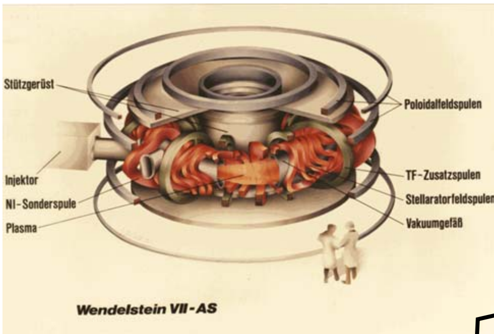
BILFINGER BERGER
Power Services

BABCOCK NOELL

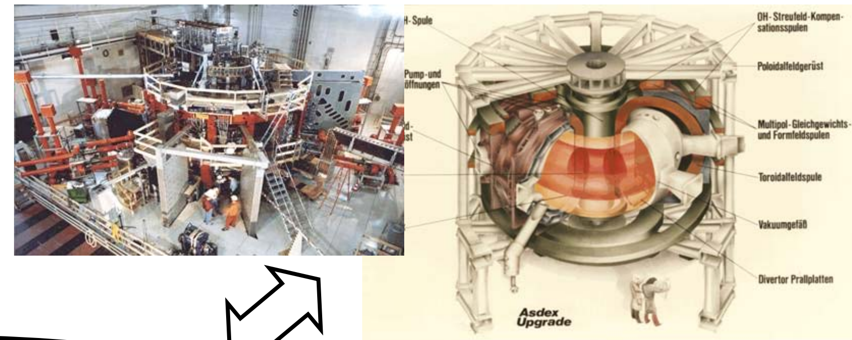
Industrial view to the fusion-
10 years for fabrication of W7-X coils

Agenda

1. Overview
1.1 Experience during former Fusion Projects



Wendelstein 7- AS 1988 - 2002

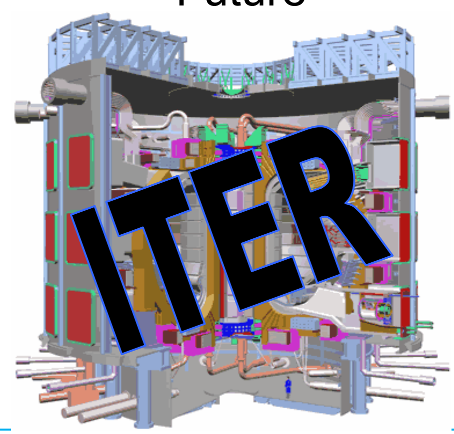


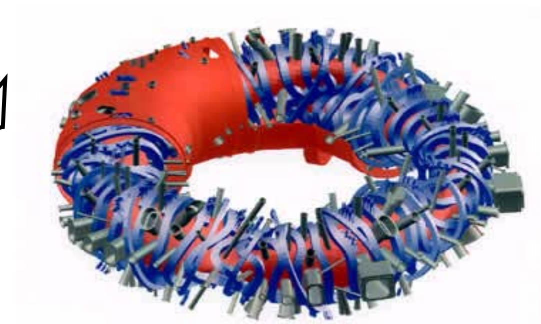
ASDEX Upgrade 1991 - up to now

Industry

Future

JET 1983 up to now

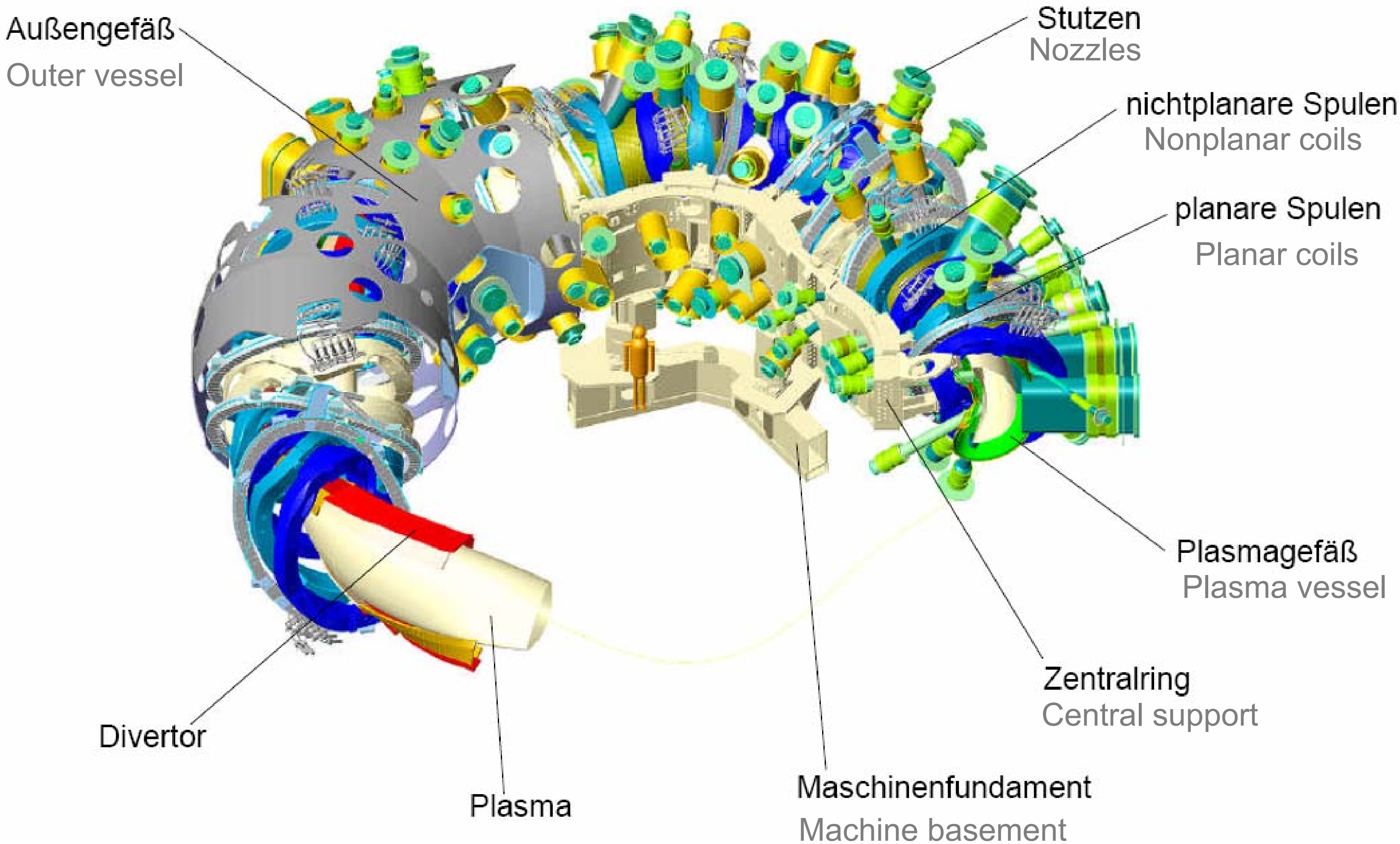




Wendelstein-7 - X 1998 erection phase started

BABCOCK NOELL

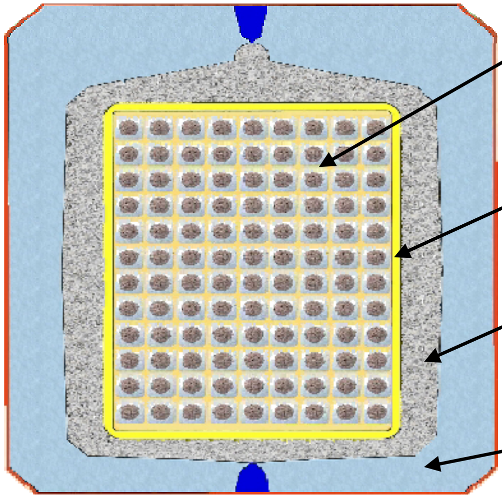
The W7-X machine



Coil types

W7-X Coil half module

Coil cross section



- 50 non planar coils form the magnetic confinement for the plasma
- 5 types of coils, 10 coils of each type
- Dimensions of a coil: 3,2 m x 2,2 m x 1,2 m
- Weight of a coil: appr. 5 t

BABCOCK NOELL

Who is BNG?

- Babcock Noell GmbH (BNG) is a mediumsize company, with 300 Employees and a Turnover of 54 mio EUR *
- BNG is located in Würzburg

- BNG is the centre of competence with world-wide responsibility for nuclear- magnet- and environment technology of the Bilfinger Berger Power Service Group.

*

acc. IFRS

BABCOCK NOELL

Product Areas

Nuclear Service

Containment lock - preparation of seal for leakage test

Nuclear Technology

Positioning of a Liner-assembly for EPR Reactor OL 3 Finland

Magnet Technology

Superconducting dipole for the LHC accelerator, CERN, Geneva

Environment Technology

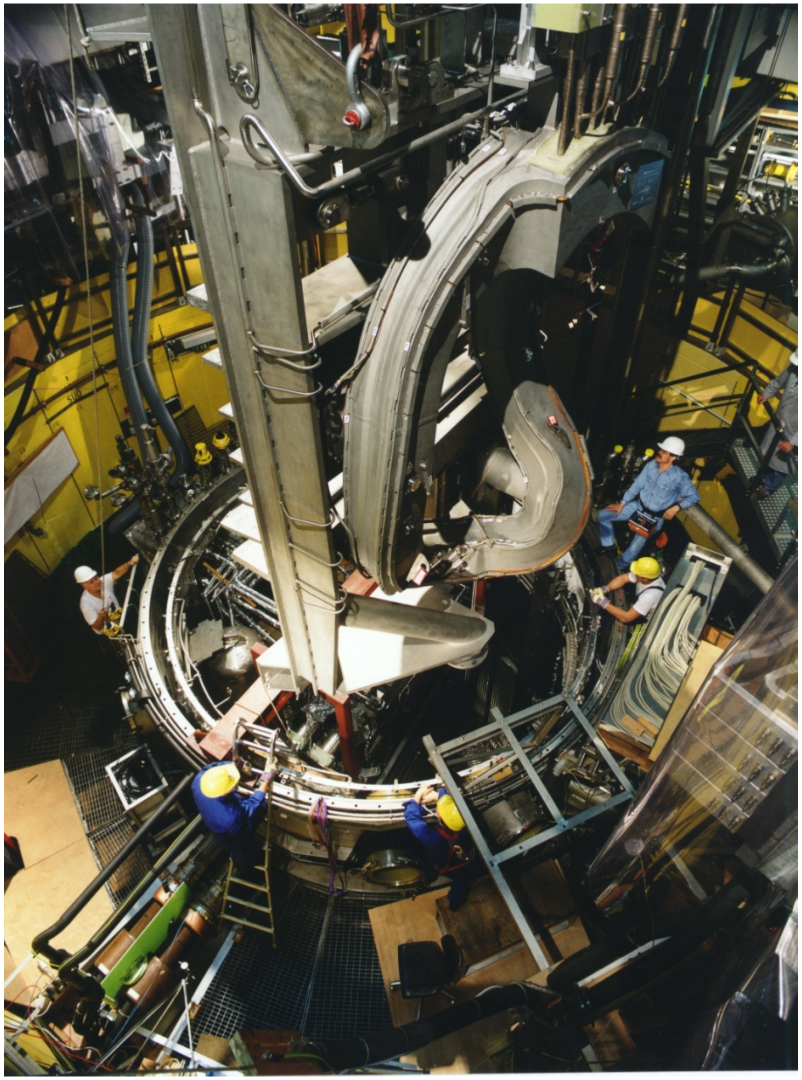
Components for flue gas cleaning systems

2. W7-X: How and why BNG

BNG has built together with ASG the W7-X DEMO coil

The Consortium Wendelstein for the Series Production:

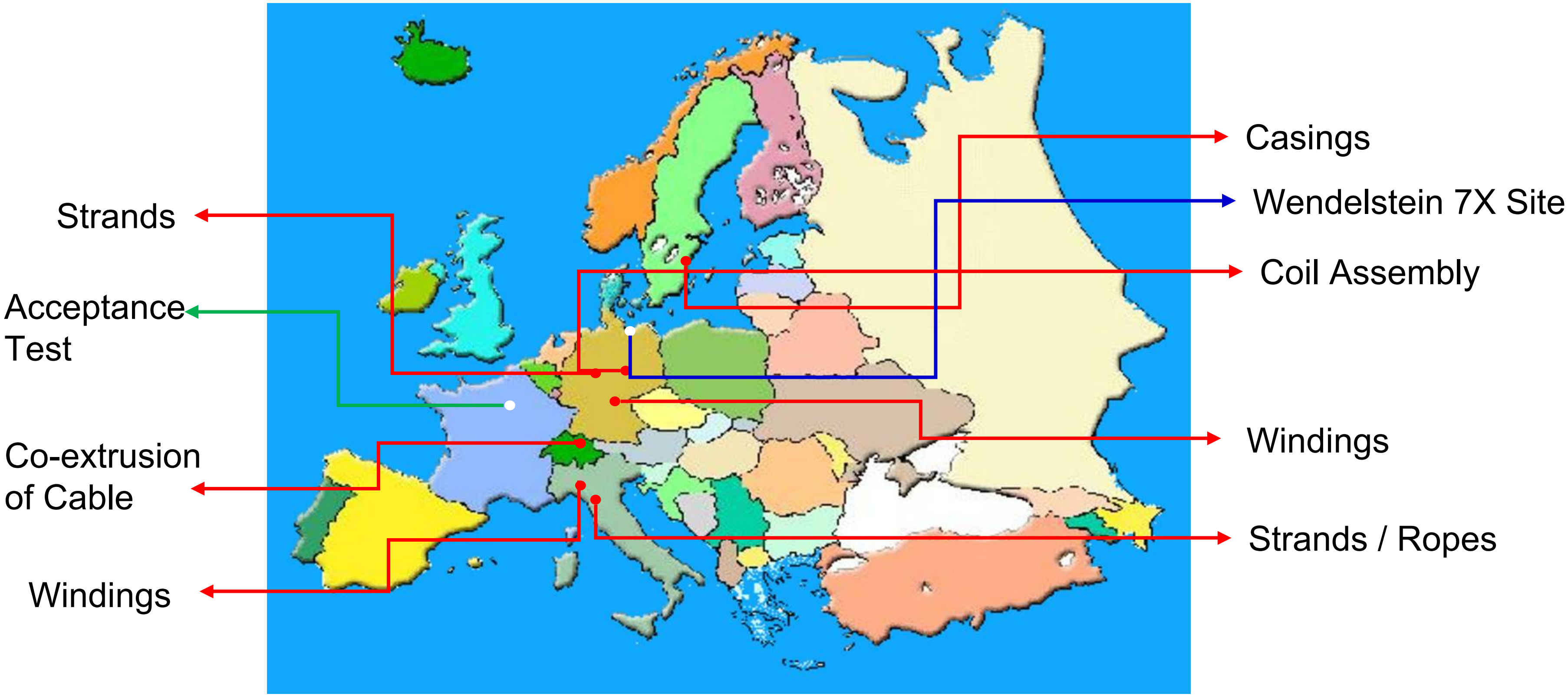
- ASG:
  Fabrication of Winding Packs Type 2, 3, and 4; Developments; Design
- BNG:
  Fabrication of Winding Packs Typ1 and 5; Assembly of Coils; Consortial Project Management; Developments; Design



Test of the DEMO-coil in TOSCA

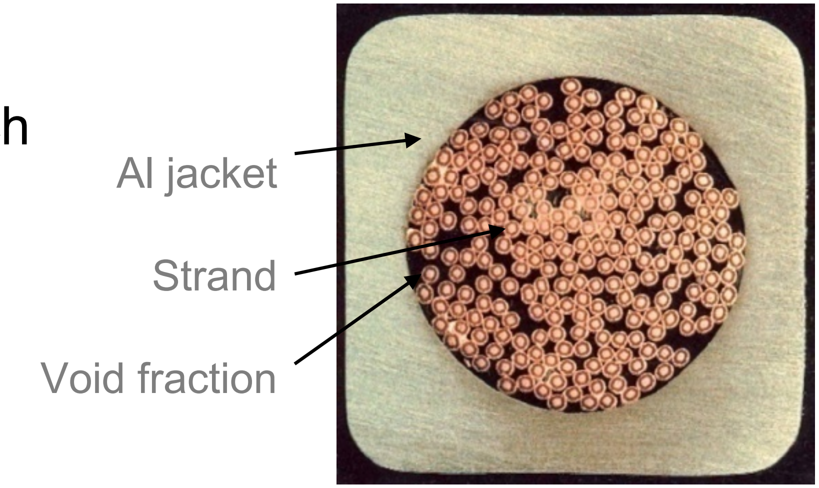
3. Manufacturing of W7-X coils
3.1 Introduction

Industrial network for “W7-X Non-planar coils”



- International industrial consortium for fabrication
- Many companies from all over Europe involved
- Network established by industry

- Before production started, an extensive development program was performed, which even had some overlap into the production phase
- During all the production period, the fabrication process was improved permanently in order to improve the quality of the conductor

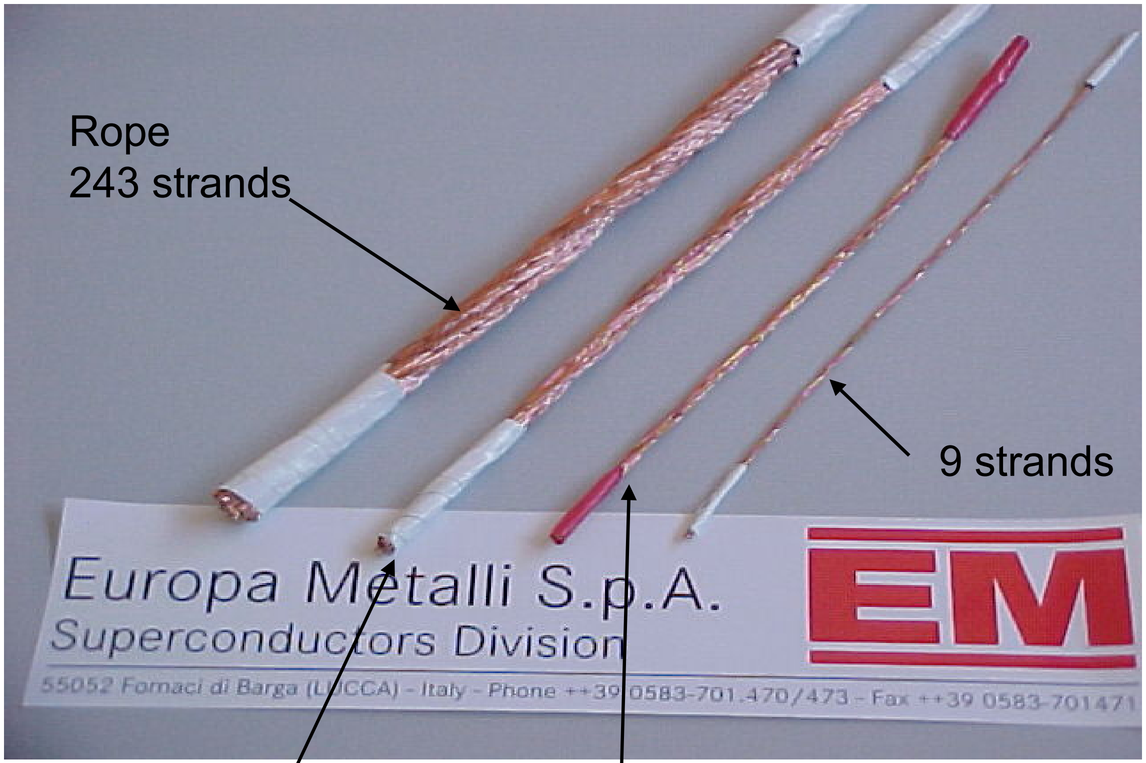


Cross section view after etching

Technical Data:

- ➢Critical current of the coil after winding: max. 32 kA at 4.2 K and 6 T, operating current of the coil 17,6 kA
- ➢CICC with Jacket made of Al alloy 6063, fabricated by co-extrusion process
- ➢Outer Dimensions (16 mm x 16 mm) ± 0,05 mm
- ➢Void Fraction (37 ± 2) %
- ➢Jacket is hardened after winding process

BABCOCK NOELL



81 strands

27 strands

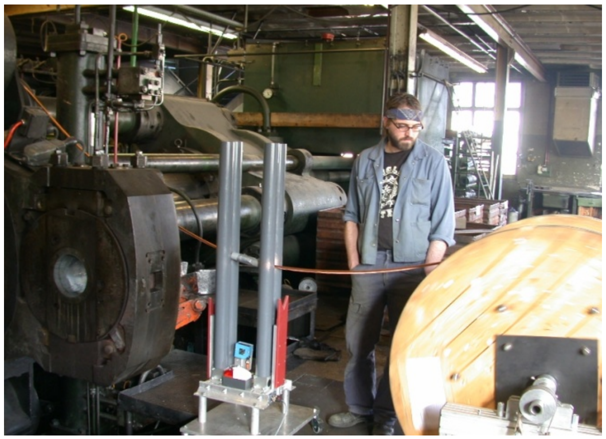
Superconductor Fabrication - Cabling :

- NbTi Superconducting Material
- Stabilisation Ratio NbTi / Cu: 2.6
- 243 strands are cabled in 5 stages to form the super-conducting rope.
- Cabling law:
  3 x 3 x 3 x 3 x 3

3. Manufacturing of W7-X coils

3.2 Superconductor

Superconductor Fabrication – Co-Extrusion



Feeding of rope into press

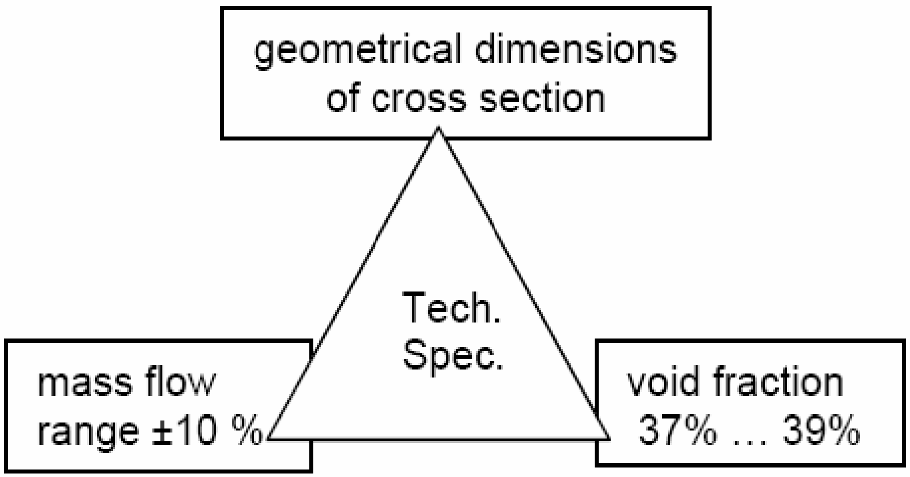
Al billet temperature check

Quenching of hot conduit with water

Conductor is stored on hasps

To match the requirements, the specification had to be optimised:

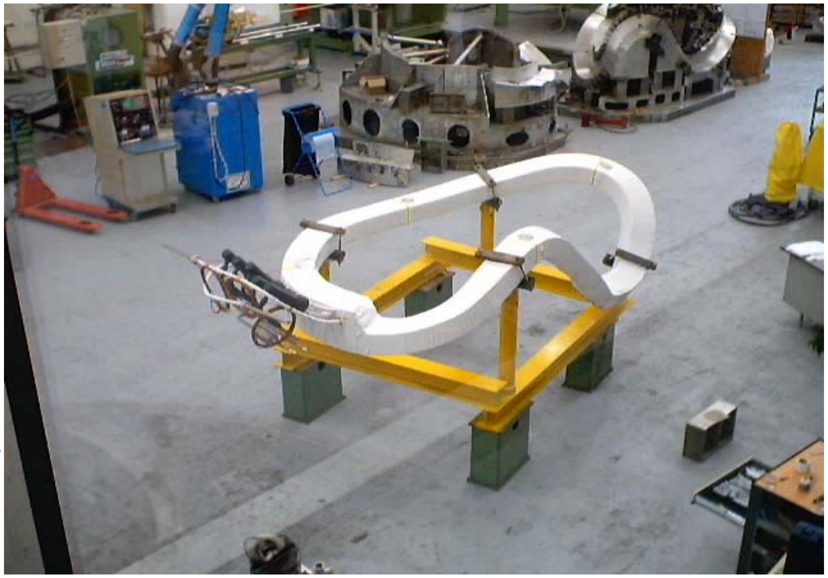
- Void fraction range was enlarged to 35 % … 39 %
- Tolerance for the outer dimension of the jacket was enlarged and some specified dimensions like "eccentricity" or "roundness" of the hole were skipped completely, as the most important property the minimum wall thickness was kept



"Magic triangle" of the SC

- The mass flow tolerance for all produced SC lengths was increased from 10 % to 20 % for the whole production taking also into account the effects of different double layer lengths (DLL)

- 30 WPs were produced by ASG, all in their fabrication halls in Genoa.
- 20 WPs were produced by BNG. BNG has placed a contract to ABB as sub supplier.
- Main challenge: All 10 coils of each type must have the same geometry within tight tolerances defined at definition cross sections



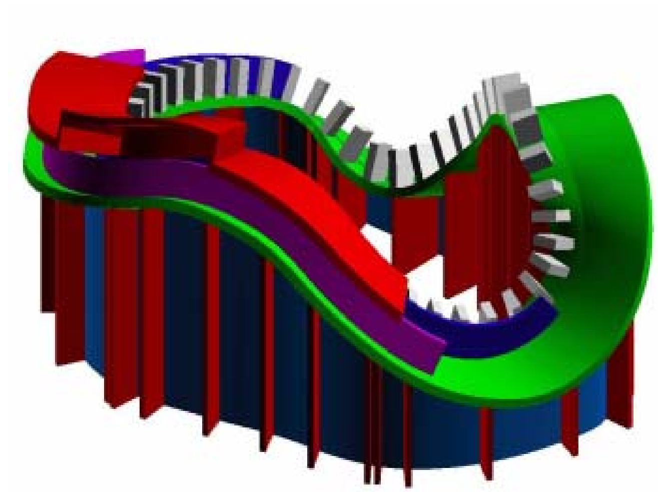
Winding Pack Type 3

Solution approach:

- ➢ Use of massive winding forms. The same winding form is used for the fabrication of all winding packs of the same type.
- ➢ Application of a sophisticated clamping system during winding and impregnation.

Winding Pack fabrication – Winding Form

- ✓ Design
- ✓ Casting
- ✓ Machining



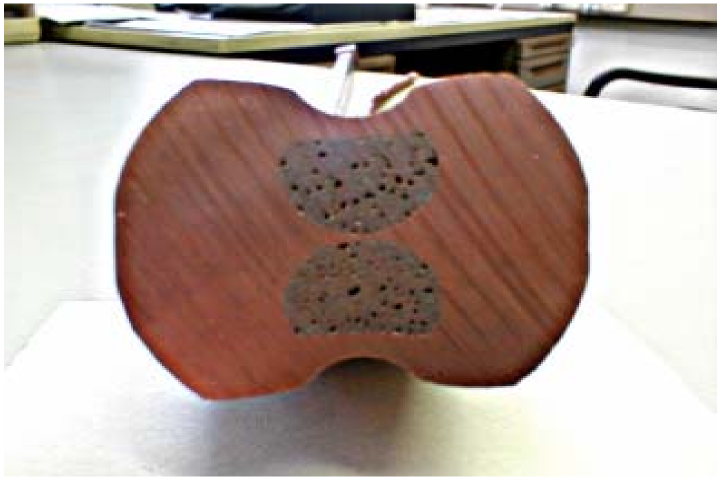
Fabrication of Winding Packs – Winding

Winding in ABB

- During winding, the conductor is formed by hand into the coil shape
- The conductor is held in position by clamps

Fabrication of Winding Packs – Interlayer Joints

- The double layers of the coil are connected by 5 interlayer joints serving both as electrical and hydraulical connections.



- The electrical connection is realised by a copper block, into which the cable is soldered and pressed. The resistance of each joint is <1 nΩ at 4 K

BABCOCK NOELL

Fabrication of Winding Packs – Insulation

Ground insulation is realised by glass tape, half overlapped

In the winding head region the conductors are protected by G11 plates, which are placed exactly

Fabrication of Winding Packs – Impregnation

Impregnated winding pack

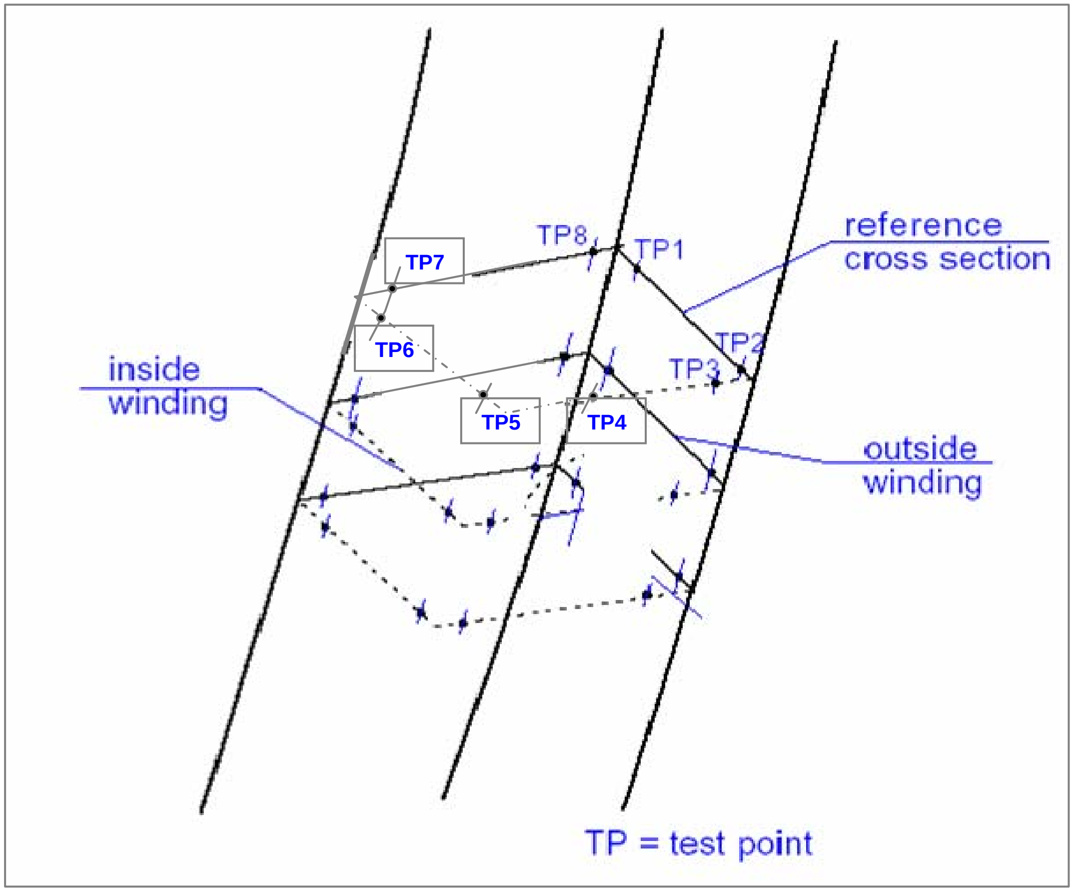
Assembly of winding pack into impregnation form

Assembly of impregnation form into impregnation vessel

Impregnation vessel after impregnation cycle

BABCOCK NOELL

Fabrication of Winding Packs – Geometrical Measurement

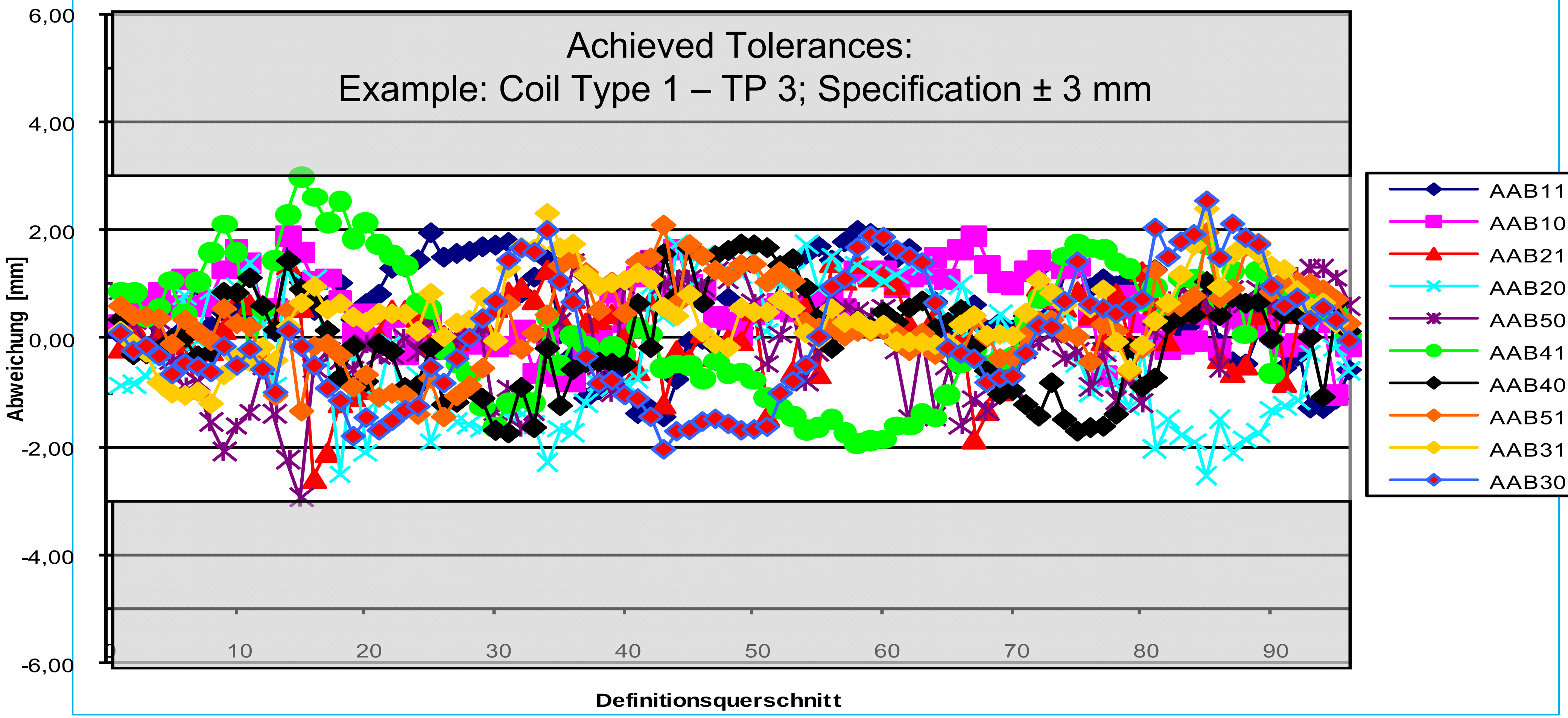


Coordinate Measurement on
8 Points for each of
96 definition cross sections

Requirements:
MP1 and 2: ± 5 mm
MP3 and 4: ± 3 mm
MP5 and 6: +3 – 0 mm
MP7 and 8: ± 3 mm

BABCOCK NOELL

Fabrication of Winding Packs – Geometrical Measurement



3. Manufacturing of W7-X coils
3.4 Coil Cases

Case of prototype coil

Case of non planar coil

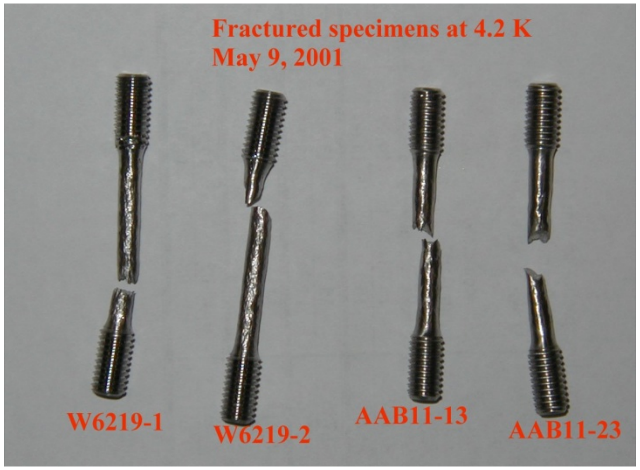
Compared to the prototype coil:

- More complex geometry
- Higher varying wall thicknesses
- Tighter geometrical tolerances
- Need of less expensive fabrication method due to number of coils (for the prototype case made of segments)

Solution approach: cast half rings

- Cases are cast from stainless steel type EN 1.3960 (equivalent 316 LN)
- By special composition and heat treatment, its physical parameters are optimised:
  - Yield strength > 800 MPa
  - Elongation at fracture > 25%
  - Permeability < 1.01
  - Good weldability

Case material specimen



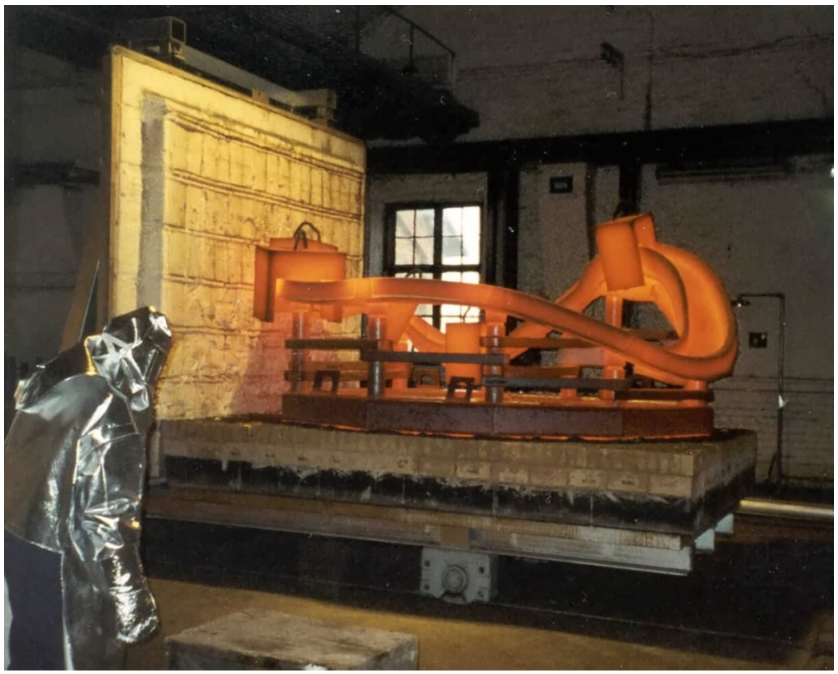
Fabrication of Casings - Steps

1. Pouring with special material composition

2. Fettling

BABCOCK NOELL

Fabrication of Casings - Steps

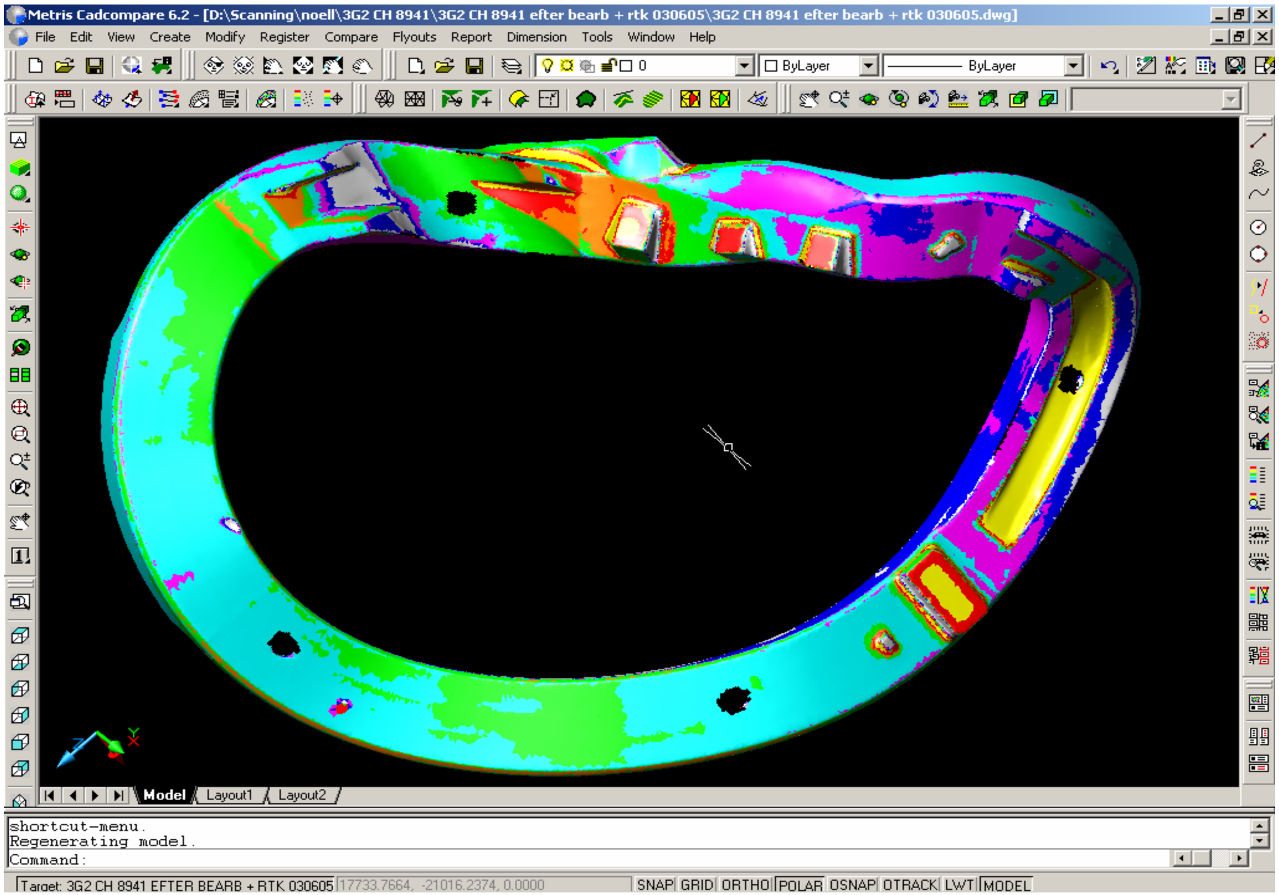


3. Heat treatment with 1100°C

4. Machining

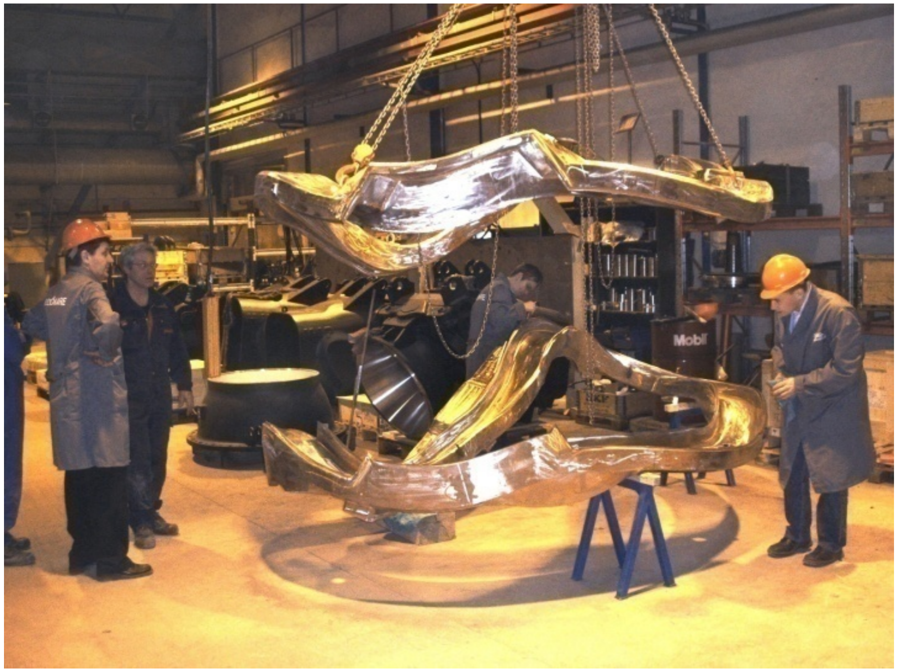
BABCOCK NOELL

Fabrication of Casings: 5. Dimensional Check



- > +5mm: 5,5%
- +3mm ... +5mm: 4,3%
- +2mm ... +3mm: 10,8%
- +1mm ... +2mm: 25,9%
- 0mm ... +1mm: 27,3%
- -1mm ... 0mm: 13,5%
- -2mm ... -1mm: 8,2%
- < -2mm: 4,5%

Fabrication of Casings - Steps



6. Fitting and acceptance

7. Delivery to Zeitz

3. Manufacturing of W7-X coils
3.5 Assembly

View into the workshop in Zeitz

3. Manufacturing of W7-X coils
3.5 Assembly

BABCOCK NOELL

- The winding pack is inserted into the case
- The half rings of the case are welded together (so-called closure weld)
- The winding pack is embedded
- Additional support elements are welded on the case
- Final machining takes place including threads and drillings
- The coils shape is controlled by a 3D measurement
- The case cooling system is mounted
- Works acceptance test

Insertion of winding pack into Case

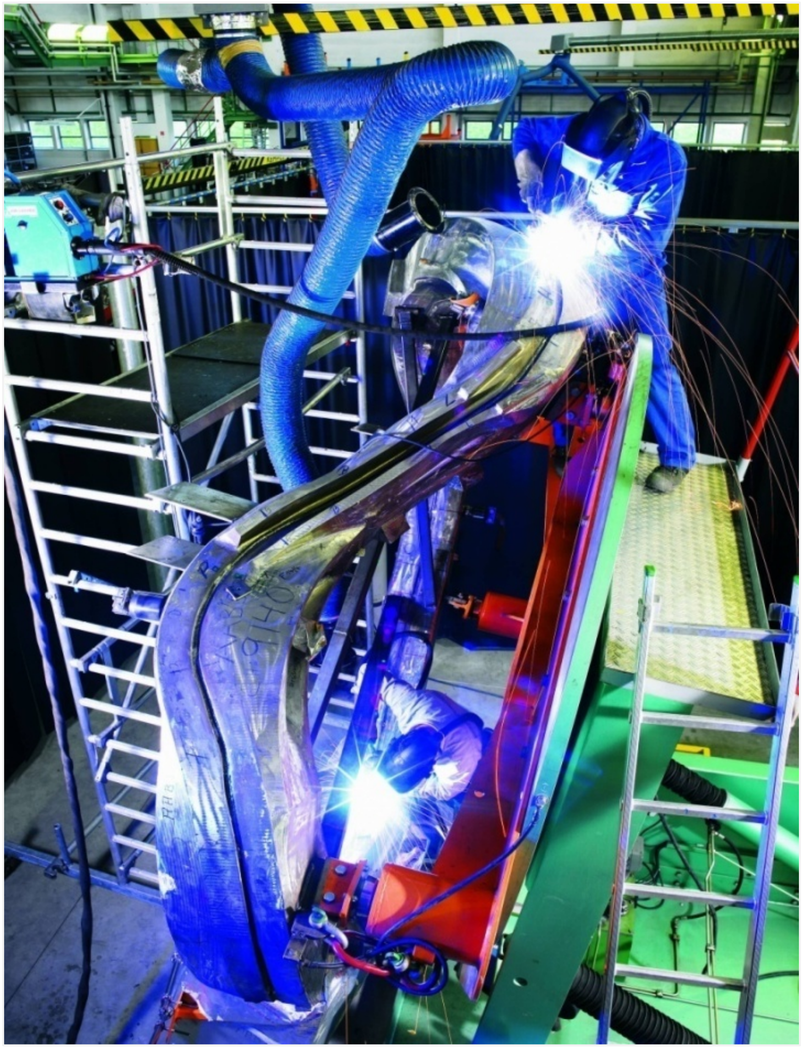
Coil assembly - Insertion of winding pack into Case

Case does not fit ?

ready

Coil assembly – Welding of half rings

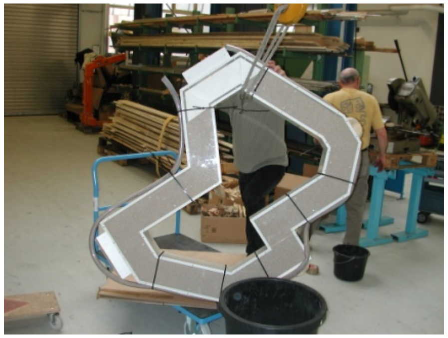
Welding and NDT of the root



Welding of the coil cases on special welding table

BABCOCK NOELL

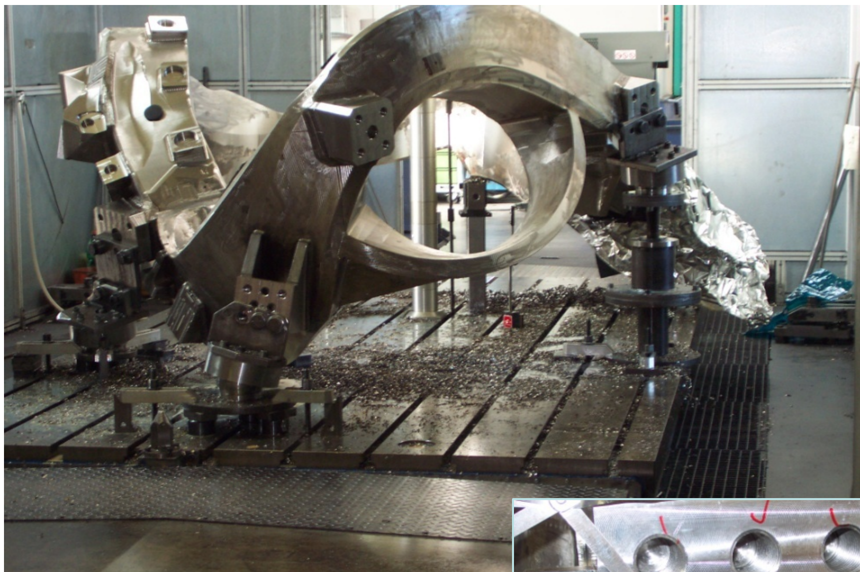
Coil assembly - Embedding



Qualification of procedure with mock up

Embedding of the coils

Coil assembly – Final machining and measurement



Final machining

Check of threads with templates

Automatic 3 D measurement of coil after final machining

Coil assembly – Manufacturing of cooling system

Fitting of the cooling tubes

Welding of Cu stipres

Soldering of Cu stripes
to the SS cooling tube

W7-X Manufacture - Challenges

- Development of a sophisticated case cooling system during production
- Repair of winding shortages and insulation/impregnation defects
- Modification of already assembled supports at finished and partly finished coils –> partial disassembly of coils, re-machining of coils
- Reduction of geometrical tolerances at finished and partly finished coils → partial disassembly of coils, re-machining of coils

3. Manufacturing of W7-X coils
3.6 Quality Assurance

- Production is accompanied by documents showing all production and test steps in detail and sequential order (so called Quality Inspection and Production Plan QIPP)
- Important steps of testing or production are agreed as notification or hold points between the fabrication and the customer
- The contents of those documents are agreed mutually and are mandatory also for sub suppliers
- Several tests accompanied the complete production, also internal tests

QIPP is always present on the coil

DPT of welds

Videoscopic investigation of components, tubes or welds here: T-piece

3. Manufacturing of W7-X coils
3.6 Quality Assurance, Test program

Geometrical Tests

3 D measurements with the FARO arm are carried out during several steps of fabrication:

- ➢ Measurement of the Winding pack after delivery
- ➢ Measurement of the reference pins before and after embedding
- ➢ Measurement of the surface in order to define the areas of final machining
- ➢ Measurement after machining
- ➢ Measurement of wall thickness in special regions with US

3. Manufacturing of W7-X coils
3.6 Quality Assurance, Test program

Hydraulic Tests

Pressure and leak tests are performed:

- On the winding packs after impregnation
- On the cooling tubes before assembly of the Cu stripes
- On the finished coil

Mass flow measurements are performed

- On the conductors
- On the winding pack
- On the finished coil
- At Saclay at Cryotemperature

Leak test of Winding Pack

Electrical Tests

DC and AC high voltage tests are carried out:

- DC test in air with 13 kV, in Vacuum with 9,1 kV (Paschentest)
- AC test with 4 kV pp in air
- All tests performed on the impregnated winding packs before and after delivery to Zeitz
- If necessary, at several steps during the assembly or during or after repair
- Before delivery to Saclay
- At Saclay at room and cryo temperature (10 kV; 3.2 kV pp respectively)

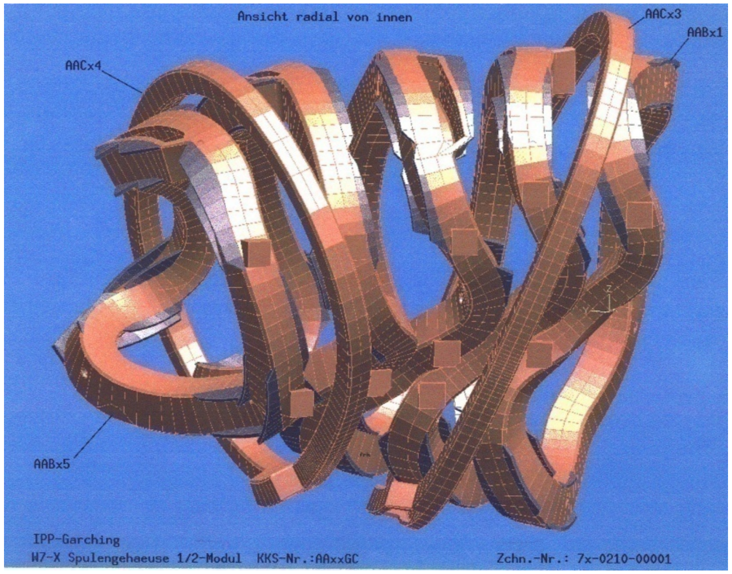
BABCOCK NOELL

Summary of Acceptance Tests in Saclay

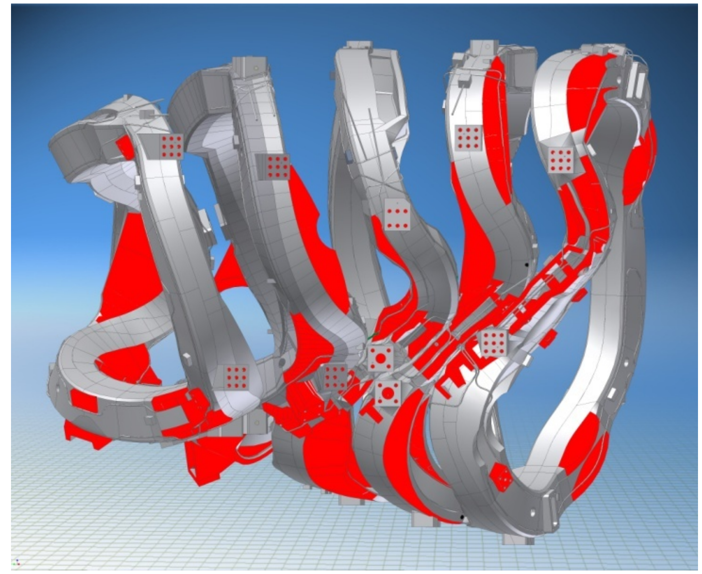
- All coils passed full current and quench tests successfully. T_{cs} was higher than specified, which gives some operational reserve.
- All coils passed the hydraulical and leak tests successfully. At room temperature the leak rate was below $1 \cdot 10^{-8}$ mbar l/s
- The mechanical behaviour of the coils showed up as expected.
- Coil resistance (due to interlayer joints) was below 5 nΩ
- High voltage tests on several coils revealed problems with the first generation QD-cable in vacuum (Paschen)conditions and with insulation failures.

4. Problems and Specials

4.1 3-Dimensional Castings



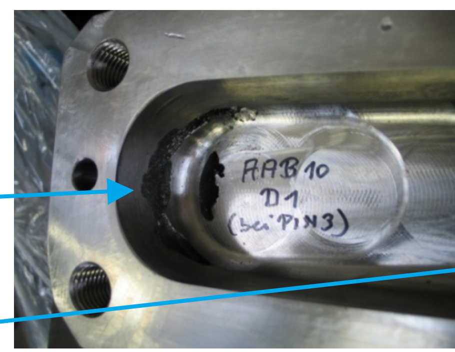
Design of the casings in the Specification



Design of the casings now – red: additional material

New case design required a change of the fabrication method -> cast half rings with problems:

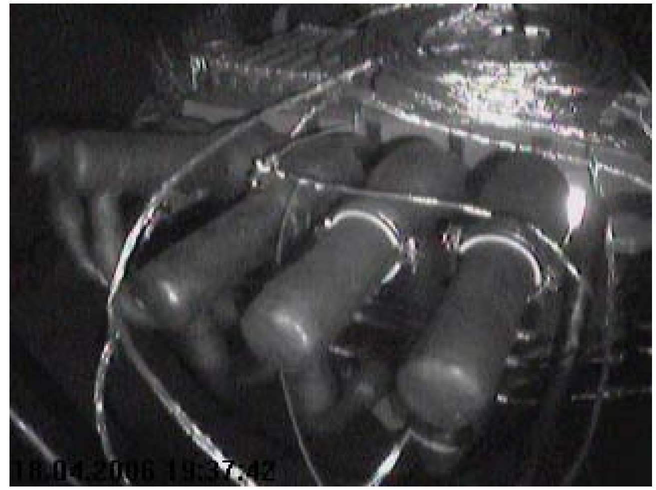
- ➢Different wall thicknesses -> region for shrinkage
- ➢ Too thick material -> no x-ray possible –> LINAC investigation



4. Problems and Specials
4.2 Insulation Defects

BABCOCK NOELL

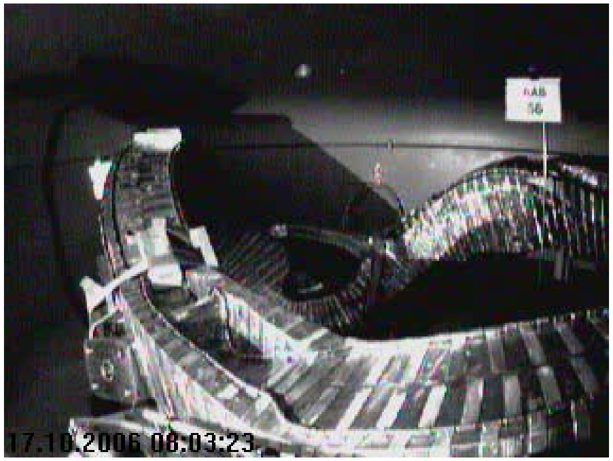
1. High voltage test of the coil in vacuum („Paschentest“)



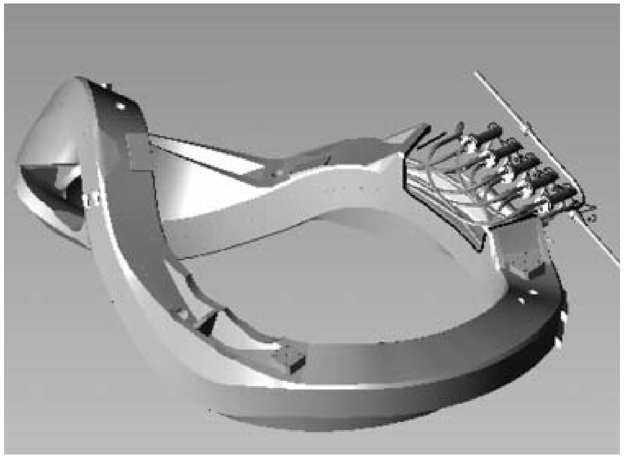
2. Discharges in the region of the insulation defect visible with video system

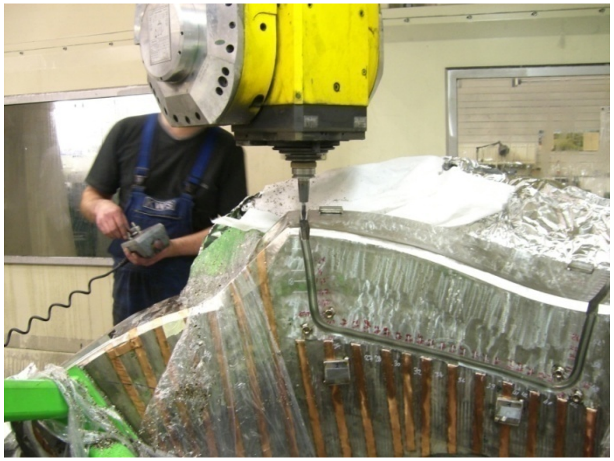
3. Repair of the insulation in the affected region

4.3 Manufacturing Failures



1. Failure detected by „Paschentest“


2. Repair concept


3. Machining of opening


4. Access to affected region

5. Repair of Winding Pack


6. Repair finished

4. Problems and Specials
4.5 Changes during Project

Change/Subject	Content/Reason of the change
Casing design	Complete changed design of the casings with 30% more weight lead to the cast half rings
Cooling system	Several different Cu applications were qualified due to new casing design, final solution with 1200 Cu stripes per coil welded to the casing
QD wire	Original QD cable was not “Paschen-tight” and had to be replaced by an improved one
SC specification	Specified requirements did exclude each other
Casing design and supports	New static calculations requested new supports and increased welding seems of the supports
Coil tolerances	The assembly concept in IPP was reviewed and the coils did collide with each other, closer tolerances and additional machining of the coils
Paschentest applied	Repair of in total 38 Winding packs, increase of original insulation thickness and quality was necessary
Support design	New assembly concept of IPP and changed mechanical system

BABCOCK NOELL

Technical Lessons:

- Casting of such 3D shaped components is a very complicated task. It needs strong effort and close monitoring of all tests in order to find as many improvements as possible, which can be realised economically.
- The machining and accuracy requirements are at the limits of what is technically feasible at present.
- One can repair winding packs and even coils, if short circuits are detected at later fabrication steps only
- Realisation of design changes during running fabrication is possible, but causes a lot of additional effort, time shift and cost increase

BABCOCK NOELL

General Lessons:

- Fix essential requirements early!
  (interfaces, design, specification and acceptance criteria)
  Otherwise there is the danger of disturbance or interruption of production
- Establish a suitable and reasonable quality assurance
  Performing the right tests at the right time
- Establish a sophisticated maintenance concept for tooling
- Execute expediting for components consequently
- Experience and continuity are key-factors for the project teams
- Standard procurement procedures can hardly be applied. A qualifications process and adjusted contractual regulation (e.g. on liabilities) are necessary.

BABCOCK NOELL

General Lessons:

The Benefit is, that all participants of this project have gained technical expertise, for instance:

- Better understanding of critical manufacturing steps
- Extending of assembly and repair procedures
- Successful processing of large projects under the pressure of modifications
- All participants had to act coordinated to achieve a common goal

Due to the experience we have gained during this project we are well prepared for future challenges !

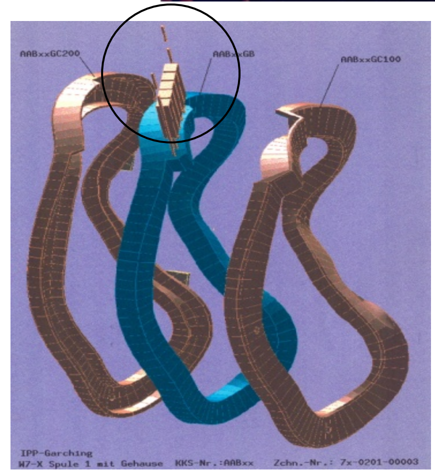
BABCOCK NOELL

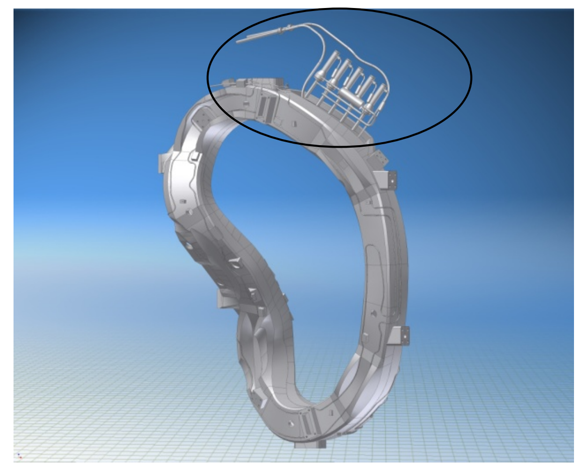
1998

- 18.12.1998 Signature of contract with IPP for series production

1999

- Contracts with ABB, VAC
- Change of the cases design
- Coil connection area shall be changed (pictures)





2000

- Search of an assembly hall
- Contract with Österby for casings
- Start of Superconductor production

5. Review about a 10-Years-Project

2001

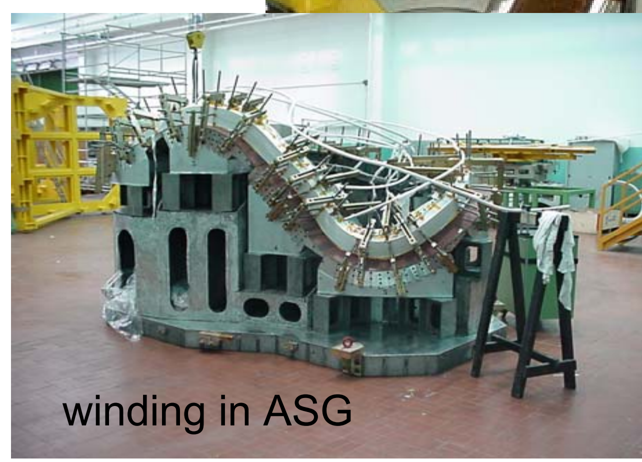
- Cooling-Mock ups
- Start of winding at ABB and ASG after receipt of SC
- Delivery of 1st casing

2002

- Delivery of 1st winding pack
- Assembly of 1st coil in Zeitz

2003

- Österby, PEM and C-CON in top form
- Design Change: new supports
- 1st test of coil in CEA



winding in ASG

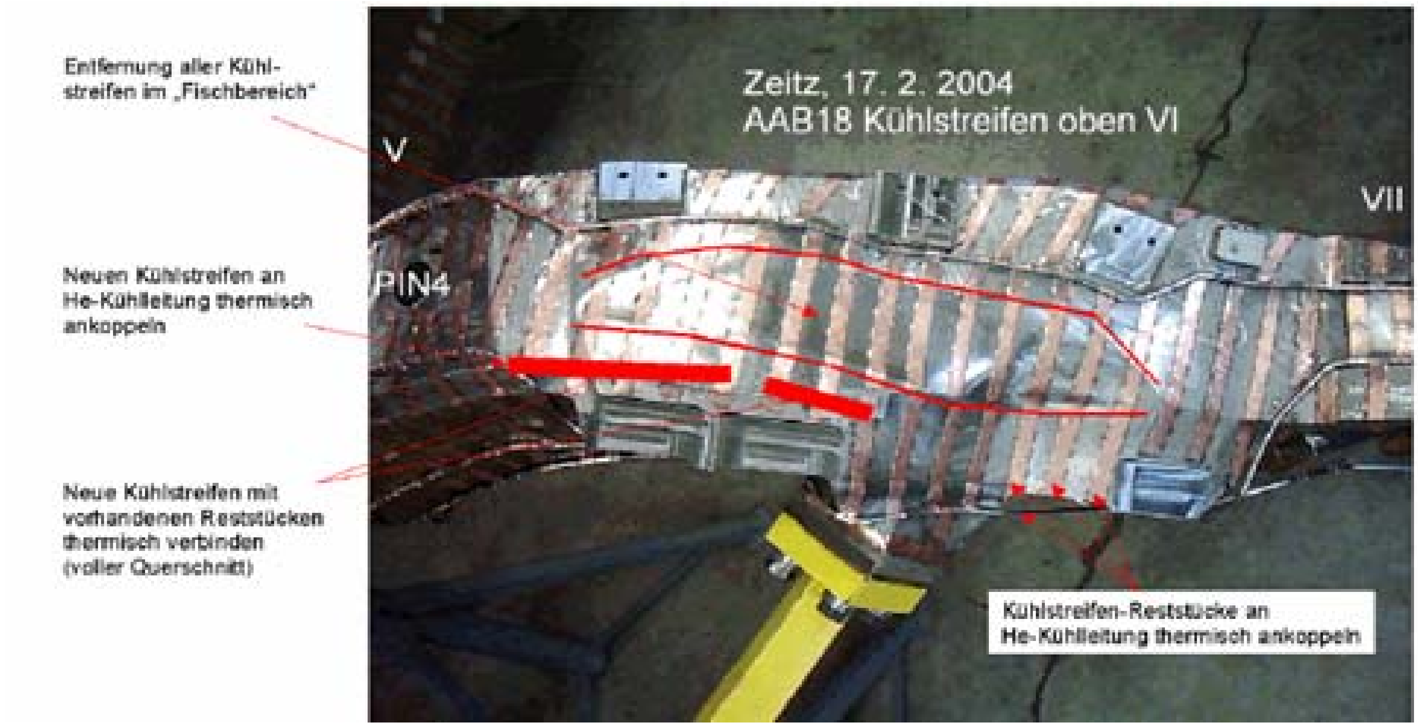
2004	2005

2004

- Design Change with new word: „fish area“
- Foundation of the working group for casings

2005

- Last case delivery on 11.11.2005
- Birth of the “Paschentest“
- Design Change Type 5



5. Review about a 10-Years-Project

2006

- „Hospital“- year
- Foundation of the PST
- Delivery of last WP of ASG

2007

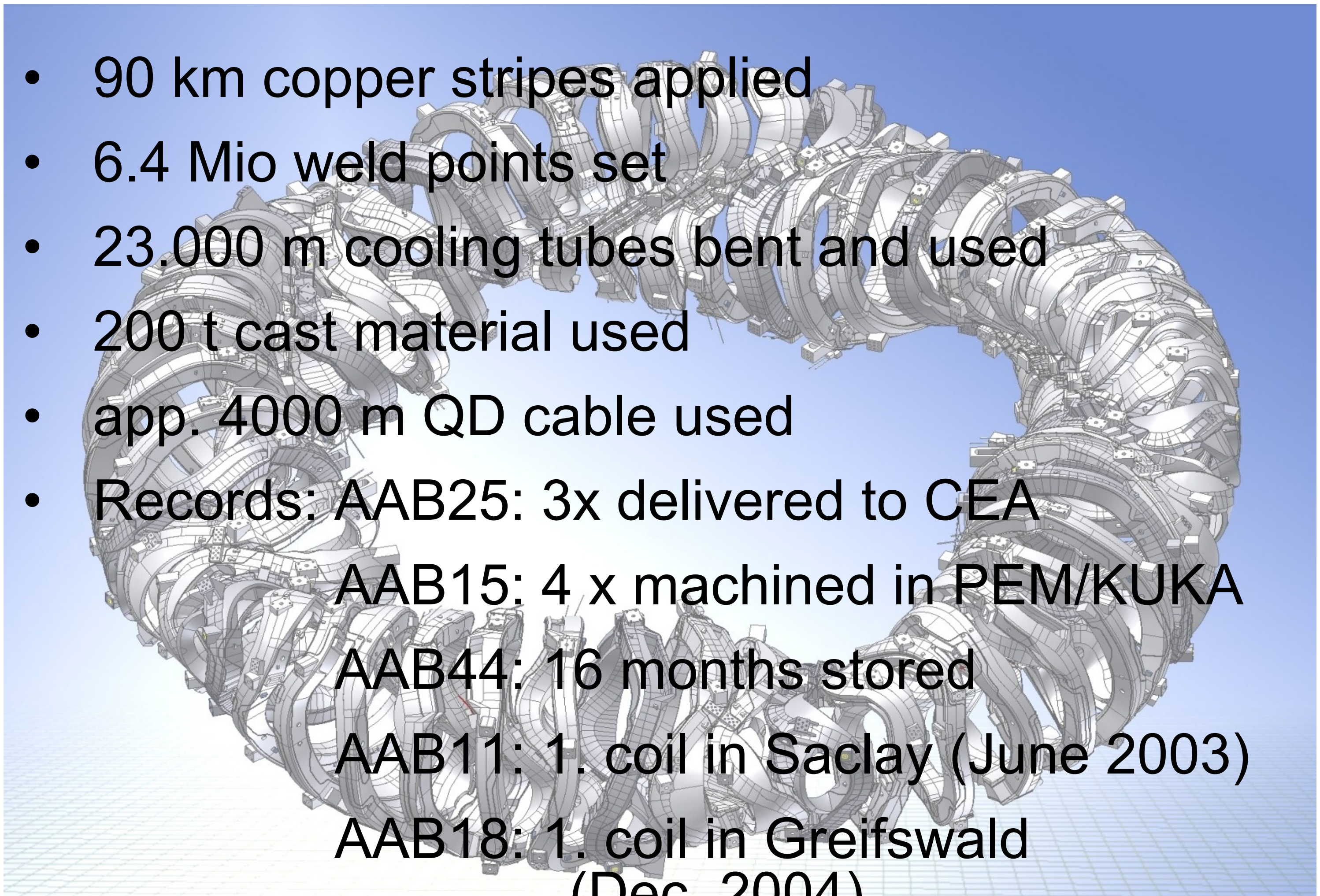
- BNG builds a „Cabrio“
- March: „over the hump“ celebration at Greifswald

2008

- 31.03.08 Ready!

- 110 progress reports issued
- 1550 letters to IPP written
- app. 800 NCRs issued
- app. 350 QIPPs handled
- app. 300 folders of documentations to be prepared

BABCOCK NOELL



- 90 km copper stripes applied
- 6.4 Mio weld points set
- 23.000 m cooling tubes bent and used
- 200 t cast material used
- app. 4000 m QD cable used
- Records: AAB25: 3x delivered to CEA
  AAB15: 4 x machined in PEM/KUKA
  AAB44: 16 months stored
  AAB11: 1. coil in Saclay (June 2003)
  AAB18: 1. coil in Greifswald (Dec. 2004)

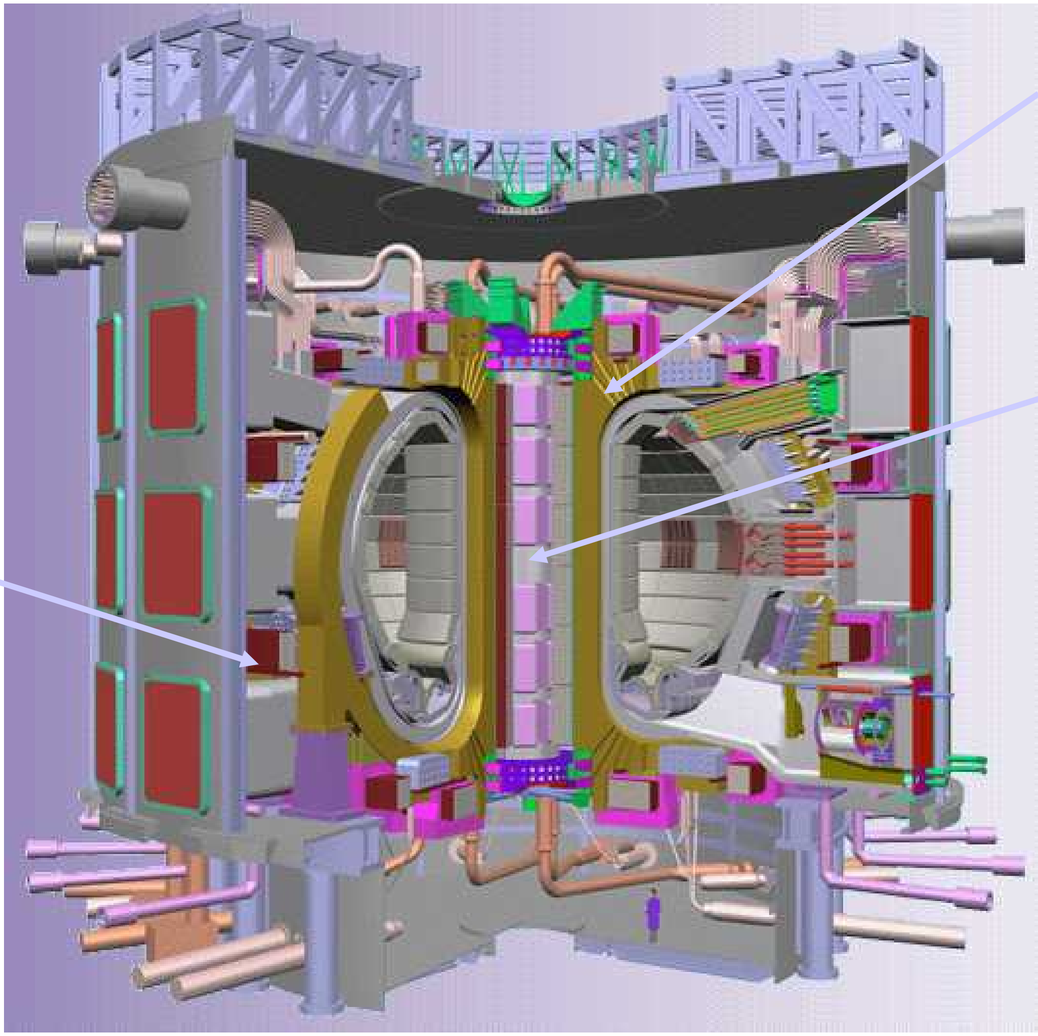
BABCOCK NOELL

- app. 850 business trips done
- app. 450.000 km went by car
- app. 160.000 flight kilometres
- „flight pioneers“ with Ryanair in April 2003
- app. 150.000 coils transport kilometres

6. Outlook: ITER

BABCOCK NOELL

ITER Coils



18 Toroidal Field Coils
9 + 1 spare coil to be fabricated in EU

Central Solenoid

6 Poloidal Field Coils

6. Outlook: ITER

BNG is working on the design of the tools for the ITER TF coils