Physics Modeling of FIRE Edge Plasma

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Presented By
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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.
Outline

• UEDGE modeling of the edge plasma, T. Rognlien
• Neutral particle modeling, D. Ruzic
• Erosion/redeposition modeling, J. Brooks
• Disruption specification, J. Wesley
• Particle fueling and pumping requirements
• Summary
<table>
<thead>
<tr>
<th>Case</th>
<th>$P_{\text{fusion}}$</th>
<th>$P_{\text{heat}}$</th>
<th>$P_{\text{divertor}}$</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>200 MW</td>
<td>60 MW</td>
<td>29 MW</td>
<td>18 s</td>
</tr>
<tr>
<td>D-D</td>
<td>5</td>
<td>16</td>
<td>8</td>
<td>214</td>
</tr>
<tr>
<td>AT Mode</td>
<td>150</td>
<td>45</td>
<td>22</td>
<td>31</td>
</tr>
<tr>
<td>High $B_T$</td>
<td>250</td>
<td>75</td>
<td>37</td>
<td>12</td>
</tr>
</tbody>
</table>
• Input parameters
  – Power to the divertor 28 MW
  – Separatrix density $1.5 \times 10^{20}$ /m$^3$
  – Wall recycling coefficient 1.0
  – Three edge transport cases
    • High conductivity $\chi = 1.5$ m$^2$/s $D = 1.0$ m$^2$/s
    • ITER Baseline $\chi = 0.5$ m$^2$/s $D = 1.0$ m$^2$/s
    • Bohm like $\chi = 0.5$ m$^2$/s $D = D_{\text{bohm}} +0.1$
      – $D_{\text{bohm}} = T_e/16$ eB
    – A case with tilted plates and wall pumping of $10^{21}$/s and Bohm like transport
# UEDGE Modeling Results

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_{em}$ (eV)</th>
<th>$\lambda_m$ (cm)</th>
<th>$T_{ep}$ (eV)</th>
<th>$N_{ep}$ ($10^{21}/m^3$)</th>
<th>$Q_p$ (MW/m²)</th>
<th>$\lambda_p$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>106</td>
<td>0.8</td>
<td>1.5</td>
<td>61</td>
<td>5.7</td>
<td>6.5</td>
</tr>
<tr>
<td>B</td>
<td>152</td>
<td>0.6</td>
<td>15</td>
<td>44</td>
<td>25</td>
<td>1.8</td>
</tr>
<tr>
<td>C</td>
<td>138</td>
<td>0.7</td>
<td>14</td>
<td>43</td>
<td>23</td>
<td>2.3</td>
</tr>
<tr>
<td>D</td>
<td>138</td>
<td>0.7</td>
<td>13</td>
<td>52</td>
<td>19</td>
<td>2.5</td>
</tr>
</tbody>
</table>
UEDGE Modeling Results

- The inner divertor is easily detached.
  - Particle flux ~ 1 MW/m²
  - Radiated power flux 1.8 MW/m²
- Addition of Be to the outer divertor cases increases the radiated power to about 5 MW/m² and decreases the particle power to 20 MW/m²
- Addition of 30-35 Torr l/s of Ne to the outer divertor causes detachment (not a steady solution yet).
- Radiated power 80 MW/m³ when detached.
UEDGE Modeling Results
• Inner divertor detaches easily
• Outer divertor heat flux 20-25 MW/m² attached
• Outer divertor can be detached with Ne addition
• Peak radiated power flux on divertor PFC ~6 MW/m²
Neutral Particle Modeling with DEGAS2

- UEDGE plasma solution used as input
- DEGAS2 gives:
  - Neutral flux to walls
  - Neutral energy spectrum to walls
- These outputs are passed on to J. Brooks to do erosion/redeposition modeling
DEGAS2 Results

Inner divertor

Outer divertor

Flux (m\(^{-2}\)s\(^{-1}\))

Distance along plate (m)
Erosion/Redeposition Modeling

• Objective: Compute 1st wall and divertor net erosion rates, plasma contamination, and tritium codeposition, from sputtering.

• Method: Use REDEP/WBC impurity transport code package using FIRE plasma/geometry with DEGAS2 code neutrals calculation and VFTRIM-3D and other sputtering coefficients.

• Completed analysis: Tungsten erosion for divertor outer plate, "pure tungsten" surface, preliminary plasma model.
Erosion/Redeposition Modeling

• Inputs: Outer plate and magnetic field geometry, plasma ion and electron profiles, DEGAS2 neutral flux. 0.1 % oxygen ion flux assumed.

• WBC Monte code used to compute detailed (single-particle, kinetic, sub-gyro motion) characteristics of sputtered tungsten transport. Code includes sputtered atom velocity distribution, electron impact ionization, Lorentz force motion, magnetic/Debye dual-structure sheath, impurity-plasma charge changing and velocity changing collisions.
Erosion/Redeposition Modeling

• WBC redeposition parameters used as input to REDEP (integral equation type) code for computation of self-consistent gross and net erosion rates over entire outer divertor region.
• Results are favorable—essentially zero net erosion and plasma contamination predicted.
Erosion/Redeposition Modeling

- **REDEP Analysis:** Sputtering erosion of a tungsten coated FIRE outer divertor plate for high recycle plasma with 0.1 % oxygen content.

- Net erosion rate is essentially zero due to very high redeposition of sputtered material.
Erosion/Redeposition Summary

• Tungsten is an excellent material choice from the sputtering erosion/redeposition standpoint.
• Most sputtered tungsten is ionized in the (magnetic) sheath. Strong frictional forces and/or sheath electric field then cause very fast ion redeposit.
• There is essentially zero net erosion and plasma contamination.
• Gross tungsten sputtering is due mostly to plasma impurities (oxygen) and self-sputtering, and not plasma fuel ions.
Disruption Specifications

• Based on the database assembled for ITER
• Thermal quench phase
  – 33 MJ plasma stored energy
  – Variation of values from data
  – Uncertainty in understanding
  – Uncertainty in extrapolation to FIRE
  – Range of values specified for FIRE
## Disruption Specifications

<table>
<thead>
<tr>
<th></th>
<th>Low End Flux (MJ/m²)</th>
<th>Reference Flux (MJ/m²)</th>
<th>Most Likely (MJ/m²)</th>
<th>High End Flux (MJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Divertor</td>
<td>8</td>
<td>13.4</td>
<td>31</td>
<td>96</td>
</tr>
<tr>
<td>Outer Divertor</td>
<td>4</td>
<td>6.8</td>
<td>16</td>
<td>48</td>
</tr>
</tbody>
</table>
Disruption Specifications

• Current Quench Phase
  – Magnetic stored energy 35 MJ
  – Current decay time 2-6 ms
  – Average energy deposition to first wall 0.5 MJ/m²
  – Toroidal peaking factor 2:1
  – Thermal modeling predicts <0.1 mm melting of Be per disruption.
Disruption Specifications

• Halo currents
  – The product of maximum halo current and the toroidal peaking factor is constant for the worst case
  – The maximum halo current at the worst location is 200 kA
Particle Fueling and Pumping

- Particle fueling requirements
  - Plasma particle content $10^{22}$
  - Energy confinement time 0.65 s (0.5-0.8 s)
  - Particle confinement $2-10 \tau_E$
  - Fueling efficiency 50%
  - Maximum fueling rate 75 Pa m$^3$/s

- Pumping rate required to remove He
  - Fusion burn rate $10^{20}$/s (200 MW)
  - He fraction in divertor 2% with wall recycling 0.5
  - Pumping rate required 100 Pa m$^3$/s
Summary

• UEDGE modeling predicts 20-25 MW/m² heat flux on the outer divertor
• UEDGE shows the divertors can be detached
• There is no predicted erosion of W divertor plates
• Disruption conditions are specified
• Particle fueling of 75 Pa m³/s is required
• Particle pumping of 100 Pa m³/s is required