FIRE Divertor Design

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M. Ulrickson

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

- Overview
- Plasma flux structure
- Plasma Heat Loads (Results from T. Rognlien)
- Design Description (Dan Driemeyer, Boeing)
- Disruption Analysis (Input from C. Kessel)
- Main Issues to be addressed
- Summary

OverView

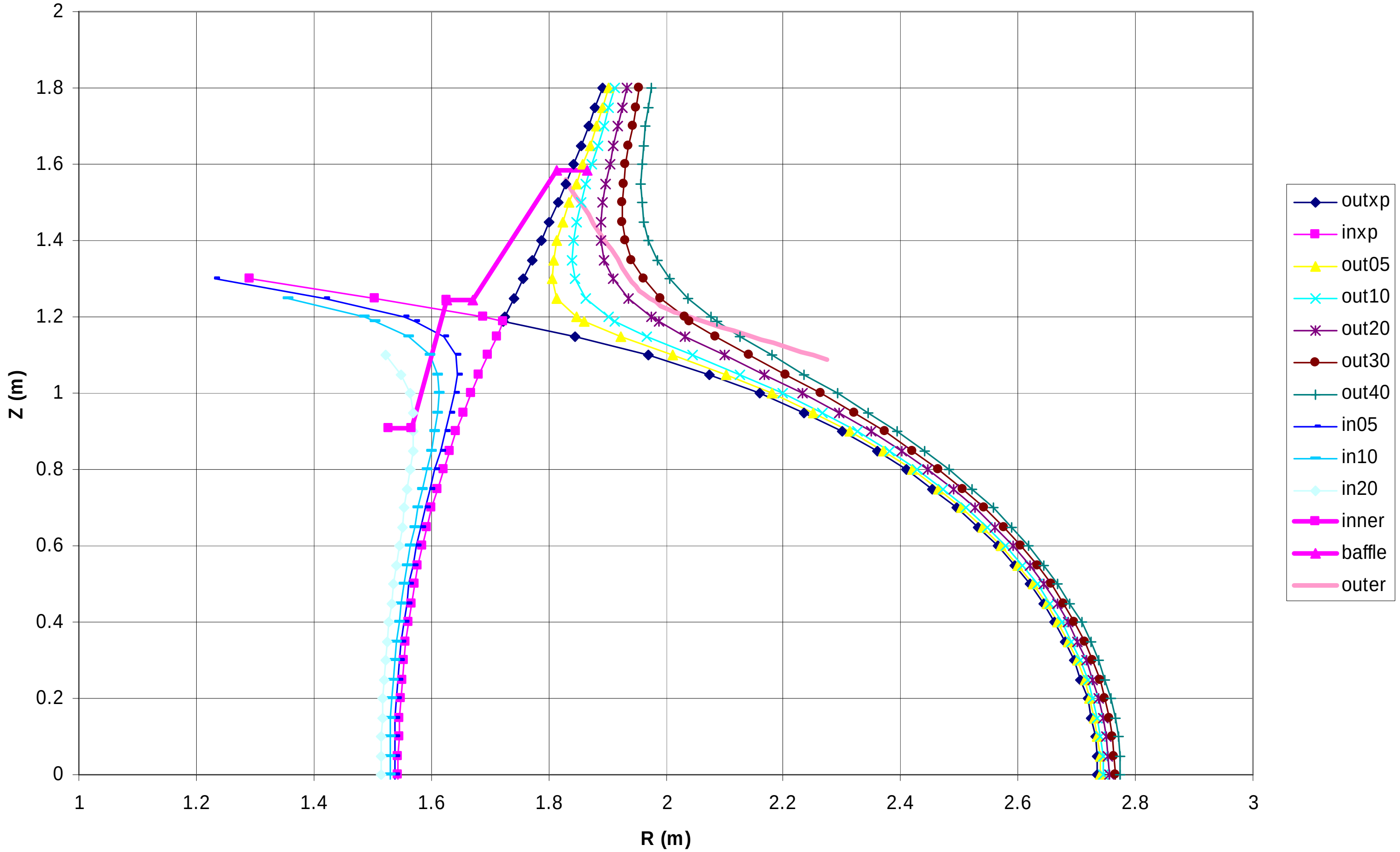
Power Balance Assumed

- **Heating Power: 30 MW**
- **Plasma Gain: 5**
- **Fusion Power: 150 MW**
- **Alpha Power: 30 MW**
- **Total Plasma Heating: 60 MW**
- **Core Radiation: 10% 6 MW**
- **Power to SOL: 54 MW (split evenly up/down)**
- **Radiation in the SOL: 20% 11 MW**
- **Radiation in divertor:10% 4 MW**
- **Total Power to the Divertor plates: 40 MW**

Overview

- We assumed a double null divertor because:
  - We can use active heat load balancing (active cooling)
  - There is some evidence that double null mitigates ELMs
  - The active area of the divertor is increased, lower heat loads (see Rognlien results)
- The increase from 2 to 2.14m was done without a proportional increase in height which meant the distance from the x-point to the plates decreased, but the heat is spread more.
- The plasma current increased which may make the eddy currents worse (see Disruption section)

Plasma Flux Geometry in FIRE



Divertor Heat Flux

UEDGE is a plasma/neutral fluid code

- **Features of UEDGE**

  Physics:

  – **Multispecies impurities; var. n, $u_{||}$, $T_{e,i}$, ϕ**

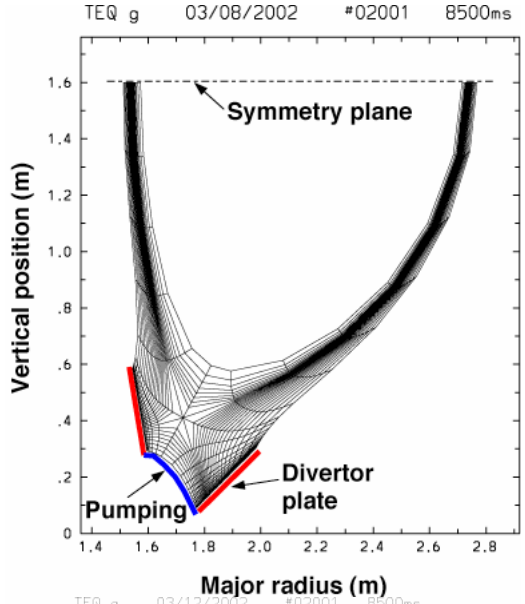
  – **Flux-limited kinetic corrections**

  – **Reduced Navier-Stokes neutrals or Monte Carlo coupling**

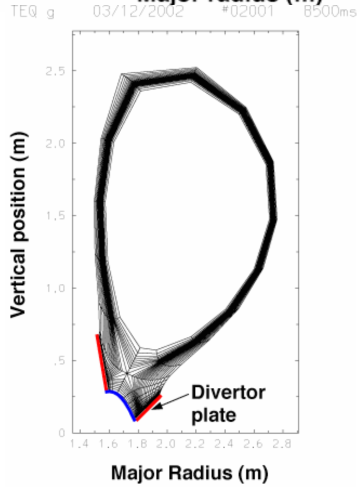
  – **Multi-step ionization and recombination; sputtering**

FIRE is designed for a double-null divertor

- FIRE divertor must tolerate 28 MW into the SOL (DN)
- For 150 MW fusion power, helium must be removed at a rate of 5×10^{19} particles/sec
- Edge density is set to 3×10^{20} m^{-3}
- Unity recycling with PF pumping



Double null



Single null variant

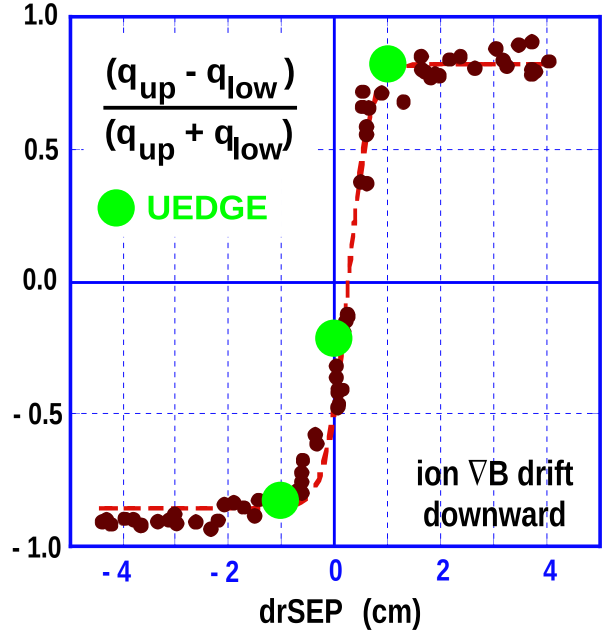
UEDGE Modeling Results

- Core-edge temperatures are inconsistent with that required for good core confinement
- A single-null FIRE variant has more than 2 times the peak heat flux of the double-null
- Neon injection can induce partial detachment
- Helium pumping in the private flux region appears adequate
- Peak power scales nearly inversely with density and with anomalous diffusion coeff.
- Midplane profiles show scaling with core-edge density and transport coefficients

Power Balance is Sensitive to DN Balance

- UEDGE now treats range from single-null to double-null
- Double nulls reduce peak heat flux, but balance is delicate
- ExB flows and currents produce asymmetries
- Code reproduces measured DIII-D heat flux imbalance

DIII-D heat-flux asymmetry between upper & lower divertors - T. Petrie

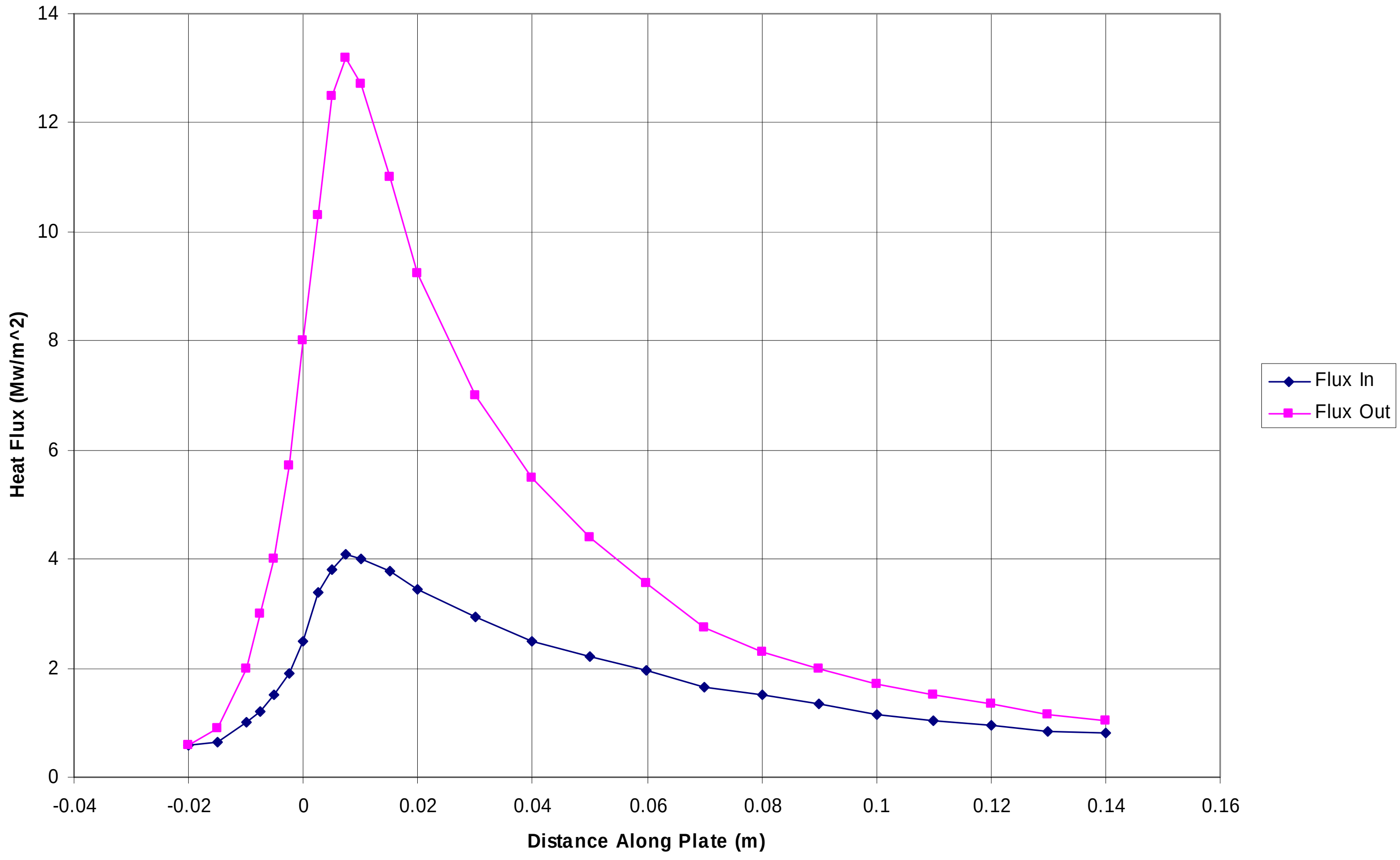


drSEP - distance between two separatrices at outer midplane

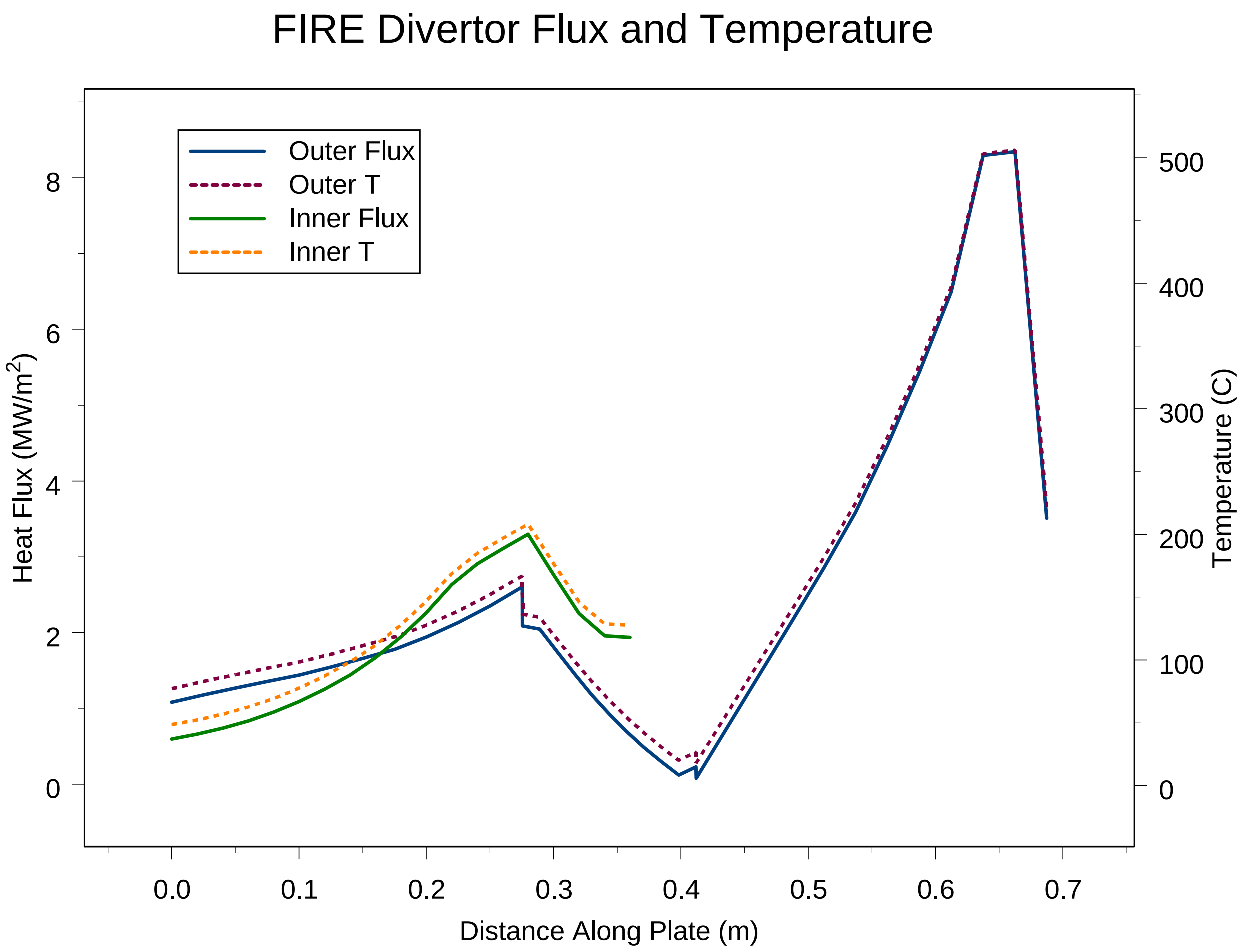
A number of uncertainties remain

- Peak heat flux scales inversely with unknown anomalous transport coeff.
- Reabsorption of hydrogen radiation at high densities & stability of detachment
- Maintaining double-null power balance
- Redeposition/removal of beryllium to/from surfaces
- Consistency of pedestal temperature with good core confinement
- Size and impact of ELMs

SOL Heat Loads from UEDGE

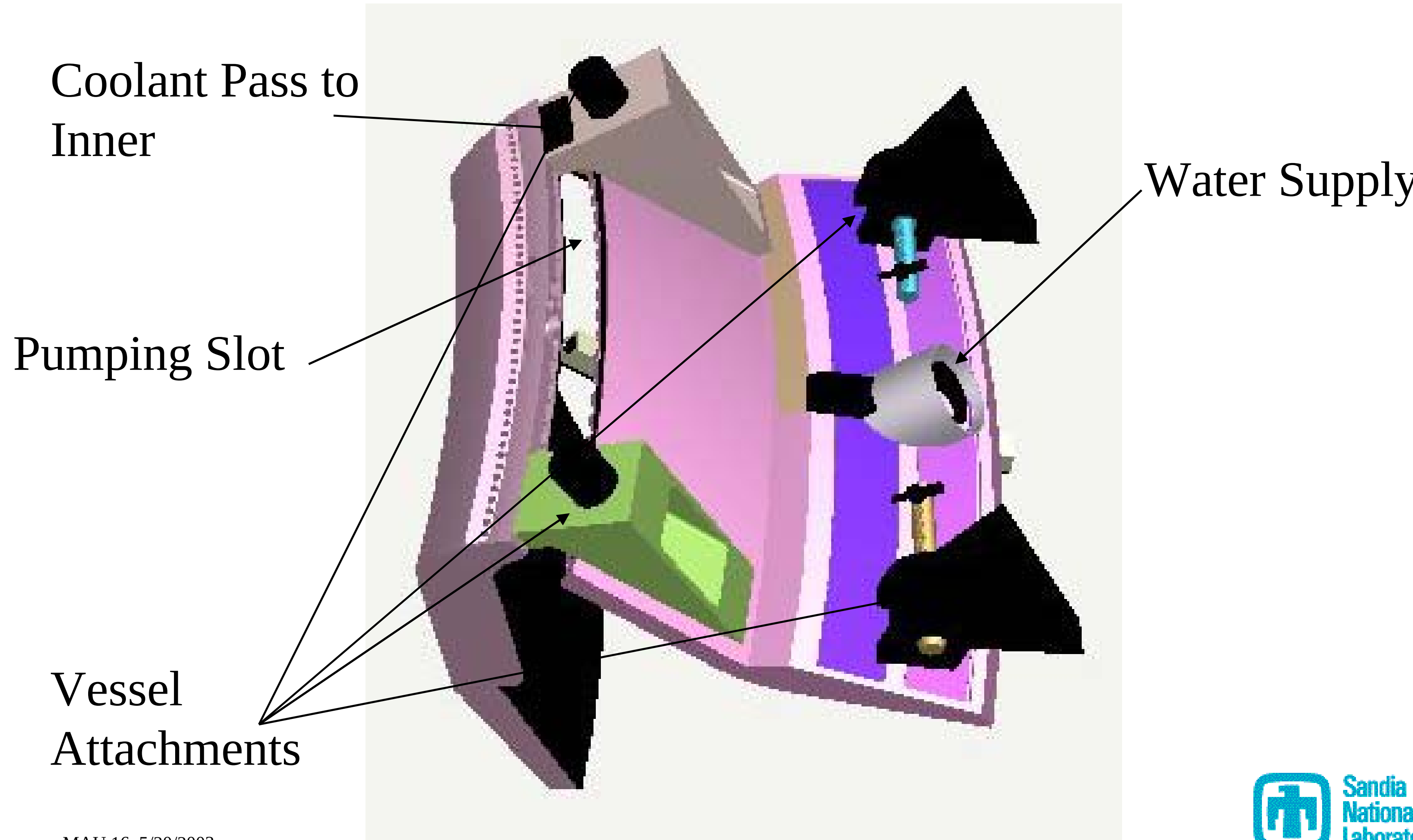


Heat Loads on the Divertor



Engineering Design of FIRE Divertor (Boeing)

FIRE Divertor Design



Disruption Cases

Disruption Modeling with TSC

- Data provided by C. Kessel, PPPL
- Two Scenarios considered:
  - Vertical disruption with maximum I_p dot
  - Vertical disruption with maximum halo currents
- Current versus time was provided for about 900 filaments representing the plasma
- This plasma model was input to OPERA to drive a transient eddy current calculation
- 1/16th of FIRE was modeled in OPERA

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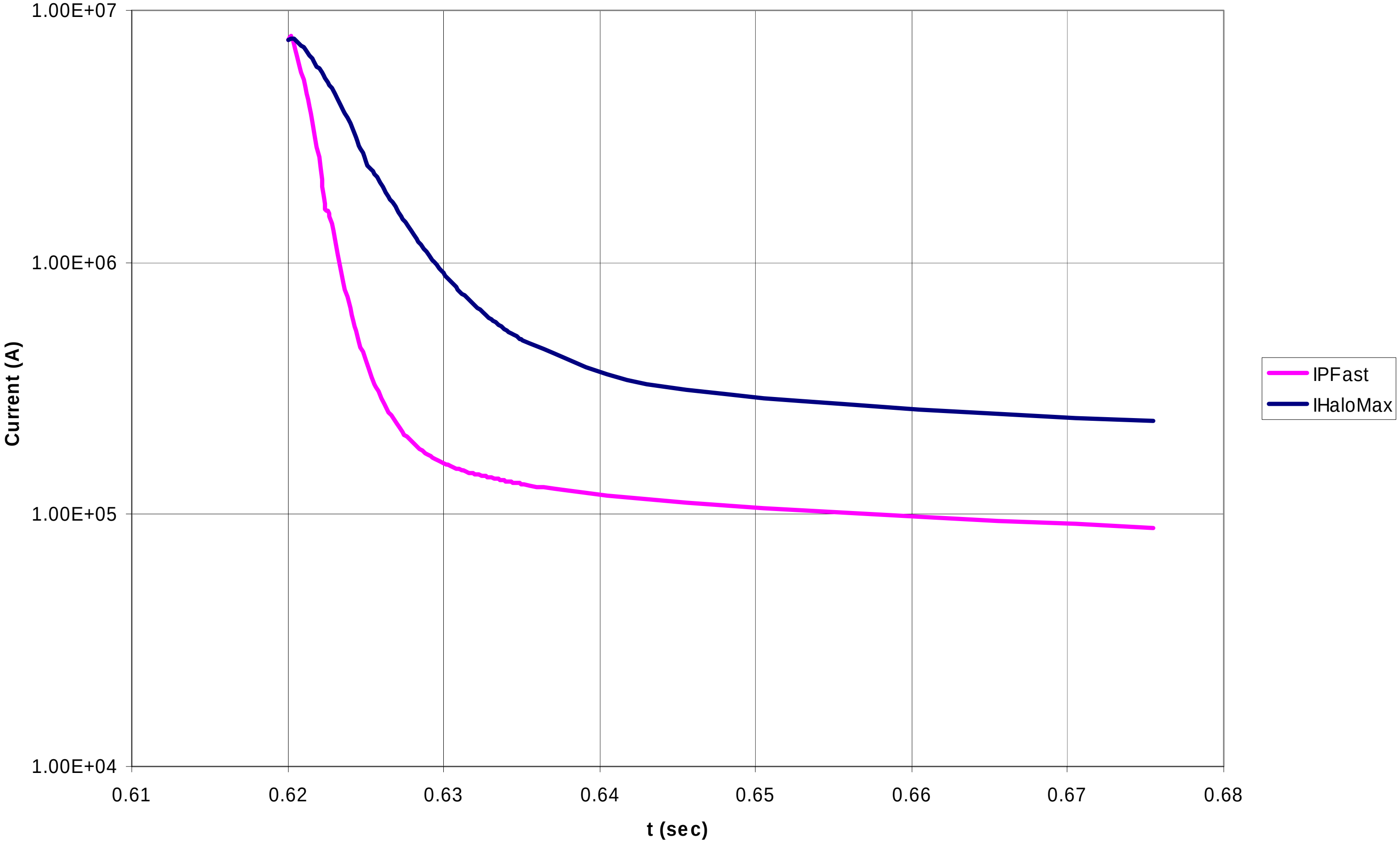
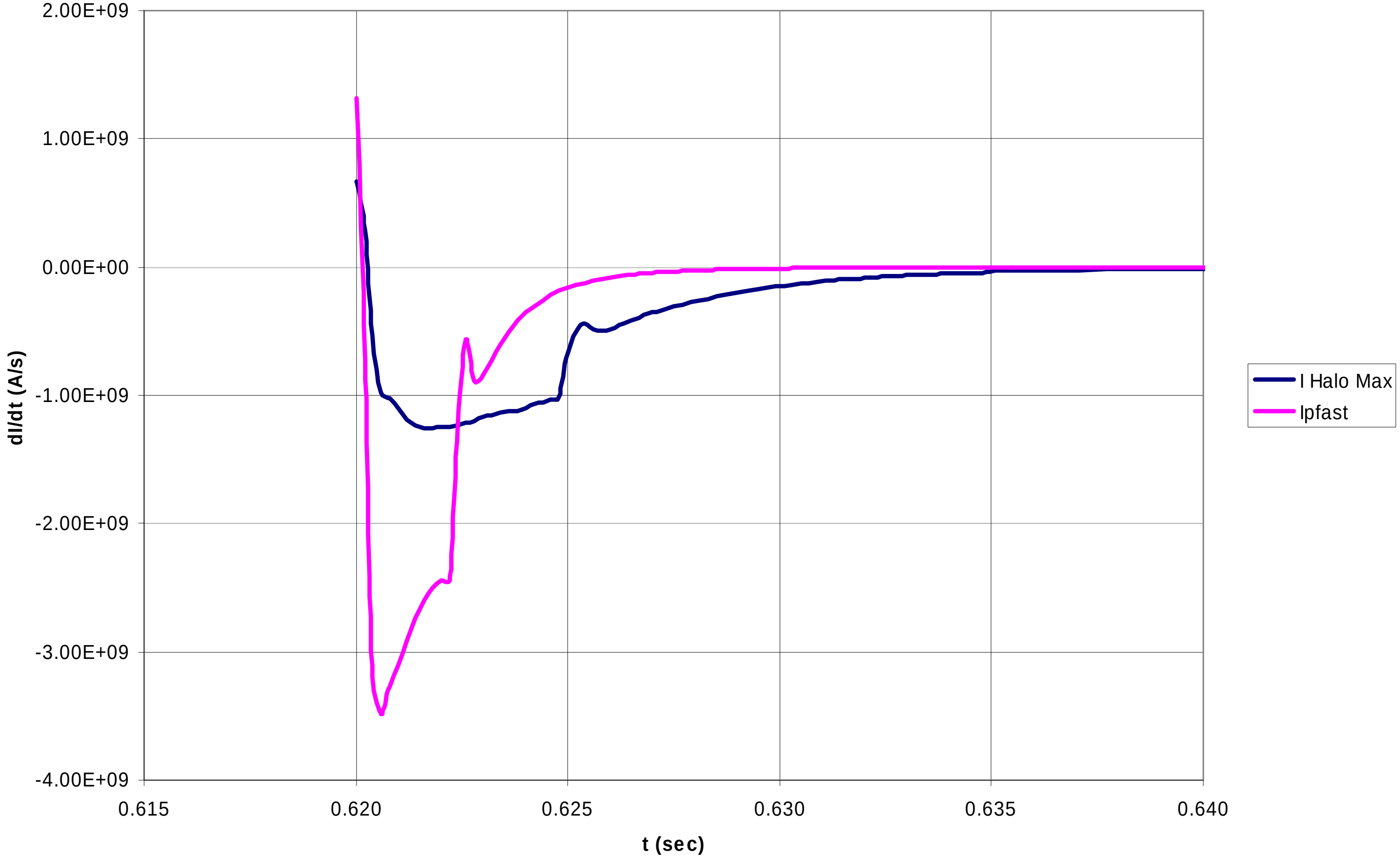
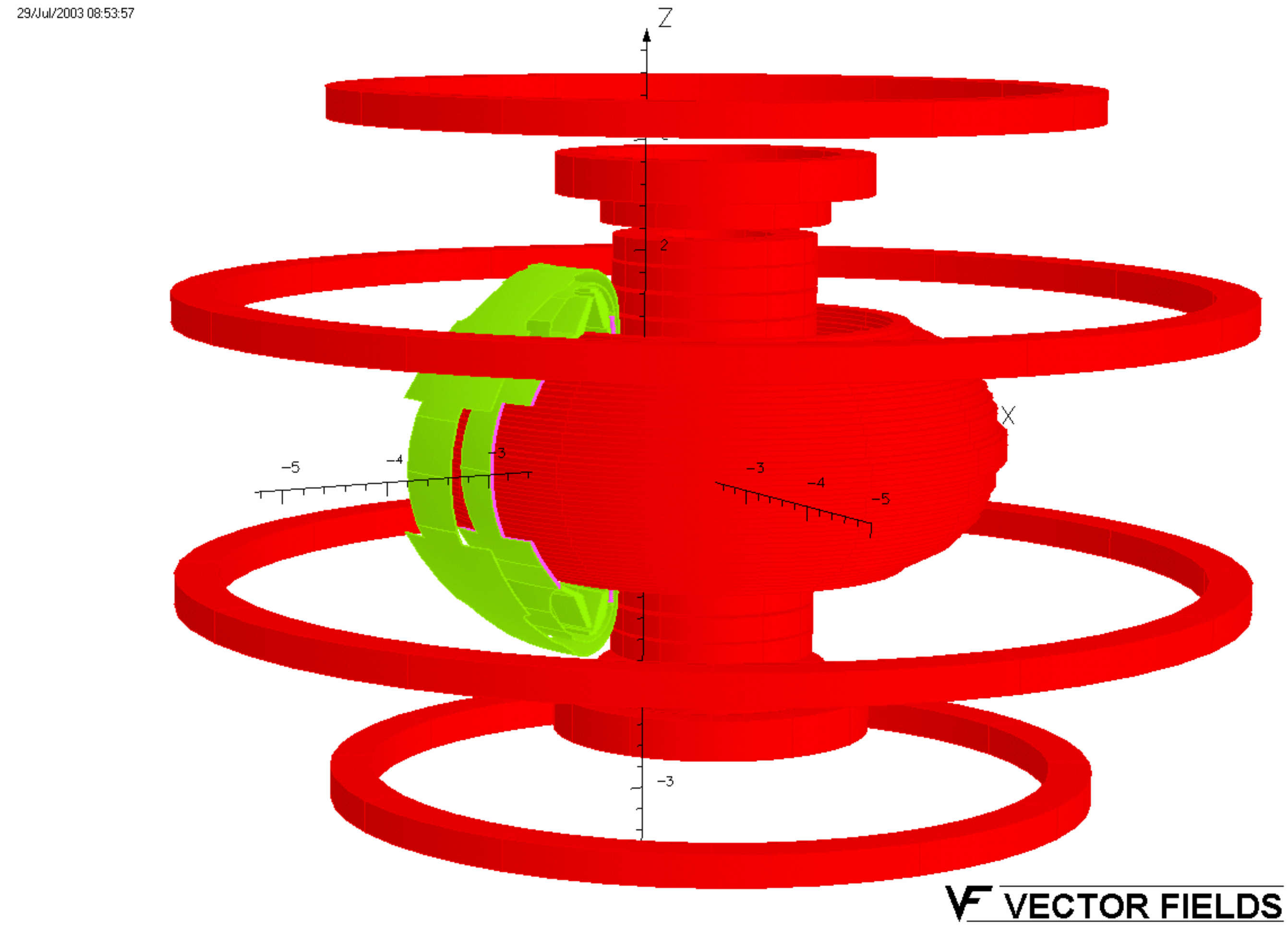
Disruption Cases from TSC



Idot in Disruption Cases



OPERA Model Of FIRE



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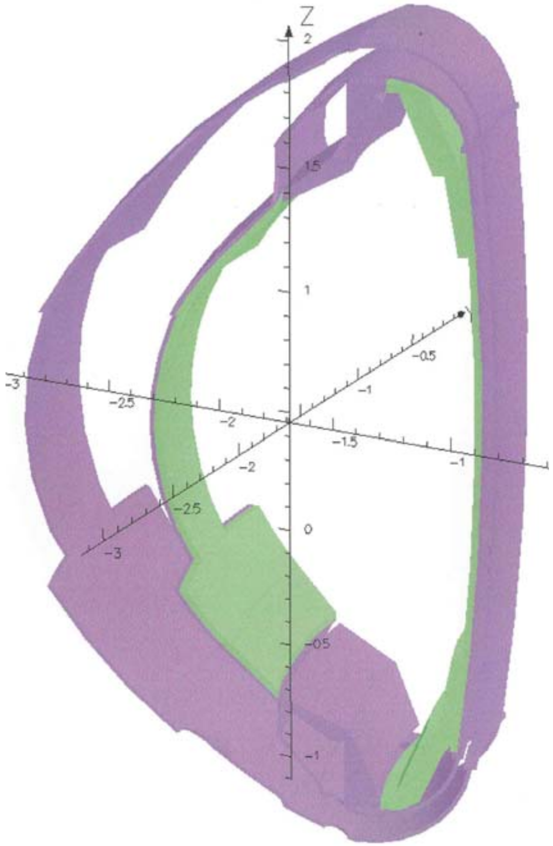
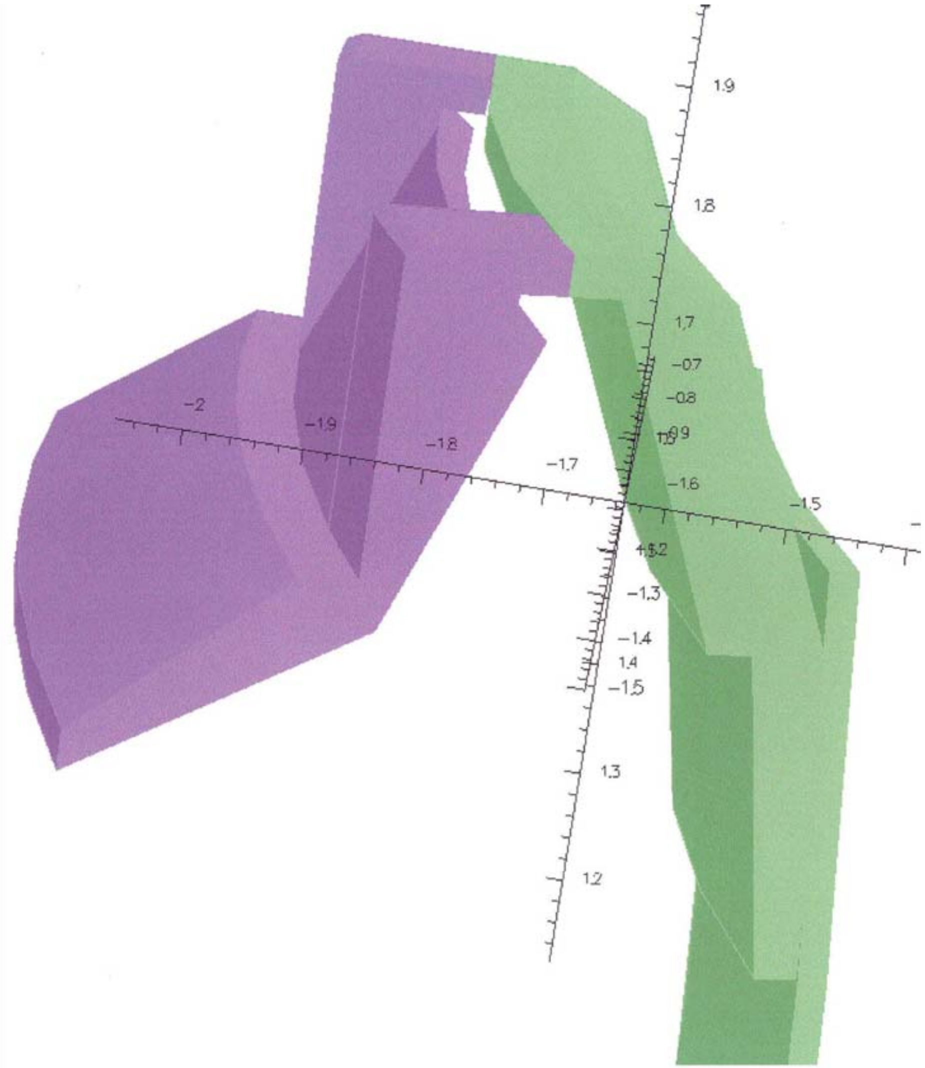
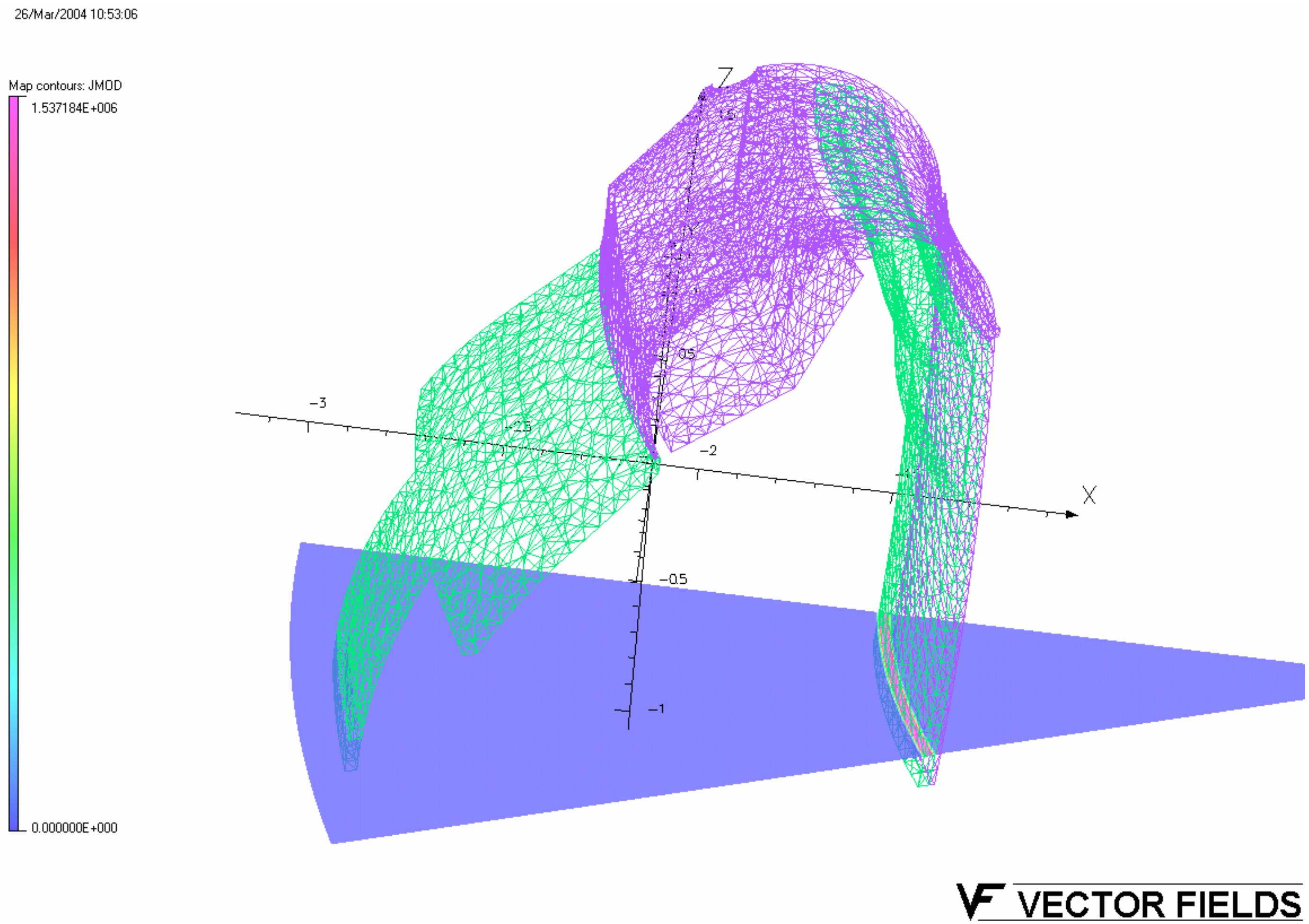
OPERA Model of FIRE Sector



Opera Model of FIRE Divertor



Induced Currents in I_{Pmax} VDE



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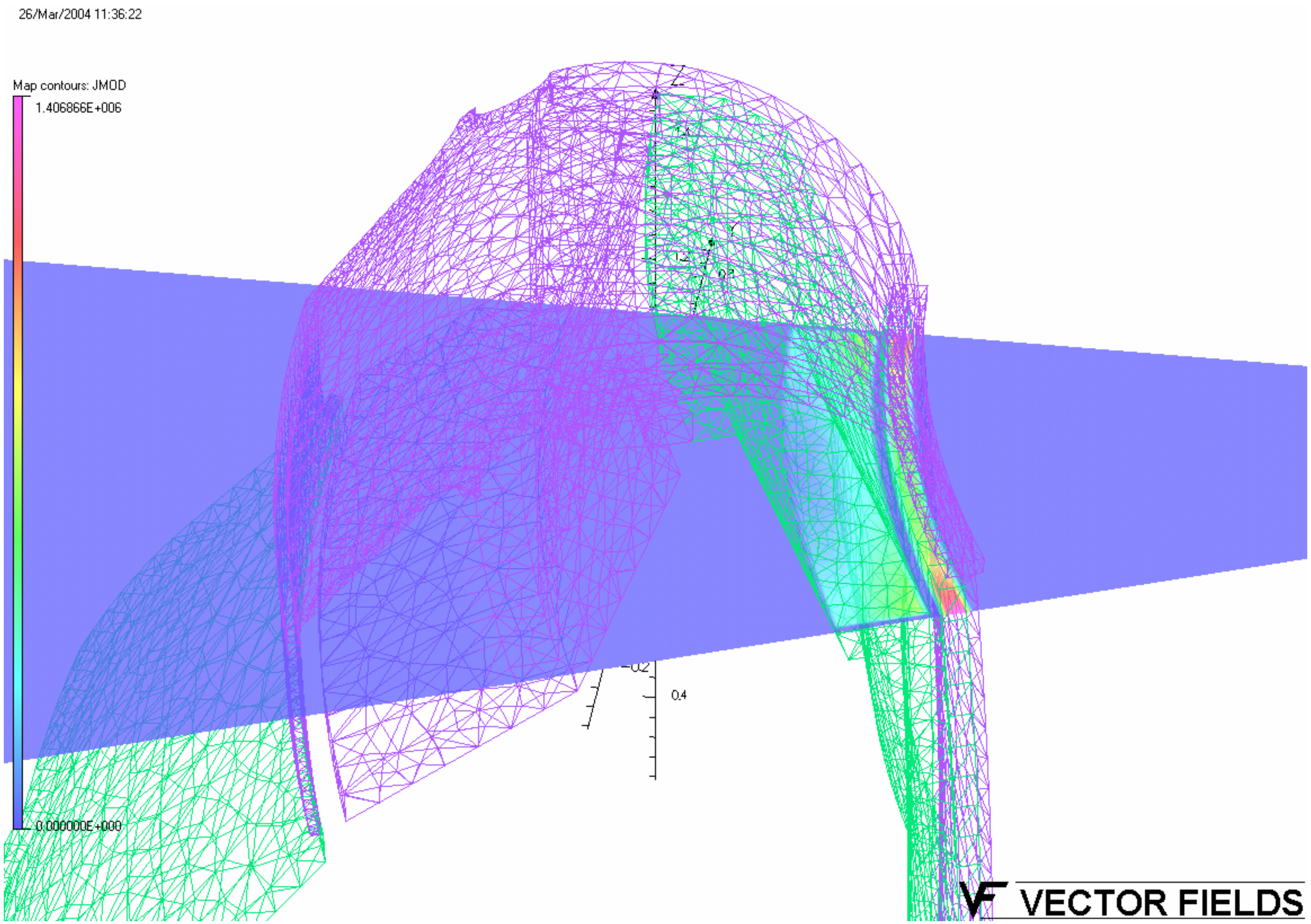

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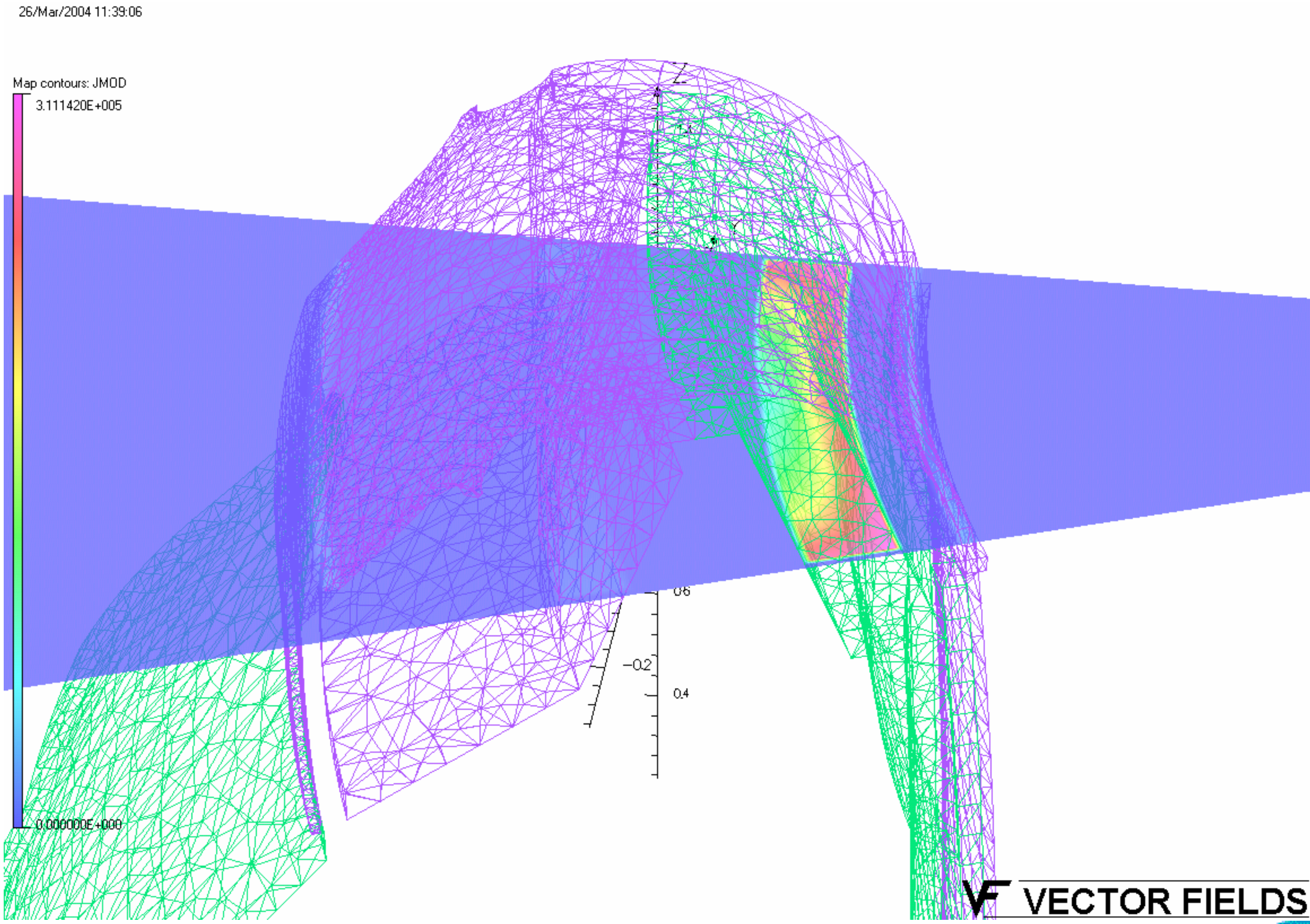

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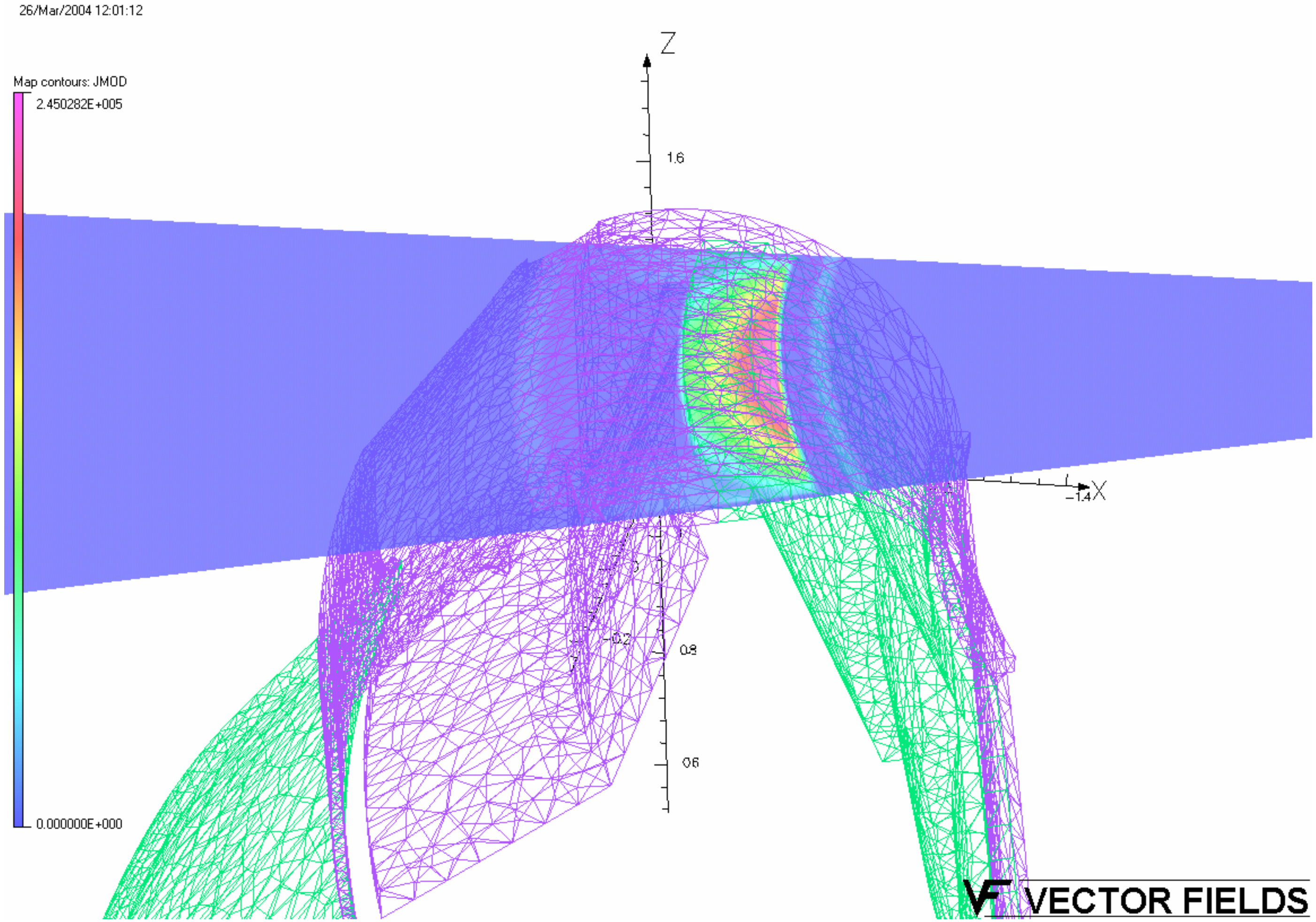


Results of OPERA Model

- In some small regions of the new divertor components the induced forces are about 2 times higher than for the 2 m design.
- On average the induced forces are less than 20% higher than for the 2 m design.
- Since the moments and loads on the supports depend sensitively on the location of the forces, we cannot tell whether the design has adequate margin for disruptions.
- The transient nature of the forces must be taken into account in detailed design.

ELM Effects

Estimate of ELM Heat Loads

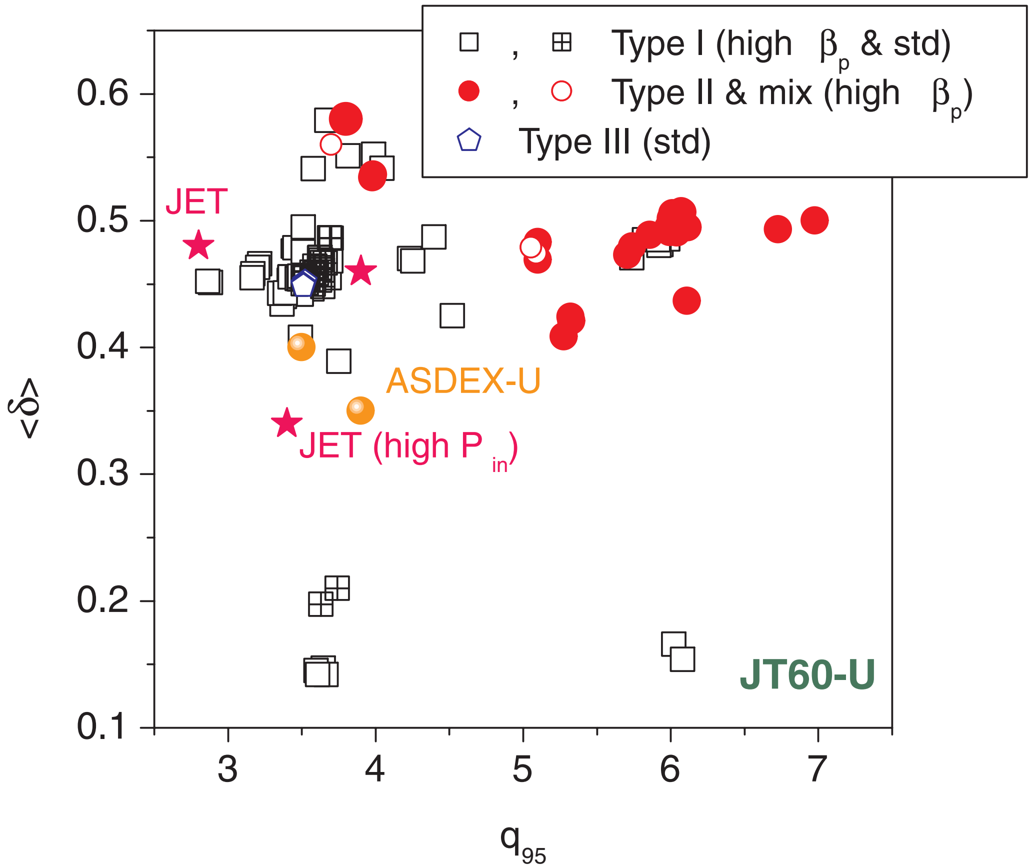
- **Best understanding of ELM energy losses at Snowmass indicated 3.6 MJ in a typical Type I ELM**
- **All of the ELM energy goes to the outer divertor**
- **The effective area of the outer divertor is 2.4 m^2**
- **The energy deposition is 1.5 MJ/m^2**
- **The melting threshold is between 0.5 and 1.5 MJ/m^2 depending on the ELM duration (0.1 or 1.0 ms)**
- **Type I ELMs are a life limiting event for the divertor.**

Type II ELMs

- At high density (n_{ped} >70% nGR), ELMs losses can become purely convective with ∇TELM~0
- Conditions of access vary: high δ is required (possibly q95 >3.5)
- High βp (JT60-U) and proximity to DN (ASDEX-U, JT60-U?)
- Type II ELMs in ETB H-modes so far observed for pedestal parameters near the Type I-III transition (ASDEX-U, and mixed ELM regime in JET and DIII-D QDB)
- DIII-D Locked Mode coils reduce ELM size without affecting confinement

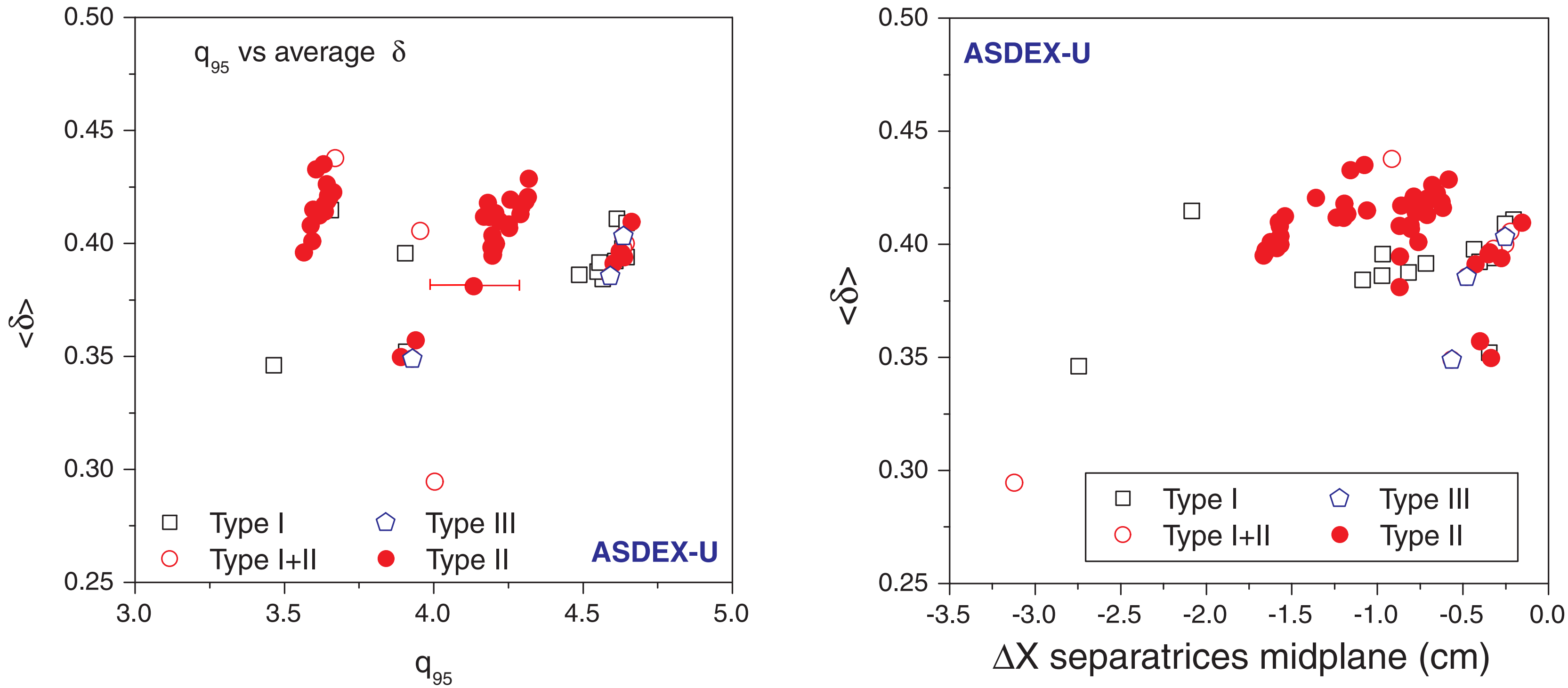
From Saibene, EPS

High Triangularity Effect on ELMs



From Saibene, EPS

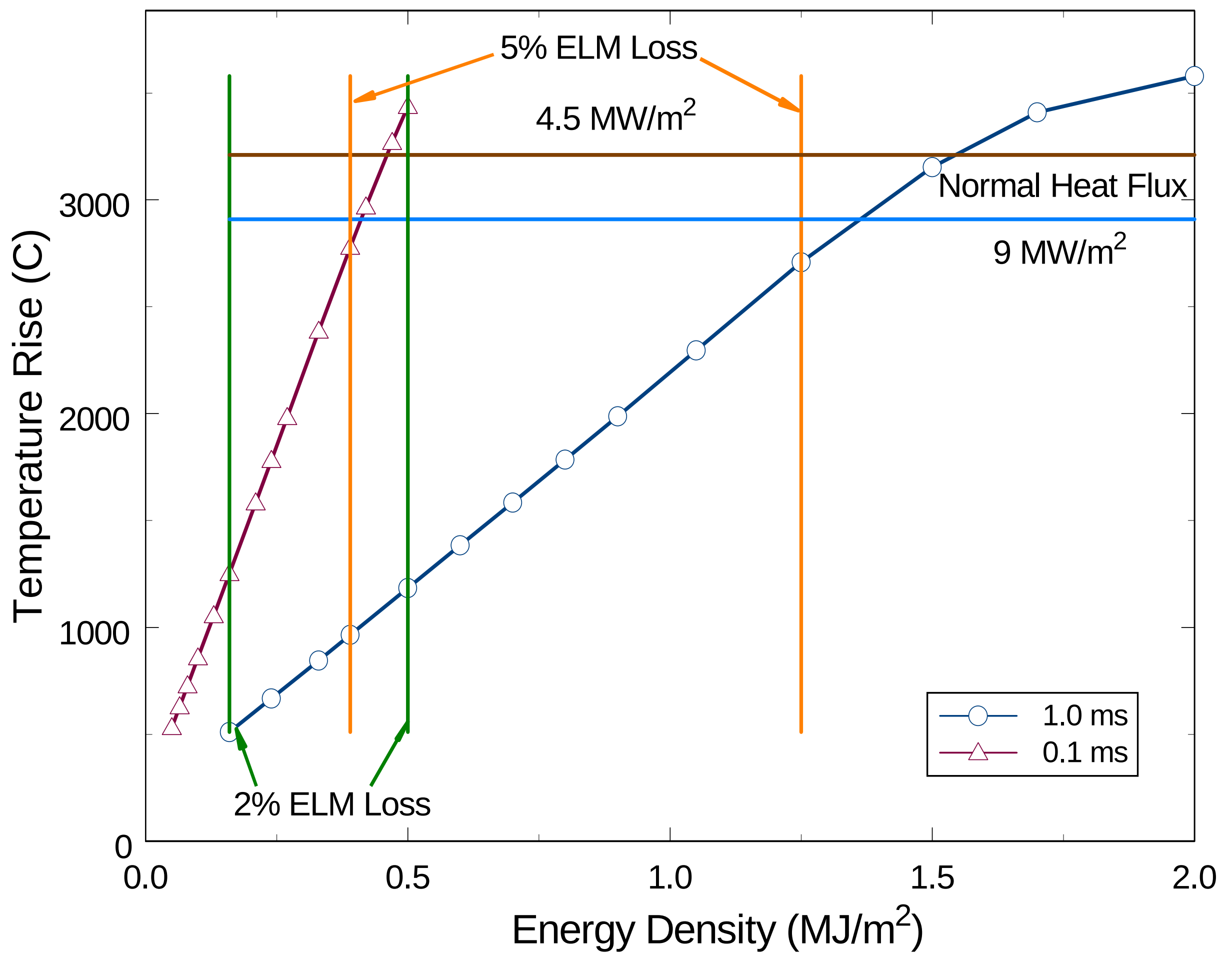
Type II in ASDEX-U: Quasi DN configuration



- **Type II require high δ (as JET and JT60-U) and n_e**
- **Proximity to DN configuration is essential**

From Saibene, EPS

Allowed ELMs on FIRE



Remaining Open Issues

- **The disruption forces on the new design need to be compared to the forces in the 2.0 m design. If there is a large difference the supports for the divertor will have to be refined. (will be done by 3/30)**
- **The effect of deposited Be on the performance of the W divertor need to be determined (upcoming TPE experiments).**
- **The pumping speed of the new configuration needs to be calculated (should be better than the old design because there are fewer obstructions.**

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Remaining Open Issues

- **Analysis of the divertor loads on the vacuum vessel needs to be done (local reinforcement may be needed).**
- **Thermal stress analysis for the new design needs to be done (heat loads are lower than the old design unlikely there is a problem). (Baxi is working on this)**
- **ELM erosion testing should be done (starting 3/31 at SNL).**

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ELM Simulations on W Rods

- EB1200 at SNL has two independent e-guns
- We will use one to apply steady state heat flux (FIRE and ITER like) and the other (unscanned) to simulate ELMS (up to 1.5 MJ/m^2 in <1ms)
- This testing will be conducted at a few Hz and result in thousands of ELMS in less than a days operation.
- Damage to the W surface will be monitored during cycling.

ITER Overlap

- FIRE peak heat flux is very similar to the ITER peak heat flux
- The FIRE duration is long enough to require active cooling of the divertor (steady state is possible)
- The Be first wall is the ITER choice also (First Wall heat loads are similar).
- ITER is considering an all W option and a mixed W/Be option because of the continuing problem with T retention in C.

Conclusions

- The divertor design has been updated to the new major radius (2.14 m)
- Heat flux to the divertor has been updated using UEDGE and the newest edge transport parameters.
- Heat flux is reduced because of lower fusion power, greater flux spreading, and increased transport.
- The divertor operating temperatures are reduced and it is not as necessary to use impurity radiation to spread out the power.

Conclusions II

- Two disruption cases are being used to determine disruption forces: maximum current decay rate and maximum halo currents
- Analysis of disruption induced eddy currents is being conducted using the OPERA code.
- Because of the lower heat fluxes the margins for ELM heat deposition have been increased.