Design of the FIRE Plasma Facing Components

Presented to the NSO PAC

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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.

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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

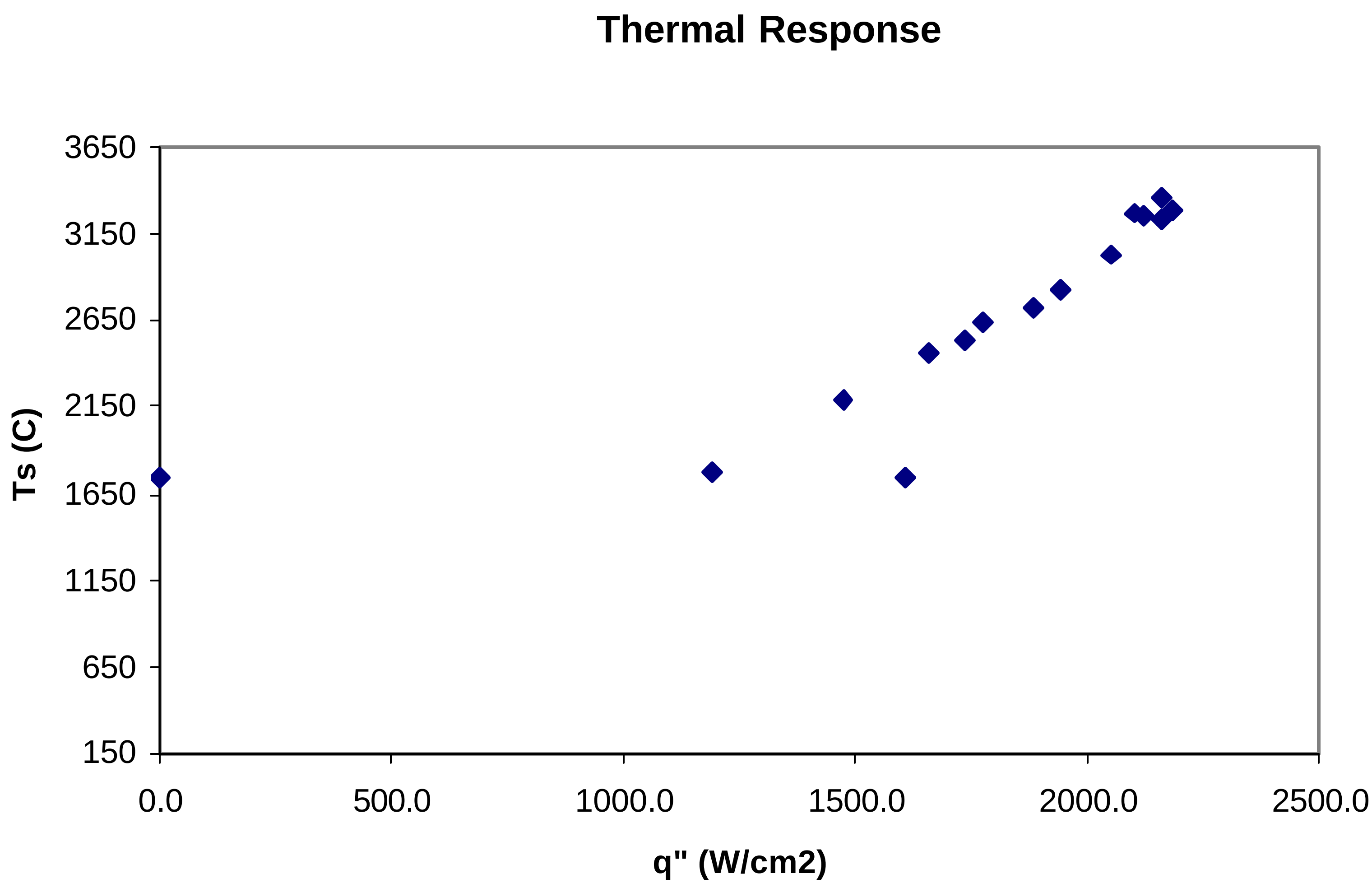
Why Choose W Surface for the Divertor?

- 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

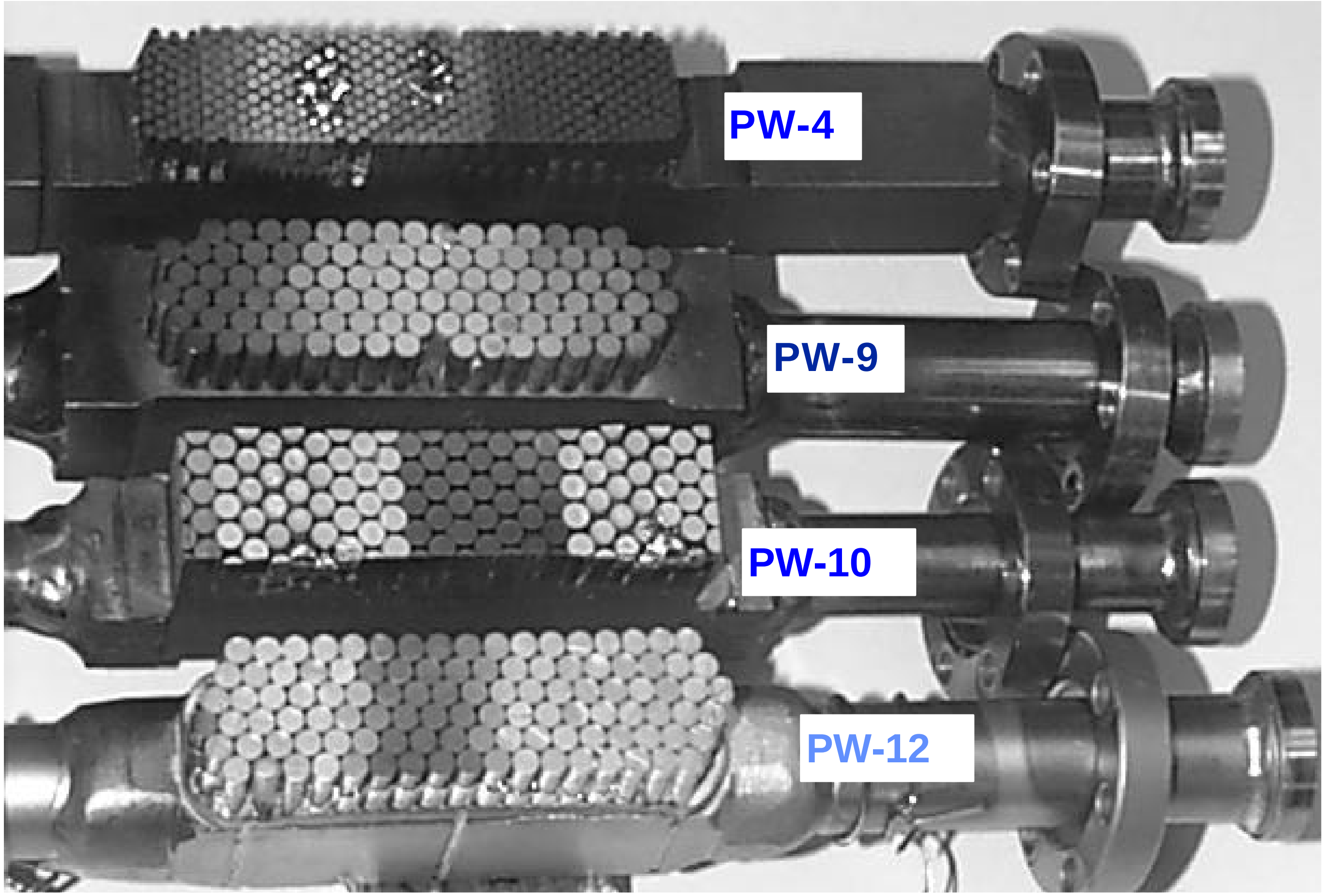
Why Choose W Surface for the Divertor?

- 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/m^2 without damage
- High Z materials have very low predicted erosion and low T retention

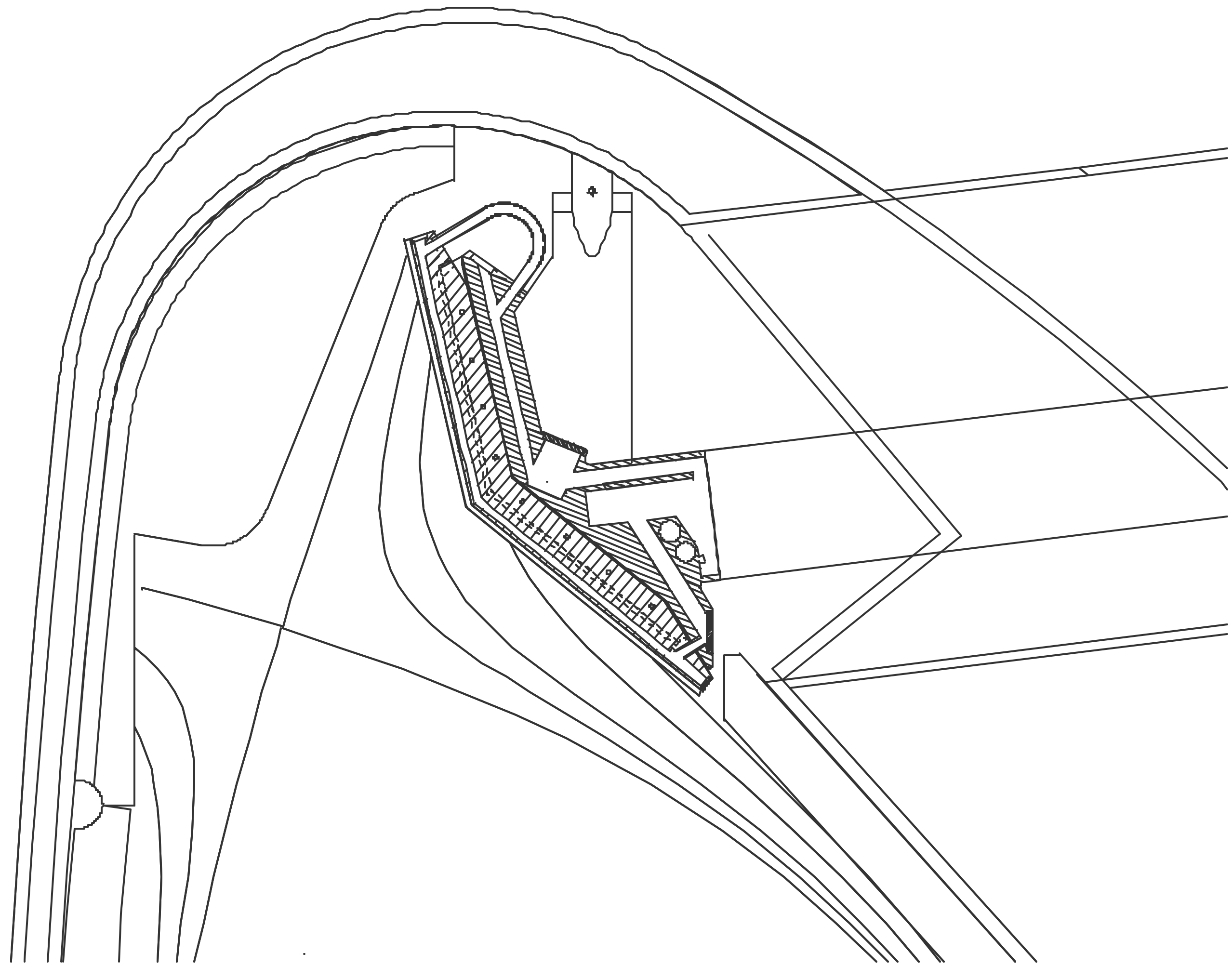
Thermal Testing of W Rod Mockup



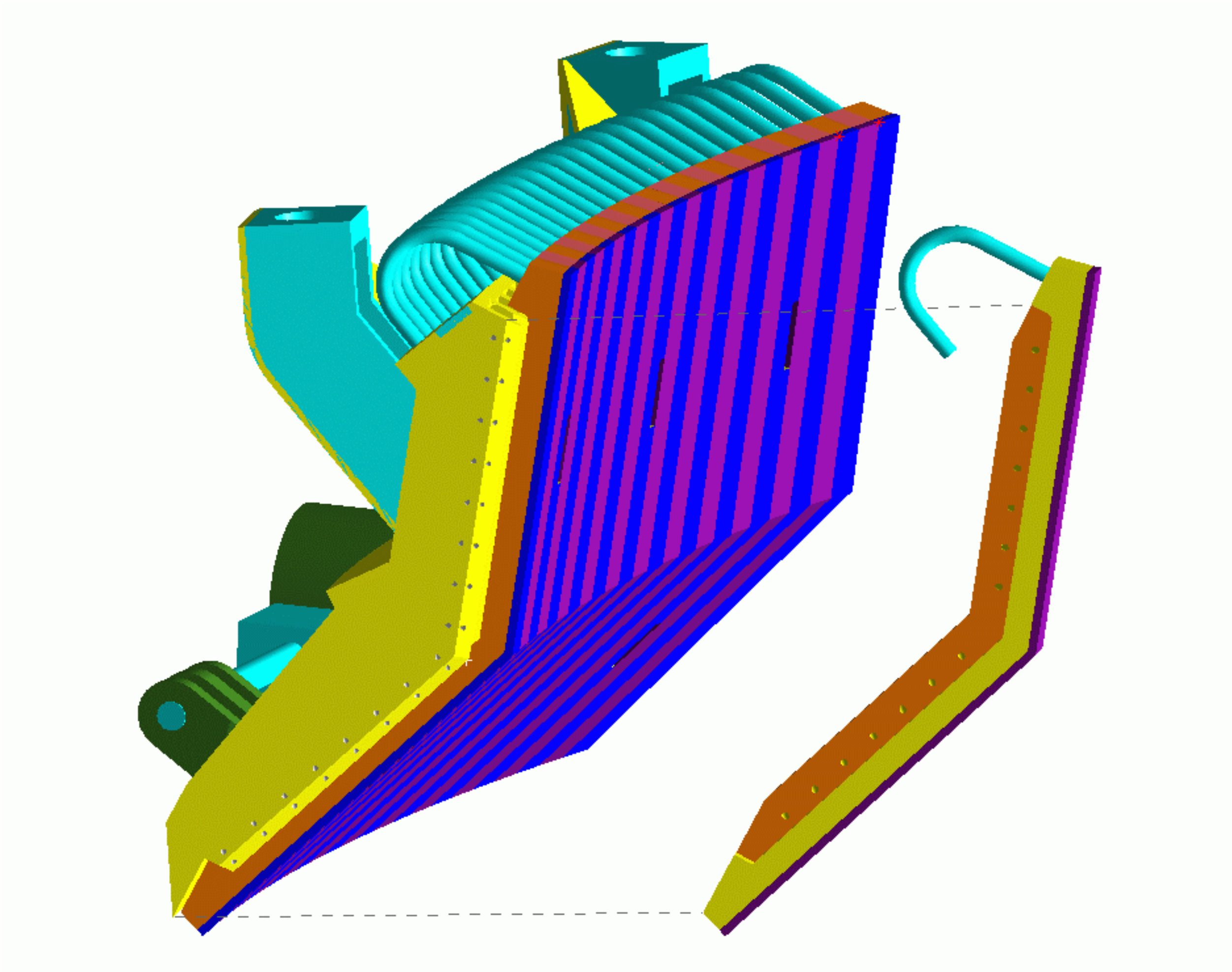
W Rod Test Articles



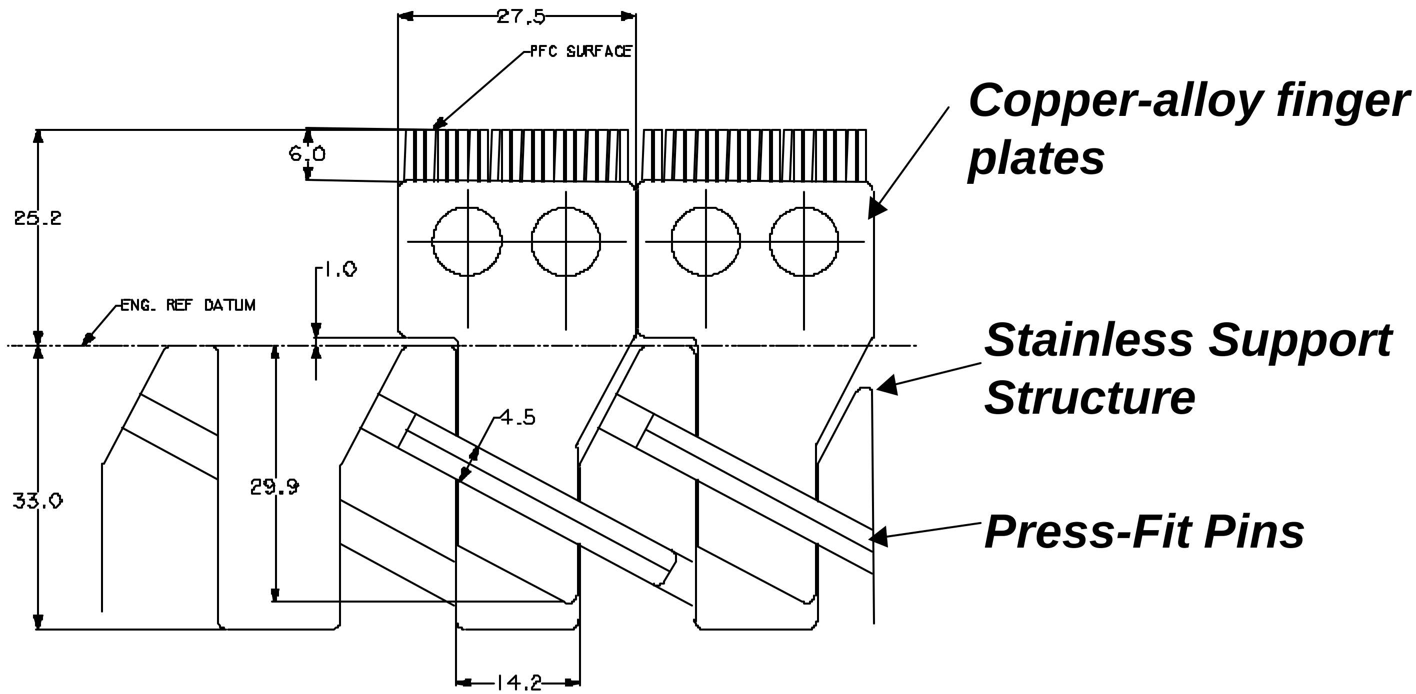
FIRE Divertor Design



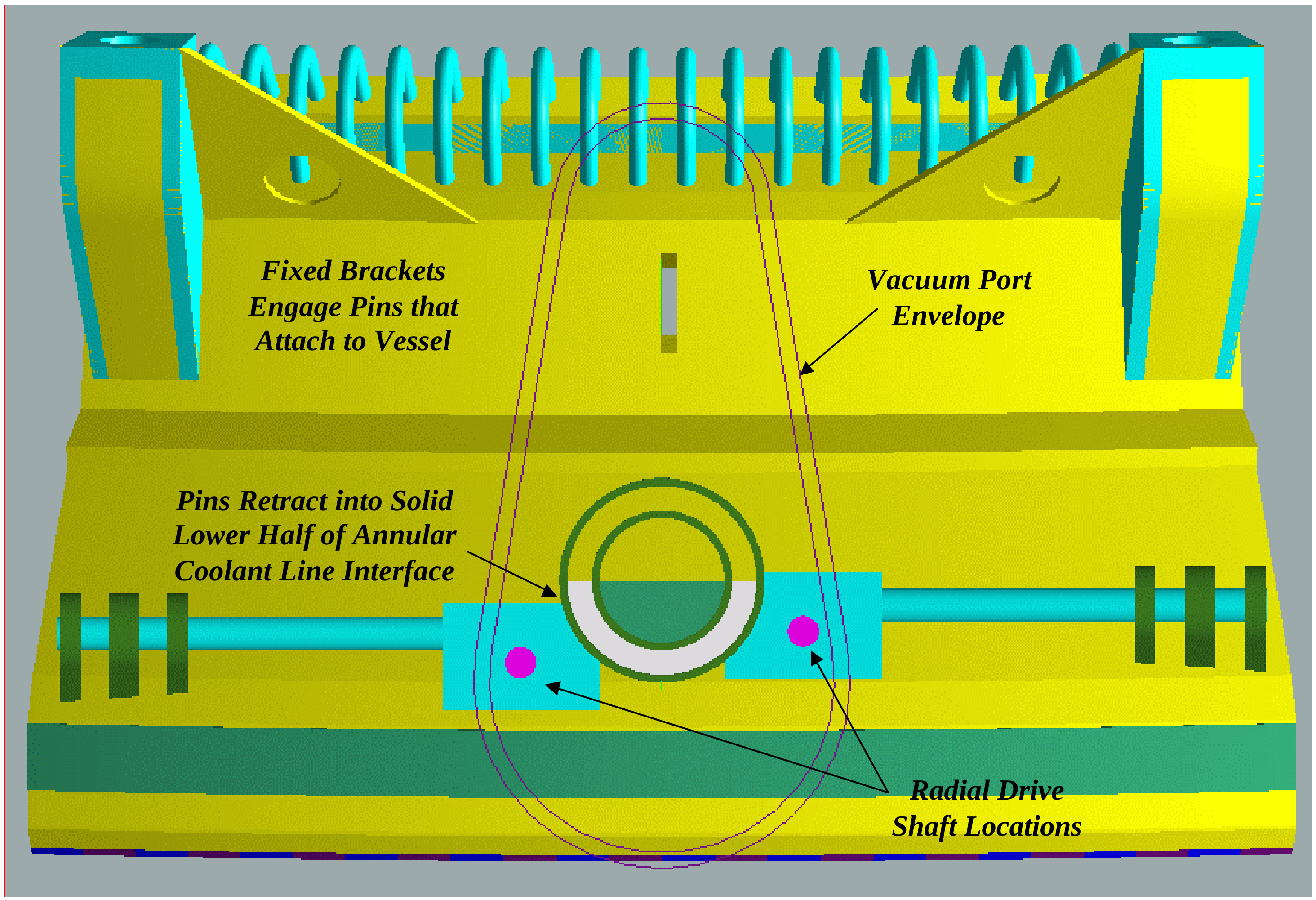
Outer Divertor Design



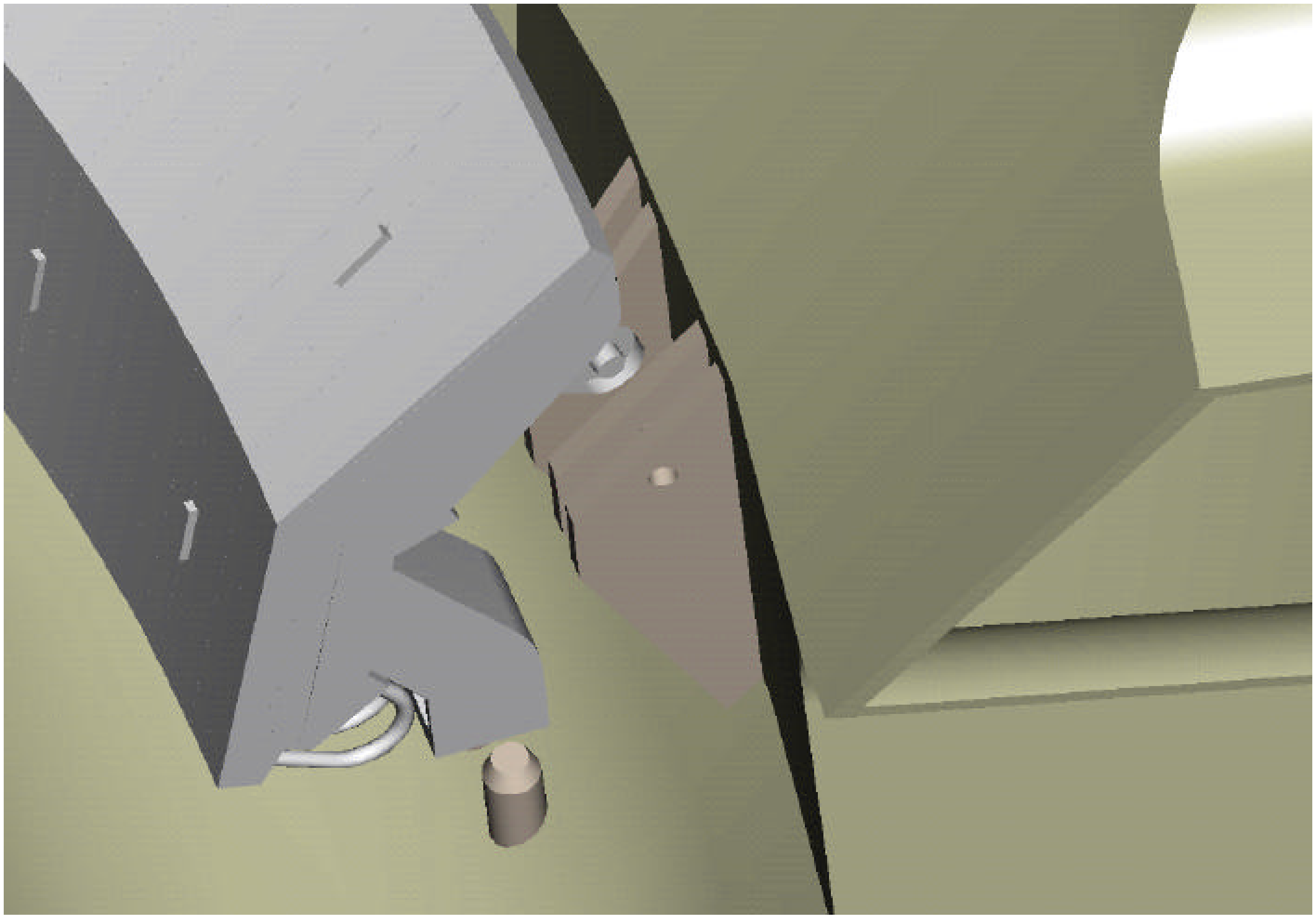
Outer Divertor Design



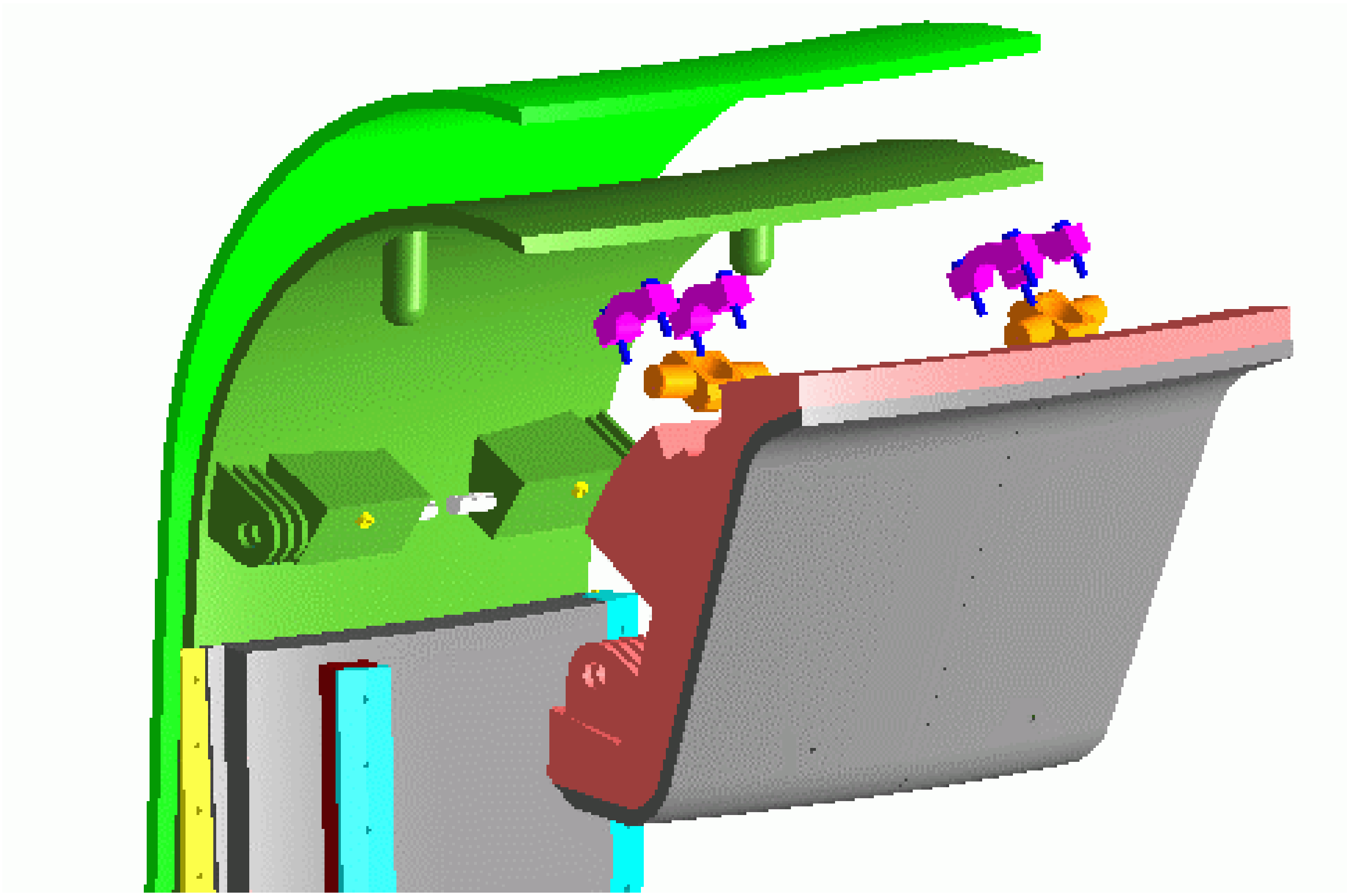
Backside of Outer Divertor



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

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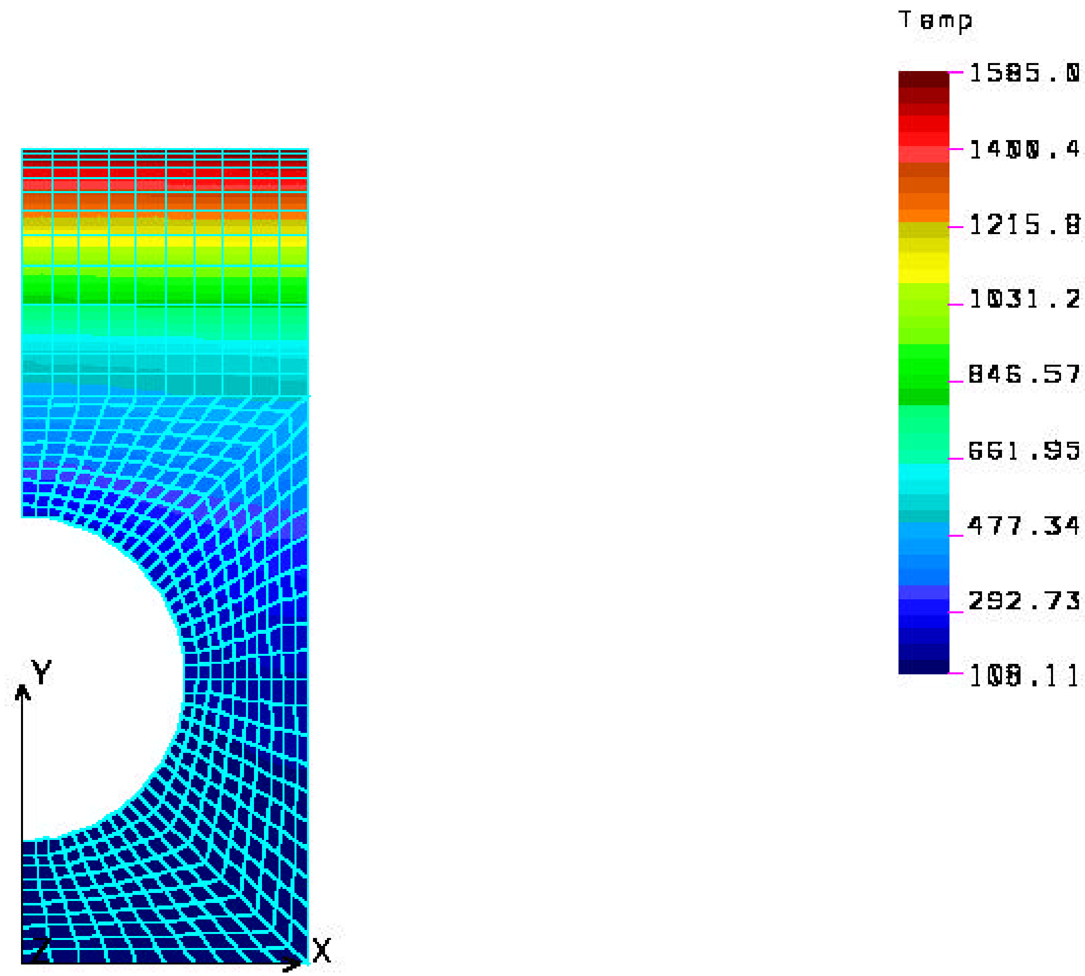
Thermal Analysis of PFCs

	10 T Baseline (52 MW, 18 sec)			12 T Mode (66 MW, 12 sec)		
Divertor Module Parameter	**Inner**	**Baffle**	**Outer**	**Inner**	**Baffle**	**Outer**
Total Power Distribution (MW)	8.3	10.4	33.3	10.6	13.2	42.2
Avg Power to Module (MW)	0.26	0.33	1.04	0.33	0.41	1.32
Peak Power to Module (MW)	0.45	0.56	2.25	0.57	0.71	2.85
Pulse Length (sec)	18	18	18	12	12	12
Max Total Energy Input (MJ)	8.1	10.1	40.4	6.8	8.6	34.2
Module Volume (m^3)	0.0076	0.0476	0.0437	0.0076	0.0476	0.0437
Module Mass (kg)	67.7	339.2	388.5	67.7	339.2	388.5
Initial Temperature (°C)	30	30	30	30	30	30
Average Final Temp (°C)	122	105	–	101	93	–
Front (W) Surface Temp (°C)	220	250	–	193	193	–
Rear Surface Temp (°C)	92	–	–	75	–	–

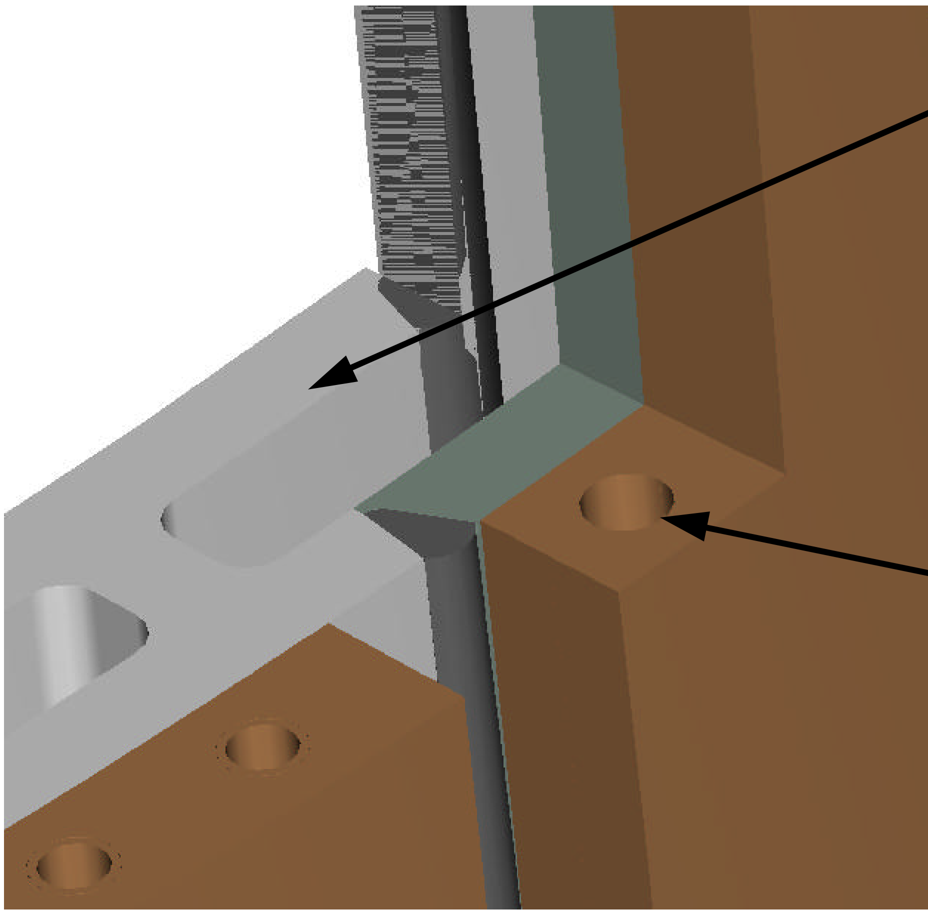
Thermal Analysis of PFCs

	Long Pulse (17 MW, 215 sec)			Long Burn (44 MW, 31 sec)		
Divertor Module Parameter	**Inner**	**Baffle**	**Outer**	**Inner**	**Baffle**	**Outer**
Total Power Distribution (MW)	2.7	3.4	11.0	7.0	8.8	28.2
Avg Power to Module (MW)	0.09	0.11	0.34	0.22	0.28	0.88
Peak Power to Module (MW)	0.15	0.18	0.74	0.38	0.48	1.90
Pulse Length (sec)	215	215	215	31	31	31
Max Total Energy Input (MJ)	31.8	39.8	159.1	11.8	14.7	58.9
Module Volume (m^3)	0.0076	0.0476	0.0437	0.0076	0.0476	0.0437
Module Mass (kg)	67.7	339.2	388.5	67.7	339.2	388.5
Initial Temperature (°C)	30	30	30	30	30	30
Average Final Temp (°C)	100	325	–	146	139	–
Front (W) Surface Temp (°C)	153	>700	–	251	350	–
Rear Surface Temp (°C)	80	–	–	112	–	–

Thermal Analysis of PFCs



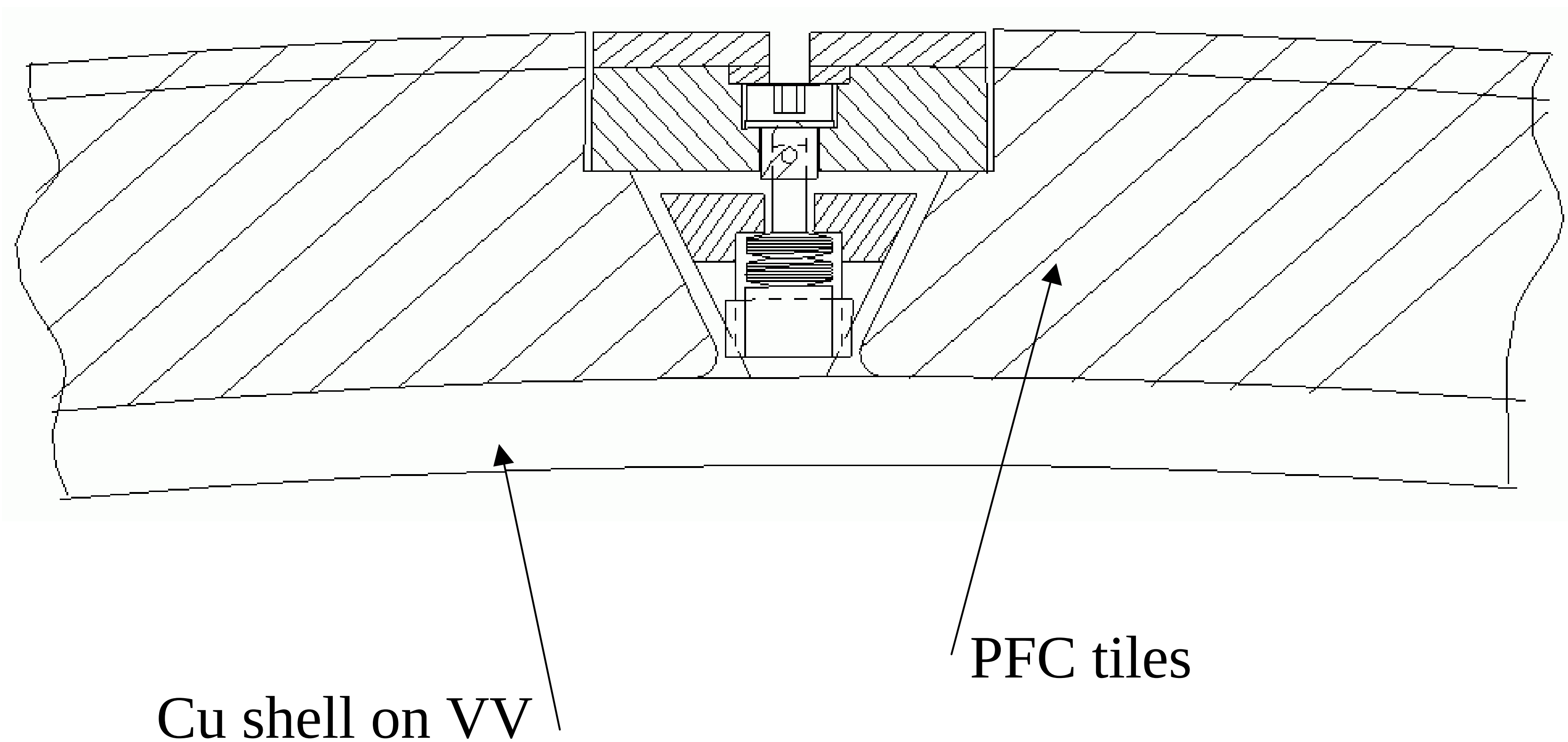
Cooled Cu Shell on VV



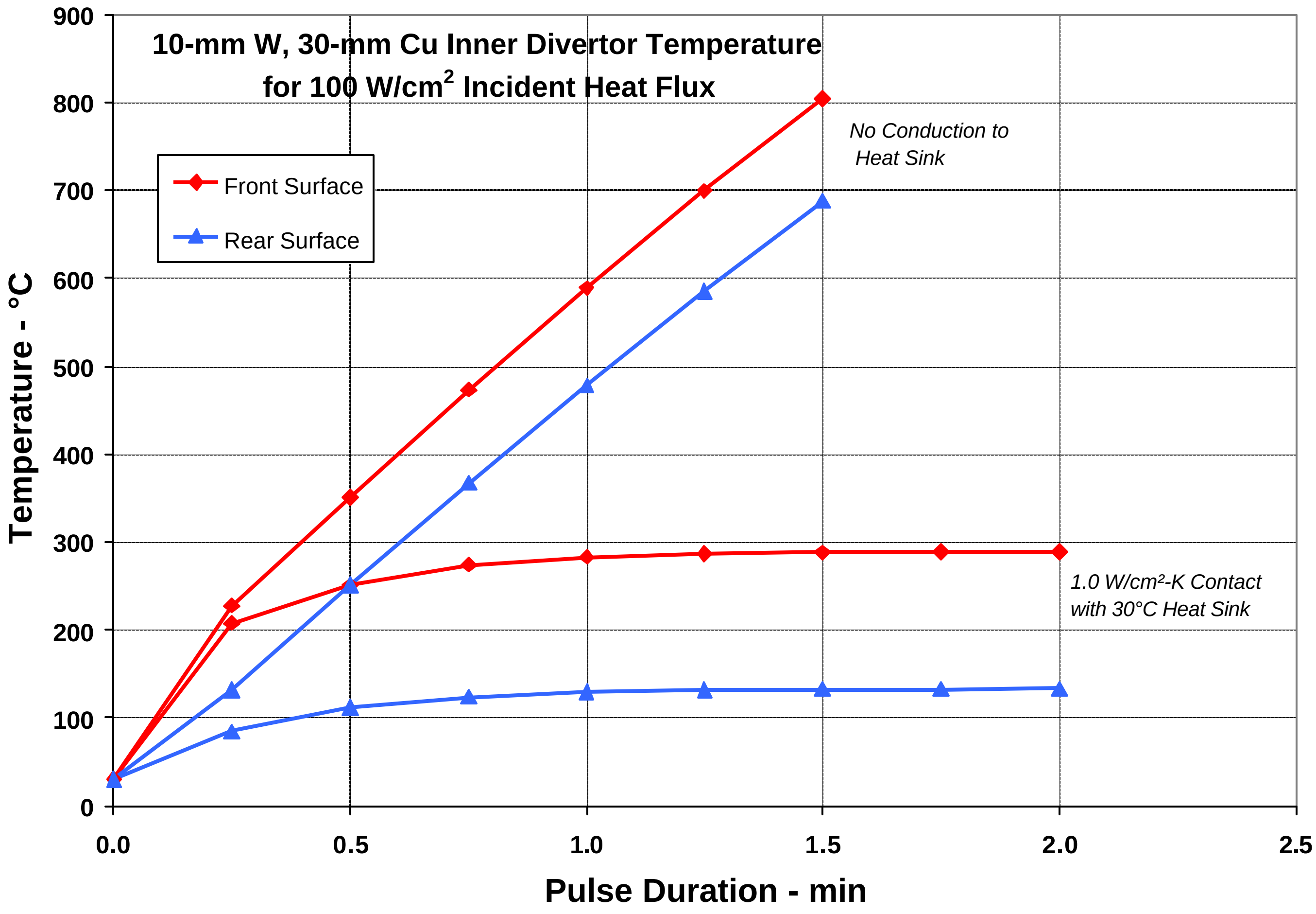
Double layer VV (SS)

Copper layer with cooling channels

Design of 1st Wall and Inner Divertor



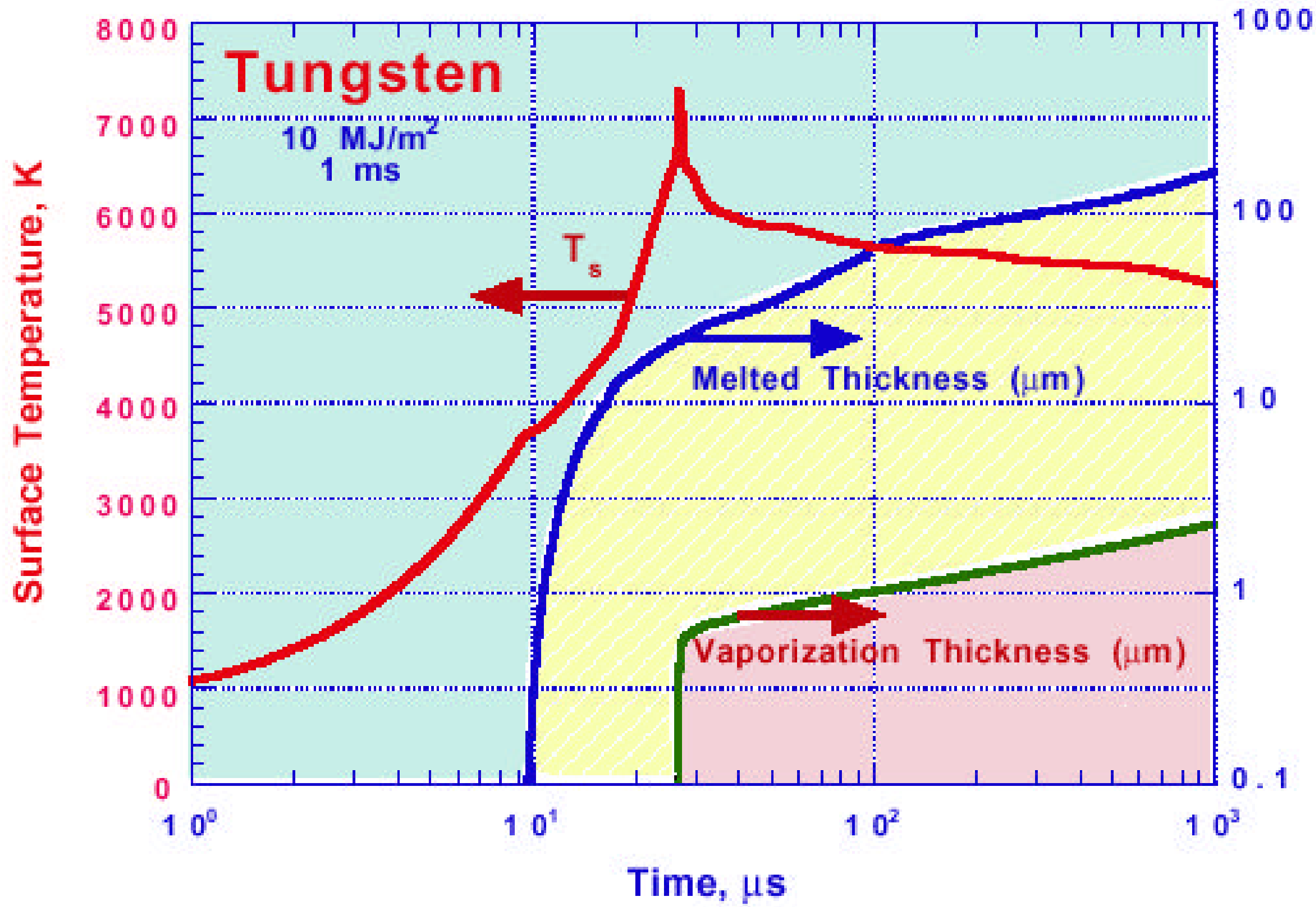
Thermal Analysis of PFCs



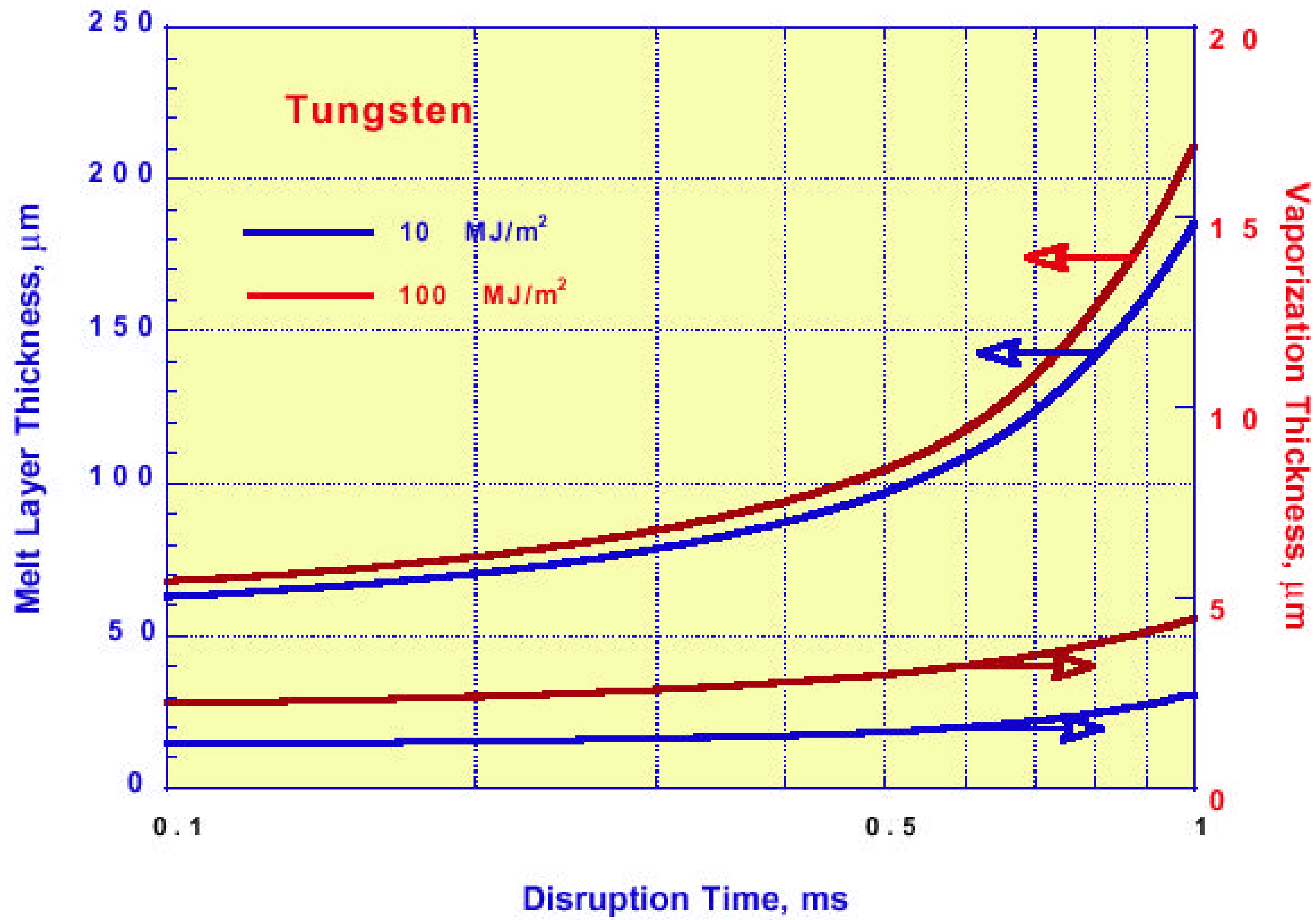
Analysis of Disruption Thermal Loads

- 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 10μs after the disruption begins
- Vaporization begins 15 μs later than melting
- The amount of vaporized material is limited by vapor shielding

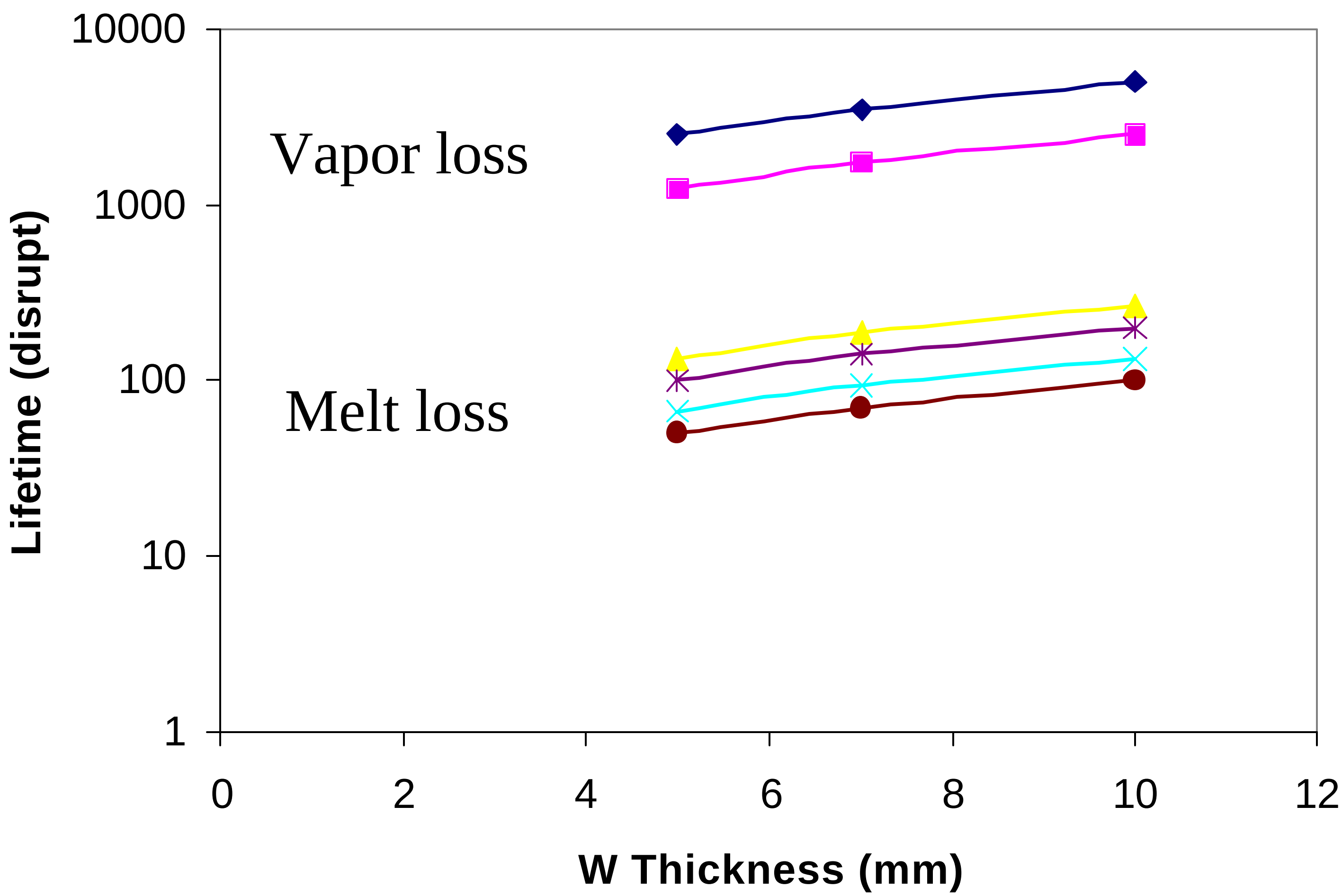
Analysis of Disruption Heating



Analysis of Disruption Heating



PFC Lifetime Due To Disruption Erosion



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

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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** mW
- **The L/R time is about 0.04 s**
- **The peak induced current is about 300 kA inductively**

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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 mW
- 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 .17 mW 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).

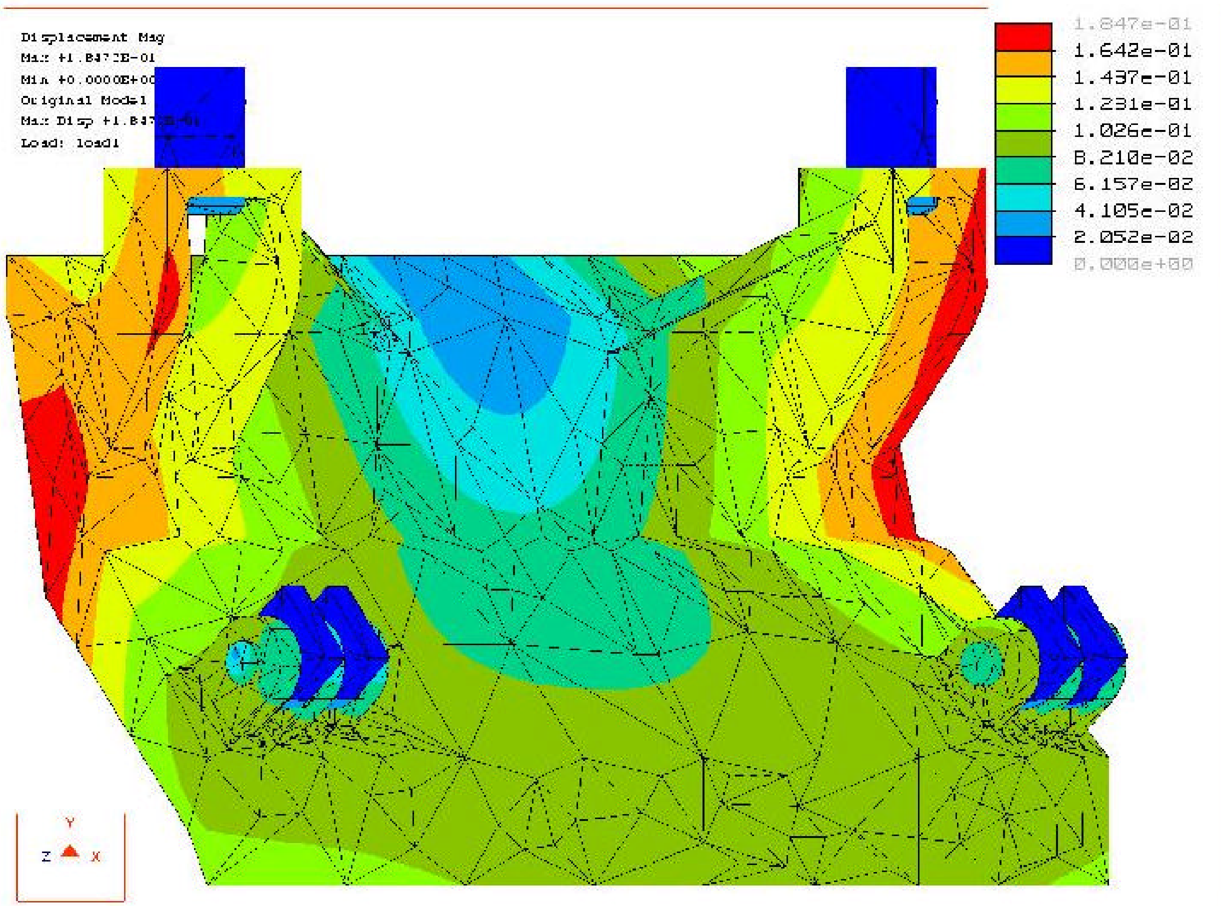
Eddy Currents

- 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



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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**

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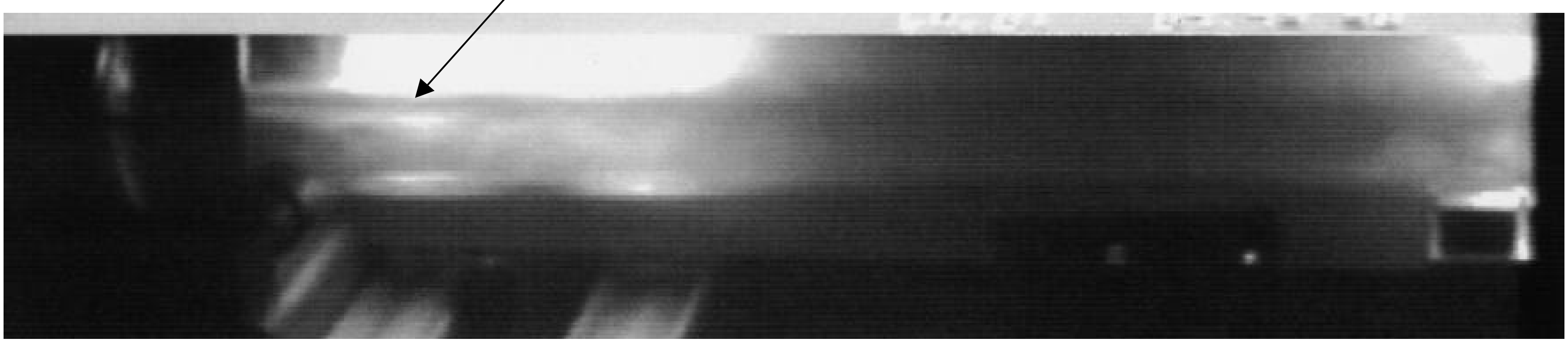
Liquid Jets for Disruption Mitigation

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.

Parameter	DIII-D Goal	Achieved to Date
Reynolds No.	**1.2E6**	**8.2E5**
Weber No.	**7.6E6**	**3.7E6**
Jet L/D	**2000**	**1000**

360 m/s Water Jet



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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

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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