SIMULATION OF A HIGH-b DISRUPTION IN DIII-D SHOT #87009

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

- **In experiment mode grows faster than exponential**
- **Theory of ideal growth in response to slow heating**
  (*Callen, Hegna, Rice, Strait, and Turnbull, Phys. Plasmas 6, 2963 (1999)*):

Heat slowly through critical b: $b = b_c(1+g_h t)$

Ideal MHD: $w^2 = -\hat{g}^2_{MHD}(b/b_c - 1)$ ➔ $g(t) = \hat{g}_{MHD}\sqrt{g_h t}$

Perturbation growth:

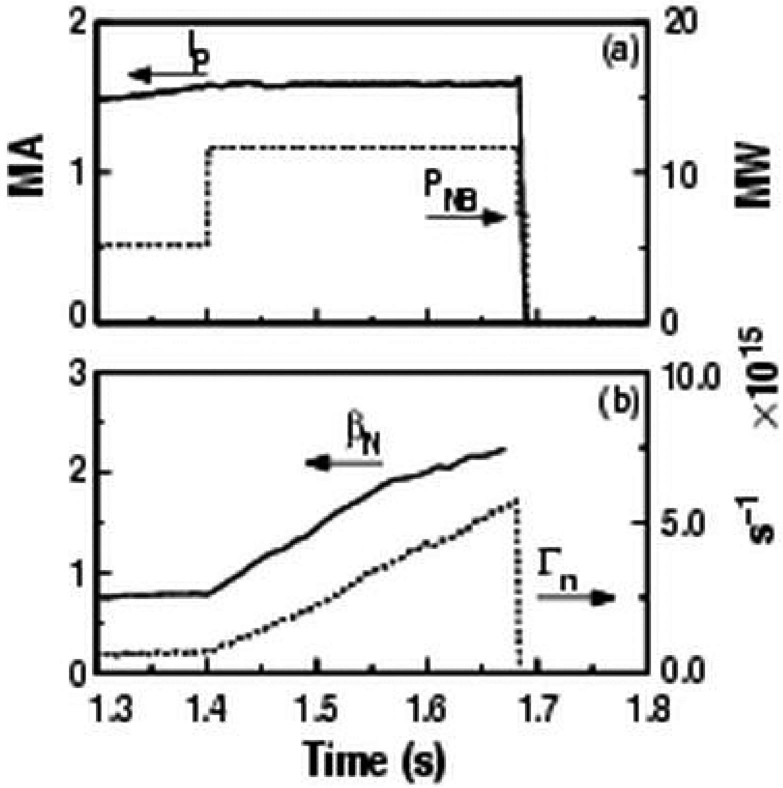
$$\frac{dx}{dt} = g(t)x \;➔\; x = x_0 \exp[(t/t)^{3/2}], \quad t = (3/2)^{2/3}\hat{g}^{-2/3}_{MHD} g_h^{-1/3}$$

As $\hat{g}_{MHD} \rightarrow 0, \quad g_h \rightarrow 0$

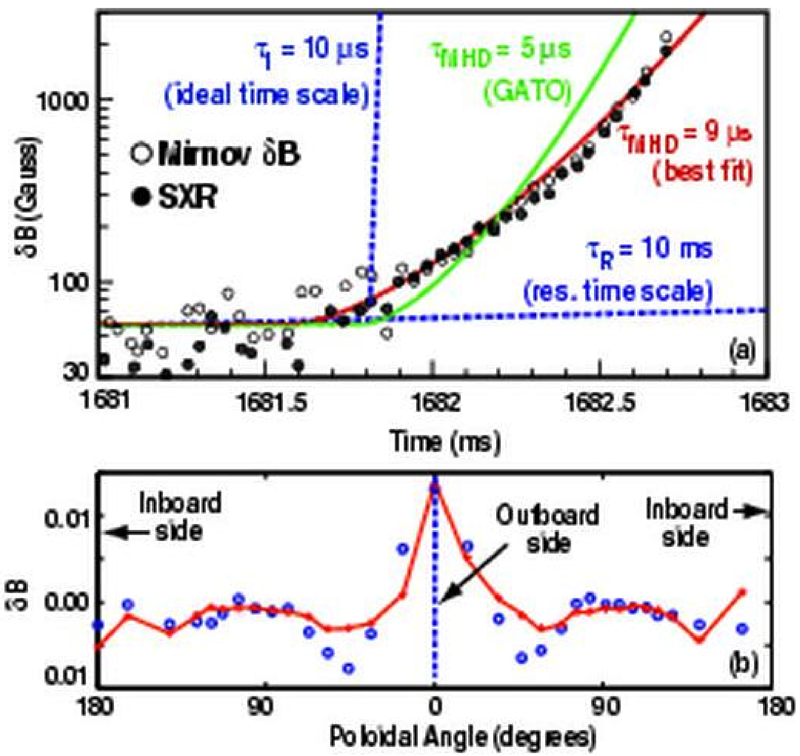
mode does not grow because it is exactly at marginal point

DIII-D SHOT #87009 Observes a Mode on Hybrid Time Scale As Predicted By Analytic Theory

- **High-b disruption slow heating**



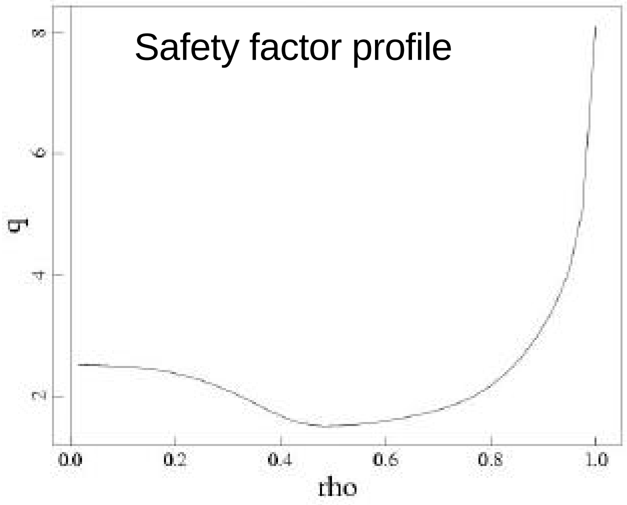
- **Growth is slower than ideal, but faster than resistive**



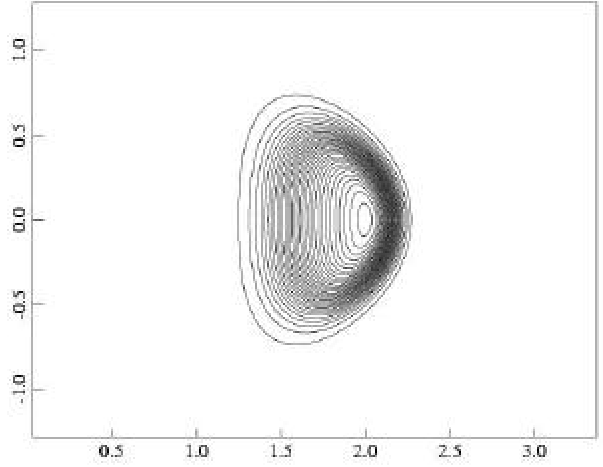
Callen et.al, Phys. Plasmas 6, 2963 (1999)

Initial Simulations Performed Using Fixed Boundary

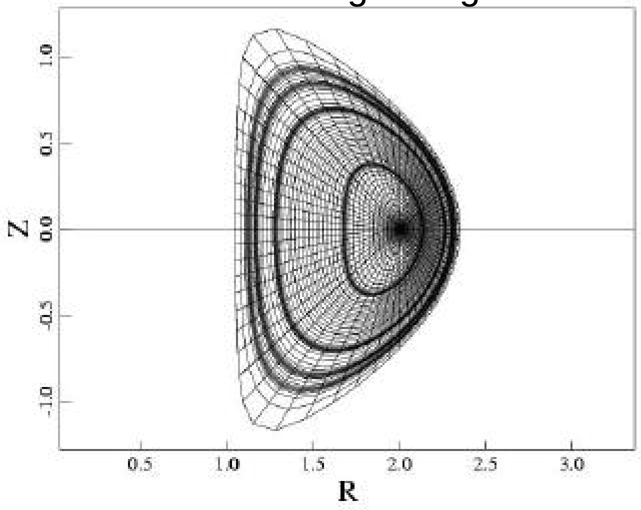
- **Equilibrium reconstruction from experimental data**
- **Negative central shear**
- **Gridding based on equilibrium flux surfaces**
  - **Packed at rational surfaces**
  - **Bi-cubic finite elements**


Safety factor profile

Pressure contours

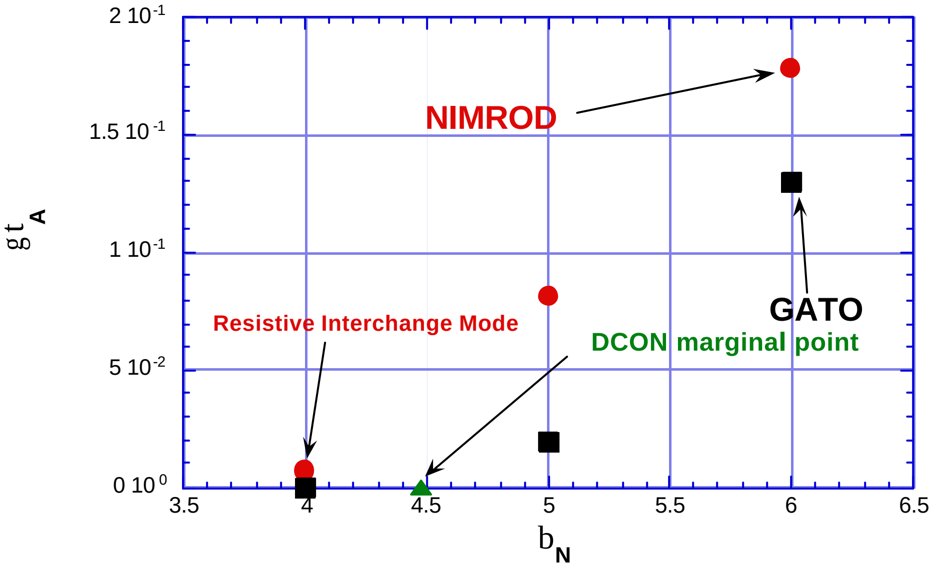


Poloidal gridding



Fixed Boundary Simulations Require Going to Higher Beta

- Conducting wall raises ideal stability limit
  - Need to run near ritical b_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

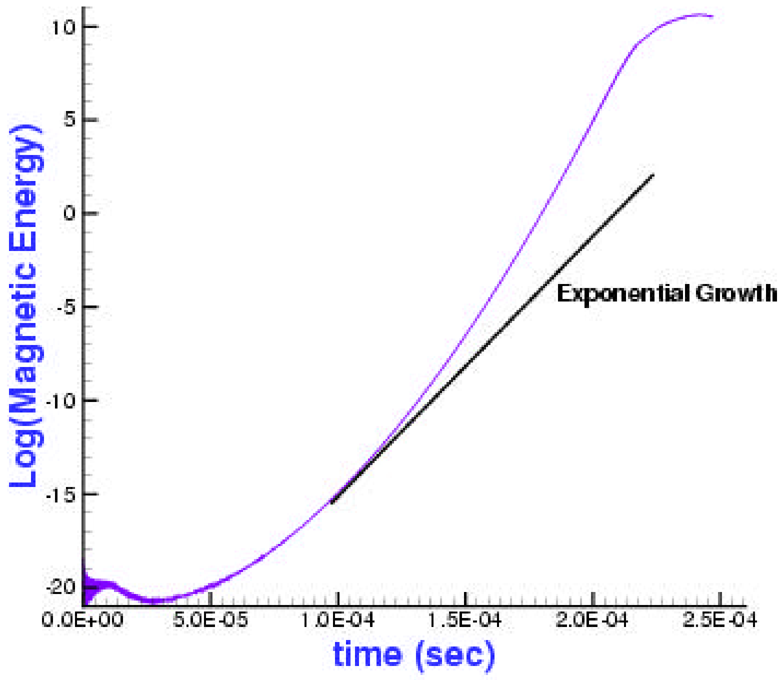
- **Initial condition: equilibrium below ideal marginal b_N**
- **Use resistive MHD**
- **Impose heating source proportional to equilibrium pressure profile**

$$\frac{¶P}{¶t} = \quad ..... \quad + g_H P_{eq}$$

$$\Rightarrow \quad b_N = b_{Nc}(1+g_H t)$$

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

Log of magnetic energy in *n* = 1 mode vs. time
$S = 10^6$ Pr = 200 $g_H = 10^3$ 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 $x \sim \exp[(t - t_0)/t]^{3/2}$**
- **Time constant scales as**

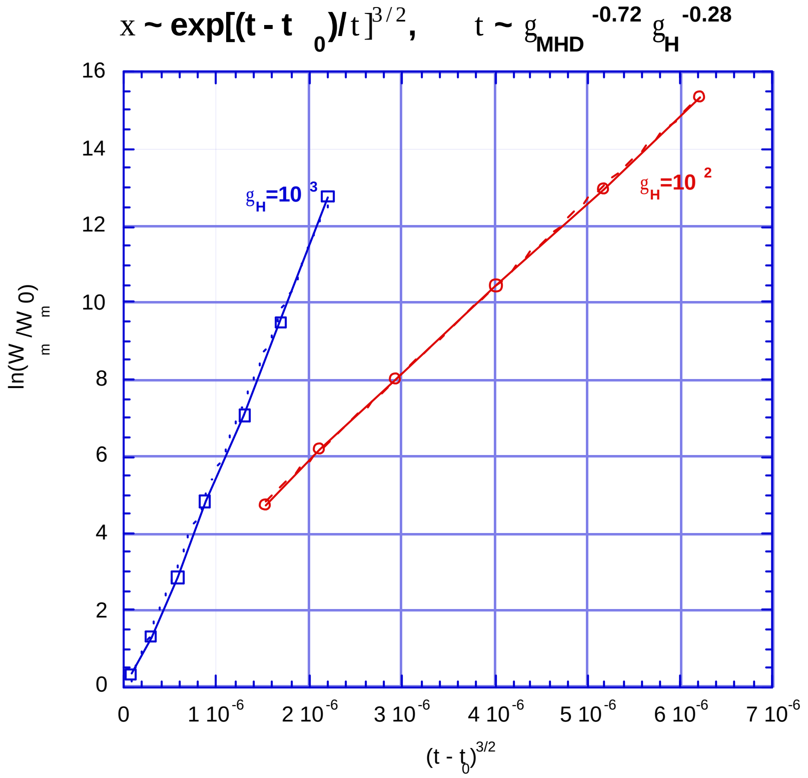
$$t \sim g_{MHD}^{-0.72} g_H^{-0.28}$$

- **Compare with theory:**

$$t = (3/2)^{2/3} \hat{g}_{MHD}^{-2/3} g_h^{-1/3}$$

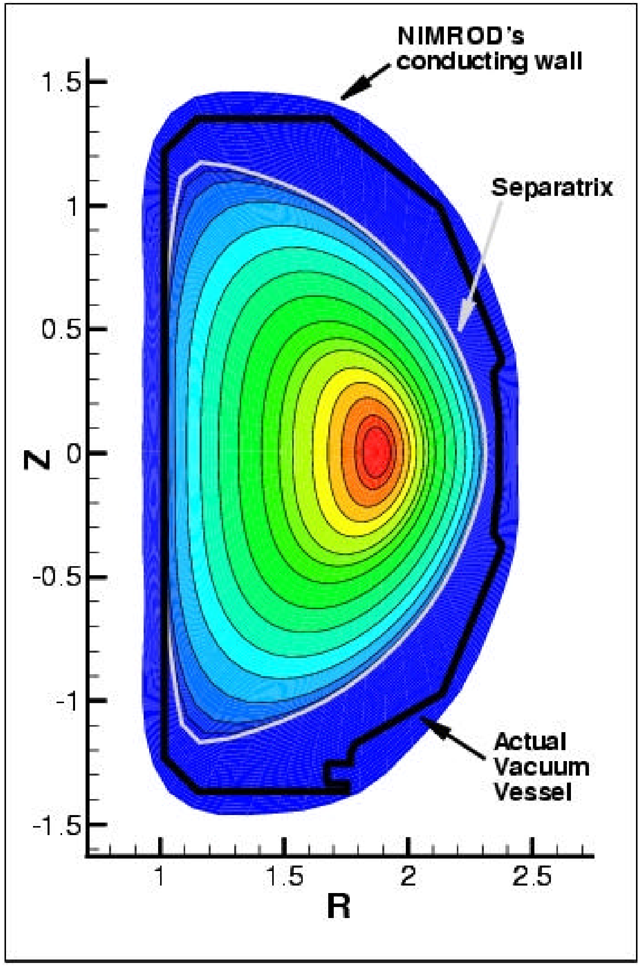
- **Discrepancy possibly due to non-ideal effects**

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



Free-Boundary Simulations Based on EFIT Reconstruction

- **Pressure raised 8.7% above "best fit" EFIT**
- **Boundary of computational domain is vacuum vessel, NOT the limiter.**
- **Uses Fourier version of actual conducting wall (based on representation from M. Chance's VACUUM code)**
- **Works well for B_n=0 boundary conditions**
- **V_n=0 boundary conditions OK because this allows flux from limiter, like experiment.**

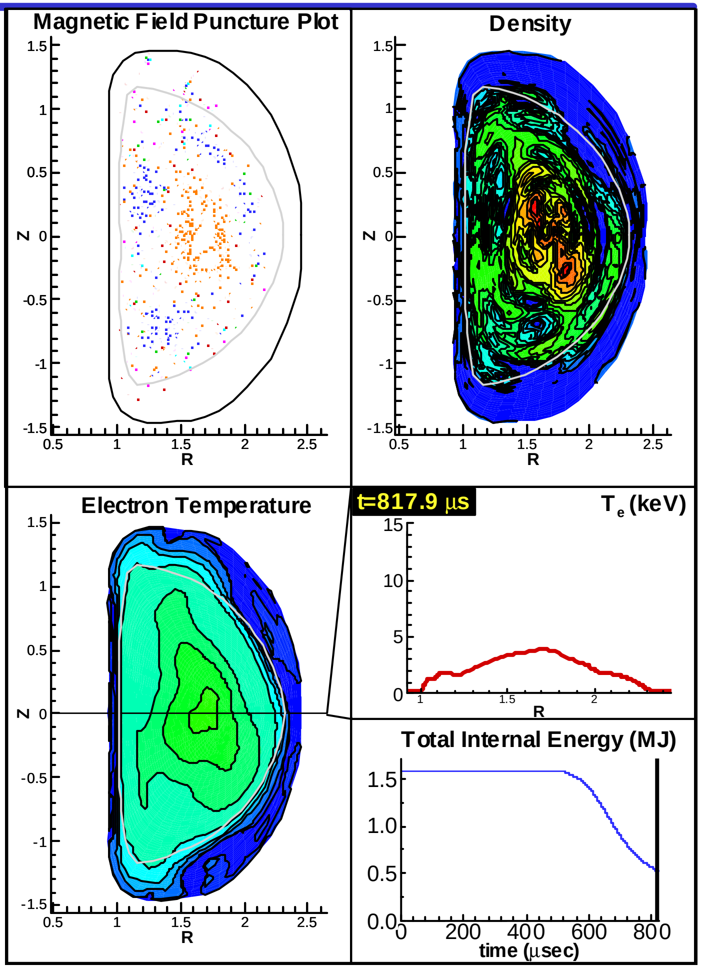


Initial Simulations Above Ideal Marginal Stability Point Look Promising

- Simulation includes:
  - $n = 0, 1, 2$
  - Anisotropic heat conduction $k_{par}/k_{perp}=10^8$
- Ideal modes grow with finite resistivity ($S = 10^5$)

- Because magnetic field becomes stochastic, heat lost to wall preferentially at divertor by parallel heat conduction

- Disruption is very different from conventional wisdom of plasma hitting the wall.



Is Heat Flux at Wall Too High?

- Time for crash ~ 200 μsec.
- Energy lost: 1 MJ
- Power ~ 5 GW
- Assuming area of wall ~50 m^2:

Average wall load = 100 MW/m^2 !!!

- ITER design: Primary wall max. = 0.5 MW/m^2
  Port limiter max. = 8.0 MW/m^2

⇒ Might need model for radiation heat losses

Beginning collaboration with D. Whyte, UW-Madison

Conclusions

- *Fixed-boundary simulations*
  - Heating through b limit
  - Super-exponential growth, in agreement with experiment and theory

- *Free-boundary simulations*
  - Initial low S results look promising:
    - Can simulate non-axisymmetric modes through loss of internal energy due to anisotropic heat conduction.
    - Loss of internal energy is due to rapid stochastization of the field, and not a violent shift of the plasma into the wall.

Future Work

Future work will investigate:

- Heating the plasma through the marginal point
- Simple models of radiative heat loss
- Higher Lundquist values
- More toroidal mode numbers
- Better diagnostics for detailed comparisons with experiments
- More recent simulations of disruption mitigation experiments

Free boundary simulatins provide new opportunities for MHD simulations to contribute to understanding of edge physics.