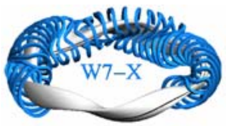
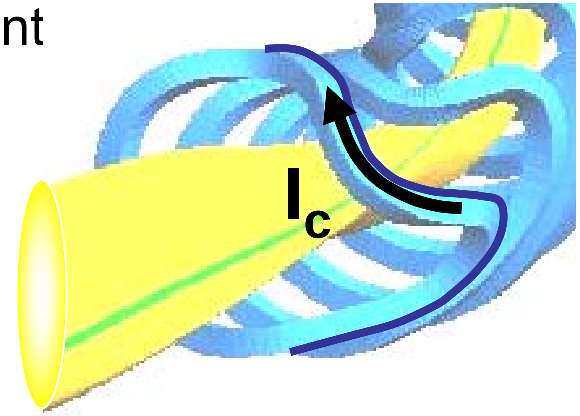
Physics, Technologies and Status of the Wendelstein 7-X Device



F. Wagner
on behalf of the W7-X team
IPP, BI-Greifswald, EURATOM association



Stellarators: toroidal devices with external confinement

External confinement:

toroidal and poloidal field from modular coils

➡ 3-D magnetic flux geometry
steady-state operation with superconducting coils
no net-toroidal current
no current driven instabilities (disruptions, neo-cl. tearing modes..)

3-D magnetic flux geometry:

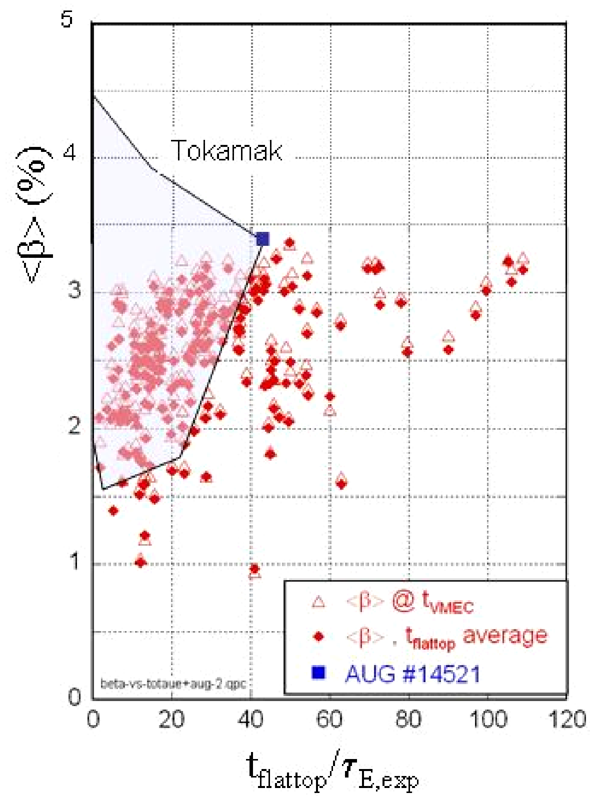
collisionless orbit losses ➡ stellarators need optimisation ➡ **W7-X**

W7-AS: The predecessor of W7-X

Improved equilibrium with reduced Shafranov shift due to reduced $\langle j_{\parallel}^2\rangle / \langle j_{\perp}^2\rangle$
Operation in the H-mode
Operation at high density ($n_e \le 4\times10^{20}$ m^{-3})
Above $n_e = 10^{20}$ m^{-3}: operation in the HDH mode
(H-mode energy, L-mode impurity confinement; no ELMs)
$\langle\beta\rangle \le 3.4$ %; quiescent operation close to operational boundaries

Development of the island divertor

Quasi-steady state operation



Beta against flat-top time normalised to the plateau confinement time
Status: end of 2003

Design principles of W7-X

Optimised stellarator of the Wendelstein family

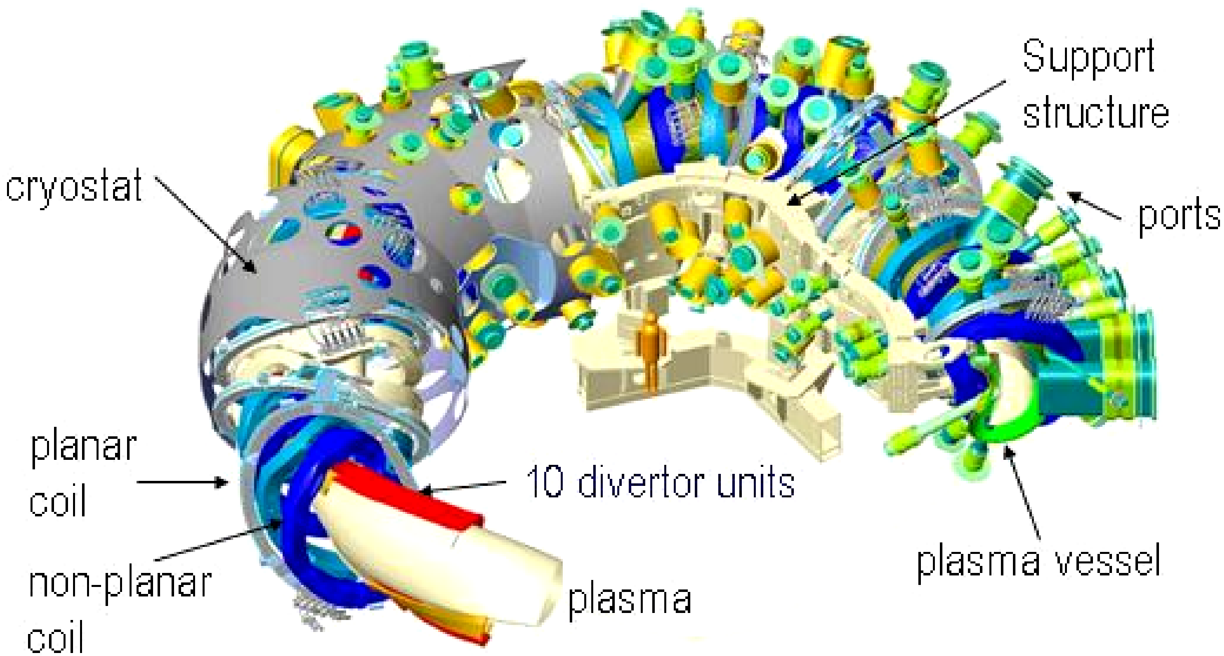
Optimisation following quasi-iso-dynamicity principle:

The optimisation of W7-X leads to:

- good and nested flux surfaces
- low Shafranov shift thanks to a ratio of $\langle j_{\parallel}^2/j_{\perp}^2 \rangle \sim 0.5$
- equilibrium and stability $\langle \beta \rangle \leq 5$ %
- low neoclassical fluxes
- small bootstrap current
- edge-island chains as basis of the island divertor

	W7-AS	**W7-X**
R_o (m), a_{eff} (m), Vol (m^3)	2, 0.18, 1.3	5.5, 0.55, 30
B (T), iota	2.5, 0.25 – 0.55	2.5, 0.72 -1.25
Number of non-planar coils / conductor	45, **Cu**	50; **NbTi**
Number of planar coils / conductor	10; Cu	20; NbTi
Heating power (ECRH, NBI, ICRH) (MW)	2.5, 3, 1	10, 5 (20*), 3 (9*)
Pulse length, energy turn around (MJ)	**3 sec**, 5	**30 min**, 1800

Layout and goals of W7-X



Goal: demonstration of principle reactor suitability of the optimised stellarator

LHD, **NCSX** and **W7-X** will explore the „best of all“ helical configuration

This development will be parallel to **ITER**; W7-X will start operation in 2010

Final decision for DEMO
Alternatives:
either: 3D system with geometrical complexity but quiescent and steady-state
or: geometrical simplicity but external current drive + current driven modes

Components: non-planar coils

NbTi CiC-conductor.

Embedding: quartz sand and epoxy

Welded casing made out of cast-steel

4 coils have been tested at CEA in Saclay

All coils passed cryo-test

34 (out of 50) winding packs are built

17 coils are in different stages of assembly

Comments:

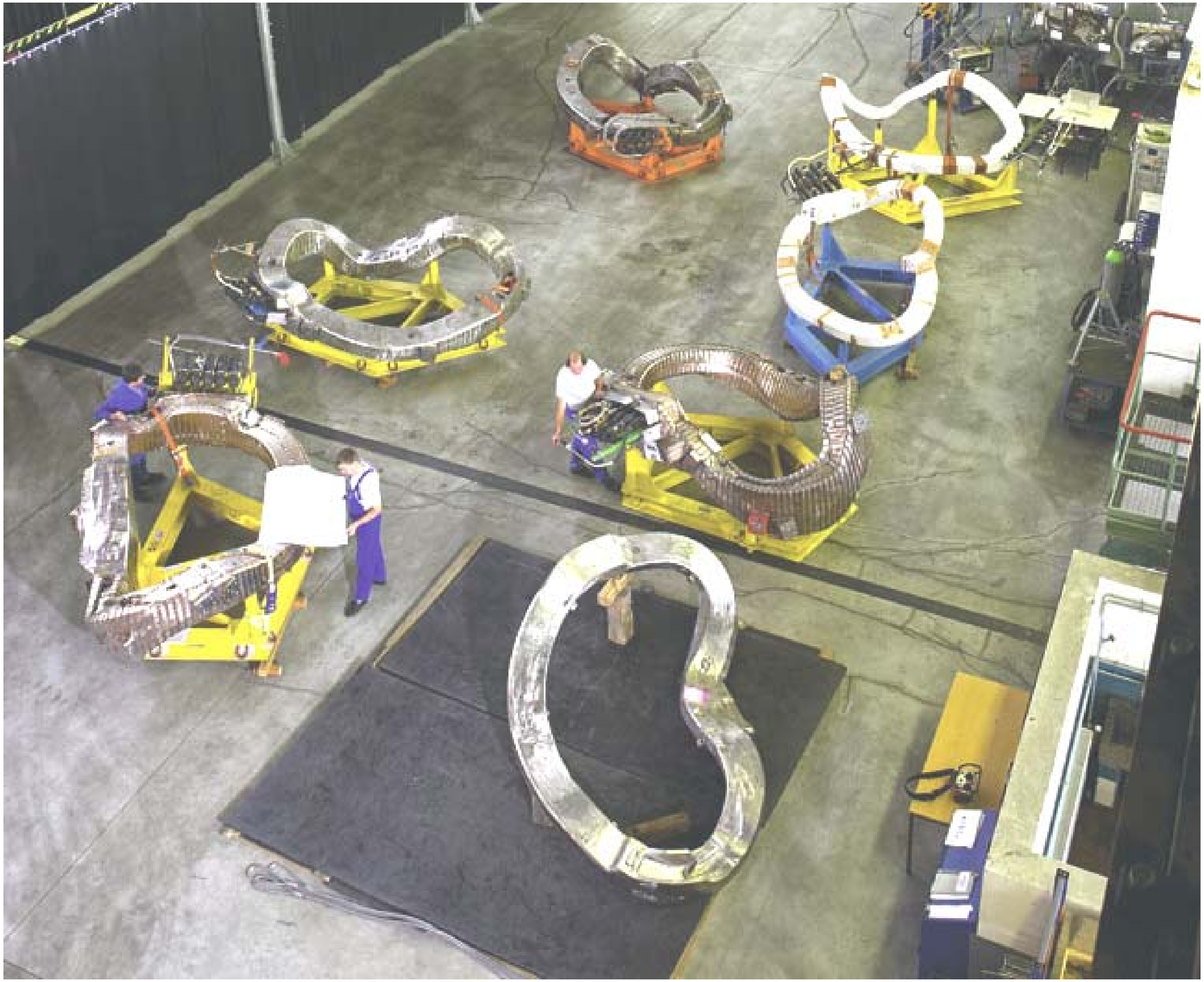
All casings to be X-rayed

Quench-detection wire: Kapton insulated
enclosed by metallic shield

Accurate final machining of contact areas

High fabrication accuracy required
to avoid field errors

View into the fabrication hall of BNN-Zeitz



Components: planar coils

13 out of 20 winding packs fabricated

10 coils in different stages of assembly

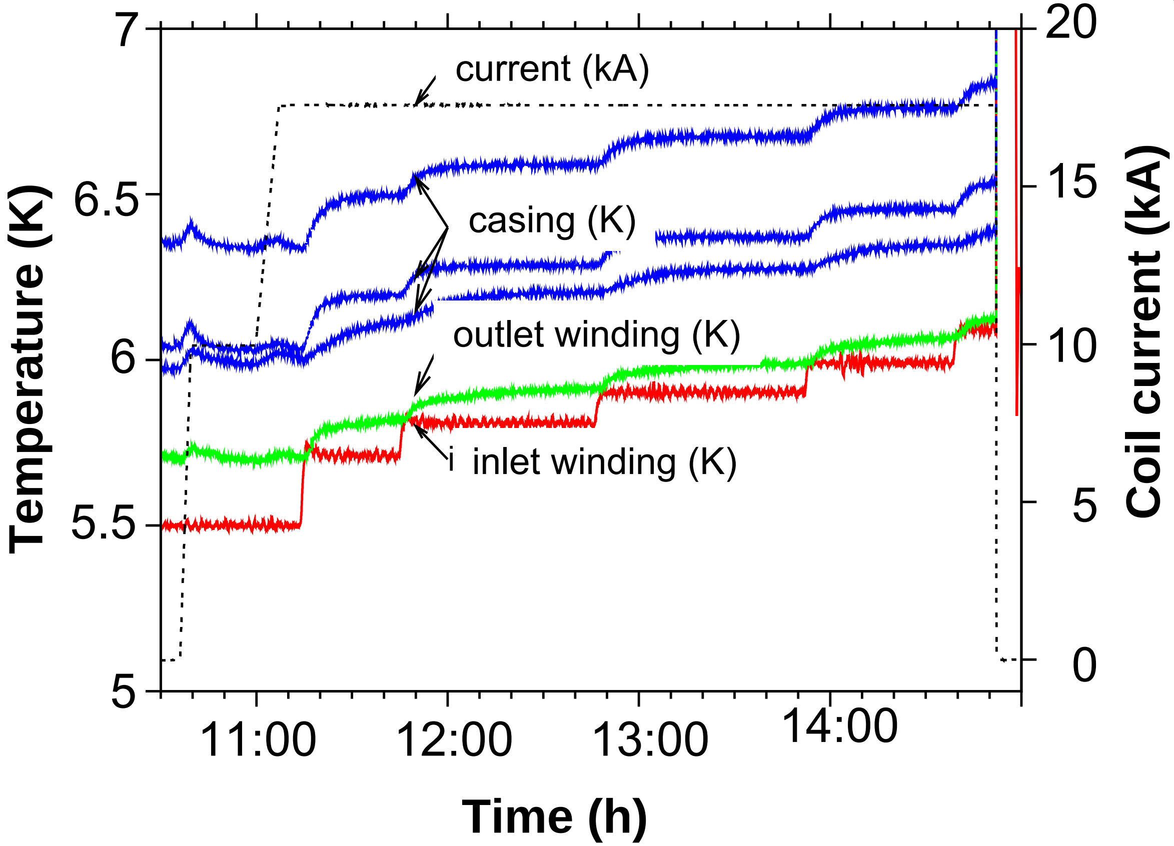
4 coils tested at cryogenic temperature

All coils passed cryo-test

Components: cryo-tests at CEA, Saclay

nominal current in self field
quench and temperature margin test
flow test, leak test
high voltage (HV) AC and DC test
interlayer joint resistance measured
stress and deformation measurements.

Temperature and current signals during current quench test.

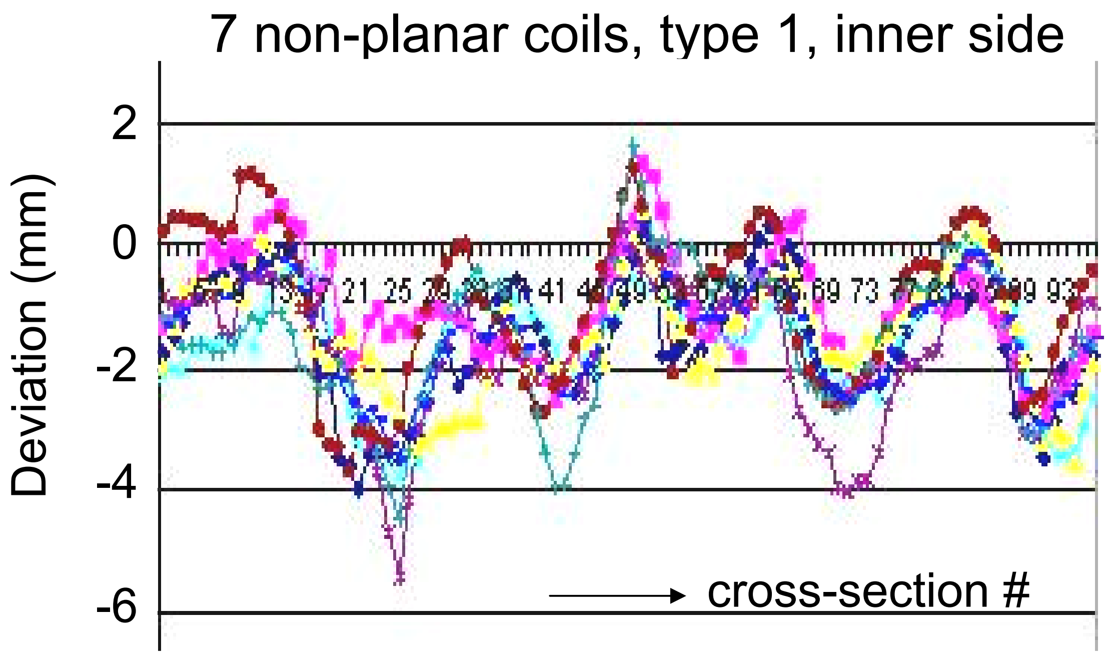


The quench occurred at 6.1K

Under operational conditions:
Safety margin > 1K

Components: fabrication error analysis

Deviations from CAD-model



Fabrication errors = systematic errors + random errors

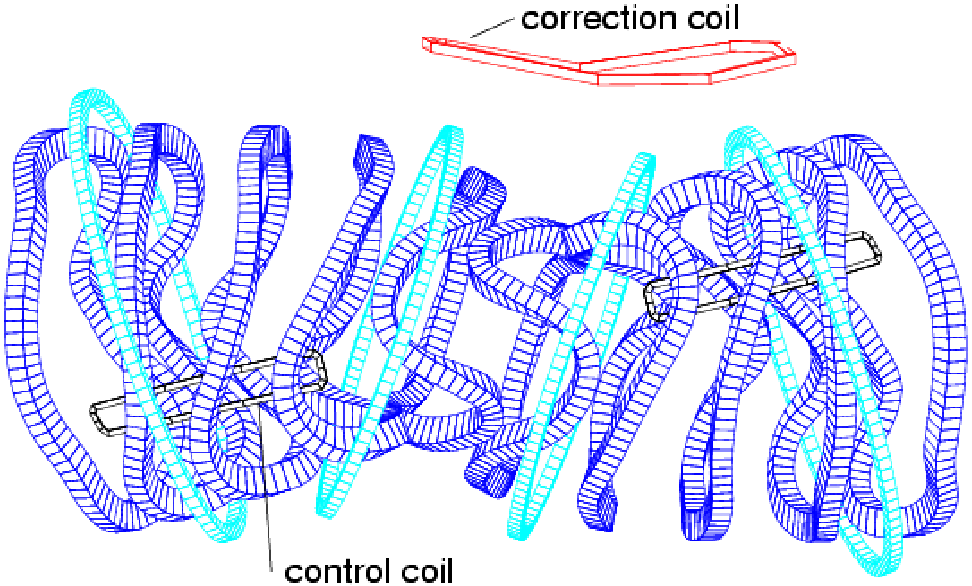
systematic errors: do not disturb 5-fold symmetry

random errors: cause perturbed magnetic fields =
asymmetric edges islands (→ exhaust)
islands at rational iota values
ergodized zones

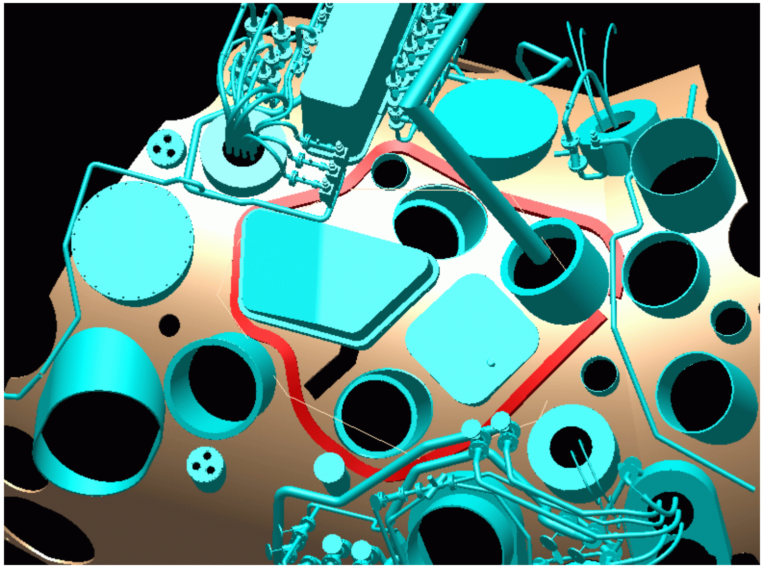
Expected field error from coils: $\Delta B/B \sim 1\times10^{-4}$; tolerable error: $\Delta B/B \sim 2\times10^{-4}$

Measures to cope with field errors

Coil system with correction coils



External correction coil



1) divertor (control) coils
to compensate B_{33} and B_{44}
2) external correction coils
to compensate B_{11} and B_{22}
resonant components

one coil per field period

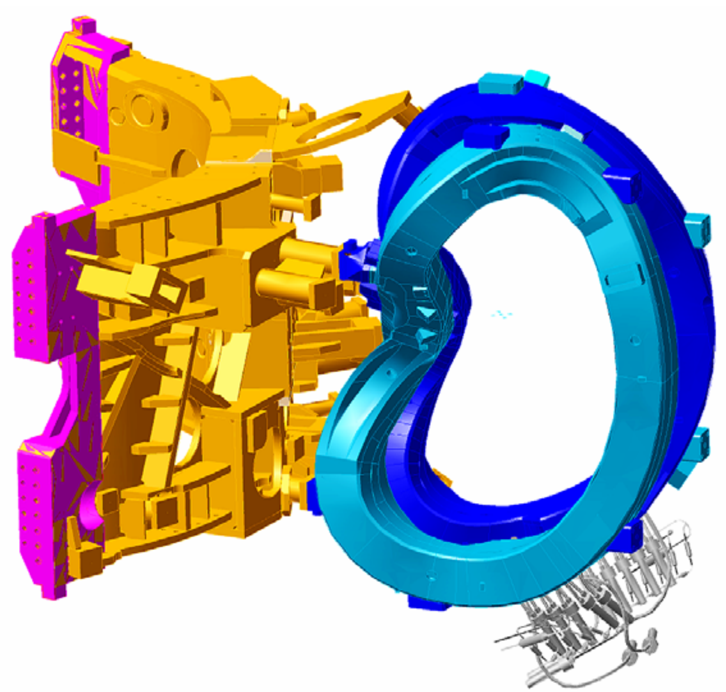
performance at 50 kA total current per coil

$\Delta B/B = \sqrt{(B_{11}^2 + B_{22}^2 + \ldots\ldots\ldots)} \sim 4\times10^{-4}$

e.g. $B_{11}/B_0 \sim 2 \times 10^{-4}$; $B_{22}/B_0 \sim 2 \times 10^{-4}$

Coil support: to central ring

Connection between non-planar coils and central support ring

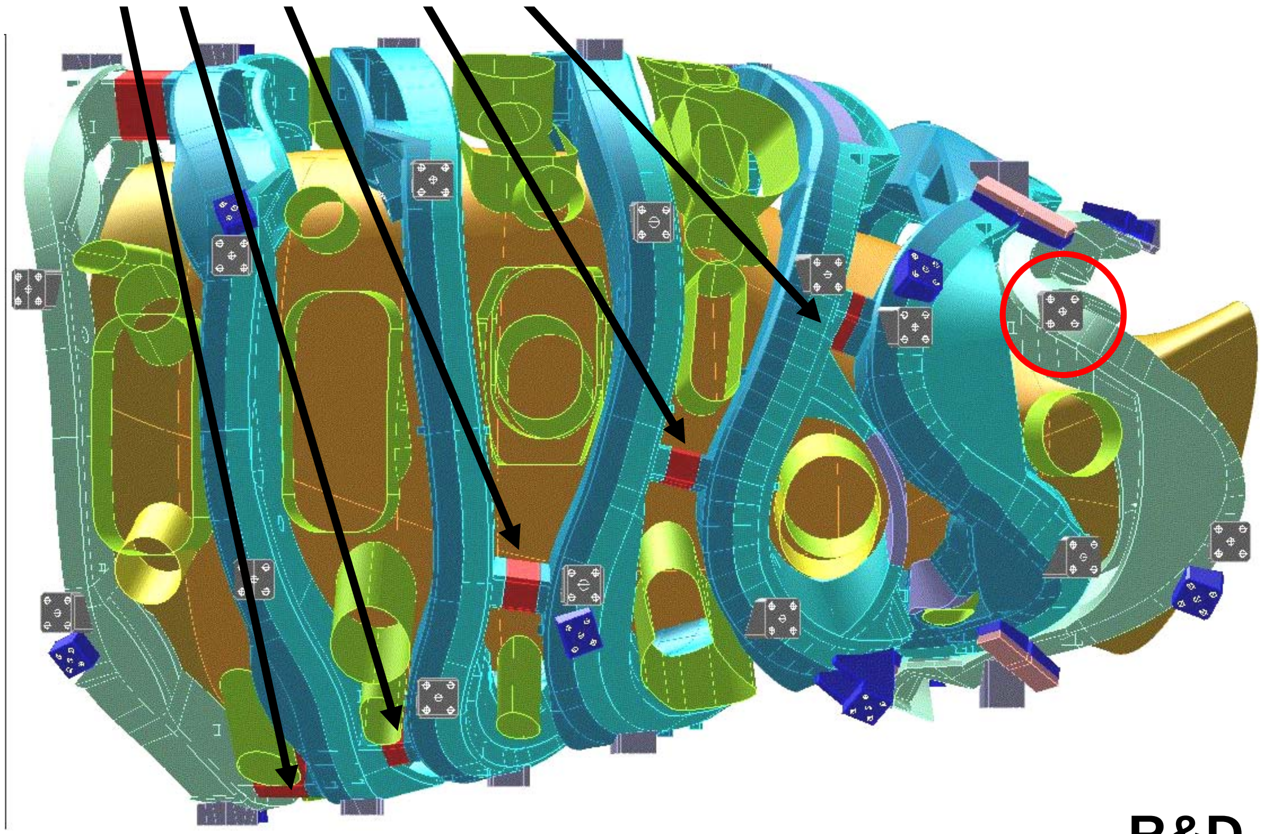


Sector of central ring

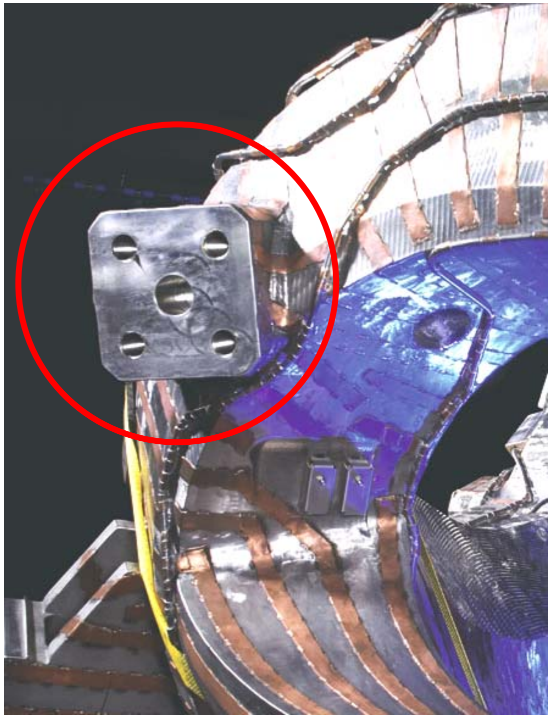
Connection is screwed
using ~ 400 mm long rods
in the form of a matrix of screws (up to 3x3)

Support between coils: low-field side

Lateral support elements



Coil support element



R&D

Welding tests in FZJ

Optimise welding process

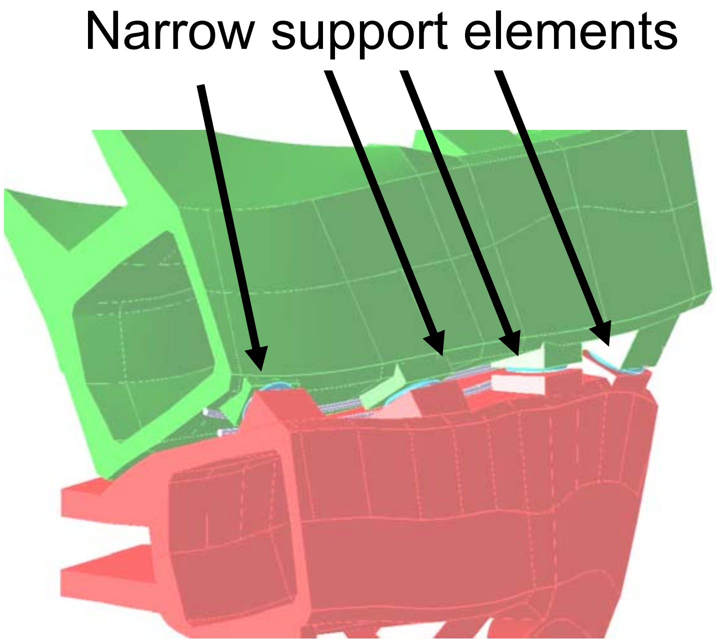
Reduce distortions due to welds

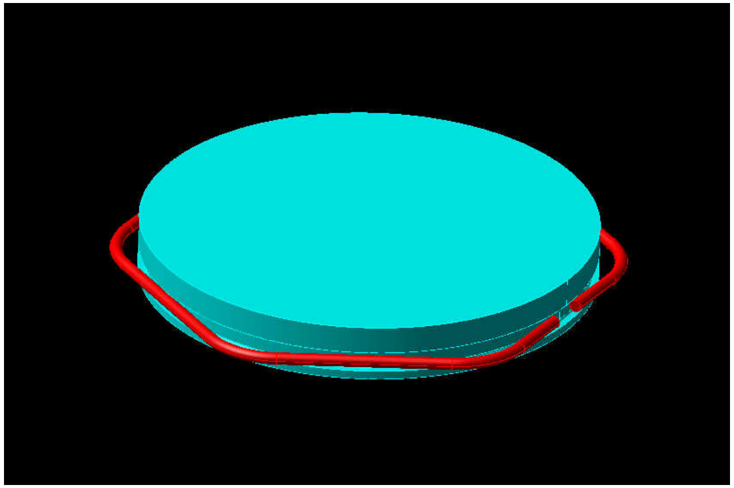
Minimize induced stresses

Torsion and bending moments
up to 130 or 230 MNmm, respectively

Only welded connections within modules

Support between coils: high-field side





Forces up to 1.5 MN are transmitted

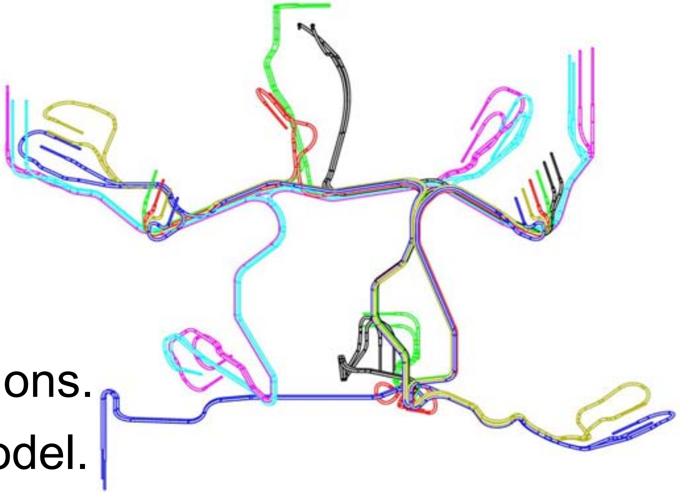
The contact zones must allow sliding (< 2mm) and tilting (<0.5°)

Central element: AL-bronce pad with a MoS_2 layer (lubrication) protected by SiO_2

The design has been confirmed by roomtemp. tests under real loads

Low-temp. tests under vacuum are in progress

Bus system



Developed by **Forschungszentrum Jülich**

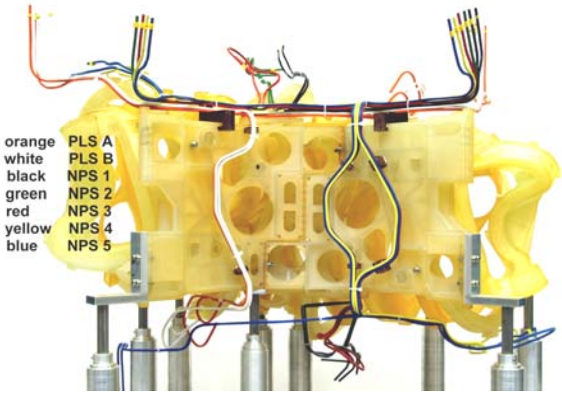
Superconducting current connections

- between coils and
- coils and the current supply terminals.

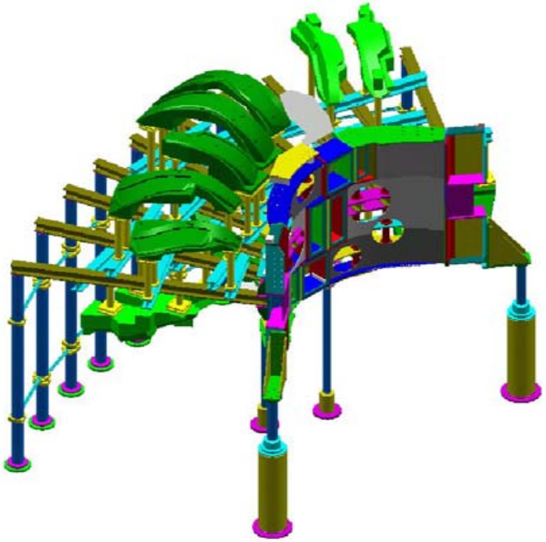
The bus lines are routed bifilar to minimize field perturbations.

The complicated assembly is optimised by using a 1:1 model.

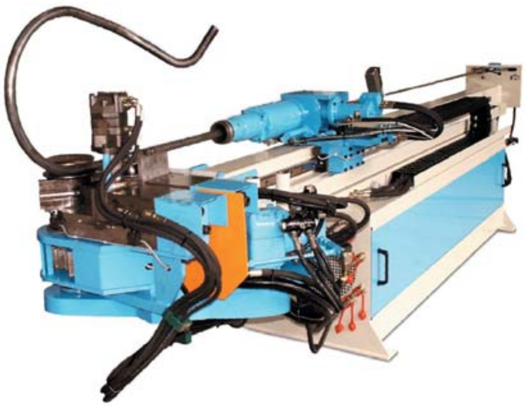
Insulation checks include Paschen-tests; also the quench situation will be studied.



1:10 model for optimisation of routing



1:1 model to adjust the connectors



CNC machine for 3-dimensional bending of superconductor

Further components

Plasma vessel

Outer vessel

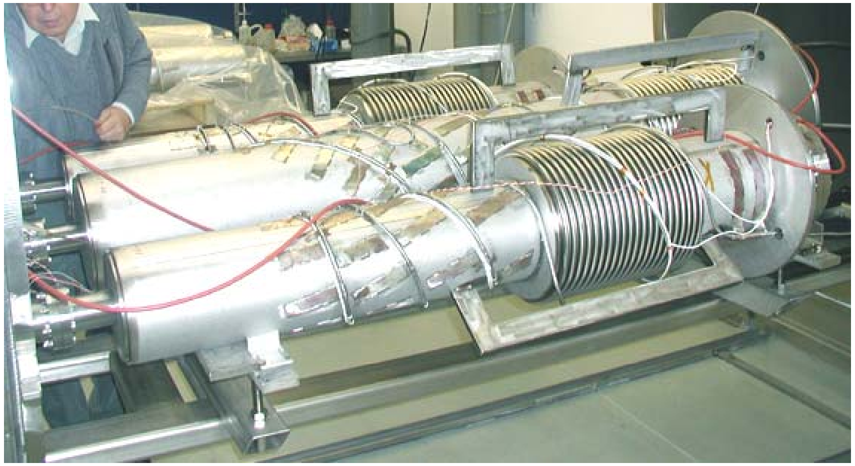
All half-shells manufactured
Opening cut into first half-shell

matched to the 3-D shape of the plasma
formed from 200 welded steel rings
split into 10 sectors
each again is split into 2 sectors to allow the assembly of the first coil.
The vessel can be cooled (RT) or heated (to 150 °C).
The vessel sectors for one module are delivered to Greifswald.

Further components

Thermal insulation of plasma vessel

Ports



299 ports for heating, diagnostics, supply

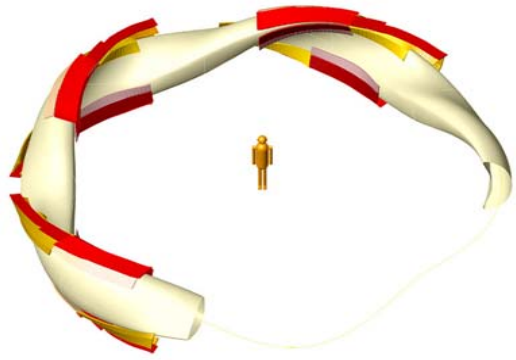
120 delivered

Multi-layer insulation (MLI) + actively cooled thermal shield.
MLI: aluminized crinkled polyimid (Kapton) foils with glass fabric: 0.93 W/m^2
Twenty thermal shield panels per half-module cooled by gaseous He.
Panels made out of laminated epoxy-glass resin containing three copper meshes
Thermodynamical, electro-dynamical and mechanical behaviour
confirmed by tests + FE calculations

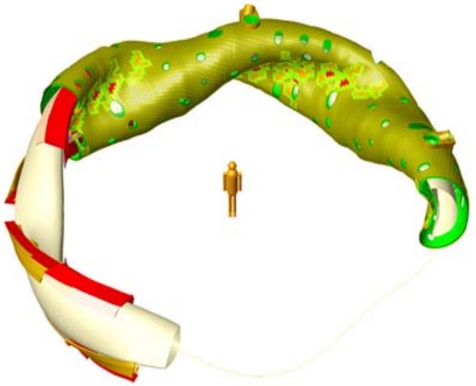
Assembly

Plasma

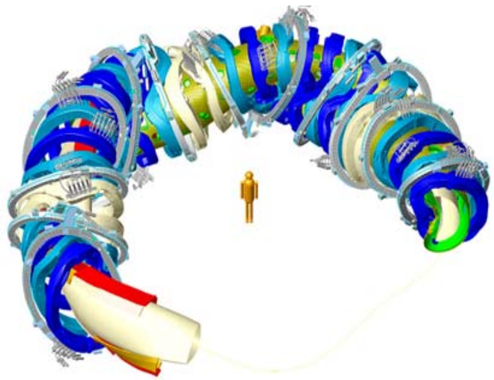
Divertor



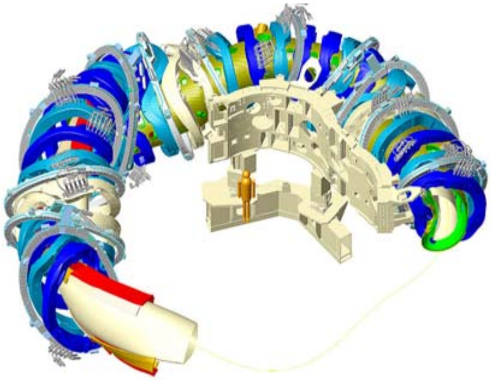
Plasma vessel



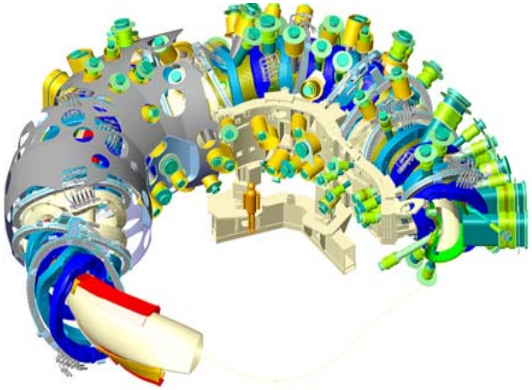
Non-planar and planar coils



Central support ring



Outer vessel + ports



Challenges for assembly

Plasma vessel half-module split into two pieces for assembly of the first coil.
 After coil assembly, the two vessel pieces are welded.
 The tolerance range for this process is 3 mm.
 A trial welding has shown that this accuracy can be met.

The 6 t coils have to be positioned to an accuracy of about 1.5 mm.
 The assembly accuracy is monitored by laser tracker.
 Assembly trials have shown that this accuracy can be met.

Detailed numerical studies and assembly trials ensure collision-free paths
 for the coils to their final positions
 for the 299 ports
 for the bus-bar system comprising of 25 individual conductors per module.

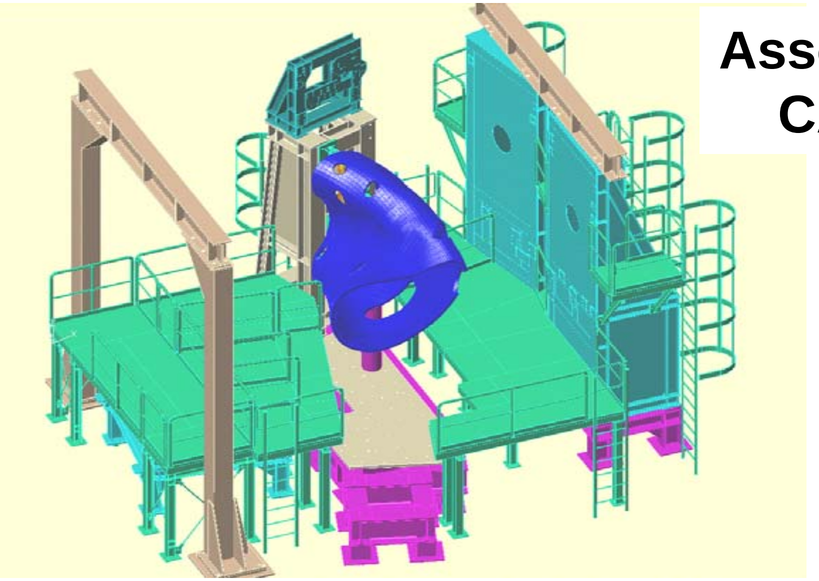
Leak-tightness of all welds, which generally are along non-standard contours.

Insertion of the narrow-support elements at restricted accessibility.

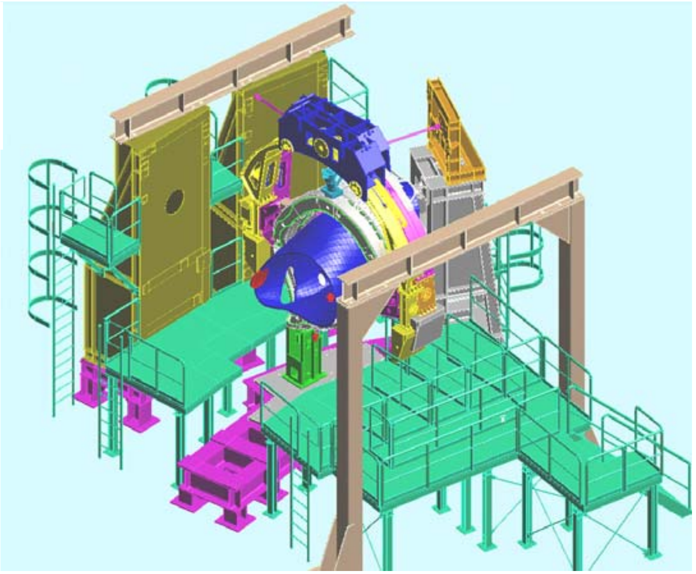
Continuous control of assembly accuracy to ensure small field perturbations.

Periphery: optimisation in terms of use of space, assembly sequence, logistics…

Assembly platforms and trials



Assembly stand 1
CAD drawing



Assembly stand 1
with
pasma vessel sector
during assembly test

Assembly stand 1
during
coil assembly test

ITER relevance of W7-X

W7-X is the last large superconducting device in Europe before the start of ITER
It serves to train European industry in fusion technology, quality assurance…

Development of long-pulse technology
- superconductivity
- cryo-technology
- heating
- exhaust

Metrology techniques in assembly

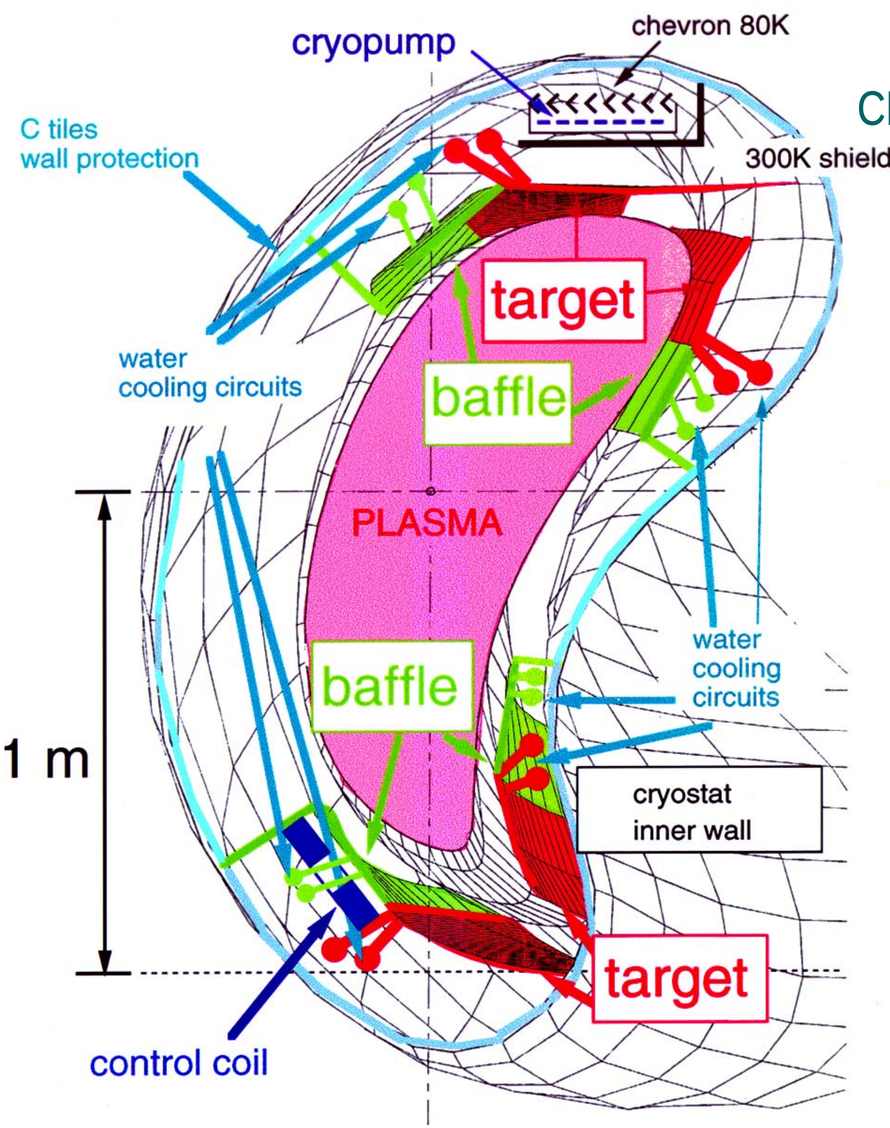
Provision of steady-state operational experience:
- plasma control
- diagnostics
- data-acquisition

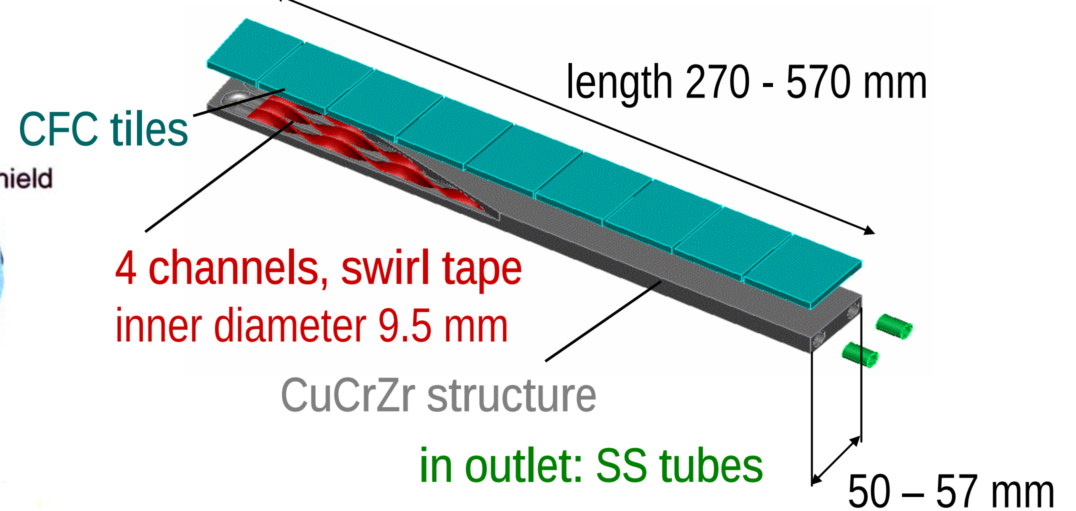
Two examples in detail:
- Plasma facing components
- ECRH (+ HV-PSM system)

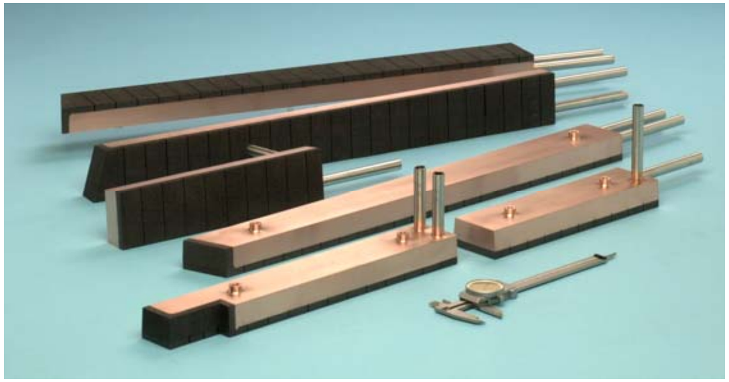
Component	Principal manufacturer	Country
Non-planar coils	Cons. BNN-ANSALDO + sub-contractors	Germany, Italy, Switzerland, Sweden
Planar coils	TESLA	Great Britain
Central coil support	ENSA	Spain
Coil assembyl tool	RST	Germany
Plasma vessel	MAN-DWE	Germany
Outer vessel	MAN-DWE	Germany
Ports	ROMABAU	Switzerland
Thermal insulation	MAN-DWE	Germany
Graphite for PFCs	SNECMA	France
Target module	PLANSEE	Austria
Coil power supply	ABB	Switzerland
Control coil P.S.	JEMA	Spain
HV power supply	THALES	Switzerland
Gyrotrons	TED, CPI	France, USA

Plasma facing components: Divertor

Target: 19 m², 890 water-cooled elements, operation up to 12 MW/m²





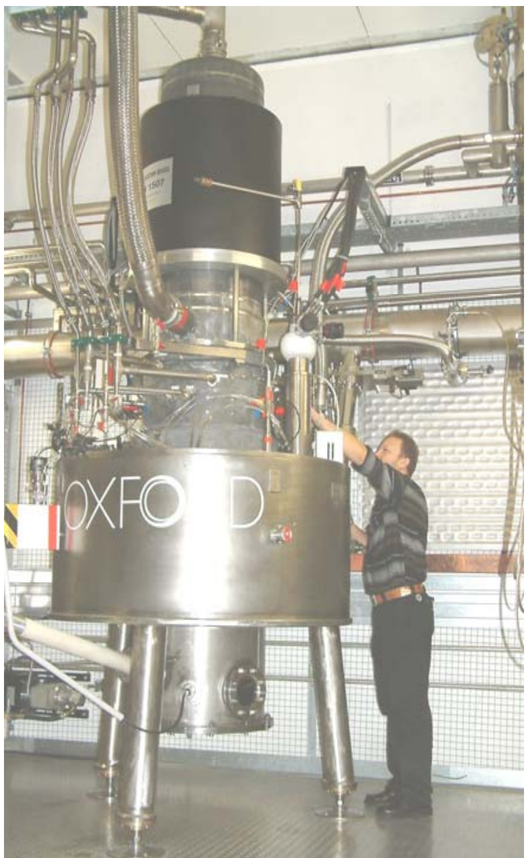


Pre-series elements
(PLANSEE AG, 09/2004)

Electron Cyclotron Resonance Heating

140 GHz
10 x 1 MW, 30 min

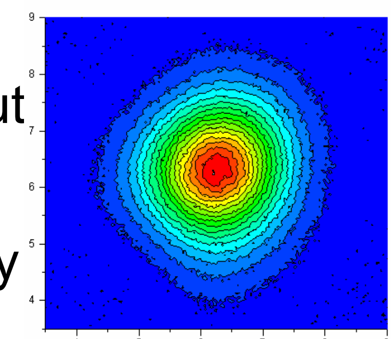
THALES Maquette



CPI Prototyp

Beam duct with mirrors and beam dumps

Beam at output



• High beam quality
• Agreement between designed and measured beam parameters for long distance transmission

Conclusions

W7-X will test the power plant suitability of optimised stellarators

The project development is at the transition to assembly

W7-X will play a specific role in the EU fusion programme beyond 2010

- **it is a relevant supplement to the main tokamak line**
  - ***complex geometry, steady-state capability, no current-driven modes***
  - ***simple geometry, current drive, current-driven instabilities***
- **it will train fusion scientists and engineers**
- **it will be a tool satisfying academic standards thanks to its novel concept**

W7-X will continue the programme of Tore Supra

- the development of long-pulse technology (PFC)

W7-X has a high ITER relevance

- **it develops the fusion know-how of EU industry**
- **ITER will benefit from the industrial capabilities generated by W7-X**
- **W7-X will develop experience in steady-state plasma operation**
- **PFC with ITER power densities;**
- **ECRH 140GHz (170); optical transmission line fulfills ITER requirements**