Steady-State In Vessel Components for the Wendelstein 7-X Stellarator

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on behalf of the W7-X Team

Table of Content

I. Overview

II. Divertor Components

III. Wall Protection Components

IV. Component Testing

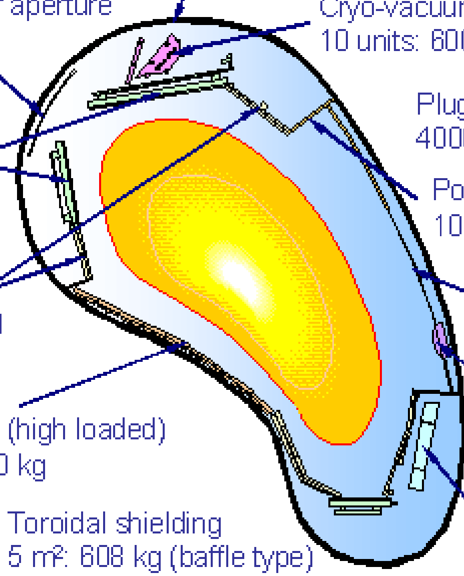
V. Component Assembly

VI. Conclusions

In-Vessel Components for steady-state Operation

Main Features

- Surface 265 m^2
- Mass approx. 33,8 tons
- 250 000 parts
  130 000 non-standard parts
  4000 different profiles
- 4.5 km internal cooling piping
  with about 900 branches



Location of in-vessel components,
"Bean-shape" cross-section
at 0° toroidal angle

Two step approach requires intermediate components:

- Inertial cooled divertor (TDU) for first operation phase
- Actively cooled high-heat-flux (HHF) divertor for steady state phase

Table of Content

I. Overview

II. Divertor Components

III. Wall Protection Components

IV. Component Testing

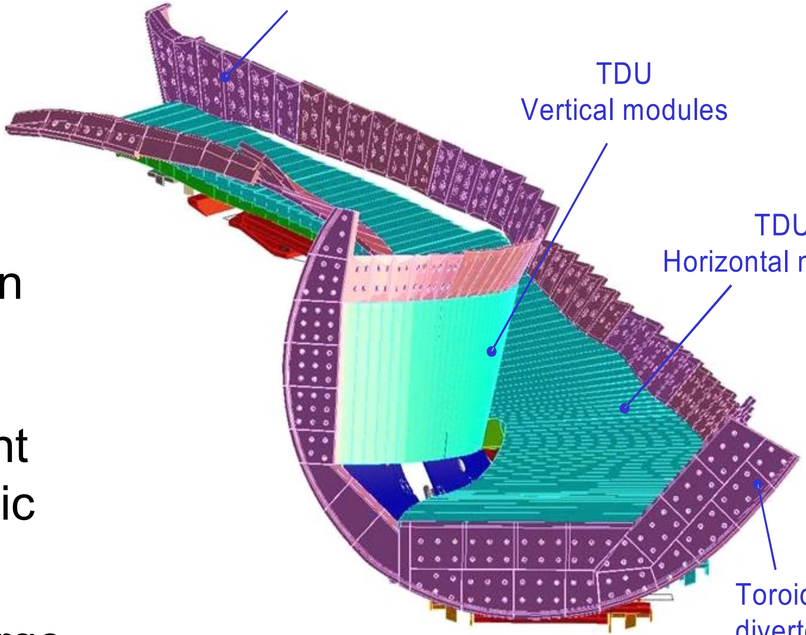
V. Component Assembly

VI. Conclusions

Test Divertor (TDU)

Test Divertor, inertial cooled for Commissioning

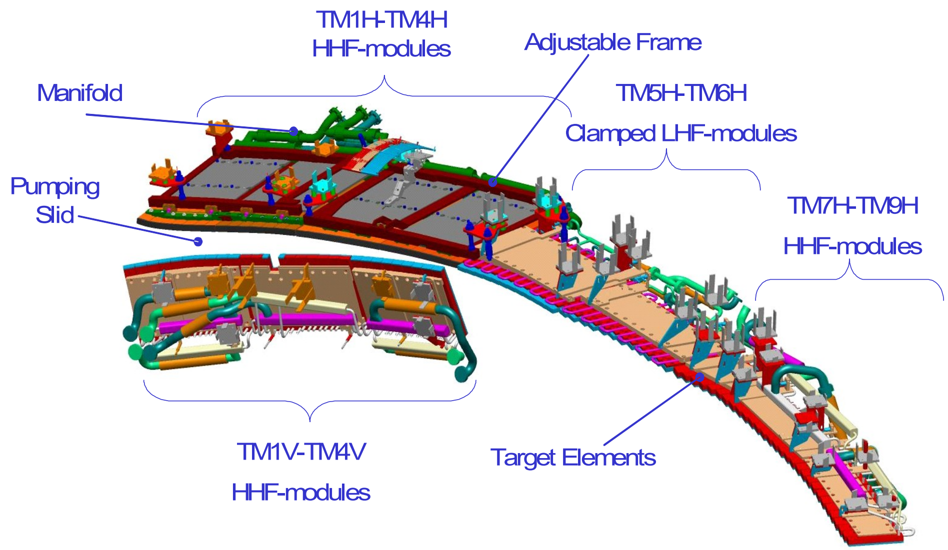
- $25 m^2$ TDU: solid graphite tiles
- Will be installed by 2014
for the first operation phase
of W7-X
- Simple structure, installation, adjustment, diagnostic integration
- Same geometry as HHF divertor
- Ease of assembly and adjustment after machine start up to magnetic configuration of W7-X
- Purpose: development of discharge scenarios for high heat flux divertor
⇨ optimized operation of
high heat flux divertor

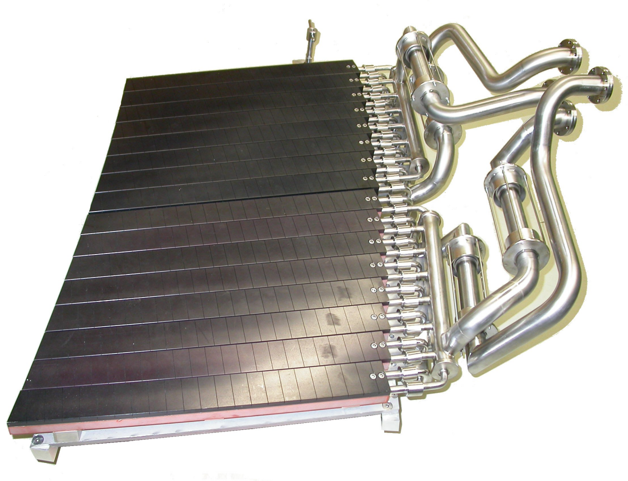


Test divertor (TDU)-target concept, with baffle-modules and toroidal divertor closure

High-Heat-Flux Divertor, required for Steady-State Operation

- 10 divertor units installed up down symmetrically
- Divertor unit: set of horizontal and vertical target modules
- Target module: set of target elements





Prototype module with manifolds on adjustable frame

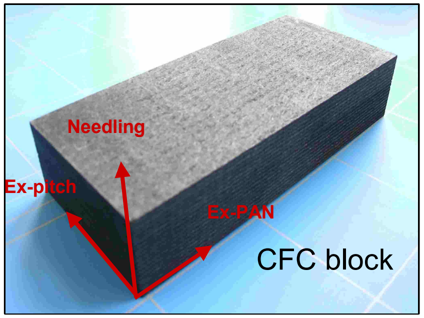
Main characteristics:

	10 MW/m²	1 MW/m²
Total area	19 m²	6 m²
Target modules	100	20
Target elements	890	250
Plasma facing material	CFC	Graphite

High-Heat-Flux Divertor

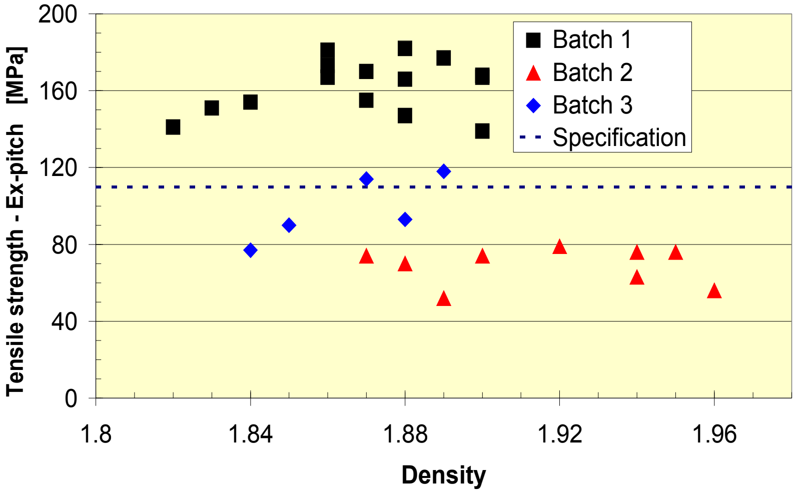
Fabrication: CFC NB31

- 3D-anisotropic material with complex manufacturing process
- Planned fabrication: from 2001 to 2003 (delivered in 2006…)



Thermal conductivity	Temperature [°C]	Minimum [W.m^{-1}.K^{-1}]	Average [W.m^{-1}.K^{-1}]
Ex-pitch	RT	260	300
	800	120	140
Ex-PAN	RT	100	110
	800	48	55
Needling	RT	85	100
	800	40	45

Tensile strength [MPa]	Minimum
Ex-pitch	110
Ex-PAN	20
Needling	5



- Scattering of tensile strength in the ex-pitch fibre direction between delivered batches
- Around 900 kg available for pre-series and serial productions of target elements

↳ Additional qualification steps

Target Elements for steady-state Operation: Design

Thermal performances:

- Max. stationary heat flux — 10 MW/m^2
- Max. power per element — 100 kW

Technology:

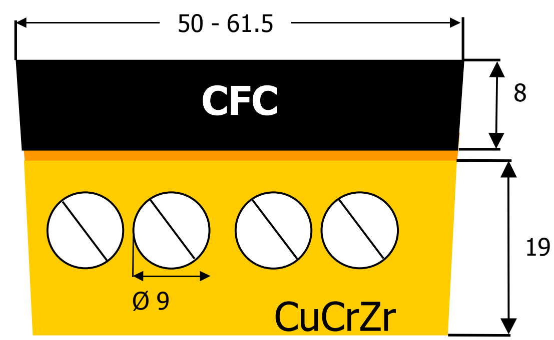
- Heat sink — CuCrZr
- Plasma facing material — CFC NB31
- Interlayer CFC-heat sink — bi-layer*
  (*=AMC® tiles with HIP OFHC-Cu)
- Joining CFC-heat sink — EBW
- Cooling — swirl tapes

Water-cooling characteristics:

- Max. inlet/outlet temp — 30°C / 80°C
- Static pressure — 1 MPa
- Velocity — 8-10 m/s

PLANSEE

890 elements - 13 types
250 ≤ length ≤ 595 mm



Cross-section

Target Elements for steady-state Operation: Fabrication

- ~900 elements, 13 types, ~18000 CFC tiles
- Pre-series achievements: bi-layer, improved heat sink
- Original launching of serial fabrication: 2004 (not started…)

Raw materials
CFC NB31

→ AMC®-NB31 tiles

→ bi-layer tiles
HIP of OF-Cu

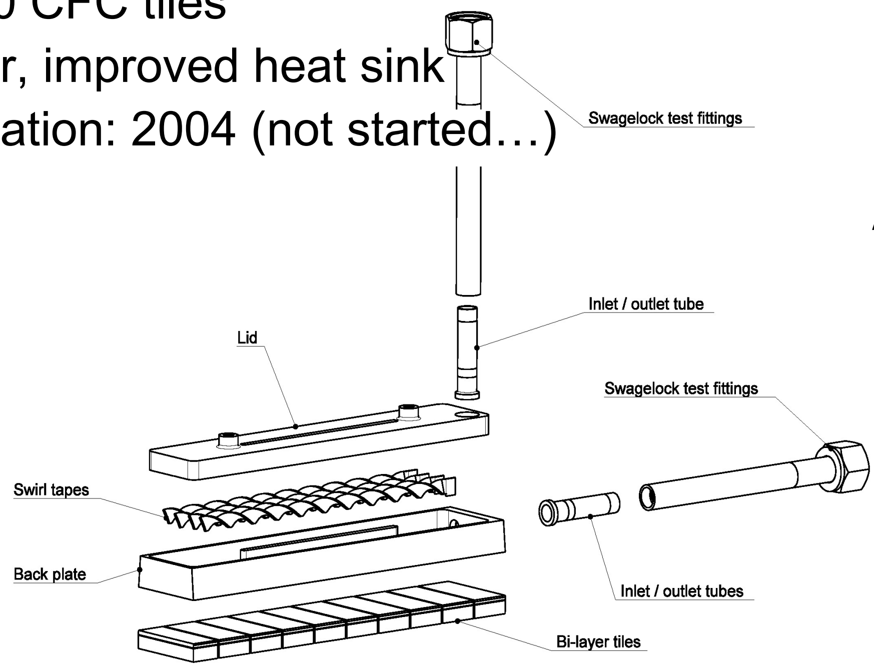
Raw materials
CuCrZr, stainless steel, Ni

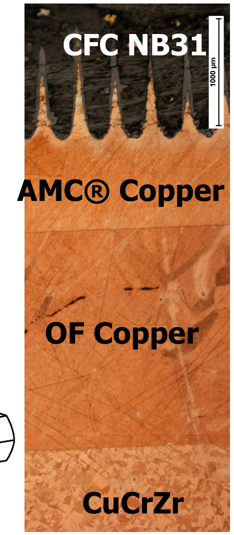
→ Lids, back plates
Twisted tapes, i/o tubes

→ CuCrZr cooling structure
e-beam welding

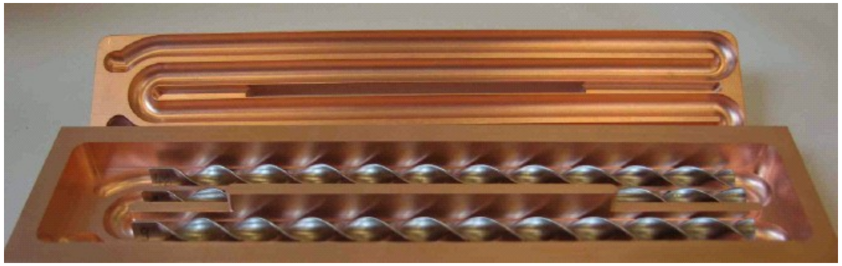
→ **Target element**
e-beam welding

[Inspections between steps are not shown]





Bi-layer



Heat sink

Target Elements for steady-state Operation: Pre-series phase

- Planning: ~1 year from end 2003 to end 2004 (not completed in 2008…)
- Pre-series 1, 2, 3, 4 = ~ 60 full-scale elements manufactured: 100% HHF tests in GLADIS

Extended pre-series activities:

- To minimize risks for serial fabrication
- To guarantee W7-X HHF divertor operation
- Boundaries: planning, budget, manpower, contractual matters

Results of the last pre-series test campaign (2008):

- 100% accepted: 10 elements or 100 tiles (100 cycles @ 10 MW/m^2, 10s) without failure
- Extended cycling: up to 10 000 cycles @ 10 MW/m^2, 10s with no visible cracks (1 element)
- Simulation of transient overloading: 1000 cycles at 20 MW/m^2, 3s without failure
- Extended heat flux: 24 MW/m^2 (15 MW/m^2 design), close to interface melting temperature
- Critical heat flux: 31 MW/m^2 (25 MW/m^2 specified), without armor

Conclusion:

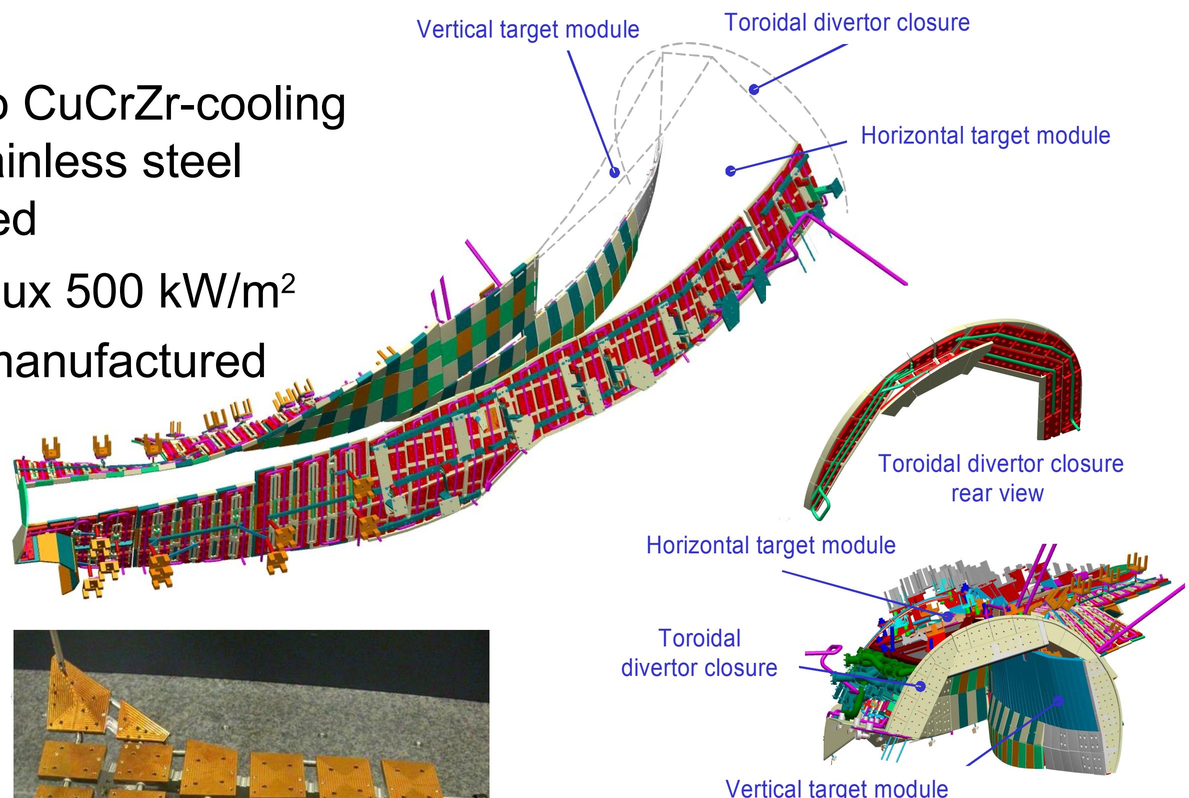
- The bonding technology between CFC tiles and CuCrZr heat sink is qualified
- Further development and verification of the cooling structure and end-tile design required

Baffle Modules

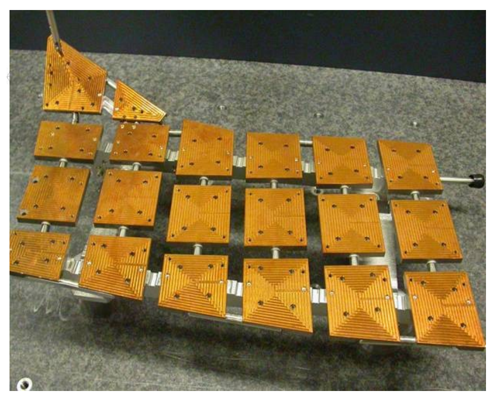
Actively cooled Baffle Module and Toroidal Divertor Closure

Baffle Module:

- Graphite-tiles clamped to CuCrZr-cooling structures onto which stainless steel cooling meander is brazed
- Peak steady state heat flux 500 kW/m²
- 170 baffle modules, 50 manufactured



Baffle module with graphite tiles



Cooling structure

Toroidal Divertor Closure:

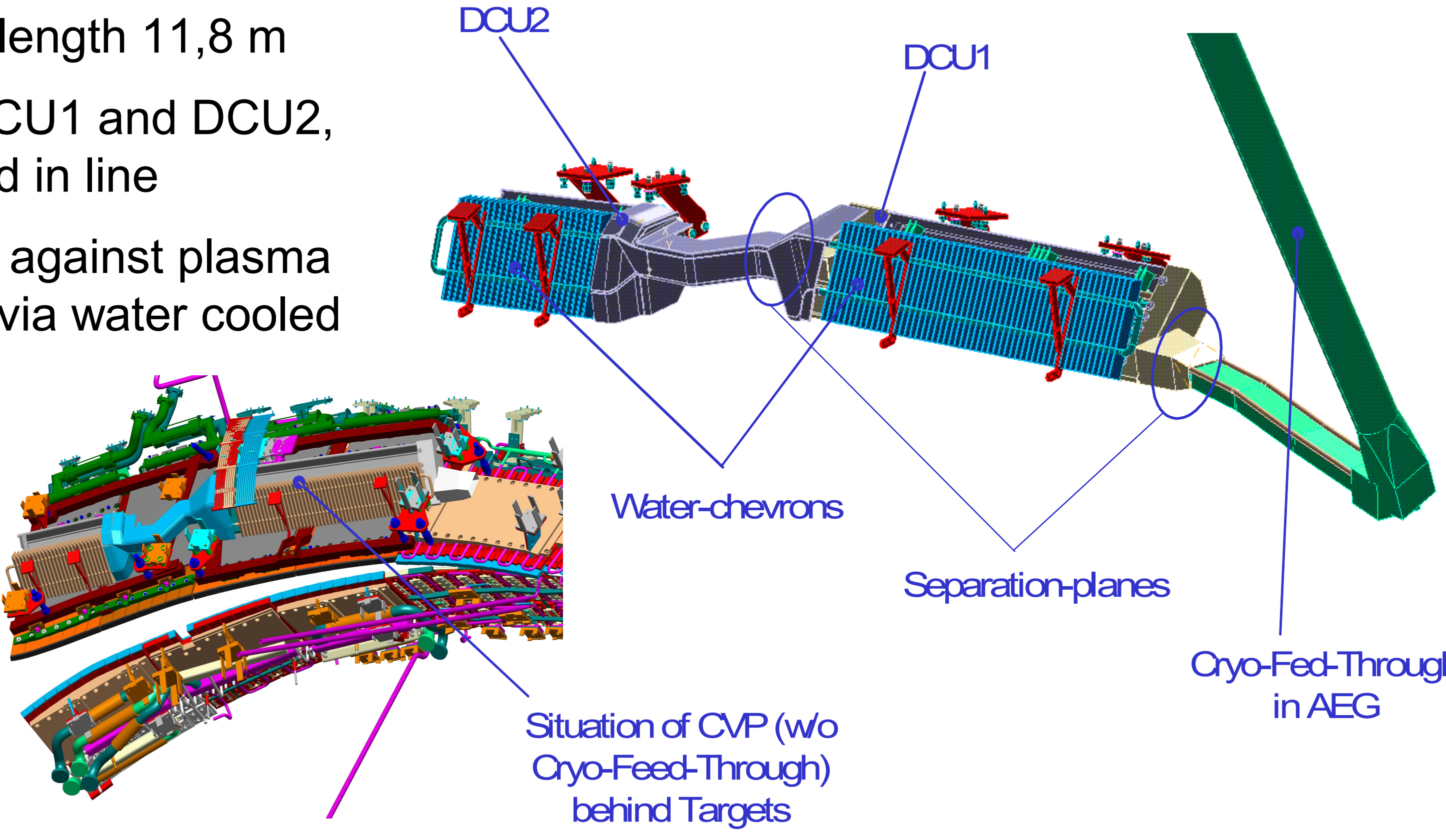
- 10 modules
- Baffle-type technology
- Concept available

Cryo Vacuum Pump with Cryo-Feed-Through

Design based on ASDEX Upgrade – cryo vacuum pump

10 identical pumps:

- Effective length 11,8 m
- 2 units DCU1 and DCU2, connected in line
- Shielding against plasma radiation via water cooled chevrons

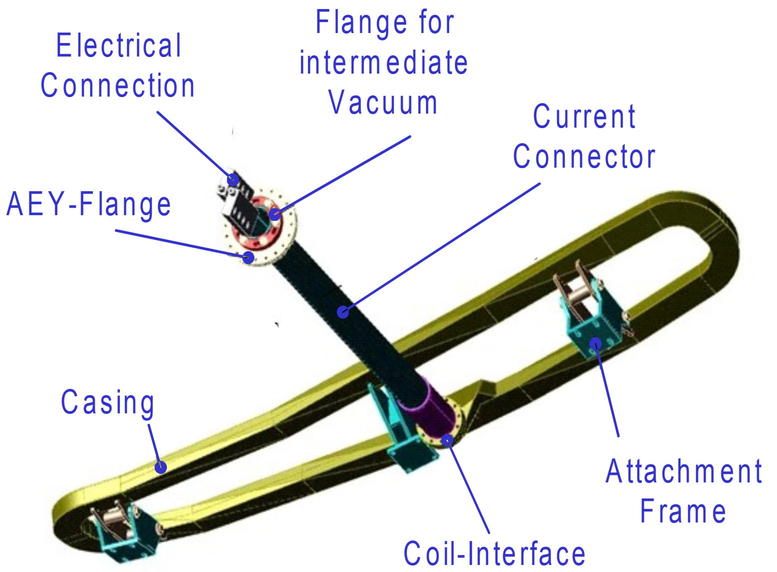


About 80% of parts manufactured - **Only installed for second phase operation**

Control Coils

Control Coils with Current-Connectors

- 10 Control coils, located behind baffles, manufactured by BNG, water-cooled
- 8 turns hollow Cu-conductor, allows to sweep target point by ± 1-2 cm and to correct minor error fields.
- Electrical current 2,5 kA DC, 625 A AC at between 1 -20 Hz.



All coils are delivered, tested and accepted

Control coil in test facility at IPP

Table of Content

I. Overview

II. Divertor Components

III. Wall Protection Components ←

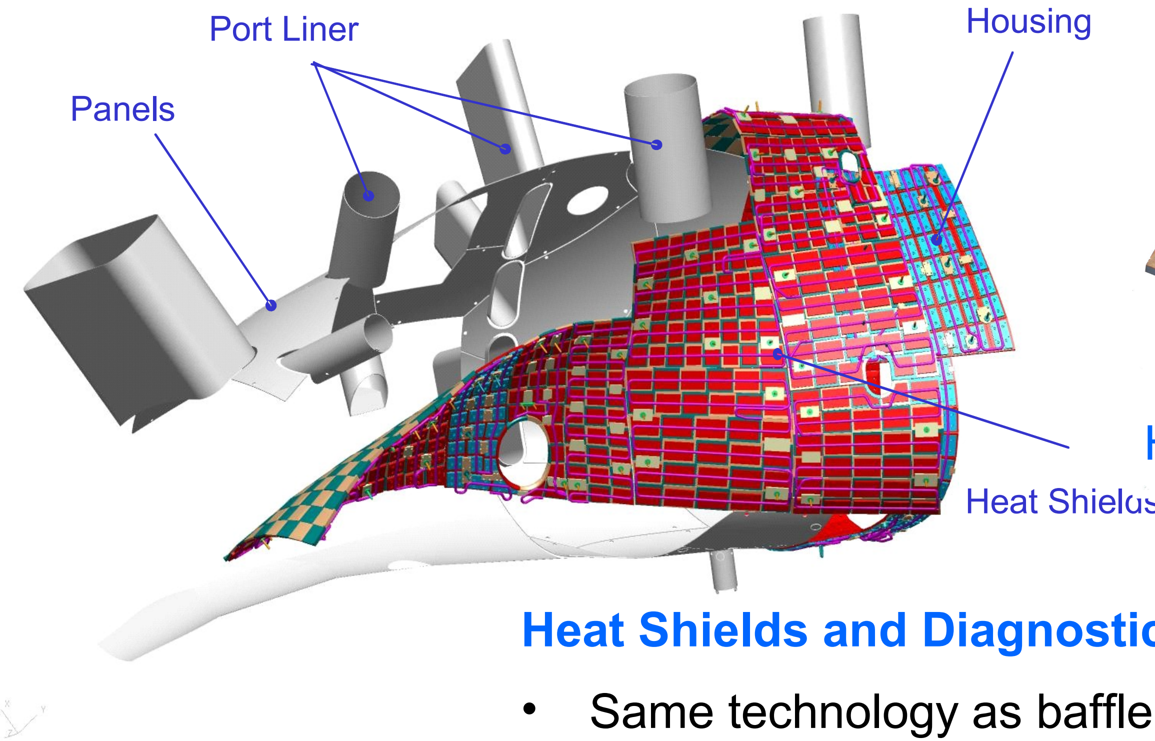
IV. Component Testing

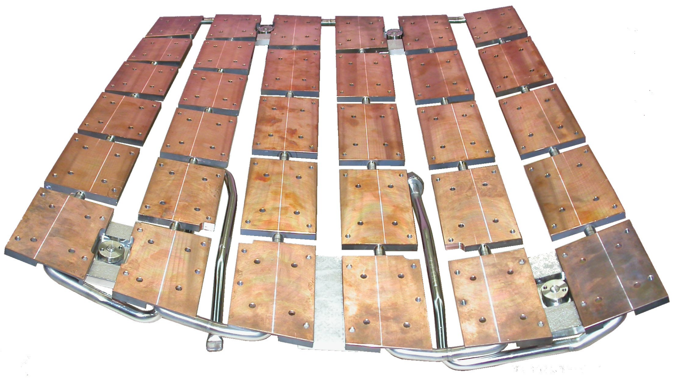
V. Component Assembly

VI. Conclusions

Wall Protection

Wall Protection for steady-state Operation: Heat Shields, Housings, Panels and Port liner





Heat shield without graphite tiles

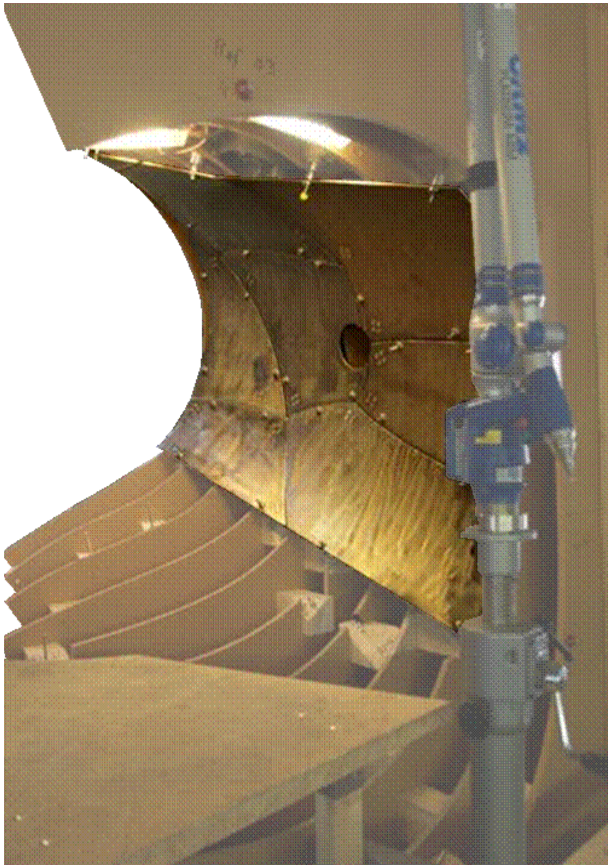
Heat Shields and Diagnostic Housings:

- Same technology as baffle modules
- Peak steady state heat flux 300 kW/m^2
- Actively cooled
- 162 heat shields required, 101 manufactured

Panel Elements in thermally low loaded Areas

Panels, Poloidal Divertor Closure and Pumping Gap Panels :

- Manufactured at MAN-DWE
- Peak steady state heat flux 200 kW/m²
- Quilted steel panels
- Actively cooled
- 320 panels, 200 delivered to date

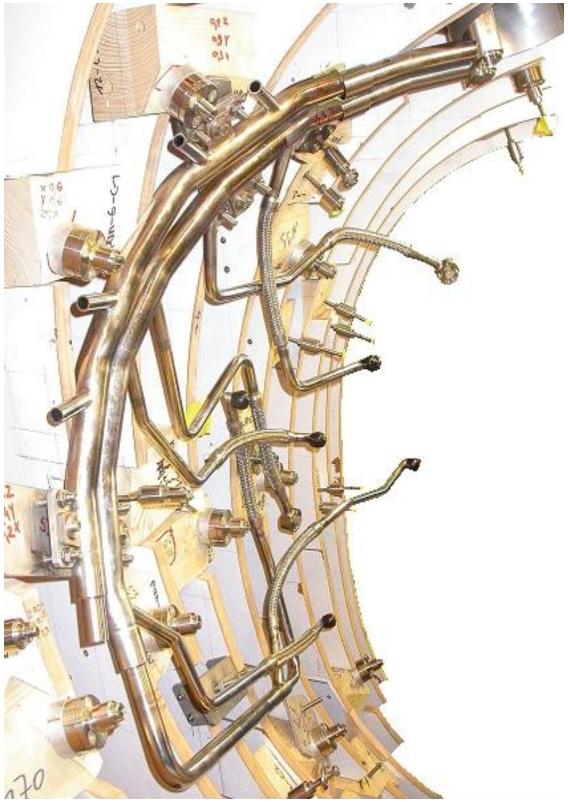


Panels installed in 1:1 wooden mock up of plasma vessel (top)

Panel, view from the rear (left)

Cooling Circuits

Plug-Ins and Cooling Circuits



Cooling circuit prototype, installed in 1:1 wooden mock-up of the plasma vessel

Cooling Circuits:

- 170 cooling circuits in 70 variants and versions
- Ca. 4,5 km pipe work in plasma vessel
- 900 branches
- 1500 components to be supplied, approx. 1500 interfaces and 3800 joints
- The first components are manufactured

Prototype plug-in

Plug-Ins:

- 80 plug-ins, 8 variants and several versions
- Up to 9 feed-throughs per plug-ins
- Some with diagnostic cabling

Table of Content

I. Overview
II. Divertor Components
III. Wall Protection Components
IV. **Component Testing**
V. Component Assembly
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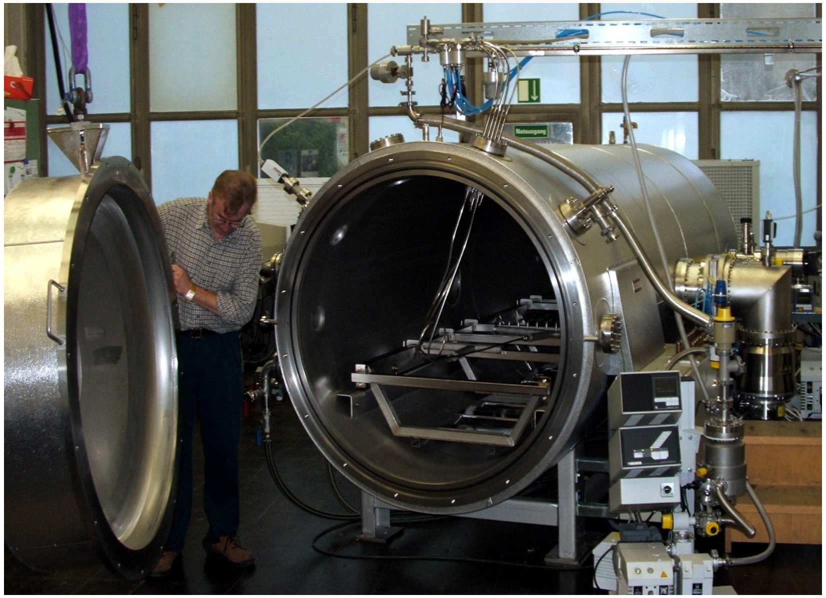
Component Testing

Component Testing at ZTE (Workshop of IPP Garching)

Vacuum chamber for hot leak tests:

- Diameter 1,2 m, length 3 m
- Integral leak tests from room temperature to 160 °C
- Cold leak tests at LN2-temperature
- Used for all in-vessel components
  - Targets
  - Control coils
  - Baffles
  - Heat shields, panels



Vacuum chamber

Others:

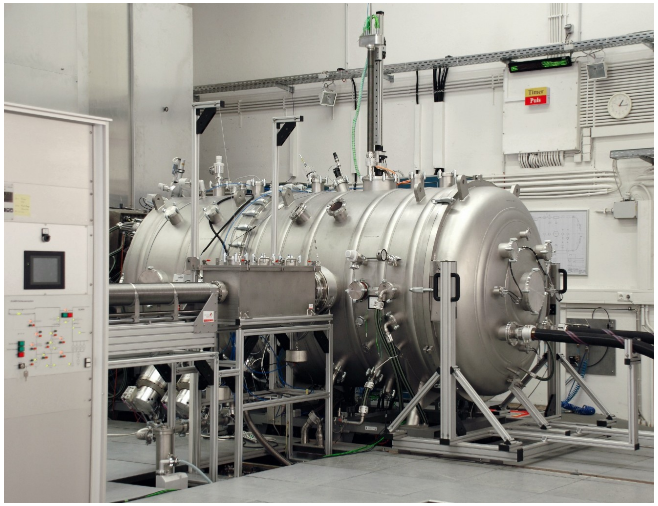
- Electrical test stand for control coils
- Hydraulic test facility
- 1:1 wooden mock up of plasma vessel segment

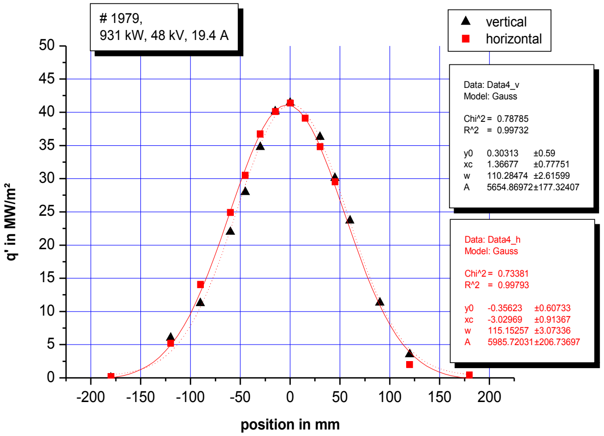
Component Testing

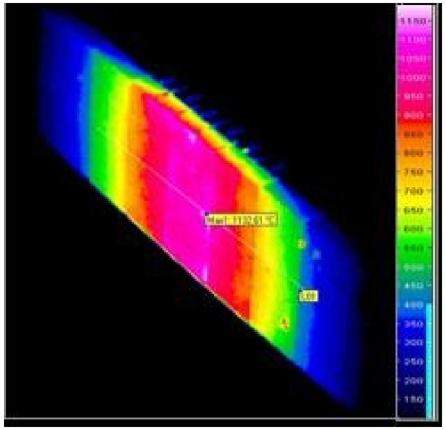
GLADIS, HHF-testing at IPP-Garching (Material Research Department)

GLADIS facility:

- Max. ion beam power 1,4 MW
- Heat flux density 52 MW/m²
- Pulse duration 0.1 – 15 s
- Use for W7-X HHF-Tests on:
  - Target elements during development, definition of acceptance criteria, envisaged for serial acceptance tests
  - Panels to verify un-cooled operation







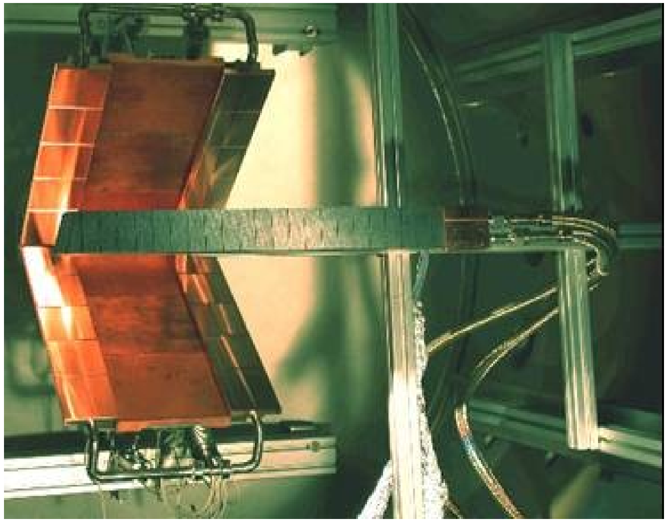


Table of Content

I. Overview
II. Divertor Components
III. Wall Protection Components
IV. Component Testing
V. **Component Assembly**
VI. Conclusions

Component Assembly

General Strategy:

- In-vessel components are installed in parallel to other machine assembly
- Verification of assembly technology, assembly procedures, metrology and training is carried out with prototypes, real components in mock-ups and real plasma vessel segments
- Installation of components that are replaced for steady state operation
  - Install inertially cooled test divertor for commissioning phase (for steady state operation an actively cooled high heat flux divertor will be installed together with the cryo vacuum pump)
- Installation of components that are removed during preparation for steady state operation
  - Installed - but not connected to the cooling system – baffles
- Install all other components that are required for steady state operation, some of which must be cooled even in the commissioning phase
  - Cooling supply for wall protection
  - Wall protection
  - Control coils

Component Assembly

Assembly Strategy:

- Assembly of wall protection components in the plasma vessel is parallel to other activities in torus hall and connection of the machine modules
- For this a well developed assembly and logistics strategy is required
- Interaction with diagnostics, particularly for cabling and routing, as well as heating systems needs to be well defined
- Assembly of in-vessel components should be kept off the critical path
- Divertor components and wall protection tiles will be installed in the final phase in order to minimize the risk of damage

Table of Content

I. Overview
II. Divertor Components
III. Wall Protection Components
IV. Component Testing
V. Component Assembly
VI. Conclusions ←

Conclusions

In-Vessel components for W7-X:

- All components designed for **steady-state operation at 10 MW**
  - actively cooled

- Design and production of the In-Vessel components for phased operation of W7-X shows **significant progress**.

- The **Test Divertor Unit** design is well advanced, test module in work.

- Geometrical and hydraulic layout of the **high heat flux targets** is tested with a prototype module.
  - Extensive high heat flux testing has verified the technology of the standard **target elements**.

Conclusions

In-Vessel components for W7-X:

- All **control coils** are available.
- 80% of the parts for the **cryo vacuum pumps** are manufactured.
- 30% of **baffle modules** and 60% of **heat shield** structures are assembled. Procurement of graphite tiles for both components is running.
- Approximately 60% of the **wall panels** are delivered by MAN-DWE.
- Prototypes of **cooling circuits** and **plug-ins** have been successfully built and tested. Serial production of the cooling circuits has started.

Conclusions

In-Vessel components for W7-X:

Delivery of components to IPP Greifswald has started.

The In-Vessel Component activities must continue at a high level over the next years to meet the machine assembly program.