	3x3x3x3x3 or similar
Number of strands	243
Jacket	AlMgSi (6063)
Wall thickness	> 2 mm
Outer dimension	16 x 16 mm^2
Al jacket 0,2% yield strength	<150MPa as extruded at room temperature
	>285MPa hard condition at 4 K
Void fraction	37 ± 1%
Mass flow rate tolerance	± 10%

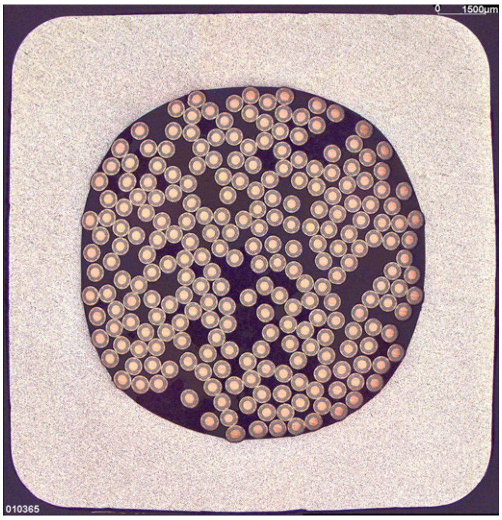

Fig.3: Cable-in-conduit conductor in a jacket of 6063 Aluminum alloy

3. Manufacturing procedures

The coil suppliers, the consortium Babcock Noell Nuclear – Ansaldo Superconduttori for the non-planar coils and TESLA for the planar coils, entrusted the consortium EAS (former Vakuumschmelze) – OCSI (former Europa Metalli) with the fabrication of the superconductor. The manufacturing sequence and repartition between the two companies was the following:

(i) The strand needed is contributed from the two companies in equal shares.

(ii) The cabling is being performed at the OCSI works in Fornaci di Barga (Italy) in five steps. After the last cabling step the cables are compacted by hard metal dyes. In the course of the project it turned out that the cables were not free of broken strands. In order not to waste too much material it was agreed between the companies and IPP that two broken strands in 50 m minimum distance were acceptable in a conductor length, if not used in layer 1, which sees the highest field during operation.

(iii) The cable check for non-conformities and the preparation for co-extrusion are being done by EAS at Marti Supratec, Zurich. At the beginning there were many discussions about acceptability, as the

cables have a quite irregular optical aspect. It turned out that with the chosen cabling law 3x3x3x3x3 this is unavoidable as all sub-cables have a triangular shape, which causes deep grooves between sub-cables. After some optimisation trials acceptability standards were set, which were respected during the further production. Possibly with an ITER-like cabling law – i.e. 3x4x4x5 one would have got better and more homogeneous cable patterns.
(iv) The Co-extrusion to embed the cable in the aluminium jacket is being done by EAS at Alu Menziken (Switzerland). Only certified billets of aluminium alloy 6063 are being used for co-extrusion in a conventional press for aluminium profiles equipped with a special tool to introduce the superconductor cable into the centre of the aluminium flow. Billet and press temperatures, extrusion pressure and speed were kept constant as far as possible and were recorded. In order to be able to extrude several conductor lengths in one go they were coupled together by steel ropes. This allowed to stop the process to load the billet for the next length. The length of the connecting steel rope was long enough to cover the overlapping zone between two billets.
(v) The final control and tests on the superconductor lengths were performed and documented at OCSI premises (surface quality, wall thickness, leak- and pressure test, flow rate). The strands were characterized by the relevant supplier (Ic, n, RRR). The Al-quality tests were performed by EAS

4. Overview on the conductor test data

The data measured on the strands extracted from the cables after co-extrusion and on the aluminum jacket are listed in table 2. The strand quality from both manufacturers was very homogeneous and met the specification, except a very few strands having a slightly low Ic due to a higher Cu:NbTi-ratio. This material was accepted to be used in the lower field double layers. The mechanical data of the aluminum alloy were well within the specification in the soft state, but also after the hardening treatment at 160°C. The values were high enough that after about ¼ of the production and after having determined a scaling factor between the values at ambient temperature and helium temperature, the low temperature tests were dropped except on a few confirming samples.

Table 2: Summary of QA tests on extracted strands and on the jacket material

	Specified	Mean value	Maximum	Minimum	Stand. Dev.
Triplet Ic(6T,4.2K) [A]	>450	495	535	432	19
n-value	> 35	49	63	41	2,7
RRR	>160	210	311	164	20
Al-0.2%-yield at RT [MPa] in the extruded state	<150	115	137	97	7
Al-0.2%-yield at RT [MPa] after hardening treatment	>225	248	267	226	6
Al-0.2%-yield at 7K [MPa] after hardening treatment	>285	297	330	287	7

The contractual specification asked for a void fraction of 37 ± 1 % and a mass flow at 20 bar pressure drop of ± 10 % in respect to the nominal value established at the beginning of the production. Many parameters influence the mass flow as the pressure drop, the length of the conductor, the temperature, the ambient pressure. The latter two were normalized to 20°C and 1013 mbar. Besides the void fraction further influencing parameters are the quality of the strand surface and of the cable, which cannot easily be quantified. From experimental data it was not possible to establish a clear dependence between mass flow and the void fraction. Due to the high number of parameters, which partially depend also on the extrusion parameters and the extrusion tool characteristics (several tools were used), the conductor supplier was not able to respect the originally set tolerances. They had to be relaxed in agreement with IPP to 37 ± 2 % for the void fraction and 4300 l/h ± 20 % helium mass flow at a pressure drop of 20 bar. This is reflected in Fig. 4. Some conductors slightly above the tolerance were accepted in a non-conformance procedure. All others outside of the tolerance band had to be refused for the use in the coils. Partially they are used for the W7-X bus bar system.

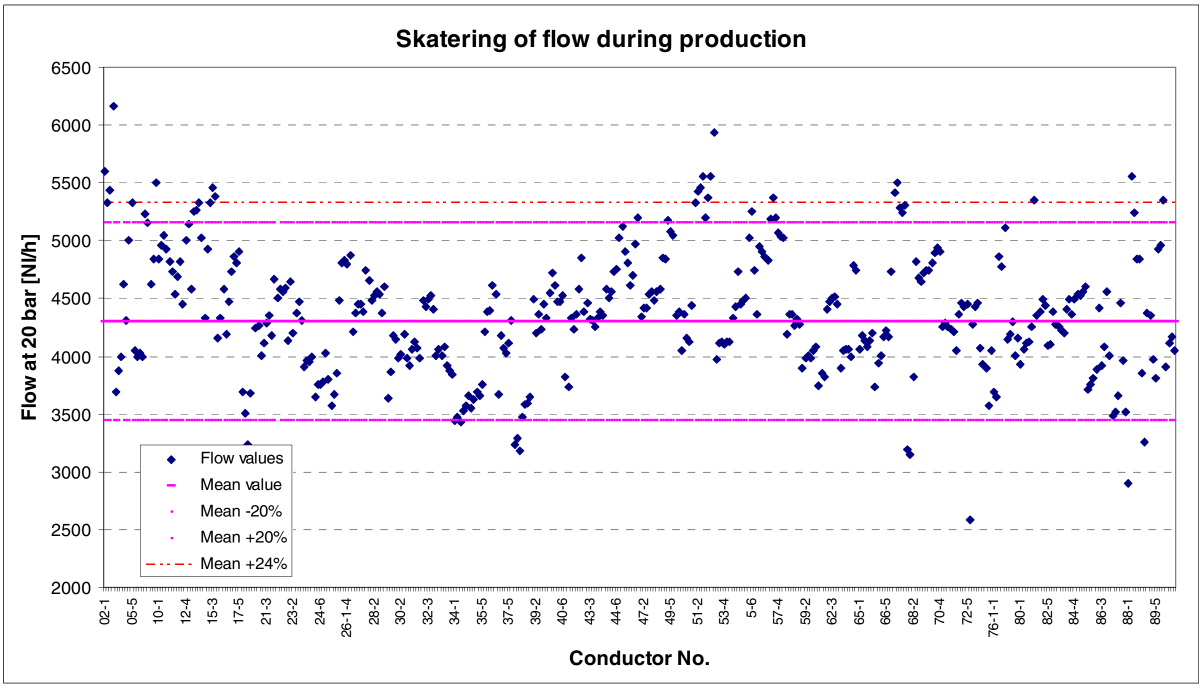

Fig. 4: Scattering of the mass flow rate at 20 bar pressure drop over the production.

In addition it turned out that after winding, heat treatment and impregnation the mass flow through the conductor lengths was increased by about 350 l/h with a standard deviation of ± 250. Therefore the reference value for the flow in the double layers of the coils was set to: 4700 l/h ± 20 %. All values outside these limits were matter of non-conformance procedures.

5. Results of short sample and single coil tests

After fabrication of the first conductors for the W7-X project some short samples were produced to test the conductor behaviour and the joint technology. The outcome of these tests can now be used to compare them with the results of the single coil tests, which are performed on each coil.

5.1 Short sample tests in the SULTAN facility of CRPP Villigen

Short samples of the W7-X conductor were tested in the SULTAN facility of CRPP-Fusion Technology, Villigen (Switzerland), the results of which were summarised in a 'Report on the tests of two samples of W7-X joint and conductor' (27.08.2003). Scaling formulas and related parameters given in this report for the W7-X conductor can be used for comparison.

Applying these parameters and using the specified values for the strand and for the extruded conductor one can plot Ic(T) at 6 T and compare the specified values with the short sample test results, as shown in Fig.5. While the measured curve follows nicely the curve of the strand specification at higher temperatures and lower currents, above about 21 kA and below 5 K the critical current cannot be reached because of premature or sudden quenches [3] occur at about Iq = Io' – bT . (Io = 31.8 kA, b = 2 kA/K). Nevertheless the operating currents of W7-X are well below the region where premature quenches could occur.

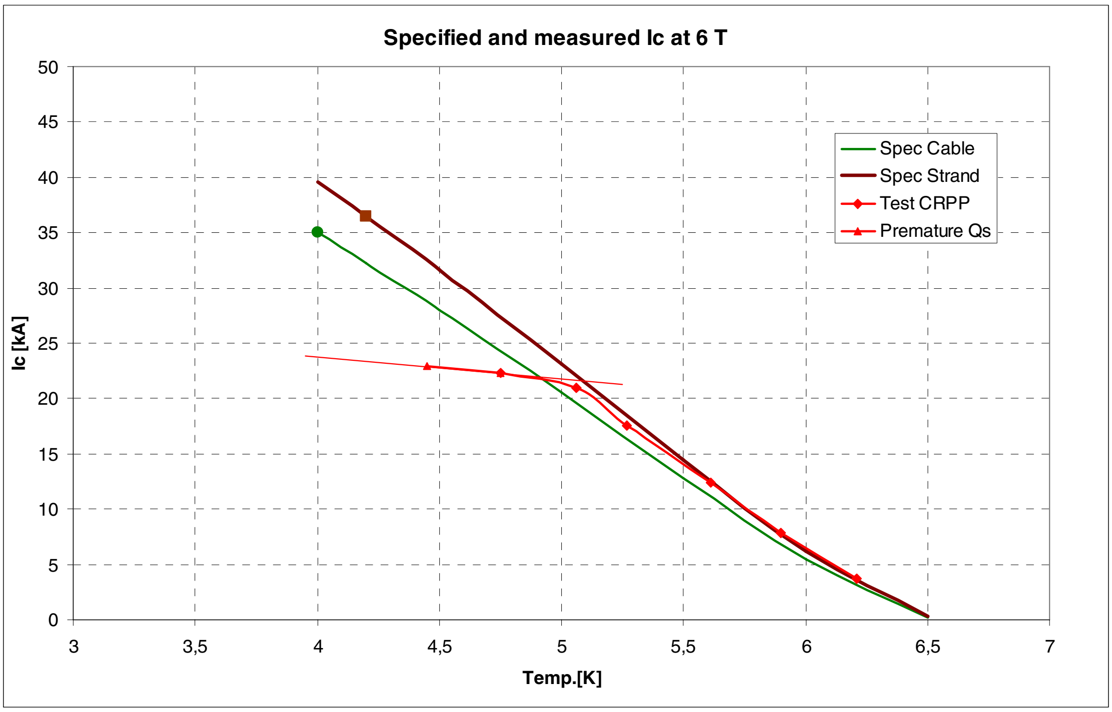

Fig. 5 Specified critical currents of the W7-X conductor in comparison with the short sample measurements. The measured Ic follows nicely the strand specification until below 5 K premature quenches occur at Iq = Io' – bT. (Io' = 31.8 kA, b = 2 kA/K)

5.2 Single coil tests at CEA Saclay

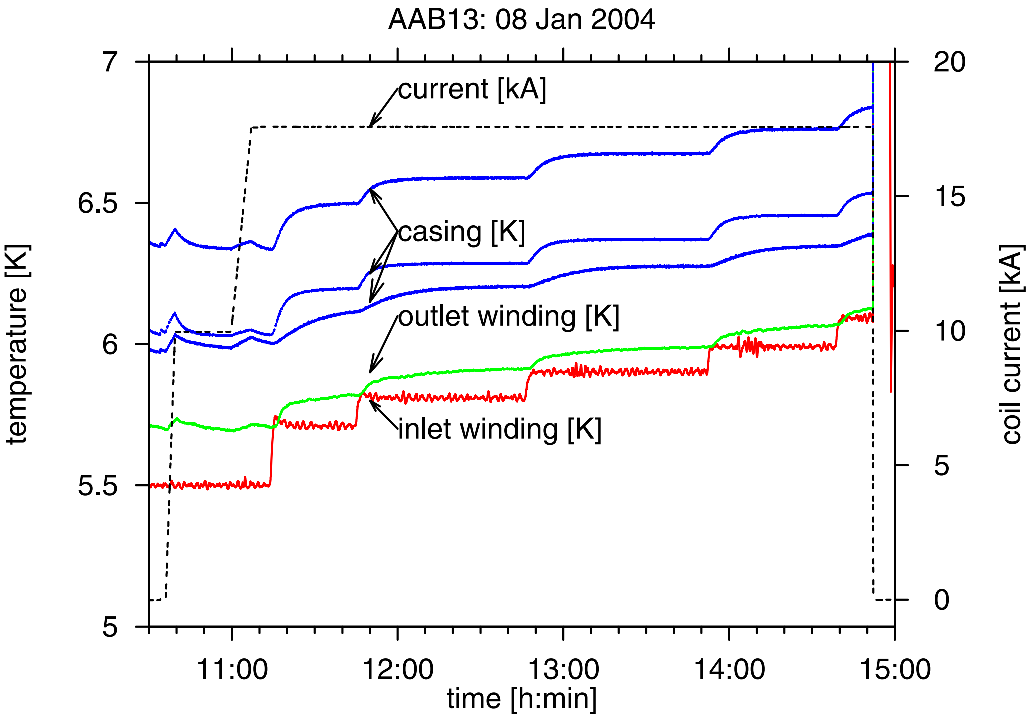

Fig.6: The coil AAB13 was energised up to the nominal current of 17.6 kA corresponding to a maximum field of 5.12 T. Then the inlet temperature was increased slowly in steps until the quench occurred at 6.1 K, which is in good agreement with the expectation from the short sample test.

The single coil tests are performed in the scope of a collaboration contract at CEA Saclay. In this test arrangement it is only possible to reach the conductor limits by increasing the temperature until the coil quenches [4]. Fig. 6 shows the example of such a test and the results on the first coils are summarised in table 3.

Table 3: Summary of single coil test results

Coil No.	Non-Planar Type 3 AAB13/18	Non-Planar Type 4 AAB24	Planar Type 3 AAC 51/52/53
Max. Field [T]	5.12	5.04	2.44
Current [kA]	17.6	17.6	16.0
Expected Tcs	5.85	5.9	7.2
Quench temperature [K]	6.1 - 6.3	6.2	7.4 – 7.5

Taking into account that the quench temperatures are slightly higher than the current sharing temperatures, the results are in good agreement with the prediction from the short sample tests.

6. Conclusions

Nearly 100 % of the conductor lengths needed to fabricate the 50 non-planar and 20 planar coils of the W7-X Stellarator is fabricated.

The strand quality of both companies is very similar and reproducible.

The conductor fabrication, namely the jacketing with aluminium alloy, turned out to be feasible. Nevertheless there would be a potential to develop and optimize the W7-X conductor further to a more homogeneous quality and a more rational fabrication.

Due to too many influencing parameters it was not possible to meet the specification concerning void fraction and mass flow. Therefore the related requirements had to be relaxed.

In the course of the contract also some other non-conformities, like broken or low Ic strands, were accepted when it was excluded that they could degrade the coil performance

Premature quenches were observed during short sample tests in SULTAN at currents well above the maximum operating currents of the W7-X coils.

The cold tests of the coils at CEA Saclay confirm the predicted conductor performance.

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