Dynamics of a Major Disruption of a DIII-D Plasma

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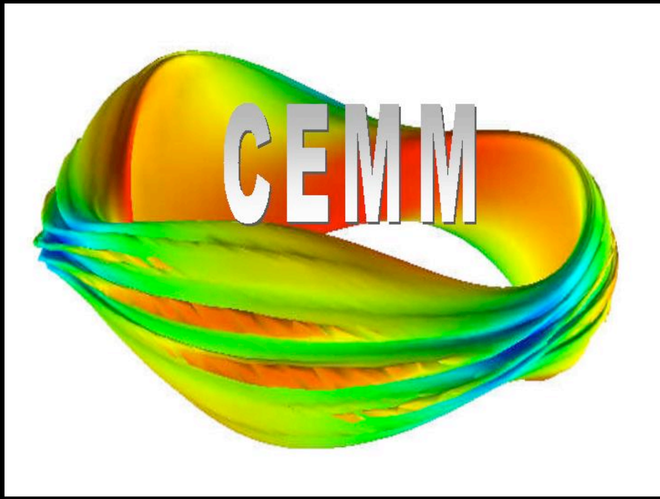

Center for Extended Magnetohydrodynamic Modeling

Outline

- Motivation
  - High-beta disruption discharge: #87009

- NIMROD Modeling
  - Fixed boundary - time dynamics
  - Free-boundary - Heat loading

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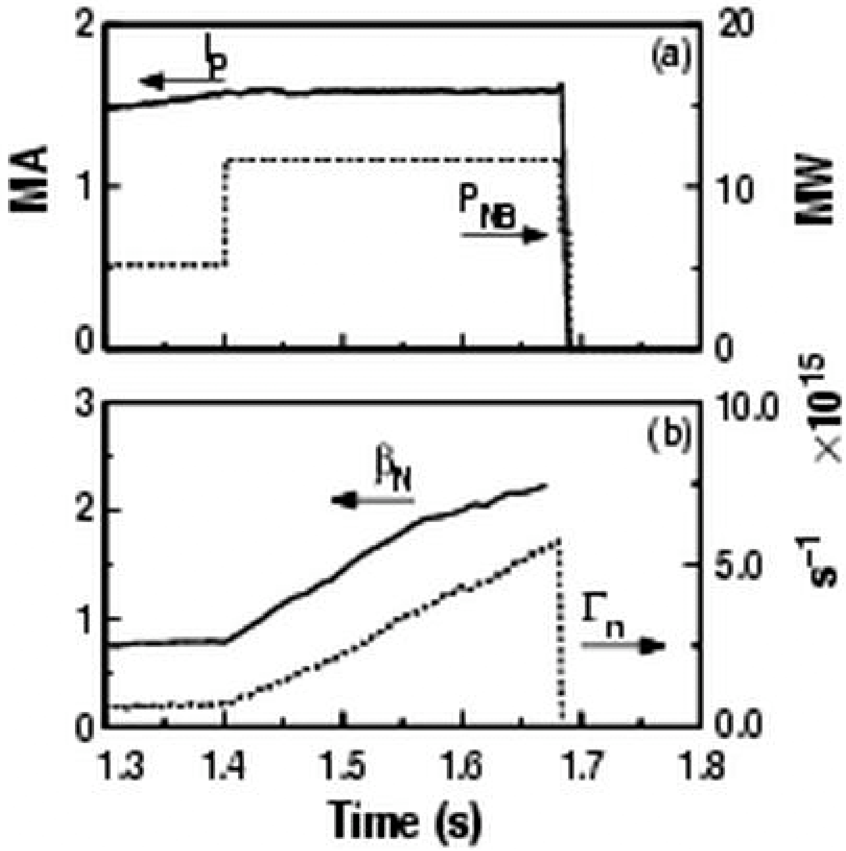
DIII-D SHOT #87009 Observes a Plasma Disruption During Neutral Beam Heating At High Plasma Beta



Callen et.al, Phys. Plasmas 6, 2963 (1999)

Resistive MHD Equations Used to Numerically Model Disruption

- **MHD Equations Solved:**
  - **Density Equation:**

$$\frac{\partial n}{\partial t} + \nabla \cdot n\mathbf{V} = 0$$

  - **Momentum Equation**

$$\rho\left(\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\cdot\nabla)\mathbf{V}\right) = \mathbf{J}\times\mathbf{B} - \nabla p - \mu\nabla^2\mathbf{V}$$

  - **Resistive MHD Ohm's Law:**

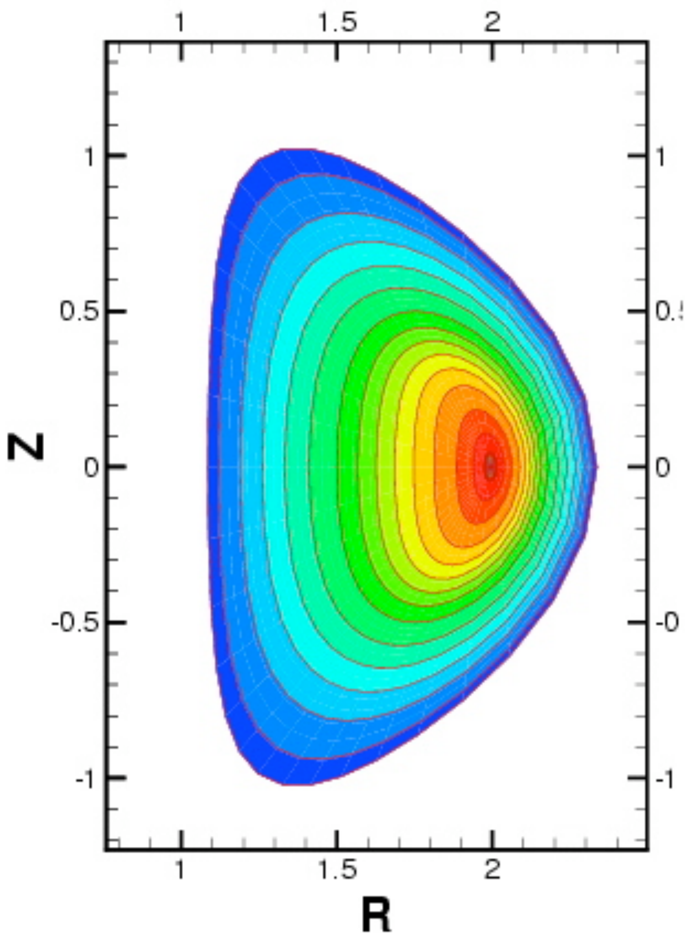
$$\mathbf{E} = \underbrace{-\mathbf{V}\times\mathbf{B}}_{\text{Ideal MHD}} + \underbrace{\eta\mathbf{J}}_{\substack{\text{Resistive}\\ \text{MHD}}}$$

  - **Temperature Equations:**

$$\frac{\partial T_\alpha}{\partial t} + \mathbf{V}_\alpha\cdot\nabla T_\alpha + \gamma T_\alpha \nabla\cdot\mathbf{V}_\alpha = -(\gamma-1)\nabla\cdot\mathbf{q}_\alpha + (\gamma-1)Q_\alpha$$

$$\text{Currently}: \quad \mathbf{q}_\alpha = -\kappa_{\parallel}\mathbf{bb}\cdot\nabla T - (\kappa_\perp - \kappa_\parallel)\nabla T$$

Two Types of Simulations Performed to Explore Disruption Dynamics

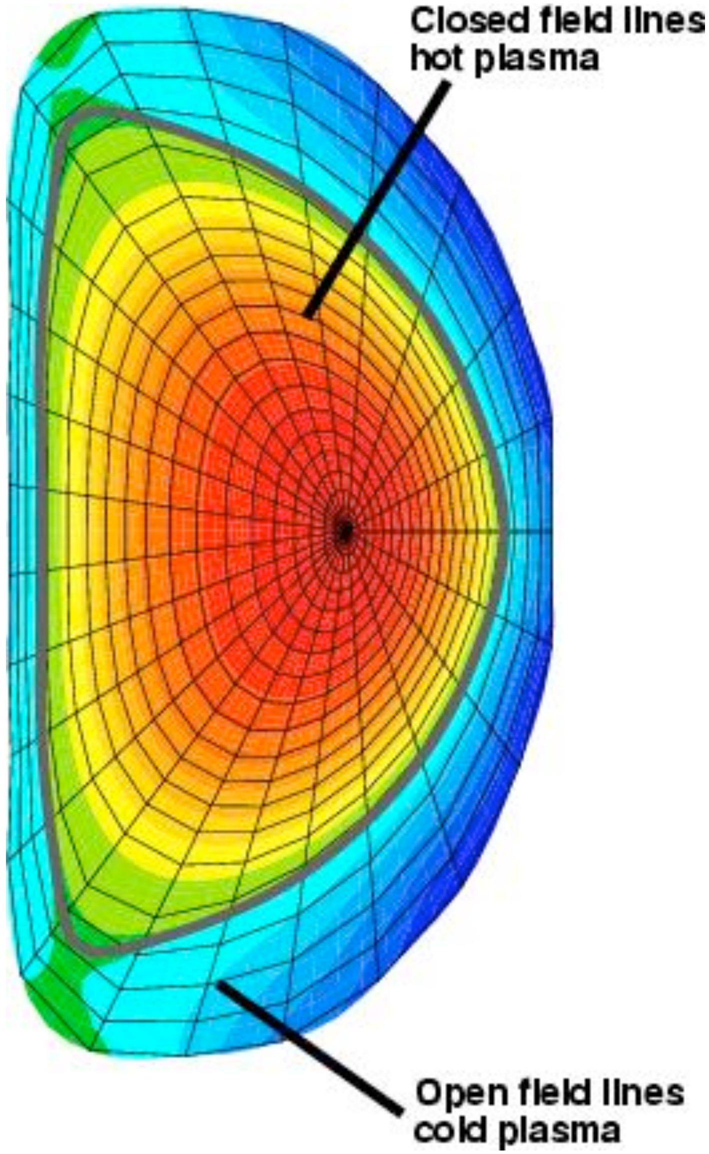


Fixed Boundary

- Computational boundary is set by last closed flux surface
- Makes computations easier

Used to explore time dynamics

Two Types of Simulations Performed to Explore Disruption Dynamics



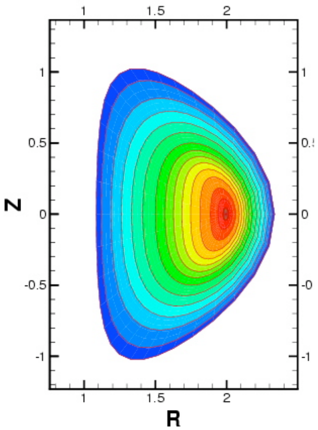
Free Boundary

- Computational boundary is set by vacuum vessel
- Spitzer resistivity: $\eta \sim T^{-3/2}$
  - –Suppress currents on open fieldlines
  - –Large gradients in 3D
- Requires accurate calculation of anisotropic thermal conduction

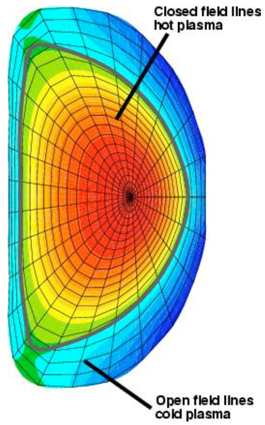
Used to explore spatial dynamics

esp. of heat transport and wall loading

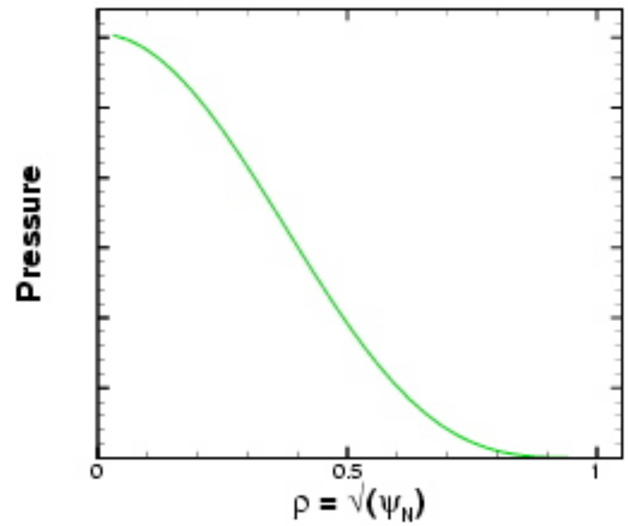
Two Types of Simulations Performed to Explore Disruption Dynamics

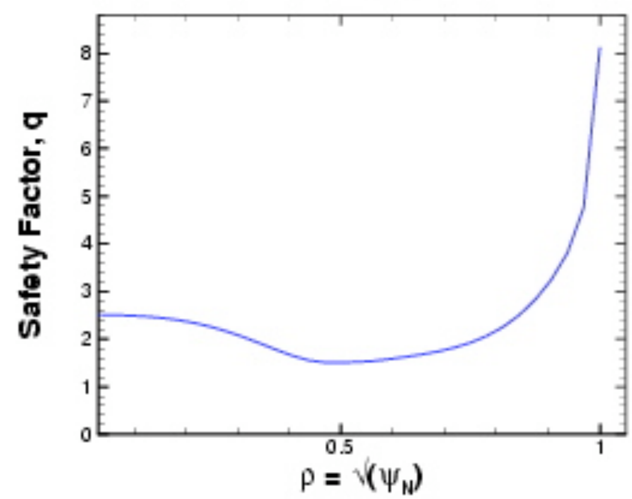


Fixed Boundary
time dynamics



Free Boundary
spatial dynamics





Equilibria:
- **L-mode edge**
- **Reverse shear q_{min}~1.6**

Mode Passing Through Instability Point Has Faster-Than-Exponential Growth

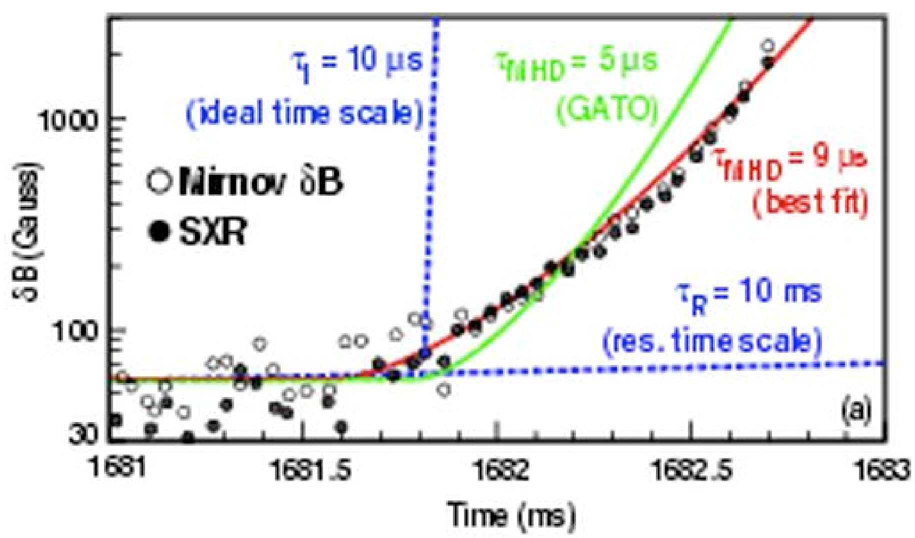
- **Theory of ideal growth in response to slow heating**
  (*Callen, Hegna, Rice, Strait, and Turnbull, Phys. Plasmas 6, 2963 (1999)*):

Heat slowly through critical β: $\beta = \beta_c(1+\gamma_h t)$

Ideal MHD: $\omega^2 = -\hat{\gamma}^2_{MHD}(\beta/\beta_c - 1)$ ➔ $\gamma(t) = \hat{\gamma}_{MHD}\sqrt{\gamma_h t}$

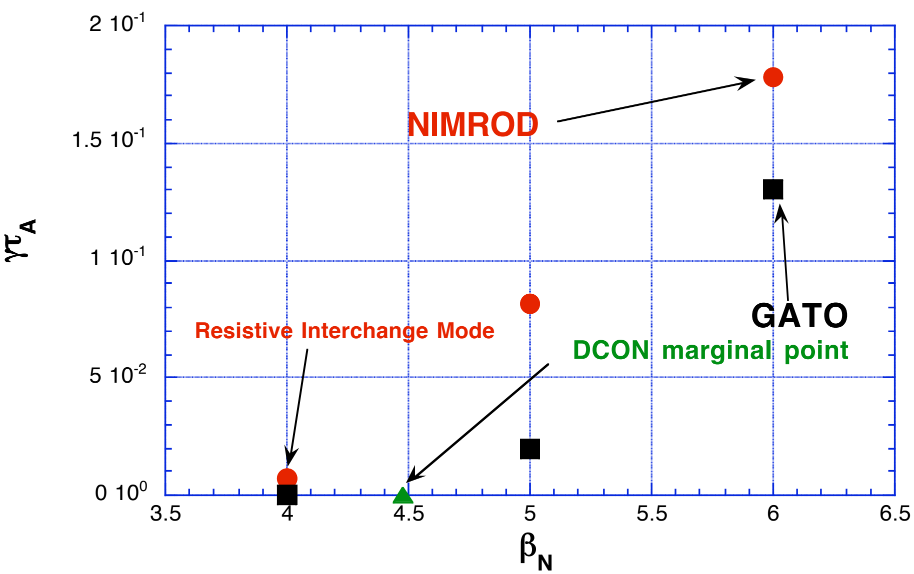
Perturbation growth: $\dfrac{d\xi}{dt} = \gamma(t)\xi$

$$\xi = \xi_0 \exp[(t/\tau)^{3/2}], \quad \tau = (3/2)^{2/3}\hat{\gamma}_{MHD}^{-2/3}\gamma_h^{-1/3}$$



Fixed Boundary Simulations Require Going to Higher Beta

- **Conducting wall raises ideal stability limit**
  - **Need to run near critical β_N for ideal instability NIMROD gives slightly larger ideal growth rate than GATO**
- **NIMROD finds resistive interchange mode below ideal stability boundary**



Nonlinear Simulations Find Faster-Than-Exponential Growth As Predicted By Theory

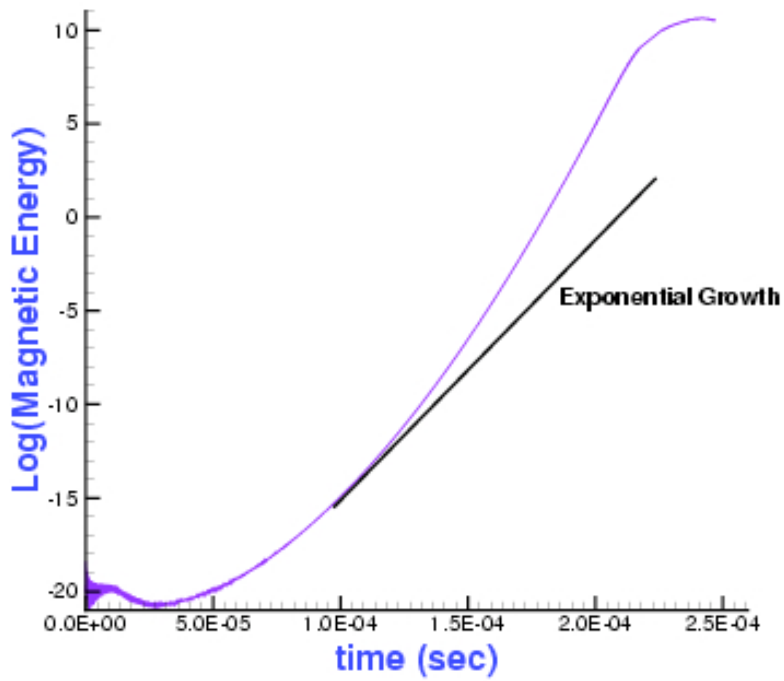
- **Impose heating source proportional to equilibrium pressure profile**

$$\frac{\partial P}{\partial t} = \quad \ldots\ldots \quad + \gamma_H P_{eq}$$

$$\Rightarrow \quad \beta_N = \beta_{Nc}(1+\gamma_H t)$$

- **Follow nonlinear evolution through heating, destabilization, and saturation**

Log of magnetic energy in $n = 1$ mode vs. time
$S = 10^6$ Pr = 200 $\gamma_H = 10^3$ sec^{-1}



Scaling With Heating Rate Gives Good Agreement With Theory

- NIMROD simulations also display super-exponential growth
- Simulation results with different heating rates are well fit by $\xi \sim \exp[(t\text{-}t_0)/\tau]^{3/2}$
- Time constant scales as

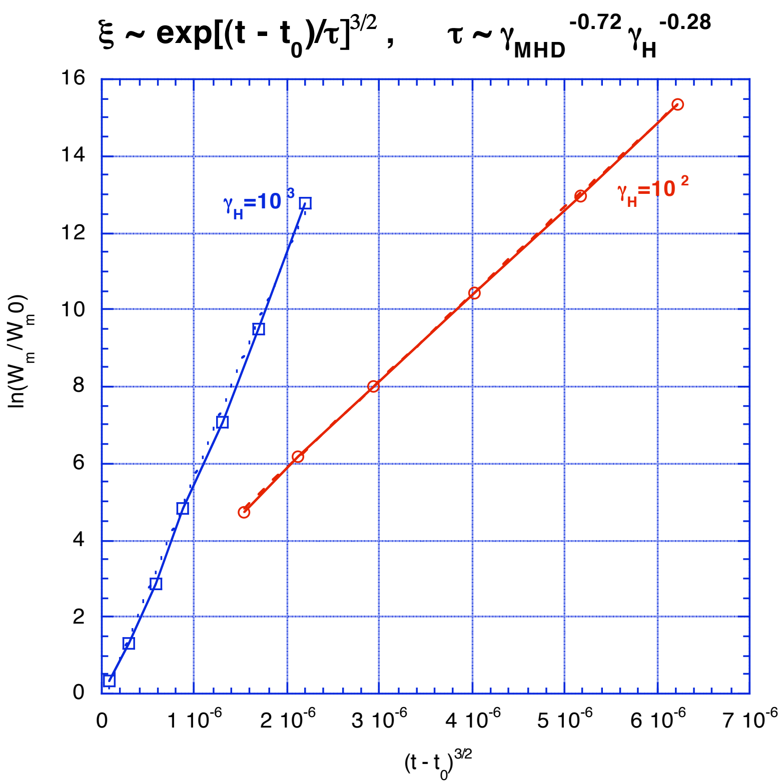
$$\tau \sim \gamma_{MHD}^{-0.72} \gamma_{H}^{-0.28}$$

- Compare with theory:

$$\tau = (3/2)^{2/3} \hat{\gamma}_{MHD}^{-2/3} \gamma_{h}^{-1/3}$$

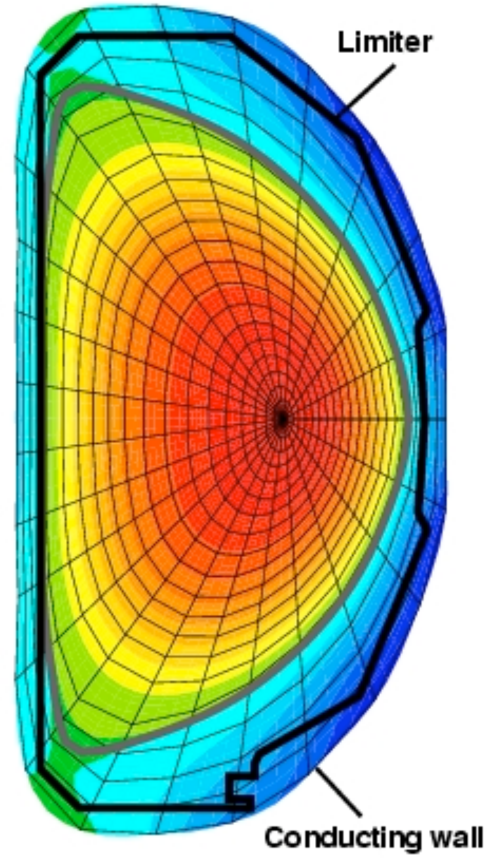
- Discrepancy possibly due to non-ideal effects

Log of magnetic energy vs. $(t - t_0)^{3/2}$ for 2 different heating rates

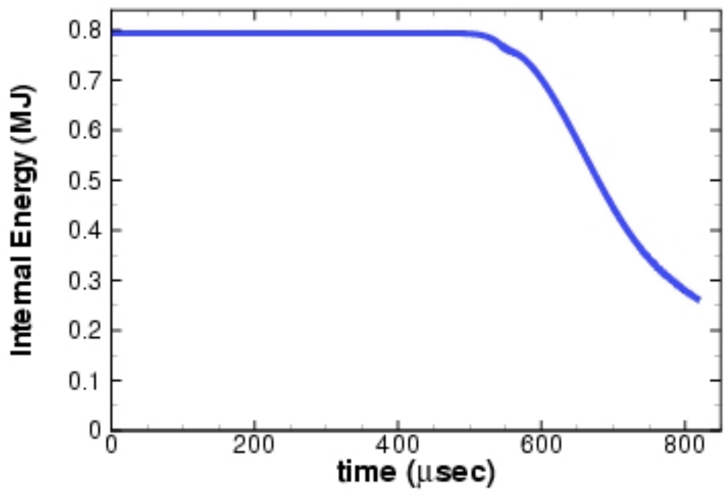


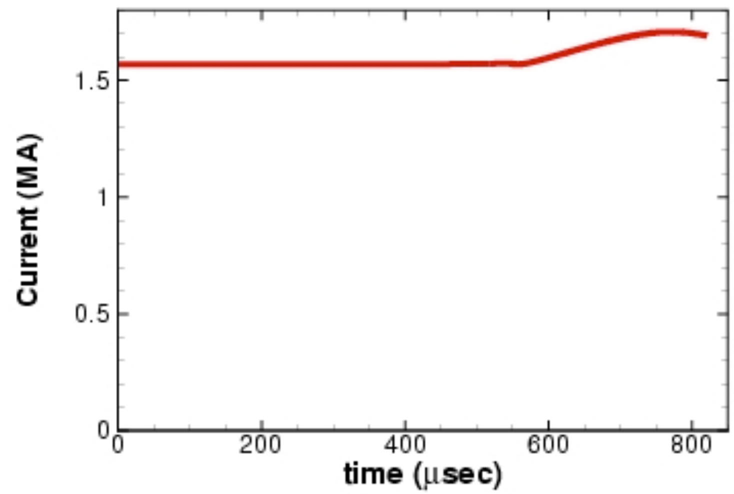
Goal of Simulation is to Model Power Distribution On Limiter during Disruption

- Pressure raised 8.7% above best-fit EFIT
- Above ideal MHD marginal stability limit
  Ideal modes grow with finite η ($S = 10^5$)
- Simulation includes:
  - Anisotropic heat conduction (with no T dependence) $\kappa_{par}/\kappa_{perp}=10^8$
- Plasma-wall interactions are complex and beyond the scope of this simulation
- No boundary conditions are applied at limiter for velocity or temperatures.
  - This allows fluxes of mass and heat through limiter
  - Normal heat flux is computed at limiter boundary



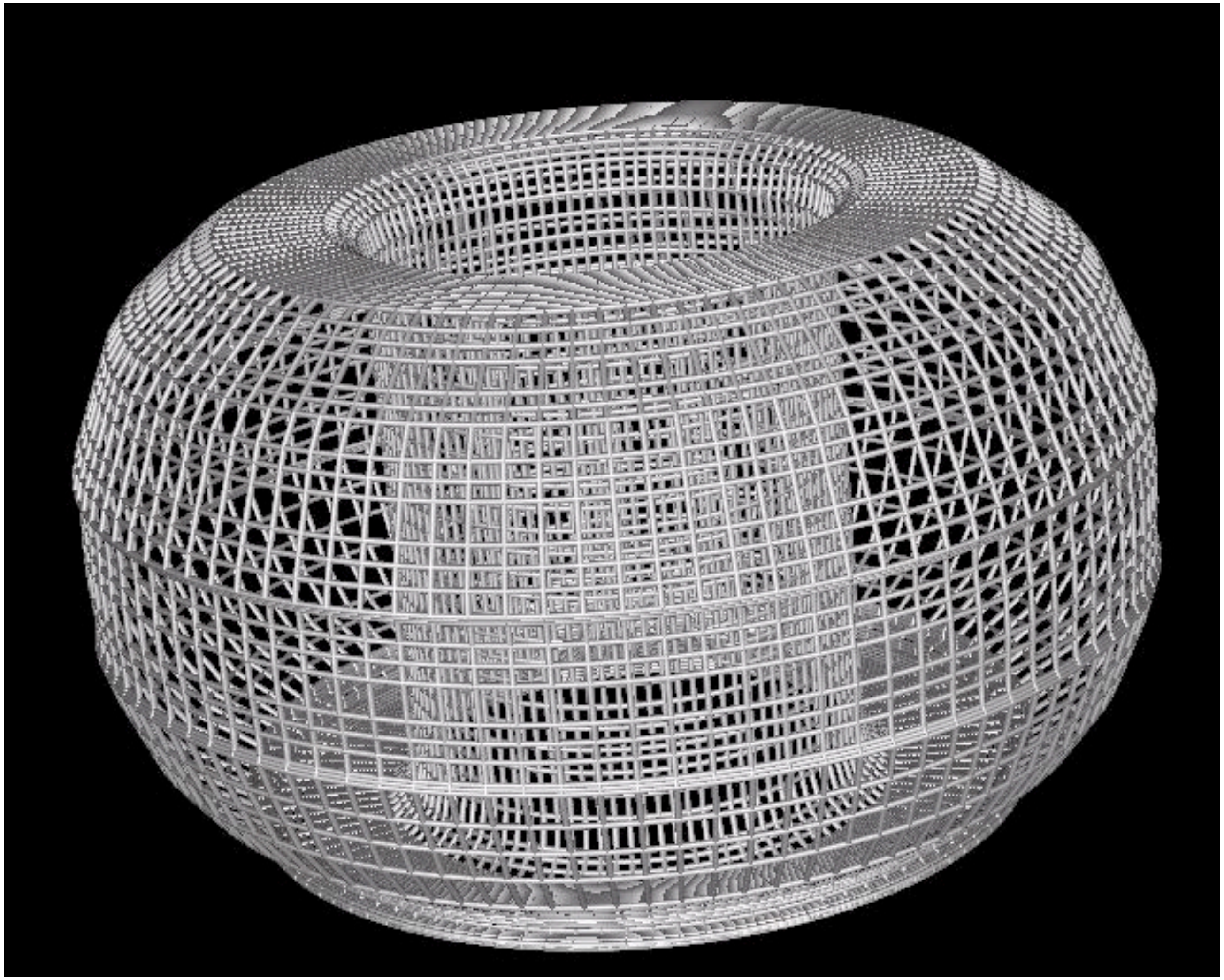
Simulation Shows Rapid Loss of Internal Energy and Current Spike





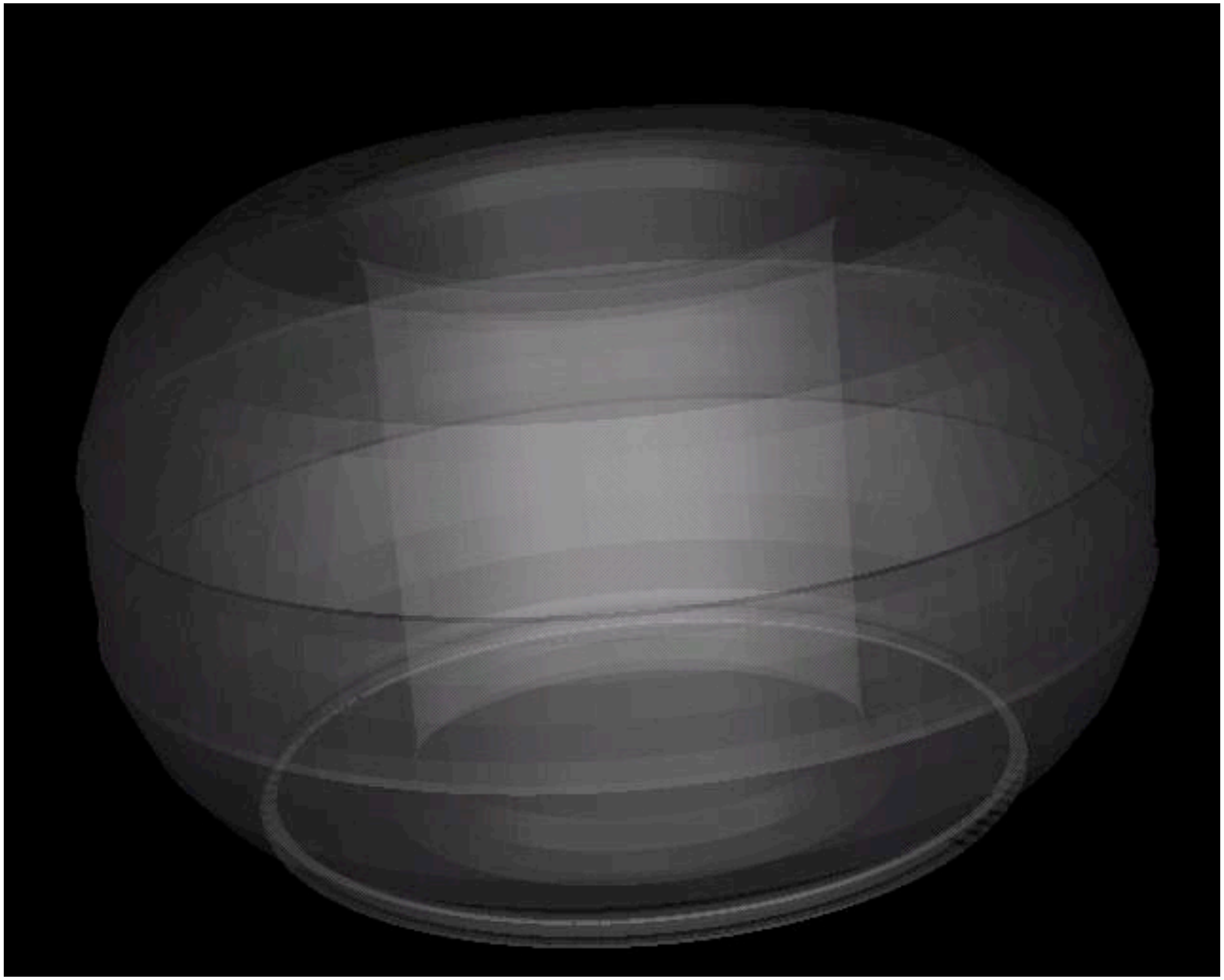
Plasma loses 60% of magnetic energy in ~200 microseconds

Movie Shows Dynamics of Disruption



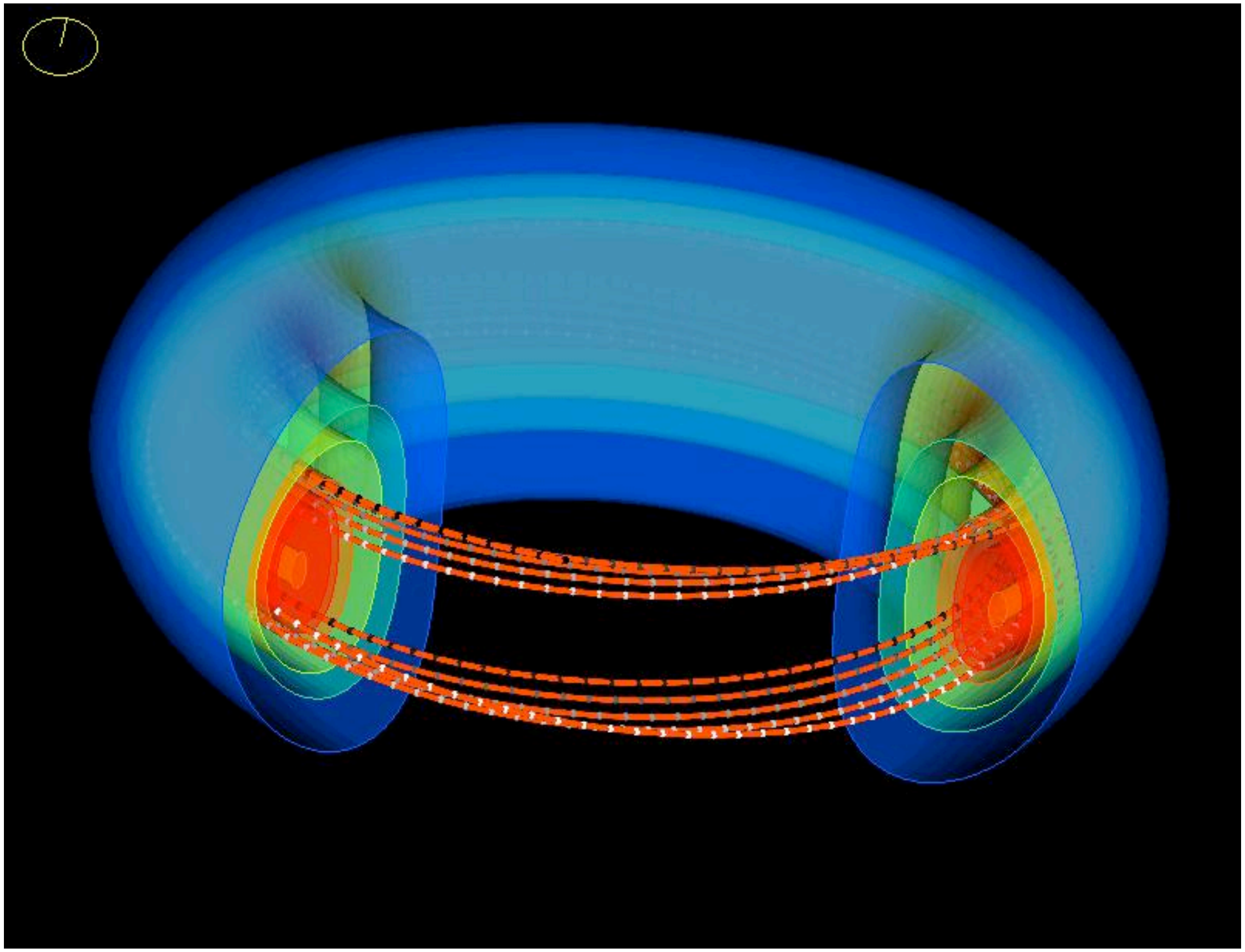
DIII-D Limiter Geometry

Movie Shows Dynamics of Disruption



Initial Heat Flux is Low

Movie Shows Dynamics of Disruption

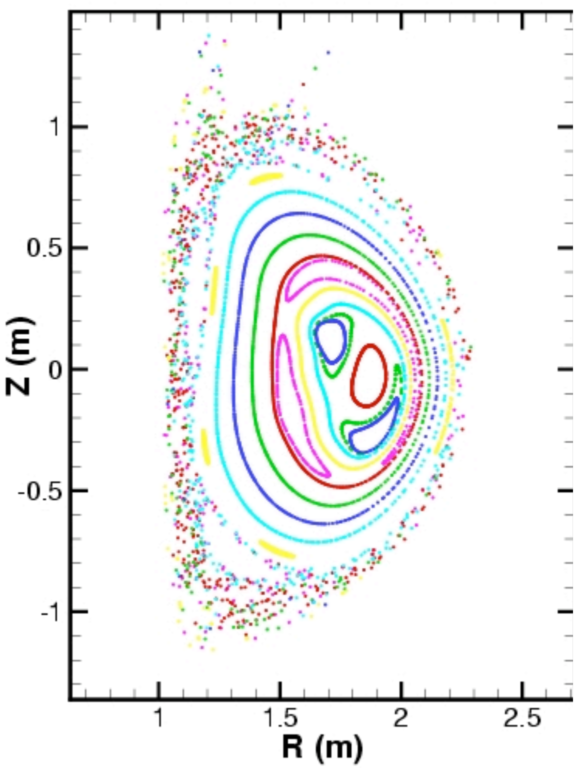


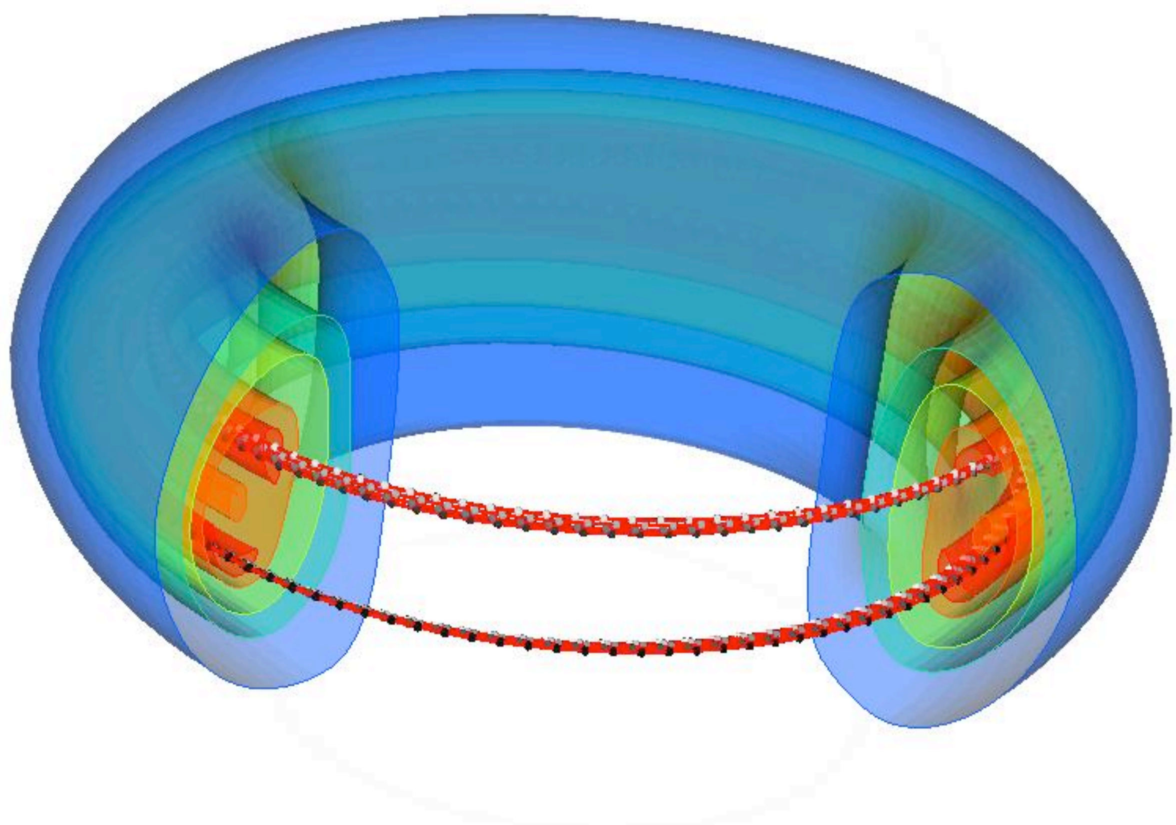
Temperature Isosurfaces
Fieldline colored by temperature
Nodes indicate distance along fieldline

Movie Not Included In This File

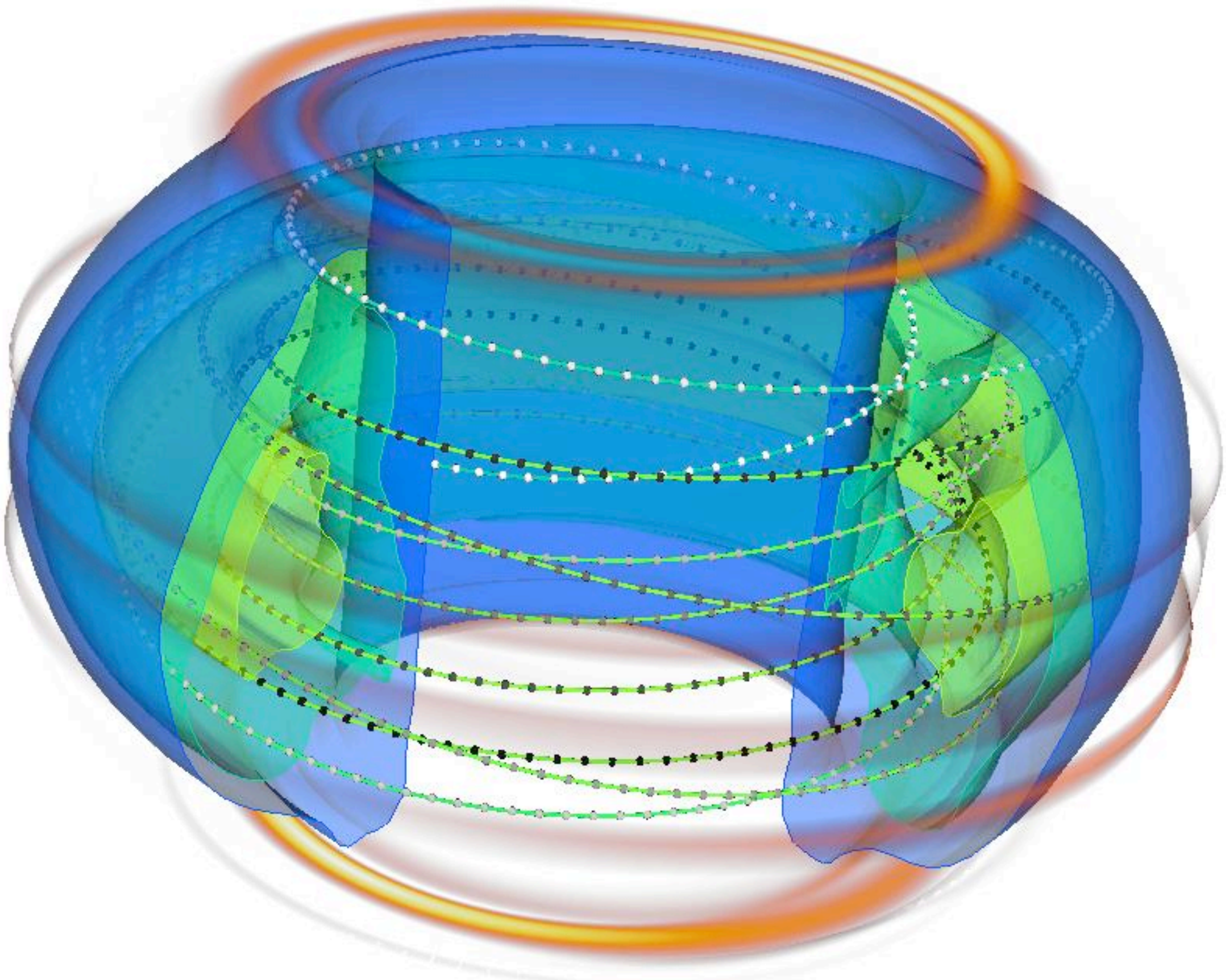
- **See: http://nimrodteam.org/HBD for movie and related information**

Macroscopic Islands Appear
At 2/1 Rational Surfaces

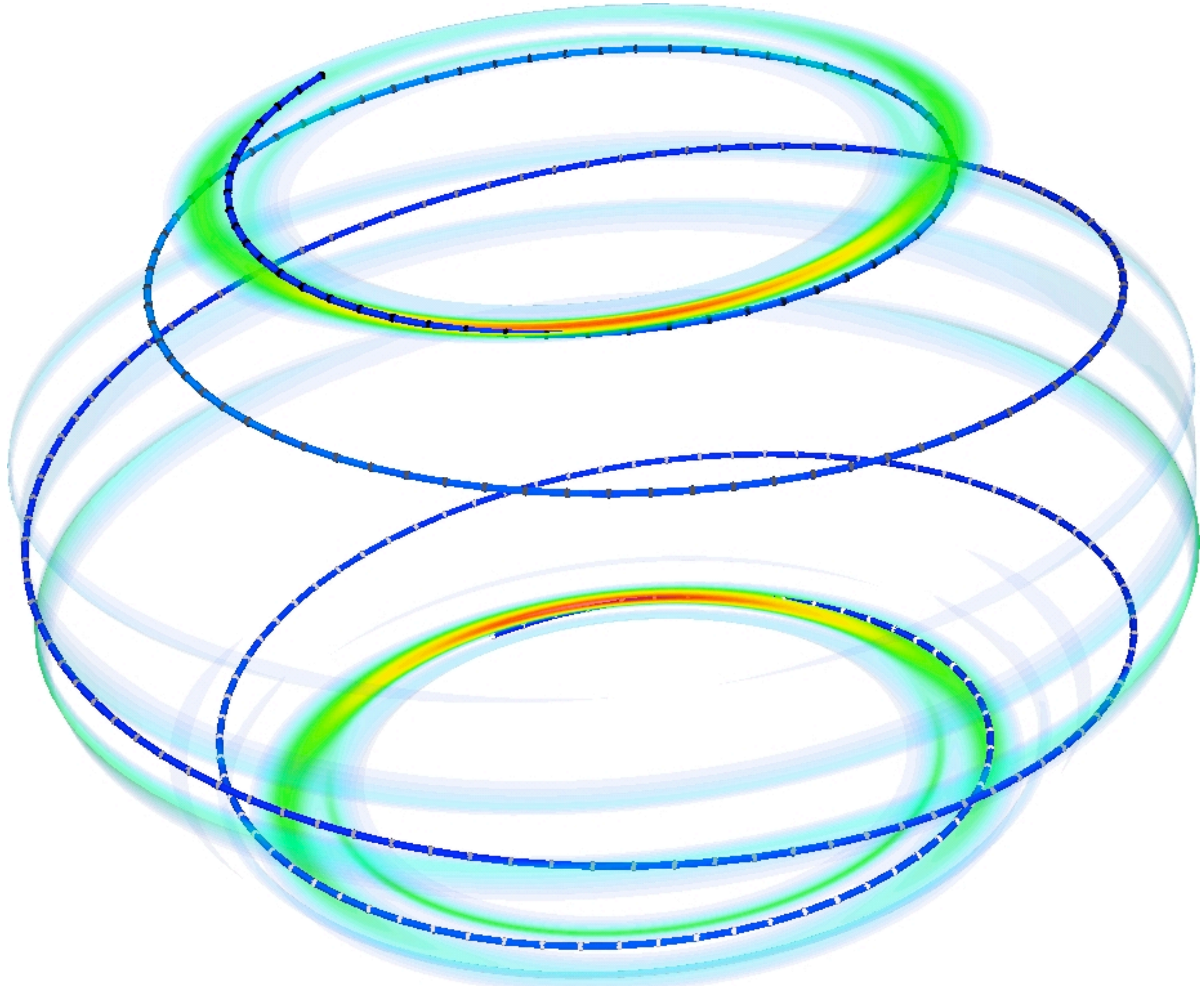




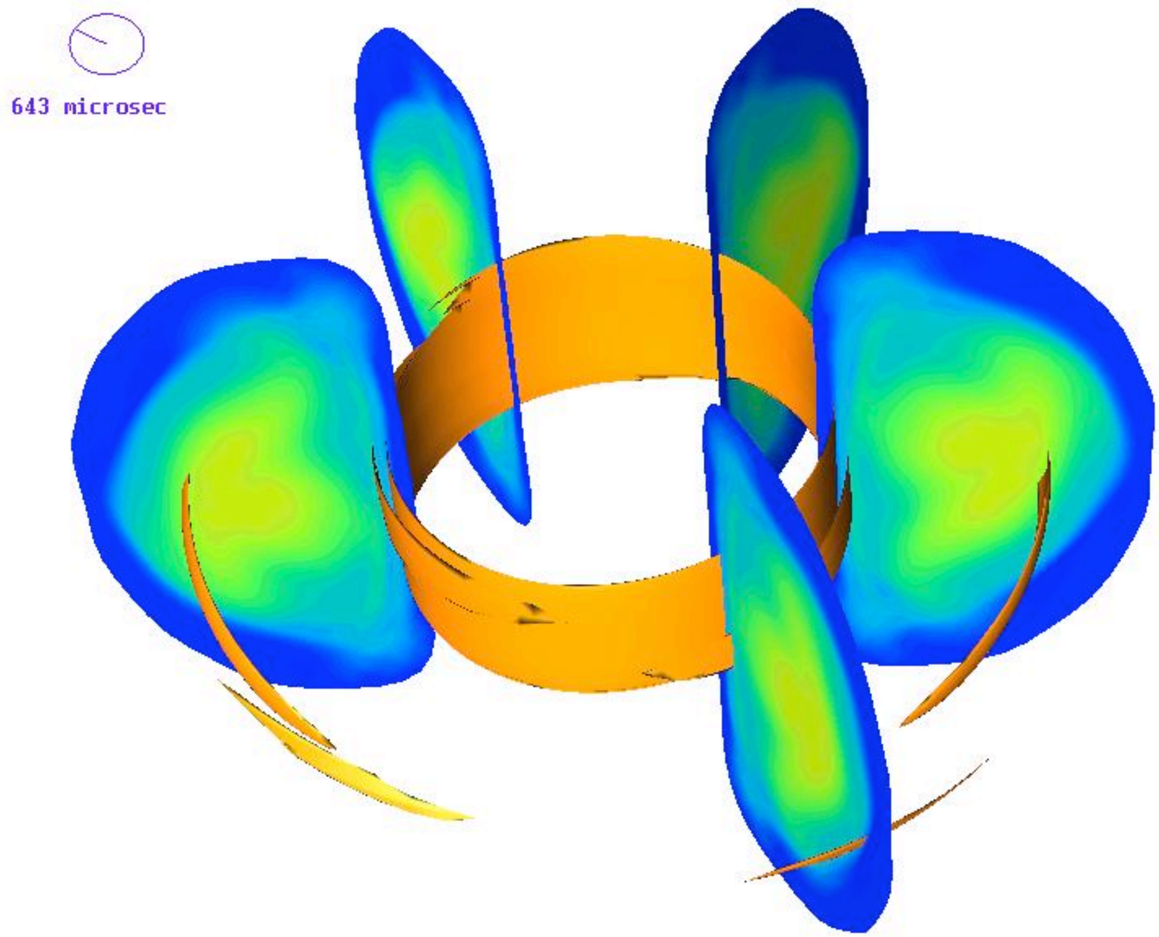
Heat Flux is Localized Poloidally And Toroidally



Localized Areas Of Heat Flux on Top and Bottom Divertors Connected Topologically

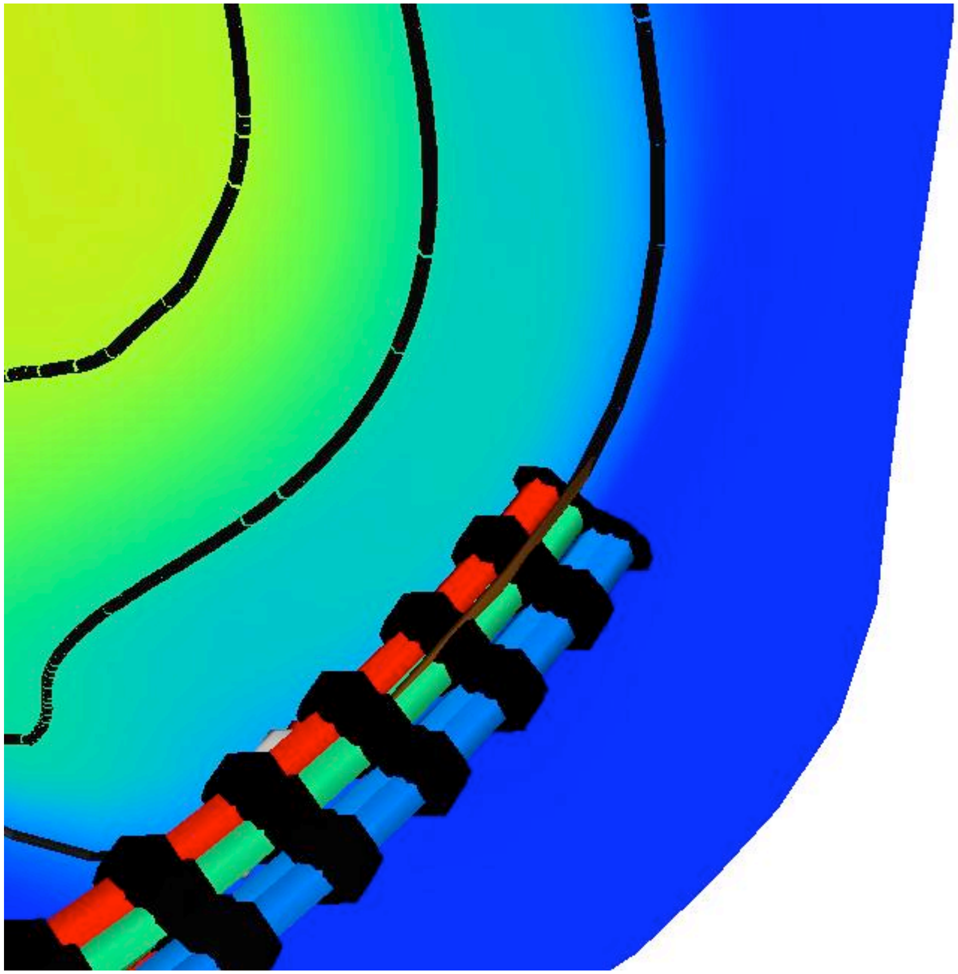


What Sets Critical Topological Group of Fieldlines?



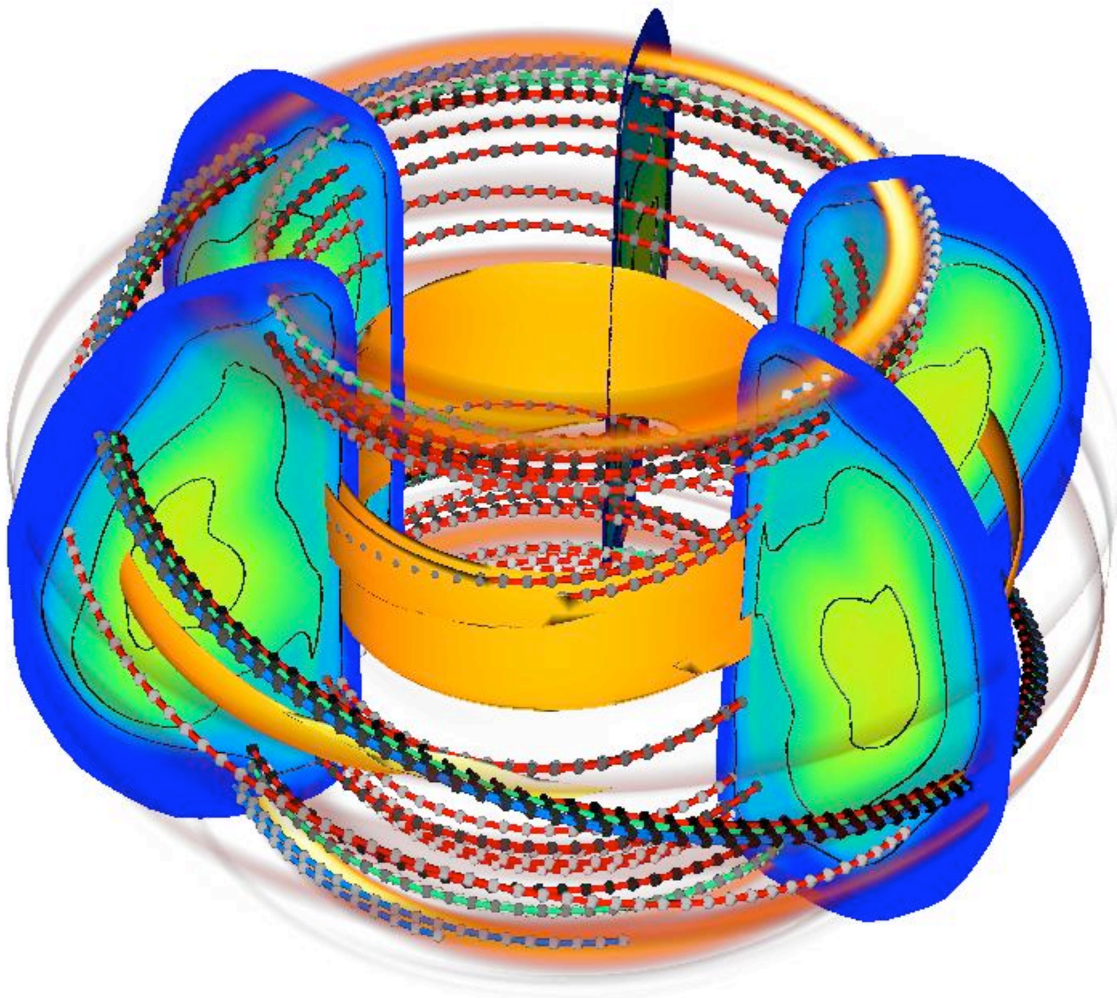
- **Isosurface of magnitude of heat flux**

What Sets Critical Topological Group of Fieldlines?



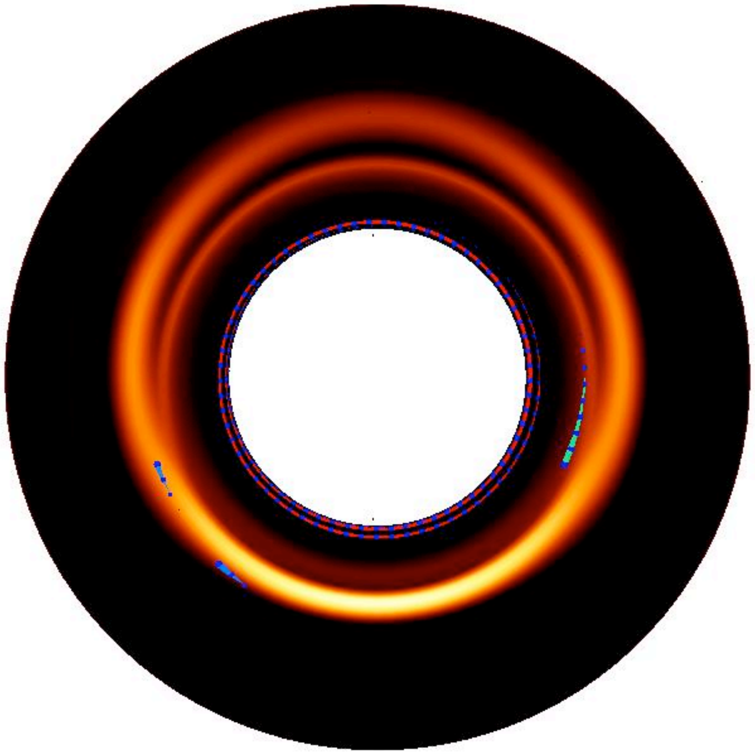
- **Four fieldlines are started from this region. Color denotes total length of fieldline**

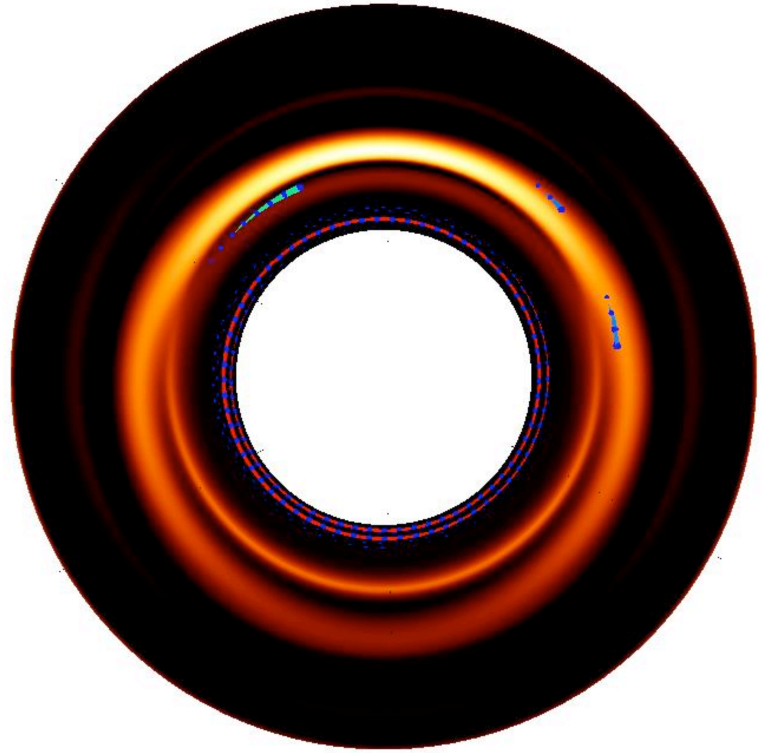
Boundary Between Open And Closed Fieldlines Key to Understanding Wall Loading



- **Red fieldlines are completely confined. Green and blue are not**

Boundary Between Open And Closed Fieldlines Key to Understanding Wall Loading





- Top view
- Bottom view

Conclusions

- Heating through β limit shows super-exponential growth, in agreement with experiment and theory in fixed boundary cases.

- Qualitative agreement with experiment: ~200 microsecond time scale, heat lost preferentially at divertor.

- Heat flux is localized poloidally and toroidally as plasma localizes the perpendicular heat flux, and the parallel heat flux transports it to the wall.

- Wall interactions are not a dominant force in obtaining qualitative agreement for these types of disruptions (fast, internal mode).

- Loss of internal energy is due to rapid stochastization of the field, and not a violent shift of the plasma into the wall.

Future Directions

- Direct comparison of code against experimental diagnostics
- Disruption simulations in H-mode discharges
- Improvements of model:
  - heat flux model
    - Temperature-dependent diffusivities
    - Landau-fluid closures
    - Integral heat flux closure (Eric Held)
  - Impurity model (*V. Izzo, R. Granetz, D. Whyte*)
  - Resistive wall B.C. and external circuit modeling
  - Two-fluid modeling
- Simulations of different devices to understand how magnetic configuration affects the wall power loading