FIRE Plasma Facing Components

Pre-Conceptual Design

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Outline

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• Why Choose Double Null?
• UEDGE Modeling Results
• Why Choose W Surface for the Divertor?
• FIRE Divertor Design
• ELMs on FIRE
• Disruption Specifications & Analysis
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Participants

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Divertor Design Requirements

• All PFCs remotely maintained
• Materials selection
  – Divertor W rod surface
  – Water cooled copper alloy heat sinks
  – First wall plasma sprayed Be surface on Cu
• First wall and inner divertor attached to cooled copper skin on vacuum vessel
• Eddy current forces determine the strength of attachments and back plates
• Double null configuration
Why Choose Double Null?

• There are results that indicate vertical stability can be improved by operating the single null plasmas slightly off center vertically. Double null plasmas should be even better.

• Since the PFCs are actively cooled, we can use the power in the coolant to monitor or control up/down ratio. The time constant of the plates is < 1s.

• The average power loading is lower in a double null configuration. We are near the power handling limit.
## Operating Scenarios

<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>150 MW</td>
<td>20 MW</td>
<td>28 MW</td>
<td>20 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>200</td>
<td>45</td>
<td>22</td>
<td>20</td>
</tr>
</tbody>
</table>
## 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/m$^2$)</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 (2%) to the outer divertor cases increases the radiated power to about 6 MW/m² and decreases the particle power to 20 MW/m²
- Addition of Ne to the outer divertor causes partial to full detachment (~12 Mw/m² to ~6 MW/m²)
FIRE Divertor Capability

• Outer divertor
  – Maximum power load 20-25 MW/m²
  – Pulse length unlimited (actively cooled)

• Inner divertor and baffle
  – Maximum power load 1-5 MW/m²
  – Pulse length 10-50 s with passive cooling

• First Wall
  – Power 0.3-0.6 MW/m² for up to 50 s passive cooling
Particle Pumping Requirements

• Loss of particles from the plasma:
  – Number of particles in the plasma $1 \times 10^{22}$
  – Energy confinement time 0.5-0.8 s (use 0.65 s)
  – Particle confinement time 2-10 $\tau_E$
  – Fueling rate required $3.1 \times 10^{21}$/s (1.25-10 $\times 10^{21}$/s)
  – Assuming the fueling efficiency is 50% implies $6.2 \times 10^{21}$/s (23 Pa m$^3$/s; range 10-75 Pa m$^3$/s)

• Recommendation 75 Pa m$^3$/s maximum fueling rate (net equal D and T)
Particle Pumping Requirements

• Particle pumping rate required for He removal
  – Fusion burn rate $1 \times 10^{20}/s$ (200 MW)
  – He fraction in the divertor 0.02
  – Wall recycling coefficient 0.5
  – Required divertor pumping is $1.4-2.7 \times 10^{22}/s$ (50-100 Pa $m^3/s$)
  – Very similar to the previous estimate

• Recommendation provide pumping for up to 100 Pa $m^3/s$
Why Choose W Surface for the Divertor?

- Both TFTR and JET have observed large amounts of T retention in redeposited carbon layers and dust (substantial amounts far from the divertor)
- Mechanisms involving hydrocarbon radical transport were presented at PSI
- There is no effective method for removing these layers
- Predicted tritium inventories are mg per burn second
Why Choose W Surface for the Divertor?

• Tungsten or Molybdenum have been successfully used on ASDEX-U and C-Mod
• The results of the ITER development program have shown W on Cu can withstand up to 25 MW/m² without damage
• High Z materials have very low predicted erosion and low T retention
FIRE Divertor Design

- Pumping slot
- Outer divertor
- Coolant manifold
- Passive plate
- Inner divertor
- Baffle
- Plasma X-point
Tungsten Rod PFC Design

Rods 7 mm long

Dimensions:
- Height: 32 mm
- Width: 100 mm
ELMs on FIRE

• ELM Energy Deposition on the FIRE Divertor Plates assumed
  – Either 2% or 5% of stored energy lost
  – Energy deposited over either the same footprint as normal operation or a greater area up to three times larger
  – The duration of the ELM was between 0.1 and 1 ms
• ELMS are no problem if no surface melting occurs
ELMs on FIRE

• Melting will not occur if the energy deposition is less than the intersection of the temperature rise curve and the normal operating line

• Most of the 2% cases are acceptable, few of the 5% cases are acceptable
  – Limit for 0.1 ms duration is about 0.3 MJ/m² (partially detached operation, 12 MW/m²)
  – Limit for 1.0 ms duration is about 1.0 MJ/m² (partially detached operation, 12 MW/m²)

• We must reduce the magnitude of ELMs
ELM Analysis For FIRE

- Normal Heat Flux
  - 6 MW/m²
  - 12 MW/m²
  - 25 MW/m²

- ELM Loss
  - 2% ELM Loss
  - 5% ELM Loss

Temperature Rise (°C) vs. Energy Density (MJ/m²)
Possibilities for ELM Mitigation

• Report - G Saibene – EFPW 2001

• At high density (nped >70% nGR), ELMs losses can become purely convective (particle ELMs), with $\nabla T_{ELM}\sim 0$: minimum Type I?

• Total suppression of Type I ELMs in JT-60U, AUG & DIII-D QDB, partial in JET & DIII-D. C-Mod is a special case (no Type I ELMs!)
  – Conditions of access vary: high $\delta$ is required (possibly $q_{95} >3.5$)
  – High $\beta_p$ (JT60-U) and proximity to DN (ASDEX-U, JT60-U?)
  – Key requirement: high edge shear!!
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.
Halo Currents

• Taking either a peaked or a uniform distribution gives the same halo current in the worst location.
• For 16 divertor modules the maximum halo current is 200 kA.
• Module size
  – Inner poloidal length: 0.58 m current path: 0.14 m
  – Outer poloidal length: 0.68 m current path: 0.41 m
• The force exerted on a module is
  – Inner: 0.3 MN
  – Outer: 0.77 MN
PC-Opera Capabilities

• Calculates the vector potential given an array of current carrying filaments and materials (including magnetic materials)
• Fully 3-D version
• The TSC model of VDE has about 1400 current filaments
• The FIRE geometry requires about 15,000 elements for a proper description
• Time dependent current drive capability used.
PC Opera Model
t=0.303 s, Passive Plates
PFCs VDE $t = 0.303$ s
Outer Divertor Plate VDE

Force

Eddy Current
Inner Divertor & Baffle $t = 0.302$

Note current loops through thickness.
Disruption Mitigation

• There have been several important developments concerning disruption prediction in the last ~4 yrs
  – Several groups have developed a neural network that predicts a disruption is about to occur
    • the networks have predicted disruptions with 50 ms warning and an accuracy >90% with <5% false alarms
  – The networks require training to properly use the diagnostics available
    – This is sufficient warning to take action to mitigate the effects of a disruption
• Massive gas puff has mitigated disruptions on DIII-D
Summary

- Addition of neon to the outer divertor channel can help control divertor heat loads.
- Type I ELMs are a life limiting phenomenon for the outer divertor. Additional R&D on mitigation methods is needed.
- Highly radiative disruptions (i.e., mitigated with gas puff) are likely to cause slight melting of the Be first wall.
- At the pre-conceptual design level the stresses in the divertor structure are acceptable.