Lessons learned during design, construction and commissioning of the magnet system for Wendelstein 7-X

Compiled by Thomas Rummel
Outline

- Wendelstein 7-X Overview
- Lessons learned during
  - Design, Production and Test of
    - Superconductor
    - Superconducting coils
  - Commissioning
- Summary

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Overview

Parameters of W7-X

Major radius: 5.5 m
Minor radius: 0.53 m
Plasma volume: 30 m$^3$
Plasma surface: 110 m$^3$
Magn. field (on axis): < 3 T
Magn. field energy: 620 MJ
Heating power: 10 - 30 MW
Plasma pulse length: 30 min
Machine height: 5.5 m
Machine diameter: 16 m
Machine mass: 725 t
Cold mass: 425 t
Overview Magnets

Non-planar coils

Planar coils
Key data of the W7-X superconductor (for all coils and bus bars)

- **outer dimensions**: 16 x 16 mm²
- **wall thickness**: > 2 mm (Al alloy)
- **number of strands**: 243
- **strand diameter**: 0.57 mm
- **void fraction**: 37 ± 2 %
- **cabling law**: 3x3x3x3x3
- **Ic (6 T / 4.2 K)**: > 150 A (strand)
- **number of filaments**: 144 (NbTi)
- **filament diameter**: 26 µm
- **Cu/Sc ratio**: 2.6 ± 0.1

**Jacket:**
- Aluminum Alloy AlMgSi (6063)
- Yield strength Rp0.2
  - <150 MPa (soft, room temp.)
  - >280 MPa (hardened, 4 Kelvin)
- Allows bending radii of 120 mm
The production sequence of the W7-X superconductor:

- Strand production
- Cabling (5 steps)
- Cable check and preparation for the co-extrusion

- Co-extrusion of the aluminum jacket
- Final tests of the conductor
- Delivery to the customers

**Summary:**
- First conductor in 2001
- Last conductor in 2006
- Finally 390 parts (about 60 km) produced, tested and delivered for coils, bus bars and spares
Experiences and lessons from W7-X conductor production

- The start of the series production of the superconductor was delayed by 18 months to set up the cabling and co-extrusion process to meet the void fraction and the geometry.

Changes of many parameters to achieve a stable production process:

- stabilisation ratio Cu/NbTi
- strand diameter
- filament diameter
- void fraction
- tolerance of He gas flow
- twist pitch of 1st cabling stage
- twist pitch of 5th cabling stage
- dimensions 16 x 16 (mm)

With a proper pre production R&D and optimization program this could have been avoided.
Experiences and lessons from the W7-X conductor production

- It turned out to be complicated to deliver according the required and agreed schedule which led to further delays. The reasons were technical problems, but also partially due to the complicated relationship, if competitors form a consortium.

  Try to avoid a consortium, formed by competitors. A possibility could be a clever selection of production technologies.

- The design is mainly focused on “technical” parameters. The influence of the design to the production process should not be forgotten. A design is a good design only, if it allows a stable series production.

  The design of the conductor should respect production methods and should be accompanied by production test of representative quantities.
Cabling law 3x3x3x3x3

With the chosen 3x3x3x3x3 cabling law all the subcables become a triangular shape.
Typical cabling irregularities of a 3x3x3x3x3 cable
A slightly different 3x4x5x4 cable (240 strands) would have been better compressible and thus the grooves would have been less pronounced and the cable pattern more homogeneous.

A 4-stage cable would also have brought a reduction of production time and cost.
Experiences and lessons from W7-X conductor production

- Dealing with non-conformities requires a substantial amount of resources and experiences.

  Resources for the analysis of con conformities should be allocated (either to be developed in-house or hired externally).

  Define rules for each class of failures and follow the rules for similar failures. This saves time for respective discussions.
Experiences and lessons from W7-X conductor production

- Only during production the manufacturer learned how to measure mass flow, leak rate, jacket quality or to handle the conductor during tests.

  A clear definition of clean conditions, QA and test procedures and inspection devices has to be given in the specification, based on pre series production.

- The quality assurance and related documentation for the conductors needed additional efforts from IPP.

  Quality procedures and electronic data filing has to be agreed in advance.
  Close monitoring of the whole production incl. tests and of the time schedule is necessary.

- There was sufficient margin to accept some broken strands or reduced critical currents in the layers 2 to 6 of the winding packs of the coils.

  2 or 3 grades of conductors could have been used for the different layers to reduce costs.
Main technical parameter of the non planar coils

<table>
<thead>
<tr>
<th><strong>Non-planar coils</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>number of differently shaped types</td>
<td>5</td>
</tr>
<tr>
<td>casings</td>
<td>cast stainless steel</td>
</tr>
<tr>
<td>weight per coil</td>
<td>about 5.5 tons per coil</td>
</tr>
<tr>
<td>dimension</td>
<td>( \approx 3.5 \text{ m} \times 2.5 \text{ m} \times 1.5 \text{ m} )</td>
</tr>
<tr>
<td>nominal current</td>
<td>17.6 kA at 4 K and 6 T</td>
</tr>
<tr>
<td>Number of turns</td>
<td>108 (6 double layers)</td>
</tr>
<tr>
<td>safety margin current</td>
<td>( I_{\text{crit}} \geq 35 \text{ kA at 4 K and 6 T} )</td>
</tr>
<tr>
<td>nominal insulation voltage</td>
<td>6 kV dc</td>
</tr>
<tr>
<td>nominal voltage over terminal ends</td>
<td>1 kV (Highest discharge voltage between terminals which occurs in operation)</td>
</tr>
<tr>
<td>resistance over coil</td>
<td>&lt; 6 n( \Omega )</td>
</tr>
<tr>
<td>leak rate</td>
<td>&lt; 10 (-7 \text{ mbar l/s at RT and 4 K} )</td>
</tr>
<tr>
<td>mass flow winding pack</td>
<td>&gt; 0.6 g/s at 4 K</td>
</tr>
</tbody>
</table>
\( p(\text{in})=6 \text{ bar, } \Delta p < 1 \text{ bar} \) |
| mass flow tolerance at RT | 4700 l/h ± 20% |
\( p(\text{in})=20 \text{ bar, } 20^\circ\text{C} \) |
| nominal he-pressure | 20 bar |
| life cycle | 15 years, 50 cool downs, 50 quenches and 5000 full current changes |
## Planar Coils

<table>
<thead>
<tr>
<th>Planar coils</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>number of differently shaped types</td>
<td>2</td>
</tr>
<tr>
<td>Number of coils per type</td>
<td>10</td>
</tr>
<tr>
<td>windings</td>
<td>36 turns, divided into 3 double layers</td>
</tr>
<tr>
<td>casings</td>
<td>Welded and bolted stainless steel plates</td>
</tr>
<tr>
<td>weight per coil</td>
<td>about 3 tons per coil</td>
</tr>
<tr>
<td>dimension</td>
<td>≈ 4 m diameter</td>
</tr>
<tr>
<td>nominal current</td>
<td>16 kA at 4 K and 6 T</td>
</tr>
<tr>
<td>nominal insulation voltage</td>
<td>4 kV dc</td>
</tr>
<tr>
<td>resistance</td>
<td>&lt; 2.5 nΩ at 4 K</td>
</tr>
<tr>
<td>leak rate</td>
<td>&lt; 10⁻⁷ mbar l/s at RT and 4 K</td>
</tr>
</tbody>
</table>

![Planar Coils Image](image-url)
Winding of the non planar winding packs

Winding work at ABB (Germany)

Winding work at ASG (Italy)

Pictures by courtesy of BNN, ABB, ASG
Winding pack AAB13 after impregnation and with conductive paint
Non Planar Coils

Average deviations of the non planar winding packs

Non-Planar WPs

- abs. dev. (to CAD)
- rel. dev. (to mean shape)

Average deviations of the non planar winding packs

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Planar Coils

Planar Winding Packs

Average deviations of the planar winding packs

Result: - The accuracy meets the requirements
- Similar to the accuracy of the non planar winding packs
## Accuracy of the Coils

<table>
<thead>
<tr>
<th>Category</th>
<th>Deviation Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Non Planar winding packs</td>
<td>Absolute: &lt; 3 mm,</td>
</tr>
<tr>
<td></td>
<td>Relative: &lt; 2 mm</td>
</tr>
<tr>
<td>20 Planar winding packs</td>
<td>Absolute: &lt; 3.5 mm,</td>
</tr>
<tr>
<td></td>
<td>Relative: &lt; 1.5 mm</td>
</tr>
</tbody>
</table>

### Conclusion:
- Achieved accuracy within the requirements
- No significant difference between non planar (3 D) coils and planar coils
**Coil casing production**

<table>
<thead>
<tr>
<th>properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>casing</td>
<td>made by two cast half shells welded together</td>
</tr>
<tr>
<td>case material</td>
<td>DIN 1.3960 (eq. to AISI 316LN)</td>
</tr>
<tr>
<td>cobalt content</td>
<td>&lt; 500 ppm</td>
</tr>
<tr>
<td>Yield strength (Rp0.2)</td>
<td>&gt; 800 MPa at 4 K</td>
</tr>
<tr>
<td>Breaking elongation</td>
<td>&gt; 25 %</td>
</tr>
<tr>
<td>permeability</td>
<td>&lt; 1,01</td>
</tr>
<tr>
<td>permeability for welds</td>
<td>&lt; 1,05</td>
</tr>
<tr>
<td>contour tolerance</td>
<td>outer side +/-5mm</td>
</tr>
<tr>
<td></td>
<td>side faces +/-5mm</td>
</tr>
<tr>
<td>contour tolerance in spec. defined collision areas</td>
<td>side faces +/- 3mm</td>
</tr>
<tr>
<td></td>
<td>inner side +/-2mm</td>
</tr>
<tr>
<td>different machined support blocks</td>
<td>central, assembly, weight, lateral, narrow supports partially cast or welded</td>
</tr>
<tr>
<td>position tolerance of thread holes / or fitting holes</td>
<td>0.2mm till 0.6mm</td>
</tr>
</tbody>
</table>
Non planar coils

Coil production
Summary:

- First coil in 2003
- Last coil in 2008

Delays due to:
- Late delivery of Superconductor
- Repairs:
  - Insulation
  - QD-cables
  - Welds
- Design changes:
  - structural reinforcements

- What else?
  - Paschen tests have proven as a very efficient tool to verify the quality of an insulation
Planar Coils

Summary

First coil in 2003
Last coil in 2007

Delays due to:
• Late delivery of Superconductor
• Repairs:
  • Insulation
  • QD-cables
  • Welds
  • Soldering of cooling tubes to copper blocks

• Design changes:
  • structural reinforcements
Lessons learned (focused on electrical insulation)

The design of the components has to respect the insulation which will be applied during the manufacturing process.

A rounded outer shape and a good accessibility without hidden areas help to manufacture the insulation and increase the quality.

The efforts to create a reliable handmade insulation are often underestimated. The failure rate is by far higher than by using VPI.

Therefore it is strongly recommended to find a design which allows to use vacuum-pressure-impregnation of the complete winding pack (not only parts of it).

Higher effort for development of the impregnations case would have been at the end cheaper and faster than the repairs.
Lessons learned

The workshop for the winding and insulation work must be clean to avoid any damage of the insulation system.

A guideline of electrical tests has to be implemented for all steps of the manufacturing process from the beginning on. The test equipment should be identical in different workshops. The customer should witness the tests.

As earlier the tests will be done in the production process, as easier a repair can be done. Do not relay on one test after fabrication. Require intermediate tests, too. Paschen Tests (HV test under reduced air pressure) are a powerful method and can be combined with the leak test.

It is recommended to implement a safety margin into the manufacturing process by an high test voltage at the beginning, which will be gradually reduced during the manufacturing until the final acceptance test in the workshop.
Example for the definition of the test voltage:

- Maximum voltage to ground during a fast discharge: 2 kV
- Maximum voltage to ground during a fast discharge assuming an undetected ground fault (which might be difficult to detect in superconducting systems): 4 kV

⇒ + 50 % margin = 6 kV = “Nominal voltage”

- Test voltage for the production: 2 x “Nominal voltage” + 1 kV = 13 kV (=100%)
Non Planar Coils

Manufacturing and factory acceptance test

Acceptance tests at 4 K

W7-X assembly preparation

Assembly and commissioning

100% of the test voltage = 13 kV

80% of the test voltage = 10.4 kV

70% of the test voltage = 9.1 kV

40% of the test voltage = 5 kV

Transition of property

Transition of responsibility

Result

The test voltage of 5 kV provides
β a comfortable margin of 3 kV in a faultless system and
β a sufficient margin of 1 kV in case of a ground fault and
β does not pose a high long term risk for the insulation.
Communication is always an issue…

Support blocks were intended to be welded onto the casing. Due to changes in the production technology of the casings from welding of forged plates to casting an improvement was announced: casting the blocks together with the casing could save time. Unfortunately the geometry was optimized for welding but not for casting (sharp edges, no smooth transition from main body to casing.

Result: bubbles and holes
Recommendation: Analysis of proposed improvements should be made under integration of the designer and of manufacturing experts.
Coil Test under cryogenic conditions

- All coils were tested up to the nominal current
- Two cryostats, hosting two coils each
- Cool down within 10 days, test duration 1 week
- Full current tests at 5 K in the self field:
  - Thermal Stability
  - Deformation
  - Mechanical stress in the casings
- Quench test at selected coils to check the margin
- High voltage tests
- Helium leak tests
Summary

- First coil tested in 2003
- Last coil tested in 2009
- In total 99 tests (due to repairs and changes during the coil fabrication)
- Finally all coils accepted
- Superconductivity was never the problem!
Lessons learned:

- Cold tests are mandatory to identify failures which could otherwise risk the total project.
- The majority of the failures appeared during the first cool down, but the most dangerous failure (interlayer short) only after the test with nominal current.
- Cold testing is itself a project and should be handled accordingly.
- It should be clear from the very beginning (or at least when the specification of the magnets is finalized), if there will be cold tests, because it influences strongly the test strategy during the production.
- It is mandatory to have personal from the customer on site, which have also the knowledge about production and the intended use of the magnets in the machine.
- Cold tests make the commissioning easier (confidence, failure localization).
- **Superconductivity was never the problem.** Application of electrical insulation, imperfect stainless steel and aluminum welds, reliable function of sensors (temperature sensors, strain gages) posed the problems.
Prepared for the first plasma (Dec. 2015)
Commissioning is a point of an important transition:

From a

Component

to a

System
In W7-X there are seven electrical circuits with 10 coils of the same type each, bus bars, joints and current leads.

- BS = bypass switch;
- FDBU = fast discharge breaker unit (two bypass switches, two DC breakers and one explosive fuse);
- $R_D$ = discharge resistor;
- $L_1, L_2, ..., L_{10}$: ten coils of the same type in series (1 H per circuit)
- Joint

Normal conducting bus bar
Superconducting bus bar
Cryostat

Power Supply +/- 30 V
Magnet safety system
Magnet circuit

Power Supply +/- 30 V

FDBU

Rd

BS

Magnet safety system

Not tested before at high inductive load

Current lead

Normal conducting bus bar

L1

Coil

L2

Coil

Cryostat

Superconducting bus bar

L10

Coil

Current lead

Not tested before under cryogenic conditions with current
Challenges of the commissioning of the magnet system:

- Operation of the superconducting bus bars and of the joints for the first time ever,
- Operation of the quench detection system together with sc coils, bus bars, current leads for the first time,
- Operation of the power supplies with a high inductive load (factor 300 higher than the dummy load),
- Operation of the cryo plant under the final load for the first time
- Co-ordination between magnets, cryogenics, vacuum systems, mechanical engineering, computer networks, main control room,….
The commissioning was divided into six phases:

i. Vacuum tests of the cryostat
ii. Cu-coil systems tests
iii. Cryogenic tests of the cryostat
iv. Vacuum tests of the plasma vessel
v. Superconducting magnet coil systems tests
vi. Preparation for the first plasma
The strategy for the commissioning is divided in several main steps:

1. Test of the seven coil groups one by one up to the required current for the first plasma operation phase,

2. Test of the seven coil groups together up to the current foreseen for the first plasma operation phase only.

3. Higher currents for further plasma campaigns will require again a commissioning phase.
Stepwise increase of the currents in all circuits up to:

- 12.8 kA in the non planar coil circuits and
- 5 kA in the planar coil circuits

• adjustment of the controller to the magnetically coupled circuits
The cool down ran smoothly. The mass flow and its distribution was successfully adjusted. The thermal insulation is working well.

The Quench detection system was successfully adjusted and is working stable.

The several levels of the current were reached and operated without problems (no quenches).

The accuracy of the power supplies’ controllers and the electrical and thermal long term stability during “pulses” of up to 8 hours as well as the reproducibility are well within the specification.

Slow and fast discharges of the coil circuits were performed in the expected manner. The cryo plant is able to manage the amount of gas, but need up to one day to recover.

The displacement and the stresses in coils and support elements are far below any critical limit and in good agreement with the FE calculations.

There are no signs of too high resistances of the joints.

The magnet system commissioning took 21 days.

The warm-up ran smoothly and without severe disturbances.
Lessons learned

- Commissioning in parallel to assembly induces additional efforts, but is not an unsolvable problem.
- Paper work for preparing the commissioning is tedious but mandatory.
- For complex commissioning tasks, a trial run has proven to be very important.
- For preparation of commissioning, also the peripheral systems have to be monitored and coordinated in detail (time issue).
- Changes in the sequence or additional tests require much more organizational effort compared to the component tests.
- Issues during Magnet system commissioning came not from the magnets, but from periphery!
- Proposal for improvement: Use the power supply, quench detection, magnet safety system, and cryo plant already for the cold test of the magnets. For large and heavy magnets this would pose also handling and transportation advantages.

Just a reminder:
The successful commissioning of the magnets is not the end, it is the begin of the commissioning for the intended use of the machine....
A competent project team must be set up prior to design completion, component specification, and start of procurement. Any lack in the work done at this stage will create dramatically higher efforts, in cost and time, later in the project.

There must be five to ten persons in the project that know the machine from a\textendash}z. Clear project structures and responsibilities are mandatory. Matrix structures should be avoided wherever possible.

As time goes by: the total duration of the project from first application 1990 until first plasma in 2015 created unexpected loss of (design) knowledge during the realization. Future projects might even exceed the professional lifetime of the crew members. An active recruitment management to have a proportional mix of the ages could be a way out (the better way would be to shorten the duration of projects\ldots).

“Margin can only be replaced by more margin!” A lack of generous margins, clearances, and reasonable tolerance levels implies uncontrolled and unnecessary increase of complexity and frequent changes. This has a strong impact on time, costs, and manpower demands (and potentially sours the relationship to funding bodies). Margins should be an essential part of the design, should reserved as long as possible and spent only in case repairs are not possible.
- The superconducting magnet system is the technical heart of the machine.
- It’s procurement and assembly was running nearly over the whole construction period of the machine from 1998 until 2013.
- A number of important lessons had to be learned by all (!) partners.
- Wendelstein 7-X magnets turned into a success story: At the end the magnet system was produced, assembled and commissioned successfully.
- Thanks to the intensive tests in advance, the commissioning was performed without substantial problems.
- Meanwhile the magnet system is in regular operation. Two plasma operation campaigns of Wendelstein 7-X were successfully completed.
- The preparation for the third campaign has just been started with the beginning of the cool down last Friday.
Thank you!

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