Plasma Edge and Surface Interactions Modeling

A Technology Perspective

M. Ulrickson

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Outline

- Key needs for design of new machines
- Progress on modeling
- Challenges For Moving Forward
- Conclusions

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Key Needs For Design

- Equilibrium Properties
- Scrape-off layer properties
- Heat and Particle Loads on Divertor PFCs
- Temporal Peaking Specification (ELMs)
- Disruption Energy Deposition and Induced Currents

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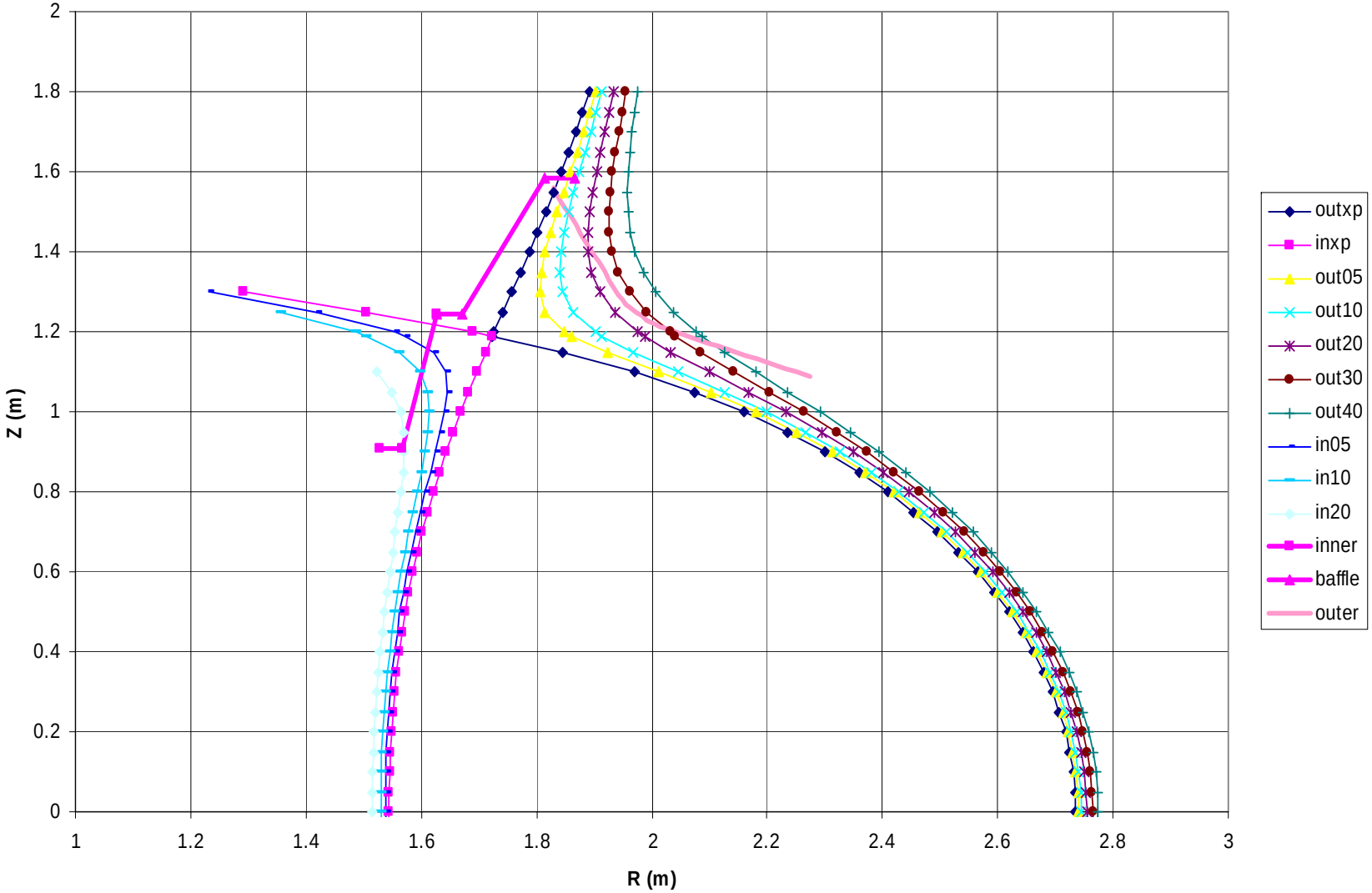
Flux Geometry in FIRE



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Scrape-off layer properties

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

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UEDGE Modeling Results

- 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 coefficient
- Midplane profiles show scaling with core-edge density and transport coefficients

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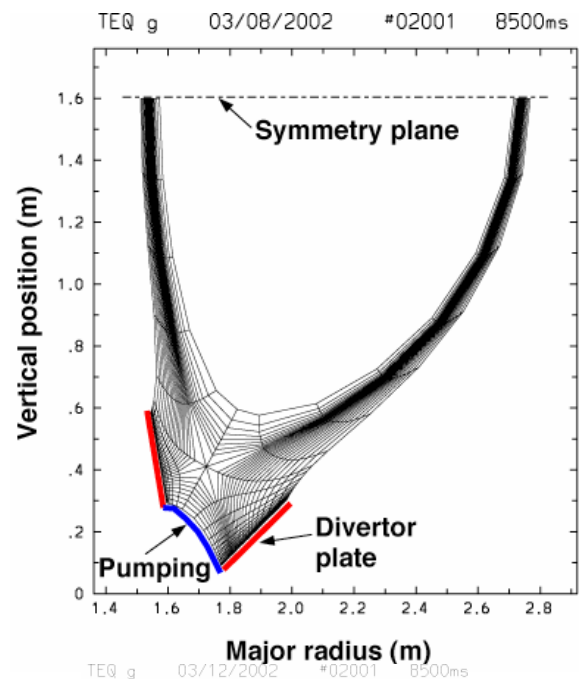
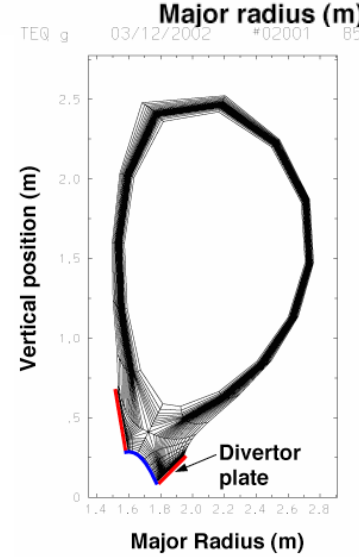
FIRE designed for double-null divertor

- 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

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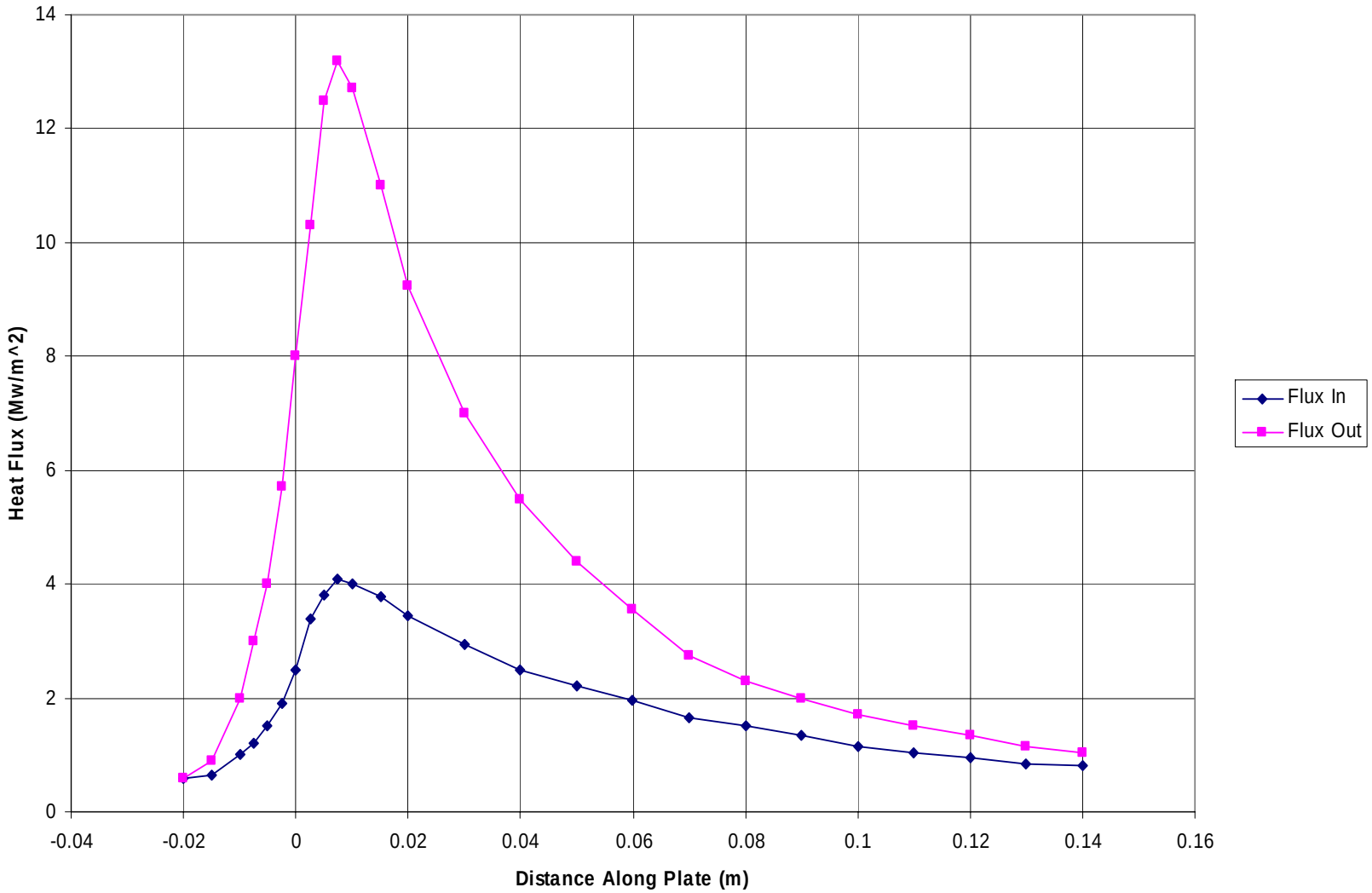
Heat and Particle Loads on Divertor PFCs

SOL Heat Loads from UEDGE



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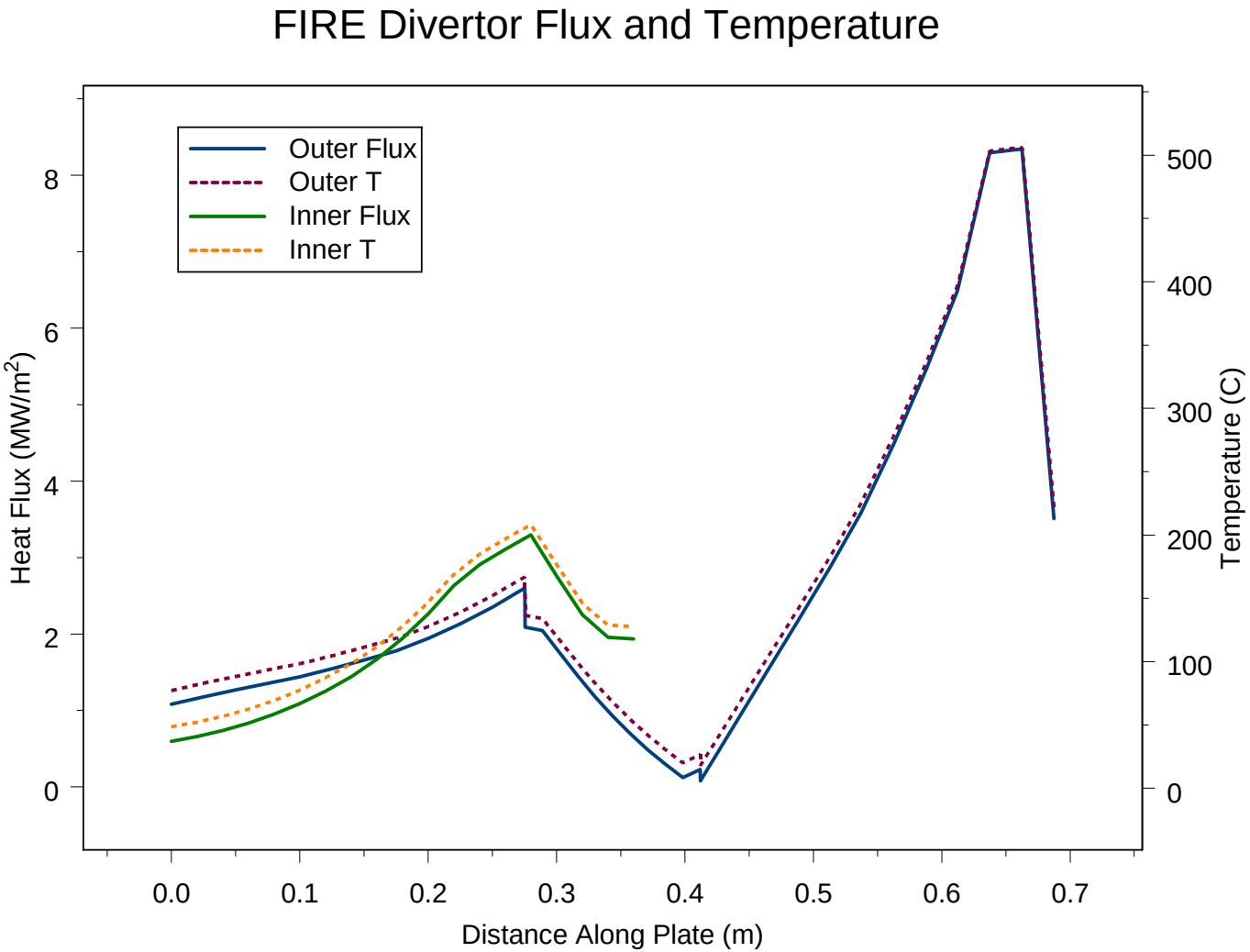
Heat Loads on the Divertor



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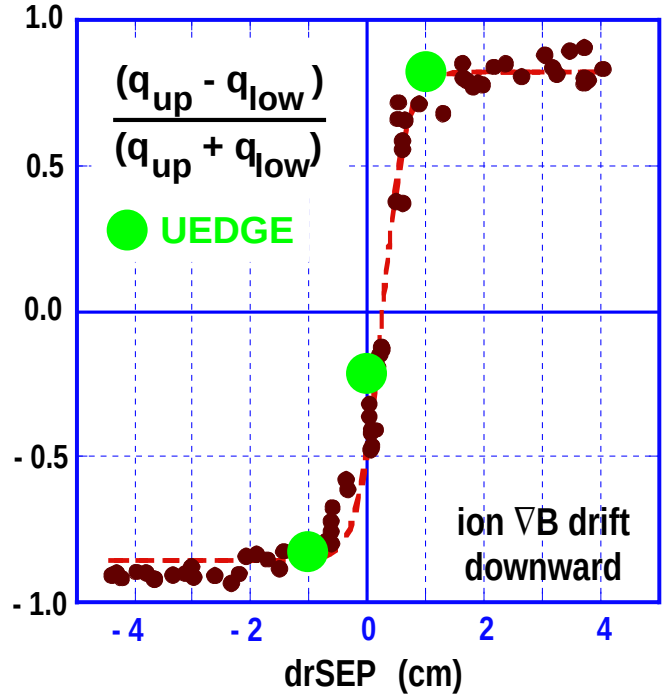
Power Balance is Sensitive

- 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

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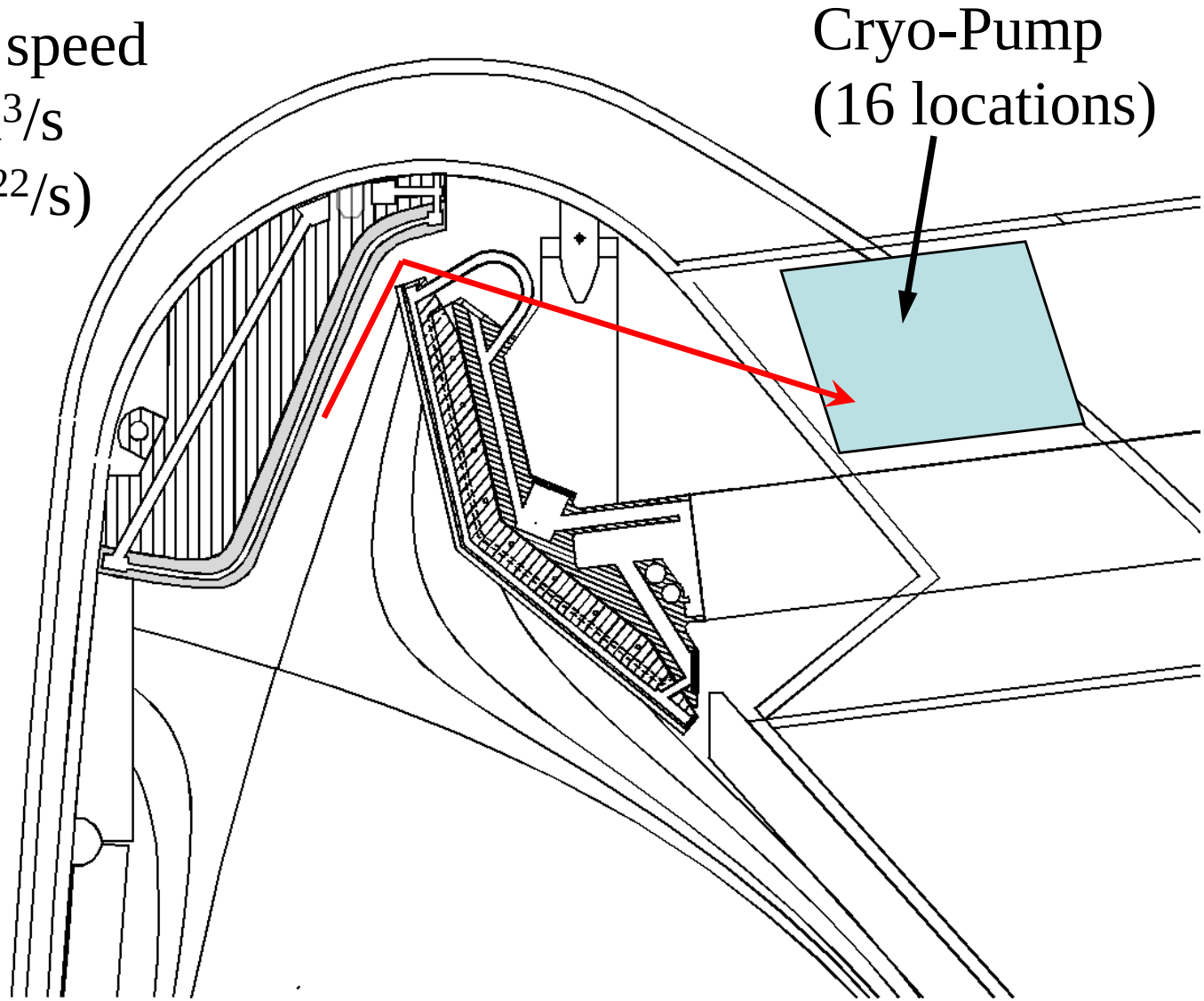
Divertor Pumping Geometry

Pumping speed
100 Pa/m^3/s
(2.5 x 10^{22}/s)



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Temporal Peaking Specification (ELMs)

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.

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The Problem with ELMs

- ELM Energy Deposition on the FIRE Divertor Plates assumed
  - Either 2% or 5% of stored energy lost
  - Energy deposited is estimated to be 0.3 to 1.2 MJ/m^2 with a duration of 0.1 ms
- ELMS are the greatest threat to long lifetime PFCs (disruption mitigation is likely to be effective)
  - Melting, thermal fatigue,
- Either ELM mitigation methods are found or plasma operation will have to be less optimized (less confinement)

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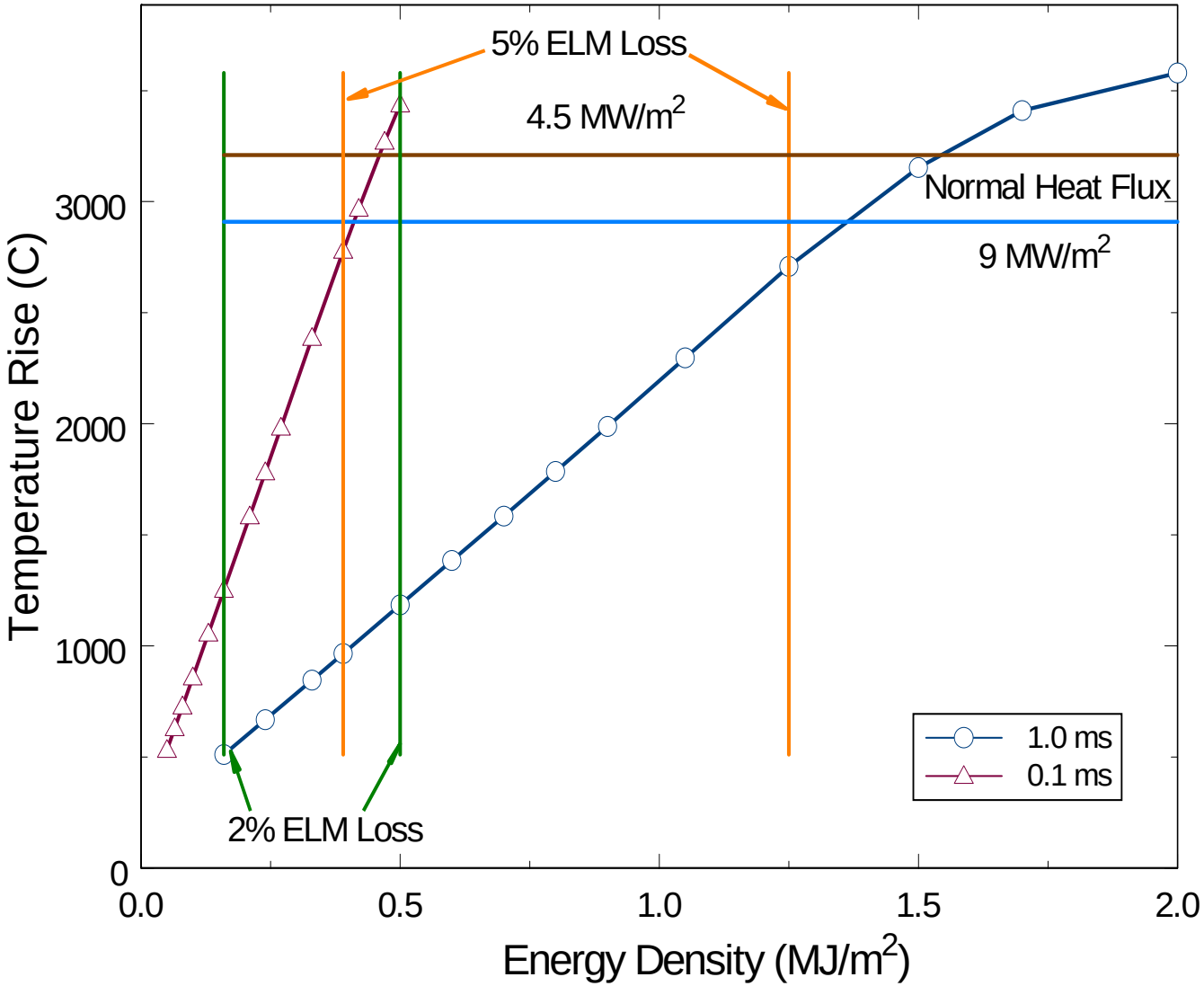
Allowed ELMs on FIRE



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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

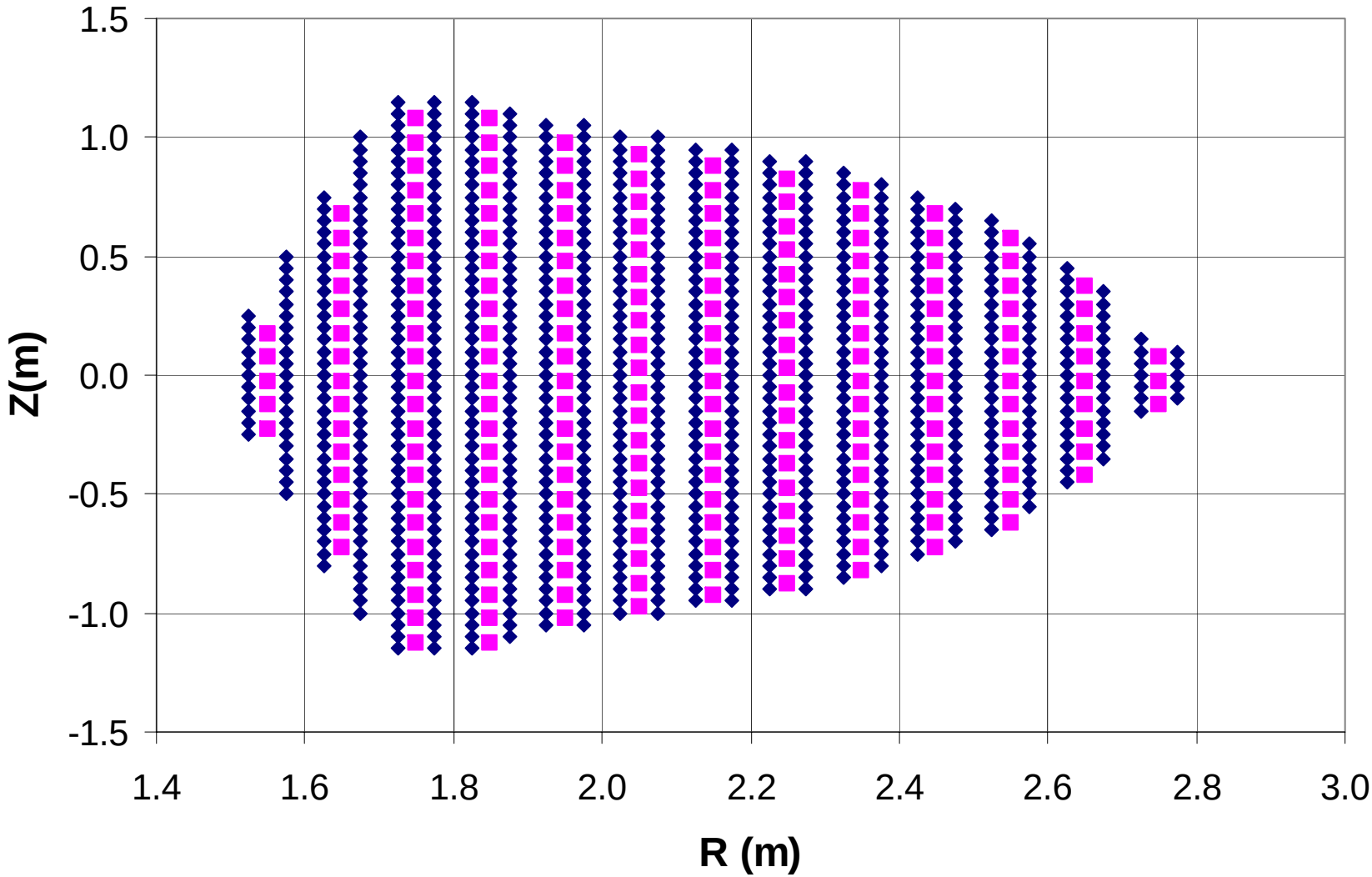
Disruption Energy Deposition and Induced Currents

Disruption Modeling with TSC

- 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
- The plasma filaments had to be reduced in number to reduce the disruption analysis time (external field pattern not altered)
  - How to judge how far this can be taken?

Data provided by C. Kessel, PPPL

Plasma Filaments



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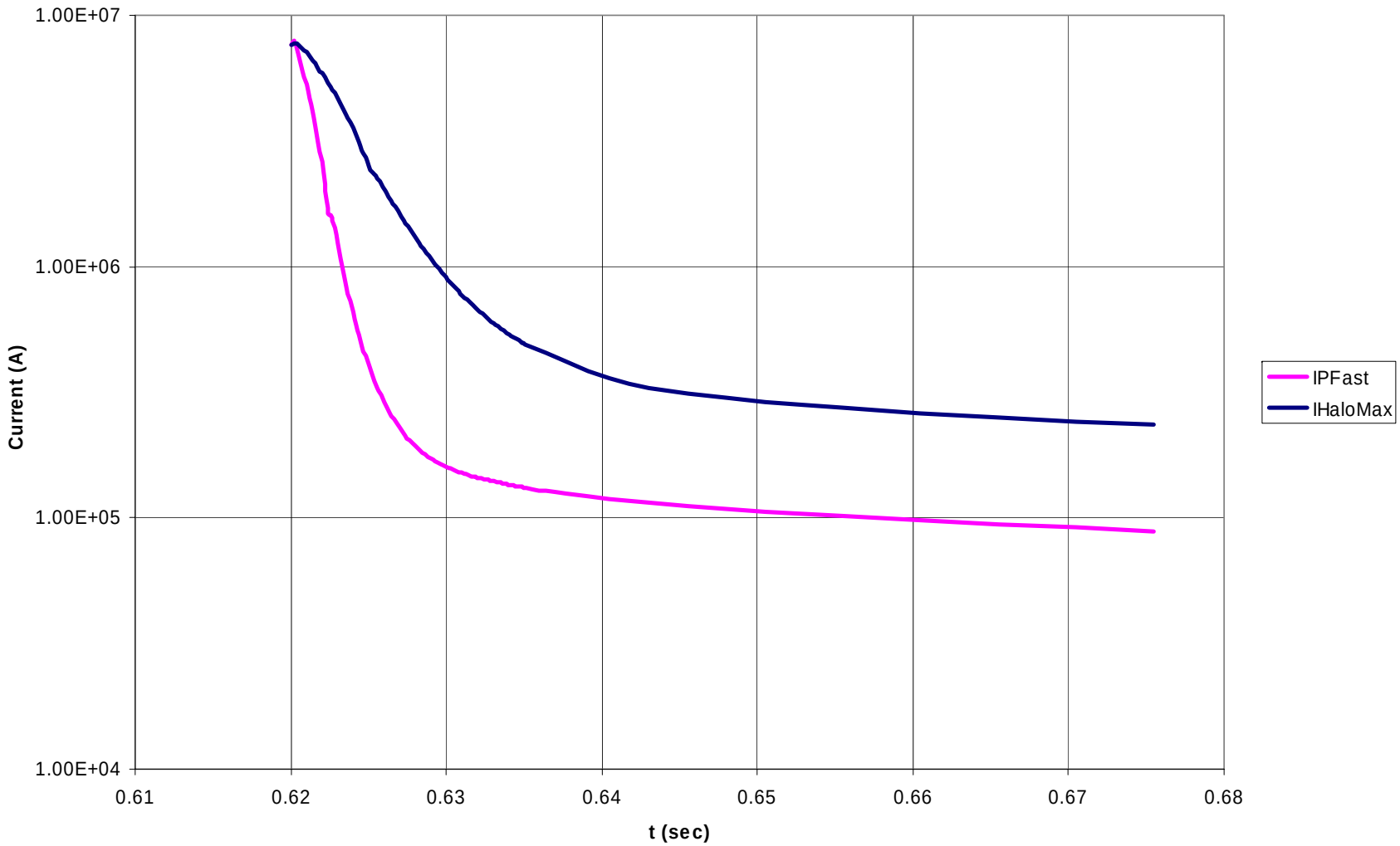
Disruption Cases from TSC



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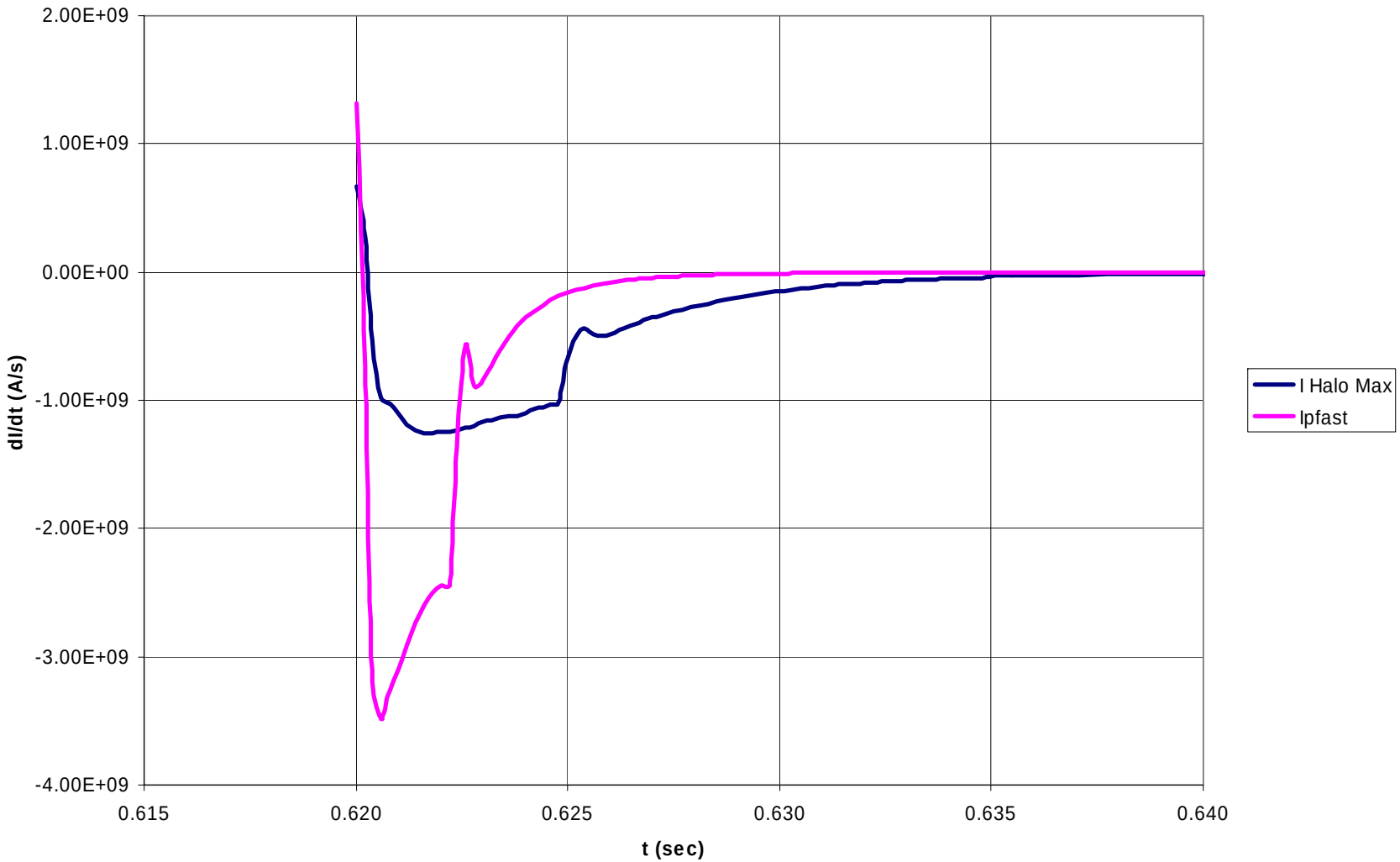
Idot in Disruption Cases



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Halo Currents

- Halo currents are typically prescribed by a fraction of the plasma current and a toroidal peaking factor (both empirical)
- Taking either a peaked or a uniform distribution gives the same halo current in the worst location.
- The maximum halo current range is from 200 kA/module (FIRE) to about 300 kA/module (ITER).

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Progress On Modeling

- More fidelity
  - Inclusion of non-fluid neutrals treatment in UEDGE
  - Inclusion of EXB drifts
  - Coupling of UEDGE with WBC/REDEP
- Standard output formats
  - EQDISK files for magnetic geometry

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Challenges For Moving Forward

- Standardized interface with UEDGE
- Simplified output from TSC
- Analytic methods to replace Monte Carlo methods (improved throughput)
- Improved ELM models leading to ⇒
- Understanding and control of ELMs
- Understanding of variation of χ_e, χ_i, D, v_{conv}, etc. with plasma parameters

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A Specific Request

- Alcator C-Mod is planning to install a cryo-pump soon
  - The location is in the upper divertor chamber
  - In single null operation, the particle flux to the upper divertor should be strongly influenced by convective transport
- Compute the expected performance of the cryo-pump using the best combination of codes
  - Excellent test of convection models
  - Excellent test of coupling of SOL and neutral models

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Conclusions

- There is a need for standard interfaces with SOL codes and operating mode codes that provide data needed for PFC design without excessive details
- The coupling of SOL and accurate neutral models is very important
- Control of ELMs is essential for long pulse future fusion devices
- Progress in mitigating disruptions is very promising

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