ITER Divertor:
Requirements, Design and EU R&D

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Outline

Requirements
Design
R&D results
Procurement
Conclusions
Requirements
Main Function of the Divertor

The main function of the divertor system is to exhaust:
- the major part of the alpha particle power
- helium and impurities from the plasma
ITER Divertor

Design parameters

- **Total power**: 150 MW
- **Surface heat flux (MW/m²)**
  - Steady state (400s, 3000 cycles, CFC/W): 10/5
  - Transient (10 s, 300 cycles): 20
- **Neutron volumetric heating**: max 10 MW/m³
- **Neutron damage**: 0.2-0.3 dpa
- **Disruption heat loads**: 10-100MJ/m² x 0.1-10ms x 300 cycles
- **ELMs heat loads**: 0.5-1.5 MJ/m² – freq. 1 Hz
### Thermal Design Loads

(in MW/m\(^2\) )

<table>
<thead>
<tr>
<th></th>
<th>Operating regimes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Semi-detached plasma</td>
<td>Attached plasma</td>
</tr>
<tr>
<td>Inner vertical target (lower section)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Inner vertical target (upper section)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Inner neutral particle reflector plate</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Outer vertical target (lower section)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Outer vertical target (upper section)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Outer neutral particle reflector plate</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hot liner</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Dome</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>High Heat Flux Components</td>
<td>Fossil Fired Boiler Wall (ABB)</td>
<td>Fission Reactor (PWR) Core</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td><strong>Design</strong></td>
<td>![Design Diagram]</td>
<td>![Design Diagram]</td>
</tr>
<tr>
<td><strong>Heat Flux</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- average MW/m²</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>- maximum MW/m²</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Max heat load MJ/m²</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lifetime years</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>Nr. of full load cycles</td>
<td>8000</td>
<td>10</td>
</tr>
<tr>
<td>Neutron damage dpa</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Structure material</td>
<td>Ferritic-Martens. steel</td>
<td>Zircaloy - 4</td>
</tr>
<tr>
<td><strong>Coolant</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- pressure MPa</td>
<td>28</td>
<td>15</td>
</tr>
<tr>
<td>- temperature °C</td>
<td>280-600</td>
<td>285-325</td>
</tr>
<tr>
<td>- velocity m/s</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>- leak rate g/s</td>
<td>&lt;50</td>
<td>&lt;50(SG)</td>
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</table>
Possible scenarios for divertor replacements (DDD 2004)

<table>
<thead>
<tr>
<th>Divertor set</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td>Operation</td>
<td>H</td>
<td>D-D</td>
<td>D-T</td>
<td>D-T</td>
<td>D-T</td>
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<tr>
<td>Strike point armour</td>
<td>CFC</td>
<td>CFC or W</td>
<td>W</td>
<td>W</td>
<td>W</td>
</tr>
<tr>
<td>Disruption Frequency</td>
<td>%</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>6</td>
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<tr>
<td>Lifetime</td>
<td>pulses</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>8000</td>
</tr>
</tbody>
</table>
Inner Vertical Target

Outer Vertical Target

Dome (Tungsten)

Cassette body

240 cm

340 cm

54 Cassettes each ≈ 8.3 tons
Divertor main features

General

54 Cassette Bodies, of which
• 6 diagnostic cassettes
• 10 instrumented cassettes

54 Outer Vertical Targets (2 halves)
54 Inner Vertical Targets (2 halves)

54 Dome/Liners
Cassette

- is reusable to minimise activated waste
- provides neutron shielding,
- routes the water coolant
- supports the different PFCs

Mass: 5.6 ton

Multilink attachment
The inner and outer VT are the PFCs which in their lower part interact directly with the scrape-off layer plasma and in their upper part act as baffles for the neutrals.
The **dome** sees mainly radiation and charge exchange neutrals. It also baffles neutral particles and protects the liner and the neutral particle reflector plates from the plasma.

**Mass:** 0.9 ton

A **semi-transparent liner** that protects the cassette body from direct line-of-sight view of the plasma, while allowing He and other impurities to be pumped away.
Pumping route

- Vertical Targets/Baffles (W-part)
- Vertical Targets (CFC-Part)
- Dome
- V-shaped divertor slots
- Transparent Liner for Pumping
- Cassetle Body
- Pump channel
Divertor coolant route
Divertor coolant design parameters

Inlet temperature: 100 °C
Inlet water pressure: 4.3 MPa
Total pressure drop: 1.21 < 1.4 MPa
CHF margin: 1.57 > 1.4
Total flow rate: 934 < 1000 kg/s
Multilink attachments
Multilink functions

Accurate Location of PFC.

Transmission of the EM loads on the PFC to the Cassette (11.6 t Cat 2; 15.5 t Cat 3 on a single link).

Accommodation of displacements associated with temperature differentials between the PFC and Cassette, and EM loading.

Provision of electrical and thermal continuity.

The connections have to be dismantled and remade for PFC replacement

Connection replacement has to be performed remotely as active components are involved.

<table>
<thead>
<tr>
<th>Table 1 – Main design features of the multilink attachments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeve outer diameter</td>
</tr>
<tr>
<td>Sleeve inner diameter</td>
</tr>
<tr>
<td>Pin outer diameter</td>
</tr>
<tr>
<td>Pin inner diameter</td>
</tr>
<tr>
<td>Pin Material</td>
</tr>
<tr>
<td>Lug diameter</td>
</tr>
<tr>
<td>Lug thickness</td>
</tr>
<tr>
<td>Link thickness</td>
</tr>
<tr>
<td>Lug Material</td>
</tr>
<tr>
<td>Link Material</td>
</tr>
<tr>
<td>Mandrel material</td>
</tr>
<tr>
<td>Design Load (ITER Cat 3)</td>
</tr>
<tr>
<td>Design load (ITER Cat 2)</td>
</tr>
</tbody>
</table>
Multilink Attachments

ENEA
**PFC Assembly** is achieved by using a loose fitting tubular pin, and expanding the pin to fit the connected components.

The method used for expanding the pin is to draw a tapered mandrel, through the hole in the tubular pin, by swaging the pin.

**PFC Dismantling** is achieved by pin removal/extraction.
The sleeved pin design has been qualified for

- Load capacity, and connection functionality.
- Pin swaging – for component clearances, mandrel diameter and swaging force (up to 13 t)
- Pin Extraction – feasibility has been demonstrated; extraction forces determined for the actual connection lengths (6 t)
EM loads due to VDEs

VDEs followed by a fast current quench
- They generate the largest eddy currents and thus moments on the PFCs
- They drive the design of the PFC multilink attachments

VDEs followed by a slow current quench
- They generate the largest halo currents on the cassette body
- They drive the design of the CB/VV locking system

Downward VDE simulation
Full cassette model (CB, DL, 2 OVT, 2 IVTT)

LT – Calcoli-Efremov
Summary for EM loads:
SDVDE-II, SDVDE-III, FDVDE-II, FDVDE-III
(linear and exponential events)

Module of EM forces is within $|F| = 0.43 \ldots 1.98 \text{ MN}$

\[ \text{in } \sim 5 \ldots 22 \text{ times more than Dead Weight of Divertor cassette} \]
Maximum $|F|$ is at SDVDE-III, case “inward”.

Module of EM moments is within $|M| = 0.3 \ldots 2.43 \text{ MN} \cdot \text{m}$
(relatively to mass center $X_c = 5.6$ m, $Z_c = -3.9$ m)

\[ \text{Maximum } |M| \text{ is at FDVDE-III} \]

( The main integral load is the vertical moment component $M_z = 2.4 \text{ MN} \cdot \text{m}$, it gives static toroidal reaction forces $F_y \sim \pm 0.8 \text{ MN}$ in CB inner and outer supports)
CB-VV locking system
Preload of bolts and cassette Body (CB)

CB radial preload force $F_R = 345$ kN (19 mm displacements)

Latest solutions
R&D results
Definitions

- Armour
- Heat sink
- Cooling tube
- Coolant
- Support structure
CFC to heat sink joints

CFC

Pure copper interlayer

CuCrZr

AMC
Pre-brazed casting
Brazing

HIP’ing
Hot Radial Pressing
Brazing
EB welding
W to heat sink joints

- Tungsten
- Pure copper interlayer
- CuCrZr
- Cu casting
- HIP’ing
  Hot Radial Pressing
  Brazing
  EB welding
Option 1

W flat tiles with tube cooling (upper half)

CFC monoblocks (bottom half)
Option 2 (superseeded)

W monoblocks (upper half)

CFC monoblocks (bottom half)
High heat flux results

Vertical Target
Medium-Scale Prototype

Test results

W macrobrush:
15 MW/m² x 1000 cycles

CFC monoblock
20 MW/m² x 2000 cycles

CHF test > 30 MW/m²
Vertical Target
Full-Scale Prototype

**W monoblocks:**
10 MW/m² x 1000 cycles

**CFC monoblock**
10 MW/m² x 1000 cycles
20 MW/m² x 1000 cycles
23 MW/m² x 1000 cycles
Vertical Target component with W armour

Tested in FE200 facility (50°C-12 m/s – 3.3MPa)
- 5 MW/m² x 100 cycles
- 10 MW/m² x 1000 cycles
- 20 MW/m² x 1000 cycles
Vertical Target Medium Scale Prototype by Hot Radial Pressing

3000 cycles at 10 MW/m² on CFC and W
2000 cycles at 20 MW/m² on CFC and 15 MW/m² on W

experimental critical heat flux of 35 MW/m² was determined on the CFC part
Neutron-Irradiation Experiments

PARIDE 3:
- temperature: 200°C
- target fluence: 0.2 dpa

PARIDE 4:
- temperature: 200°C
- target fluence: 1 dpa

High Flux Reactor
Petten, Netherlands
Decrease of thermal conductivity in CFC and W

**CFC**

At RT, thermal conductivity was reduced to 10% of the unirradiated value after 1 dpa. At 800°C, the thermal conductivity was reduced to 1/3 of the unirradiated value at 1 dpa. Partial recovery of the CFC thermal conductivity was observed during the post-irradiation high heat flux test (see figure below).

**W**

At RT, thermal conductivity was reduced to 73% of the unirradiated value after 0.6 dpa (which corresponds to 1 dpa in CFC). At 800°C, the reduction of the thermal conductivity was negligible.

The degradation of the W thermal conductivity under irradiation will not be an issue for the ITER divertor operation during the T phase.
Testing of irradiated CFC Mock-Ups

After irradiation to 0.2 dpa, CFC flat tile showed a failure limit of 19.5 MW/m².

After irradiation to 0.2 dpa, CFC monoblock was tested at 12 MW/m² without failure. (Test limited by decrease of the CFC thermal conductivity).

After irradiation to 1 dpa, test was limited to 15 MW/m² for both flat tiles and monoblocks.
Testing of irradiated W Mock-Ups

Unirradiated
- 1000 cycles x 14 MW/m² – no failure

200°C, 0.1 and 0.5 dpa in tungsten
- Failure limit: 10 MW/m²

Unirradiated
- 1000 cycles x 20 MW/m² – no failure

200°C, 0.1 and 0.5 dpa in tungsten
- Successfully tested up to 18 MW/m²

The irradiated pure Cu interlayer leads to a reduction of the high heat flux performances in a flat tile geometry.
The monoblock solution seems not to be affected by this problem.
Thermal fatigue testing of a tungsten macrobrush mock-up irradiated in the PARIDE 3 experiment

Irradiation condition:
200°C – 0.1 dpa (in W)

High heat flux test:
1000 cycles at 10 MW/m²
Development of acceptance criteria

Scope
To provide an analytical and experimental basis for the definition of acceptance criteria for the divertor PFCs
To correlate defect with the non-destructive testing evidence (US and IR thermography).

Milestones
The upgrading of the SATIR infrared examination test bed to increase the defect detection capability for CFC armoured components
Manufacturing of artificial defect mock ups (Plansee, Ansaldo)
US testing, SATIR, FEM analysis (Ciemat-Tecnatom, CEA)
HHF testing (AREVA)
US testing, SATIR infrared testing (Ciemat-Tecnatom, CEA)
Non-destructive and destructive examinations of mock-ups (FZJ)
Definition of acceptance criteria
CFC monoblock mock ups

<table>
<thead>
<tr>
<th>Defect position</th>
<th>Material Pair</th>
<th>Location angle</th>
<th>Δθ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC/Cu</td>
<td>Location angle = 0°</td>
<td>Δθ=20°, 35°, 50°, 65°</td>
<td></td>
</tr>
<tr>
<td>CFC/Cu</td>
<td>Location angle = 45°</td>
<td>Δθ=20°, 35°, 50°, 65°</td>
<td></td>
</tr>
<tr>
<td>Cu/CuCrZr</td>
<td>Location angle = 0°</td>
<td>Δθ=40°</td>
<td></td>
</tr>
<tr>
<td>Cu/CuCrZr</td>
<td>Location angle = 45°</td>
<td>Δθ=20°, 40°, 60°</td>
<td></td>
</tr>
</tbody>
</table>
W monoblock mock ups

<table>
<thead>
<tr>
<th>Defect position</th>
<th>W/Cu</th>
<th>Location angle = 0°</th>
<th>Δθ = 20°, 35°, 50°, 65°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect position</td>
<td>Cu/CuCrZr</td>
<td>Location angle = 0°</td>
<td>Δθ = 15°, 30°, 45°</td>
</tr>
</tbody>
</table>
Samples

There are **112 samples** split in two batches:
- 56 HIPing Technology \(\rightarrow\) Plansee
- 56 Hot Radial Pressing Technology \(\rightarrow\) Ansaldo Ricerche

Each batch of **56 samples** includes:
- 28 CFC monoblocks
  * 26 “short”
  * 2 “high”
- 14 W monoblocks
- 14 W flat tiles
Investigation of repair techniques

Activity ongoing at Plansee and Ansaldo
CFC, W Monoblock basic
CFC, W Monoblock repaired
Qualification of different grade CFC mock ups

SNECMA NB41, New Dunlop 3D, SNECMA N11, SNECMA N31

HHF test campaign
Screening test at 5 MW/m²
3000 cycles at 10 MW/m²
Screening test at 5 MW/m²
1000 cycles at 20 MW/m²
Screening test at 5 MW/m²
Objectives

Address some manufacturing issues

Verify the hydraulic design of the divertor.

Definition of a proper procedure to drain and dry the divertor components.

The assembly and integration procedures to be demonstrated on a full-scale prototype with realistic tolerances, dimensions, weight and accessibility.
Outer and Inner Vertical Target Dome Liner, Cassette
Hydraulic testing of divertor prototypes.

Pressure drop vs. flow rate have been measured on Outer and Inner Vertical target and Dome Liner (ENEA Brasimone)

<table>
<thead>
<tr>
<th>CEF 1 design parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank design pressure (MPa)</td>
<td>0.5</td>
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<tr>
<td>Loop design temperature (°C)</td>
<td>140</td>
</tr>
<tr>
<td>Pump max. flowrate (kg/s)</td>
<td>2 x 70</td>
</tr>
<tr>
<td>Pump max. head (MPa)</td>
<td>2 x 1.2</td>
</tr>
<tr>
<td>Electrical heater power (kW)</td>
<td>2 x 60</td>
</tr>
</tbody>
</table>
Divertor coolant design parameters

- Inlet temperature: 100 °C
- Inlet water pressure: 4.3 MPa
- Total pressure drop: 1.21 < 1.4 MPa
- CHF margin: 1.57 > 1.4
- Total flow rate: 934 < 1000 kg/s
Comparison between experimental and numerical (Relap 5) pressure drops
Time Schedule

- Integration by the first half of 2008
- Hydraulic tests of divertor system by end 2008
- The full divertor prototype may be delivered to Finland for RH testing

- Divertor refurbishment platform (ENEA Brasimone)

DTP2 Tampere (Finland)
Procurement
### Divertor Procurement Sharing

<table>
<thead>
<tr>
<th>1.7 Divertor</th>
<th>Component</th>
<th>Credit (kIUA)</th>
<th>Sharing</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1: Cassette Body and Integration</td>
<td>11.2</td>
<td>🇪🇺</td>
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<tr>
<td>P2</td>
<td>2A: Outer Vertical Targets</td>
<td>28.5</td>
<td>🇯🇵</td>
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<tr>
<td></td>
<td>2B: Inner Vertical Targets</td>
<td>20.2</td>
<td>🇪🇺</td>
</tr>
<tr>
<td></td>
<td>2C: Dome</td>
<td>15.0</td>
<td>🇷🇺</td>
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<tr>
<td></td>
<td>2D: High Heat Flux Tests</td>
<td>8.0</td>
<td>🇷🇺</td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>82.9</strong></td>
<td></td>
</tr>
</tbody>
</table>

Reference:
*Final Report of Negotiations on ITER Joint Implementation*
(Attachment 2_C “Common Understandings on Procurement Allocation”), 1 April 2006
17.P1 “Divertor Cassette Integration”
   • 1 full-scale prototype + 54 cassettes + 6 spares
   • Installation of the PFCs
   • Installation of the diagnostics equipments

17.P2 “Divertor Plasma-Facing Components
   • 1 full-scale prototype + 54 Inner Vertical Target + 6 spares
Divertor Vertical Target Qualification Prototypes

The aim of the activity is to demonstrate the EU Party capability to carry out the VT procurement, in advance of the procurement start.

The Party is “qualified” if at least 2 of the prototypes meet the acceptance criteria and at least one withstands the high heat flux qualification tests.

The contracts activities are started on Feb.2007 and are being completed
Full monoblock version

Mono-flat tile version

The companies involved are: Plansee SE (A) and Ansaldo Ricerche (I)

The selected prototype versions are: full monoblock and mono-flat tile

CFC material: SNECMA NB41
Summary
Summary

The ITER divertor is ready for procurement but it is an experimental component and the operational regimes that will allow its use without risk have to be demonstrated.

EU has performed the R&D necessary for divertor procurement (Inner vertical target, cassette, integration)

- High heat flux component technology is compatible with ITER requirements
- Integration issues have been addressed.

The divertor procurement pre-qualification phase has been initiated. This is aimed at minimizing the manufacturing and operational risks.