Plasma Exhaust and Divertor Designs in Japan and Europe Broader Approach, DEMO Design Activity

Topics are selected from *Chapter 4: Divertor and Power Exhaust* in final report of Broader Approach (BA) DEMO Design Activity (DDA) Phase-I (2020 Feb.)

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28th IAEA Fusion Energy Conference (virtual), 10-15 May 2021
Power exhaust concepts and challenges for JA and EU DEMOs

- EU and JA BA-DDA study covers common aspects of divertor physics and engineering design: water-cooled single-null divertor and appropriate geometry for plasma detachment.
- Both concepts handle similar thermal heating power ($P_{\text{heat}}$), and require large total radiation fraction ($f_{\text{rad}} = P_{\text{rad}}/P_{\text{heat}} \geq 80\%$) in order to reduce the peak heat load ($\leq 10\ \text{MWm}^{-2}$):

**Divertor power handling is determined by requirements of $f_{\text{rad}}^{\text{main}}$ and the plasma performance.**

**JA DEMO challenge (steady-state op.):**
Lower $I_p$ and higher $HH$ with ITER-level $f_{\text{rad}}^{\text{main}}$ ⇒
Large divertor power handling: $P_{\text{sep}}/R \sim 30\ \text{MWm}^{-1}$

**EU DEMO challenge (pulsed op.):**
Higher $I_p$ and ITER-level $HH$ with large $f_{\text{rad}}^{\text{main}}$ by high-Z seeding ⇒ ITER-level $P_{\text{sep}}/R = 17\ \text{MWm}^{-1}$

**JA DEMO higher-$\kappa$ proposal ($\kappa_{95}=1.75$) [1] rather than JA DEMO 2014 ($\kappa_{95}=1.65$) [2] is shown: having advantages on power exhaust in main plasma and divertor.**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>line-$n_e^{\text{main}}$ $(10^{20}\text{m}^{-3})$</td>
<td>0.86</td>
<td>0.87</td>
</tr>
<tr>
<td>$n^{\text{GW}}$ $(10^{20}\text{m}^{-3})$</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>$n_{\text{imp}}^{\text{main}}/n_e^{\text{main}}$ (%)</td>
<td>0.6 (Ar)</td>
<td>0.039 (Xe)+Ar</td>
</tr>
<tr>
<td>$P_{\text{heat}} (P_\alpha+P_{\text{aux}})$, MW</td>
<td>435</td>
<td>457</td>
</tr>
<tr>
<td>$P_{\text{rad}}^{\text{main}}$ (MW)</td>
<td>177</td>
<td>306</td>
</tr>
<tr>
<td>$f_{\text{rad}}^{\text{main}} (P_{\text{rad}}^{\text{main}}/P_{\text{heat}})$</td>
<td>0.41</td>
<td>0.67</td>
</tr>
<tr>
<td>$P_{\text{sep}}$ (MW)</td>
<td>258</td>
<td>154</td>
</tr>
<tr>
<td>$P_{\text{sep}}/R_p$ (MWm$^{-1}$)</td>
<td>30</td>
<td>17</td>
</tr>
</tbody>
</table>

Divertor design and Power exhaust simulation

Conventional design concepts in JA & EU are based on the ITER divertor:

- Both DEMOs: Divertor leg is extended (outer $L_{\text{div}}$=1.6 m: 1.6 times longer than ITER).
- JA: Baffles cover divertor plasma for large $P_{\text{sep}}/R$ handling ⇔ EU: Open and shallow geometry (ITER-level $P_{\text{sep}}/R$) to increase tritium-breeding area and reduce weight & process for remote maintenance.
- JA: Dome and reflectors are installed to enhance the neutral recycling near the strike-point.
  EU: Dome and reflectors are simplified (“liner”) to reduce fast neutron flux to cassette and VV.

SONIC (JA-DEMO) and SOLPS-5.1 (EU-DEMO) simulations have been performed:

- Exhaust power ($P_{\text{out}}$ = JA: 250-300 MW, EU:150-200MW) is given at core-edge boundary.

Note: $q_{\|}$ profile width near separatrix is similar ($\lambda_{q_{\|}}$~3mm).
JA DEMO: Divertor operation in low density \((n_e^{sep} = 2-3 \times 10^{19} \text{ m}^{-3})\)

Heat load can be reduced within the operation range \((q_{target} \leq 10 \text{ MWm}^{-2})\) for \(f^*_{rad} \sim 0.8\).

- **Higher-\(\kappa\)** \((P_{sep} \sim 235 \text{ MW}, f^*_{rad} \sim 0.8)\) reduces \(q_{target}\) \((\leq 6 \text{ MWm}^{-2})\), and allow enough operation margin.

- **JA DEMO 2014** \((P_{sep} \sim 283 \text{ MW}, f^*_{rad} \sim 0.8)\): Decreasing detachment width, and increasing \(T_i\) and \(T_e\) of the attached plasma.
  \(\Rightarrow\) peak-\(q_{target}\) is increased, and margin of the power handling \((\leq 10 \text{ MWm}^{-2})\) is reduced.

- **Lower** \(f^*_{rad} \sim 0.7\) \((P_{sep} \sim 235 \text{ and } 283 \text{ MW})\) cases:
  \(\Rightarrow\) **higher** \(n_e^{sep}\) \((>2.3 \times 10^{19} \text{ m}^{-3} \text{ for DEMO higher-} \kappa , >2.7 \times 10^{19} \text{ m}^{-3} \text{ for DEMO 2014})\) is required.

**Peak-\(q_{target}\) at outer target**

In each density scan, Ar seeding rate was adjusted to obtain a given \(f^*_{rad} = (P_{rad} + P_{rad\ sol})/P_{sep}\).

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EU DEMO: Divertor power handling by Ar seed for $P_{\text{sep}}/R = 16-22$ MWm$^{-1}$.

Heat reduction was achieved for all cases by increasing $C_{\text{Ar}}^{\text{SOL}} (= n_{\text{Ar}}/n_e)^{\text{SOL}} = 0.5-2.5\%$

**Geometry effect** on plasma profile: partial detachment was not clearly seen in the open geometry.

**Baseline ($P_{\text{sep}} = 150$ MW):** heat reduction ($q_{\text{target}} \leq 10$ MWm$^{-2}$) was achieved by increasing $f_{\text{rad}}^{\text{div}} \geq 0.7$. ⇒ Low $T_e^{\text{div}}$ (≤ 5 eV) was also produced over wide outer target for $f_{\text{rad}}^{\text{div}} \geq 0.8$ ($C_{\text{Ar}}^{\text{sol}} \geq 0.8\%$).

**Larger $P_{\text{sep}}$ case:** $q_{\text{target}}$ reduction was achieved ($f_{\text{rad}}^{\text{div}} \geq 0.75$) ⇒ low $T_e^{\text{div}}$ (≤ 5 eV) was required in higher $f_{\text{rad}}^{\text{div}} \geq 0.9$ ($C_{\text{Ar}}^{\text{sol}} \geq 2\%$). Detachment ($T_e^{\text{div}} \sim 1$ eV) is seen in very high $f_{\text{rad}}^{\text{div}} \geq 0.93$.

**Ar seeding scan for $P_{\text{sep}} = 150/180/200$ MW**

*Note:* $n_e^{\text{sep}} \sim 2.8 \times 10^{19}$ m$^{-3}$ is higher than JA-DEMO

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**Diagrams:**

- **Baseline ($P_{\text{sep}} = 150$ MW):**
  - $T_e^{\text{div}}$ vs. distance from separatrix at target (m).
  - $P_{\text{rad}} (f_{\text{rad}}^{\text{div}})$: 100 MW (0.67), 111 MW (0.74), 117 MW (0.78).

- **Larger $P_{\text{sep}}$ case:**
  - $T_e^{\text{div}}$ vs. distance from separatrix at target (m).
  - $P_{\text{rad}} (f_{\text{rad}}^{\text{div}})$: 124 MW (0.62), 159 MW (0.85), 173 MW (0.87), 186 MW (0.83), 184 MW (0.92).

- **Heat reduction diagrams:**
  - $Q_{\text{target}}$ vs. $n_{\text{Ar}}/n_e$ (%) for $P_{\text{sep}} = 150$, 180, 200 MW.
  - $T_e$ at attach (JA), $T_e$ at sep. (JA), $T_e$ at peak (EU).
Design concepts for water-cooling DEMO divertor

W-PFC & CuCrZr-pipe is common baseline design based on the ITER divertor.

- ITER-like monoblock target is the first candidate for high heat load plasma facing component.
- Remote maintenance concept is also common issue: JA divertor is larger weight.
- Mechanical property of Cu-alloy and interlayer (1-2 dpa) may firstly determine PFC life time (maintenance) under DEMO n-irradiation condition, while coolant-temp. is increased (130-200°C).

**EU**: R&D of ITER-like target to reduce stress and to strengthen pipe& interlayer.

**JA**: applying ITER-like target near the strike-points (lower dose).

<table>
<thead>
<tr>
<th></th>
<th>EU DEMO [5, 6]</th>
<th>JA DEMO [1, 7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of cassettes</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Number of divertor maintenance ports</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td><strong>Weight of one cassette (ton)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFC &amp; Heat sink</td>
<td>W&amp;CuCrZr</td>
<td>W&amp;CuCrZr</td>
</tr>
<tr>
<td>Water T(°C)/ Pressure(MPa)</td>
<td>130/5</td>
<td>200/5</td>
</tr>
<tr>
<td>Dose on pipe/fpy (dpa)</td>
<td>&lt;10</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td><strong>Dome/Baffle</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PFC &amp; Heat sink</td>
<td>W&amp;CuCrZr (liner)</td>
<td>W&amp;F82H</td>
</tr>
<tr>
<td>Water T(°C)/P(Mpa)</td>
<td>180/ 3.5</td>
<td>290/ 15</td>
</tr>
<tr>
<td>Dose on pipe/fpy (dpa)</td>
<td>&lt;10</td>
<td>&lt;8.5</td>
</tr>
<tr>
<td><strong>Cassette</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>EUROFER97</td>
<td>F82H</td>
</tr>
<tr>
<td>Water T(°C)/P(Mpa)</td>
<td>180/ 3.5</td>
<td>290/ 15</td>
</tr>
<tr>
<td>Dose on struct. material/fpy (dpa)</td>
<td>&lt;6</td>
<td>&lt;3</td>
</tr>
</tbody>
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Design concepts of divertor water-cooling for DEMOs:
Optimization of two water routes is required. Coolant-temperature is a design issue.

**Parallel cooling route for inner and outer targets** is designed to avoid fast flow speed at inboard.

- **JA:** W-MB with CuCrZr/F82H-pipes was arranged for Plasma Facing Components with high/low heat load and low/high n-flux: $T_{\text{coolant}} = 200^\circ\text{C}$ is used for CuCrZr-pipe to reduce embrittlement [8].
- **EU:** $T_{\text{coolant}}$ is reduced ($130^\circ\text{C}$) to increase the critical heat flux larger than 48 MWm$^{-2}$ (for $150^\circ\text{C}$) [9]. $T_{\text{coolant}}$ ($180^\circ\text{C}$) for cassette (EUROFER97) to ensure sufficient fracture toughness at n-damage (<6 dpa).

Heat analysis of W-monorblock and CrCrZr heat sink for JA DEMO

Acceptable power load depends on heat load components and target design

Heat load profile (plasma, radiation & neutral, nuclear heat) is applied to *ITER-like fish scale target*: peak heat load to flat tile (9.1 MWm\(^{-2}\)) corresponds to 13.5 MWm\(^{-2}\) to the wetted area.

- The peak heat load is a critical, i.e. operation just below recrystallization temperature of W (1200°C). Irradiation-creep/softening of CuCrZr-pipe (351°C) is also anticipated.
- Max. heat flux from the pipe to coolant (18MWm\(^{-2}\)) is well below Critical Heat Flux (35MWm\(^{-2}\)). Power exhaust by 200°C water is acceptable even for larger heat load on W (surface-\(T_w > T_{\text{recrystalization}}\)).

<table>
<thead>
<tr>
<th>Temperature in MB target</th>
<th>Heat flux from CuCrZr-pipe to water</th>
</tr>
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<tbody>
<tr>
<td>CuCrZr</td>
<td>W</td>
</tr>
<tr>
<td>Max. T: 351°C</td>
<td>Max. T: 1193°C</td>
</tr>
</tbody>
</table>

In addition, **elasto-plastic stress analysis** was performed by repeating higher heat load (max. \(q\): 15MWm\(^{-2}\); W surface: 1400°C) \(\Rightarrow\) mechanical strain on CuCrZr pipe (\(~0.25\%) was not critical, while max. temp. became 365°C.
Summary: BA DDA for Power exhaust concept and Divertor design

Common design issues for Power exhaust and Divertor have been investigated in JA and EU.

- Requirements of $f_{rad}^{main}$ and the plasma performance determined **divertor design concept**: Challenges of **JA** (steady-state): ITER-level $f_{rad}^{main}$ (high HH) and larger $P_{sep}/R = 30-34 \text{MWm}^{-1}$ and **EU** (pulsed): large $f_{rad}^{main}$ (ITER-level HH) for ITER-level $P_{sep}/R$, contribute to optimize future reactor des.

  ⇒ Same leg length (1.6 m: longer than ITER) but different geometry (**JA**: ITER-like closer baffle, **EU**: rather open without dome and baffle) were proposed as baseline designs.

Power exhaust simulations of $P_{sep} \sim$ **JA**: 250-300 MW, **EU**: 150-200 MW with Ar seeding have been performed, by using **JA**: SONIC and **EU**: SOLPS5.1, with similar $q_{\parallel}$ profile width ($\lambda_{q_{\parallel}} \sim 3\text{mm}$):

- **Large divertor radiation fraction** ($f_{rad}^{div} = P_{rad}^{div}/P_{sep} \geq 0.8$) was required to reduce peak-$q_{target}$ ($\leq 10 \text{MWm}^{-2}$) and $T_{e,i}$ in $n_e$ range (JA: 2-3$x10^{19}$, EU:$\sim 2.8x10^{19}$m$^{-3}$) lower than ITER.

- Divertor geometry affected **partial detachment profile**.

Integrated design of **divertor target, cassette** and **coolant pipe routing** has been developed: water cooled ITER-like target (W-PFC and Cu-alloy heat sink) is a common baseline design.

- For a year long operation **under DEMO-level n-irradiation**, deterioration of mechanical properties of CuCrZr heat sink and Cu-interlayer is anticipated ⇒ restrictions of $q_{target}$ & $T_{surface}$.

- **EU** has been developing W-MB target components to reduce stress and strengthen pipe & interlayer.

- **JA**: 2 cooling loops: Cu-alloy heat sink (target, 200°C) and F82H heat sink (baffle/cassette, 290°C). ⇒ Cu-alloy/interlayer concept and Operation-$T_{coolant}$ for DEMO divertor are common critical issues.

Joint studies on Plasma exhaust and Divertor design are extended to BA DDA Phase-II (-2024).
Development of water-cooled target components for EU DEMO
Mechanical property of heat sink and joint/interlayer is a key for Cu-alloy application

Development of candidate target concepts based on W-monoblock and Cu-alloy technologies:

- Divertor target concepts are developed for water-cooled targets:
  All are based on a Cu-alloy pipe with swirl tape to increase the heat transfer at the pipe wall:

Baseline:
- **ITER-like** MB & CuCrZr pipe with Cu-interlayer
  → Reducing thickness and width to reduce thermal stresses and prevent vertical cracking.

Reducing stress and strengthen pipe & interlayer:
- **Thermal break** interlayer /CCFC
- W wire-reinforced Cu **composite pipe** /IPP
- **Functionally graded** (W/Cu) interlayer /CEA
- W particle-reinforced Cu **composite** heat sink block /IPP

- Mock-ups of each concept have been fabricated and 100-level cyclic tested in a high-heat flux facility at 20-25 MW/m² with 130°C (20°C) water cooling

Note: He-cooling by multi-jet pipe (KIT) is an option.

(New) Materials and Components for the DEMO Divertor

R. Neu¹,², A.v. Müller¹, B. Curzadd¹,², J. Riesch¹, J. W. Coenen³,⁴, H. Greuner¹, T. Höschen¹, K. Hunger¹, G. Schlick⁵, U. Siefken⁶, E. Visca⁷, J.H. You¹

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³Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung - Plasmaphysik, 52425, Jülich, Germany
⁴Department of Engineering Physics, University of Wisconsin Madison, WI 53706, Madison, USA
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⁶Louis Renner GmbH, 85232 Bergkirchen, Germany
⁷ENEA, 00044 Frascati RM, Italy
Boundary conditions for plasma facing components (PFCs)

W as PFM:
- high melting point
- low sputtering yield
- low tritium retention
- low vapour pressure

Cu (alloys) as heat sink:
- high thermal conductivity

W surface
T < 1500 K
avoid recrystallization

W bulk
T > 1100 K
avoid brittleness

Cu bulk
T > 350 K
avoid embrittlement
T < 620 K
avoid loss of strength

no overlap of optimum operational conditions

principle layout

q = 20 MW/m²

water
~ 420 K

∇T (W): 175 K/mm

∇T (CuCrZr): 65 K/mm

deep cracking observed for ITER mock-ups during cycling at 20 MW/m² due to low cycle fatigue (crack initiation) and brittle behaviour during cool down

[M. Li FED 101 (2015) 1]

[G. Pintsuk, FED 88 (2013) 1858]
Advanced materials and designs for PFCs

Concepts for improving PFCs for the European DEMO
- optimisation of shape/size → lower temperature
- thermal break concept → homogenisation of temperature
- adaption of CTE by **functionally graded material**
- improvement of material properties (strength, toughness) by **composites / fibre reinforcement**

⇒ combination of concepts can further optimise function and lifetime


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Extrinsic toughening mechanisms in fibre reinforced materials:
- stress redistribution by local energy dissipation
- effective below DBTT & under embrittled state

[J. Riesch, Phys. Scr., T167 (2016) 014006]
**W fibres and yarns**

**W fibres with small diameter (16 – 150 µm)**

- highly deformed/fine grains:
  - **high strength, ductile** already at room temperature
- potassium doping: **stable against recrystallization** up to ~ 2000 °C
- yarns show **increased flexibility and confirm higher strength** of thinner fibres

\[
\sigma_{UTS} > 3900 \text{ MPa}
\]


[necking]

[ductile failure behaviour confirmed]

[H. Gietl, J. Comp. Mater. 52 (2018) 3875]

28th IAEA FEC, May 13, 2021
Ductile behaviour of irradiated W fibres

Exceptional properties (strength & ductility) ⇒ ideal ingredient for composites for high-temperature applications
⇒ successful development $W_f/W$ and $W_f/Cu$ composites

Small fibre diameter ($\varnothing=5 \, \mu m$) allows damage of complete volume by W ions (irradiation by 20.5 MeV W-ions simulating n-damage)
⇒ no strong degradation up to 10 dpa

[J. Riesch, 17th Int. Conf. on PFMC, 2019, Eindhoven]
Production of bulk tungsten fibre reinforced tungsten (W<sub>f</sub>/W)

Production of W<sub>f</sub>/W by Chemical Vapour Deposition (CVD, decomposition of WF<sub>6</sub>)

- layers of woven W wire fabric (distance 200 – 300 µm):
  - K-doped, Ø 150µm, 1µm Yttria interface layer
- fibre volume fraction ≈ 10 - 30%, unidirectional orientation
- density ≤ 99%

Samples for mechanical and high heat flux testing
Testing of mechanical properties of $W_f/W$

- Rising load bearing capacity, pseudo-ductility
- No catastrophic failure
- Matrix failure = bulk material failure

3-Point Bending

Load [N] vs. Displacement [$\mu$m]

W fibre-reinforced Cu heat sink

cylindrical multi-layered braiding made out of continuous W fibres or yarns with a nominal diameter of 50 µm

micro-sections of a $W_f$ - Cu heat sink pipe produced by means of liquid Cu melt infiltration

[brazed joint between W mono-blocks and $W_f$ - Cu heat sink pipe](A.v. Müller, Phys. Scr. T171 2020 014003]
High heat flux testing of $W_f - Cu$ PFC mock-ups

- hot-water cooling conditions: 130°C, 40 bar, 16 m/s $\rightarrow$ DEMO relevant
- 1000 load cycles at 20 MW/m² without indication of failure
- 100 load cycles at 25 MW/m², screening up to 32 MW/m² ($\@$ 20°C, 10 bar)


- no damage of bonding & $W_f - Cu$ tube after 1000 cycles at 20 MW/m²

recrystallized surface layer
plastic deformation
Use of additive manufacturing for topology optimisation

Stress/temperature distribution W monoblock @15 MW/m²

<table>
<thead>
<tr>
<th>$Q_N$ (MW m⁻²)</th>
<th>$\sigma_{\text{max}}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>260.5</td>
</tr>
<tr>
<td>10</td>
<td>576.1</td>
</tr>
<tr>
<td>15</td>
<td>922.5</td>
</tr>
<tr>
<td>20</td>
<td>1264.2</td>
</tr>
</tbody>
</table>

Reduction of thermal stresses by a factor of 6! Note: extremely high flexibility for geometry, here deliberately classical geometry for comparison!

Optimisation of W/Cu distribution (10 MW/m² case)

Structure reproduced by bcc lattice

final avg. composition 61% W 39% Cu

[B. Curzadd et al., Nucl. Fusion 59 2019 086003]
Additive manufacturing of actively cooled W components

- Successful additive manufacturing of honeycomb and optimized W preforms
- Nearly perfect Cu infiltration of AM W skeletons
- HHF tests of optimized AM W mock-ups imminent

Summary and Conclusion

- New composite materials can help to improve DEMO PFCs to allow for larger operational margin (higher cooling water temperatures / higher thermal loads) and lifetime
  - increasing high temperature strength of Cu in the cooling structure, ameliorating consequences of Cu(-alloy) neutron damage
  - increasing fracture toughness of W
  - adjusting the thermal mismatch between armour and heat sink
  - tailored material distribution by additive manufacturing to reduce thermal stresses
- Very promising behaviour of composites materials and composite PFCs in high heat flux tests

Outlook:
First results for W fibres and $W_f$-Cu confirm superior behaviour under neutron irradiation!