Design of the FIRE Plasma Facing Components

Presented to the NSO PAC

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Presented By
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Outline

- Divertor hardware designs
- Actively cooled outer divertor and baffle design
- First wall and inner divertor design
- Disruption effects
- Important results for disruption mitigation
- Summary
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
• First wall and inner divertor attached to cooled copper skin on vacuum vessel
• Eddy current forces determine the strength of attachments and back plates
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
Thermal Testing of W Rod Mockup

Thermal Response

![Graph showing Thermal Response with q'' (W/cm²) on the x-axis and Ts (°C) on the y-axis.](image)
W Rod Test Articles
Outer Divertor Design
Outer Divertor Design

Copper-alloy finger plates

Stainless Support Structure

Press-Fit Pins
Backside of Outer Divertor

- Fixed Brackets Engage Pins that Attach to Vessel
- Pins Retract into Solid Lower Half of Annular Coolant Line Interface
- Vacuum Port Envelope
- Radial Drive Shaft Locations
Outer Divertor Attachment
Baffle Design
Thermal Analysis of PFCs

• Driemeyer (Boeing) and Baxi (GA) have performed thermal analysis of the divertor design
• The outer divertor is actively cooled with a swirl tape in the cooling channel in the copper heat sink
• The baffle is actively cooled but there is no heat transfer enhancement in the cooling channel
• The inner divertor and first wall are attached to the cooled copper liner in the vacuum vessel
## Thermal Analysis of PFCs

<table>
<thead>
<tr>
<th>Divertor Module Parameter</th>
<th>Inner (MW)</th>
<th>Baffle (MW)</th>
<th>Outer (MW)</th>
<th>Inner (MW)</th>
<th>Baffle (MW)</th>
<th>Outer (MW)</th>
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<td>Total Power Distribution</td>
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<td>0.0437</td>
<td>0.0076</td>
<td>0.0476</td>
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<td>Module Mass (kg)</td>
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<td>67.7</td>
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<td>Pulse Length (sec)</td>
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<td>Module Volume (m³)</td>
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<td>0.0076</td>
<td>0.0476</td>
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<td>Initial Temperature (°C)</td>
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<td>30</td>
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</table>
Thermal Analysis of PFCs
Cooled Cu Shell on VV

- Double layer VV (SS)
- Copper layer with cooling channels
Design of 1st Wall and Inner Divertor
Thermal Analysis of PFCs

10-mm W, 30-mm Cu Inner Divertor Temperature for 100 W/cm² Incident Heat Flux

- Front Surface
- Rear Surface

No Conduction to Heat Sink

1.0 W/cm²-K Contact with 30°C Heat Sink
Analysis of Disruption Thermal Loads

• Hassanein (ANL) used the A*Thermal code to determine the melting and vaporization of W due to thermal loads during disruptions
• Energy deposition was taken from Wesley’s analysis
• Melting begins $10\mu s$ after the disruption begins
• Vaporization begins $15\mu s$ later than melting
• The amount of vaporized material is limited by vapor shielding
Analysis of Disruption Heating
Analysis of Disruption Heating

[Graph showing the analysis of disruption heating with lines representing different energy densities for Tungsten. The graph plots Melt Layer Thickness in μm against Disruption Time in ms.]
PFC Lifetime Due To Disruption Erosion

- Vapor loss
- Melt loss

Lifetime (disrupt) vs. W Thickness (mm)
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
Eddy Currents

- Current decay rate: 3 MA/ms
- Current decay duration: 2.2 ms for 6.5 MA
- B field makes a shallow angle with the outer divertor
- Average B on outer divertor is 0.5 Tesla
- Flux cutting the plate is 0.23 Webers
- Flux change is -104.5 Webers/s
- The estimated resistance of the plate is 18 $\mu \Omega$
- The L/R time is about 0.04 s
- The peak induced current is about 300 kA inductively
Eddy Currents

• Average B on inner divertor is 2.1 Tesla
• Flux cutting the plate is 0.43 Webers
• Flux change is -200 Webers/s
• The estimated resistance of the plate is 11 μΩ
• The L/R time is about 0.023 s
• The peak induced current is about 750 kA inductively
Eddy Currents

- There is also a loop formed between the legs of the outer divertor supports.
- This loop is slightly smaller than the loop on the surface and it is all stainless steel.
- The loop resistance is about 0.17 mΩ and the L/R time is about 3 ms (resistive effects will limit the current).
- This loop can be broken by insulating one of the legs (easy to do).
Eddy Currents

• The force on the edge of an outer plate is about 1.9 MN
• The force on the edge of an inner plate is about 2.8 MN
• This is a 2.5 times the halo load for the outer and 8.5 times the inner halo load

• Mitigating factors
  – The copper surface is not continuous
  – The stainless steel backing will need to be slotted
  – The convoluted path will add resistance
Eddy Current Stress Analysis

- Driemeyer (Boeing) has applied the disruption loads to the outer divertor structure and calculated the stresses in the backing plate and the mounting structures.
- The disruption stresses dominate all the other loads and determine the thickness of the backplate and mounts.
- Reduction of disruption loads would allow simplification of the design, use of cheaper materials, and save cost during fabrication.
Eddy Current Induced Stresses
Recent Results on Disruption Mitigation

• At the PSI Meeting in May there were several important papers concerning disruption prediction
  – The ASDEX group has developed a neural network that predicts the time before a disruption
    • the network has predicted disruptions with 50 ms warning and an accuracy >90% with <5% false alarms
  – A similar technique has been used on JET with good results
• This is sufficient warning to take action to mitigate the effects of a disruption
Liquid Jets for Disruption Mitigation

The liquid core of the jet is clouded by mist that surrounds the jet. This jet is traveling in air, but the next phase of the work will be into a vacuum.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DIII-D Goal</th>
<th>Achieved to Date</th>
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<tbody>
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<td>Reynolds No.</td>
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<td>Weber No.</td>
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<tr>
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</table>

360 m/s Water Jet
Summary

• A pre-conceptual design has been completed for the FIRE PFCs
• The outer divertor and baffle are actively cooled
• The first wall and inner divertor are attached to a cooled copper skin on the vacuum vessel
• Disruptions are the strongest driver in the PFC design
• A new technique for predicting disruptions has been developed that offers the potential for mitigation of disruption effects
Summary

• The divertor design is sufficient for all proposed operating modes for FIRE
• The life limiting events for the PFCs are disruptions
• Disruptions also determine the design of the backplates and mounting features
• New results suggest disruptions may be able to be mitigated