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

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on behalf of the W7-X Team
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In-Vessel Components for steady-state Operation

Main Features

- Surface 265 m²
- 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

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

Location of in-vessel components,
“Bean-shape” cross-section at 0° toroidal angle
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Test Divertor, inertial cooled for Commissioning

- 25m² 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

Protototype module with manifolds on adjustable frame

Main characteristics:

- Total area: 19 m², 6 m²
- Target modules: 100, 20
- Target elements: 890, 250
- Plasma facing material: CFC, Graphite

High-Heat-Flux Divertor, required for Steady-State Operation
• 3D-anisotropic material with complex manufacturing process
• Planned fabrication: from 2001 to 2003 (delivered in 2006…)

### Thermal Conductivity

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<tr>
<td>Ex-pitch</td>
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### Tensile Strength [MPa]

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<th>Material</th>
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<td>Ex-PAN</td>
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<tr>
<td>Needling</td>
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### 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
Steady-State In Vessel Components for the Wendelstein 7-X Stellarator

R.J. Stadler

Target Elements for steady-state Operation: Design

Thermal performances:
• Max. stationary heat flux 10 MW/m²
• 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

Unternehmung Wendelstein 7-X

Max-Planck-Institut für Plasmaphysik

High-Heat-Flux Divertor

890 elements - 13 types
250 ≤ length ≤ 595 mm

Cross-section

CFC

CuCrZr

Ø 9

50 - 61.5

8

19
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
- CuCrZr, stainless steel, Ni

AMC®-NB31 tiles
- Lids, back plates
- Twisted tapes, i/o tubes
- Bi-layer tiles
- HIP of OF-Cu

CuCrZr cooling structure
- e-beam welding

Target element
- e-beam welding

[Inspections between steps are not shown]
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/m², 10s) without failure
- Extended cycling: up to 10 000 cycles @ 10 MW/m², 10s with no visible cracks (1 element)
- Simulation of transient overloading: 1000 cycles at 20 MW/m², 3s without failure
- Extended heat flux: 24 MW/m² (15 MW/m² design), close to interface melting temperature
- Critical heat flux: 31 MW/m² (25 MW/m² 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
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

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

Heat Shields and Diagnostic Housings:
- Same technology as baffle modules
- Peak steady state heat flux 300 kW/m²
- 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)
Plug-Ins and Cooling Circuits

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

Plug-Ins:

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

Others:

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