Study of Quasi-Snowflake Divertor for CFETR by using SOLPS

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Vienna, Austria
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Outline

- Introduction for CFETR
- Preliminary Design of Snowflake Divertor
- Simulation Settings and Operational Status
- Impurity Radiation and Screening
- Conclusion
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**Introduction**

**China Fusion Engineering Test Reactor (CFETR)**

A good complement for ITER

**Main missions**
- *Fusion Power 200 MW*
- *Duty factor 0.3~0.5*
- *Tritium Self-sufficiency*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CFETR</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Current $I_p$ (MA)</td>
<td>8.5/10</td>
<td>15</td>
</tr>
<tr>
<td>Major Radius $R$ (m)</td>
<td>5.7</td>
<td>6.2</td>
</tr>
<tr>
<td>Minor Radius $a$ (m)</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Central magnetic field $B_T$ (T)</td>
<td>4.5/5.0</td>
<td>5.3</td>
</tr>
<tr>
<td>Elongation Ratio $\kappa$</td>
<td>2.0</td>
<td>1.70/1.85</td>
</tr>
<tr>
<td>Triangle Deformation $\delta$</td>
<td>0.4</td>
<td>0.33/0.48</td>
</tr>
<tr>
<td>Number of TF coils (N)</td>
<td>16</td>
<td>18</td>
</tr>
</tbody>
</table>

**Introduction**

**Injected power**
(auxiliary heating: 100 MW)

- **P\text{fusion} = 200 MW**
- **P\text{heat} = 100 + 40 MW**
- **P\text{rad} = 40 MW**

<table>
<thead>
<tr>
<th>Power handling [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P\text{fusion})</td>
</tr>
<tr>
<td>(P\alpha)</td>
</tr>
<tr>
<td>(P\text{aux})</td>
</tr>
<tr>
<td>(P\text{radcore (brem+sync.)})</td>
</tr>
<tr>
<td>(P\text{SOL} = P\alpha + P\text{aux} - P\text{radcore})</td>
</tr>
</tbody>
</table>

**PSOL/R [MW/m]**

- \(17\) MW/m

**Comparable with ITER**

**CFETR Divertor Baseline: ITER-like Divertor**

Exploring effective way to reduce \(q_{pk}\) for future fusion reactor (\(P/R \sim 80-100\))

**Snowflake Divertor**

Engineering limit:
\(q_{pk} < 10\text{ MW/m}^2\)
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### PF Coils of CFETR

<table>
<thead>
<tr>
<th>COILS</th>
<th>R(m)</th>
<th>Z(m)</th>
<th>ΔR(m)</th>
<th>ΔZ(m)</th>
<th>TURNS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS3U</td>
<td>1.415</td>
<td>4.995</td>
<td>0.650</td>
<td>1.938</td>
<td>374</td>
</tr>
<tr>
<td>CS2U</td>
<td>1.415</td>
<td>2.997</td>
<td>0.650</td>
<td>1.938</td>
<td>374</td>
</tr>
<tr>
<td>CS1U</td>
<td>1.415</td>
<td>0.999</td>
<td>0.650</td>
<td>1.938</td>
<td>374</td>
</tr>
<tr>
<td>CS1L</td>
<td>1.415</td>
<td>-0.999</td>
<td>0.650</td>
<td>1.938</td>
<td>374</td>
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</tr>
<tr>
<td>PF1U</td>
<td>3.109</td>
<td>7.642</td>
<td>1.382</td>
<td>1.111</td>
<td>616</td>
</tr>
<tr>
<td>PF2U</td>
<td>9.400</td>
<td>6.698</td>
<td>0.909</td>
<td>0.909</td>
<td>324</td>
</tr>
<tr>
<td>PF3U</td>
<td>11.554</td>
<td>2.742</td>
<td>0.909</td>
<td>0.909</td>
<td>324</td>
</tr>
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<td>PF1L</td>
<td>3.109</td>
<td>-7.642</td>
<td>1.382</td>
<td>1.111</td>
<td>616</td>
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<td>PF2L</td>
<td>9.400</td>
<td>-6.698</td>
<td>0.909</td>
<td>0.909</td>
<td>324</td>
</tr>
<tr>
<td>DC1</td>
<td>5.459</td>
<td>-7.792</td>
<td>0.909</td>
<td>0.909</td>
<td>324</td>
</tr>
<tr>
<td>DC2</td>
<td>7.640</td>
<td>-7.448</td>
<td>0.909</td>
<td>0.909</td>
<td>324</td>
</tr>
</tbody>
</table>

Additional PF coils **DC1** and **DC2** are designed to form advanced configuration.

![CFETR Geometry](image)
Although the distance between two X points is still far (quasi-snowflake, QSF) due to the limit on the coil currents, increase of flux expansion is significant.

<table>
<thead>
<tr>
<th></th>
<th>Ip [MA]</th>
<th>R[m]</th>
<th>a[m]</th>
<th>βp</th>
<th>δu/δl</th>
<th>κ</th>
<th>Rxpt [m]</th>
<th>Zxpt[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snowflake</td>
<td>10</td>
<td>5.7</td>
<td>1.59</td>
<td>0.80</td>
<td>1.09</td>
<td>0.45/0.67</td>
<td>2.01</td>
<td>4.6372</td>
</tr>
</tbody>
</table>
Divertor Geometry

- Divertor is toroidally divided into 60 modules. Each divertor module is about 10 t and has dimensions of radially 2534 mm, toroidally 640 mm and poloidally 1970 mm.

- The targets and the particle reflectors form two deep ‘V’ corners in the inner and the outer divertor private regions.

- There are gaps kept between the dome and the two particle reflectors as well as going through the cassette at outboard region, for particle pumping and controlling by the cryopump supposed installed on the flange of the lower divertor port.

- Spaces are reserved between the cassette and the VV or the first-wall for the shielding blanket or the diagnostics.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>inner</th>
<th>outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersect angle with LCFS</td>
<td>LSN:25°</td>
<td>LSN:11°</td>
</tr>
<tr>
<td></td>
<td>SF: 30°</td>
<td>SF: 26°</td>
</tr>
<tr>
<td>Distance between X-point and targets (along LCFS) (mm)</td>
<td>LSN:704</td>
<td>LSN:950</td>
</tr>
<tr>
<td></td>
<td>SF: 552</td>
<td>SF: 850</td>
</tr>
<tr>
<td>Distance between X-point and VV (along LCFS) (mm)</td>
<td>LSN:1598</td>
<td>LSN:2650</td>
</tr>
<tr>
<td></td>
<td>SF: 1477</td>
<td>SF:2935</td>
</tr>
<tr>
<td>Distance between cassette and VV (along LCFS) (mm)</td>
<td>LSN:432</td>
<td>LSN:1366</td>
</tr>
<tr>
<td></td>
<td>SF: 430</td>
<td>SF: 1163</td>
</tr>
<tr>
<td>Gap between dome and reflectors (mm)</td>
<td>240</td>
<td>487</td>
</tr>
</tbody>
</table>
Divertor Geometry

SOL width in the OMP

\[ \Delta_1 = \frac{\lambda_{D\perp}}{\lambda_p} \]

\[ \Delta_2 = \frac{\lambda_{D\parallel}}{\lambda_p} \]

- The \( \Delta_2 \) ratio of SF to LSN is \( \sim 1.5 \) for inner target and \( \sim 1.2 \) for outer target, due to the shorter distance between inner target and X-point.

- When local geometry is taking into consideration, flux expansion \( \Delta_1 \) for SF is smaller than that for LSN due to larger intersect angle for SF.
SOLPS Simulation

SOLPS - Scraped-Off Layer Plasma Simulation

2D plasma fluid code: B2.5
3D neutral Monte-Carlo code: EIRENE

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron heat flux into SOL</td>
<td>50 MW</td>
</tr>
<tr>
<td>Ion heat flux into SOL</td>
<td>50 MW</td>
</tr>
<tr>
<td>Electron thermal diffusivities</td>
<td>1.0 m²/s</td>
</tr>
<tr>
<td>Ion thermal diffusivities</td>
<td>1.0 m²/s</td>
</tr>
<tr>
<td>Particle diffusivity</td>
<td>0.3 m²/s</td>
</tr>
<tr>
<td>Pumping speed (nominal)</td>
<td>20 m³/s</td>
</tr>
<tr>
<td>Recycling</td>
<td>1</td>
</tr>
</tbody>
</table>

A **density scan** is performed by using different gas puffing rate

C is used as a substitute for seeding impurity

Separatrix density at OMP increases firstly then decreases when D2 puffing rate is relatively high, while the density at core edge of simulation mesh always increases.

The deposition position of D becomes more and more deep.
Peak heat loads

In consistent with the flux expansion

Great Improvement of $q_{pk}$ on outer divertor for SF
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Impurity Radiation

Electron Temperature

(a) Gas puffing rate: $3 \times 10^{22}\text{s}^{-1}$
(b) Gas puffing rate: $1 \times 10^{23}\text{s}^{-1}$
(c) Gas puffing rate: $2.5 \times 10^{23}\text{s}^{-1}$
(d) Gas puffing rate: $5 \times 10^{23}\text{s}^{-1}$

Impurity Radiation

(a) Gas puffing rate: $3 \times 10^{22}\text{s}^{-1}$
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(c) Gas puffing rate: $2.5 \times 10^{23}\text{s}^{-1}$
(d) Gas puffing rate: $5 \times 10^{23}\text{s}^{-1}$

$p_{\text{imp}} P_{\text{imp.rad}}$ (Wm$^{-3}$)

- $1 \times 10^{7}$
- $5 \times 10^{6}$
- $1 \times 10^{6}$
- $5 \times 10^{5}$
- $1 \times 10^{5}$
- $5 \times 10^{4}$
- $1 \times 10^{4}$
- $5 \times 10^{3}$
- $1 \times 10^{3}$
- $500$
- $100$
- $50$
- $20$
- $10$
- $5$
- $2$
- $1$
- $0.1$
Impurity Screening

**Impurity Density**

(a) Gas puffing rate: $3 \times 10^{22}\text{s}^{-1}$
(b) Gas puffing rate: $1 \times 10^{23}\text{s}^{-1}$
(c) Gas puffing rate: $2.5 \times 10^{23}\text{s}^{-1}$
(d) Gas puffing rate: $5 \times 10^{23}\text{s}^{-1}$

**Impurity Ratio**

(a) Gas puffing rate: $3 \times 10^{22}\text{s}^{-1}$
(b) Gas puffing rate: $1 \times 10^{23}\text{s}^{-1}$
(c) Gas puffing rate: $2.5 \times 10^{23}\text{s}^{-1}$
(d) Gas puffing rate: $5 \times 10^{23}\text{s}^{-1}$
D2 puffing rate
1x10^23 s^{-1}

From XP to target:
- Higher n_{imp}
- Lower T_e

Graphs showing:
- Pressure vs. Distance along SEP
- Ion density vs. Distance along SEP
- Electron Temp. vs. Distance along SEP
Impurity Radiation
SF vs. IL

Larger radiation volume
Higher radiation power density
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Preliminary design of magnetic equilibrium and divertor geometry of QSF divertor for CFETR is performed.

In the density scan SOLPS modelling, a change of divertor operational status is clearly identified from low-recycling regime to detachment. Both inner and outer $q_{pk}$ can be decreased lower than 10 MW/m$^2$ while the impurity ratio is less than 1.5%.

A comparison of out target status between QSF and IL divertor at D2 gas puffing rates of 1x10$^{23}$ s$^{-1}$ indicates the heat loads onto outer target decreases dramatically due to increased radiation volume and impurity density for QSF divertor.
Thanks for your attention !!
\( I = 0.73 B_T^{0.78} q_{cyl}^{1.2} P_{SOL}^{0.1} R^{0.02} = 1.53 \text{ mm} \)

\( \lambda_q \sim 5 \text{ mm} \)