Divertor and Plasma Facing Components

Requirements and Design

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Presented at the FIRE Review

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
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Outline

- Requirements
  - Plasma edge modeling results
  - Disruption conditions
- Plasma Facing Components
  - Materials selection
  - Outer divertor and Baffle
  - Inner divertor
  - First Wall
- Prototype testing results

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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
- 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 keep power balance. 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

Case	P_{fusion}	P_{heat}	$P_{divertor}$	Duration
Baseline	200 MW	60 MW	29 MW	18 s
D-D	5	16	8	214
AT Mode	150	45	22	31
High B_T	250	75	37	12

UEDGE Modeling

- Input parameters
  - Power to the divertor 28 MW
  - Separatrix density 1.5 x 10^{20} /m^3
  - Wall recycling coefficient 1.0
  - Three edge transport cases
    - High conductivity χ = 1.5 m^2/s D = 1.0 m^2/s
    - ITER Baseline χ = 0.5 m^2/s D = 1.0 m^2/s
    - Bohm like χ = 0.5 m^2/s D = D_{bohm} +0.1
      - $D_{bohm} = T_e/16\ eB$
  - A case with tilted plates and wall pumping of 10^{21}/s and Bohm like transport

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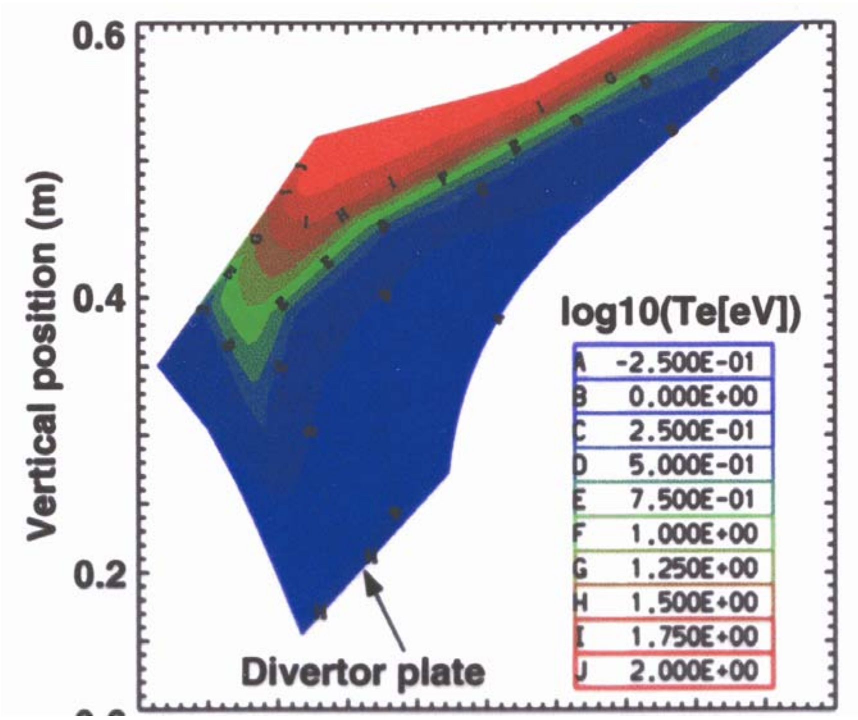
UEDGE Modeling Results

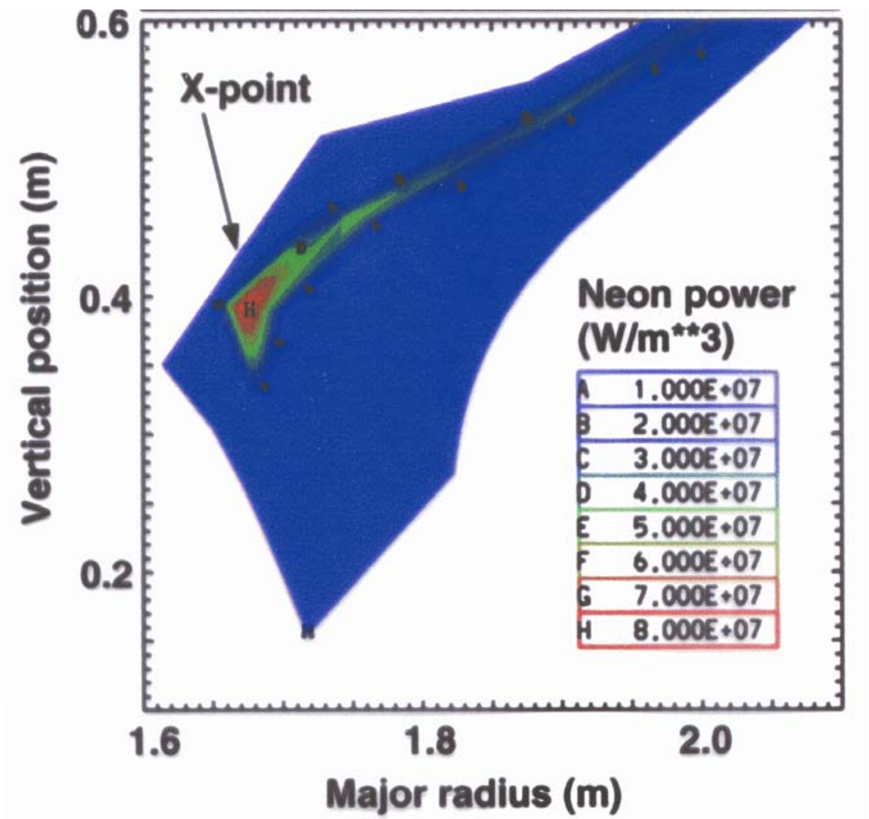
Case	Te_m (eV)	λ_m (cm)	Te_p (eV)	Ne_p ($10^{21}/m^3$)	Q_p (MW/m^2)	λ_p (cm)
A	106	0.8	1.5	61	5.7	6.5
B	152	0.6	15	44	25	1.8
C	138	0.7	14	43	23	2.3
D	138	0.7	13	52	19	2.5

UEDGE Modeling Results

- The inner divertor is easily detached.
  - Particle flux ~ 1 MW/m^2
  - Radiated power flux 1.8 MW/m^2
- Addition of Be (2%) to the outer divertor cases increases the radiated power to about 5 MW/m^2 and decreases the particle power to 20 MW/m^2
- Addition of 30-35 Torr l/s of Ne to the outer divertor causes detachment (not a steady solution yet).
- Radiated power 80 MW/m^3 when detached.

UEDGE Modeling Results





UEDGE Modeling Summary

- Inner divertor detaches easily
- Outer divertor heat flux 20-25 MW/m^2 attached (Very similar to ITER design requirements)
- Outer divertor can be detached with Ne addition
- Peak radiated power flux on divertor PFC ~6 MW/m^2
- All of these conditions are typical of all of the burning plasma devices considered over the past 5-7 years.

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FIRE Divertor Capability

- **Outer divertor**
  - **Maximum power load 20-25 MW/m^2**
  - **Pulse length unlimited (actively cooled)**
- **Inner divertor and baffle**
  - **Maximum power load 1-5 MW/m^2**
  - **Pulse length 10-50 s with passive cooling**
- **First Wall**
  - **Power 0.3-0.6 MW/m^2 for up to 50 s passive cooling**

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

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

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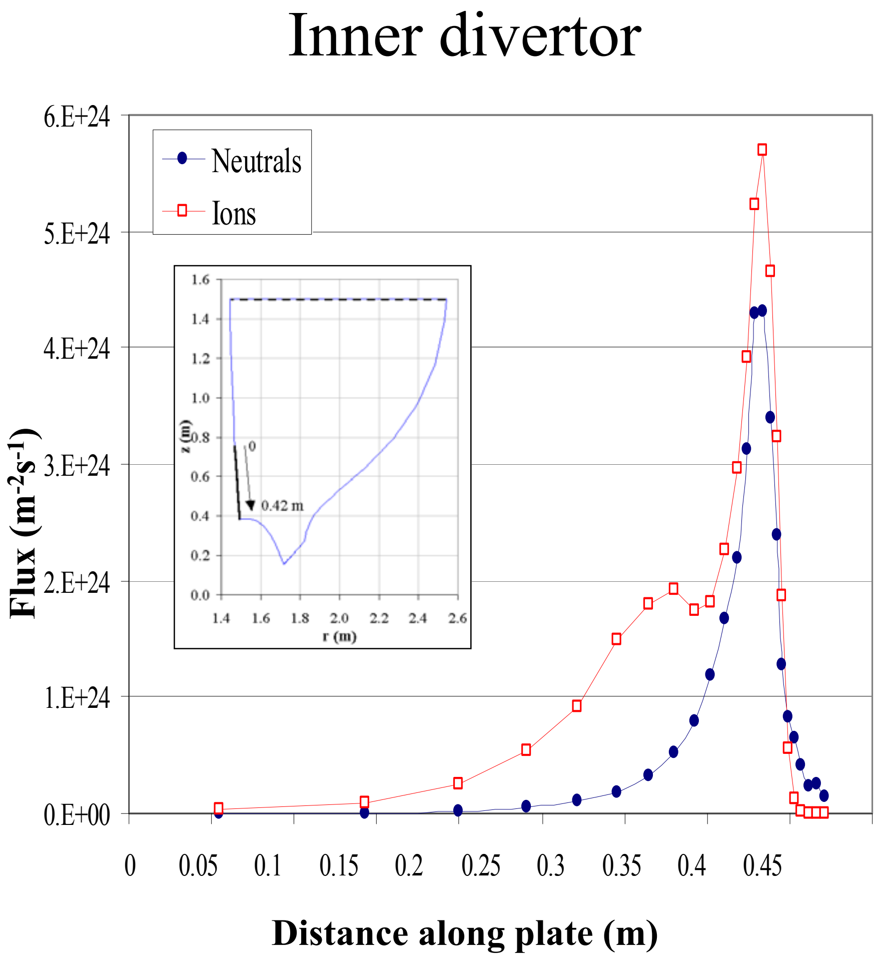
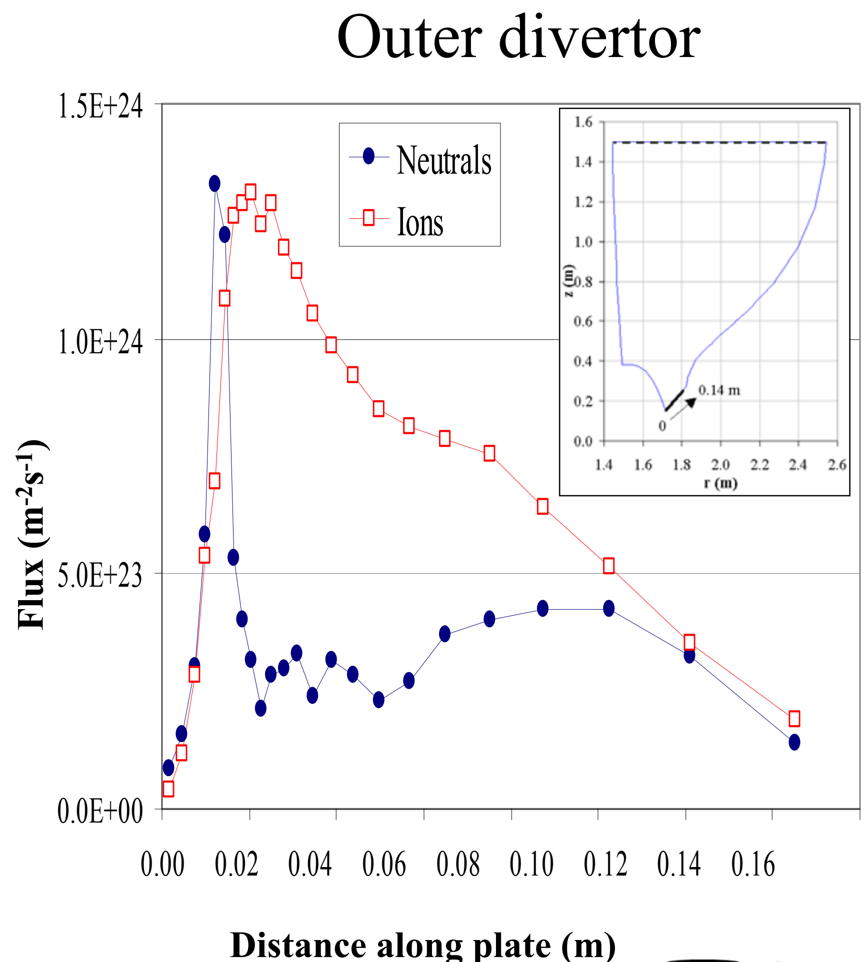
DEGAS2 Results





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.

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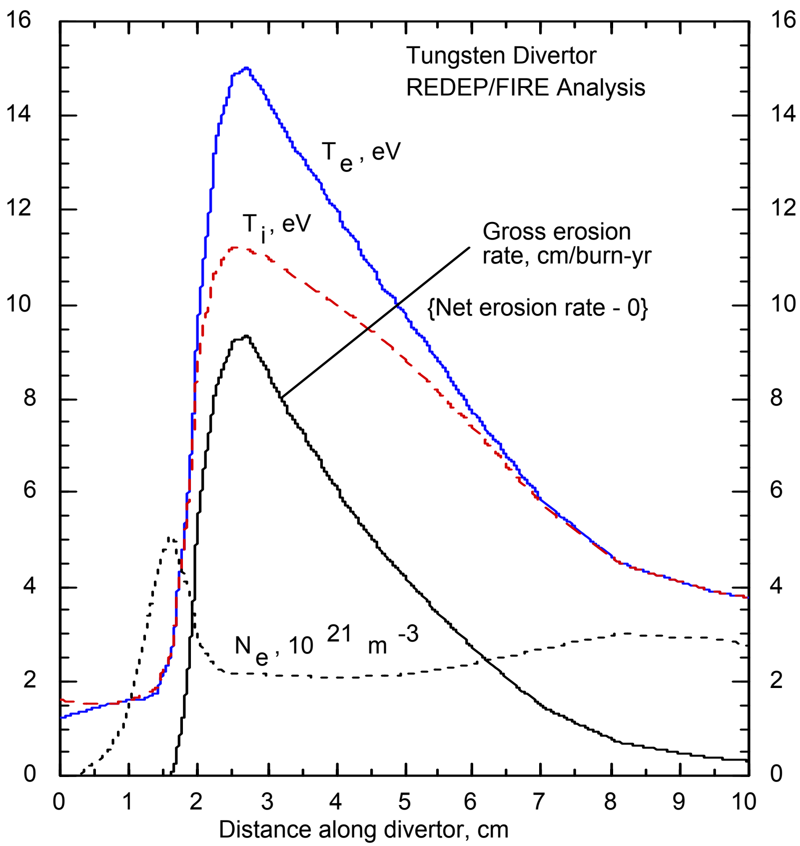
Erosion/Redeposition Modeling



- **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.**

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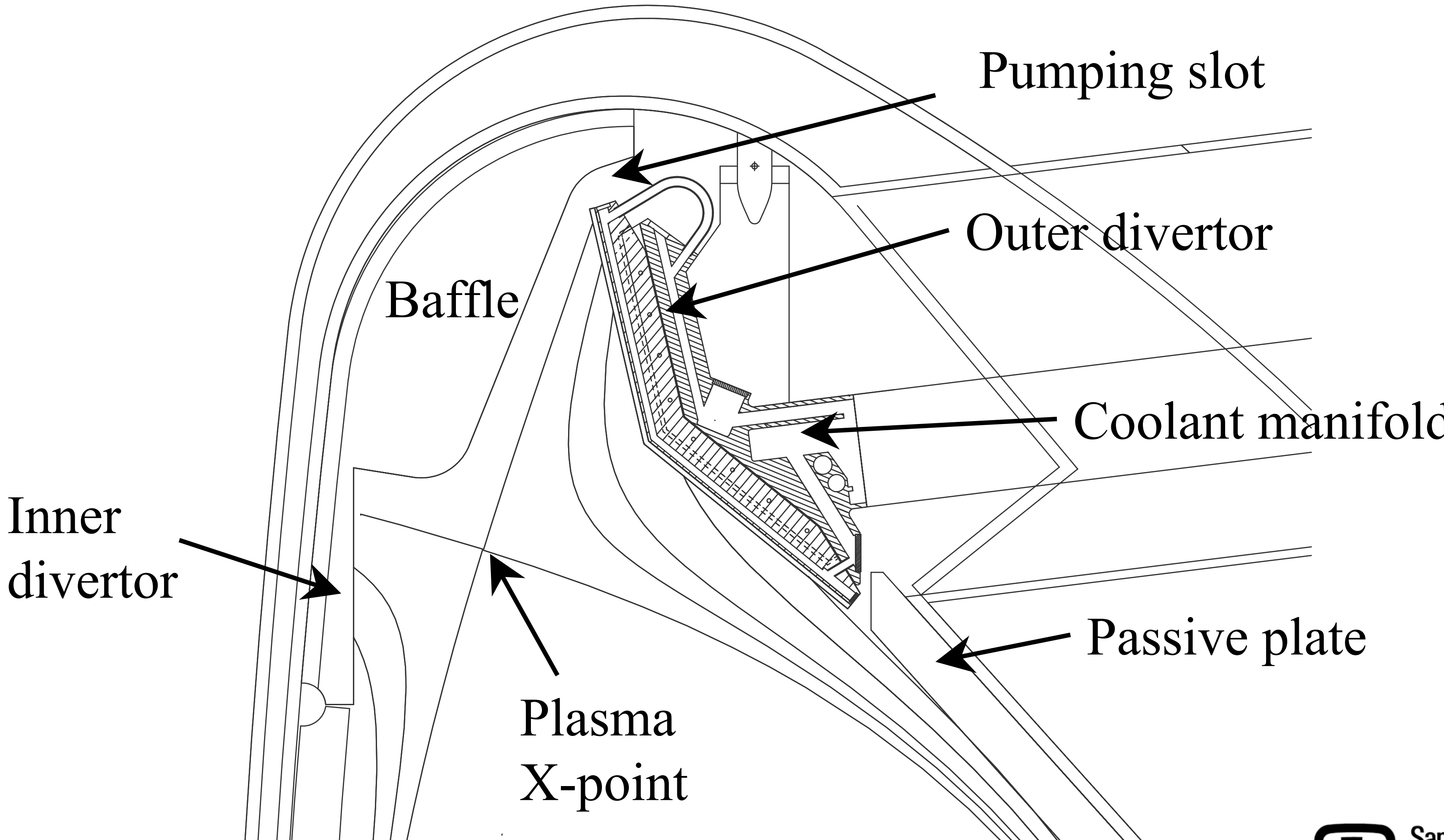
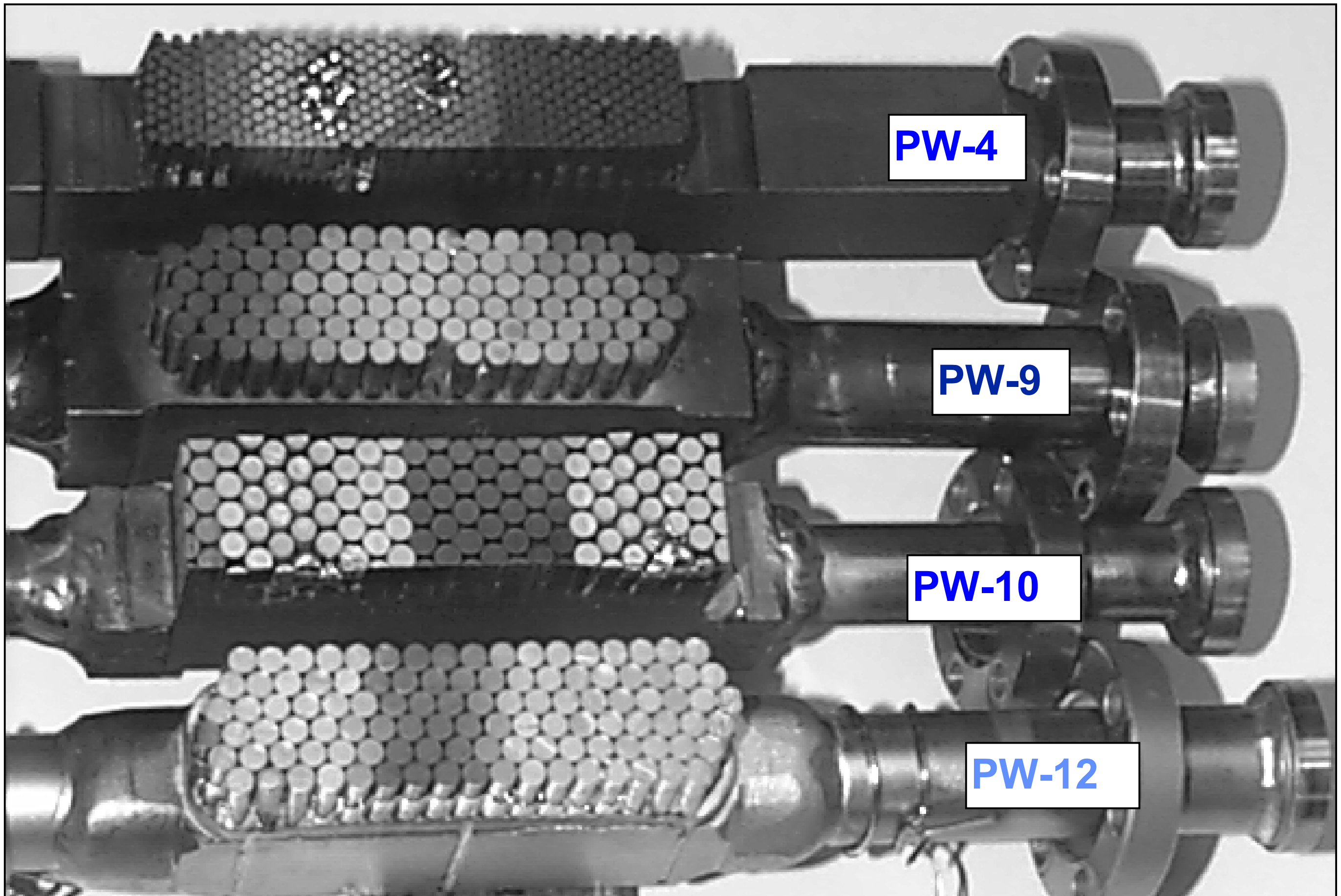
FIRE Divertor Design



Initial W Rod Test Articles



- All are 16 mm wide and 63 mm long.
- Some are 1.5 mm dia. and some are 3 mm dia.
- Rods 12 mm long.

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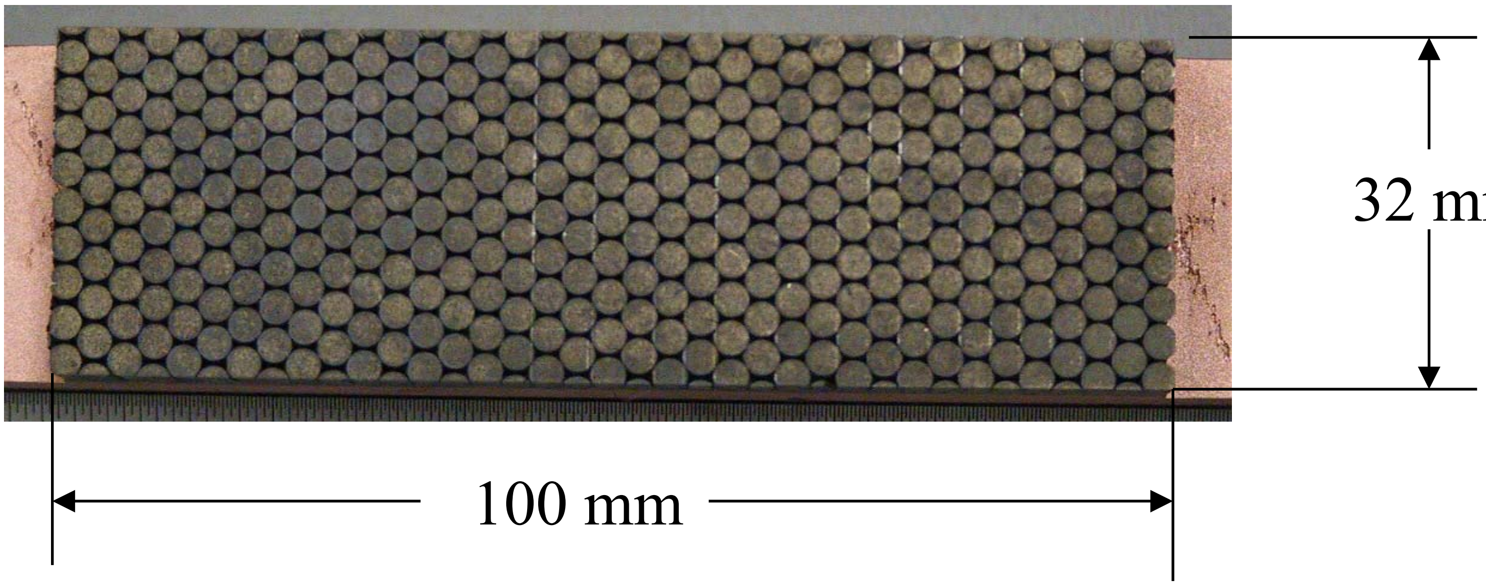
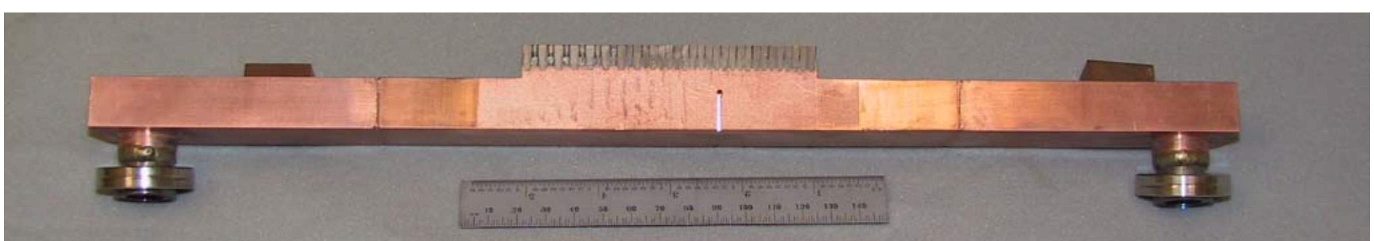
New Tungsten Rod Mockup





Rods 7 mm long

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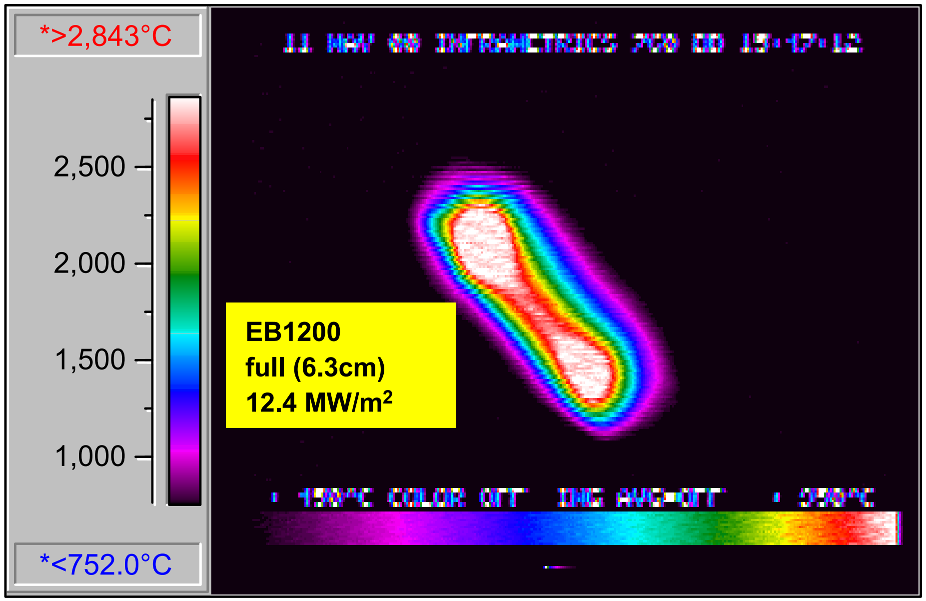
High Heat Flux Testing of W Rods



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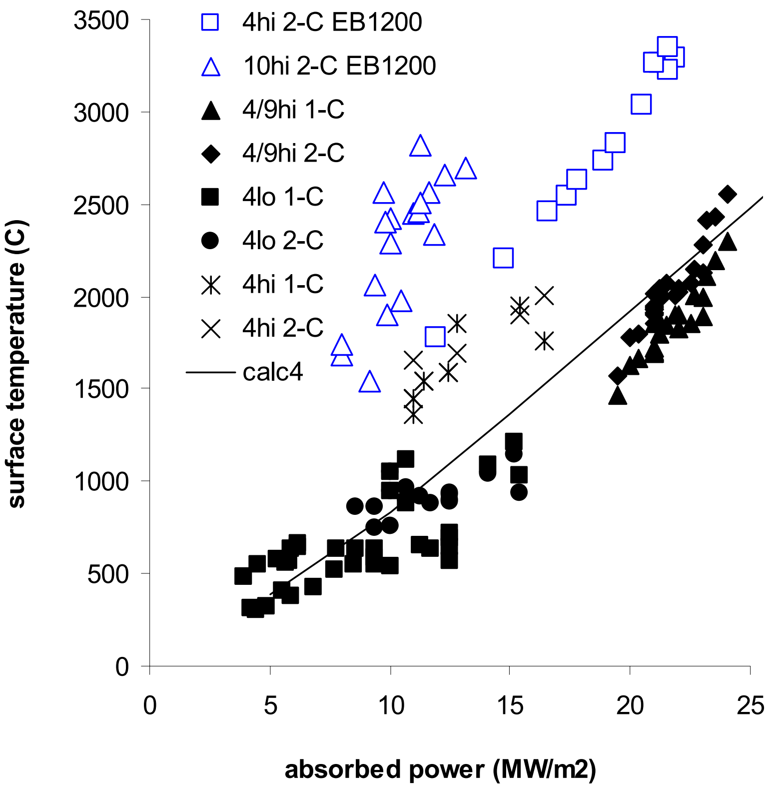
HHF Tests on W rod mockups

- **Tests on with a larger heated area (EB1200) had higher surface temperatures at a given heat flux than tests on the same mockups in EBTS.**
- **For 12 mm long rods the surface temperature limited all tests.**
- **We are shortening the rods to 7 mm for tests that will better simulate the FIRE divertor.**



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Disruption Specifications

Parameter	Value (Range)
Frequency	10% (10-30%) per pulse
Number (3,000 full E attempts)	300 (900)
Thermal energy	33 MJ
Thermal quench duration	0.2 (0.1–0.5) ms
Fraction of W_{th} to divertor	80–100%
Fraction of W_{th} to FW (baffle)	30%
In-divertor partition (in/out)	2:1 – 1:2
Poloidal localization in divertor	3-X normal SOL (1-X to 10-X)

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Disruption Specifications

Parameter	Value (Range)
Magnetic energy	35 MJ (?)
Current quench duration	6 (2-600) ms
Maximum current decay rate	3 MA/ms
Fraction of Wmag to FW, by rad	80–100%
Fraction of Wmag to FW, by cond.	0-20%
VDE frequency	TBD (1% of pulses, or 10% of disrup.)
Halo current fraction Ih,max/Ip0	0.4 (0.01-0.50)
Toroidal peaking factor	2 (1.2 = TPF = 4)

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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

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Disruption Specifications

	Low End Flux (MJ/m^2)	Reference Flux (MJ/m^2)	Most Likely (MJ/m^2)	High End Flux (MJ/m^2)
Inner Divertor	8	13.4	31	96
Outer Divertor	4	6.8	16	48

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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.

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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

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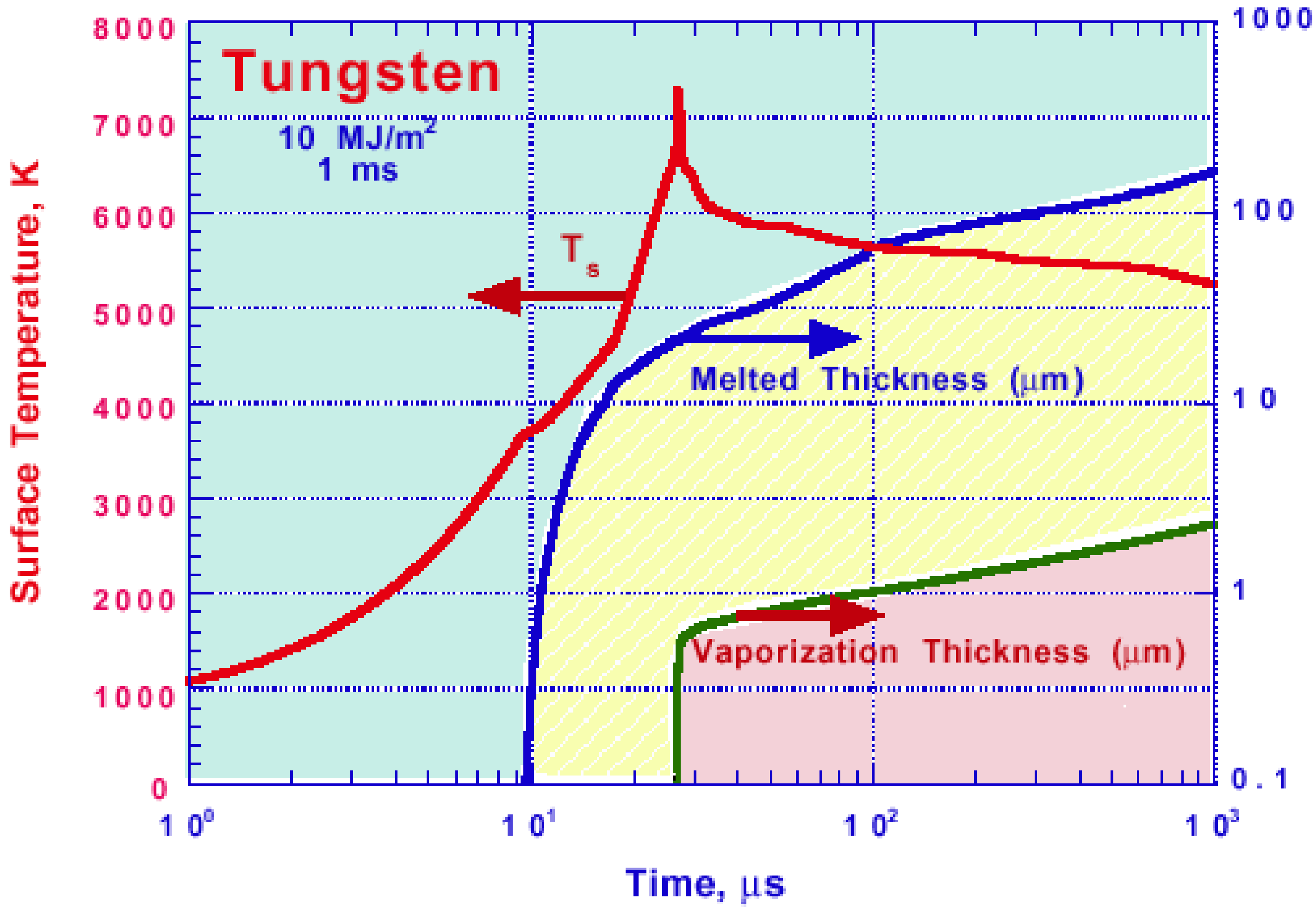
Analysis of Disruption Heating



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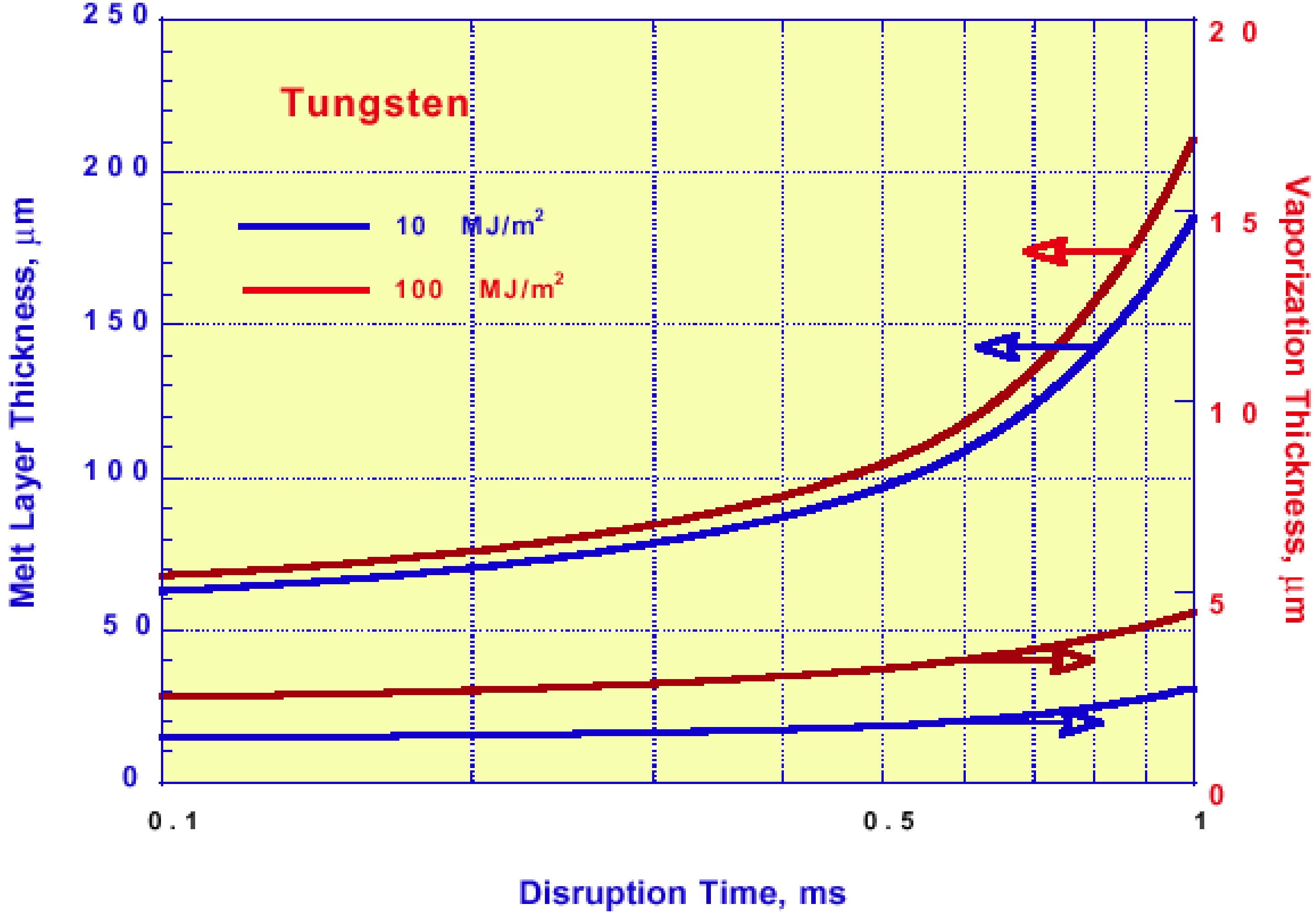
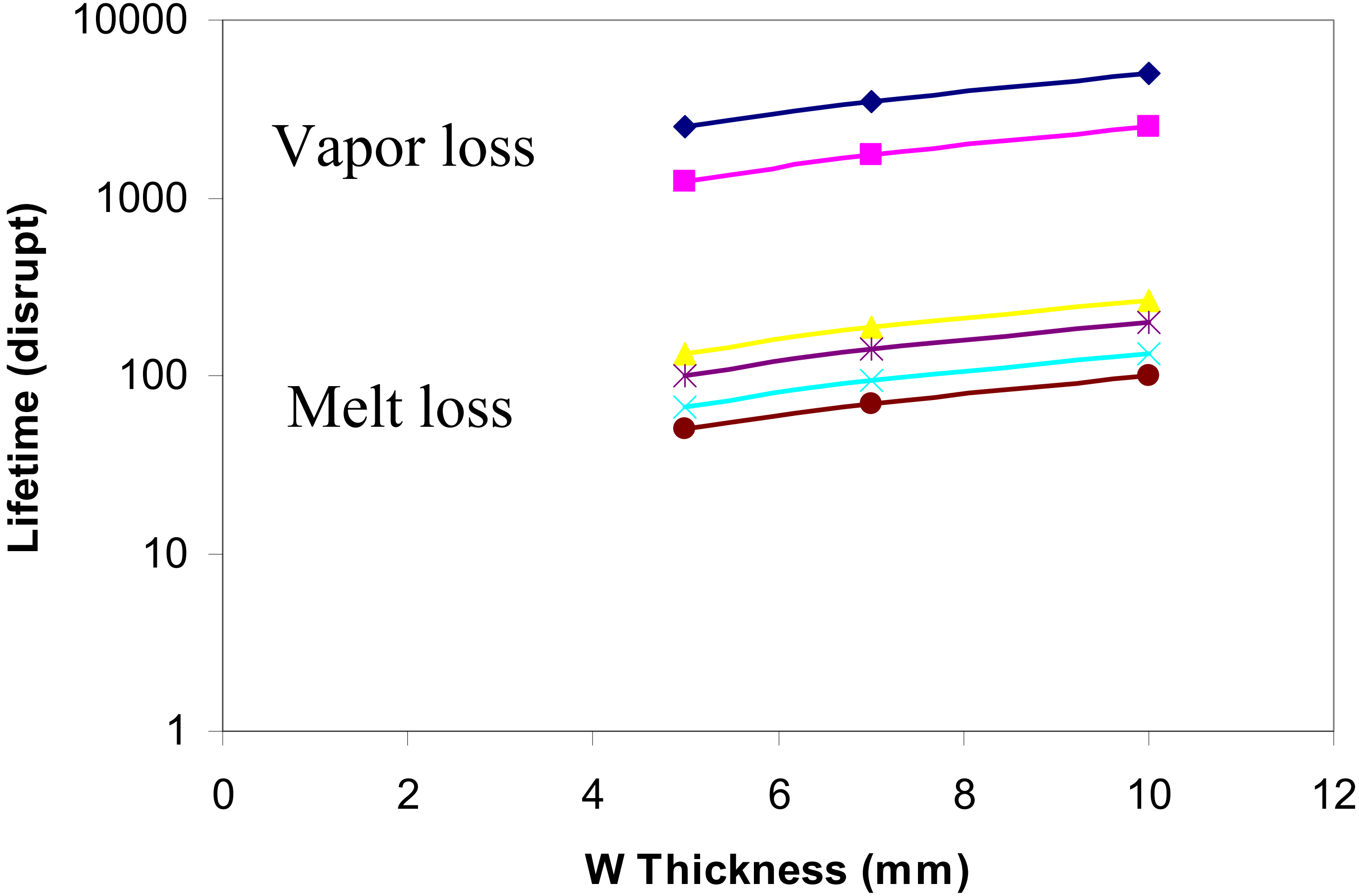
Analysis of Disruption Heating



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

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

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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 $\mu\Omega$**
- **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 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).

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PC-Opera Capabilities

- Calculates the vector potential given an array of current carrying filaments and materials (including magnetic materials)
- Using the 3-D version (started with 2-D)
- The TSC model has about 1400 current filaments
- The FIRE geometry requires about 15,000 elements for a proper description
- Time dependent current drive capability tested.

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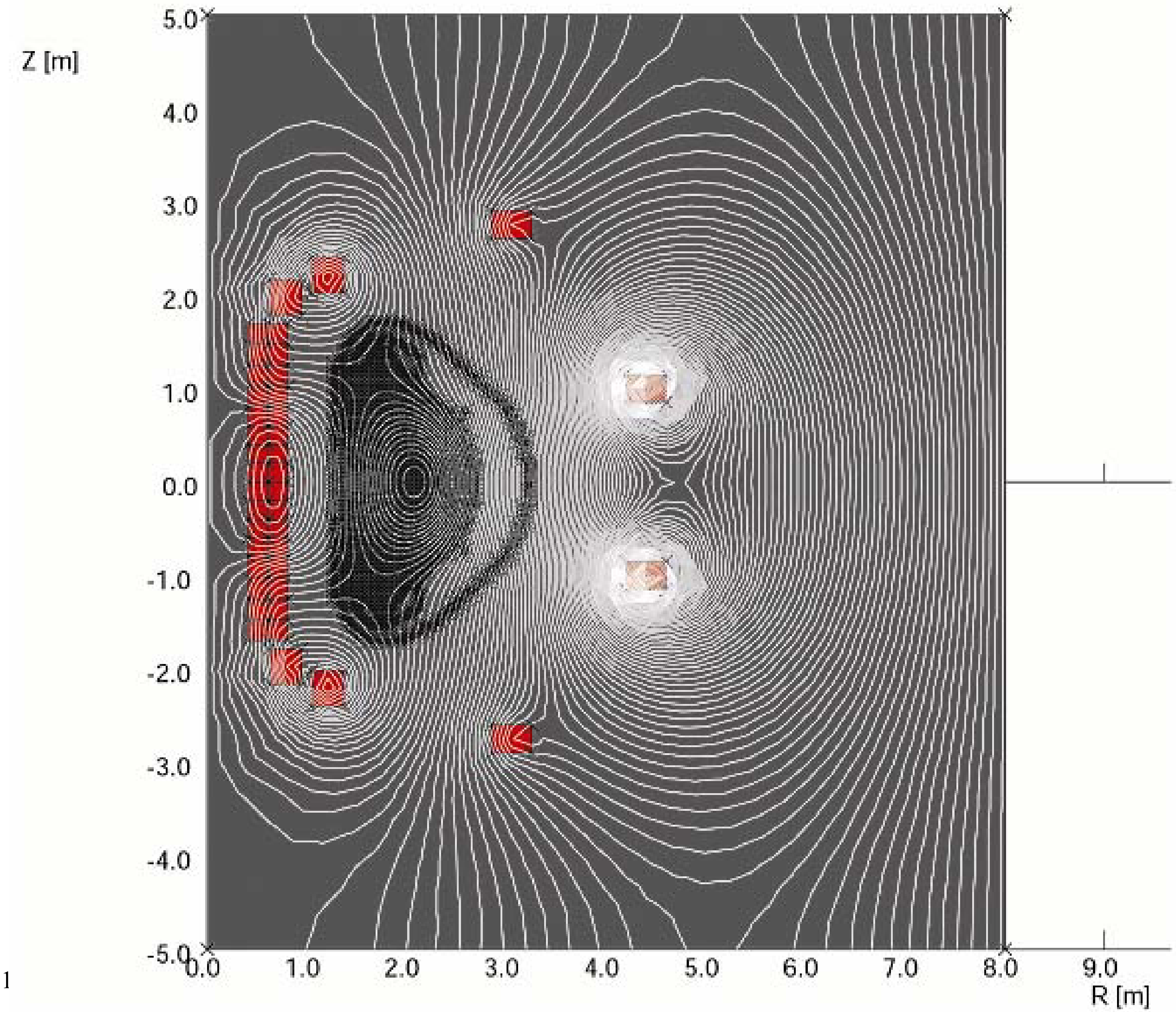
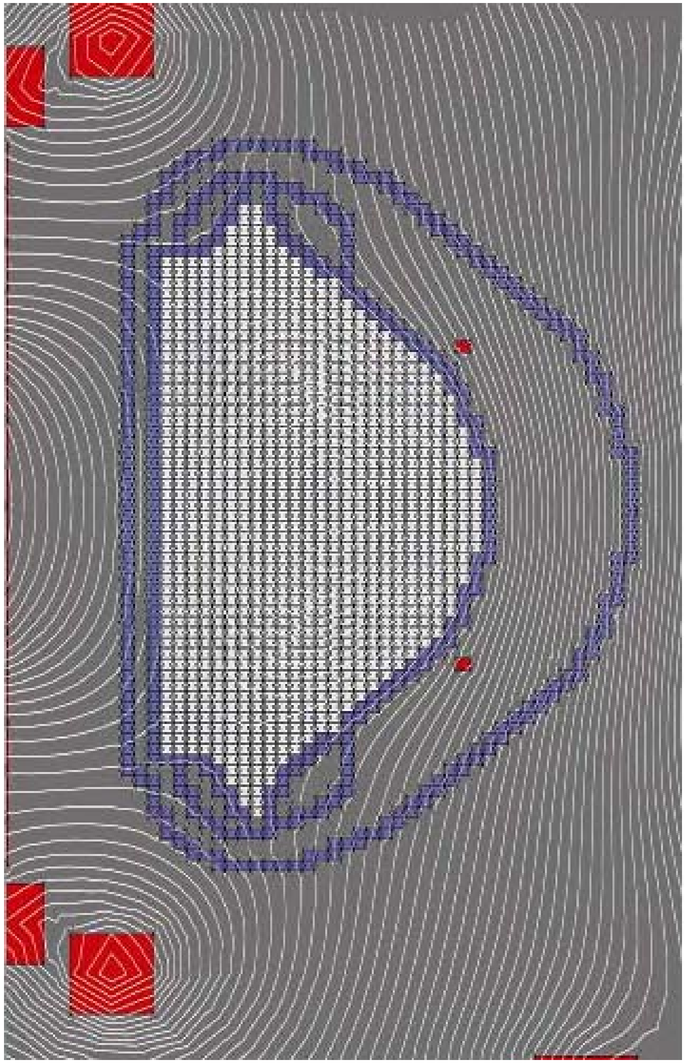
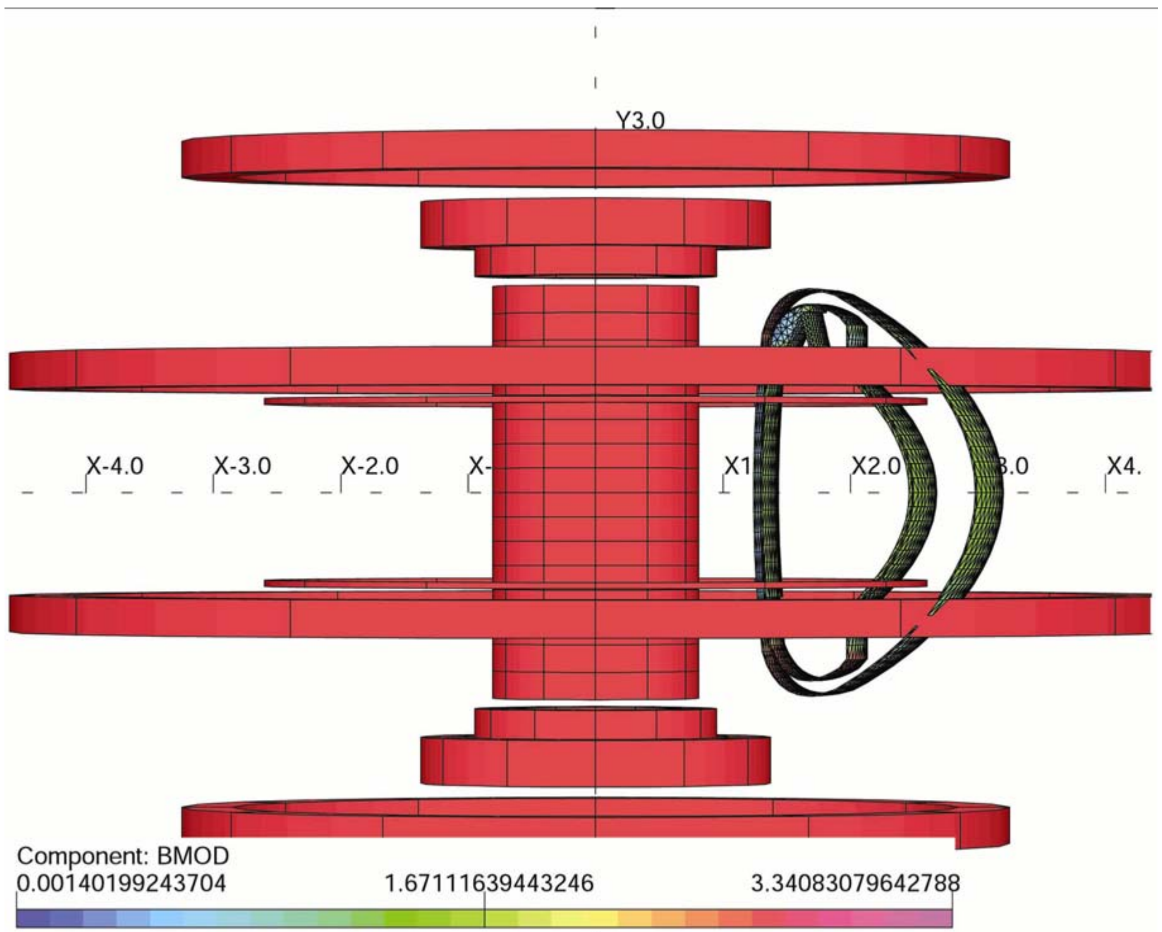
FIRE Magnetic Fields



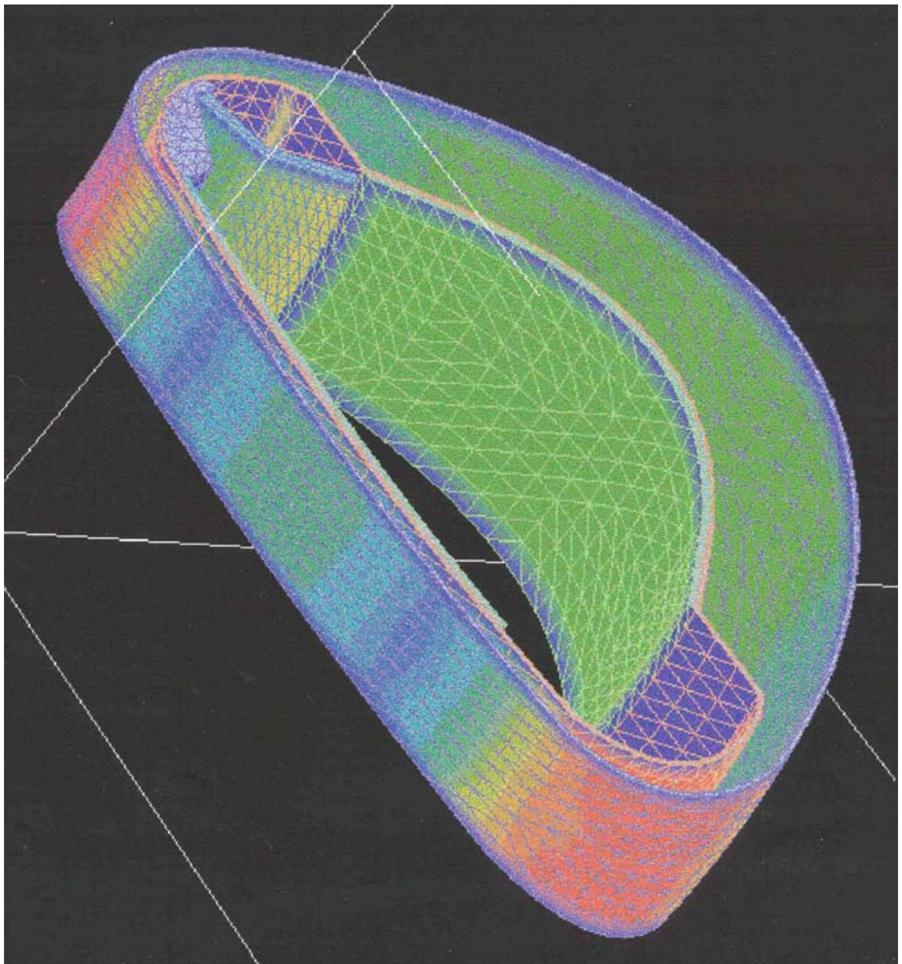
FIRE Magnetic Fields



PC OPERA Model of FIRE



Disruption Eddy Current Modeling



- 22.5° wedge of vacuum vessel and PFCs
- Copper and stainless steel elements accurately represented
- Combination of toroidally symmetric and toroidally isolated boundary conditions as appropriate
- Fully 3D magnetic fields generated from coil currents.

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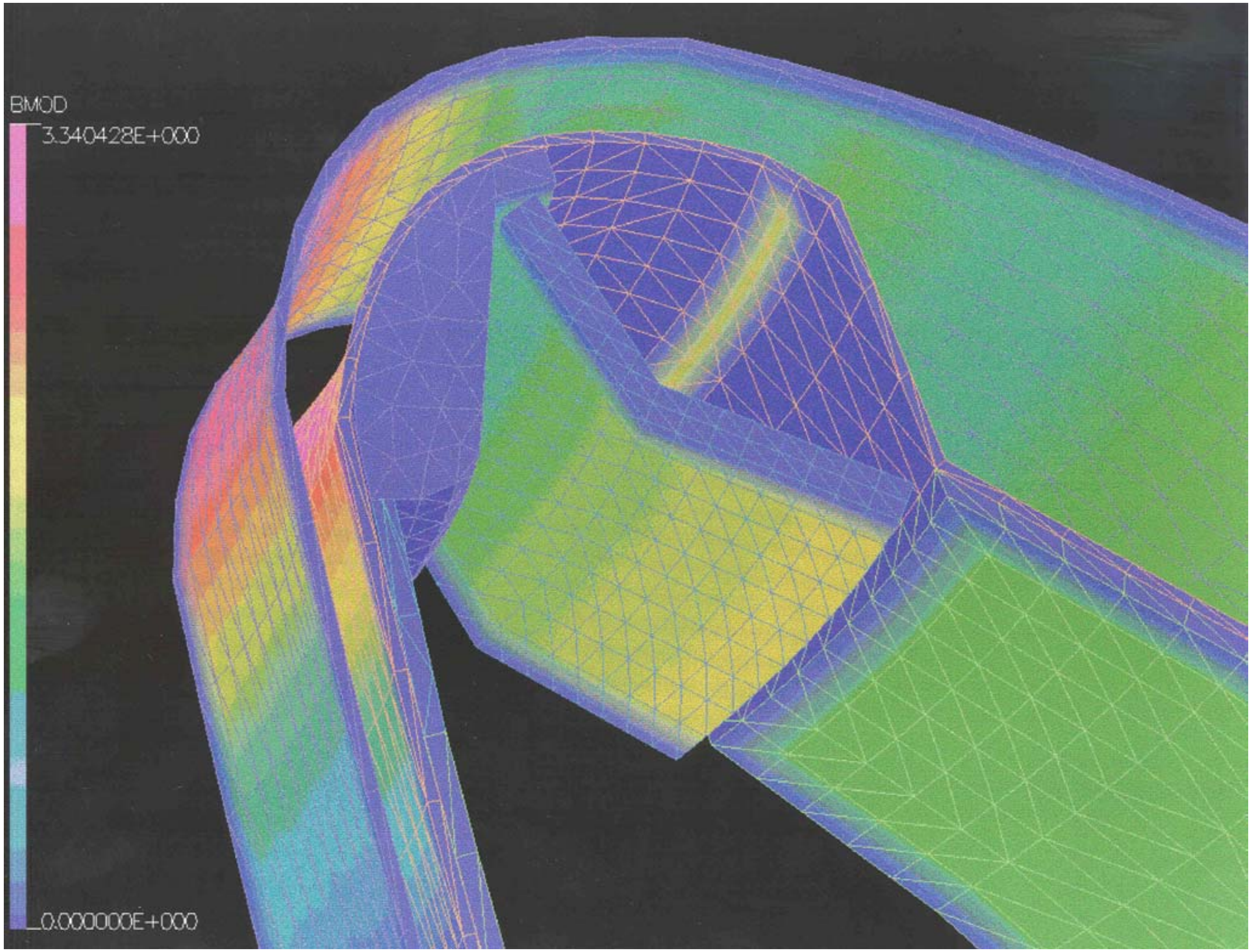
Plasma Facing Components



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Recent Results on Disruption Mitigation

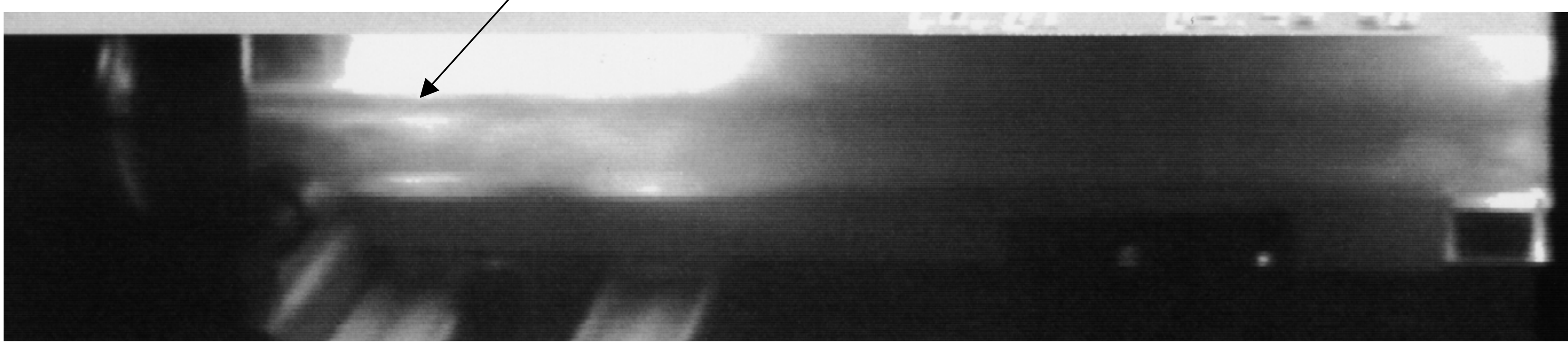
- There have been several important developments concerning disruption prediction in the last ~4 yrs
  - Several groups have developed a neural network that predicts a disruption is about to occur
    - the networks have predicted disruptions with 50 ms warning and an accuracy >90% with <5% false alarms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

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



Benefits for Technology Development

- Heat flux typical of all burning plasma designs being considered
- Pulse long enough to test active cooling
- Substantial data on PMI and tritium effects
- Remote maintenance required
- Full neutron effects not present (advantage and disadvantage)
- Excellent platform to prove disruption mitigation
- Steady state fueling and pumping

Summary

- UEDGE modeling predicts 20-25 MW/m^2 heat flux on the outer divertor
- UEDGE shows the divertors can be detached
- There is no predicted erosion of W divertor plates

Summary

- A pre-conceptual design has been completed for the FIRE PFCs
- The divertor design is sufficient for all proposed operating modes for FIRE
- 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
- Construction of a FIRE device will yield important benefits for technology development for future fusion devices

Summary

- **Disruptions are the strongest driver in the PFC design**
- **The life limiting events for the PFCs are disruptions**
- **Disruptions also determine the design of the backplates and mounting features**
- **A new technique for predicting disruptions has been developed that offers the potential for mitigation of disruption effects**

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