Fabrication, Tests and Assembly of the W7-X Magnets and Perspectives for the Technological Development of Fusion

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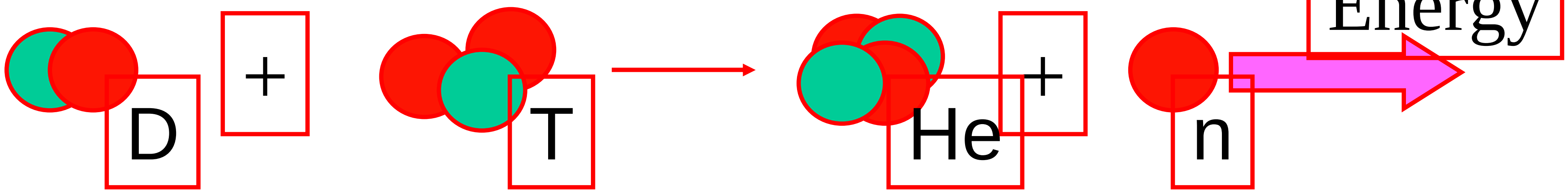
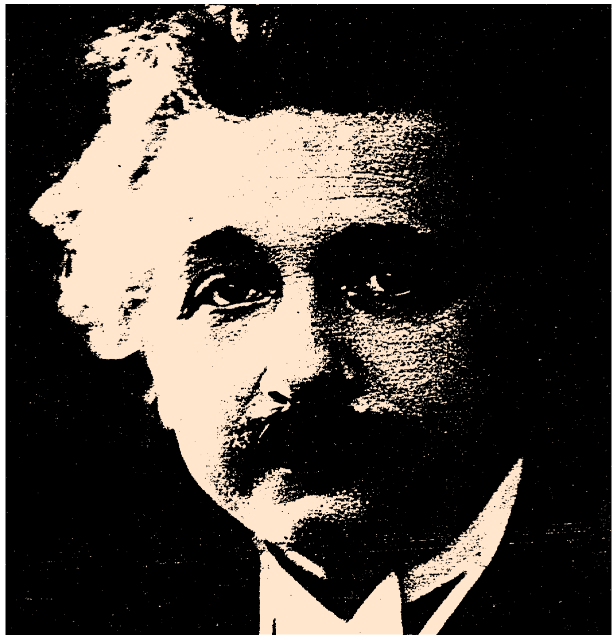
Energy by fusion

Fusion of D and T





Mass is transferred into energy: $E = mc^2$

Solar energy is fusion energy: 4 H → He + energy

4 Mtons of matter per sec transferred into energy

Conditions for fusion power

Density x Temperature x Confinement > critical value

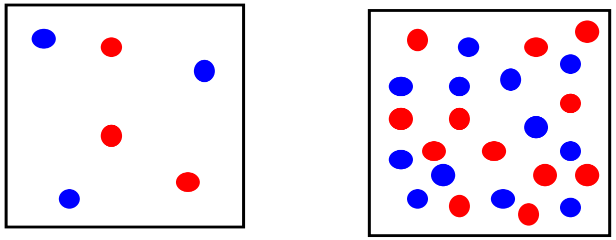
High temperature T:

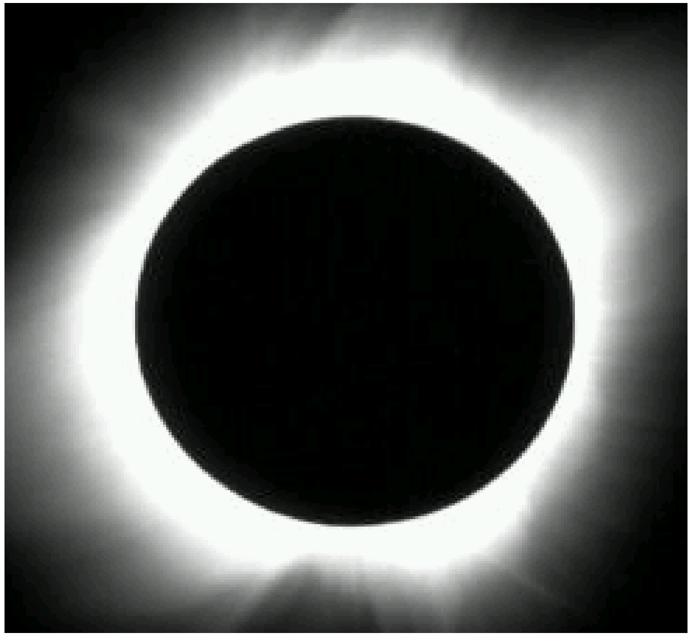
to overcome the Coulomb barrier *150 M℃* *fusion f rom the*

plasma state

High density n:

to allow for enough fusion collisions





High confinement time τ_E:

To provide thermal insulation

Sun gravity forces

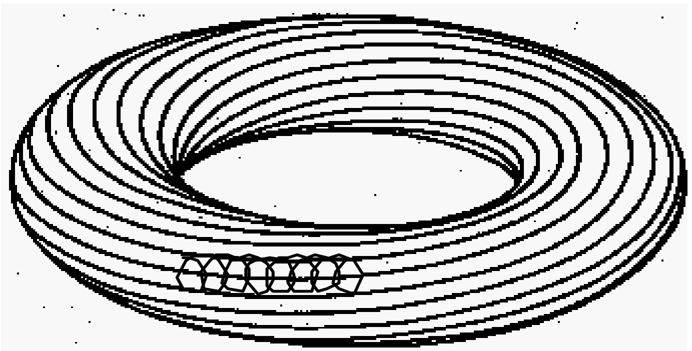
Earth magnetic forces

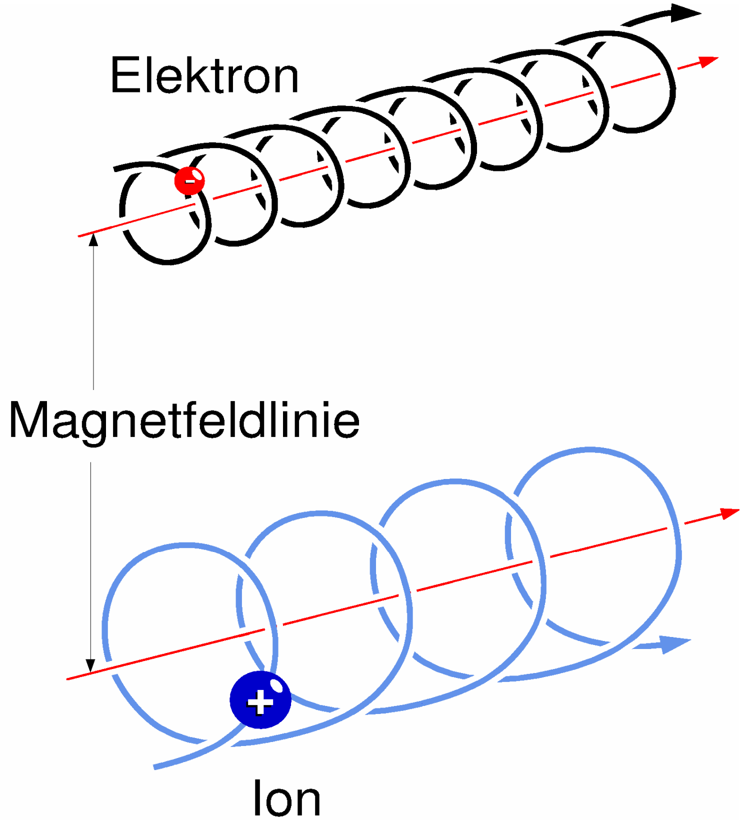
Thermal insulation needs space: fusion power plants are large (GW)

Principle of magnetic confinement

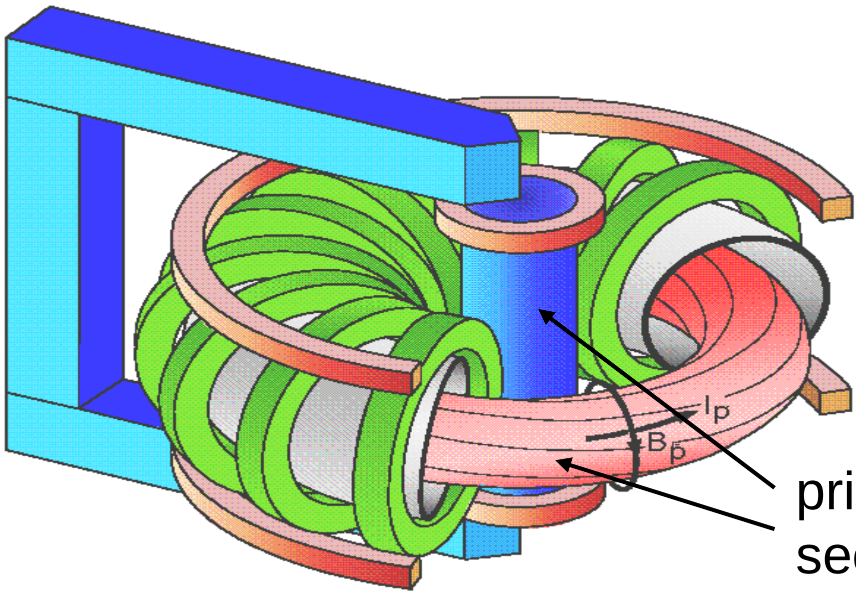
Magnetic fields force particles to spiral around a force line:
confinement in perpendicular direction

Toroidal plasma geometry:
parallel confinement

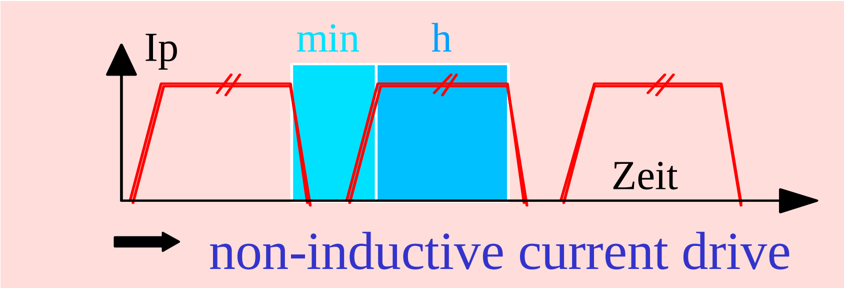




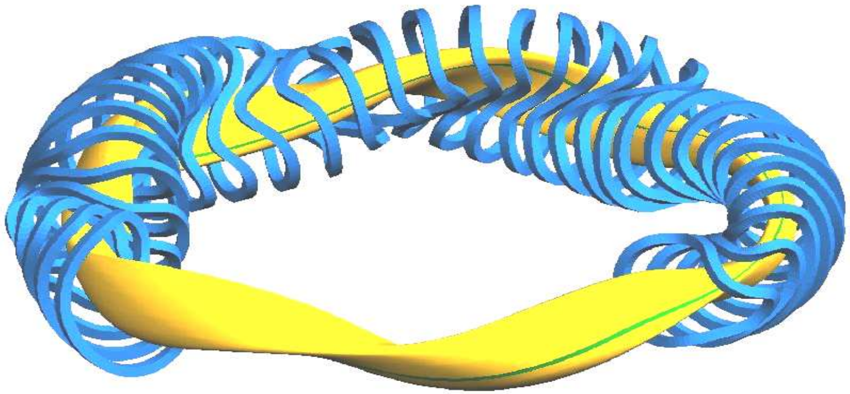
Tokamak (ITER)



Transformer principle
Plasma current is induced
Discharges are pulsed



Stellarator (W7-X) 3D



Steady-state configuration
No plasma current

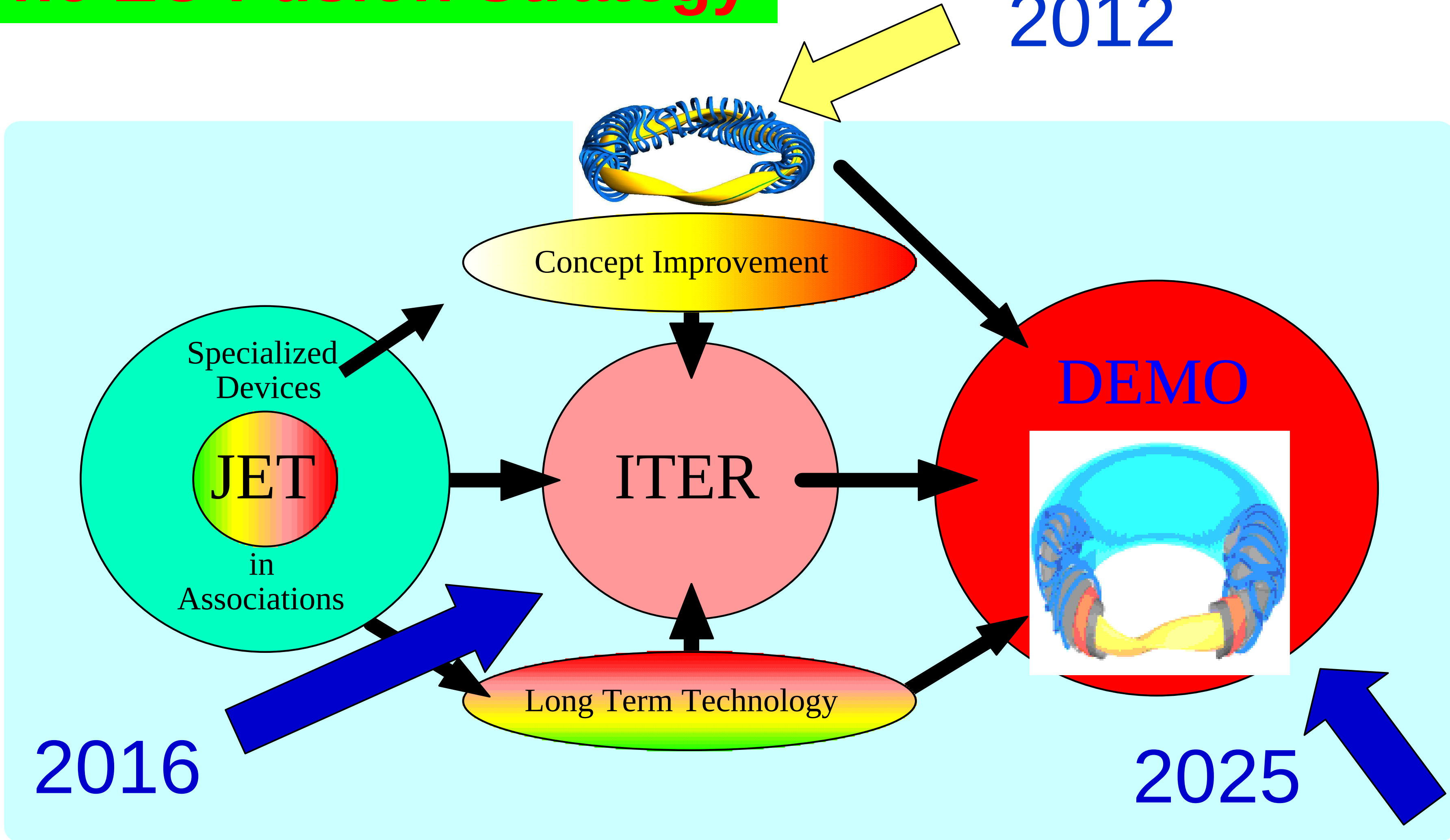
Toroidal confinement systems

Properties of Tokamaks and Stellarators

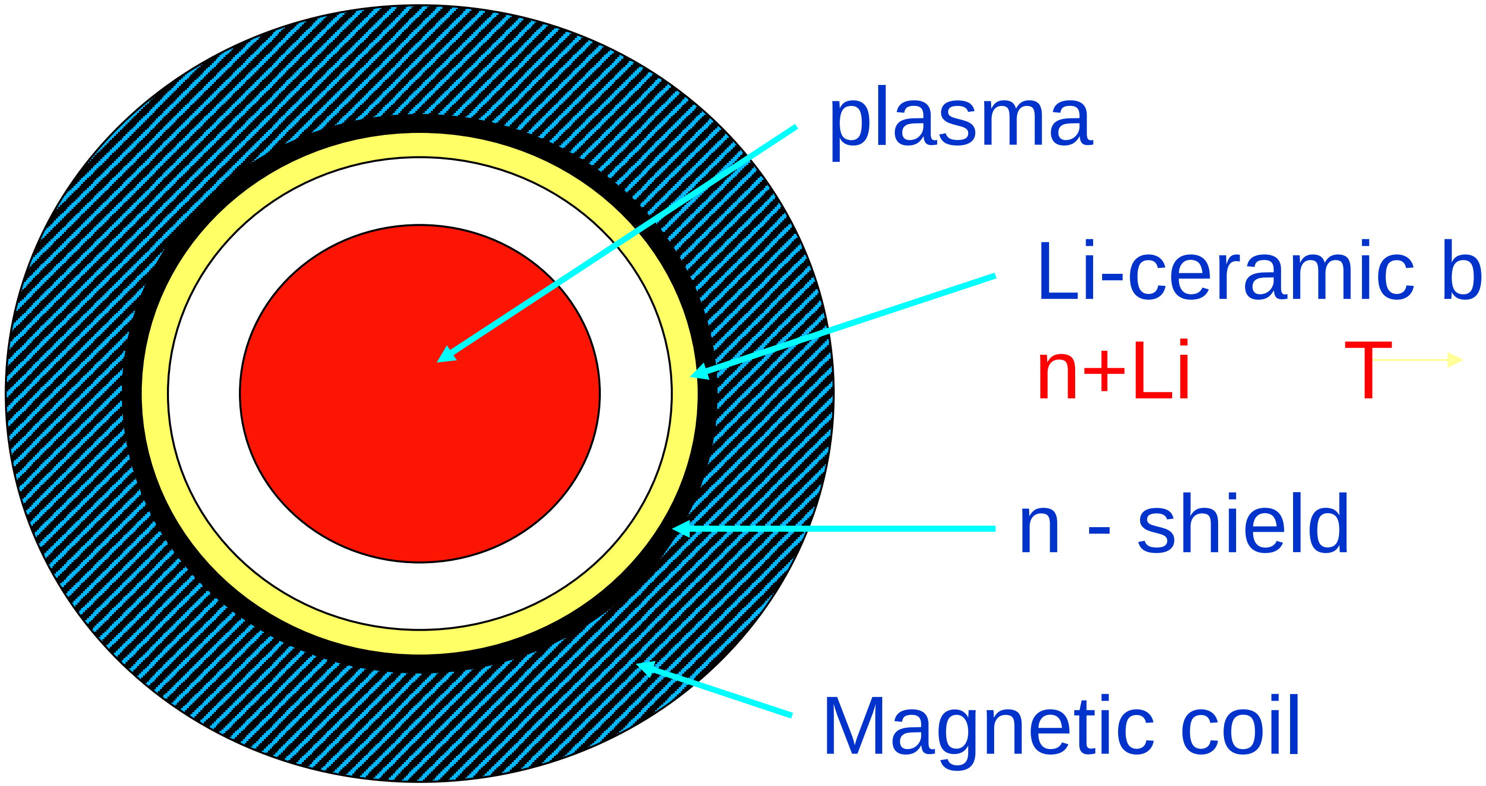
Both systems are complementary:

- in the tokamak, the current flows in the plasma
- in the stellarator, it flows in the coils
- the tokamak is pulsed
- the stellarator is for steady-state operation
- the tokamak can develop detrimental instabilities
- the stellarator is not 2-dimensional, complicated assembly and maintenance

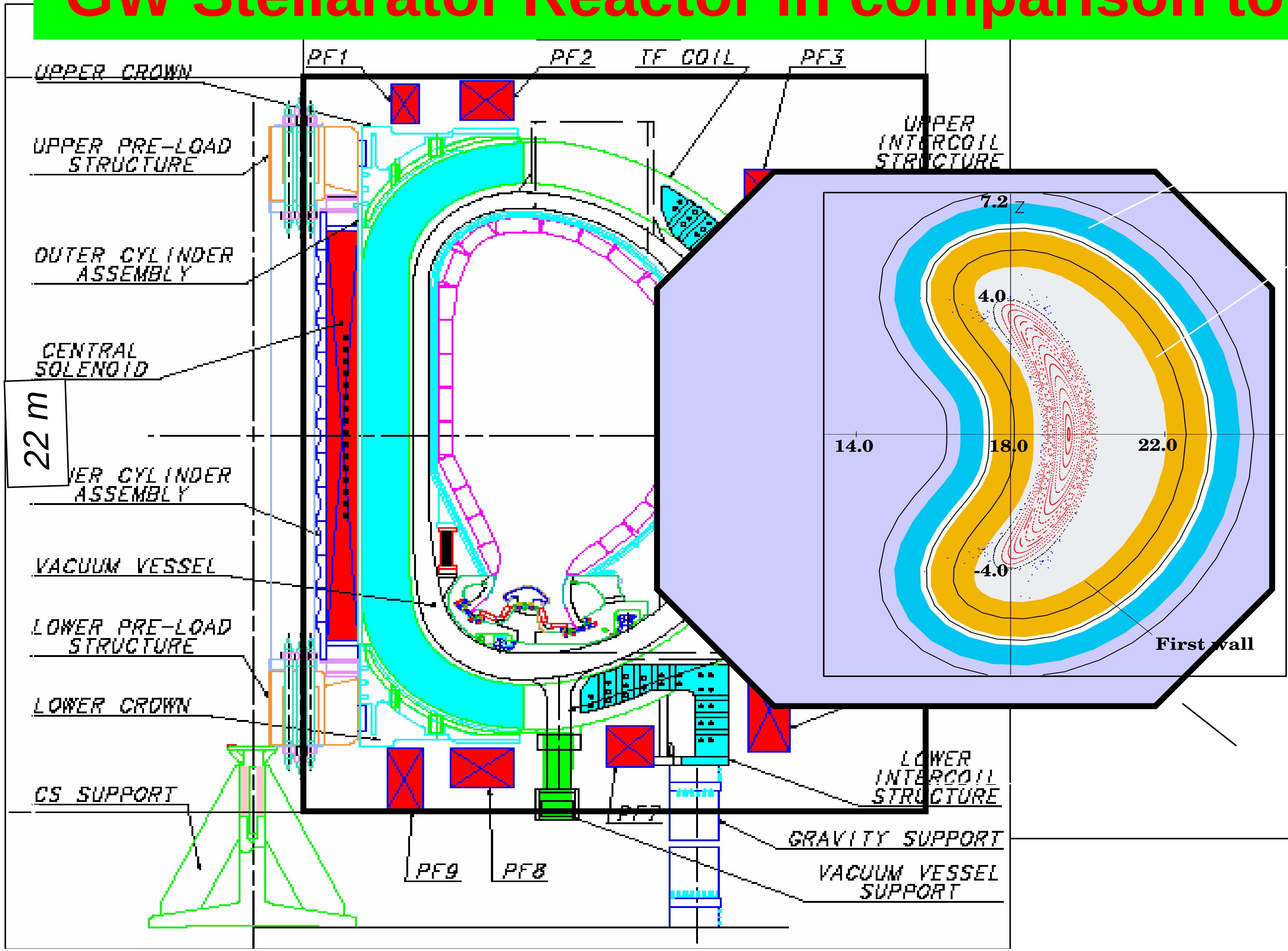
The EU Fusion Strategy



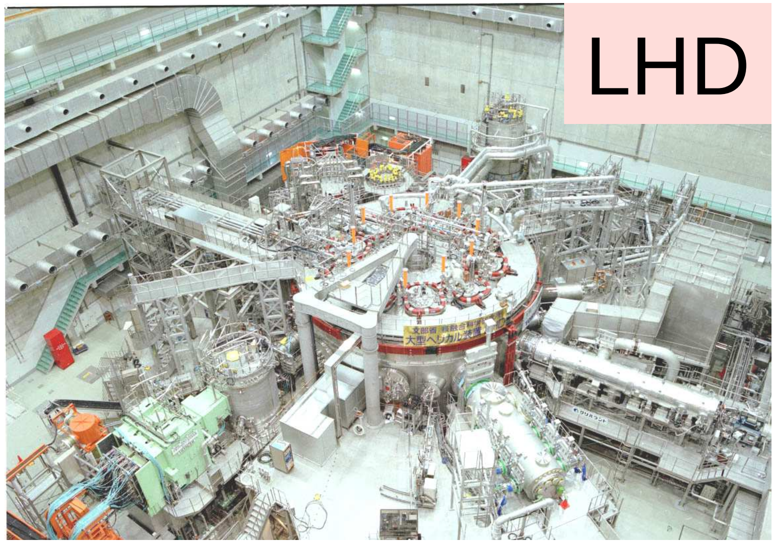
Principle set-up of a fusion reactor

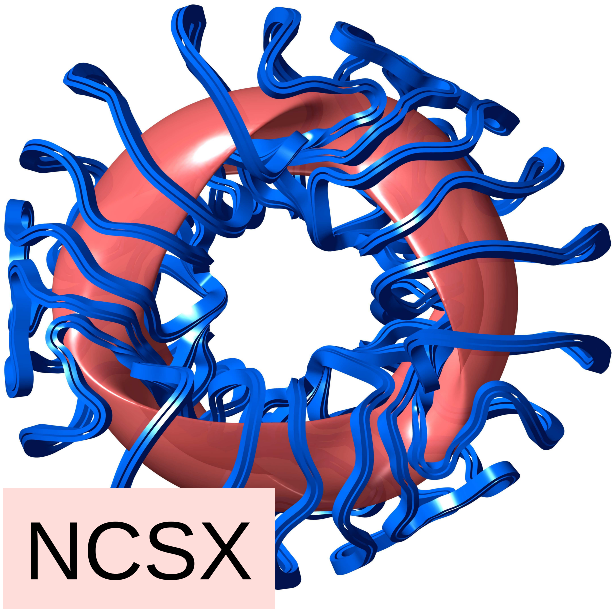


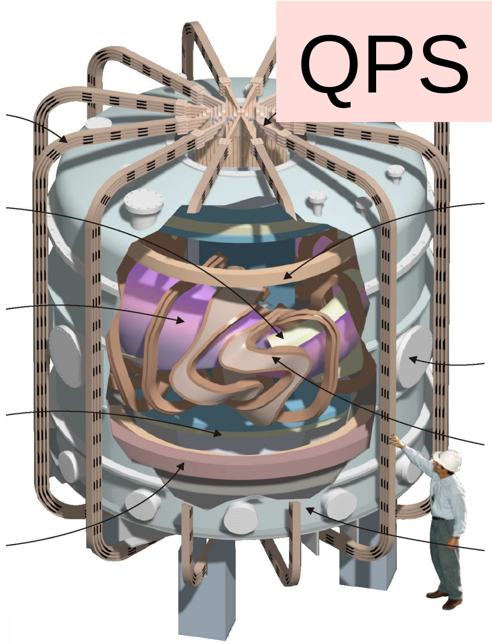
GW Stellarator Reactor in comparison to ITER

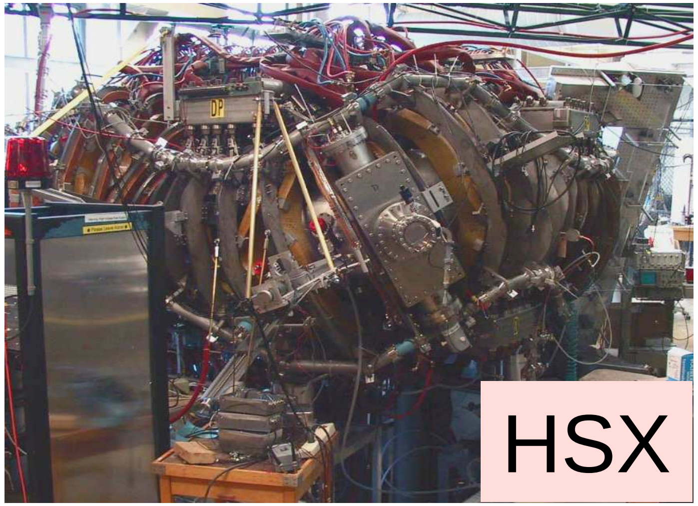


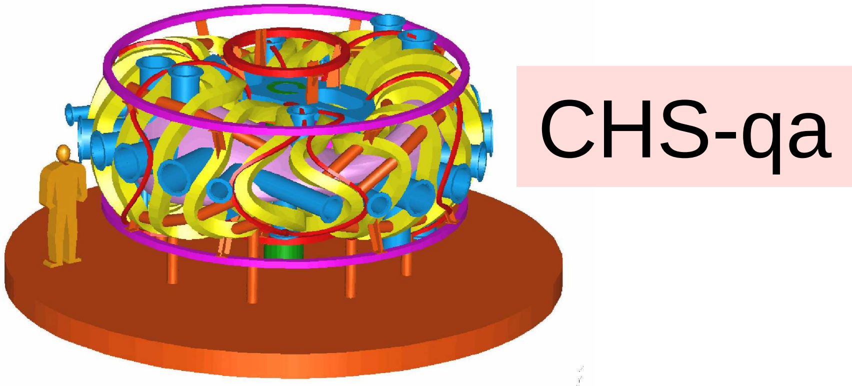
Major Stellarators in the World-Wide Programme











W7-X Magnet System

Planar coils
Nom. current 16kA@4K@6T

tesla

Non-Planar Coils
Nom. current 18.2kA@4K@6.7T

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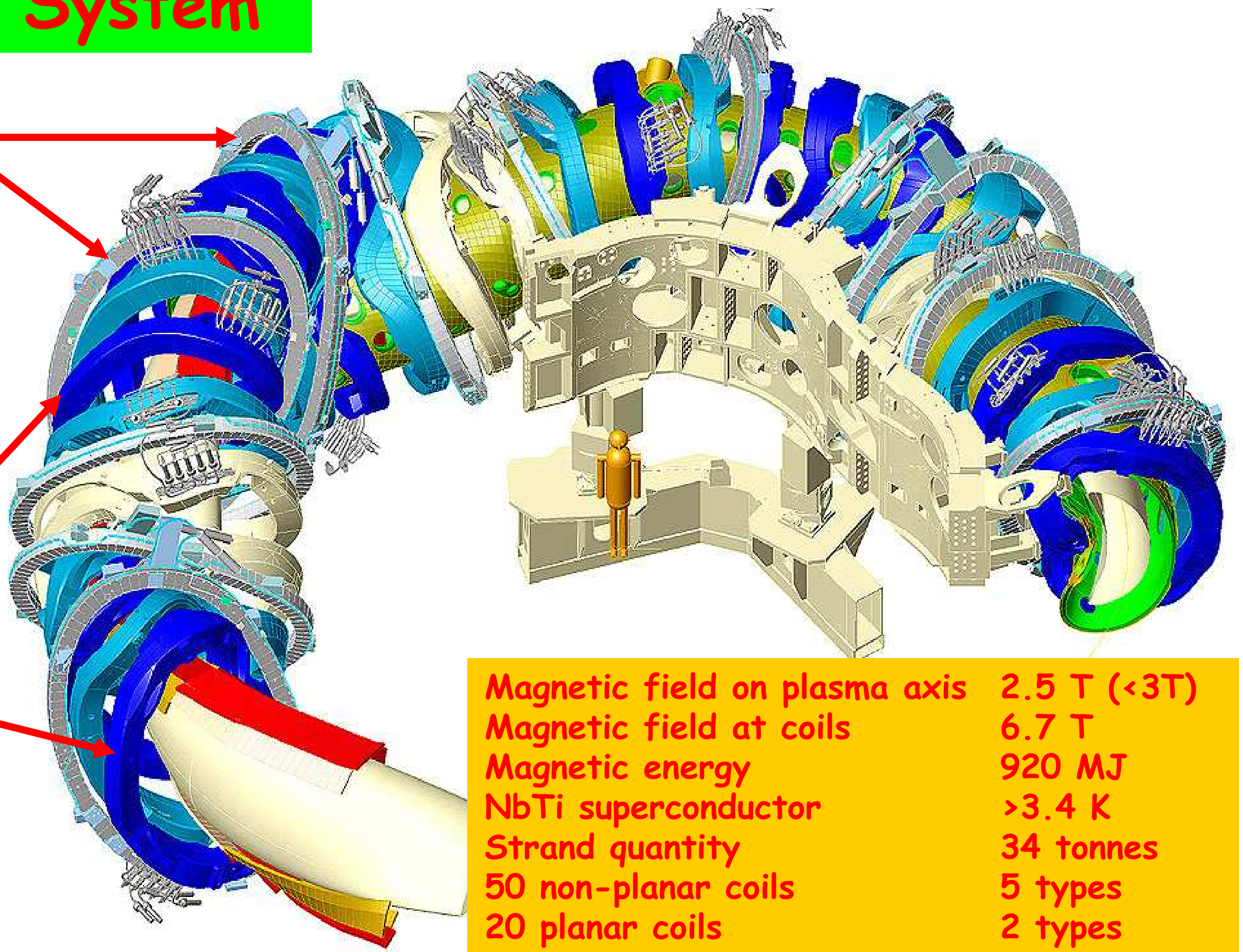
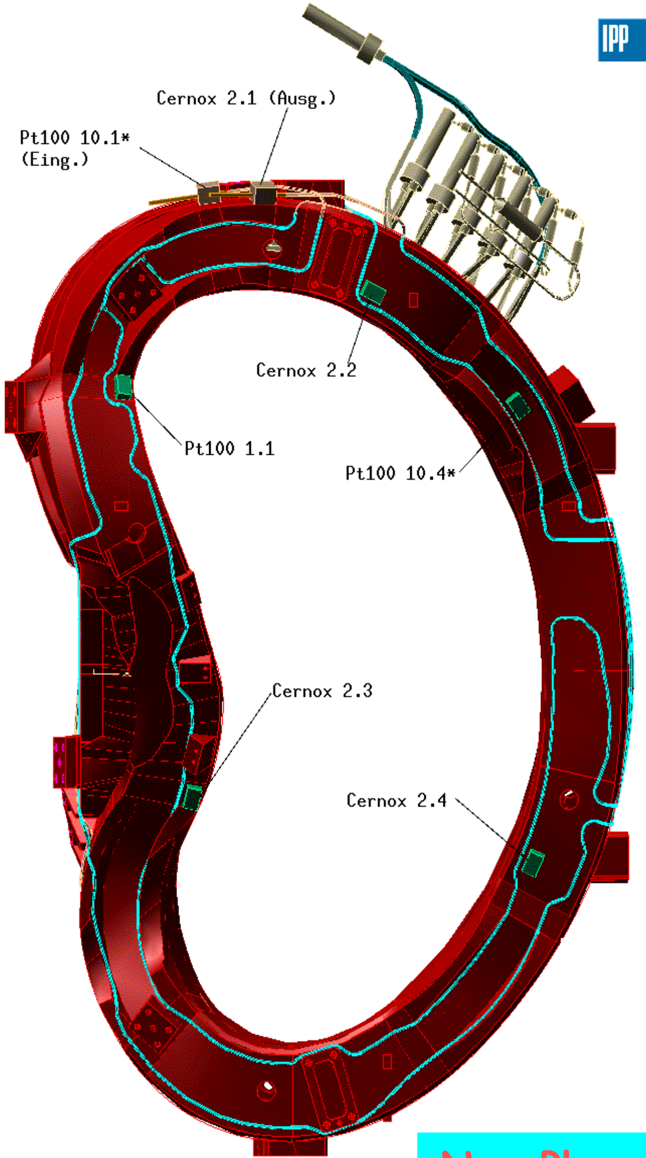
ABB

ANSALDO SUPERCONDUTTORI

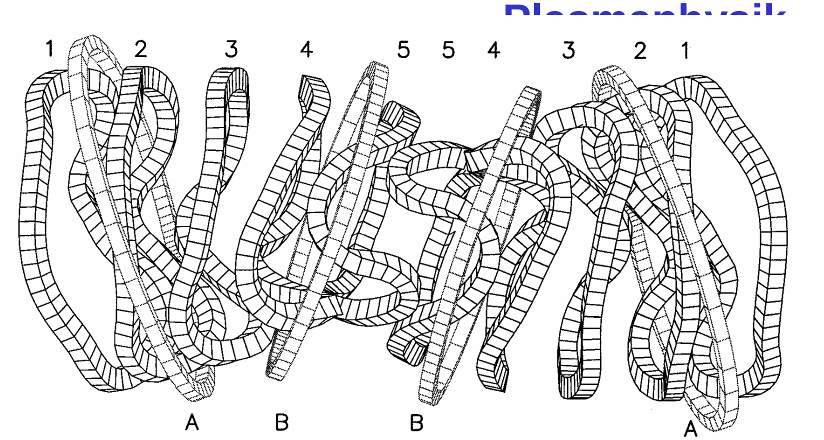


Magnetic field on plasma axis	2.5 T (<3T)
Magnetic field at coils	6.7 T
Magnetic energy	920 MJ
NbTi superconductor	>3.4 K
Strand quantity	34 tonnes
50 non-planar coils	5 types
20 planar coils	2 types
Cost	~85 MEuros

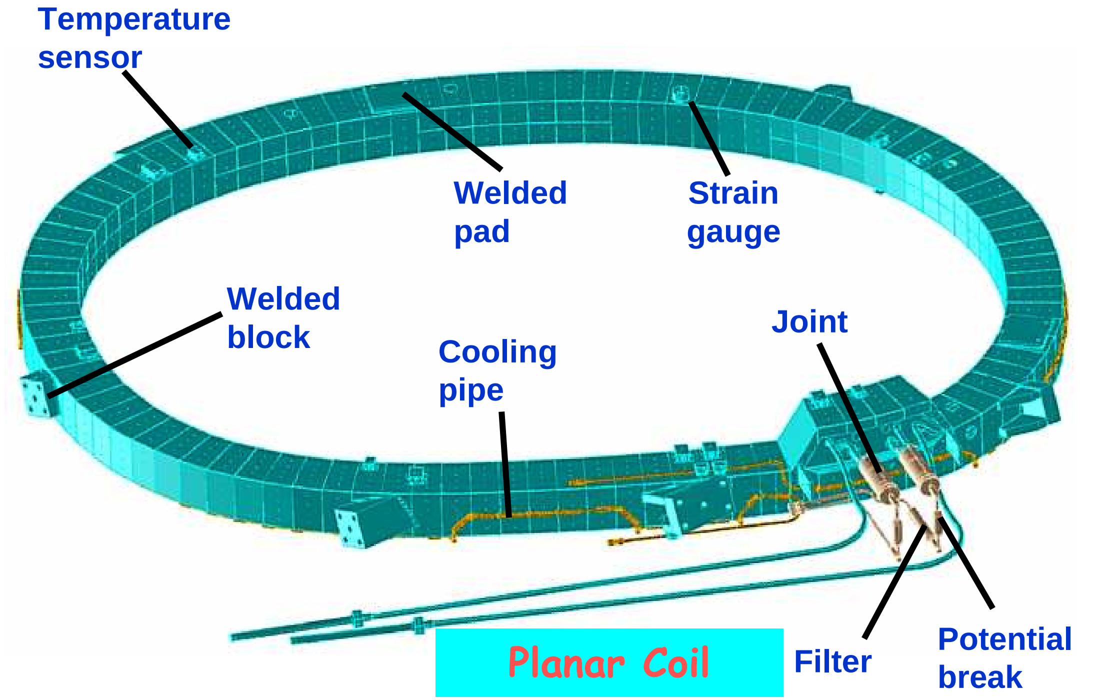
Carlo Sborchia / W7-X Basic Device
Magnet Department
e-mail: sborchc@ipp.mpg.de



Non-Planar Coil



W7-X Module Assembly (1/5)

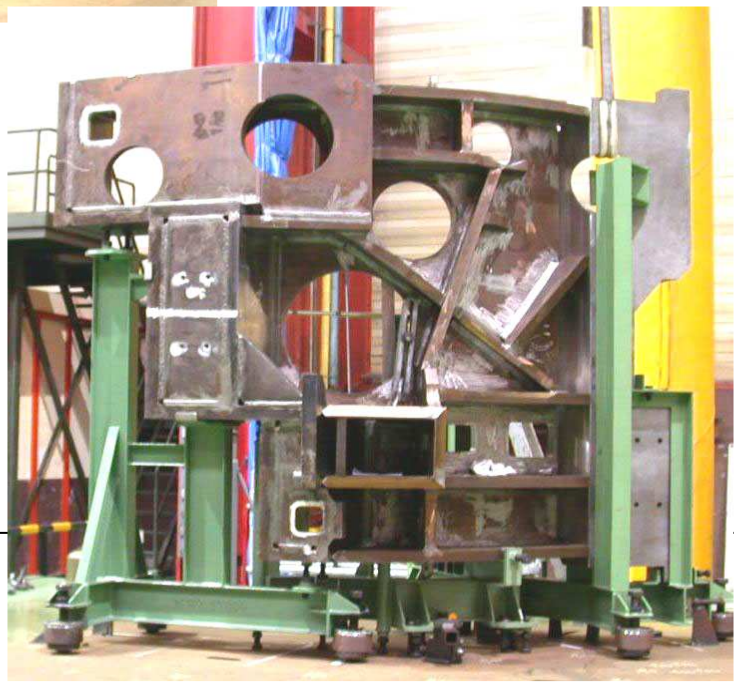


Planar Coil

Main Technical Parameters of W7-X Coils

	Non-Planar coils	Planar coils
Number of differently shaped types	5	2
Casings	stainless steel castings	stainless steel plates
Weight per coil	≈ 5.5 tons per coil	≈ 2.3 tons per coil
Main dimensions	≈ 3.5 m x 2.5 m x 1.5 m	≈ 4.0 m x 3.0 m x 0.5 m
Max. operating current	18.2 kA	16 kA
Safety margin current	Icrit ≥ 35 kA at 4 K and 6 T	Icrit ≥ 35 kA at 4 K and 6 T
Nominal insulation voltage	6 kV DC	4 kV DC
Nominal voltage over terminal	1 kV (highest discharge voltage between terminals during operation)	
Overall resistance of coil	< 6 nΩ	
Leak rate	$< 10^{-7}$ mbar l/s at RT and 4 K	
Mass flow of winding pack	> 0.6 g/s at 4 K p(in) = 6 bar, Δp < 1 bar	
Mass flow tolerance at RT	4300 l/h ± 20%, p(in) = 20 bar, 20 °C	
Nominal He pressure, test pressure	20 bar, 30 bar	
Life cycle	15 years, 50 cooldowns, 50 quenches, 5,000 full current changes	

Realisation of W7-X



Involvement of European Industry in W7-X

RST Rostock System Technik
Ein Astrium Unternehmen

A KB

tesla

Roug

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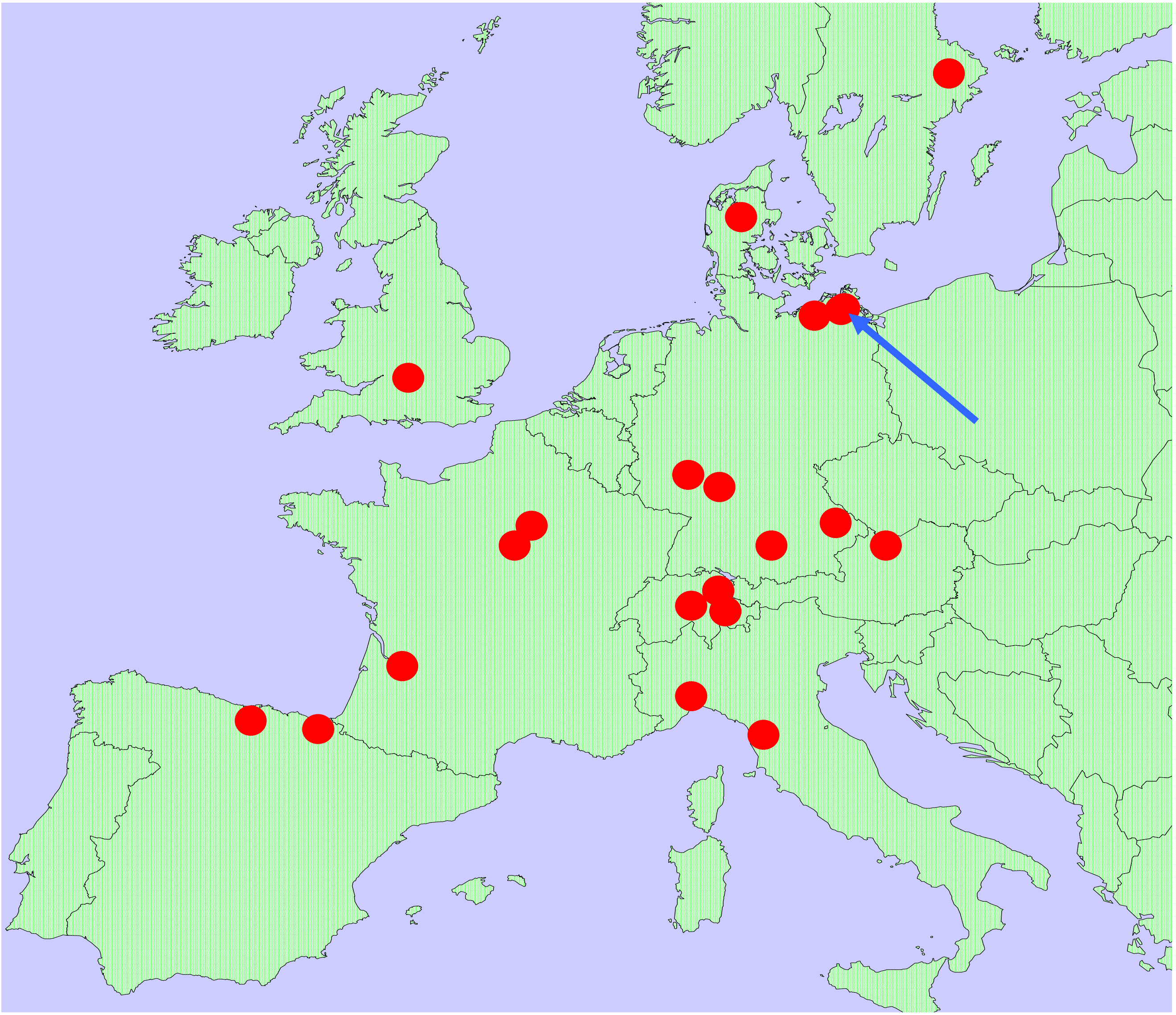
Babcock Noell Nuclear GmbH

SIEMENS

cea DSM - DAPNIA

ENSA Equipos Nucleares, S.A.



Österby gjuteri ab

MAN DWE

ROMABAU

THALES BROADCAST & MULTIMEDIA

ABB

Siempelkamp Nukleartechnik

EM

Snecma Propulsion Solide
groupe snecma

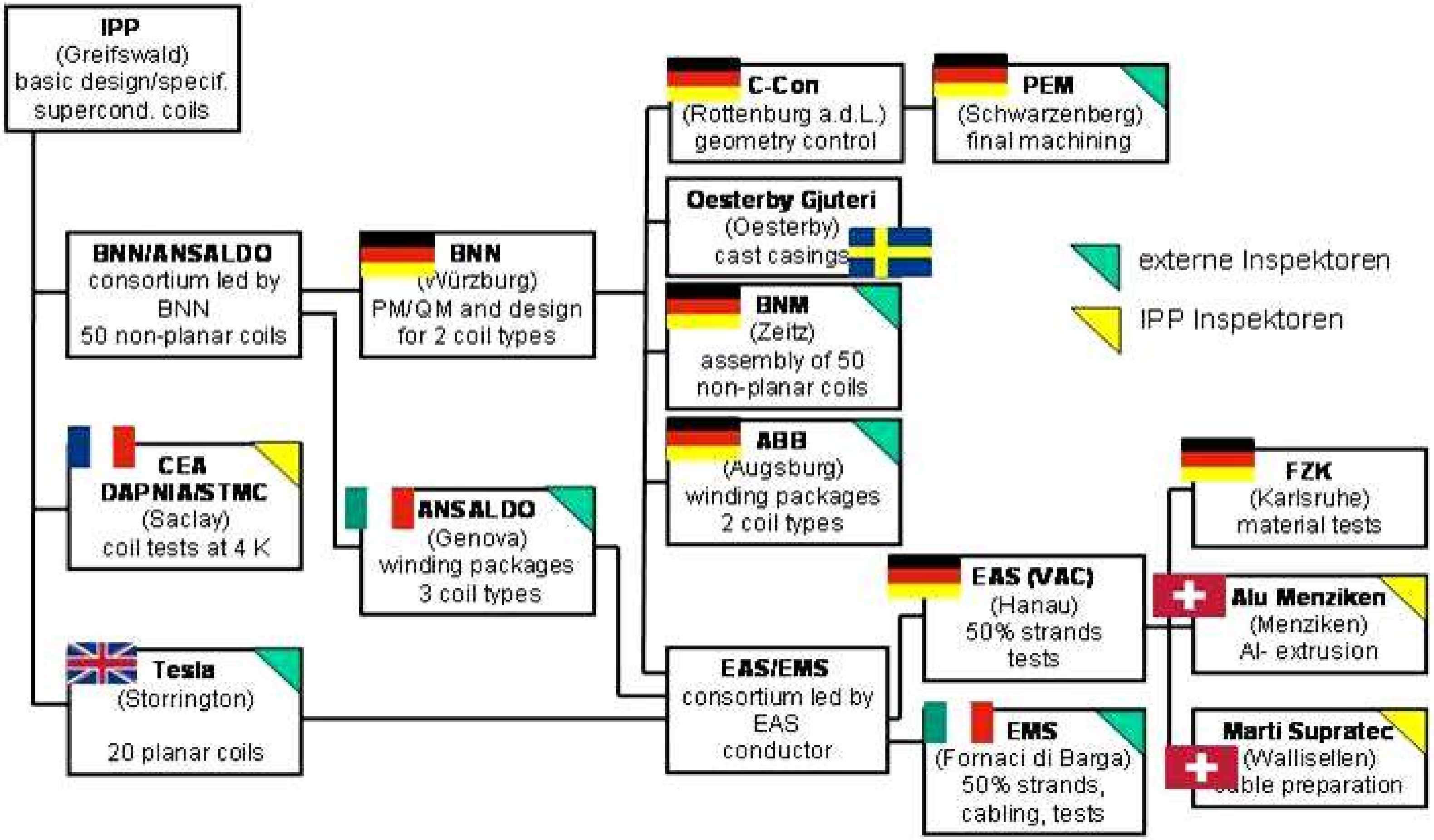
JEMA GRUPO JEMA

ALU MENZIKEN INDUSTRIE AG

VAC VACUUMSCHMELZE

ANSALDO SUPERCONDUTTORI

Organization of W7-X Magnet Production



Contracts placed in 1999 after completion of the DEMO non-planar coil fabrication and testing (at FZK)

(EMS became OCSI, now LUVATA)

Status of W7-X Magnet Manufacture

Superconductor (NbTi)

- Supply of CON (BNN/Ansaldo) and Tesla completed (360 DLLs), spare lengths for CON and IPP in progress (18 DLLs total)

Non-Planar Coils

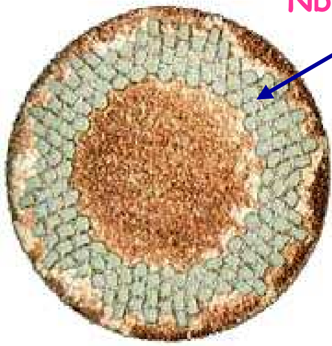
- 47 (out of 50) winding packs produced by BNN/ABB and Ansaldo Superconduttori
- Last 3 windings in production at Ansaldo
- 27 coils embedded in the stainless steel casings with quartz sand–epoxy filler
- 5 coils accepted by IPP and being prepared for assembly:
  1HM(AAB18, AAB24, AAB19) 2HM(AAB13, AAB17)

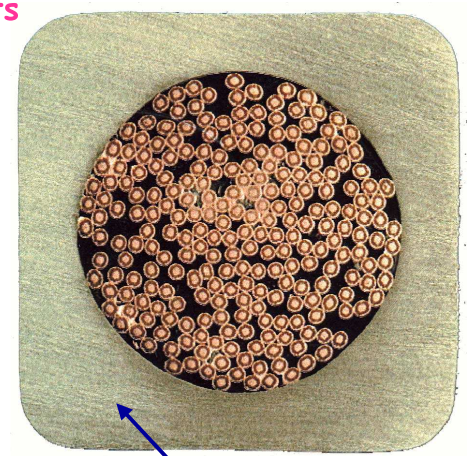
Planar Coils

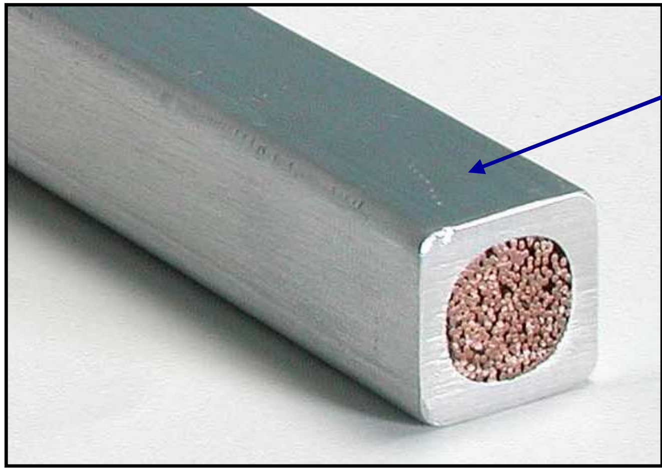
- All 20 winding packs complete, 9 coils embedded in the casing
- 3 coils accepted by IPP and being prepared for assembly:
  1HM(AAC54, AAC12) 2HM(AAC51)

W7-X Superconductor

Number of strands	243
Minimum wall thickness	> 2 mm
Outer dimensions	16 x 16 mm^2
Strand diameter	0.57 mm
Ic (6 T/4.2 K)	> 150 A
Cabling law	3x3x3x3x3
Void fraction	37 ± 2% [± 1%]
Mass flow rate tolerance	± 20% [± 10%]
Jacket	AlMgSi (6063)
Al jacket yield strength, $Rp_{0,2}$	< 150MPa soft cond. at room temperature > 280MPa hard cond. at 4 K







EAS European Advanced Superconductors

OCSI

Carlo Sborchia / W7-X Basic Device
Magnet Department
e-mail: sborchc@ipp.mpg.de

Production Sequence of Superconductor at EAS (VAC) / OCSI (EM) Consortium

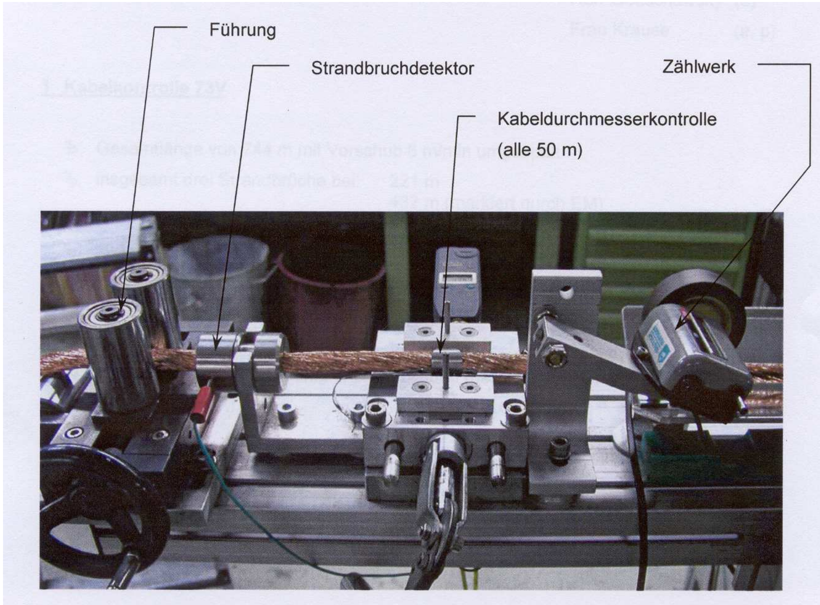
1. strand production and 50 % VAC / EAS
   50 % EM / OCSI

2. cabling at Outokumpu Superconductors Italy (OCSI), Fornaci di Barga

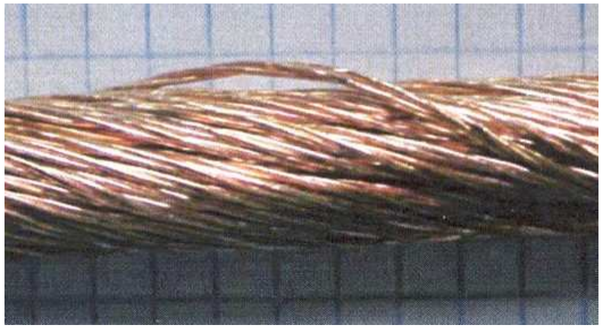
3. check of cable and preparation for co-extrusion at Marti Supratec

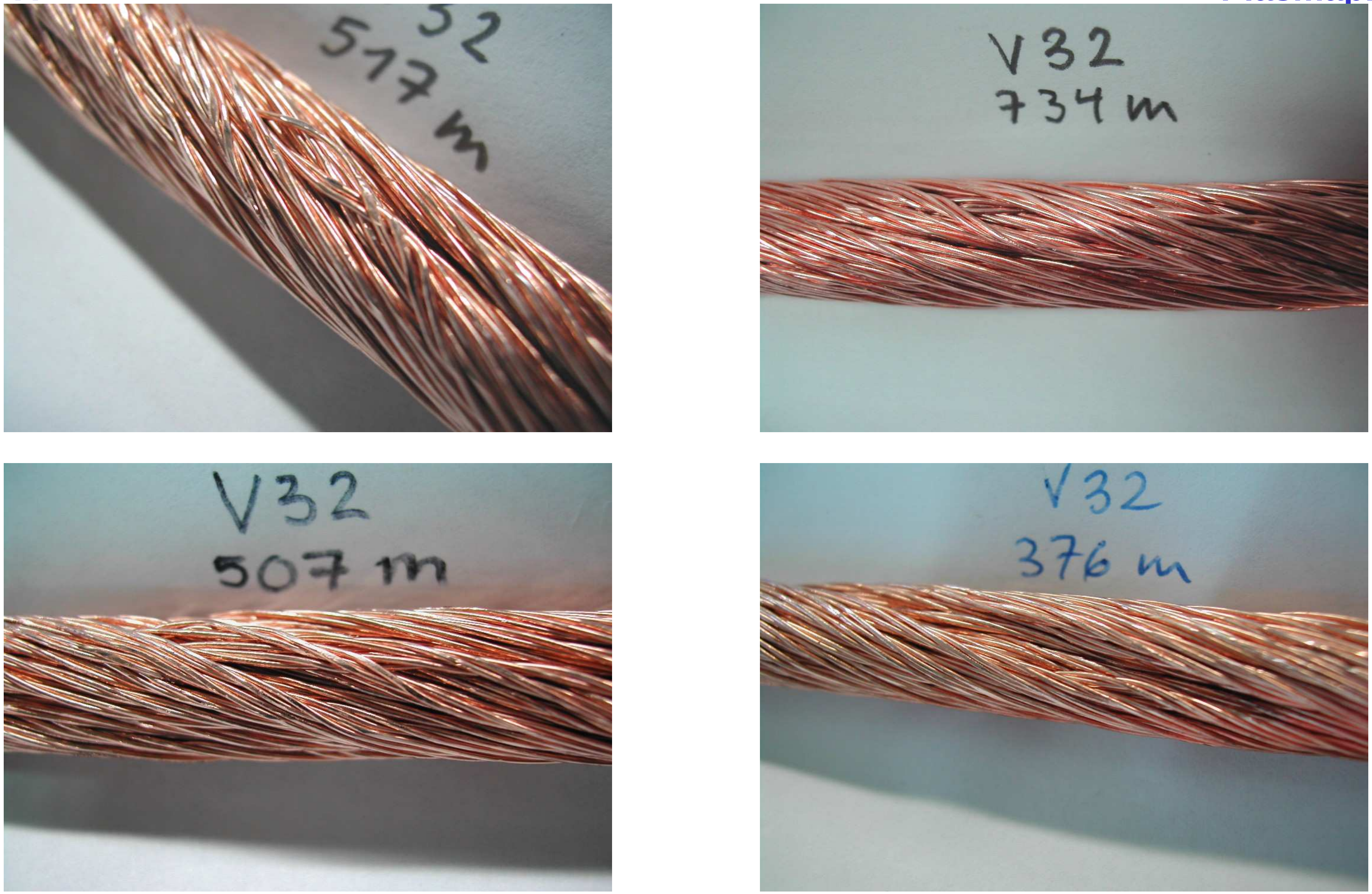
4. co-extrusion of the aluminium jacket at Alu Menziken

5. final tests on the superconductor lengths mainly at OCSI and EAS (wall thickness, pressure and leak test, flow rate, Ic, RRR)



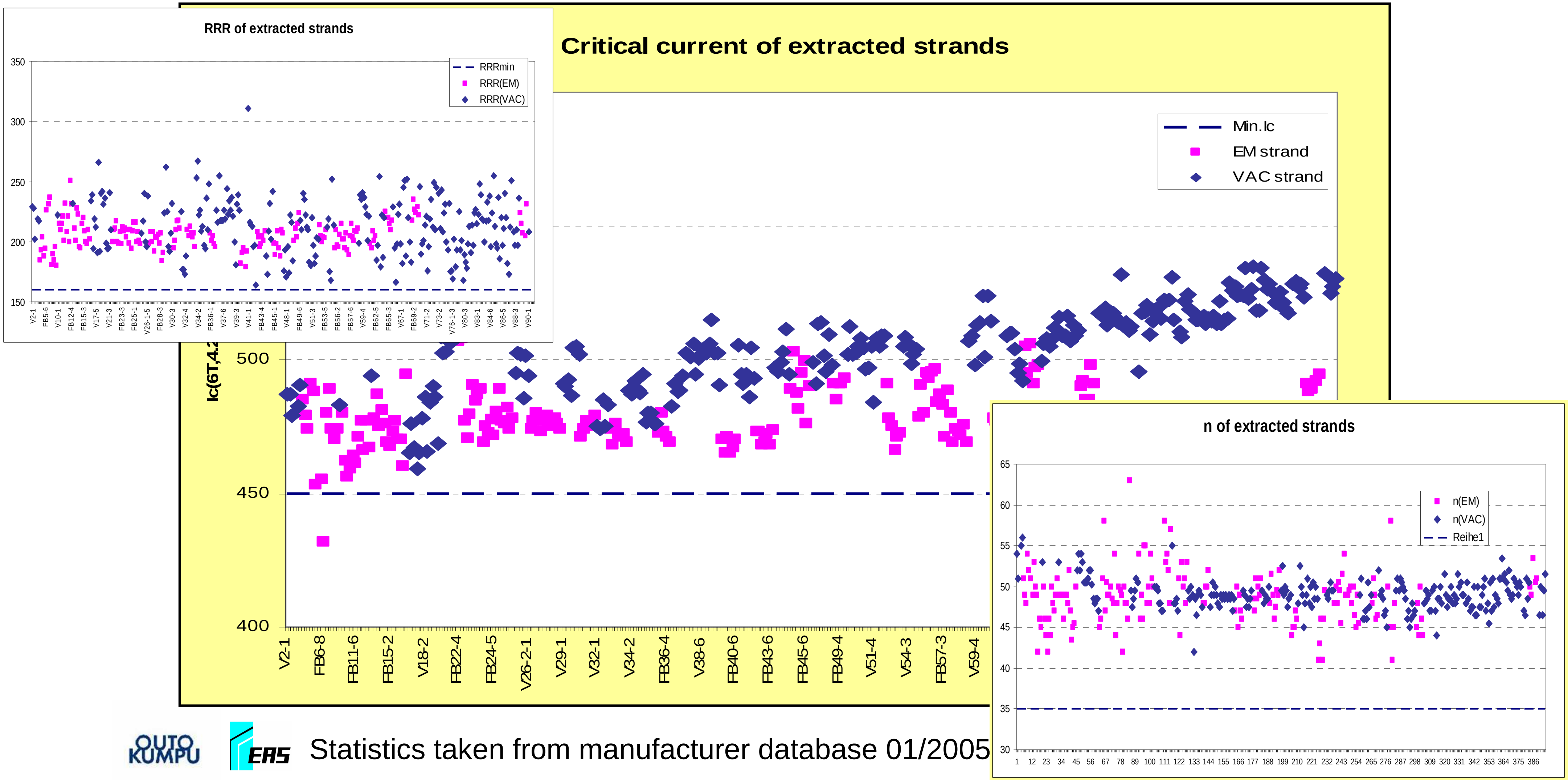
loose triplets and slings





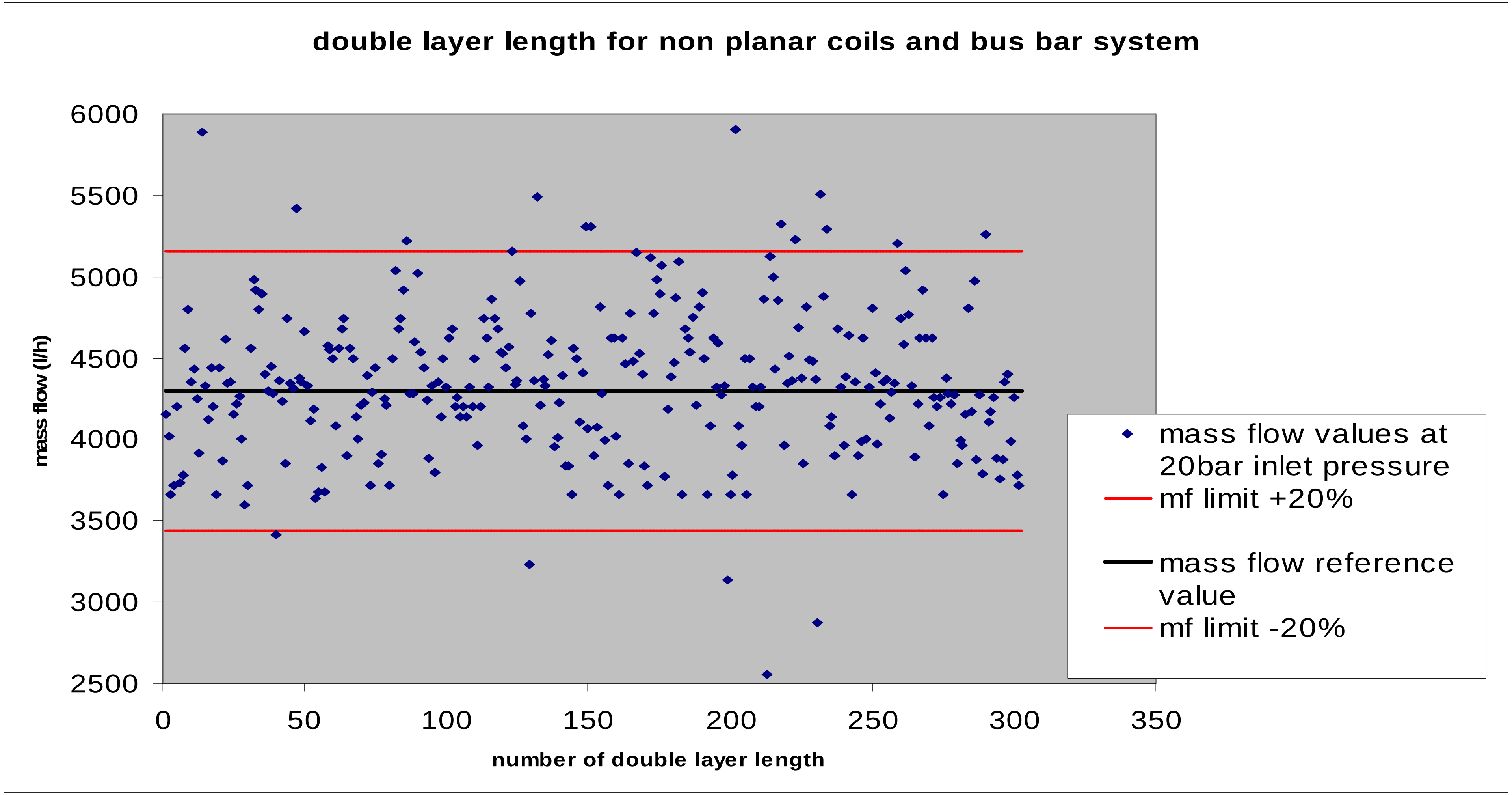
Typical cabling irregularities of a 3x3x3x3x3 cable

Statistic Evaluation of Superconductor Production Data - Ic, RRR and n values



Statistics taken from manufacturer database 01/2005

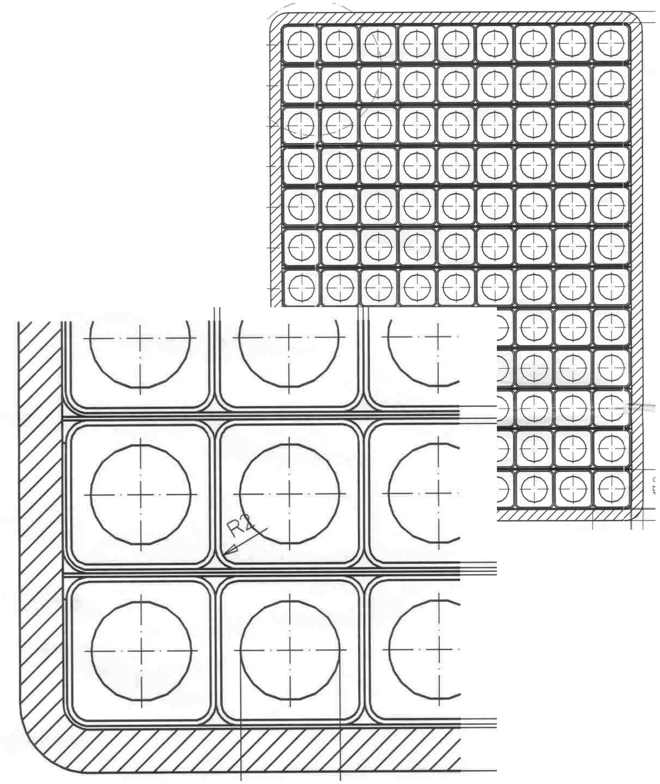
Statistic Evaluation of superconductor production data - Mass Flow Rate



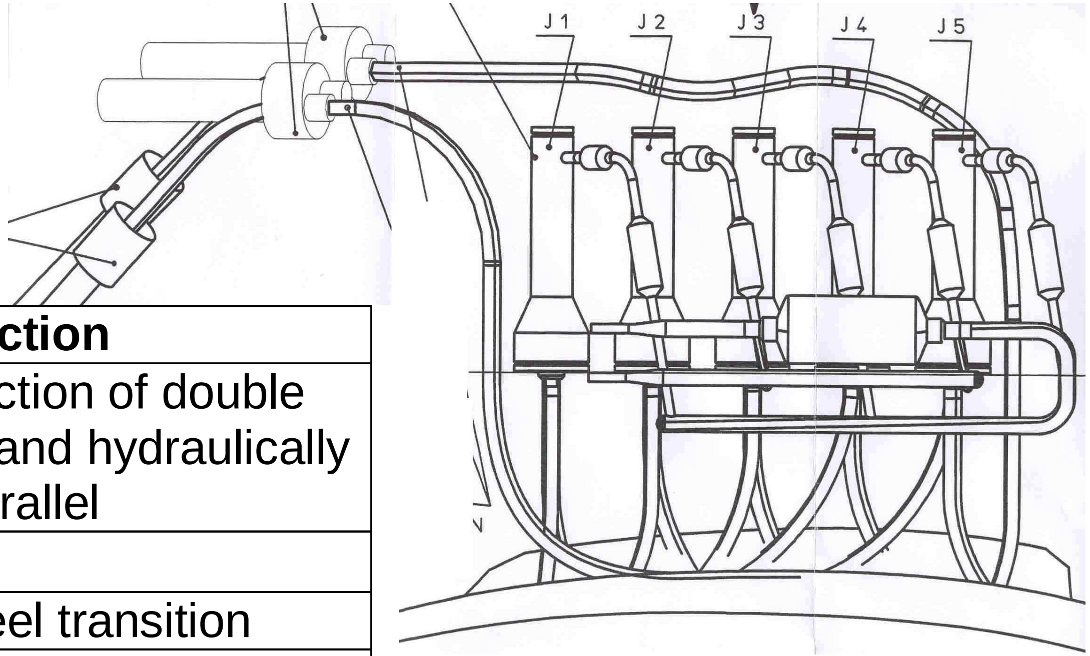
statistic taken from manufacturer data base 01/2005

Engineering Design – Non-Planar Winding Pack

	properties
winding pack	108 turns in 6 double layers; hydraulically connected in parallel
shear strength (lamination)	> 55 MPa at 4K (approx. 40 MPa at RT)
tensile and compressive stress	according to strength of hardened conductor, insulation material has to transfer this stress
glass content of insulation material	60%
geometrical accuracy	inner side -3mm side faces +/-3mm outer side +/-5mm

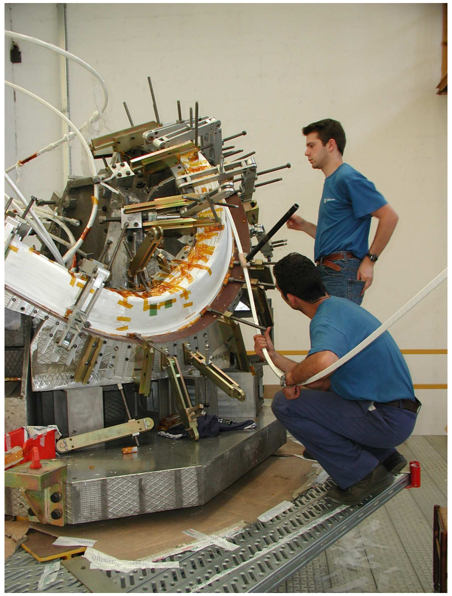


Engineering Design - Winding Pack Connection Area



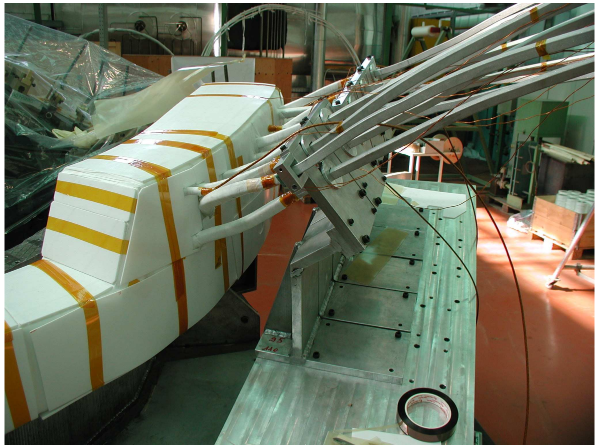
	properties/ function
joints	electrical connection of double layers in series and hydraulically connected in parallel
joint resistance	<1nΩ
material separators	Al / stainless steel transition
potential breaks	insulation of coil potential
He inlet	one filter and 3 He inlets
He outlet	two outlets by joints and 2 termination ends
geometrical accuracy	+/-10mm

Manufacturing Flow of Non-Planar Windings



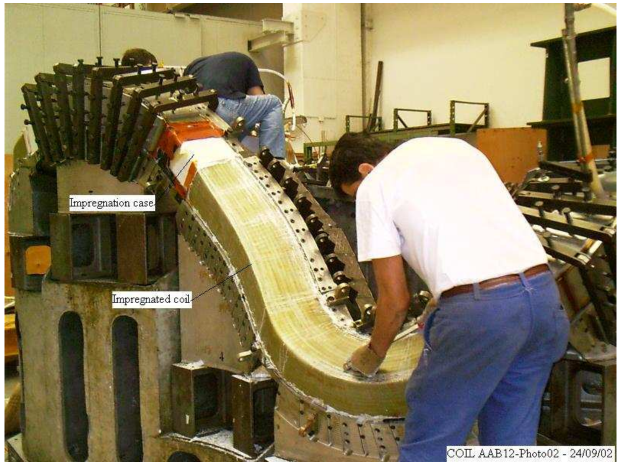
Winding

Layer Adjustment



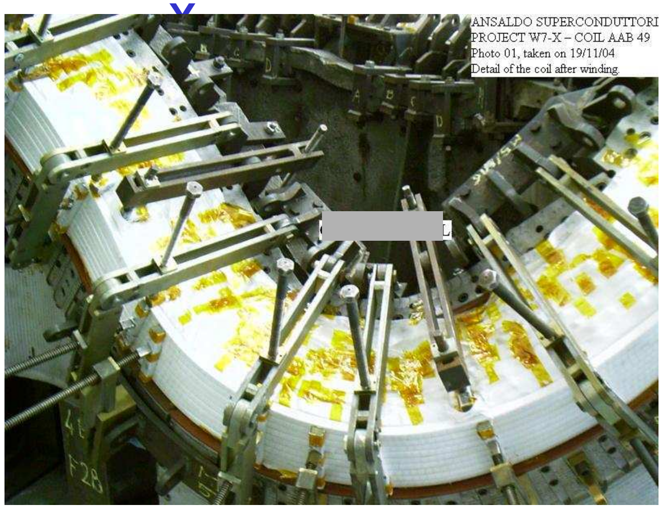
Ground Insulation

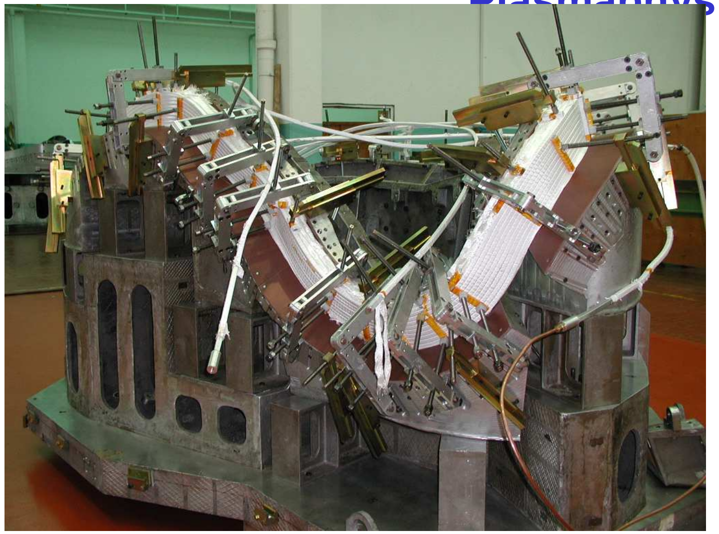
Impregnation



Dimensional Inspection

Courtesy of CON



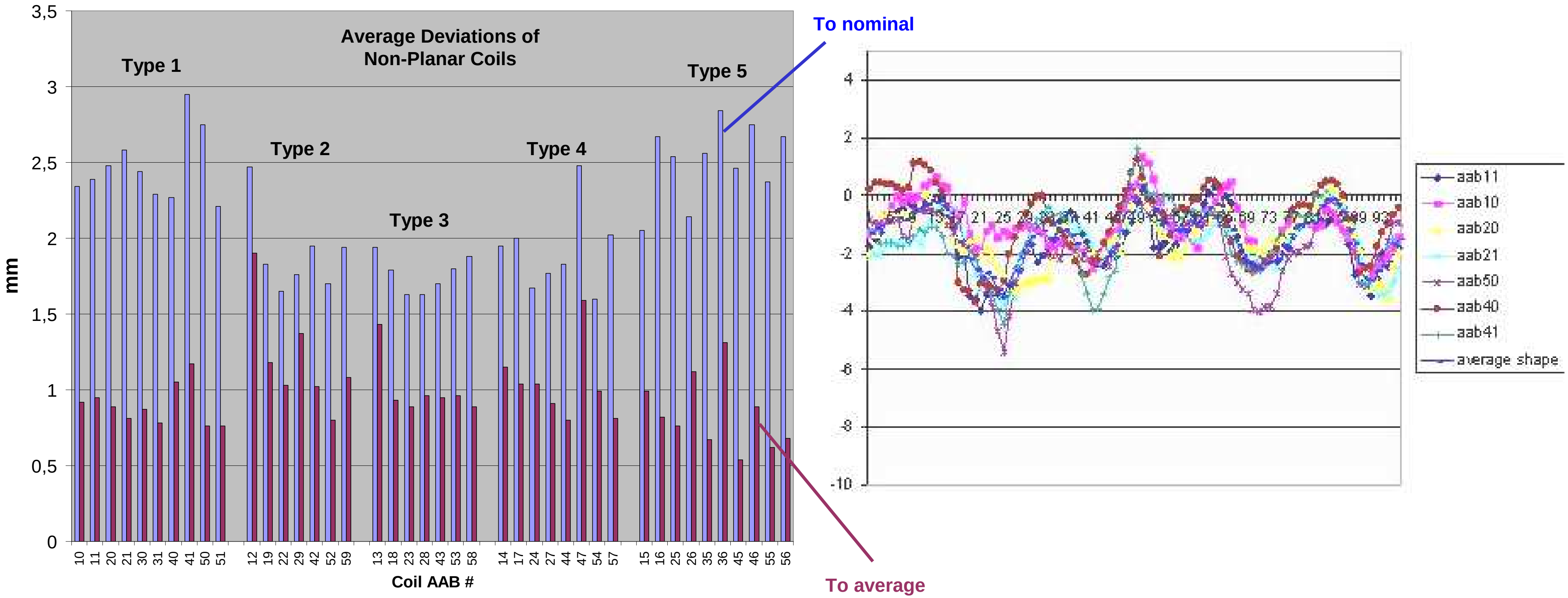


Winding of Coil Types 2, 3 & 4

Winding of Coil Types 1 & 5

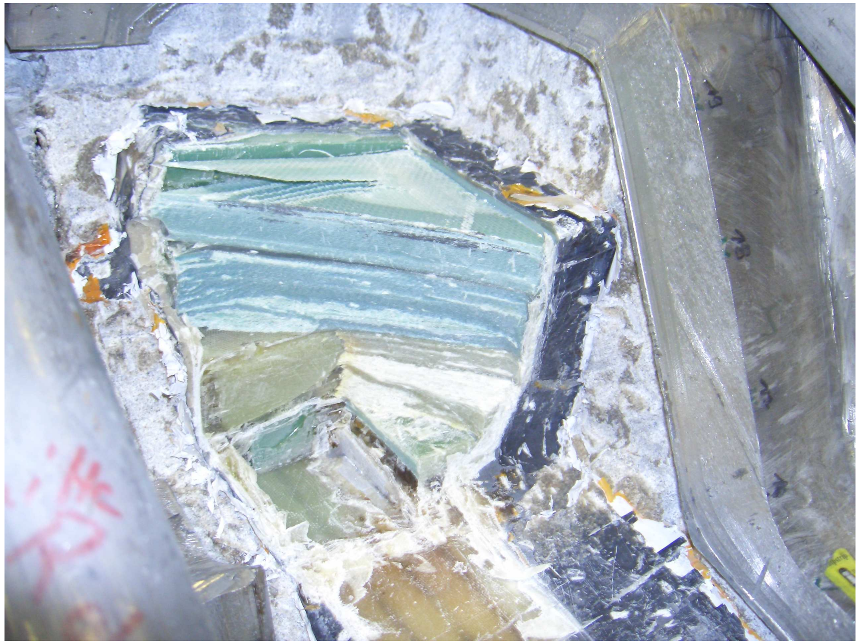
Winding Accuracy

- The accuracy of the winding packages is measured on 96 longitudinal cross sections (8 points per section) with a laser tracker
- The average relative deviations are in the order of <2 mm



Repair Work in NPC Winding Manufacture

Reconnection of QD Wires



Short Circuit in Terminal Area

Repair of QD Wire Connector & Insulation

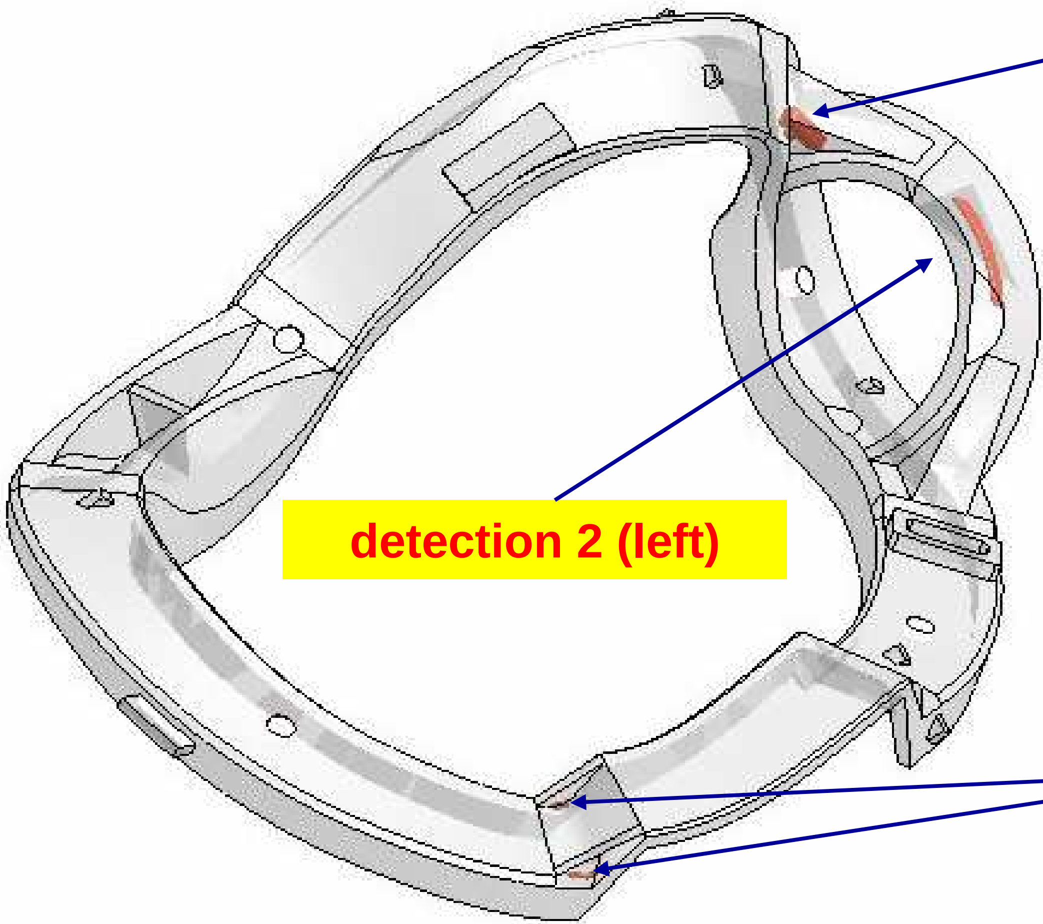
Case Production

- cast process for single half shells and blocks
- heat treatment of half shells and blocks to achieve mechanical and physical properties
- pre-machining of half shells

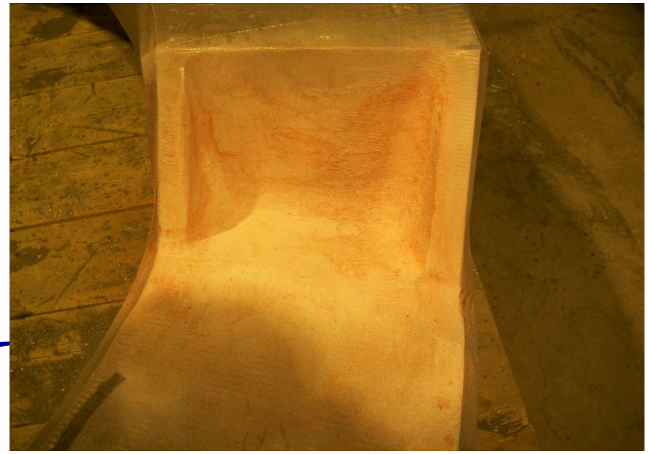
Case half shells produced by Österby Gjuteri AB in Sweden as subcontractor of BNN

Defects on NPC Casings

detection 1 (repaired)



detection 2 (left)



detections 3a and 3b (repaired)

Non-Planar Coil Final Assembly

Insertion of Winding in Half Casings

Embedding

(The casing is filled with quartz sand/resin)

Final Assembly

Coil Assembly - Winding Pack Insertion

Assembly take place at BNM in Zeitz, BNN is owner of BNM

preparation of half shells with:

- assembly of protection steel plates around closure welds
- assembly of pipes inside for as resin distribution system
- assembly of handling and helping tools

inserting of winding pack into the base shell

placement of the lid onto the assembly

start with the root of the closure weld (WIG)

Coil Assembly - Block Welding and Machining

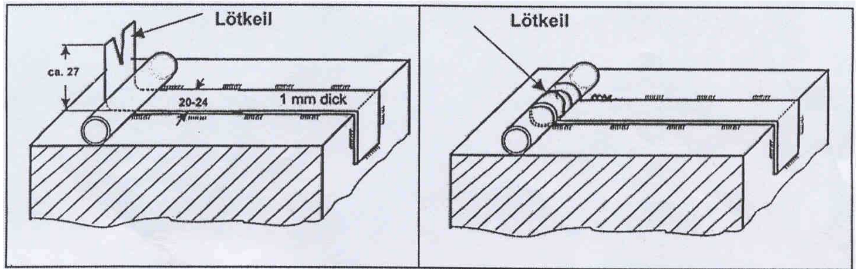
Machining takes place at PEM or KUKA in Schwarzenberg

Block welding:
e.g. central support blocks, assembly blocks, weight support blocks were placed after embedding

Machining:
of coil surface
of machined faces on blocks
of threads and fit holes

allowed tolerances
for machined faces, threads and fit holes
between 0.2mm - 0.6mm

Assembly of Cooling System and Instrumentation



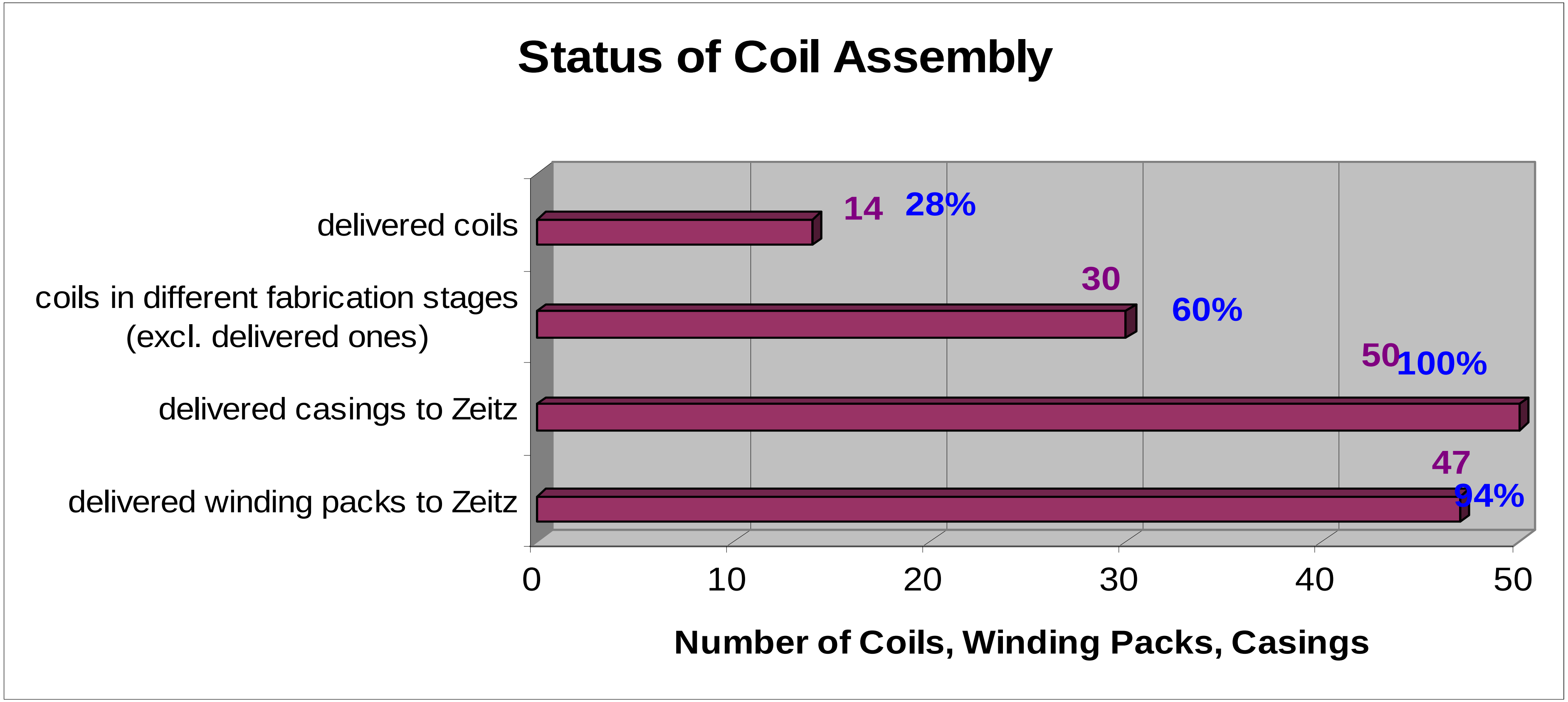
Cooling system

- placement of 4 SS cooling pipes on the steel casing
- welding of app. 150 copper stripes 20 mm wide at 40 mm distance along the casing
- soldering of copper stripes to the cooling pipes

Instrumentation

- assembly of temperature sensors and strain gauges

Non-Planar Coil Status



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Non-Planar Coil Production

Actual delivery targets

2006: 24 Coils

- achieved January 2006: 3 Coils
- February – March 2006: 2 Coils
- April – July 2006: 8 Coils
- August – Dez. 2006: 11 Coils

2007: 16 Coils

Last coil delivery in June 2007

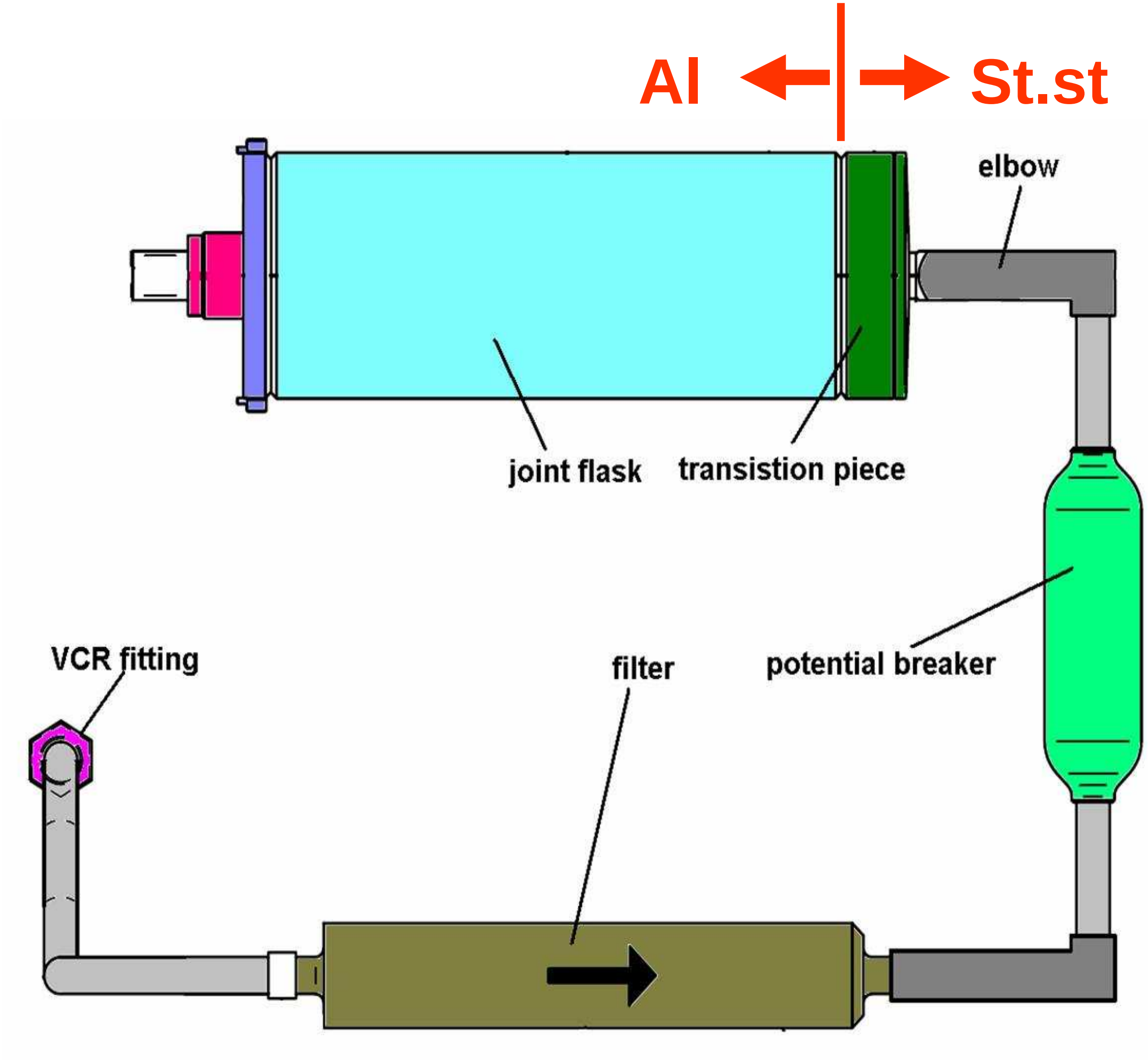
Planar Coils

Planar Coil Windings

- All 20 winding packs impregnated
- 9 finished coils embedded, 6 coils complete
- QD cable have been replaced (as for non-planar coils)
- Casing cooling pipe system had leak due to stress corrosion cracking caused by residuals of flux in the soldering of the copper blocks *thicker tubes, pre-tinning of pipes*
- Two coils showed leaks in Al welds region during cooldown at CEA Saclay *new qualification programme and repair of the existing welds* (common programme with Ansaldo and ABB)
- The coil casings are reinforced with the installation of about 400 additional pins
- Supply to be completed by June 2007

Planar Coil Assembly

Planar Coil Aluminum Welds



Cracks in cooling pipes

- Cracks in cooling pipe of coil AAC 52 due to residuals of chlorides
- Removal of all cooling pipes
- Use of new pipes (larger wall thickness)
- Pre-tinning of cooling pipes and cleaning

- Minor change of cooling tube carriers (two additional holes for a better supply of the filler material)
- Soldering pipes into blocks using non-aggressive flux and solder filler P60/40 (lead/tin)
- Soldering blocks onto copper cladding using soldering shim and non-aggressive flux
- Leaks test of cooling pipes before mounting
- Work specimen during production

Design Changes

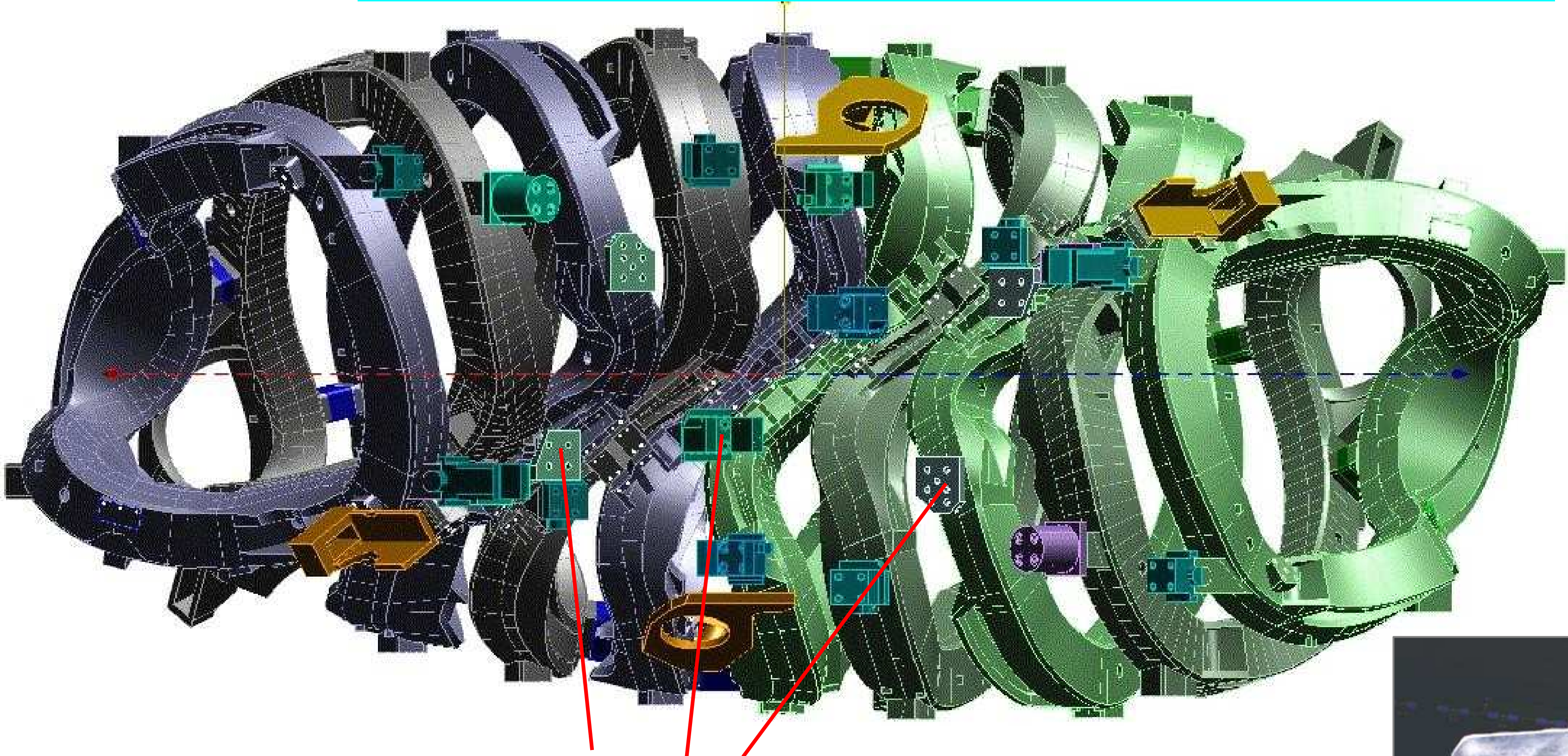
Design Changes Implemented during Production in 2004-2005

- Detailed Design of Support Structures, such as Central Supports, Narrow Support Elements, Lateral Supports, Planar Supports
- External Geometry, Routing of Cooling Pipes, Measurement Points
- Reinforcement of Structural Elements
- Implementation of ~400 reinforcing shear pins/coil in Planar Coil Casings

Quench Detection Cable and Connectors

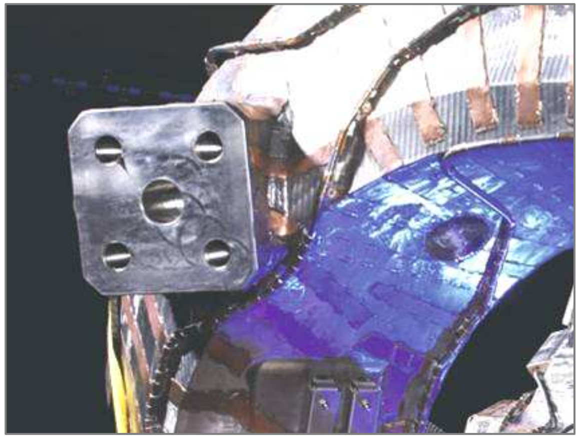
- QD Monette Cable: new cable qualified and tested in vacuum
- QD Connector Design developed and tested in vacuum after thermal cycles

Reinforcement of the Welds at the Central Supports



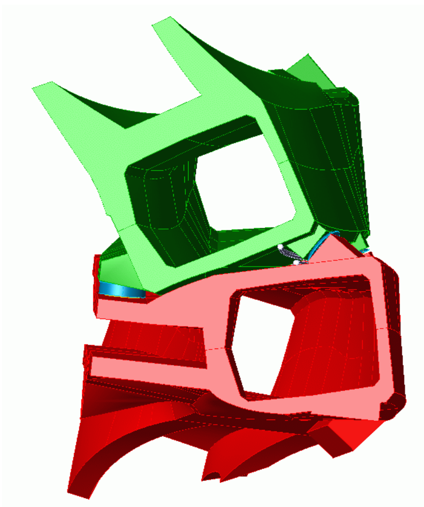
Central Support Elements (part of Central Support Structure)

Non-Planar Coils seen from the Torus

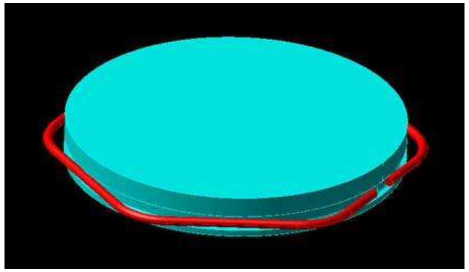


Narrow Support Element (NSE)

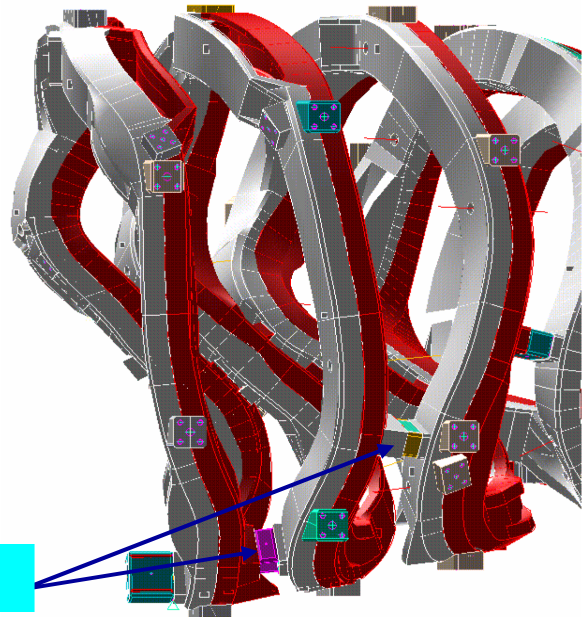
- Al-Bronze pads, MoS_2-Low Friction Interfaces with SiO_2 protection
- Tests at 150 t and stroke up to 12 mm, with a tilting angle of 0.5°
  no „stick-slip effects" up to 1400 (out of 5000) cycles
- Geometry of the NSE holding pads modified in the coil casings



Narrow Support Elements

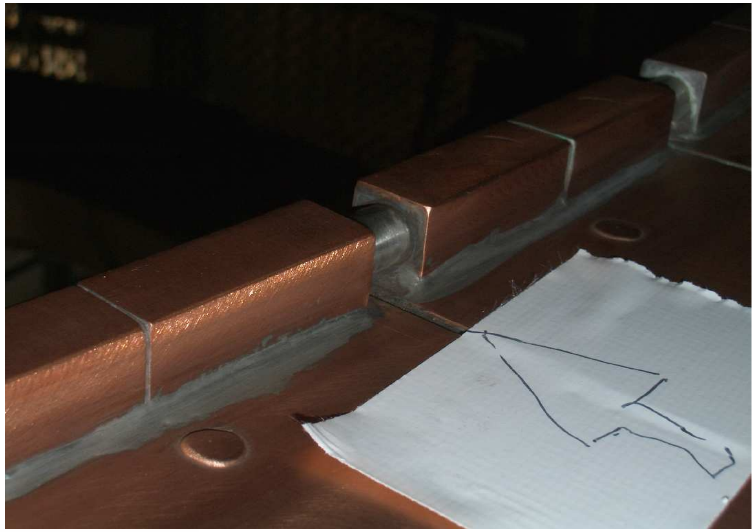


Lateral Supports

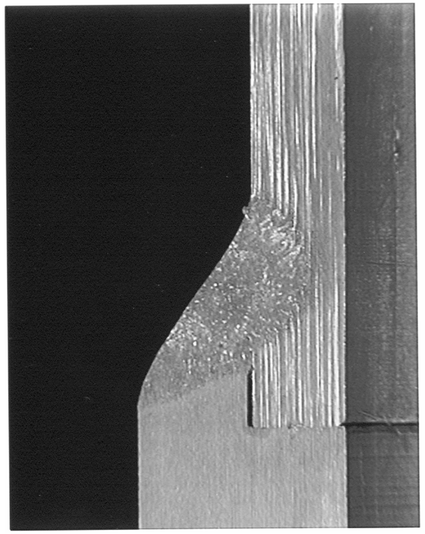


Welding/Soldering Qualification Tests

Aluminum weld qualification on full-scale samples tested at higher pressures (50-100 bar) and under thermal cycles to assess the risk of crack propagation in the welds

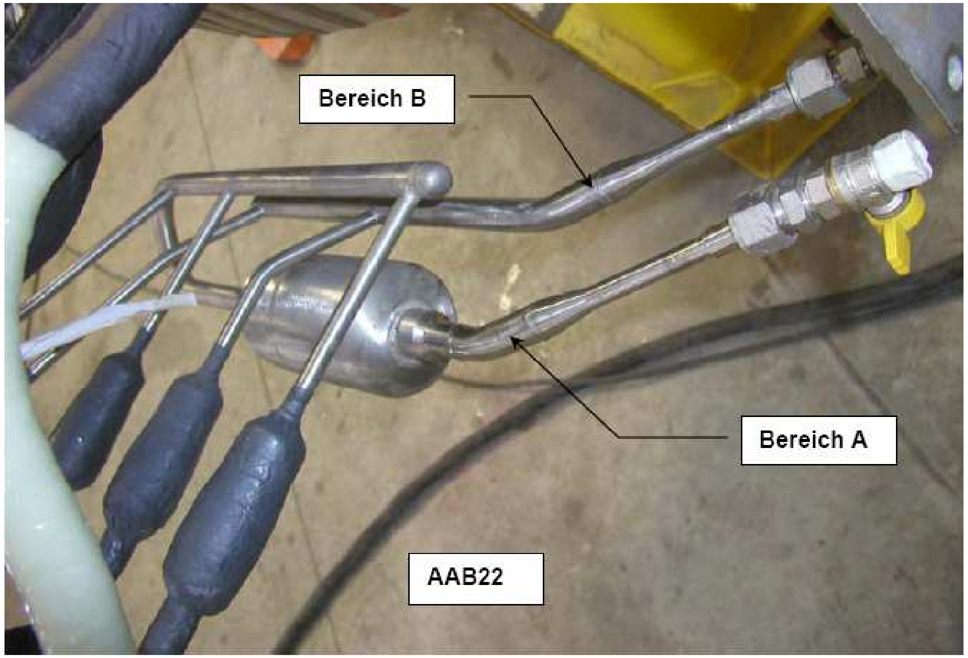


Stress Corrosion Cracking in Cooling Pipe



Al Weld at Joint Flask

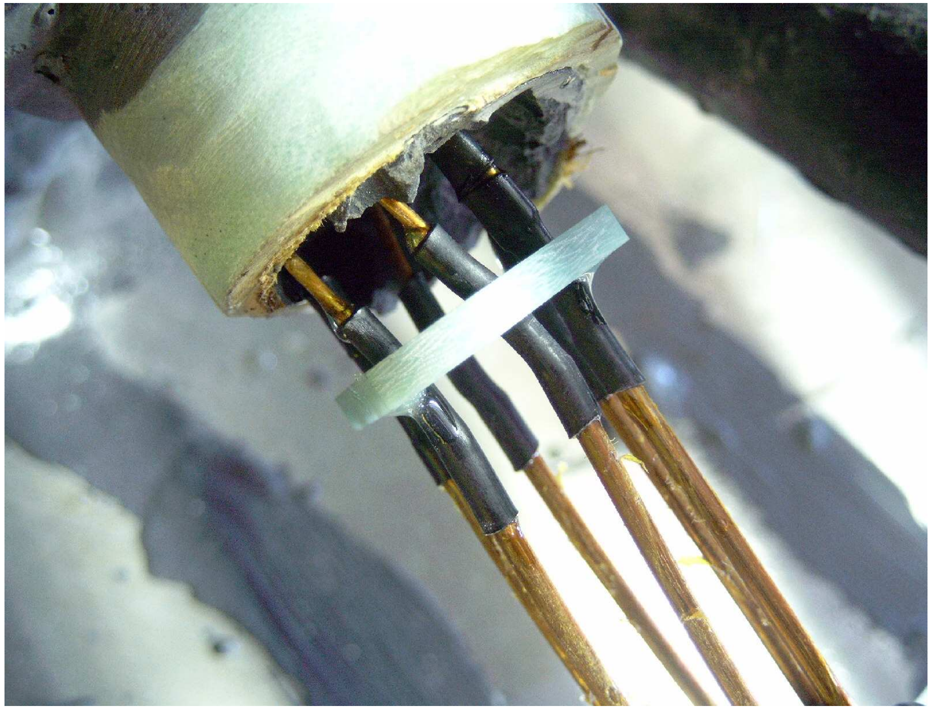
Repair of Headers and Filters

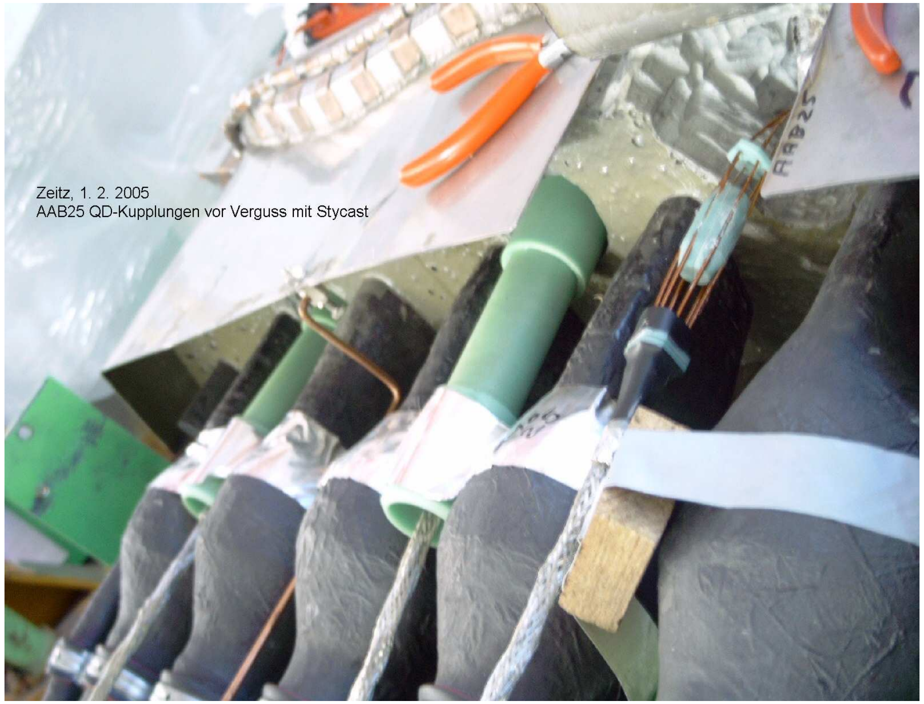


- Welding defects found at He-Inlets/ Outlets SS and Al welds on both NPC and PC.
- Rework is in progress.

High Voltage Problems

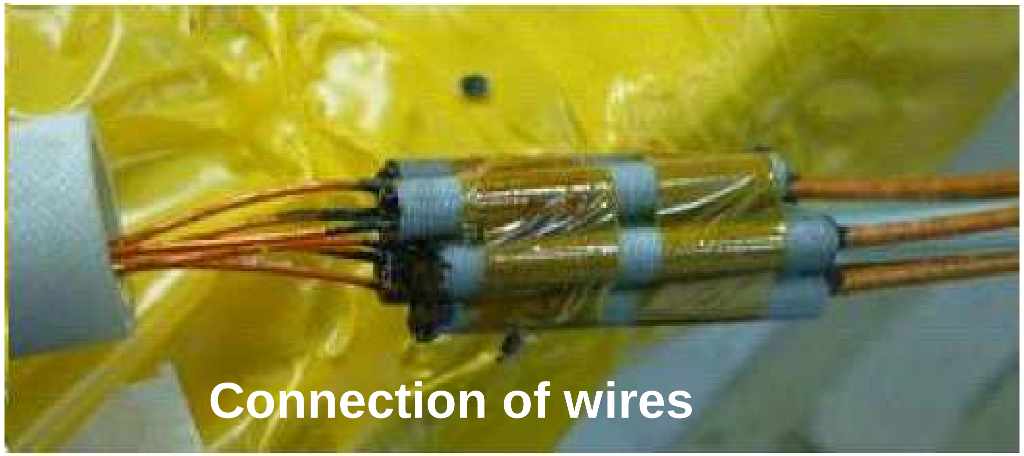
- QD cables replaced after early tests showed poor voltage strength under vacuum.
- A new set of acceptance tests in Paschen-minimum conditions (100, 20, 10, 1, 0.1, 0.01 mbar, etc.) have been implemented to improve the insulation quality.
- IPP has procured a vacuum tank to perform similar tests on-site before installation of the coils.

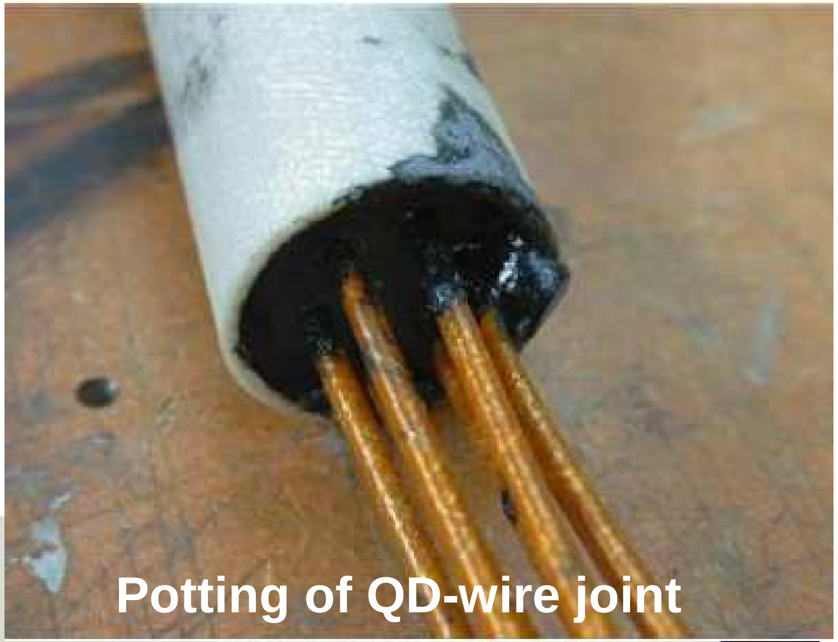


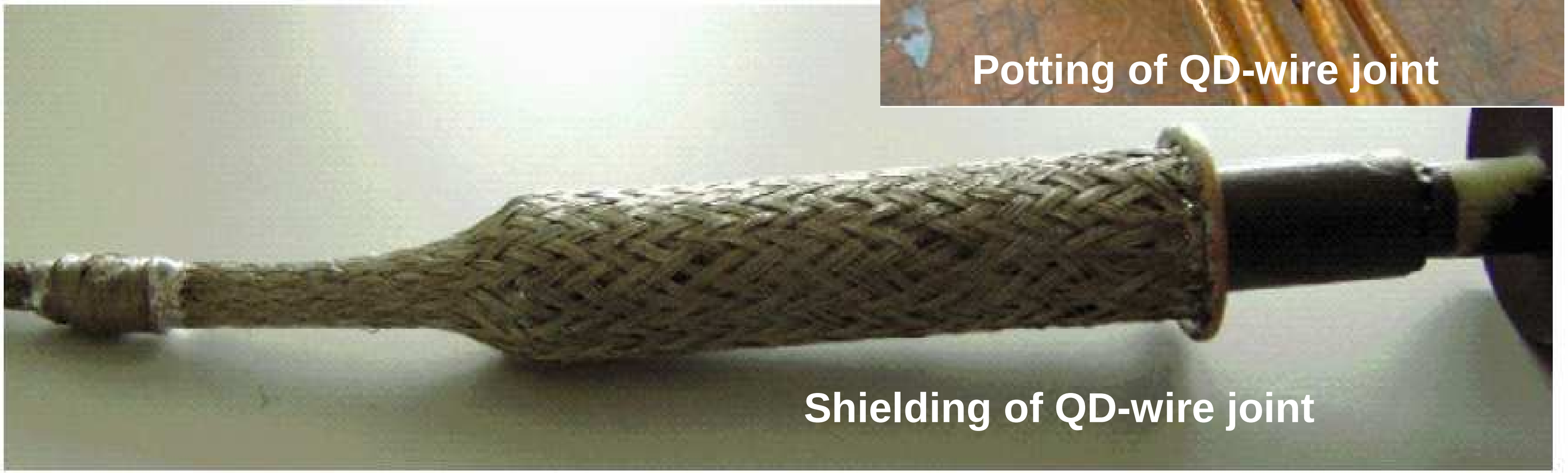


New Connectors of QD Wires for NPC

Planar Coil Quench Detection Wire







Paschen-Minimum Tests

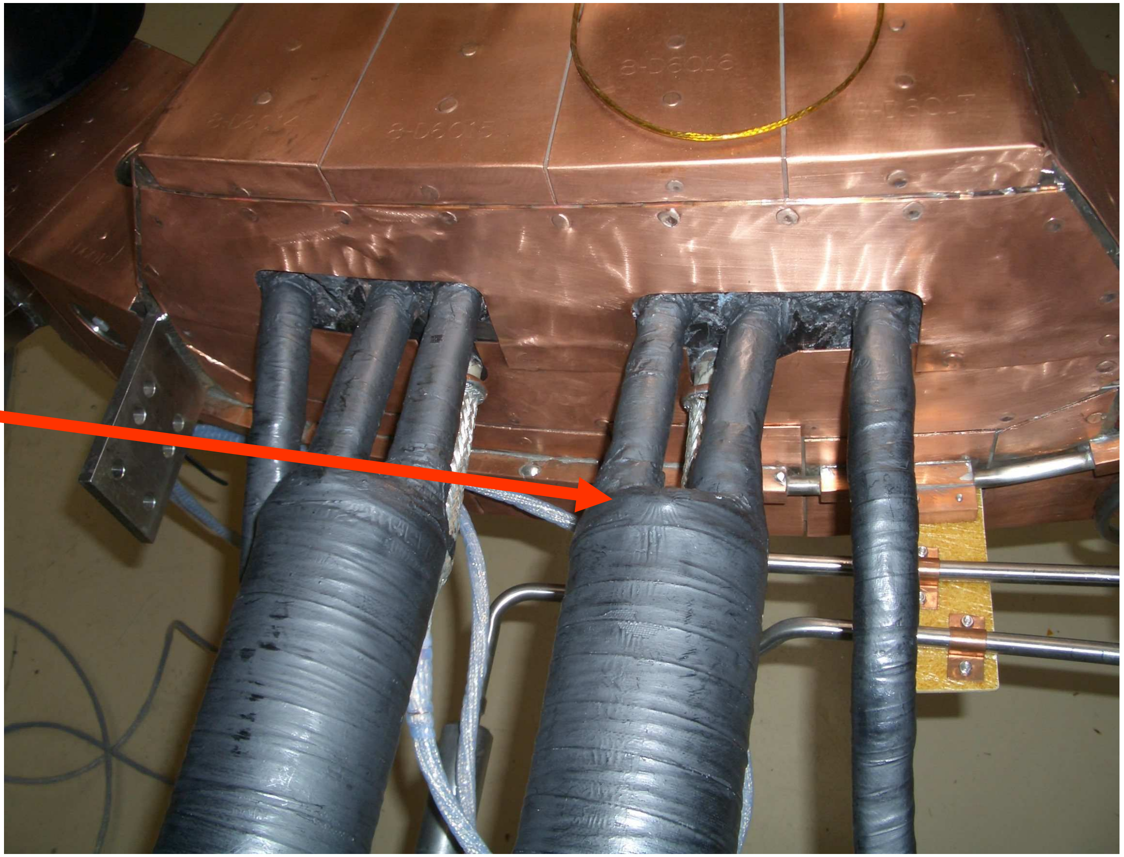
- The non-planar coils are tested in the Ansaldo vacuum tank in Genoa and the BNN tank at Zeitz. Some tests have also been performed at CEA.
- The planar coils are tested at CEA and IPP.

IPP Vacuum Tank

Typical Paschen Discharge

Paschen Test of Planar Coil

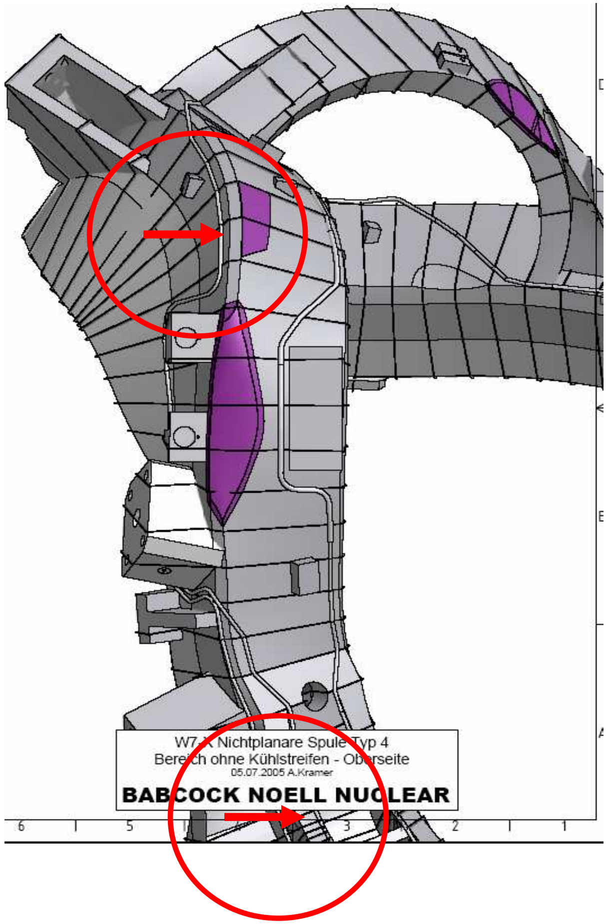
- Coil AAC53 and AAC51 were tested in Paschen conditions at CEA
- Both coils failed during the Paschen test
- HV test passed at ambient air
- Test at p=92mbar , from 2 kV flashovers with 0,5 Hz, 60-80µA
- Affected area was at the end of the aluminum cylinder



<u>Solution:</u>

- Strip down the insulation
- Re-work of insulation – better overlapping, specially prepared wraps, multiple layers, larger chamfer on edges

Current Open Issues on Non-Planar Coils



Repair of BNN/ABB termination areas

Systematic failure (holes, cavities, resin-rich areas) found under the ground insulation after cold testing (high voltage test in Paschen-minimum conditions)

Corrosion risk in NPC casing cooling systems

-Three samples have been taken out of coil AAB24 to make a detailed evaluation of the status of these pipes investigations made by MPI Düsseldorf

Assess risk of corrosion for 18 NPC already manufactured and take a decision for partial or full replacement

New pre-tinning procedure applied to next 32 coils

Design changes in progress

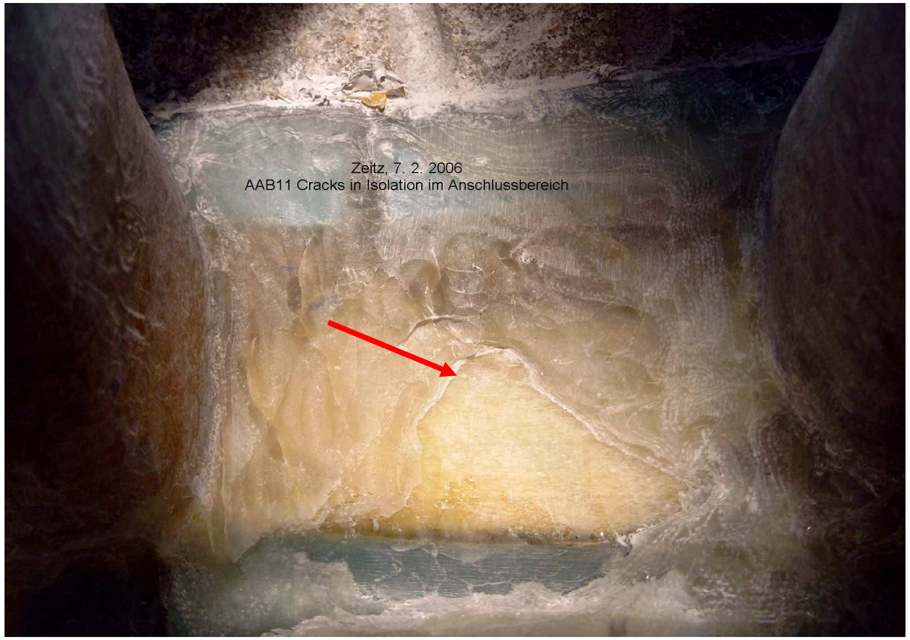
- Reinforcement of two LSE on Type 5 coils and base weld of P1 support

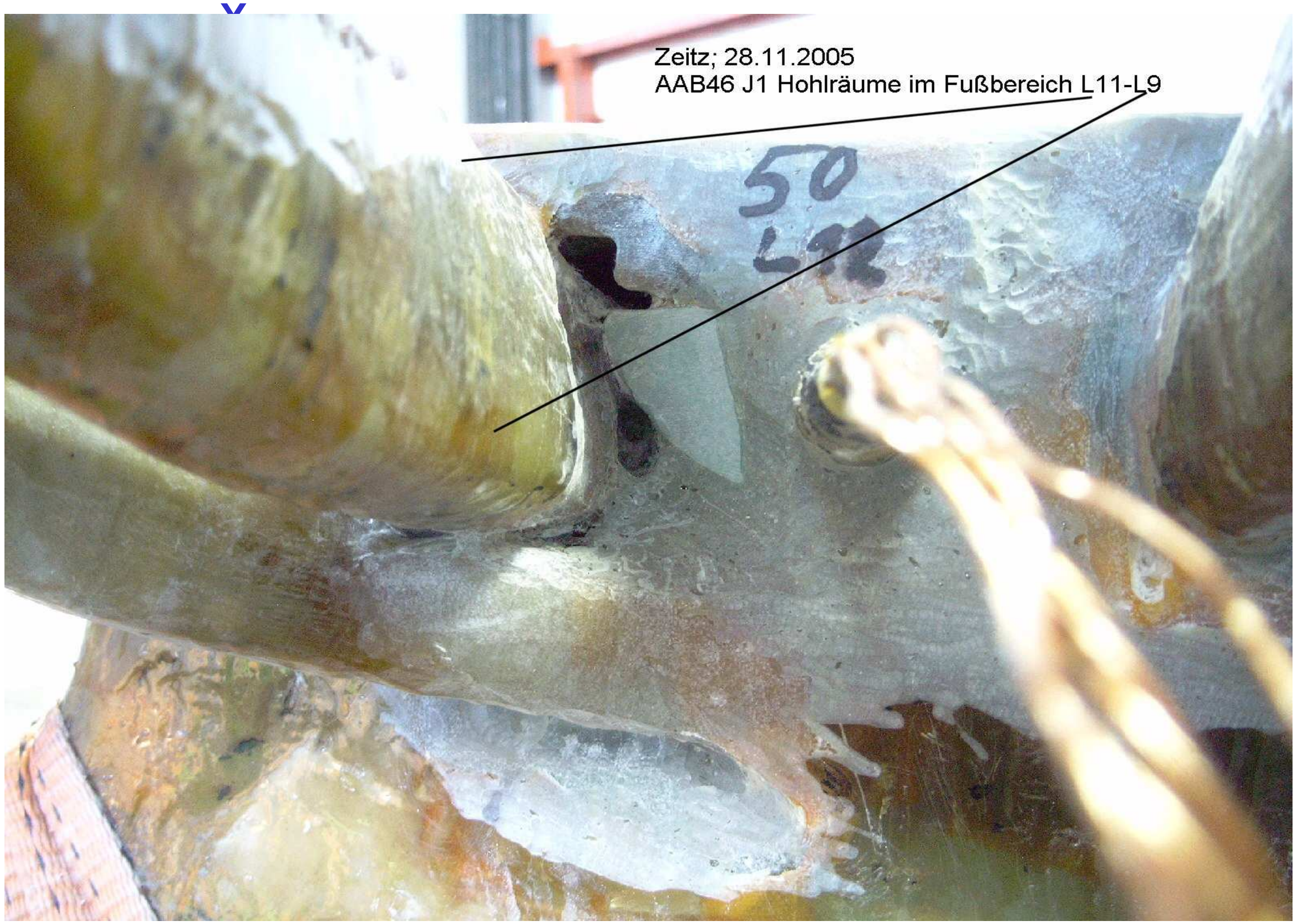
AAB25

- The whole coil termination area has been excavated
- Holes and cavities have been filled with charged epoxy and all penetrations reinfoced with glass tapes
- New cold testing foreseen in Saclay in May 2006

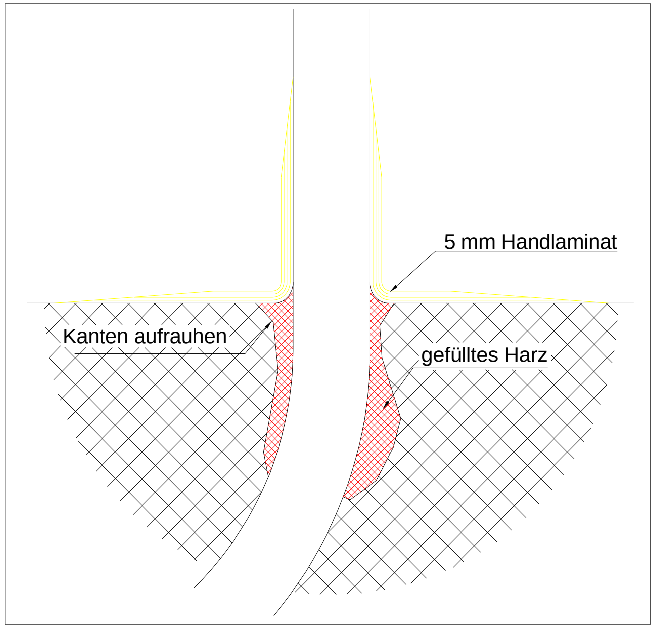
AAB11

- The coil does not present holes and cavities
- The gaps between G-11 plates (in green) have been filled with pure epoxy resin during vacuum pressure impregnation
- The pure resin has cracked down during cooldown at Saclay





Filling of Holes and Cavities

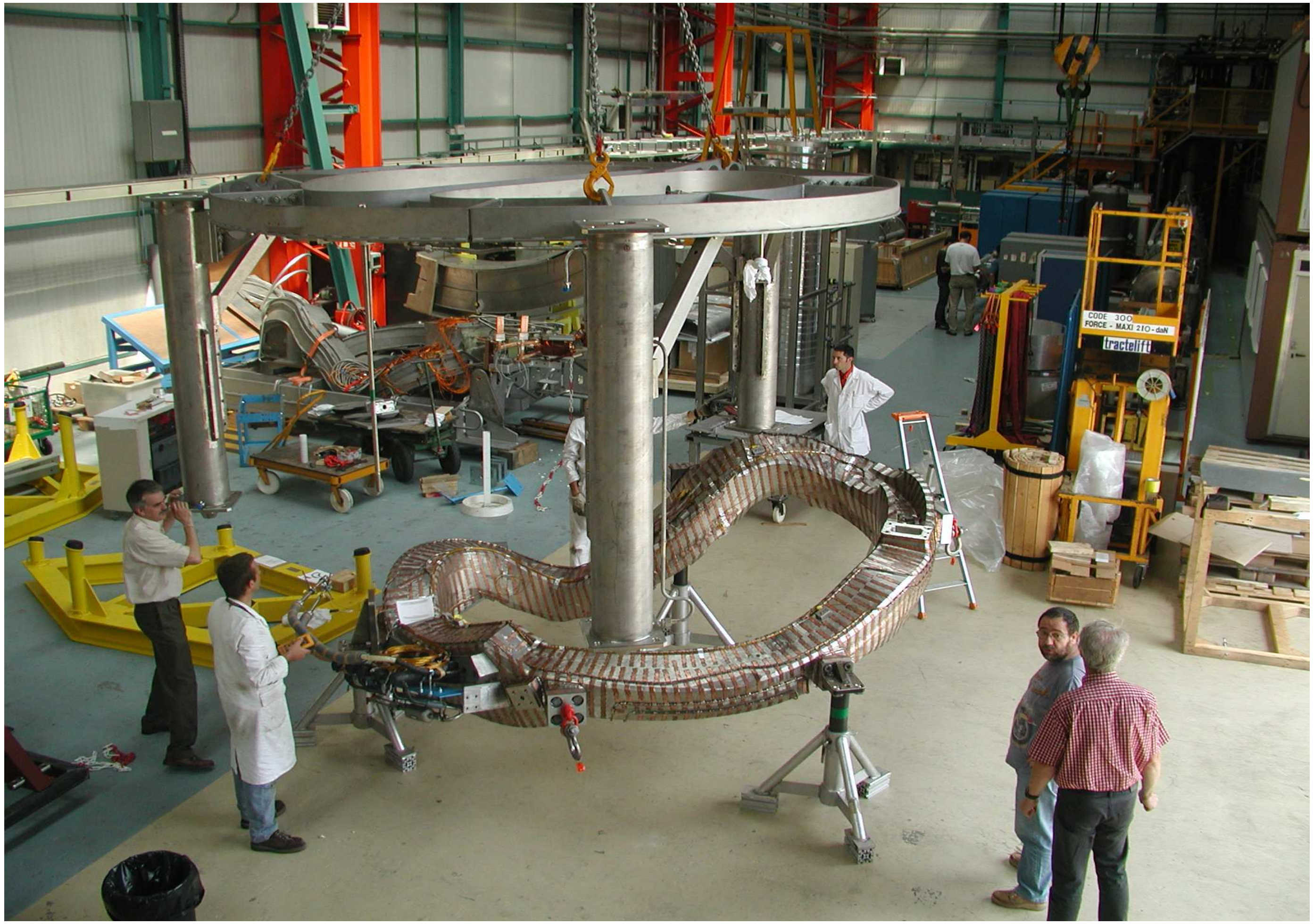



Zeitz, 29.11.2005
AAB46 freigelegter Fußbereich an J3

Cold Test Facility at CEA

DSM - DAPNIA

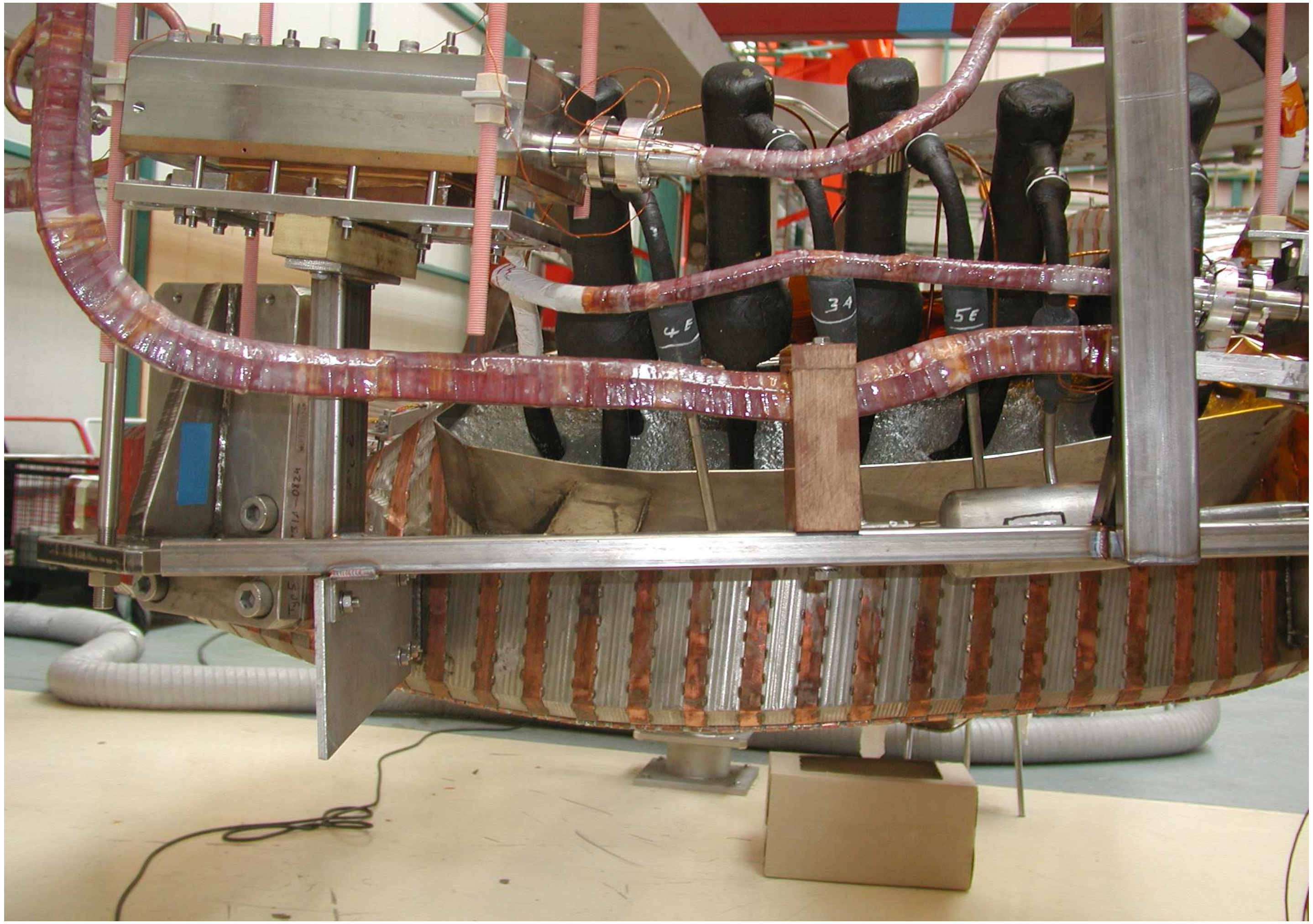
Coil preparation for testing
Installation under support ring



Coil preparation for testing
Preparation for bus bending

Carlo Sborchia / W7-X Basic Device
Magnet Department
e-mail: sborchc@ipp.mpg.de

Coil preparation for testing
Mechanical structure for bus



Overview of cold test

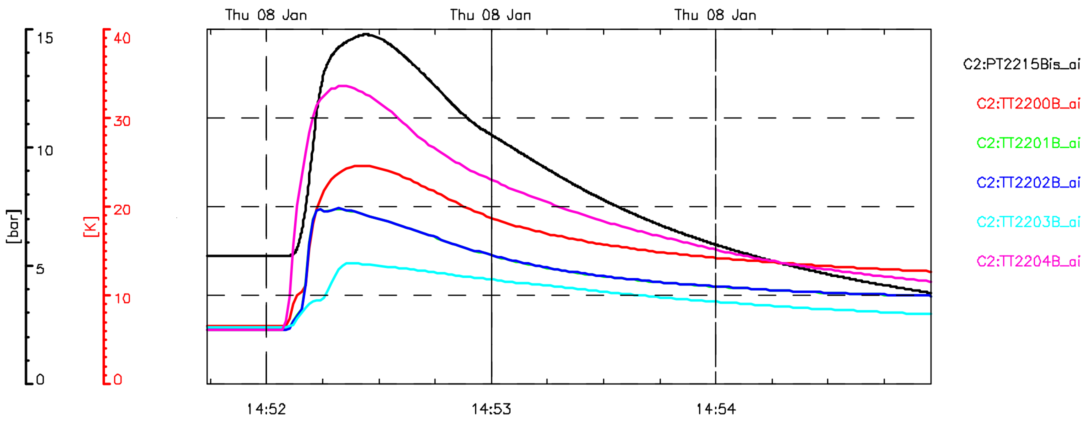
Tests at cryogenic temperature
Leak test
DC test
AC test
Nominal current
Quench
DC test after quench (not for serial coils)
AC test after quench (not for serial coils)
Warming up
heater connection
Test cryostat closed at room temperature under vacuum after warming up
DC test
Leak test
Tests cryostat open after warming up
AC test
Tests before dispatch
temperarure sensor check
strain gauges check
Extensometer check
Resistance and QD wire checks
DC insulation check
Hydraulic tests
visual checks

Overview of test results

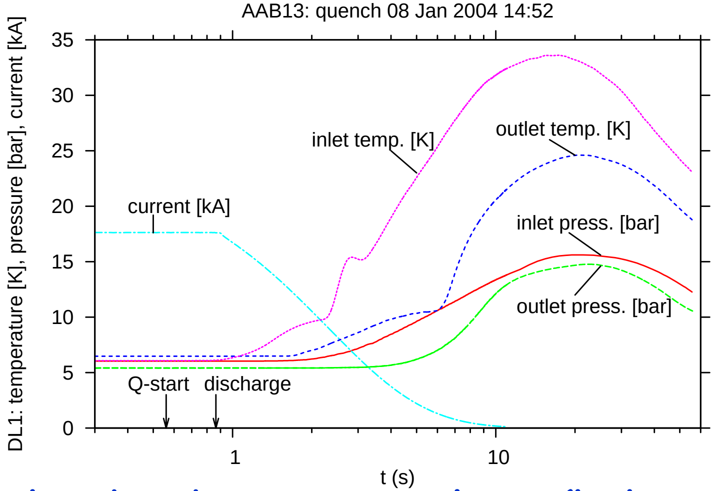
	First Arrival	Second Arrival	Third Arrival	In progress	Valid	Non valid	06
AAB11	19/06/03 au 09/12/03	08/09/05 au 08/12/05			x		
AAB12	03/10/03 au 02/12/03						
AAB13	31/07/03 au 09/03/04	22/07/05 au 22/11/05			x		
AAB17	24/08/05 au 17/10/05				x		
AAB18	11/03/04 au 05/08/04				x		
AAB19	27/05/05 au 17/10/05				x		
AAB21	27/10/05 au 19/01/06				x		
AAB22	19/01/06 au xx/xx/xx			x			x
AAB24	01/04/04 au 29/07/04				x		
AAB25	27/05/05 au 16/09/05					x	
AAB26	12/10/05 au 19/01/06				x		
AAB27	08/12/05 au xx/xx/xx			x			x
AAB28	19/01/06 au xx/xx/xx			x			x
AAB29	13/01/06 au xx/xx/xx			x			x
AAC11	06/09/04 au 05/01/05	23/02/06 au xx/xx/xx		x			x
AAC12	20/10/04 au 05/01/05	17/10/05 au 21/02/06			x		x
AAC13	23/01/06 au xx/xx/xx			x			x
AAC51	29/01/04 au 08/06/04	23/07/04 au 05/10/04	13/12/05 au 21/02/06		x		x
AAC52	30/10/03 au 04/03/04	07/09/04 au 20/10/04				x	
AAC53	04/03/04 au 08/06/04	28/09/04 au 24/01/05				x	
AAC54	13/06/04 au 13/09/05				x		

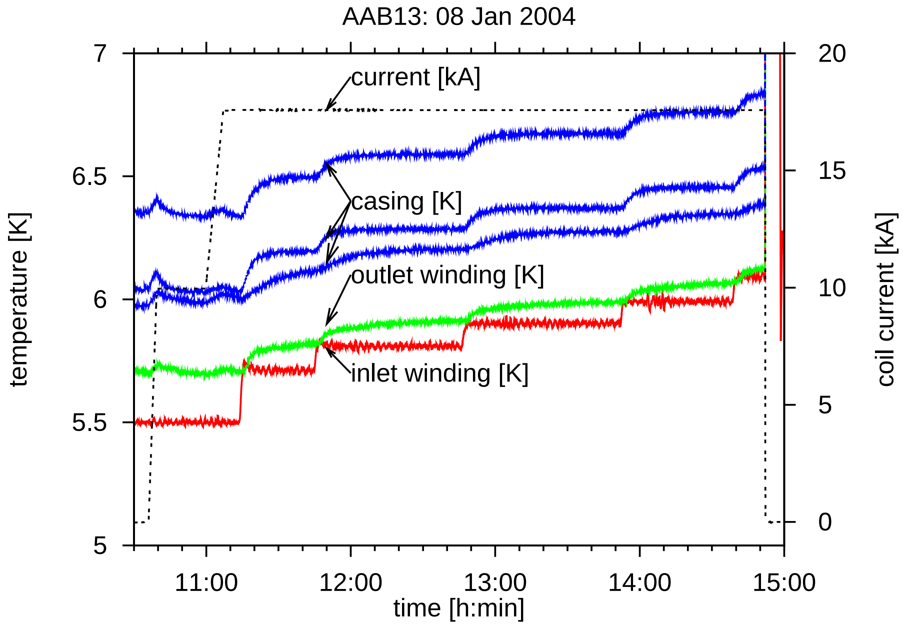
Number of coils arrived at Saclay = 29
Coils at Saclay = 6
Coil valid = 11

Quench Tests



pressure winding outlet
temperature outlet L2
temperature outlet L4+6
temperature outlet L8+10
temperature outlet L12
temperature global inlet



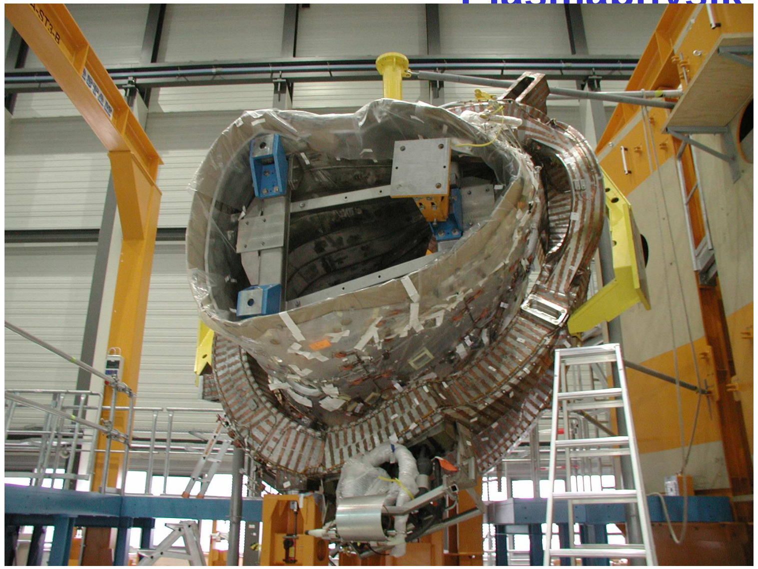


Quench induced in innermost layer (highest field) ~15 s after quench: max. pressure (15 bar) and temperature (34 K)

Quench occurred at 6.1 K against the safety margin value of 5.7 K

Coil Preparation Area at IPP

Assembly of First Half-Modules



Conclusions - 1

- W7-X is the largest superconducting fusion device under construction and the only European fusion project under construction.

- The manufacture of the W7-X coils is well advanced (~60%).
- The superconductor production is complete.

- After the re-work of QD cables and support structures, the non-planar coil production is restarting with the delivery of about 2 coils/month. Completion is expected in mid-2007.

- After the re-qualification of the soldering/welding and insulation processes, the planar coil production can continue with the delivery of about 1 coil/month. Completion is expected in mid-2007.

- This production rate cannot be followed by a similar coil testing rate. The cold tests is expected to be completed in mid-2008.

Conclusions - 2

• The manufacture of the W7-X coils has highlighted the difficulties related to the series production of several tens of superconducting magnets due to:

Detailed design and R&D programmes not completed before placement of the manufacturing contracts;

Lack of adequate and experienced resources;

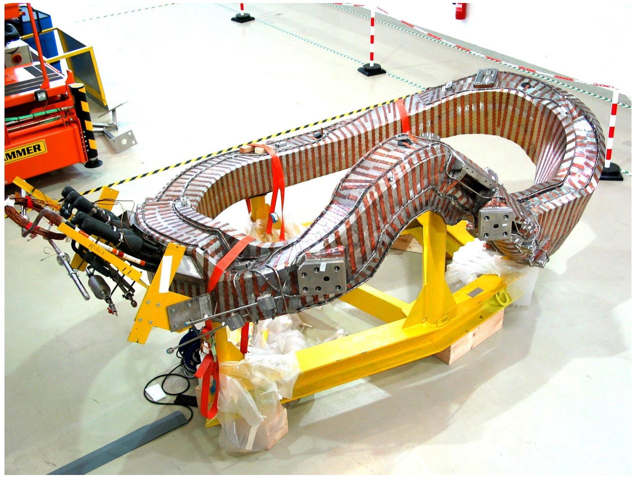
Inadequate original planning.

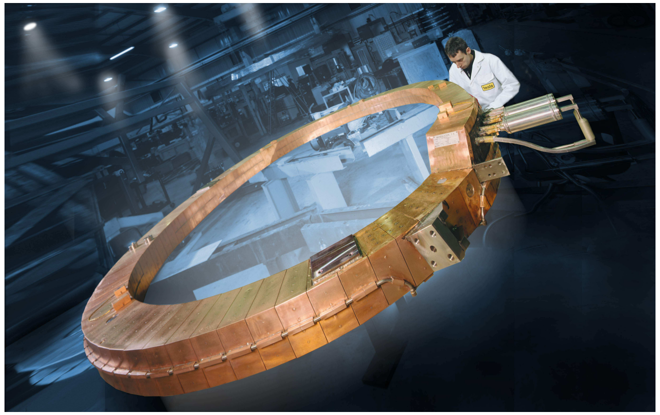
• It provides a unique and valuable experience for the construction, QA and testing of next fusion devices, namely:

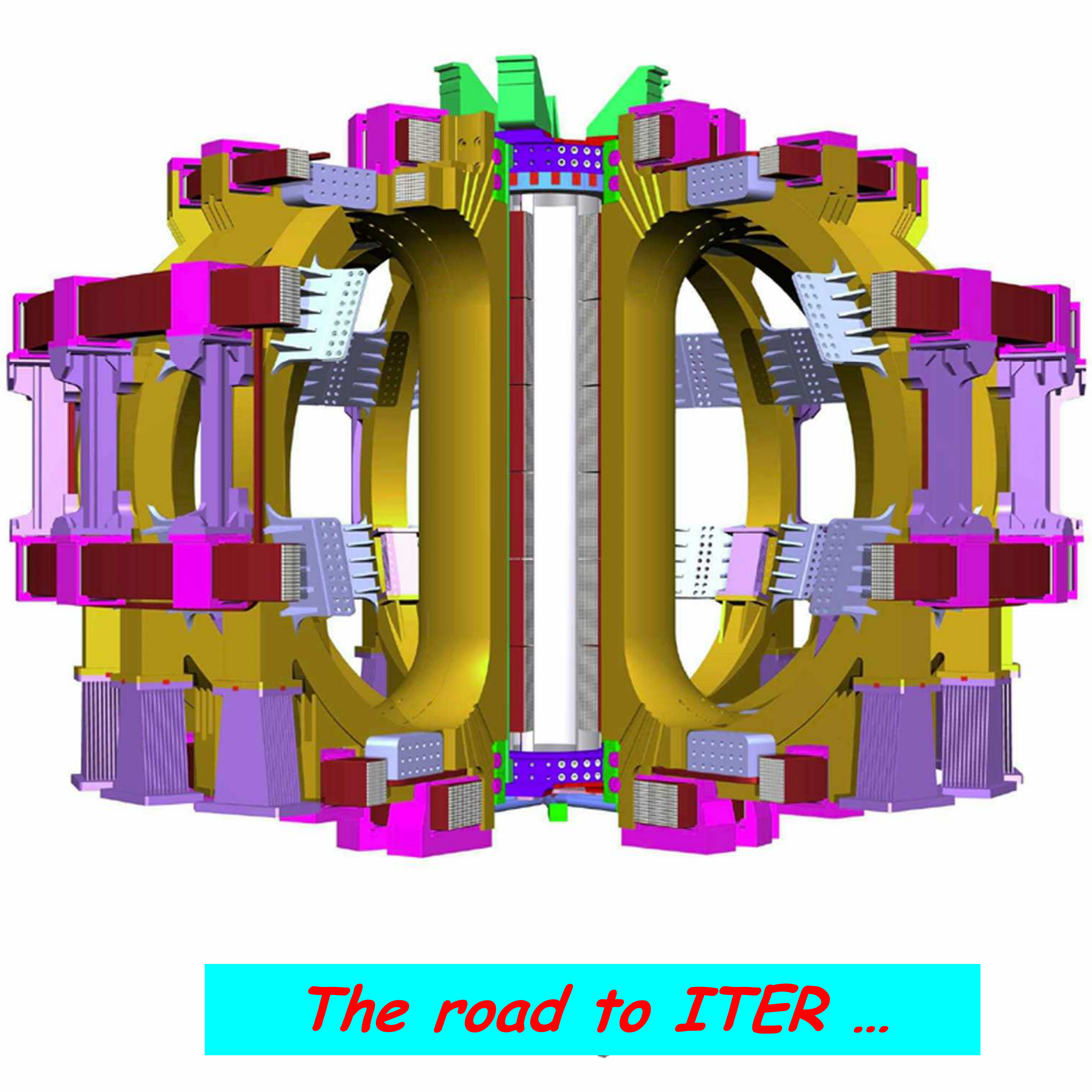
Project Management of complex industrial contracts;

Extensive QC/QA activities during manufacture with additional qualification programmes, such as high-voltage tests in Paschen conditions;

Need for cold testing of all magnets to prove their integrity and reliability.







The road to ITER …