Conceptual Design of the New Water-Cooled W/Cu Lower Divertor in the EAST Superconducting Tokamak

G.S. Xu\(^1\)*, L. Wang\(^1\), D.M. Yao\(^1\), Y.P. Chen\(^1\), H.L. Du\(^2\), C.F. Sang\(^3\), X.J. Liu\(^1\), Z.S. Yang\(^1\), H. Si\(^1\), Z.P. Luo\(^1\), G.Q. Li\(^1\), H. Li\(^1\), H.C. Xu\(^1\), Z.B. Zhou\(^1\), L. Cao\(^1\), J.D. Lore\(^4\), J.M. Canik\(^4\), R. Maingi\(^5\), H.Y. Guo\(^6\), T.J. Xu\(^1\), Z.L. Wang\(^1\), Y.W. Yu\(^1\), J.B. Liu\(^1\), S.Z. Zhu\(^1\), G.N. Luo\(^1\), X.D. Zhang\(^1\), J. Li\(^1\) and EAST team

\(^1\)Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
\(^2\)Southwestern Institute of Physics, PO Box 432, Chengdu 610041, China
\(^3\)Dalian university of Technology, Dalian 116024, China
\(^4\)Oak Ridge National Laboratory, Oak Ridge, TN, USA
\(^5\)Princeton Plasma Physics Laboratory, Princeton, NJ, USA
\(^6\)General Atomics, San Diego, CA, USA

*Email: gsxu@ipp.ac.cn
Current PFCs in EAST
W-shape graphite lower divertor

Pumping capability of the ITER-like W upper divertor is limited due to very narrow pumping channels through the cassette body.
Current status of the EAST lower divertor

- Hot spots on the lower graphite divertor is currently the main problem limiting heating power to < 3 MW for ∼100 s long-pulse H-mode operations in EAST.
- EAST now heavily rely on lithium to reduce H concentration, recycling and impurity, mainly due to the soft property of graphite.
- Cooling water speed < 4 m/s, power handling capability ≤ 2 MW/m².
- W impurity control is the key issue for high-power long-pulse operations.
Key targets for divertor operation

EAST near-term target:
EAST aims at > 400 s long-pulse H-mode operations with a full metal wall and a divertor heat load of \( \sim 10 \text{ MW/m}^2 \).

Power and particle exhaust is the key to achieve this target.

Steady-state operation of a dissipative divertor with low W sputtering and strong divertor pumping.
Strategies to achieve this target

- Mainly by increasing **divertor closure** to maximize divertor power dissipation and pumping efficiency while minimizing divertor volume for maximizing core-plasma performance
- Compatible with advanced **fully non-inductive core** scenarios
  - achieve $T_{\text{et}} < 10$ eV across entire outer target at a relatively lower separatrix density
- Have some flexibility in configuration; allow access to the **small-ELM H-mode** regimes and advanced core scenarios
  - accommodate a relatively **wide triangularity range**, $\delta = 0.4-0.6$
- Allow **quasi-snowflake** configurations with the assistance of water-cooled internal coils

---

**However**, the engineering of water-cooled W/Cu PFCs imposes strong constraints on the divertor structure design (e.g. curvature radius limit, end boxes, etc.)

- favor **simple geometry** to facilitate manufacturing and engineering **quality control** (e.g. surface alignment, leading edge avoidance), reduce cost, increase reliability
Tightly Baffled Divertor —— A new divertor concept for high-power steady-state H-mode operations

- **Vertical inner target (VIT)**
- **Horizontal outer target (HOT)**

**Dome:**
- Improve pumping

**Inclined baffle:**
- Reflect neutral towards private region, increase neutral pressure, facilitate strike-point detachment, Protect against transients

**Cryopump 75 m$^3$/s**

**Water-cooled internal coil ~30 kAt**

**Pumping duct 1.5 cm × 5 cm**

**Baffle:**
- Protect against downward strike point excursions

**Cryopump 2×6 m$^3$/s at port end ~3m long**

**ITER-like neutral communication slot:**
- Reduce in-out divertor leg asymmetry (can be sealed with SS cover)
Local particle circulation enhance neutral pressure and facilitate detachment across entire outer target.

Most heat and particles deposit on the horizontal target. Thus most particles may participate in the local circulation, enhancing neutral pressure and facilitating detachment across entire outer target.
End-box surface nearly parallel to the field lines to avoid direct exposure to heat flux

Curvature radius limit 
~90 cm

End box:
flat-type W/Cu PFC only ~5 MW/m²
High triangularity should allow access to the small-ELM H-mode regimes & core scenarios

ELM frequency \( \geq 2 \text{ kHz} \)

\( \delta \approx 0.4 \) - 0.6
Compatible with double-null operation

ITER-like cassette body with actively water cooling

Up-down sweeping operation
Horizontal target + inclined baffle $\rightarrow$ effectively trap neutral $\rightarrow$ facilitate detachment

Te $\quad$ nD0

Horizontal target $\quad$ Vertical target $\quad$ Vertical baffle

Detachment across entire outer target $n_{\text{sep}} = 2.0 \times 10^{19}$
SOLPS simulations show the advantage of horizontal target over vertical target.

Medium density: $n_{\text{sep}} \approx 1.6 \times 10^{19} \text{m}^{-3}$

- **Horizontal target**
  - Lower far-SOL $T_e$
  - Higher SOL neutral
  - Higher strike-point heat flux

- **Vertical target**

---

$D=0.3$, $\chi=1.0 \text{m}^2/\text{s}$; D0, D+, C0-C6+ (from phys and chem sputtering $y=0.03$)
SOLPS simulations show the advantage of horizontal target over vertical target.

Low density: $n_{sep} \approx 1.2 \times 10^{19} \text{m}^{-3}$

- **Horizontal target**
  - Lower far-SOL $T_e$
  - Higher SOL neutral
  - Higher strike-point heat flux

- **Vertical target**

Conditions:
- $D=0.3$, $\chi=1.0 \text{m}^2/\text{s}$
- $D_0, D^+, C_0-C_6^+$ (from phys and chem sputtering $y=0.03$)

H.L. Du
Two kinds of tungsten PFCs with actively water cooling for high/low heat-load areas

Flat-tile (2mm thickness) PFCs:
Dome and baffles (~5 MW/m²)

ITER-like monoblock PFCs:
Divertor targets (~10 MW/m²)

4→8 m/s water flow velocity
360→800 ton/hour flow rate in the water main
1→3 MPa pressure
Bakeable to ~250°C
ITER-like monoblock and flat-tile PFCs have been used in EAST upper divertor for 4 years. ITER-like cassette body with actively water cooling. W/Cu PFCs for EAST upper divertor.

- Passed ITER and CEA test
- Used in the WEST tokamak in France

20 MW/m² for 1000 cycles

- Heat load ~ 8.4 MW/m², cooling water of 20 °C, 15s/15s on/off cycles
- The mock up survived up to 1000 cycles, with surface temperature up to 1150 °C.
Add a duct at the LFS pump entrance to increase neutral pressure and pumping

The optimization is based on a semi-analytic pumping model initially developed and validated against DIII-D experiments [1,2], and later extended to better account for gas transport through ducts of finite length into the pumping volume [3].

DIII-D lower divertor

Duct

Height = 1.5 cm
Length ~ 5 cm
at bottom high-pressure position


Collaborate with J.D. Lore, J.M. Canik

R. Maingi
Design is close to optimal value for shot 50791 $\delta \sim 0.5$ shape and profiles

- Design shows only 3% reduction from optimal value for shot 50791
  - $R_{\text{sep}} = 1.748$ m

- Adding duct increases pressure by 37% (compared to $L=0$)

<table>
<thead>
<tr>
<th>Shot</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50791</td>
<td>0.5</td>
</tr>
<tr>
<td>62421</td>
<td>0.6</td>
</tr>
</tbody>
</table>

$H_{\text{max}} = 1.9$ (cm), $L_{\text{max}} = 8.9$ (cm)
Design is close to optimal values across range of outer strike point position

Optimized strike-point position

Using profiles from 50791, $R_{OSP}$ scan shows the design (Height = 1.5 cm, Length ~ 5 cm) close to the optimal values across scan
Quasi-snowflake (QSF) with 3 water-cooled internal coils for steady-state operations

Maximum current for each coil: ~ 30 kAt for 10s, ~ 8 kAt for >100s
Flux expansion and connection length for steady-state QSF vs. SND configurations

Flux expansion neat strike point

\[ f_m = \left( \frac{B_P}{B_{tot}} \right)_{MP} / \left( \frac{B_P}{B_{tot}} \right)_{SP} \]

Flux expansion for the magnetic surface passing through R-R_{LCFS}=1mm on the outer midplane

<table>
<thead>
<tr>
<th>I_p=350kA</th>
<th>Outer f_m</th>
<th>Inner f_m</th>
</tr>
</thead>
<tbody>
<tr>
<td>SND</td>
<td>2.8</td>
<td>3</td>
</tr>
<tr>
<td>QSF</td>
<td>6.6</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Outer connection length

<table>
<thead>
<tr>
<th>outer CL (m)</th>
<th>Q-SF</th>
<th>SND</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>70</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

Inner connection length

<table>
<thead>
<tr>
<th>inner CL (m)</th>
<th>Q-SF</th>
<th>SND</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>70</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Contents</td>
<td>2016</td>
<td>2017</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Physics objective</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma configuration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma facing material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compatibility of divertor geometry and plasma configuration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Divertor design and optimization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R&amp;D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype development and test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diagnostic development</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QA and QC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Summary

• An upgrade to the lower divertor is currently being planned for EAST, aiming at > 400 s long-pulse H-mode operations with a full metal wall and a divertor heat load of ~10 MW/m².

• A new divertor concept “Tightly Baffled Divertor” suited to water-cooled W/Cu PFCs with minimized divertor volume has been proposed to achieve $T_{et} < 10$ eV across entire outer target at lower separatrix density and optimized pumping by a simple closed divertor structure combining horizontal target with inclined baffle and duct.

• This divertor allows access to high-triangularity small-ELM H-mode regimes and also allows achieving quasi-snowflake configurations with the assistance of water-cooled internal coils.

• This may provide a promising tungsten divertor solution compatible with advanced steady-state core scenarios.
Thank you very much!
Backup
ITER-like W/Cu Monoblock PFCs for high-heat-load areas

- **HIP+HIP**: W/Cu mockups were manufactured successfully by a double Hot Isostatic Pressing (HIP) technology
- **NDT results**: Passed NDT check for dual bondings between W/OFC/CuCrZr tube; **HFF testing**: 10MW/m²-1000cycles passed
Flat-type W/Cu PFUs for low-heat-load areas

- **Casting + HIP**: The interface of W/Cu were joined by casting, and then the interface of Cu/CuCrZr was bonded by HIP at lower temperature of 500~600℃.
- **NDT results**: Passed NDT check for dual bondings between W/OFC/CuCrZr plate; **HHF testing**: 5MW/m²-1000cycles passed

---

**Diagram:**
- **W**
- Pure Cu interlayer
- **CuCrZr**
- **Casting or VPS/CVD**
- **HIP**
- **VHP**
- or gradient W/Cu layer
Key features of the divertor structure design

Traditional vertical outer target:

- **Advantage**: Reflect recycling neutrals towards private region, smaller angle of incidence, facilitate detachment at the strike point
- **Disadvantage**: Higher far-SOL $T_e$ and W sputtering & escape to the core

Horizontal outer target

- **Advantage**: Reflect neutrals towards SOL, lower far-SOL $T_e$ and W sputtering
- **Disadvantage**: Higher strike-point detachment threshold

Our solution combine the advantages: A closed outer divertor enclosed by horizontal outer target, inclined baffle and dome

- Direct recycling neutrals towards both SOL and private region
- Increase neutral pressure and reduce neutral escape to the core
- Facilitate detachment simultaneously at strike point and in the far SOL

An open inner divertor with vertical inner target:

- Longer connection length, lower far-SOL $T_e$ and W sputtering yield, more balanced detachment between inner and outer divertor