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Lessons learned from the manufacture of the W7-X planar coils

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Abstract. WENDELSTEIN 7-X (W7-X) is a superconducting stellarator. The planar coils are in charge to modify the magnetic filed configuration of the W7-X. The major challenges during manufacturing were the fabrication of the cable-in-conduit conductor, the accuracy of the coil cases after welding and machining and the development of electrical joints with a resistance below 1 nΩ. Leaks were detected during repetitive in the case cooling system, which were caused by stress corrosion cracking. High voltage tests in a reduced vacuum environment (Paschen conditions) revealed that the insulation had to be reinforced and the quench detection wires had to be exchanged. This paper gives an overview about the main technical challenges of the planar coils and the lessons learned during production.

1. Introduction

WENDELSTEIN 7-X (W7-X) is a superconducting helical advanced stellarator. W7-X has a superconducting magnet system, which consists of 50 non-planar and 20 planar coils. The coils are arranged in five equal modules. Two different planar coils are part of a half module. The planar coils are assembled over the non-planar coils and allow modification of the magnetic configuration. The symmetry requirements of the W7-X demand a highly repeatable coil shape.

2. Brief description of planar coils

The company Tesla Engineering Ltd. was contracted for the manufacture of the planar coils. 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 2.2 tonnes and an outer diameter of approximately 4.0 meters. The coils are wound from a cable-in-conduit-conductor (CICC). The main components of the planar coils are (see Fig.1):

- The winding package (WP) made of 36 turns of CICC

- The stainless steel coil case with support blocks and pads
- The cooling cladding of the coil case with copper plates and stainless steel pipes
- Temperature sensors, strain gauges and quench detection wires

Figure 1 shows an assembly of the planar coil type B.

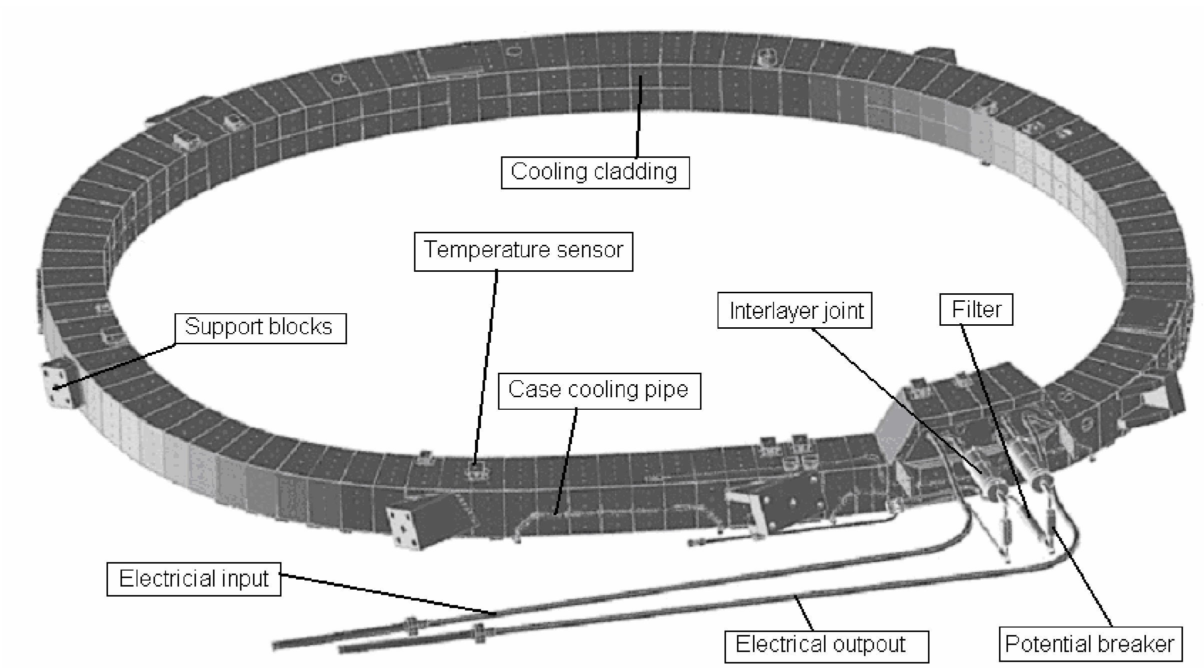

Figure 1. Planar coil type B

3. Main technical challenges

W7-X is a very complicated device which is in many respects close to the limits of existing technology. However, it also turns out standard techniques may present problems, which nobody has thought of.

During manufacturing different problems occurred and were solved using specially adapted solutions. The major difficulties were:

- Design, development, testing and qualification of a low resistance joint
- Avoiding stress corrosion cracking of stainless steel cooling tube
- Achieving Paschen-tight insulation of interlayer joints
- Leaky aluminium welds after cool down
- Operation of strain gauges

The following chapters will highlight the most difficult problems and describe how they were solved.

4. Development of a low resistance joint

In the early phases of the project, Tesla developed a design for the superconducting joints within the coils which achieved the required resistance of less than 1n . All of the design and development work was carried out by Tesla, and this included the building of a suitable cryostat and test regime to verify the performance of the joint. First samples did not fulfil the requirements, but after some improvements the quality was improved fully in accordance to the required resistance.

5. Stress corrosion cracking of stainless steel cooling pipe

The casing of the coils is covered with a copper shield and a stainless steel pipe attached to the shield. The pipe is soldered into cooling tube carriers made of copper. An aggressive flux was used for soldering stainless steel pipes into the carriers according to DIN EN 29454. Large leaks of the cooling pipes were detected after one year of storage. Pieces of the cooling pipe were inspected using SEM and micro-examination specimens (see fig.2). Stress corrosion cracking was identified as the cause for the leaks. This was due to residual chlorides from the aggressive flux, which were left because of poor access during cleaning. A new procedure for soldering was qualified. Now the pipes will be tin-plated before soldering. After that the pipes will be cleaned thoroughly while the surface is fully accessible. Soldering into the tube carriers will use a so called non clean flux. Investigations have shown that this procedure is absolutely halide free.

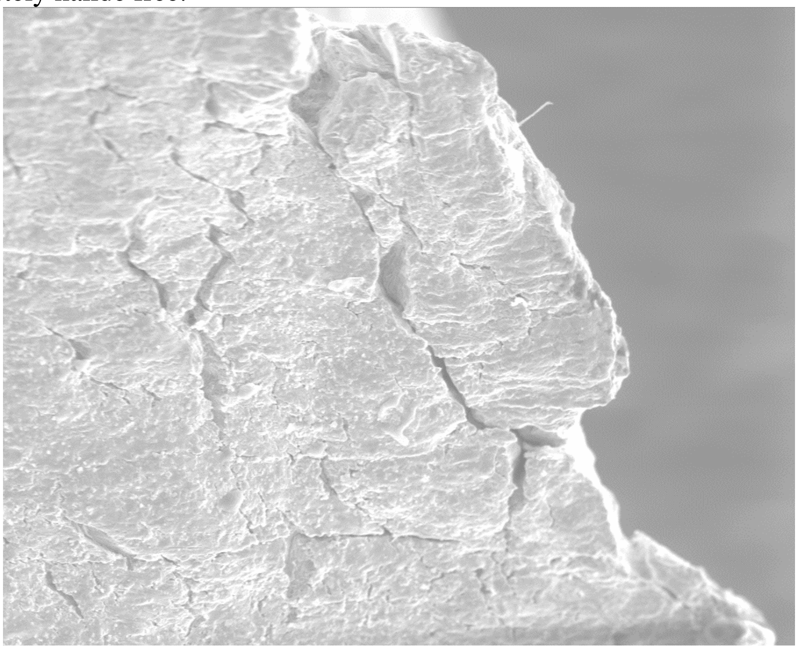

Figure 2. Stress corrosion cracks close to the fracture edge

6. Operation of strain gauges

Some strain gauges have shown strange behavior during cool-down. A detailed investigation showed that the bonding of the strain gauges was not suitable for cryogenic conditions. Measurement of stresses in cryogenic conditions is always a challenge. After extensive testing an improved bonding procedure was defined. The bonding temperature was increased by the use of a specially designed mounting tool. This allows the temperature to be well controlled during bonding and also guarantees the required contact pressure. Additionally, the glue was changed to M-bond 600. The careful preparation of the bonding, the exact temperature and the precise pressure during bonding are essential to properly fix strain gauges.

7. Leaky aluminium welds after cool down

Five planar coils have been tested in the Low Temperature Laboratory of CEA at Saclay. Although during long term vacuum tests all coils achieved the leak rate of $1*10^{-7}$ mbarl/s. Leaks appeared suddenly during the cool down. A local leak test revealed leaks in the connection between the superconductor jacket and the interlayer joint. These aluminum welds are challenging because the jacket material contains significant levels of impurities from the extrusion process, the weld must minimize heat input, the wall thickness is only 2mm, and the welding in overhead position. The failed welds were carefully removed. A modified welding procedure was qualified using a couple of full size samples. The design of the interlayer joint was modified to improve the weld penetration. Before cool down all coils will be tested at an increased helium pressure of 50 bar. Testing of the first coil has confirmed the success of the revised welding procedure.

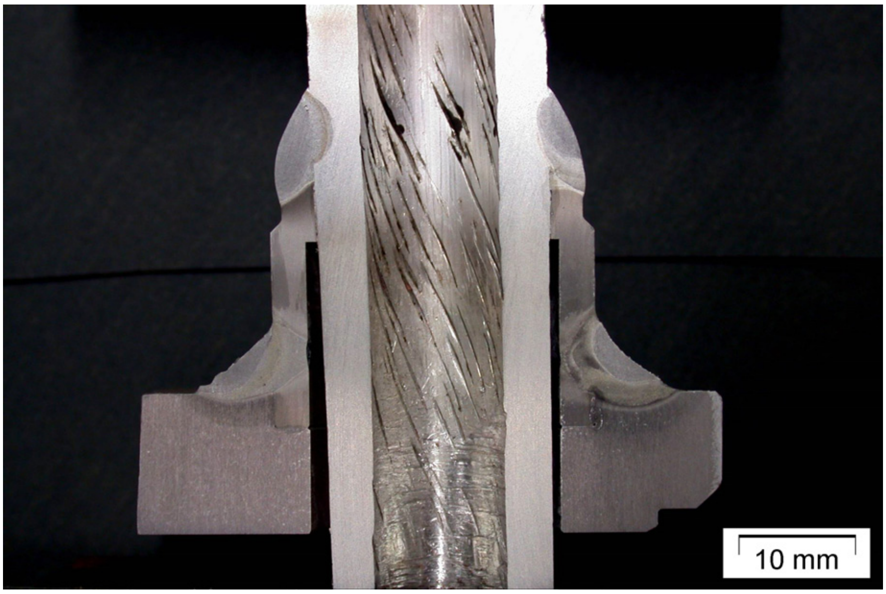

Figure 3. Macro-examination specimen of interlayer joint

8. Insulation of interlayer joints

The insulation of interlayer joints is made by cold cured resin and glass tape. High voltage tests at ambient temperature have proved an insulation resistance up to 9kV. However the first test under medium vacuum conditions (Paschen test) showed that the insulation did not work properly. Discharges occurred between the insulation of the interlayer joint and the coil case. To investigate the the insulation was stripped off completely. It was detected that resin had failed to penetrate some parts of the insulation.

In parallel an improved insulation was qualified. Samples were tested successfully up to 50kV. The following improvements were implemented:

- The insulation will be wrapped in three steps
- Each layer of insulation will be clamped while curing
- A light warm cure resin will be used
- The glass sheets will be pre-cut and the edges will be overlapped carefully
- The edges of interlayer joint body will have increased chamfers

Meanwhile the first planar coil was tested successfully in Paschen conditions. The IPP is building a large vacuum chamber to perform high voltage tests on subsequent coils under Paschen conditions.

9. Supervision and quality assurance

Tesla Engineering Ltd operates an established Quality Management System certified according to ISO 9000:2000. The system is documented and made available to all employees, and includes work instructions and Quality Control Travellers by which the quality of the product is controlled. Operatives work under the supervision of Production Managers, using Quality Control Travellers that provide an orderly sequence of each step in the manufacture, construction, inspection and testing.

Drawings require approval by the Tesla Project Manager and are then issued to IPP for approval and comment.

The documentation system also includes Non-Conformity-Reports (NCR), that document any non-conformance occurring on a coil during manufacture.

10. Conclusions

The experience with the manufacture of the planar coils has shown that all the critical components and manufacturing processes must be carefully assessed and qualified. The welding and soldering procedures are source of failures, which can be detected only with extensive campaigns of inspections, in-factory work acceptance tests and cold testing. A novelty in the W7-X production has been the introduction of high voltage tests in reduced pressure (Paschen) conditions, which are an important tool to validate the quality of the electrical insulation.

References

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