The Superconducting Magnet System of Wendelstein 7-X

Outline

- Overview
- Superconductor
- Non planar coils
- Planar coils
- Bus bar system
- Current leads

Mission

The technical mission of WENDELSTEIN 7-X

- ….
- Demonstration of the **modular structure** of the device (**modular coils**)
- Demonstration of the suitability of a **superconducting magnet system**
- ….

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): < 3T

Magn. field energy: 620 MJ

Heating power: 10 - 30 MW

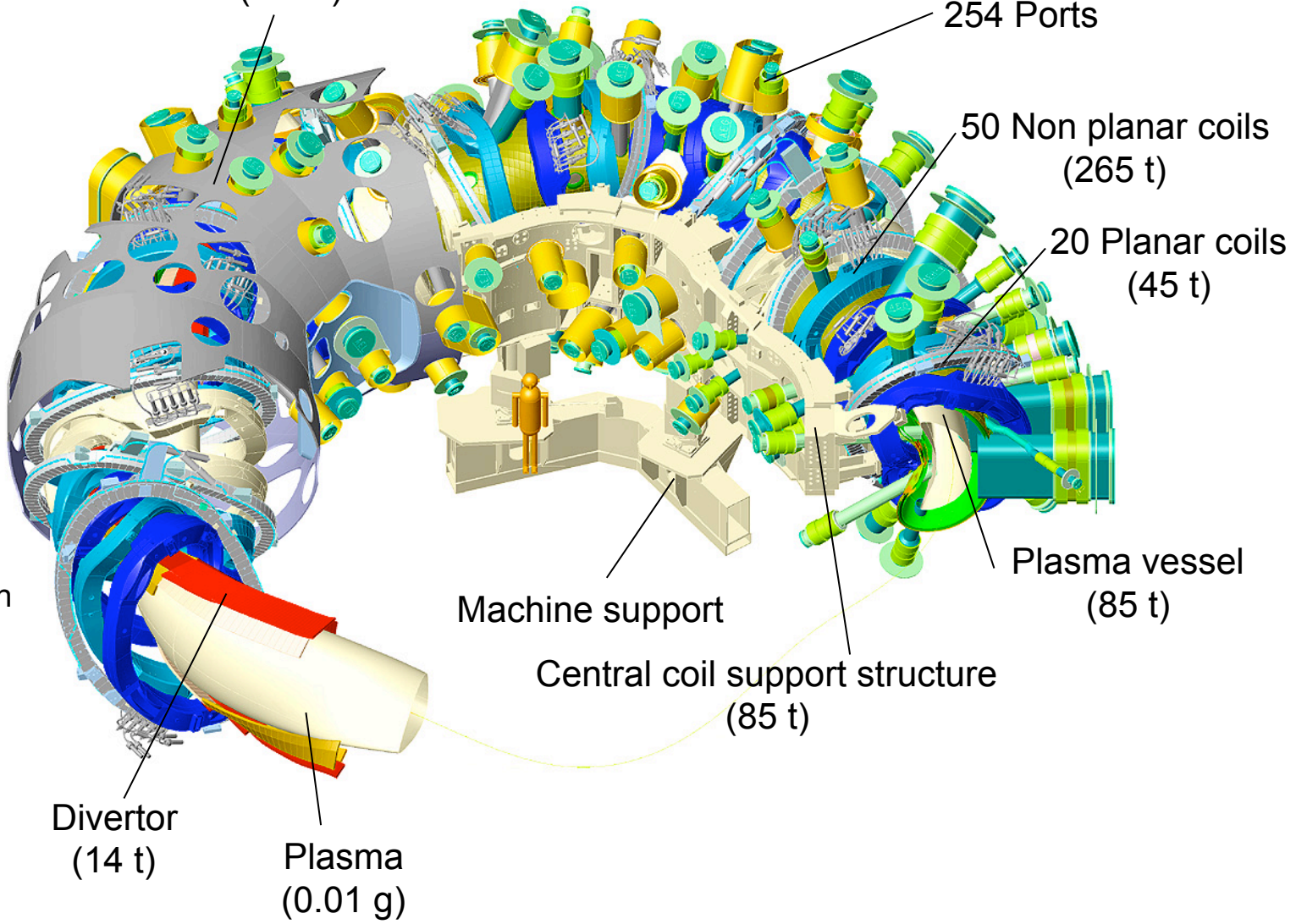
Plasma pulse length: 30 min

Machine height: 5.5 m

Machine diameter: 16 m

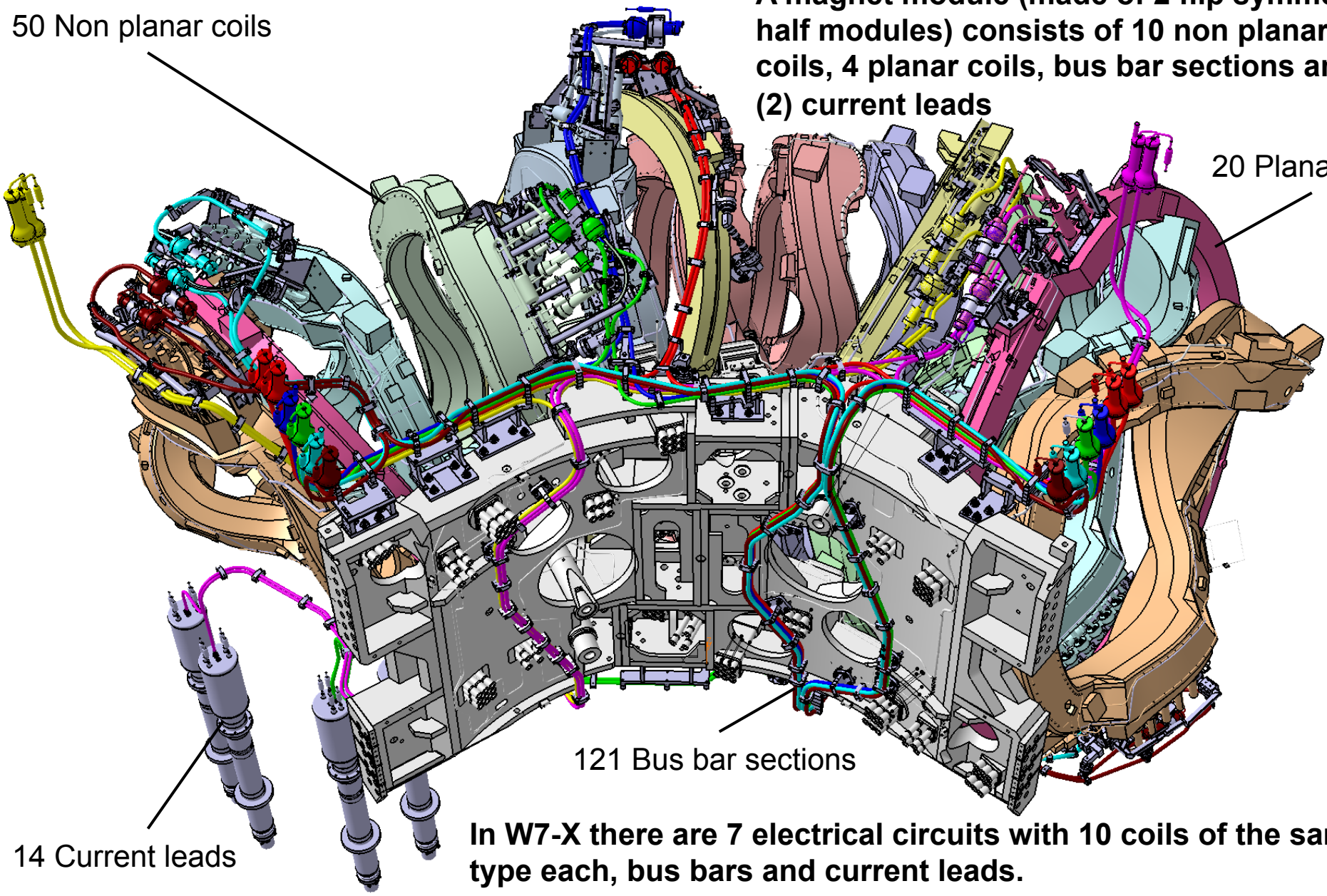
Machine mass: 725 t

Cold mass: 425 t



Superconducting magnet system

A magnet module (made of 2 flip symmetric half modules) consists of 10 non planar coils, 4 planar coils, bus bar sections and 4 (2) current leads



In W7-X there are 7 electrical circuits with 10 coils of the same type each, bus bars and current leads.

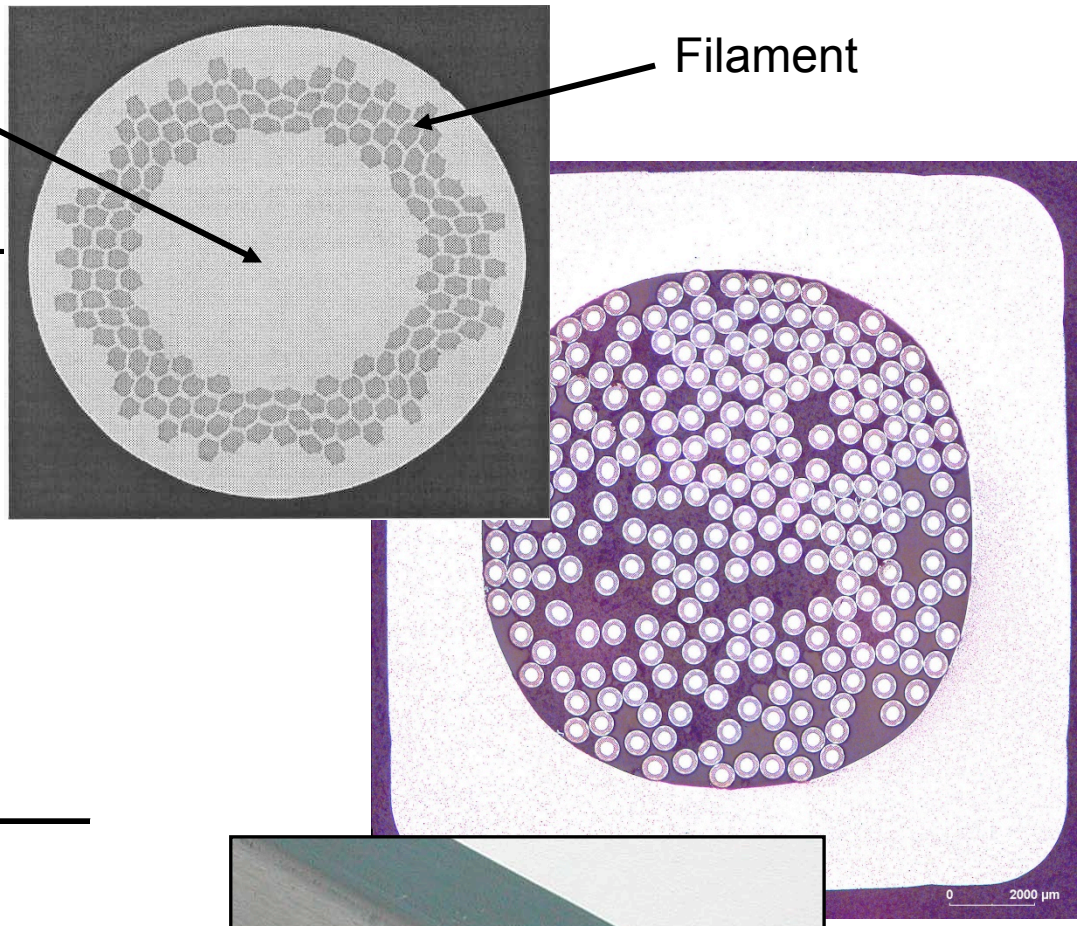
Superconductor

Key data of the

W7-X superconductor

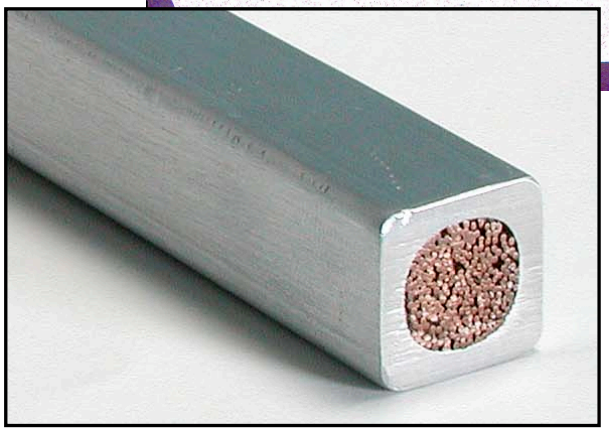
(for all coils and bus bars)

outer dimensions	16 x 16 mm^2
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

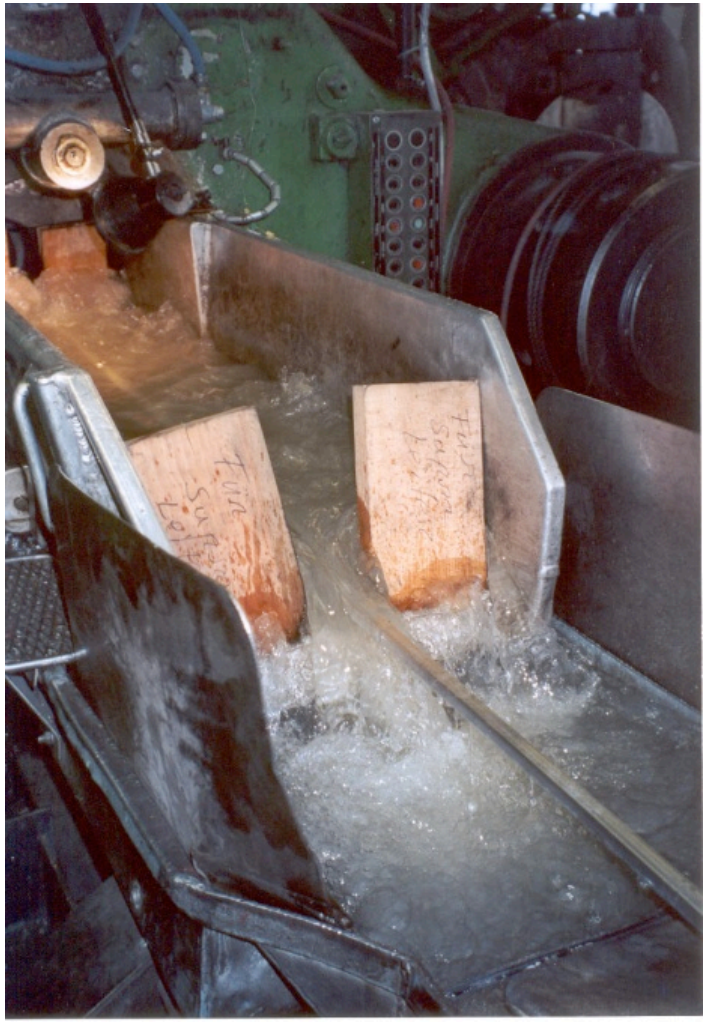


Superconductor

The production 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

- **Organizational challenge:** consortium, many involved companies in different countries
- **Technical challenge:** mass flow and void fraction



Co-extrusion

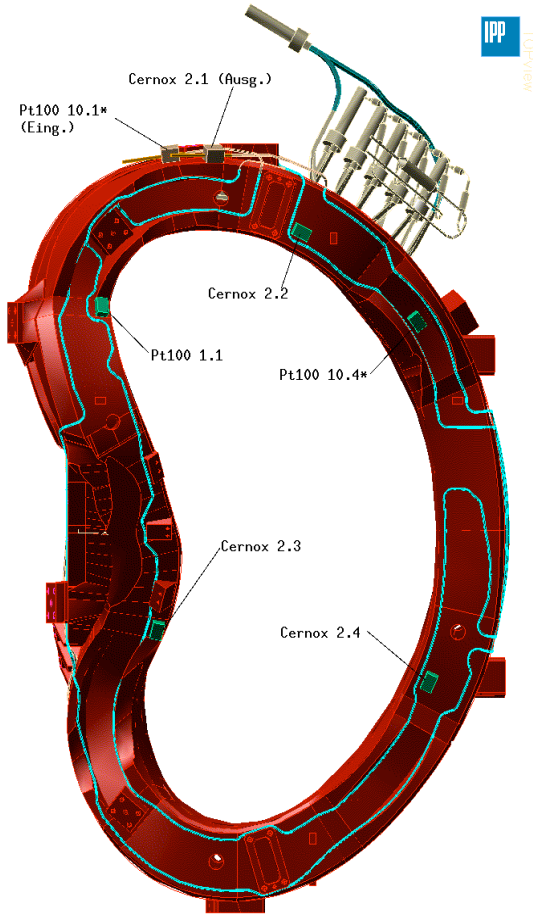
Summary:

- First conductor in 2001
- Last conductor in 2006
- Finally 390 parts (about 60 km) produced, tested and delivered for coils, bus bars and spares

Non Planar Coils

Main technical parameter of the non planar coils

	Non planar coils
number of differently shaped types	5
windings	108 turns, divided into 6 double layers
casings	cast stainless steel
weight per coil	about **5.5 tons per coil**
dimension	≈ **3.5 m x 2.5 m x 1.5 m**
nominal current	17.6 kA at 4 K and 6 T
nominal insulation voltage	6 kV dc
resistance of coil	< 6 nΩ at 4 K
leak rate	< 10^{-7} mbar l/s at RT and 4K
life time	15 years, 50 cool downs, 50 quenches and 5000 full current changes



Special challenge: three dimensional winding pack

Non Planar Coils

Winding of the non planar winding packs

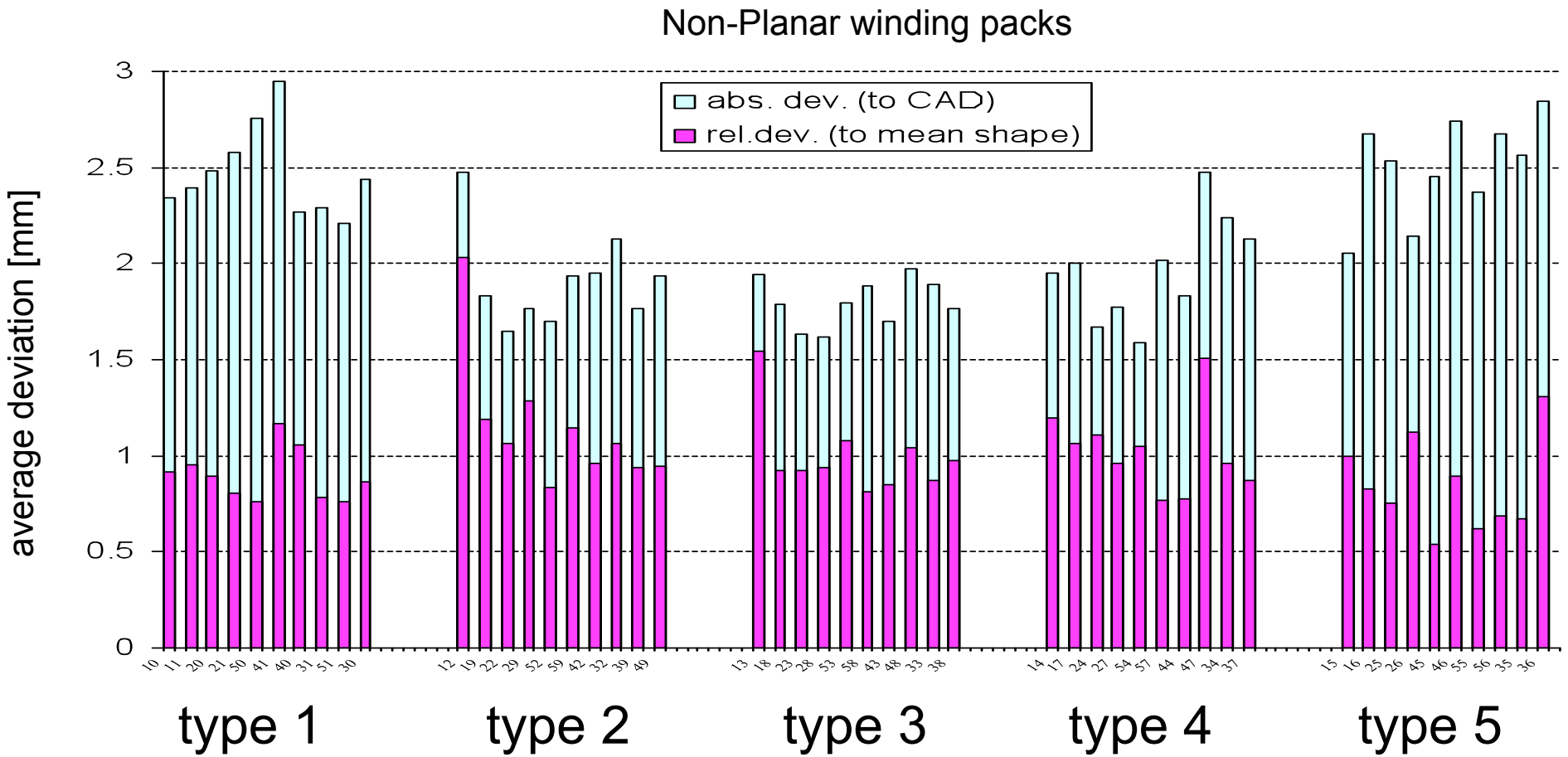
Winding work at ABB (Germany)

Winding work at ASG (Italy)

Non Planar Coils

Winding pack

Non Planar Coils



Average deviations of the non planar winding packs

Result: - The geometry meets the requirements
- Accuracy nearly independent from the shape

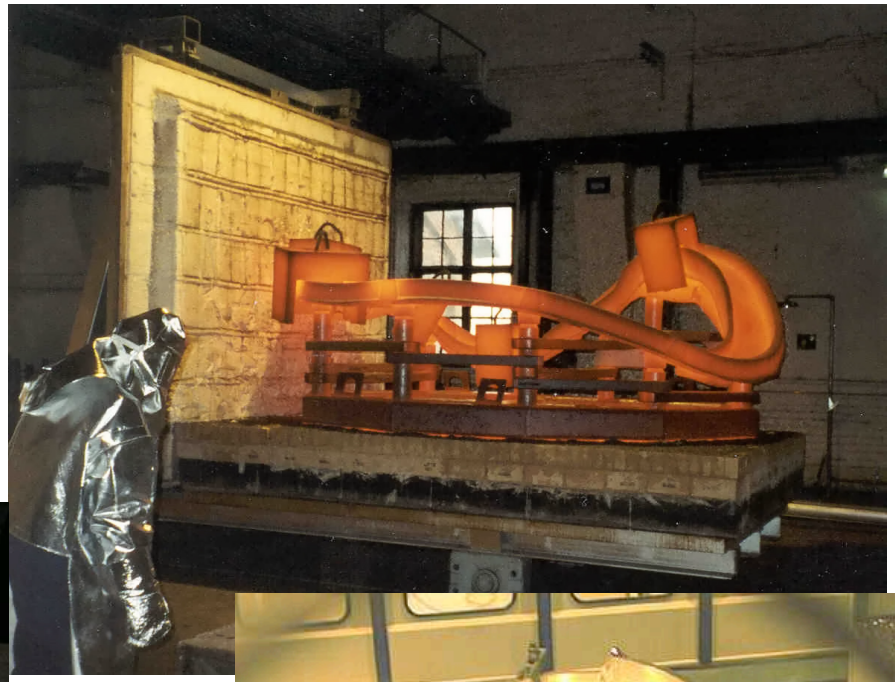
Non Planar Coils

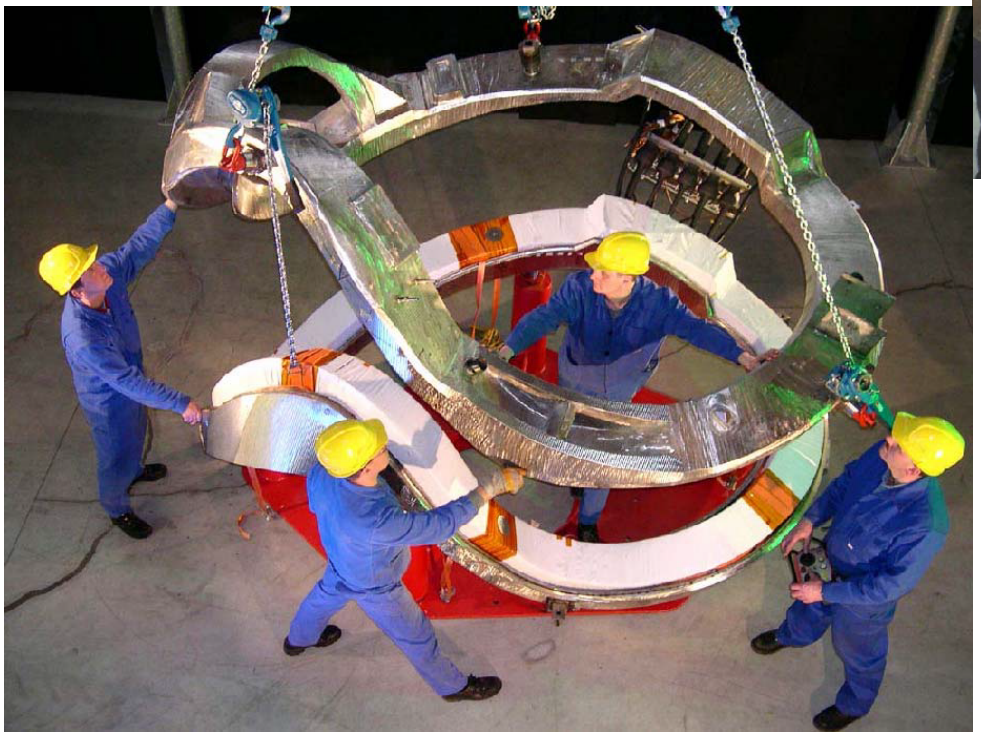
Coil casing production:

- Cast and machined stainless steel half shells

Coils assembly:

- Winding pack placed into the half shells
- Half shells connected by welding





Non planar coils

Coil production

Non Planar Coils

Summary:

- First coil in 2003
- Last coil in 2008
- Today: all 50 coils produced, tested and assembled

Delays due to:

- Late delivery of Superconductor
- Repairs:
  - Insulation
  - QD-cables
  - Welds
  - Casting defects
- Design changes:
  - structural reinforcements

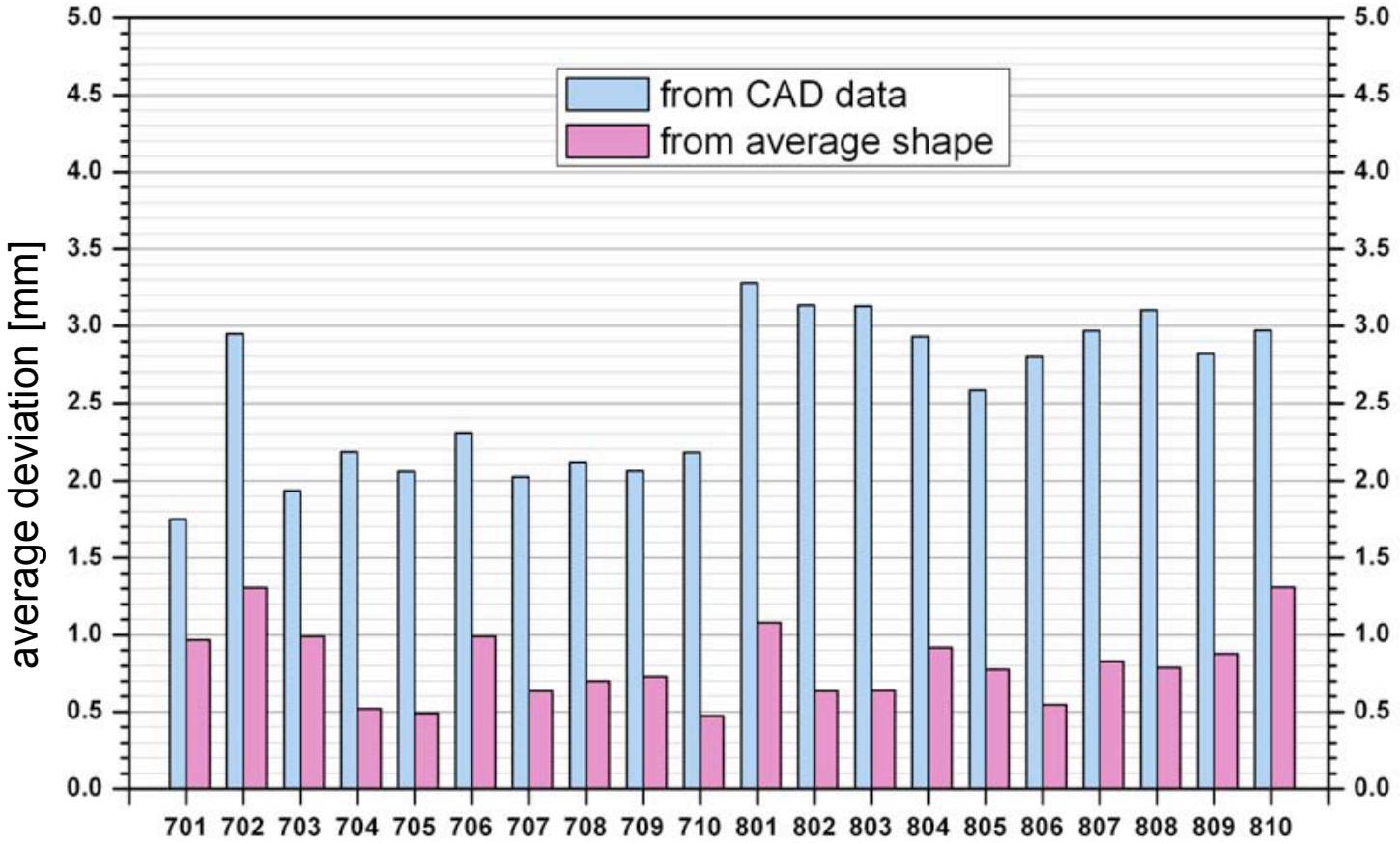
- What else ?
  - HV tests at reduced pressure (Paschen tests) have proven as a very efficient tool to verify the quality of an insulation

Planar Coils

	Planar coils
number of differently shaped types	2
windings	36 turns, divided into 3 double layers
casings	Welded and bolted stainless steel plates
weight per coil	about **3 tons per coil**
dimension	≈ **4 m diameter**
nominal current	16 kA at 4 K and 6 T
nominal insulation voltage	4 kV dc
resistance of coil	< 2.5 nΩ at 4 K
leak rate	< 10^{-7} mbar l/s at RT and 4K
life time	15 years, 50 cool downs, 50 quenches and 5000 full current changes

Planar Coils

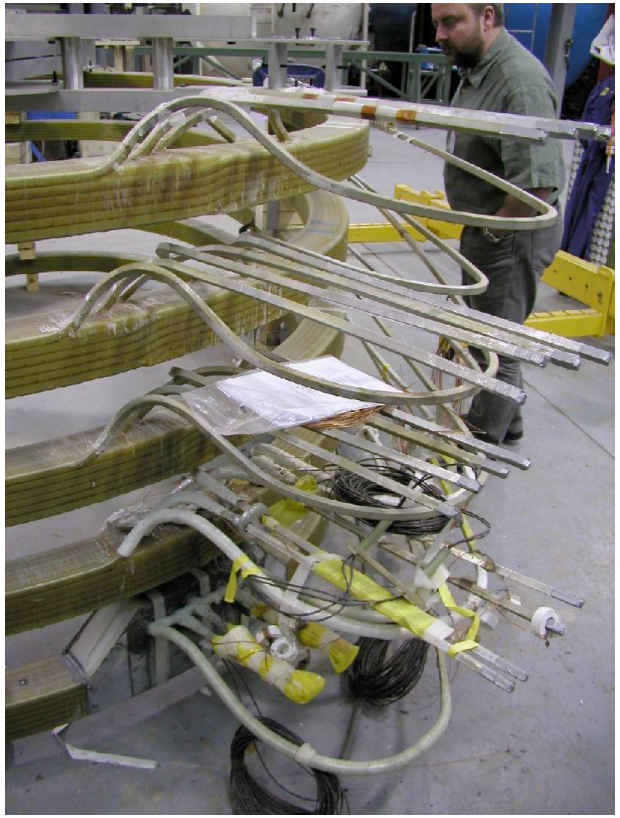
Planar Winding Packs

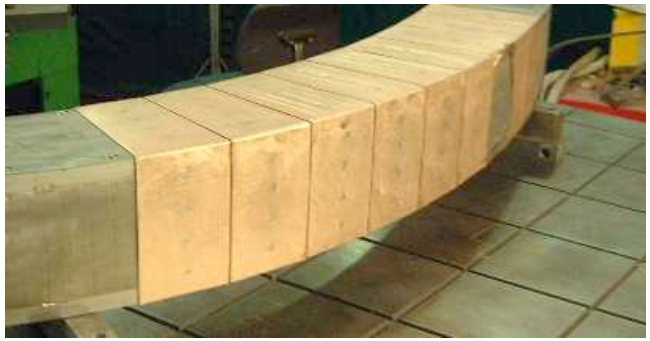


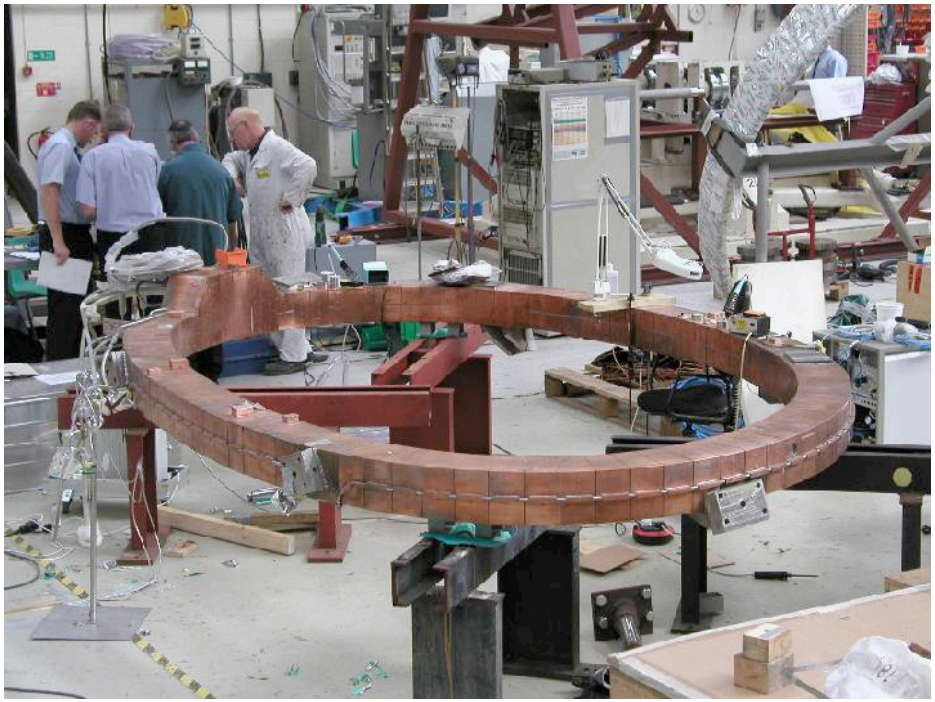
Average deviations of the planar winding packs

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

Planar Coils







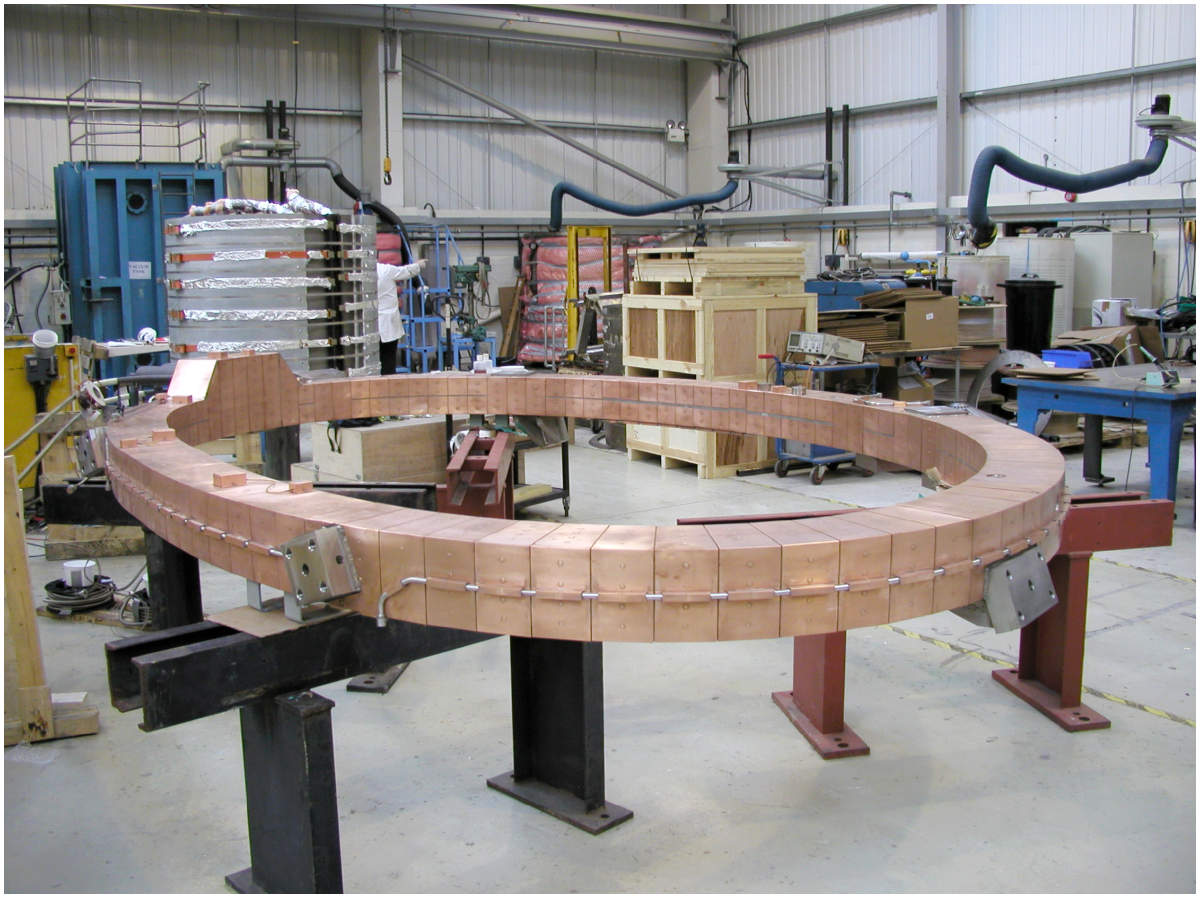
Planar Coils

Summary

- First coil in 2003
- Last coil in 2007
- Today: all 20 coils produced, tested and assembled

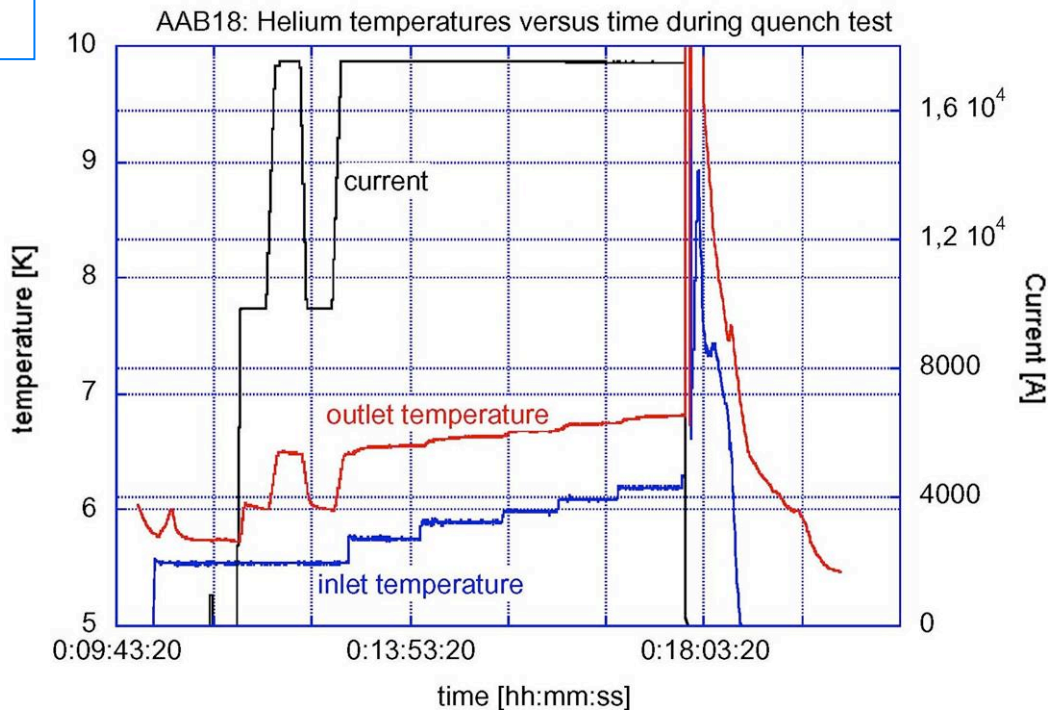
Delays due to:

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



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
- Full current tests at 5 K in the self field:
  - Thermal Stability
  - Deformation
  - Mechanical stress in the casings
- Quench test to check the margin
- High voltage tests
- Helium leak tests



Coil Test under cryogenic conditions

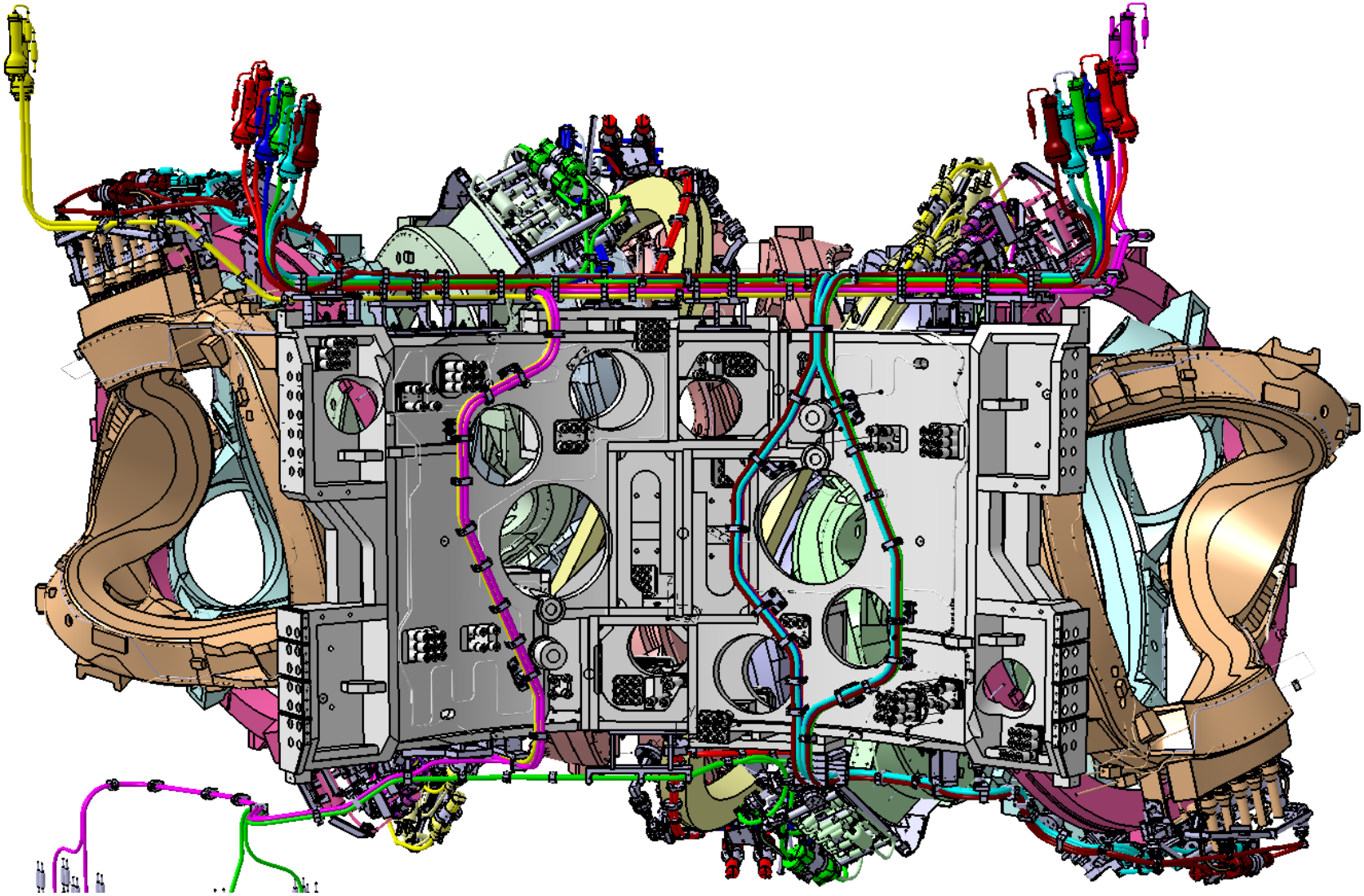
Identified problems:

- Cold leaks in welds (Al, SS)
- Cracks in the insulation
- Insufficient QD cables
- Detached sensors

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 !**

Bus bar system



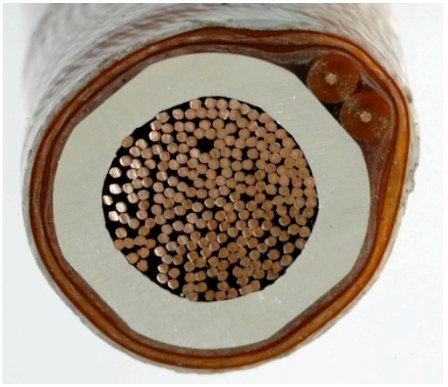
Bus bar system

- Superconducting bus bar system provide the connection
  - between the 10 coils of the same type
  - between coils and current leads
  - between bus bar section at the module separation area

- Special challenges in W7-X:
  - Different thermal expansion between coil supports (steel) and bus bars (Al)
  - Displacement of coils under load (up to 24 mm)
  - Remount ability of the joints
- **=> In total 121 bus bar sections (1.2 km), ~400 supports, ~700 clamps and 184 joints**

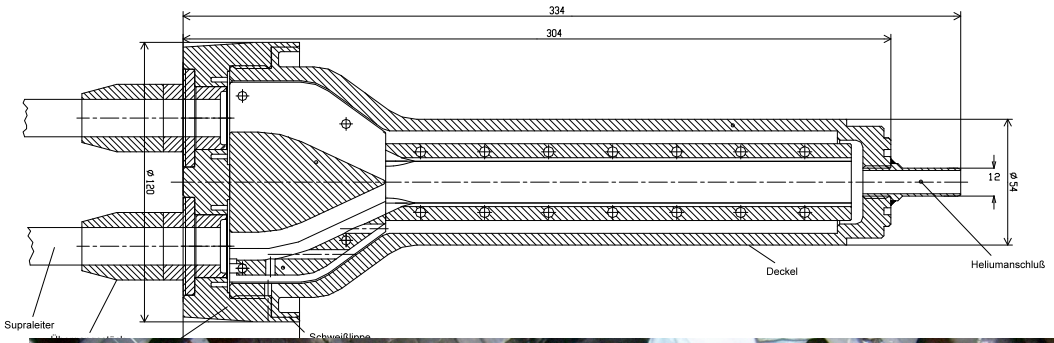
Co-operation between IPP and the Research Centre Jülich (FZJ), Germany
and the INP in Krakow (Poland)

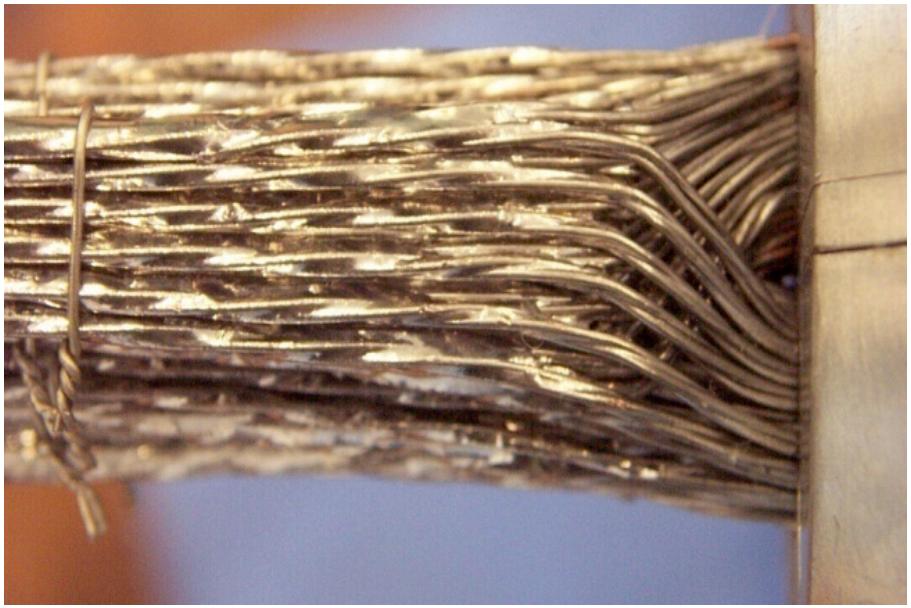
Electrical insulation:
•Thin (space)
•Flexible (movements)
•Result: Kapton reinforced glass tape with epoxy resin

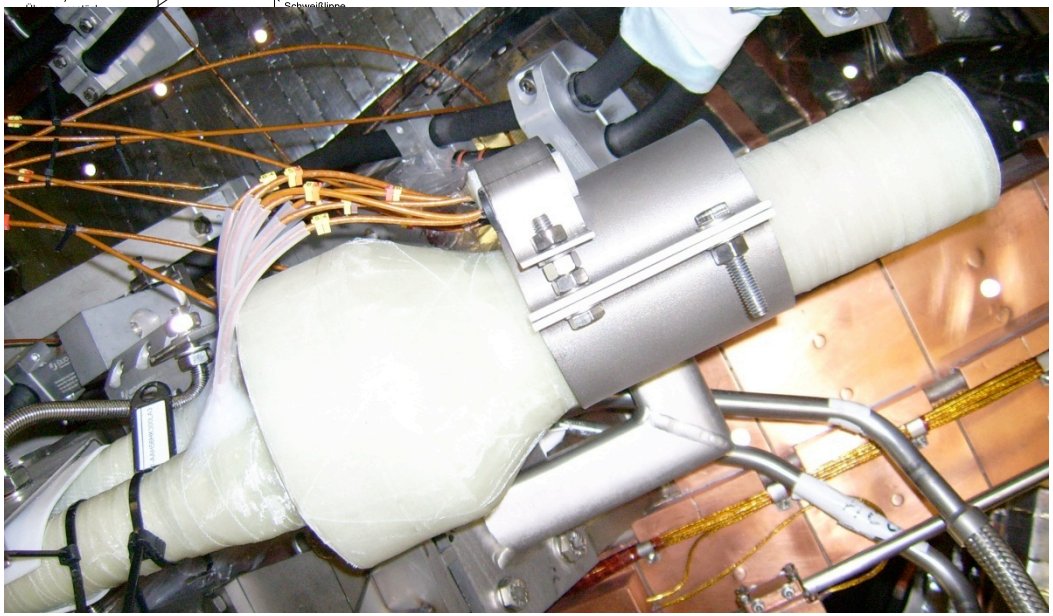


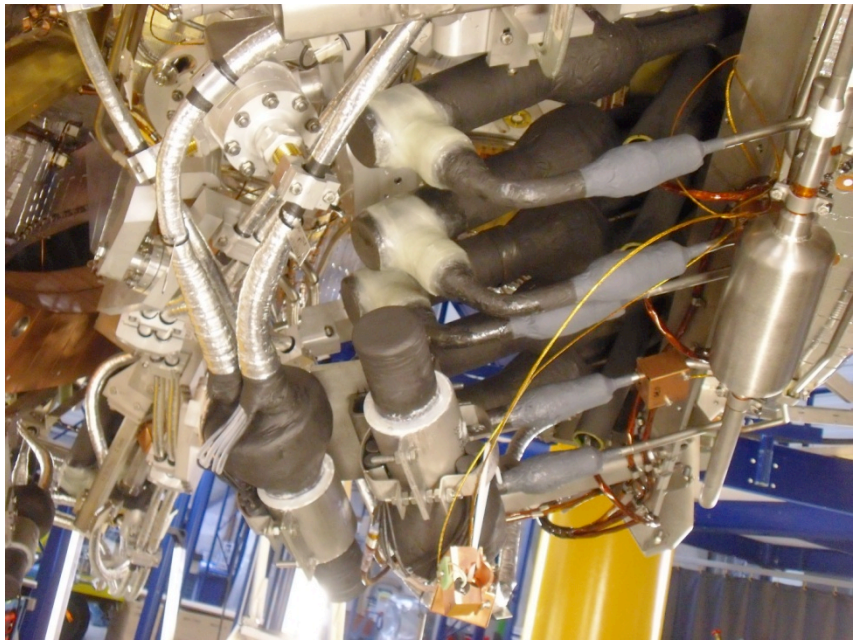
Bus bar joints

- 184 joints
- soldering of the strands of the two cables
- insert the bundle in a clamp
- Insulation made of glass tape and epoxy resin
- achieved resistance < 1nΩ

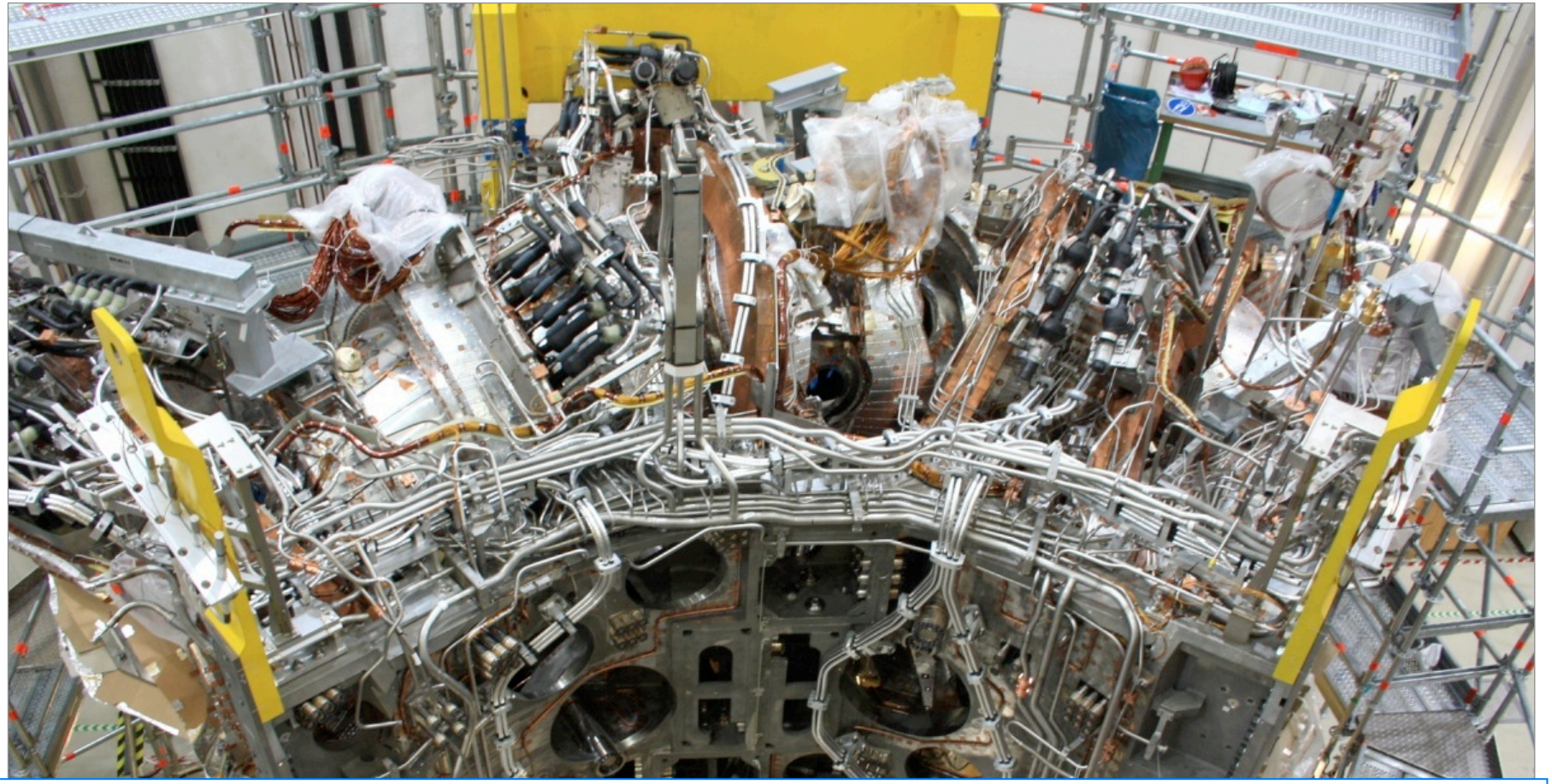








Bus bar system

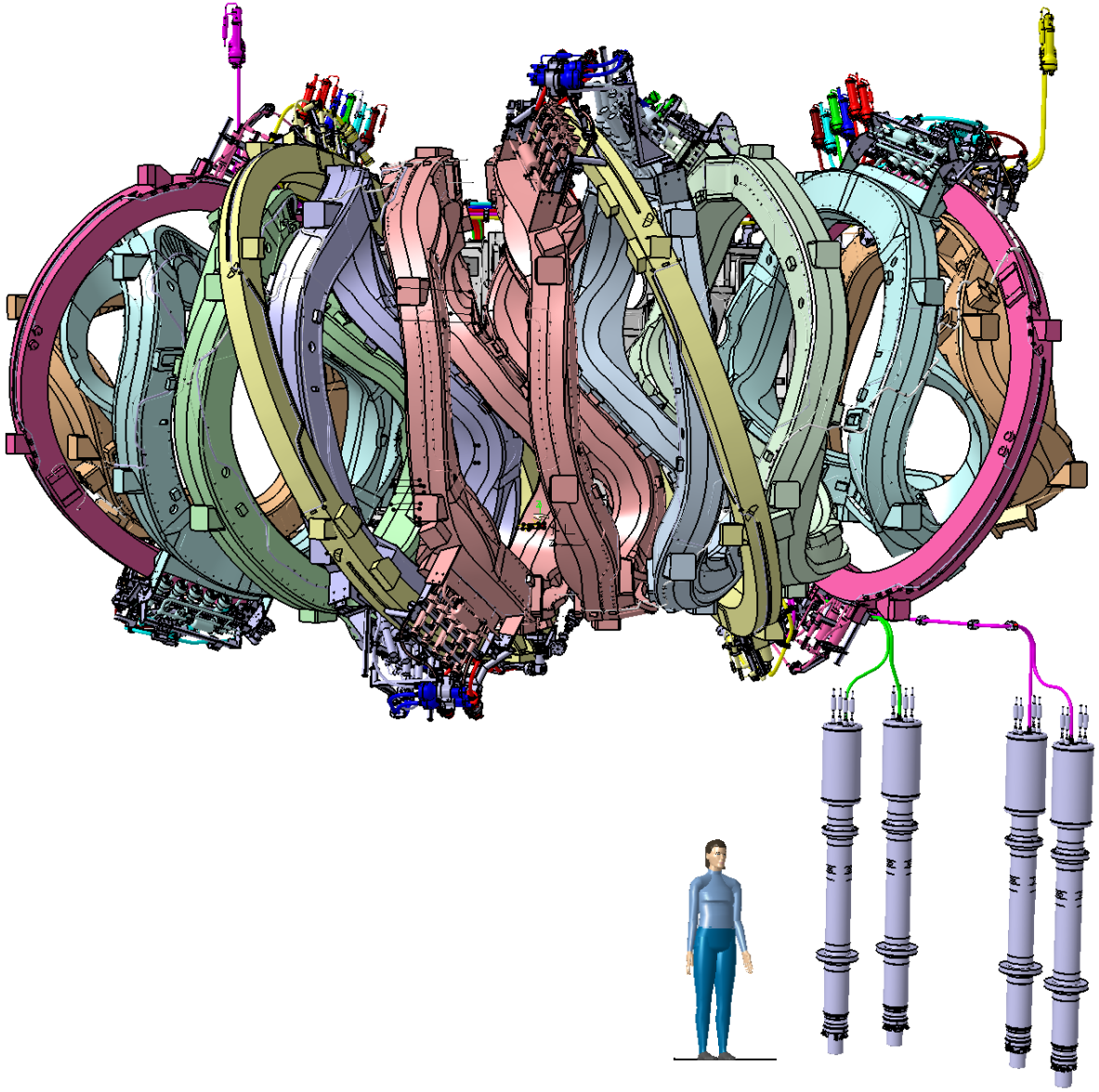


Summary

- All bus bar sections installed
- All supports and clamps installed
- 140 joints made (44 have to be made in the next months)
- **The work progress is according to schedule**

Current leads

- Provide the transfer of the electrical current from the room temperature bus bar system outside the cryostat to the superconducting parts inside the cryostat.
- Good electrical conductivity
- Bad thermal conductivity
- In W7-X seven pairs
- Current up to 18.2 kA



Current leads

Special feature in W7-X:

- Upside-down orientation (cold end at the top)
- The upside-down orientation would allow:
  - to save a lot of space in the vicinity of the machine, because no separate current lead cryostat is necessary and
  - shorter distances to the power supplies underneath the W7-X (reduced steady state power loss)
- But problems were expected for optimal and stable operation due to the occurrence of free convection inside the heat exchanger

⇒**Development program at the**

Karlsruhe Institute of Technology (KIT):

Karlsruhe Institute of Technology

- HTS current lead using Bi-2223/AgAu tapes
- optimized heat exchanger

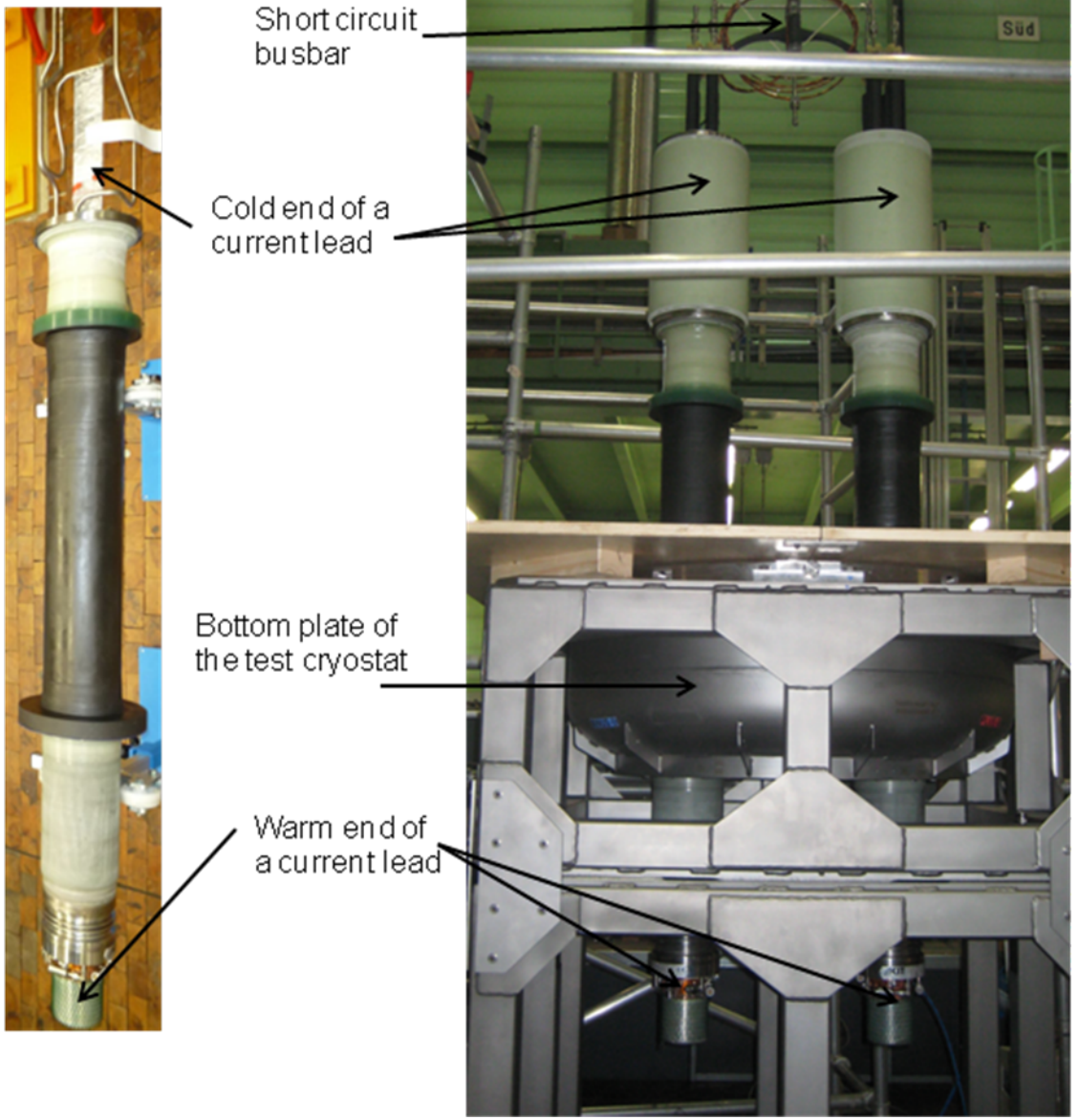
Current leads

Current lead test campaign:

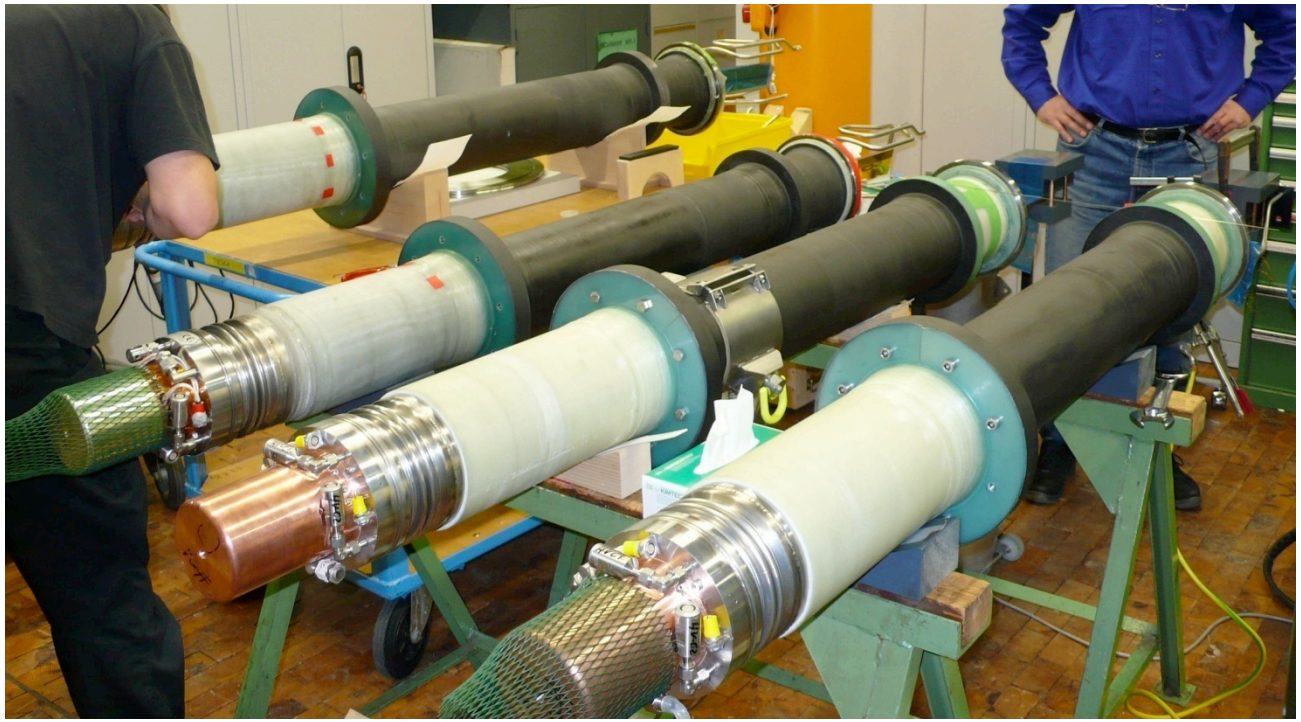
- Measurement of the heat load at different currents,
- Steady state operation at currents up to 20 kA,
- Long time test with 18.2 kA,
- Ramp test (simulating W7-X operation),
- Quench tests,
- Loss of mass flow (LOFA) tests.

Result:

Everything works as expected !



Current leads



Summary

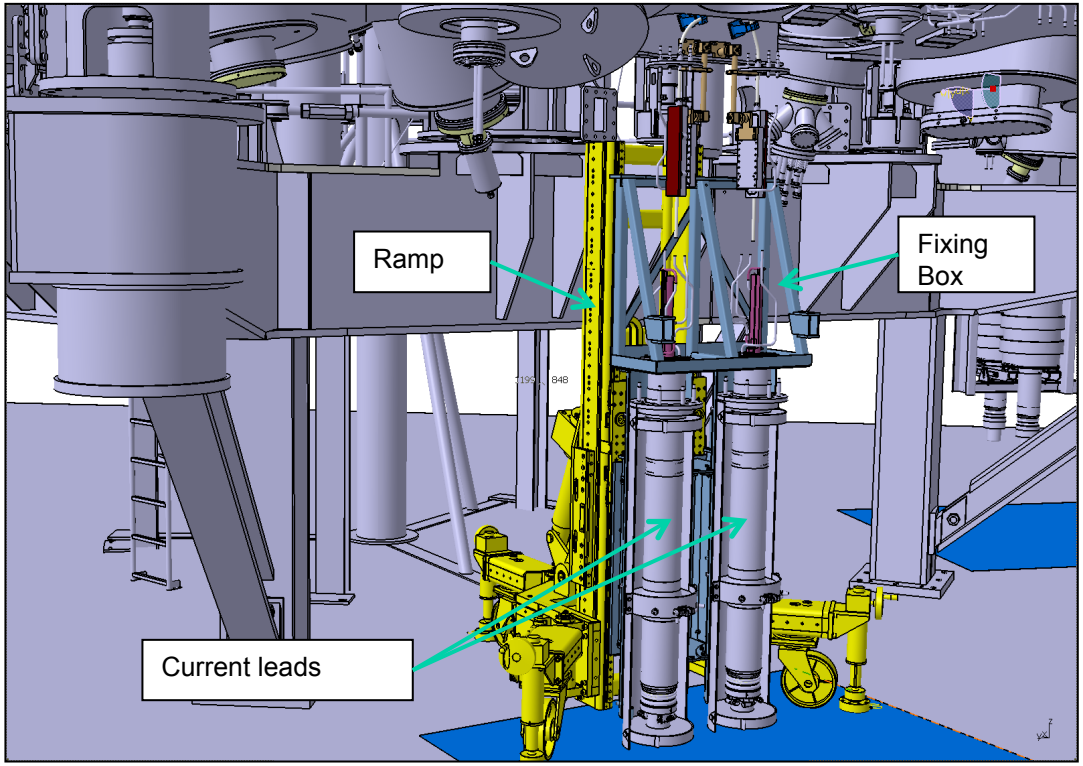
- Two prototypes successfully tested
- First CL pair delivered in 2011
- Last CL pair delivered end of 2012
- **Upside down orientation !**

Current leads

Assembly of the Current leads:

- Strategy developed by PPPL and ORNL

- Trials at a mock-up successfully running
- First assembly into W7-X expected for January 2012



Conclusion

- The procurement and assembly of a superconducting magnet system has been running over nearly the whole construction period from 1998 until 2013.
- Coils:
  - Three dimensional superconducting coils can be successfully build.
  - The achieved accuracy is nearly independent from the coil's shape.
  - Traditional working processes need also special care (welds, el. insulation).
- Bus bar system:
  - Challenging because of the space constraints, movements during operation and 3 D routing
  - Requires manual work at the machine and intensive tests
- Current leads:
  - Upside down orientation of HTS current leads successfully developed and tested

Thank you !