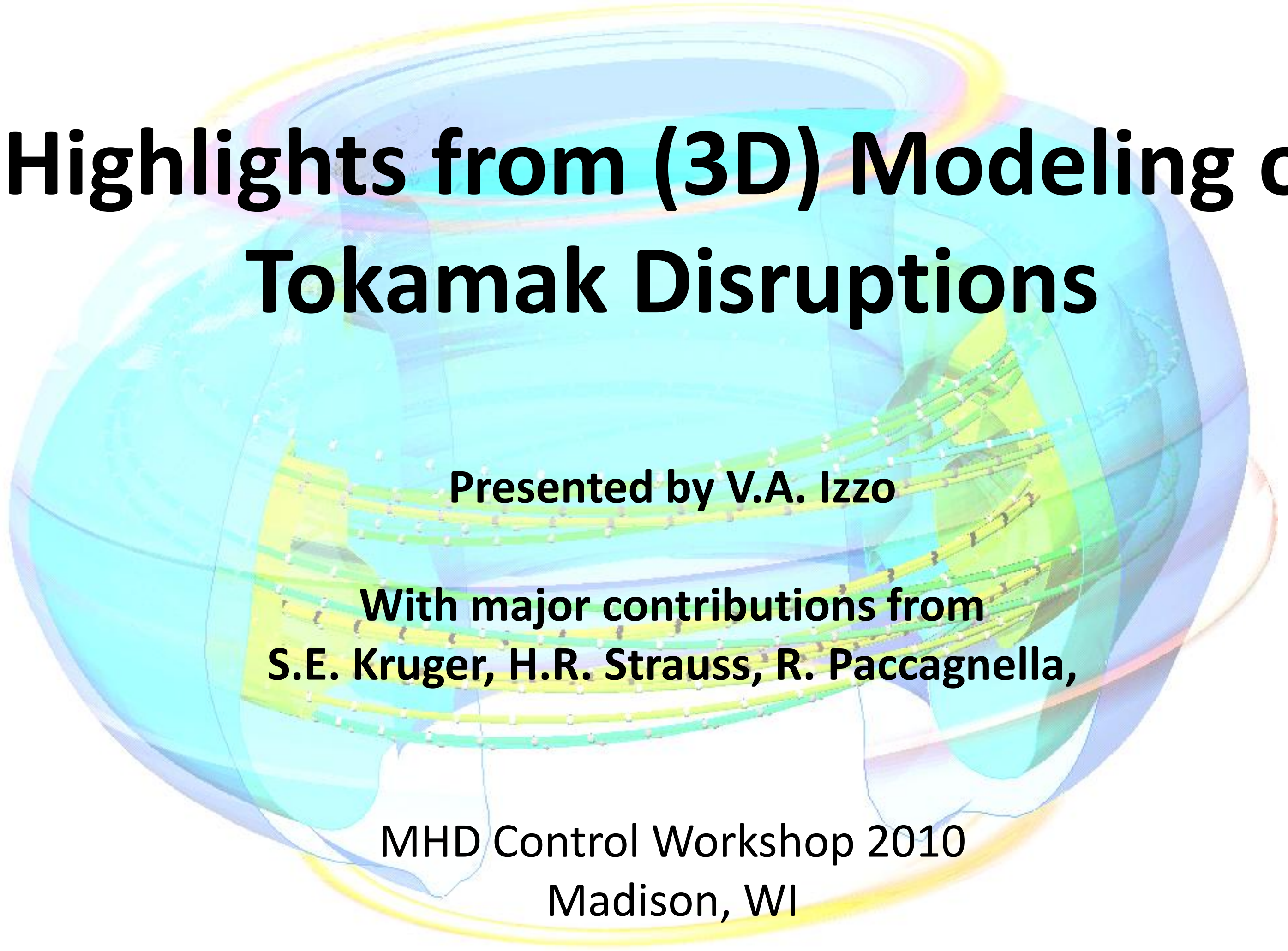


Highlights from (3D) Modeling of Tokamak Disruptions

Presented by V.A. Izzo

With major contributions from
S.E. Kruger, H.R. Strauss, R. Paccagnella,

MHD Control Workshop 2010
Madison, WI

"..onset of rapidly growing global MHD instability is always the penultimate cause of a major disruption"

-Progress in the ITER Physics Basis, Chapter 3 (2007)

MHD modeling can help predict:

Disruption onset – needed for avoidance strategies

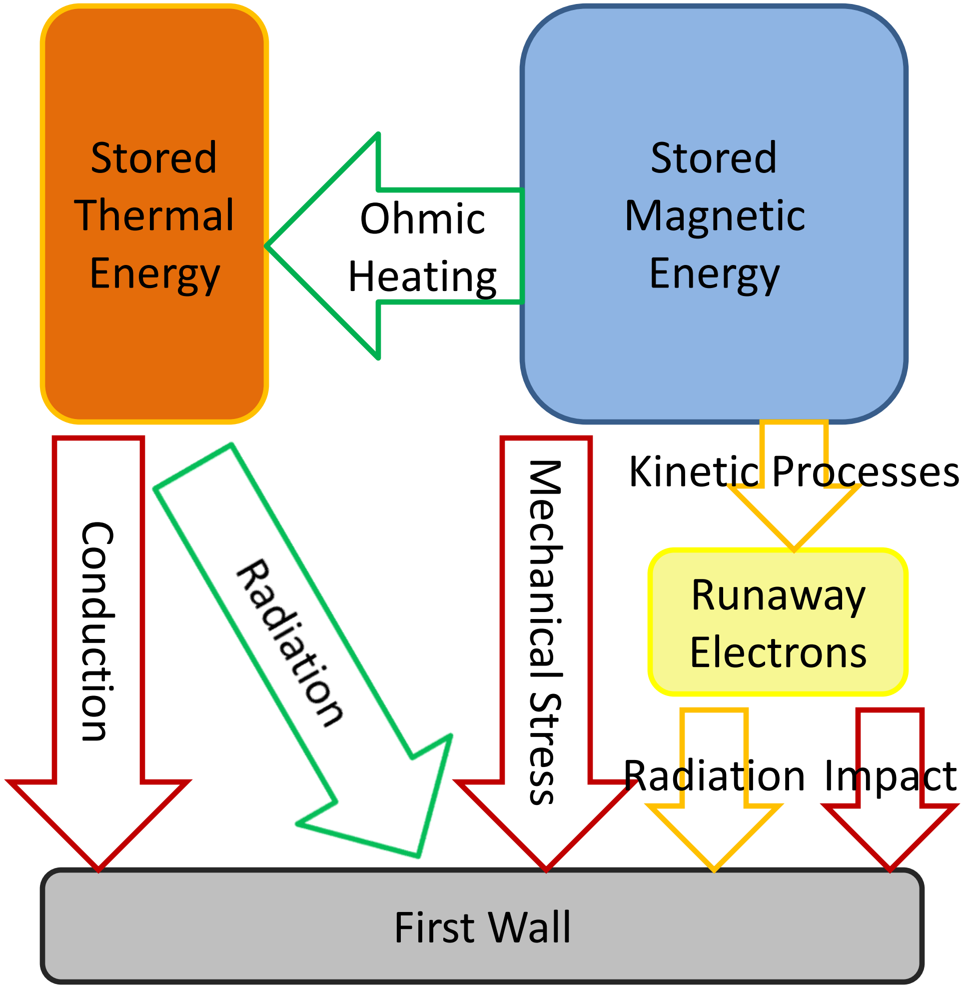
Consequences (especially 3D aspects) – needed for mitigation strategies

Three major consequences are well known:

Melting of the first wall due to large and/or localized heat loads

Mechanical stress due to currents transferred to (or induced in) wall

Large runaway electron populations eventually landing on the wall



Extended MHD Simulations have addressed each potential danger to the first wall

<u>Outline</u>

3D XMHD Modeling of:

(1) Heat flux on the first wall (Kruger): High β disruptions

(2) Halo currents/wall forces (Strauss/Pacagnella): VDEs

(3) Runaway electrons (Izzo) : Rapid shutdowns (mitigated disruptions)

Part 1. High β disruption simulations (Kruger)

PHYSICS OF PLASMAS **12**, 056113 (2005)

Dynamics of the major disruption of a DIII-D plasma[a)]

S. E. Kruger[b)]
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C. R. Sovinec
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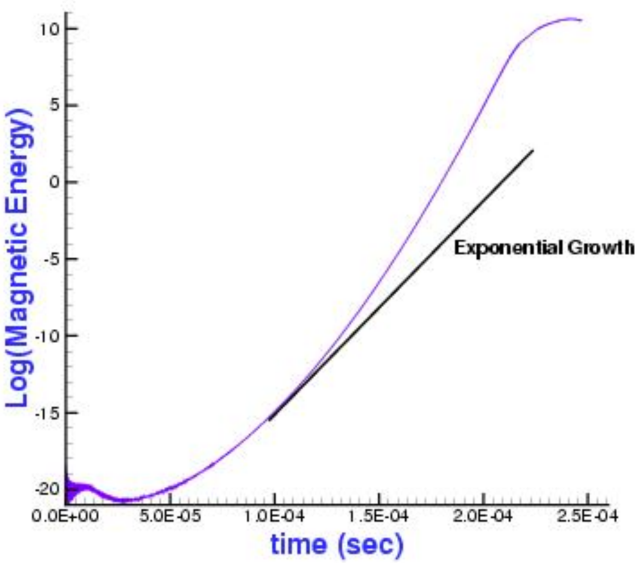
(Received 29 November 2004; accepted 21 January 2005; published online 20 April 2005)

Nonlinear NIMROD simulations of DIII-D equilibrium heated through marginal stability

Impose heating source proportional to equilibrium pressure profile

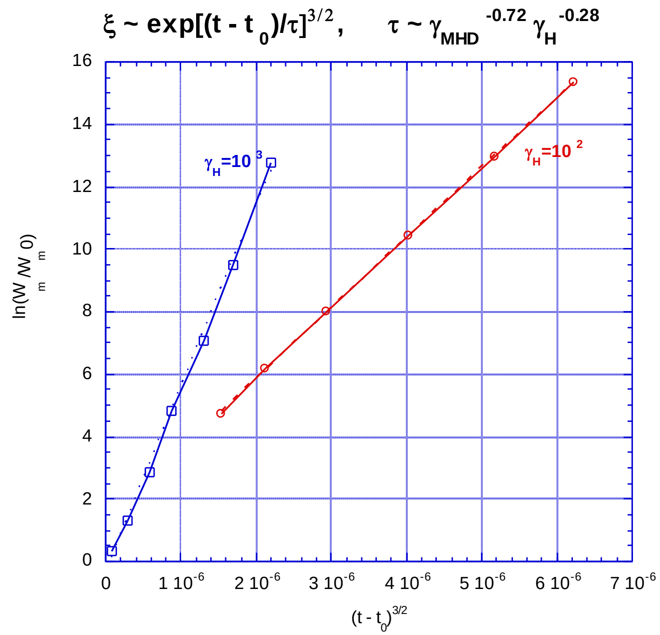
$$\frac{\partial P}{\partial t} = \quad ..... \quad + \gamma_H P_{eq}$$

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



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

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



Simulation results with different heating rates are well fit by $\xi \sim \exp[(t\text{-}t_0)/\tau]^{3/2}$

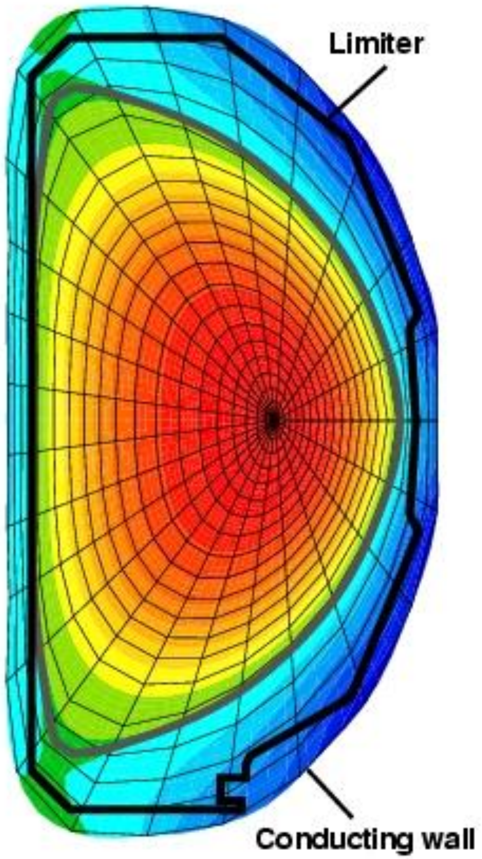
Time constant scales as $\tau \sim \gamma_{MHD}^{-0.72} \gamma_H^{-0.28}$

Compare with theory: $\tau = (3/2)^{2/3} \hat{\gamma}_{MHD}^{-2/3} \gamma_h^{-1/3}$

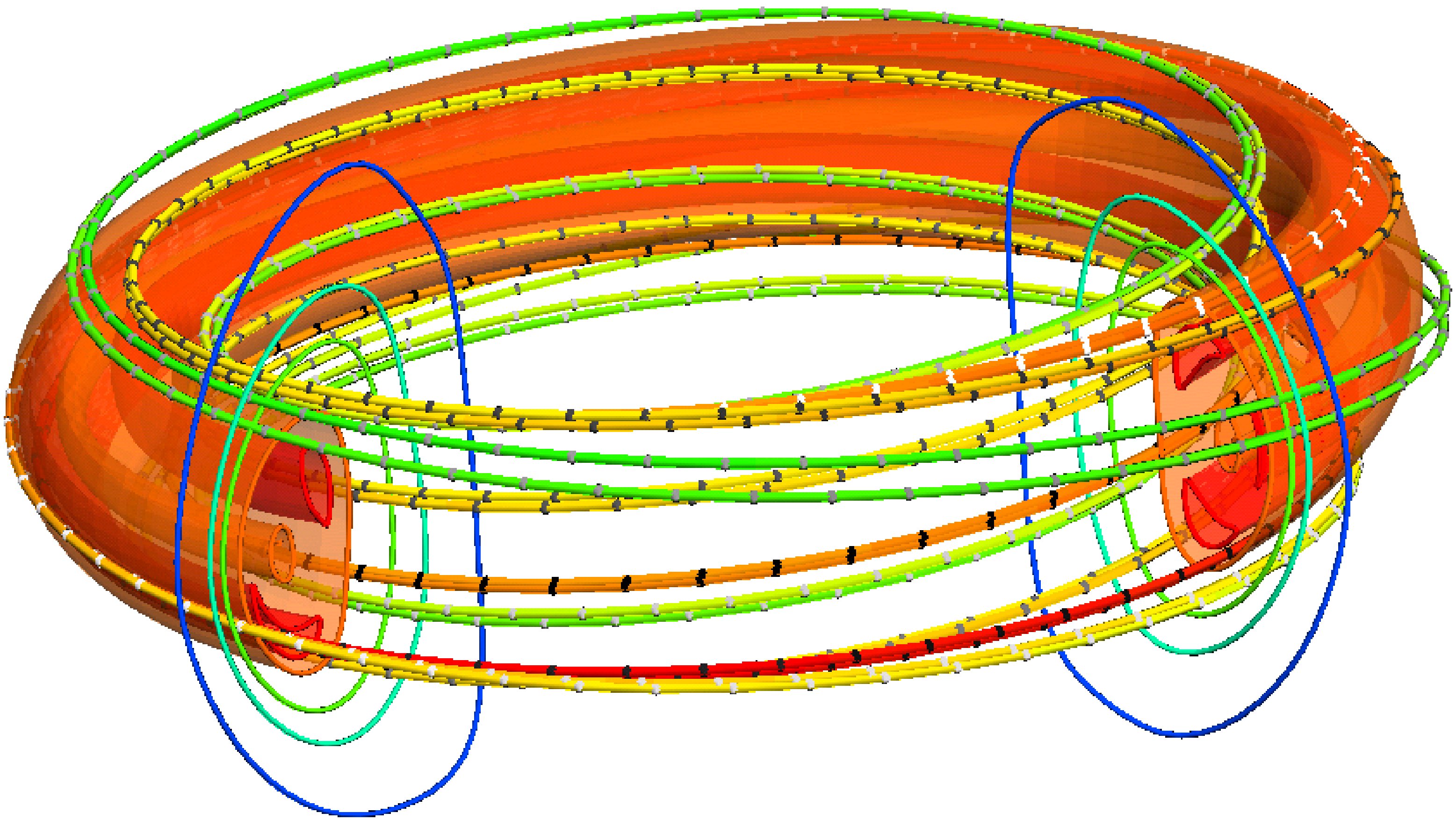
[Callen, et al, PoP **6**, 2963 (1999)]

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

- Boundary conditions are applied at the vacuum vessel, NOT the limiter.
  - Vacuum vessel is conductor
  - Limiter is an insulator
- This is accurate for magnetic field:
  - B_n=constant at conducting wall
  - B_n can evolve at graphite limiter
- 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
- Plasma-wall interactions are complex and beyond the scope of this simulation



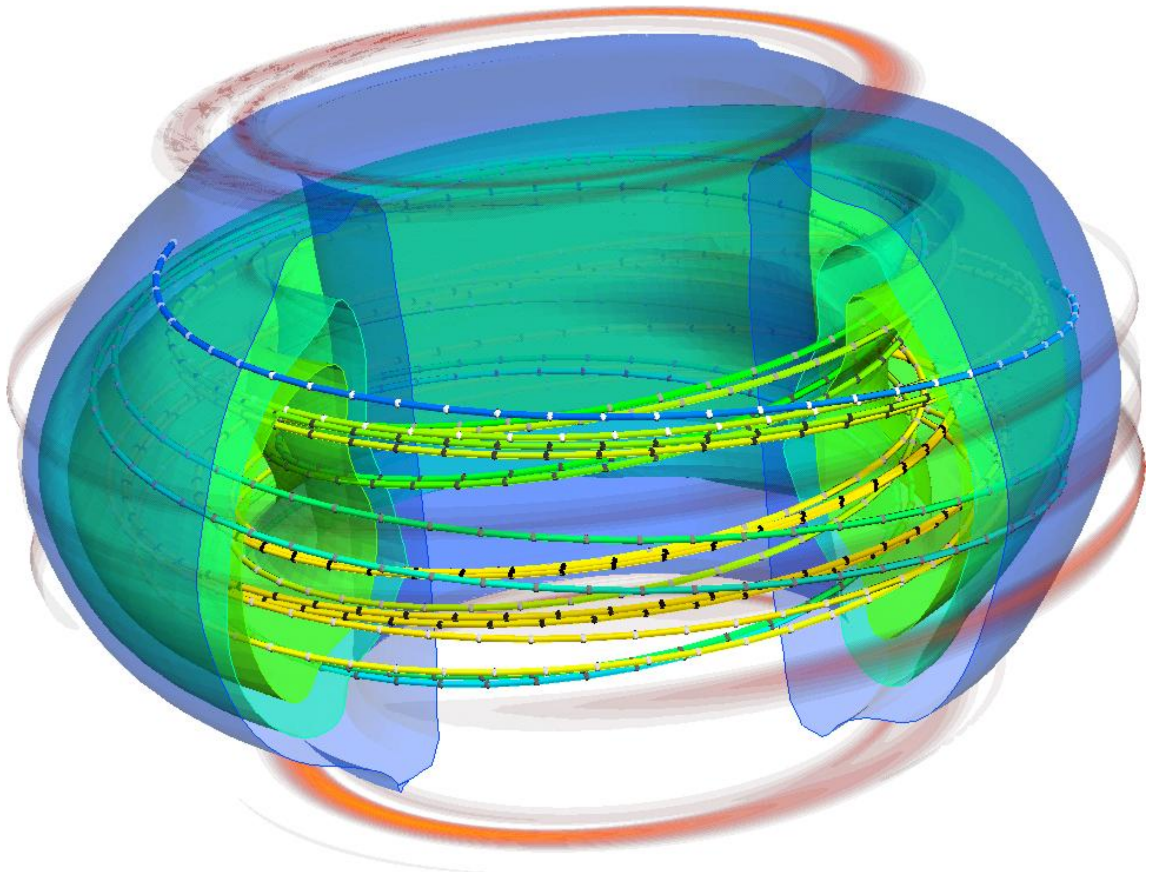
First Macroscopic Feature is 2/1 Helical Temperature Perturbation Due to Magnetic Island



Magnetic Field Rapidly Goes Stochastic with Field Lines Filling Large Volume of Plasma

- Islands interact and cause stochasticity
- Region near divertor goes stochastic first
- Rapid loss of thermal energy results. Heat flux on divertor rises

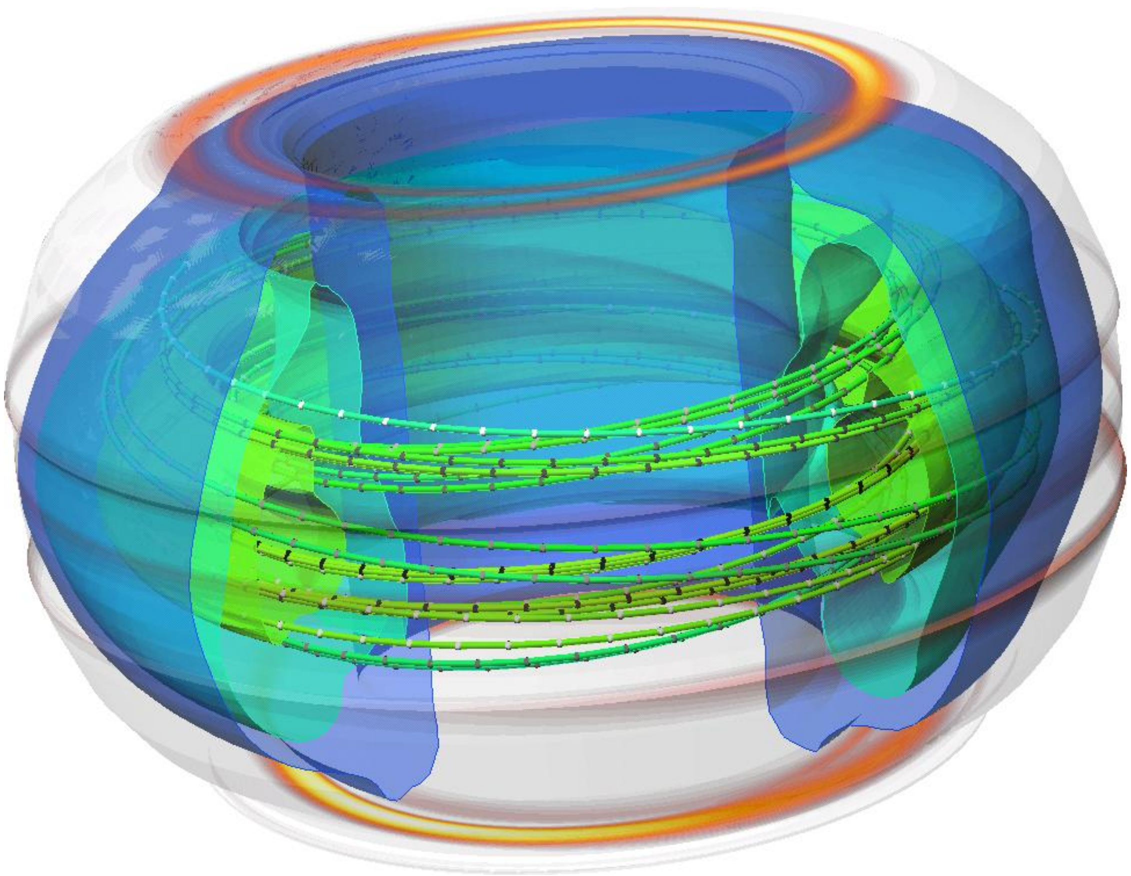
➔ Model requires highly anisotropic heat flux to accurately model thermal quench



Maximum Heat Flux in Calculation Shows Poloidal And Toroidal Localization

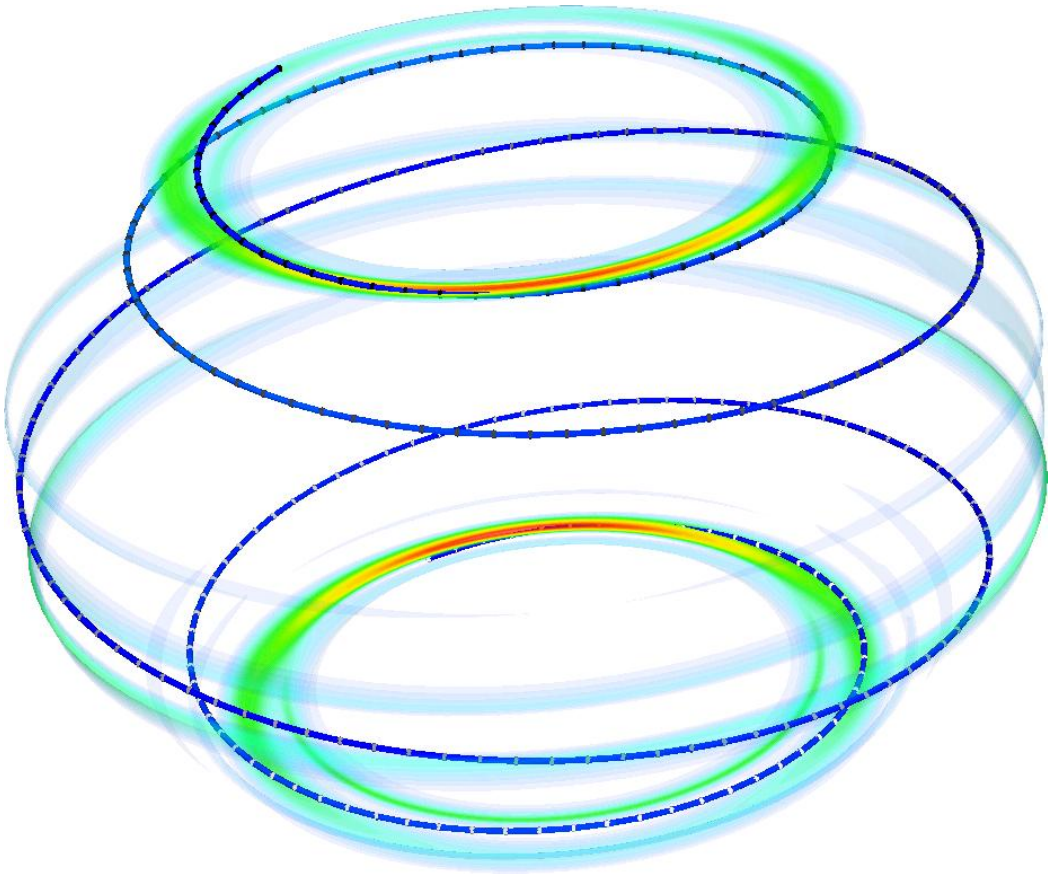
- Heat localized to divertor regions and outboard midplane
- Toroidal localization presents engineering challenges - divertors typically designed for steady-state symmetric heat fluxes
- Qualitatively agrees with many observed disruptions on DIII-D

→ Not able to make quantitative predictions for total heat flux



Heat flux localization is related to field line topology

- Regions of hottest heat flux are connected topologically
- Single field line passes through region of large perpendicular heat flux. Rapid equilibration carries it to divertor
- Complete topology complicated due to differences of open field lines and closed field lines

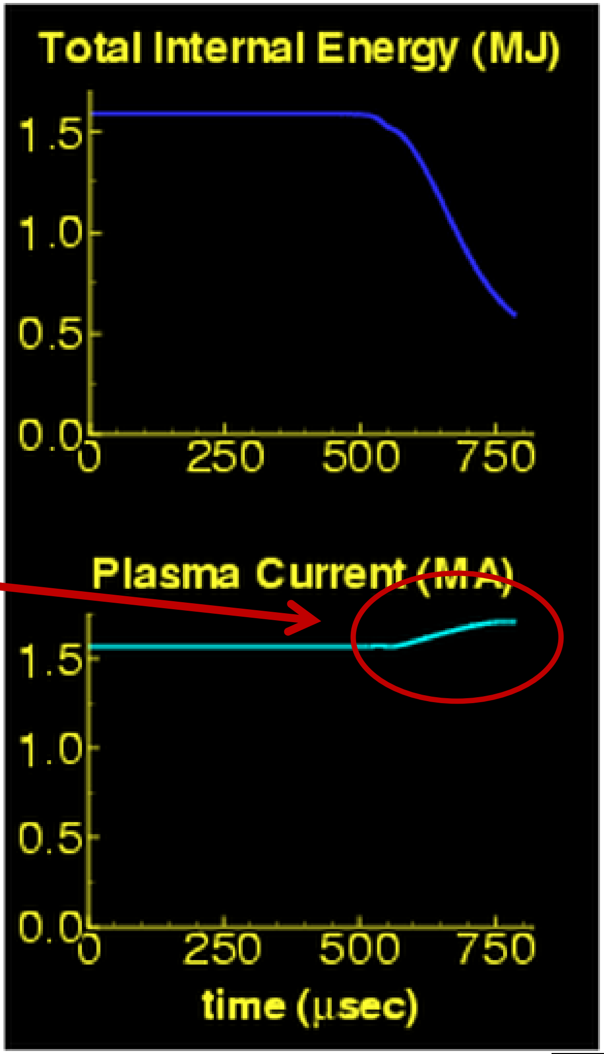


A number of qualitative similarities with DIII-D disruptions, limited quantitative comparison

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

- Plasma current increases due to rapid reconnection events changing internal inductance

- Simulation does not progress through the end of the thermal quench and into the current quench phase due to numerical difficulties



Aside on the plasma current spike (NF vol. 50, no 5)

COMMENT

Comment on ‘Plasma current spikes due to internal reconnection during tokamak disruptions’

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Received 13 February 2010, accepted for publication 6 April 2010
Published 23 April 2010
Online at stacks.iop.org/NF/50/058001

Plasma current spike associated with internal reconnection (drop in internal inductance) …

REPLY

Reply to comment on ‘Plasma current spikes due to internal reconnection during tokamak disruptions’

Leonid E. Zakharov

Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA

Received 9 March 2010, accepted for publication 6 April 2010
Published 23 April 2010
Online at stacks.iop.org/NF/50/058002

…Or associated with transfer of negatively directed ‘Hiro’ currents into the wall?

Summary of Part 1.

- Nonlinear calculations confirm theory of faster-than-exponential growth when plasma is heated through the β-limit
- Heat flux calculations at the limiter location point to the importance of 3D effects producing toroidal peaking on the divertor

Limitations:

Temperature-independent, diffusive model for parallel heat transport: “crude mode for equilibration of temperature along field lines.”

Numerical difficulties prevented simulation from progressing past late-TQ phase

Part 2. VDE simulations (Paccagella/Strauss)

Nucl. Fusion 49 (2009) 035003 (12pp)

doi:1

3D MHD VDE and disruptions simulations of tokamaks plasmas including some ITER scenarios

R. Paccagnella[1,2], H.R. Strauss[3] and J. Breslau[4]

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PHYSICS OF PLASMAS **17**, 082505 (2010)

Wall forces produced during ITER disruptions

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(Received 4 April 2010; accepted 14 July 2010; published online 20 August 2010)

Predict wall force produced by ITER disruptions

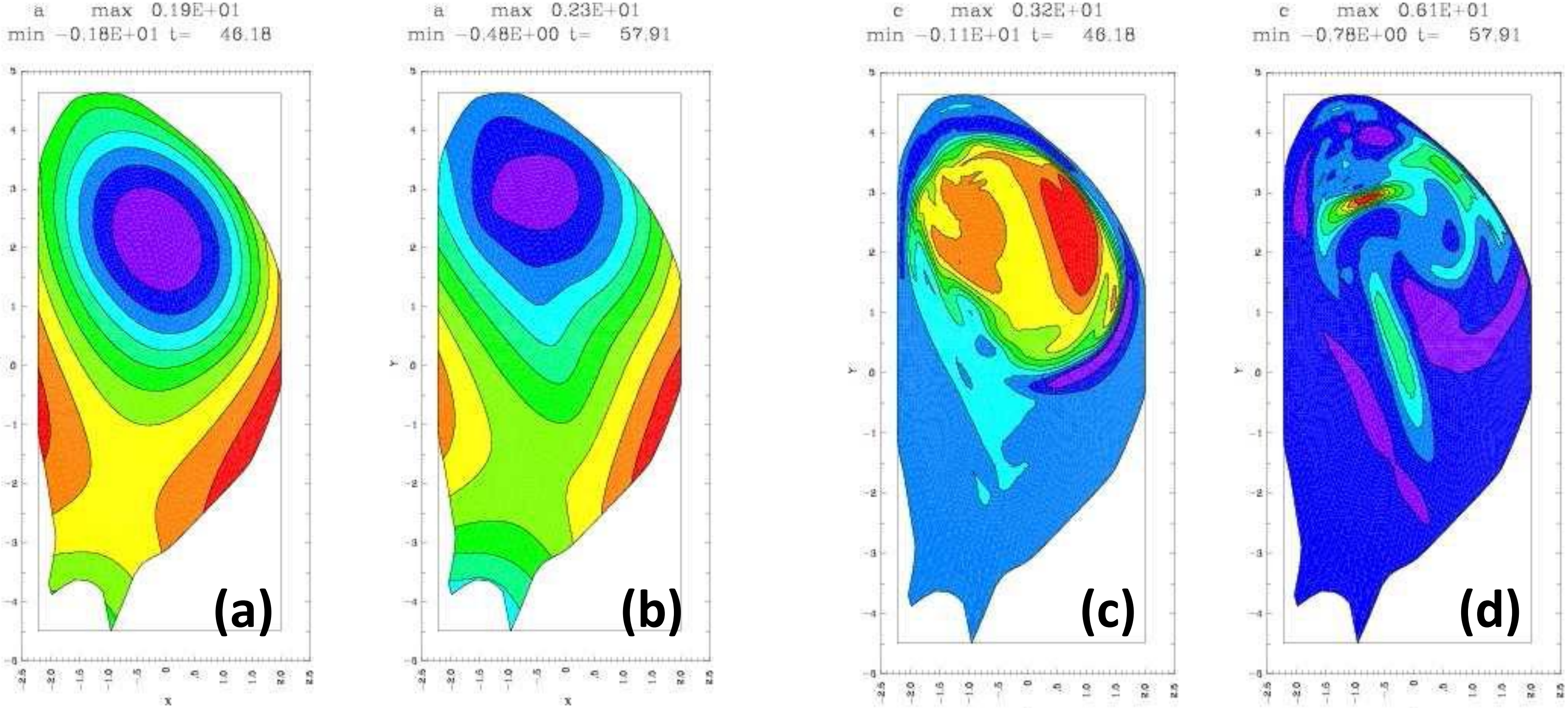
- Disruptions in ITER could cause large asymmetric (sideways) force on the walls and blanket. The worst case for asymmetric wall force may be caused by a vertical displacement event (VDE) along with an unstable kink mode.

- The force depends strongly on $\gamma\tau_{wall}$, where γ is the mode growth rate and τ_{wall} is the wall resistive penetration time. The force is maximum when $\gamma\tau_{wall} \approx 1$. When $\gamma\tau_{wall} \gg 1$ the force is small. The force also is proportional to γI^2 where I is the total current. The force is produced mainly by halo current, not induction or “Hiro” current.

M3D code simulates vertically and kink unstable plasma

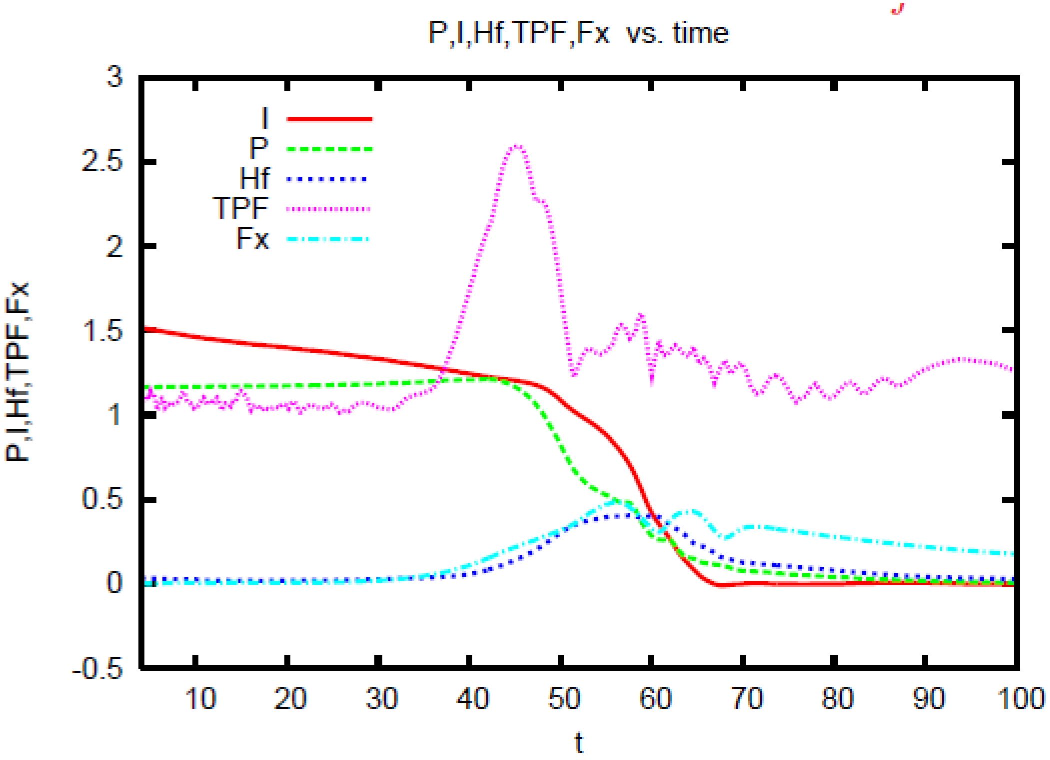
- Used XMHD (M3D), with plasma filling the volume inside the first wall. $S = 10^{10}$ in ITER might indicate ideal MHD, but would develop current sheets but not magnetic stochasticity. Fast reconnection and presumably island overlap leading to stochasticity can occur in low collisionality plasma (Aydemir, Drake, ...)
- Standard impenetrable wall velocity boundary condition $v_n = 0$ was used. Zakharov argues that plasma penetrates wall, but needs to provide a detailed theory, including equations inside the wall. Does it make a difference if plasma stops at the wall or a few microns inside it?
- Thin resistive wall model used to calculate wall current. $J_w \approx \frac{\hat{n}}{\delta} \times \left(B^v - B^p\right)$ where $\hat{n}$ is the normal to the wall, δ is the wall thickness, B^v is vacuum magnetic field outside the wall, and B^p is the field in the plasma.

VDE - kink disruption



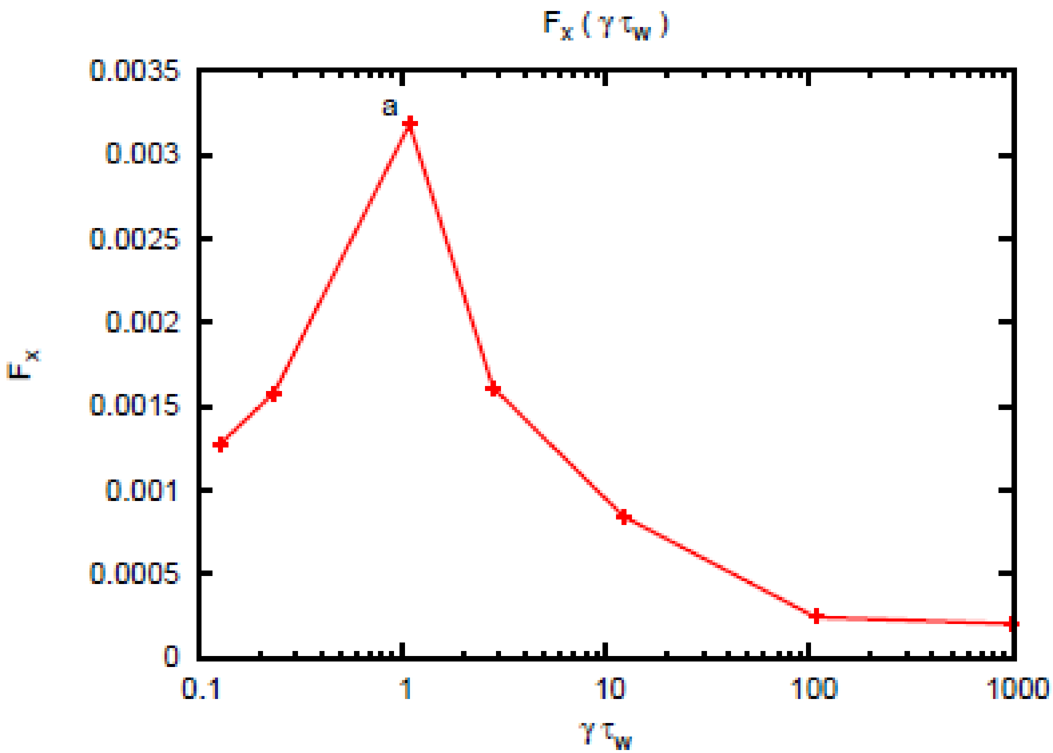
A nonlinear kink mode at time t = $46.18\tau_A$, showing (a) poloidal flux ψ, at time t =$46.18\tau_A$, (b) ψ at time t = $57.91\tau_A$, (c) toroidal current $-RJ_\phi$, at time t = $46.18\tau_A$, (d) toroidal current at time t = $57.91\tau_A$. At t = $57.91\tau_A$, the sideways force is maximum. The initial state is an ITER reference case equilibrium (FEAT15MA) rescaled to be both kink and VDE unstable. This models what might happen when the VDE causes plasma to be scraped off at the wall, lowering q. The actual scrape off process has been difficult to simulate so far.

Time dependence of I, P, TPF, H_f and F_x



Toroidal current I, pressure P, TPF, halo current fraction H_f and horizontal force F_x as a function of time for the run shown previously. The quantities I, P, and F_x are in arbitrary units. The VDE causes thermal and current quench of P and I. The close time correlation of halo current fraction H_f and horizontal force F_x indicates that F_x is produced by halo current.

Scaling of horizontal force F_x with $\gamma\tau_w$



The force tends to a limit for an ideal conducting wall $\gamma\tau_w \to \infty$, and is zero for $\tau_w = 0$. The force has a maximum for $\gamma\tau_w \approx 1$. The previous plots are of point “a”. The ITER horizontal force corresponding to point “a” is $65MN$. In JET, the horizontal force would be 2.75 MN, consistent with experiments. ➔ A more conducting wall might mitigate the wall force.

Summary of Part 2.

• Worst case for sideways forces– VDE plus kink mode– is simulated. For JET dimensions, predicts forces consistent with experimental values.

• Force is maximum when MHD growth rate times wall time is unity. More conducting wall may reduce forces.

Limitations:

• Plasma wall interaction, producing cooling and scrape-off of plasma as is contacts the wall, subsequent shrinking of current channel, is absent.
 - Related issue: velocity boundary condition

Part 3. Rapid shutdowns/Mitigated Disruptions (Izzo)

Nucl. Fusion **46** (2006) 541–547

doi:10.1088/00

A numerical investigation of the effects of impurity penetration depth on disruption mitigation by massive high-pressure gas jet

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IAEA 2010

THS/9-2

Runaway Electron Confinement Modeling for DIII-D, Alcator C-Mod and ITER

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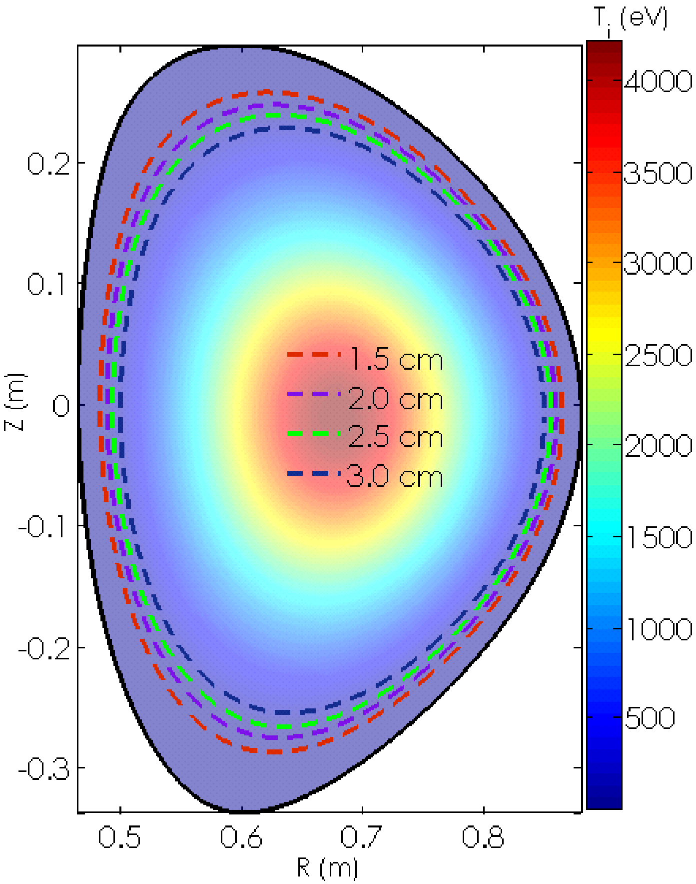
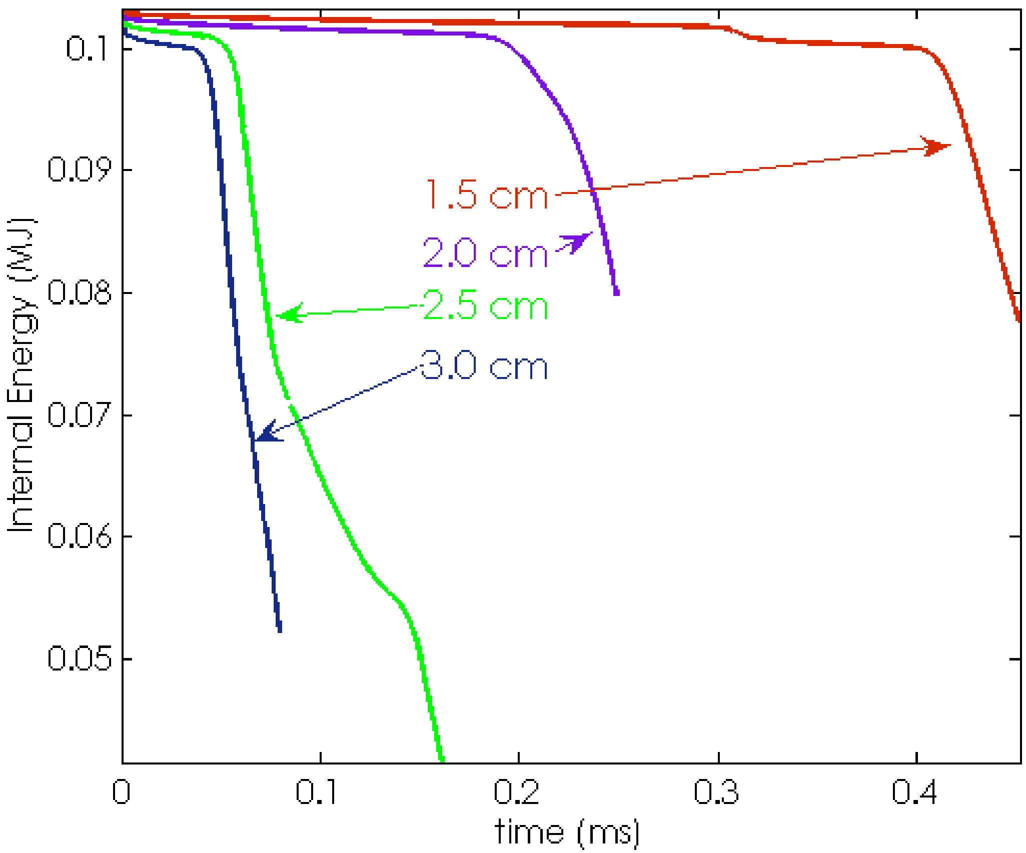
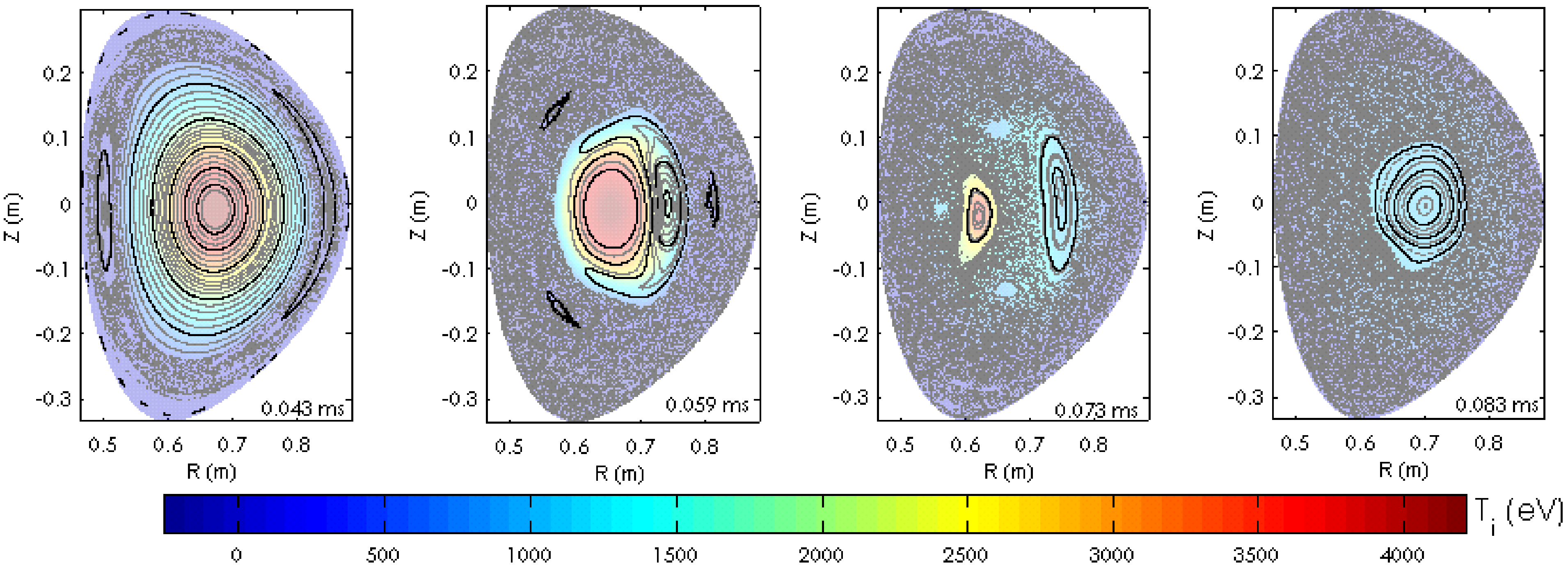
MGI in C-Mod: Radiation cools the edge, stochastic transport cools the core





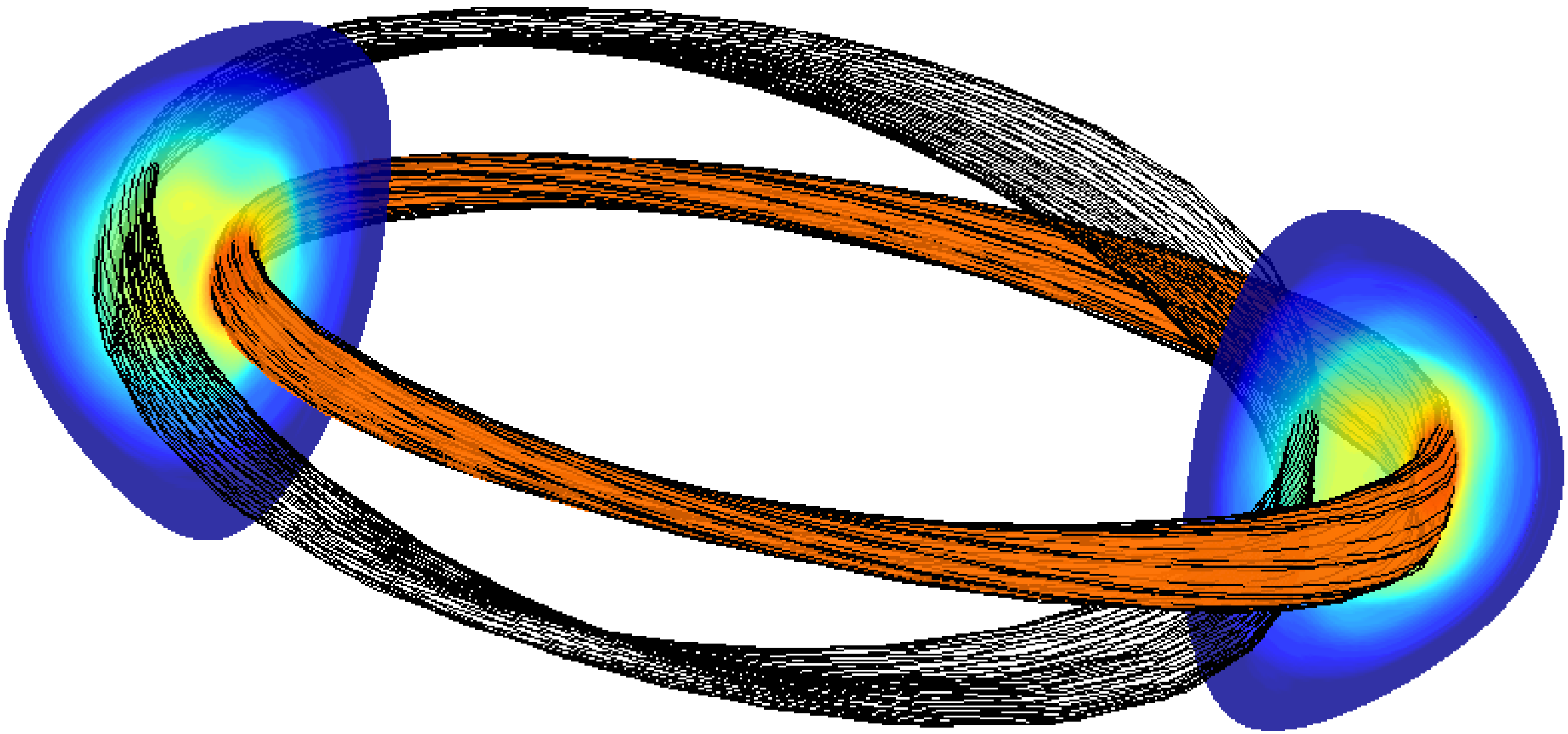
Four simulations cool edge plasma to four different depths. Core TQ onset timing changes considerably. Growth rate of 2/1 mode is greatly enhanced by cooling q=2 surface.

MGI-induced TQ is achieved by 2/1 mode followed by 1/1 mode



- 2/1 mode appears first and stochastic fields form at the edge, eventually destroying all field lines outside q=1
- 1/1 mode levels core temperature by swapping cold island with hot magnetic axis

The 1/1 mode in 3D



But, like Kruger simulations, MGI simulations get “stuck” in the late TQ phase…

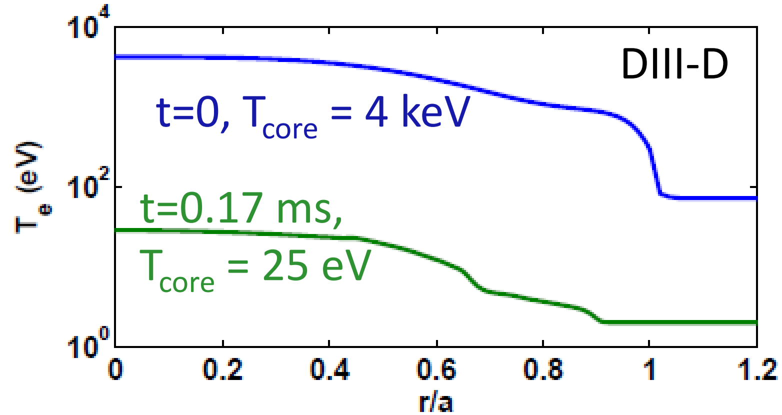
Simulations through CQ phase can be achieved with simplified cooling model

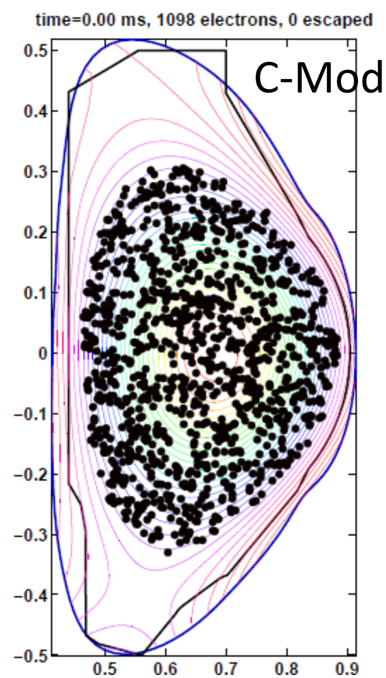
Motivated by Ar pellet experiments on DIII-D: pellets penetrate into the core

• Simplified (instantaneous) Ar delivery → compressed thermal quench (TQ) time

• **Guiding-center drift motion of test (trace) population of REs is caculated as MHD fields evolve**

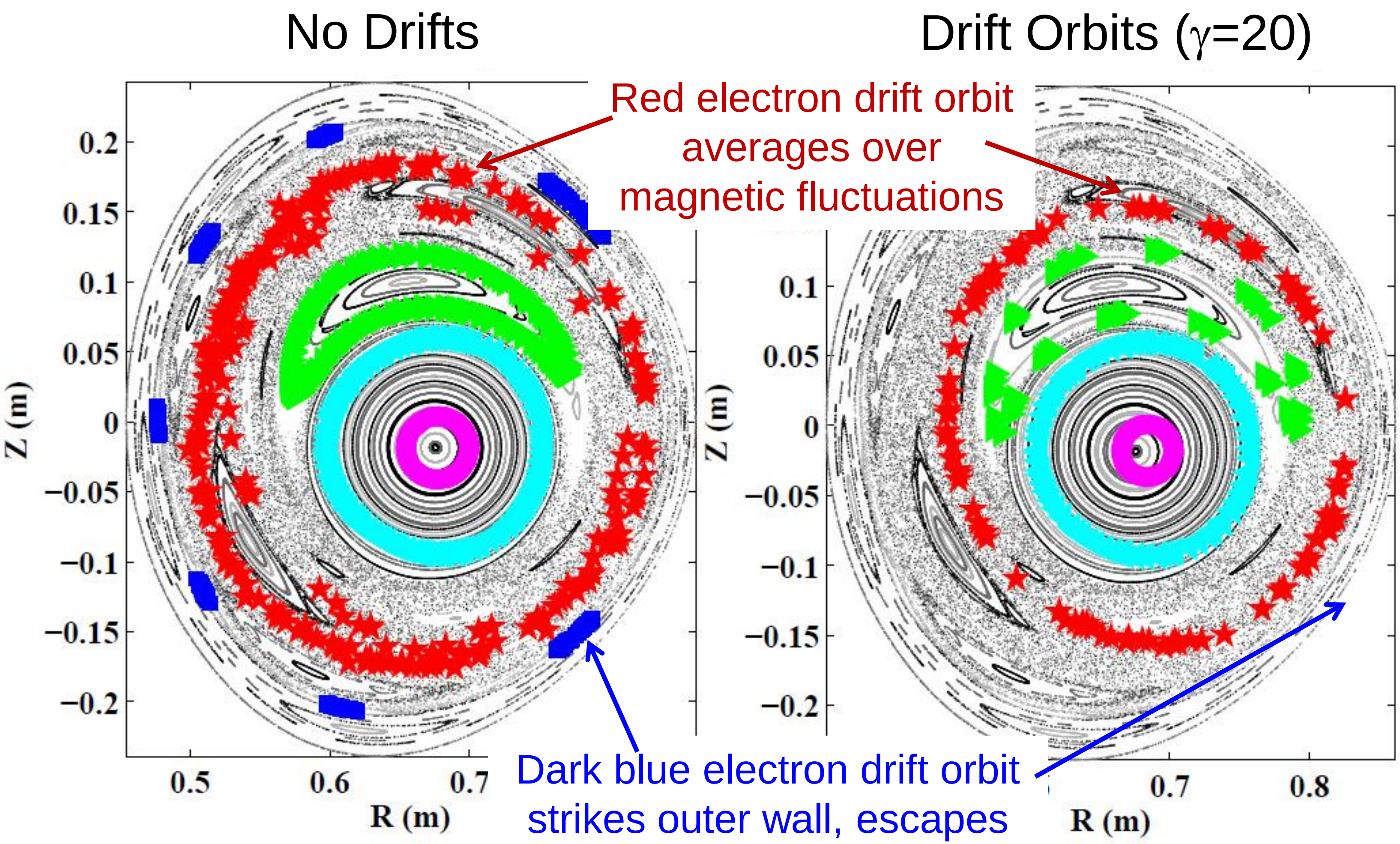
• RE orbit calculation provide info on radial RE transport and strike-points of REs on the first wall





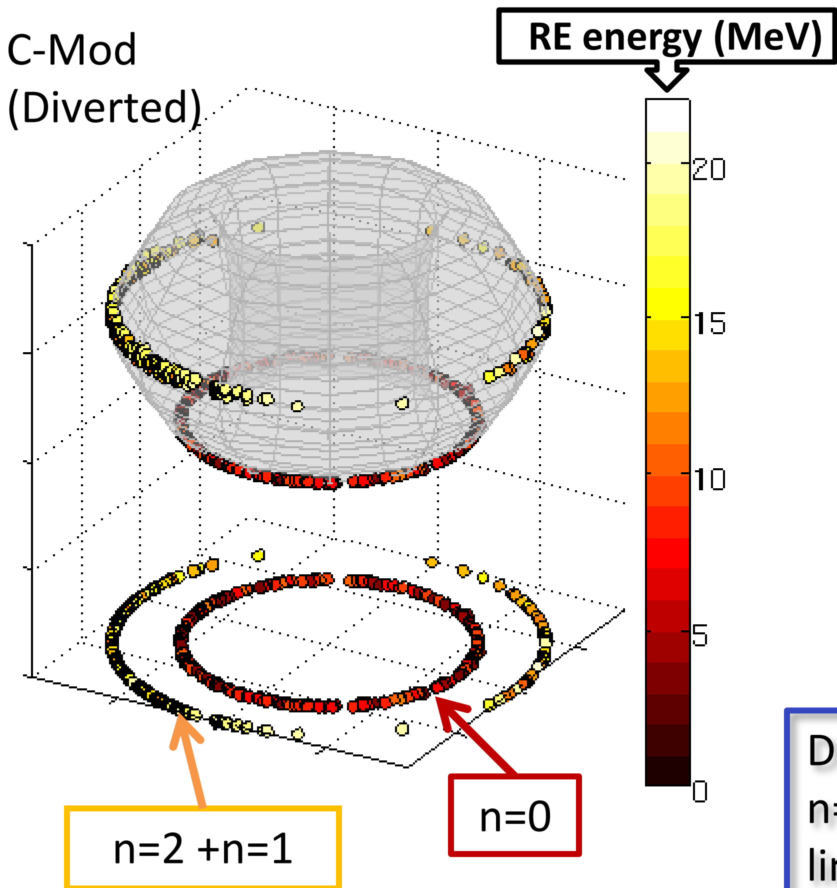
Electrons are initiated inside closed flux region with suprathermal, but non-relativistic energy (150 keV)

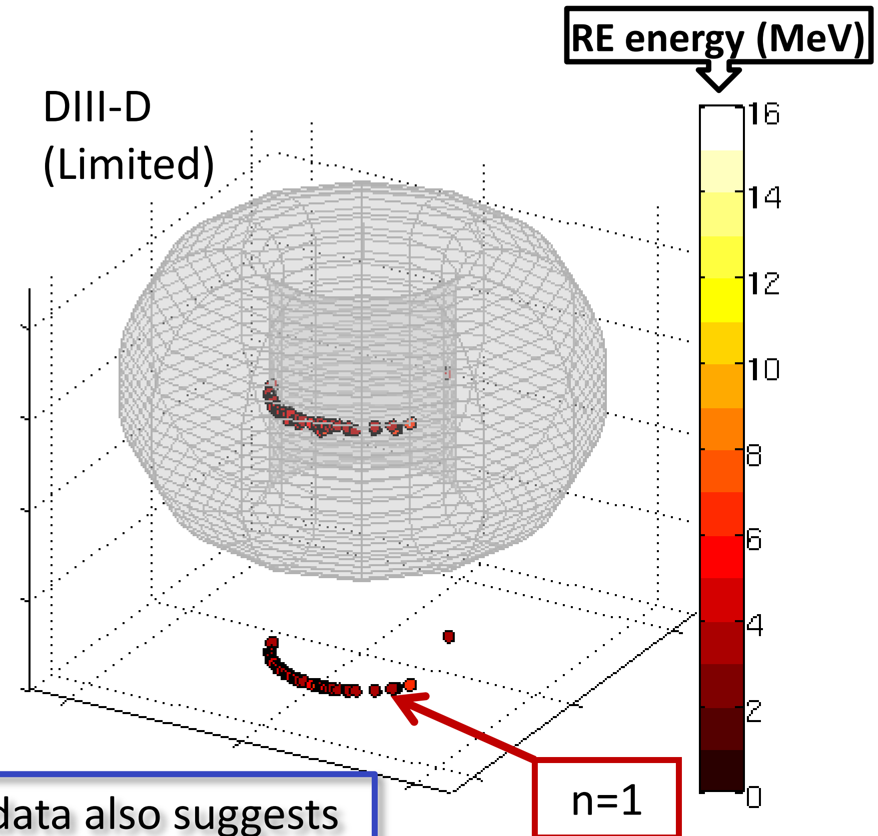
Large curvature drift can impact RE confinement positively or negatively



At MHD onset, REs escape, strike the wall in poloidally localized regions

REs strike outer divertor in toroidally symmetric pattern. Outer or inner midplane strike pattern exhibits dominant MHD toroidal mode number.

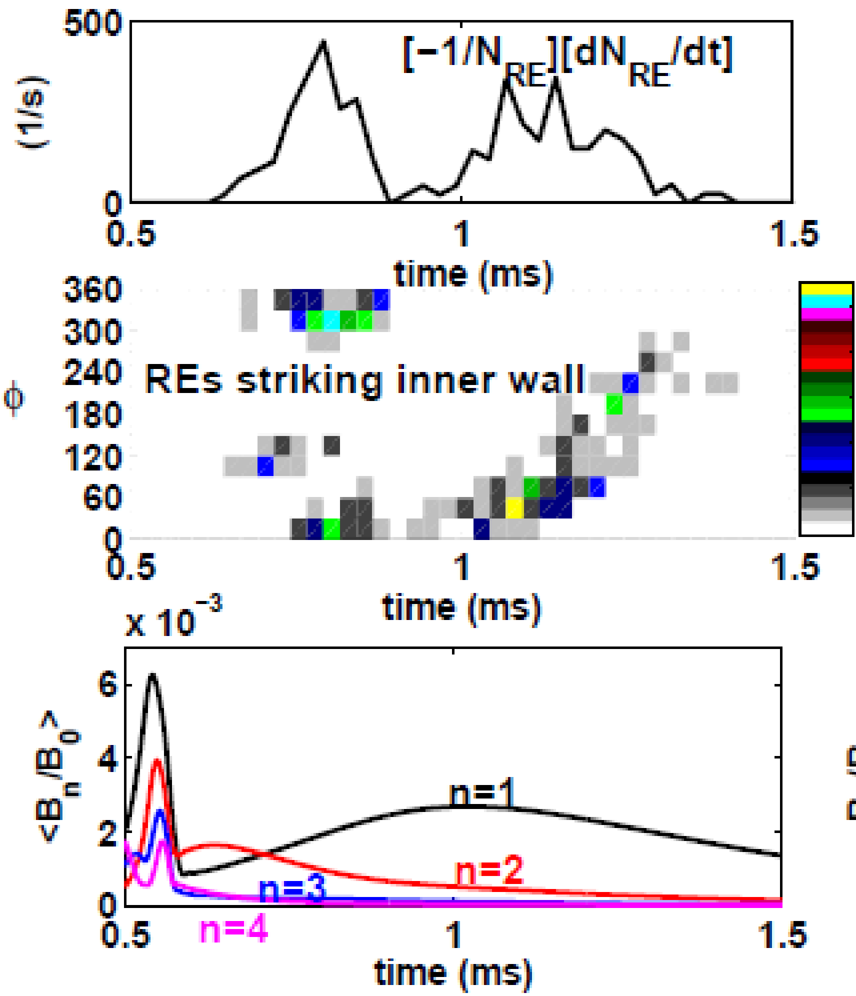




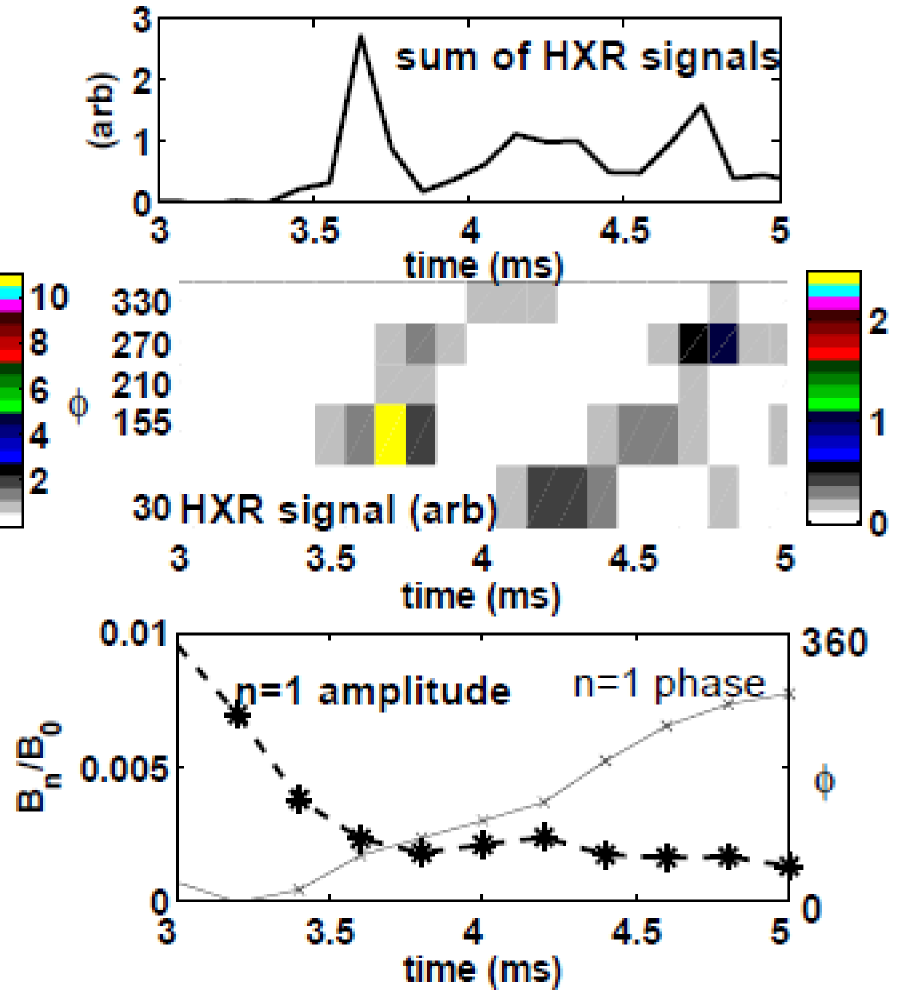
DIII-D data also suggests n=1 striking pattern in limited discharges …

DIII-D measurements support n=1 striking pattern for limited plasma

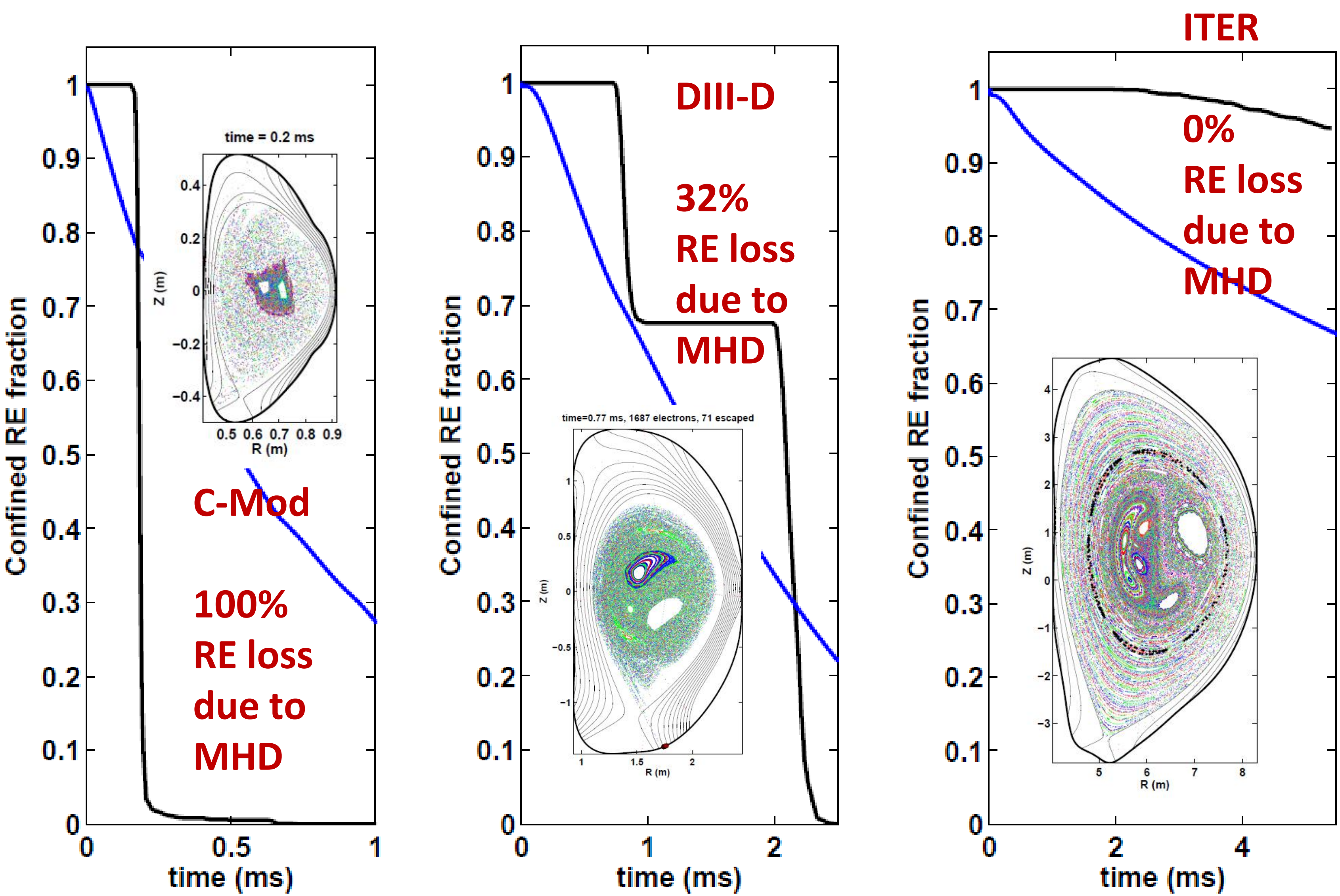
NIMROD (140586 – Limited)



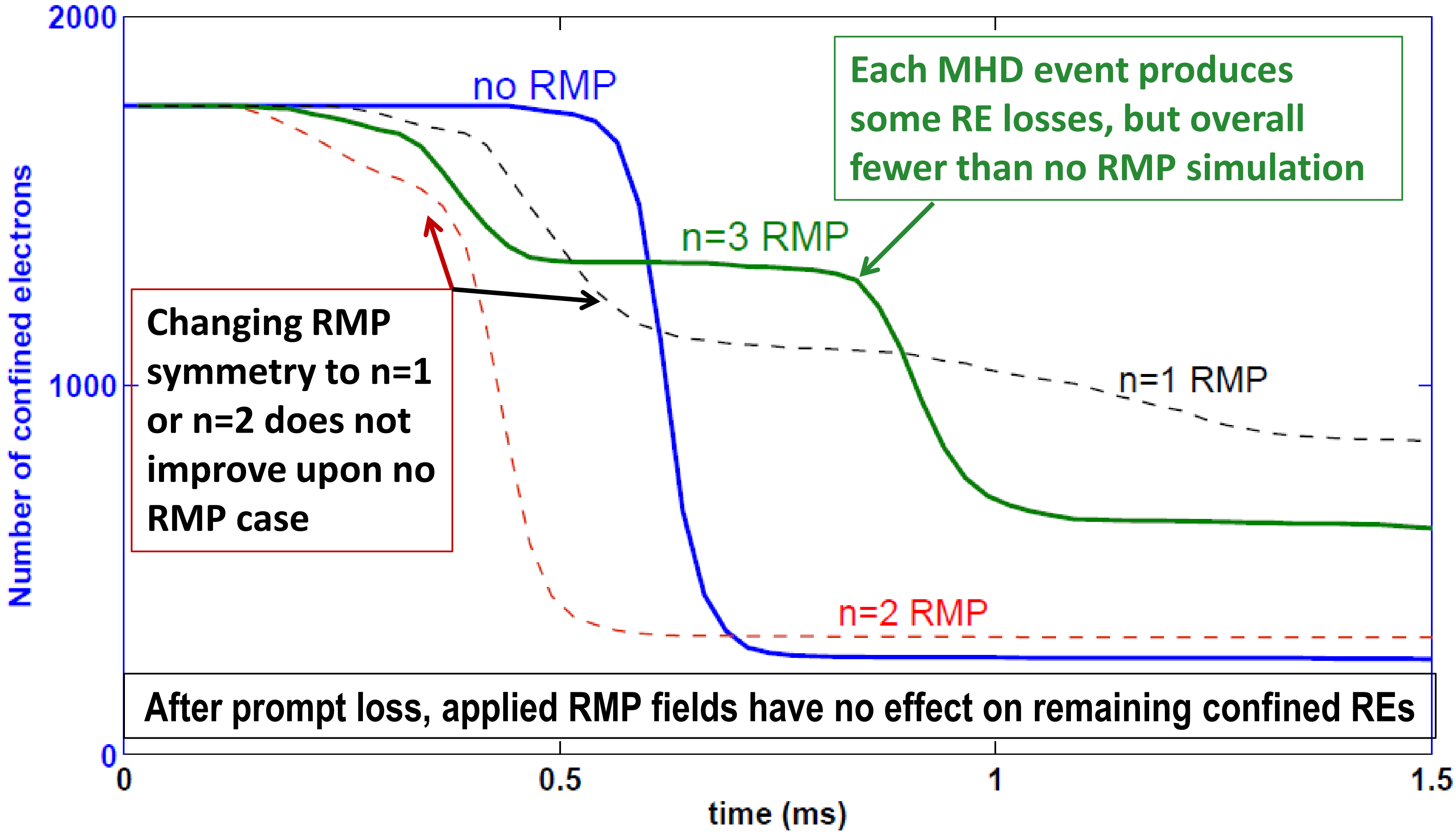
DIII-D Shot 140586



Cross-device comparison shows 1/R scaling of $\delta B_r/B$ at the edge, no RE loss in ITER



Can adding 3D fields reduce RE confinement?



Summary of Part 3.

• MGI and pellet rapid shutdown scenarios are simulated with incorporation of radiating impurity species. REs confinement is studied with drift-orbit calculations for trace RE population.

• RE confinement when TQ-triggered MHD modes reach saturation seems to improve significantly as machine size increases → may be hard to get rid of REs in ITER

Limitations:

Need more realisitic (3D) model for impurity deposition by pellet or gas-jet

Ideal wall, no vertical plasma motion …

Status and needs for disruption modeling

3D XMHD modeling has been carried out to make predictions (some quantitative, some only qualitative) for each of the major disruption consequences

Many extended features of extended MHD are needed for a disruption simulation:

-Highly anisotropic heat flux with **accurate parallel heat transport model**
-Resistive wall BC
-Improved modeling of **plasma wall interaction** when the plasma contacts the wall, including consideration of the **velocity BC**
-**Impurity source models** including MGI, pellets, as well as from the wall
-Impurity radiation, **radiation transport/opacity**
-Runway electron confinement, **generation, self-consistent RE current model**

No code with all of these features. NIMROD and M3D have each developed some capabilities the other lacks.