NUMERICAL STUDY OF A HIGH BETA DISRUPTION IN DIII-D SHOT 87009 WITH THE NIMROD CODE

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OUTLINE

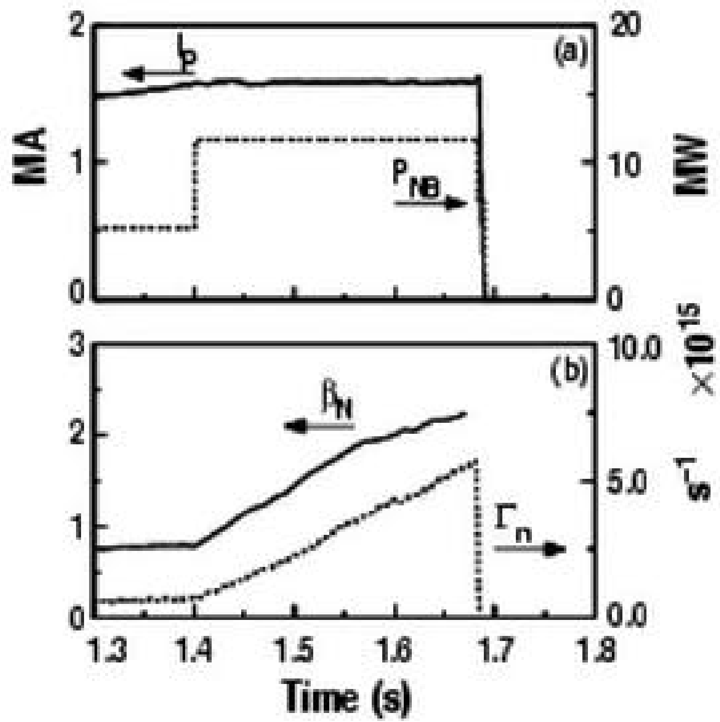
- **DIII-D shot 87009**
  - **Slow heating through critical β_N (β_{Ncrit} ~ 1) ← High-β disruption**
  - **Perturbation growth greater than usual exp(γt)**
- **Theory [Callen, Hegna, Rice, Strait, and Turnbull, Phys. Plasmas 6, 2963 (1999)]**
  - **Slow heating through ideal MHD stability boundary**

$$\beta = \beta_c(1+\gamma_h t) \rightarrow \gamma(t) = \hat{\gamma}_{MHD}\sqrt{\gamma_h t},\ \xi \sim \exp[(t/\tau)^{3/2}],\ \tau \sim \hat{\gamma}_{MHD}^{-2/3}\gamma_h^{-1/3}$$

- **Numerical simulation with NIMROD**
  - **Conducting wall on separatrix ← Larger β_{Ncrit} (β_{Ncrit} ~ 4.5)**
  - **Linear stability, comparison with GATO**
  - **Nonlinear (n = 0, 1) simulation at β_N = 5**
  - **Slow drive through critical point**

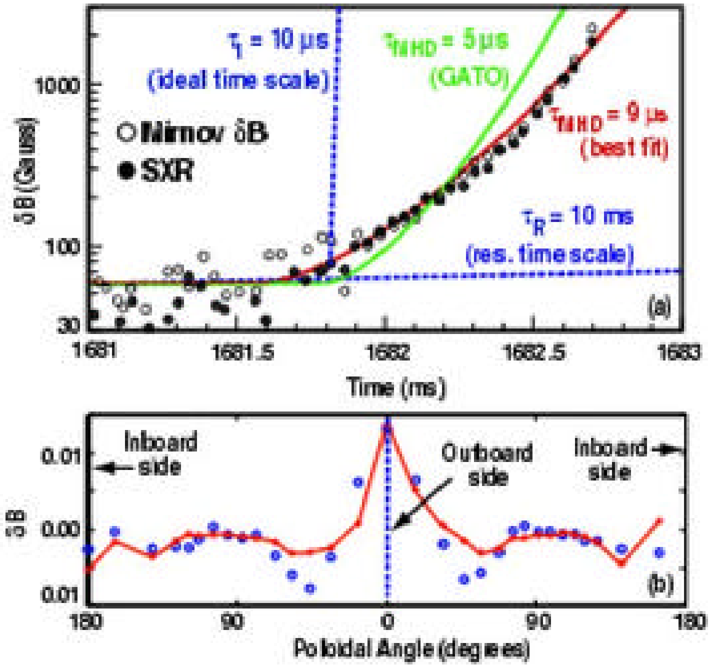
DIII-D SHOT 87009

High-β disruption when heated slowly through critical β_N



DIII-D SHOT 87009

Growth is faster than simple exponential



THEORY

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:** $\omega^2 = -\hat{\gamma}^2_{MHD}(\beta/\beta_c - 1)$

  $\Leftarrow \gamma(t) = \hat{\gamma}_{MHD}\sqrt{\gamma_h t}$

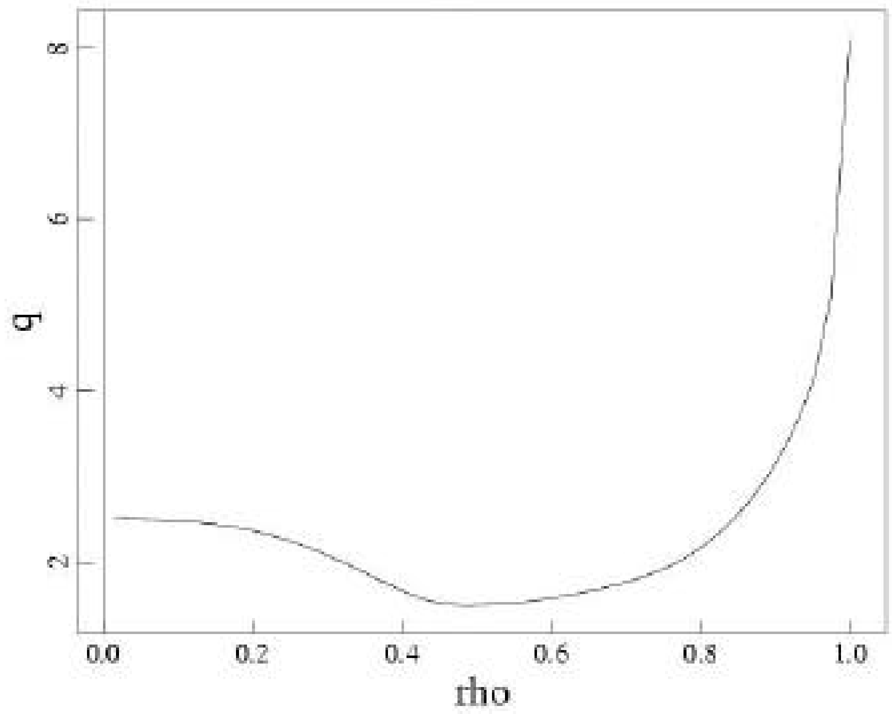
- **Perturbation growth:**

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

Good agreement with experiment

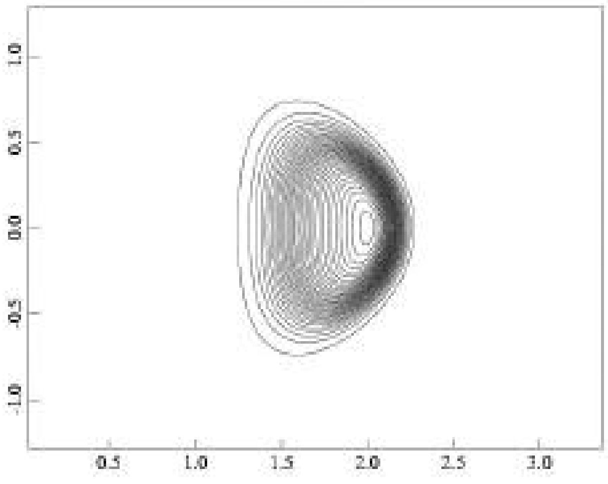
EQUILIBRIUM

q-profile

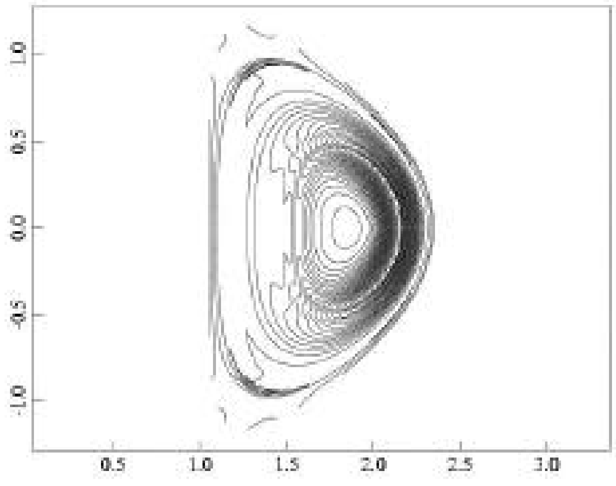


EQUILIBRIUM

Pressure

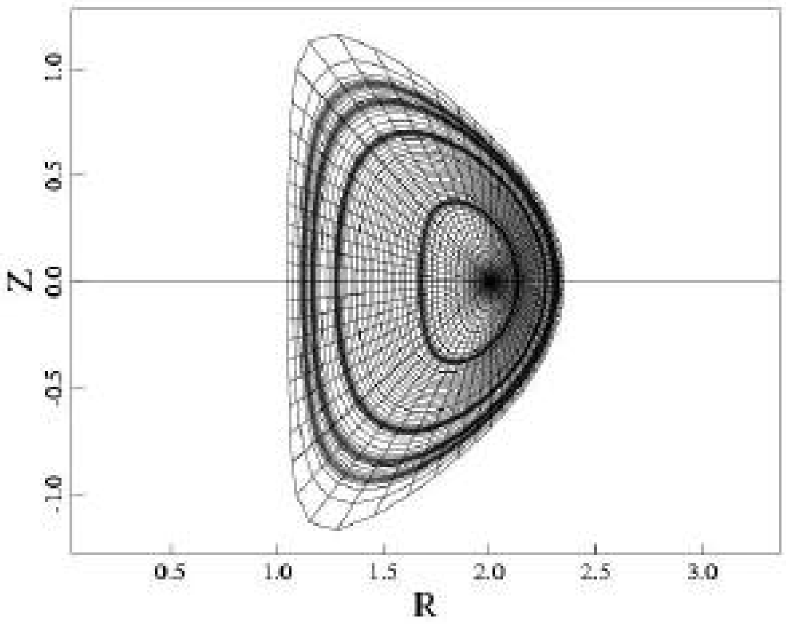


Toroidal Current



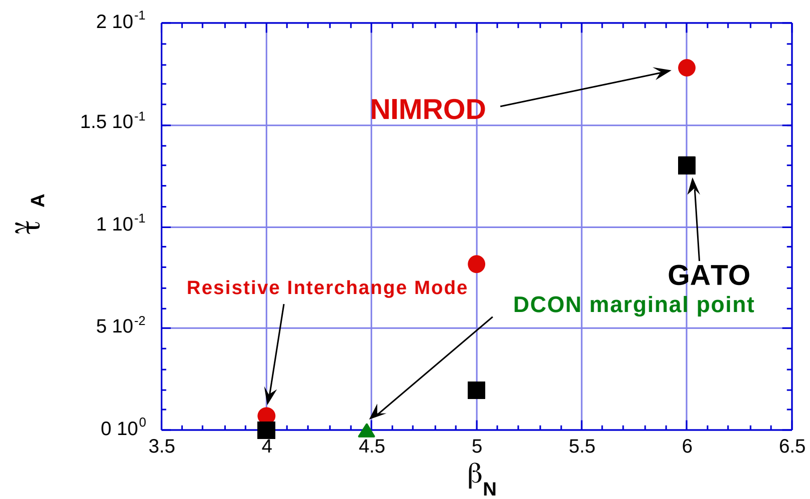
NIMROD GRID

- Packed at rational surfaces
- Bi-cubic finite elements

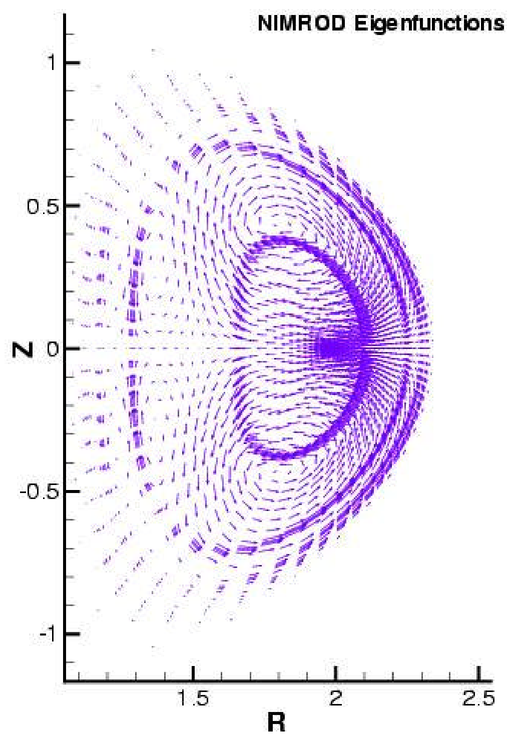


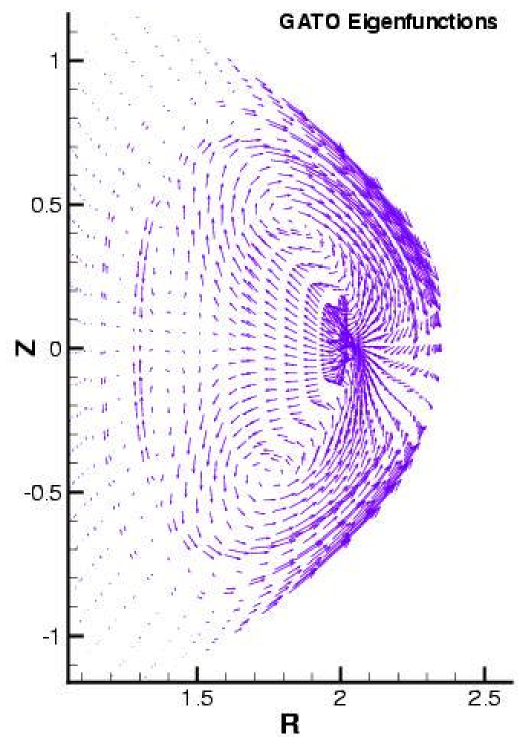
LINEAR STABILITY

- **Linear growth rate as a function of β_N from NIMROD and GATO**
- **NIMROD finds resistive interchange mode below β_{Ncrit}**



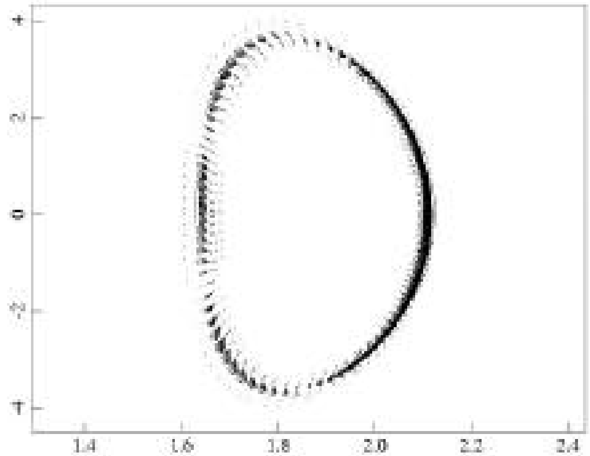
Poloidal Velocity Eigenfunctions



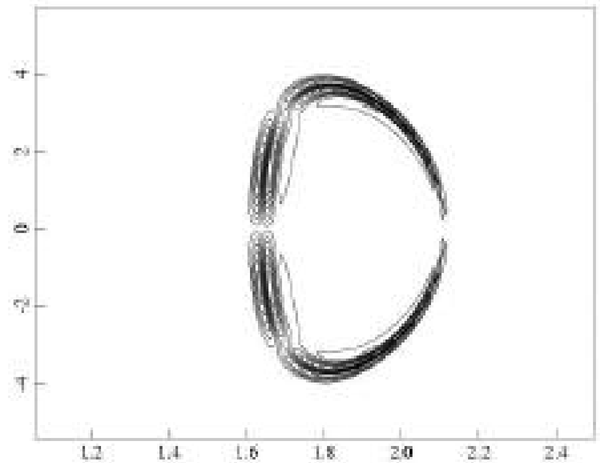


RESISTIVE INTERCHANGE MODE, β_N = 4

***n* = 1 Poloidal Velocity**

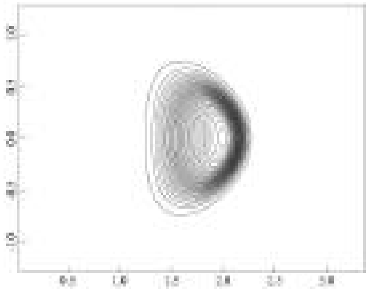


***n* = 1 Pressure**

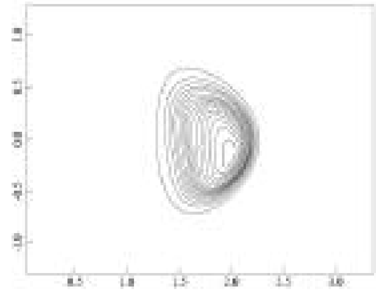


NONLINEAR EVOLUTION, β_N = 5, PRESSURE

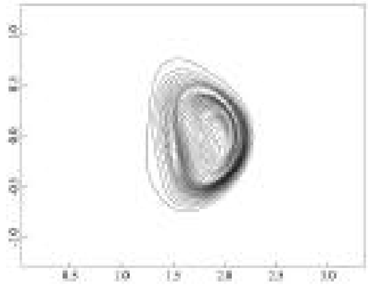
***t* = 0 msec.**



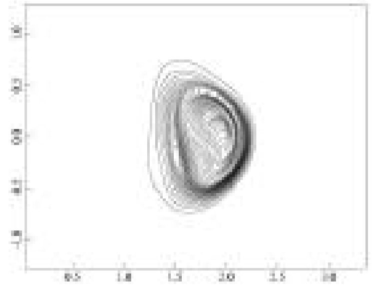
***t* = 0.120 msec**



***t* = 0.131 msec**

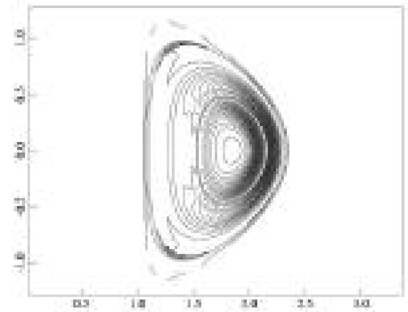


***t* = 0.135 msec.**

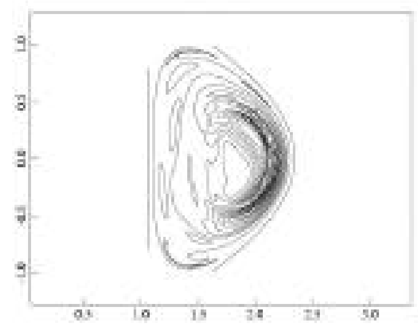


NONLINEAR EVOLUTION, β_N = 5, TOROIDAL CURRENT

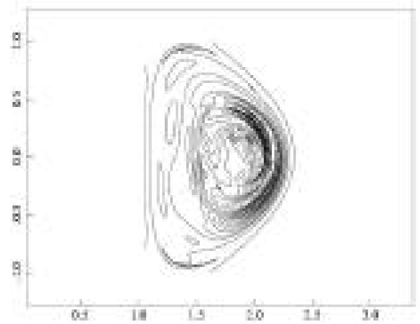
***t* = 0 msec.**



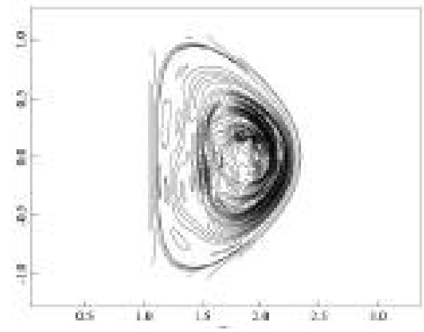
***t* = 0.120 msec**



***t* = 0.131 msec**

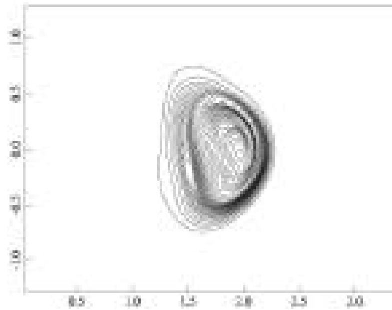


***t* = 0.135 msec.**

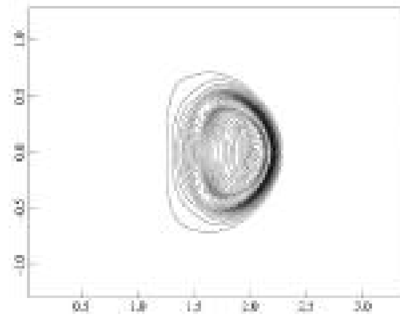


NONLINEAR PRESSURE VS. TOROIDAL ANGLE

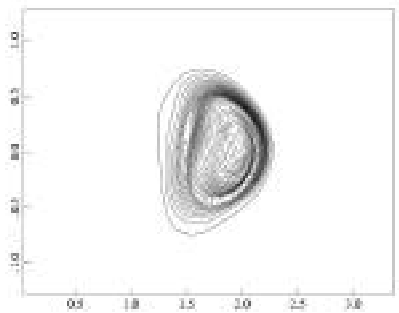
ϕ = 0



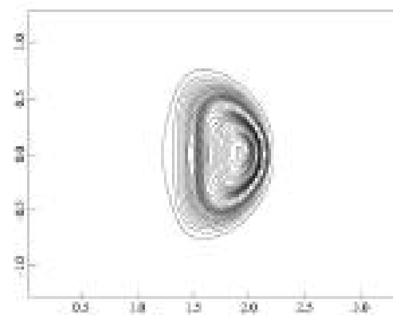
$\phi = \pi/2$



$\phi = \pi$



$\phi = 3\pi/2$



NONLINEAR SIMULATION WITH HEATING

- **Initial condition: equilibrium below ideal marginal β_N**
  - **NIMROD ==> β_{Nc} ~ 4.85 DCON ==> β_{Nc} ~ 4.45**
- **Impose heating source proportional to equilibrium pressure profile**

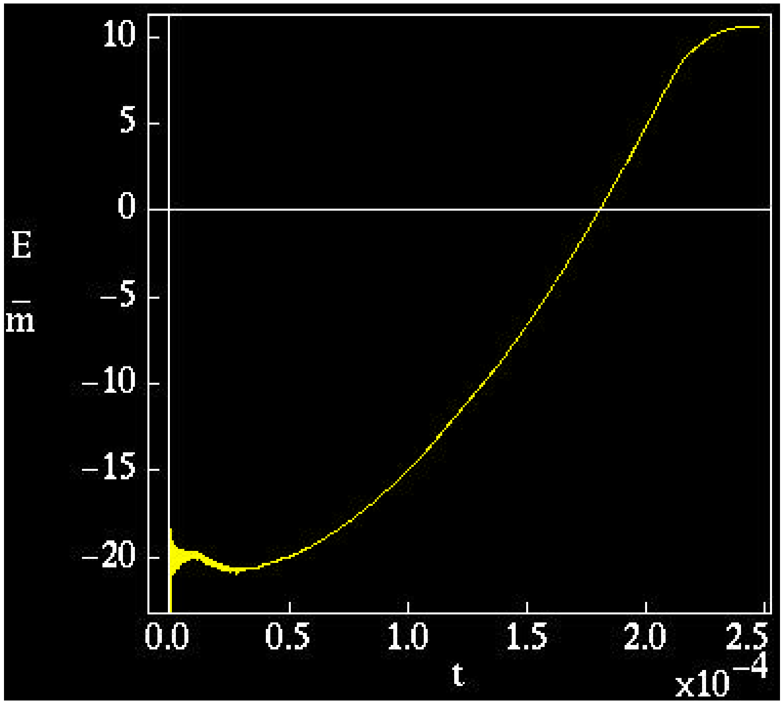
$$\frac{\partial P}{\partial t} = \;.....\; + \gamma_H P_{eq} \quad \textbf{==>} \quad \beta_N = \beta_{Nc}(1+\gamma_H t)$$

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

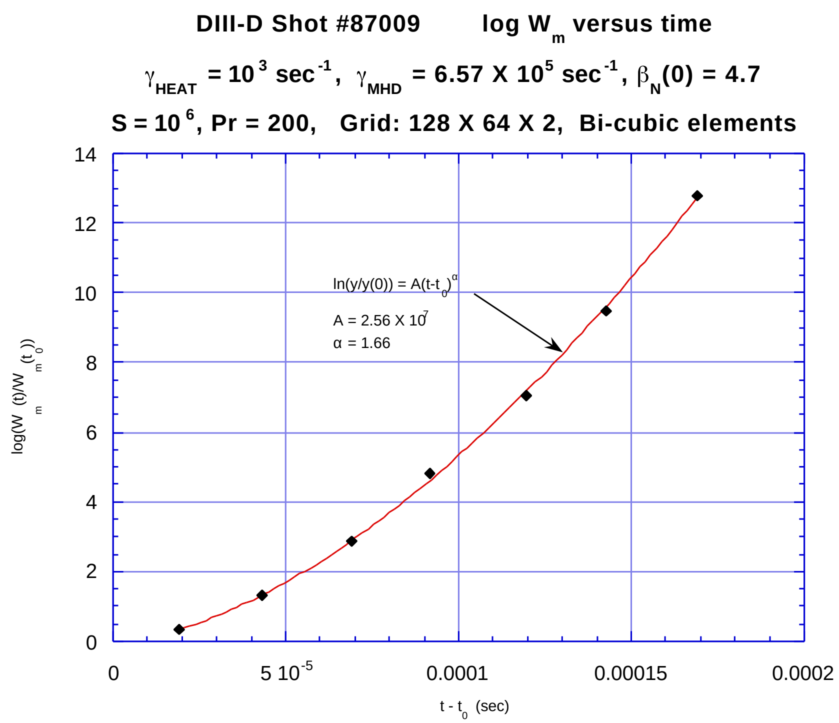
ENERGY IN UNSTABLE MODE

Magnetic Energy in *n* = 1 mode versus time

$S = 10^6$, Pr = 200, $\gamma_H = 10^3$ sec^{-1}

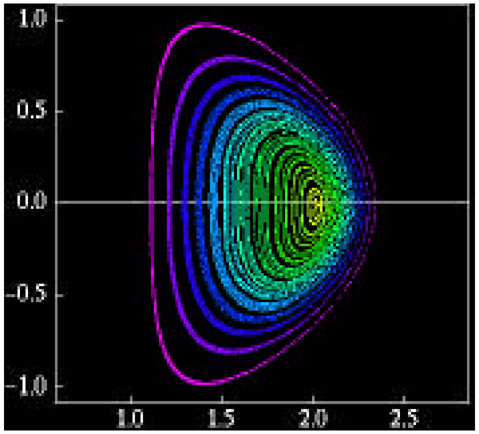


ENERGY GROWS "SUPER-EXPONENTIALLY"

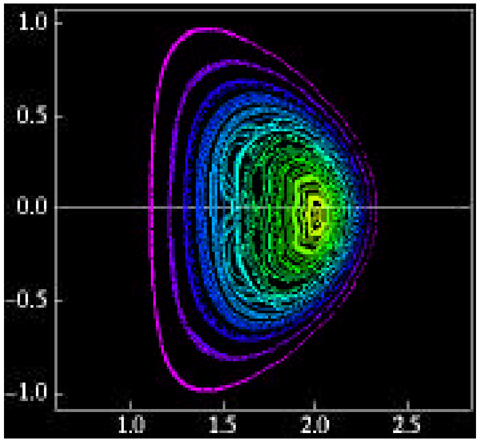


EVOLUTION OF FIELD LINES

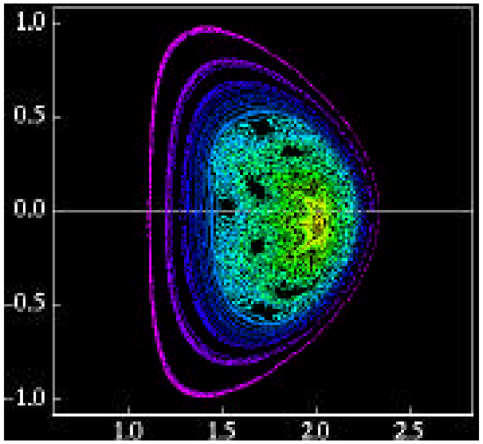
t = 1.99 X 10^{-4} sec



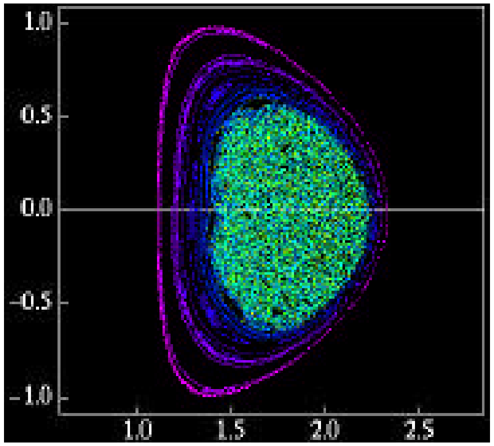
t = 2.102 X 10^{-4} sec



t = 2.177 X 10^{-4} sec

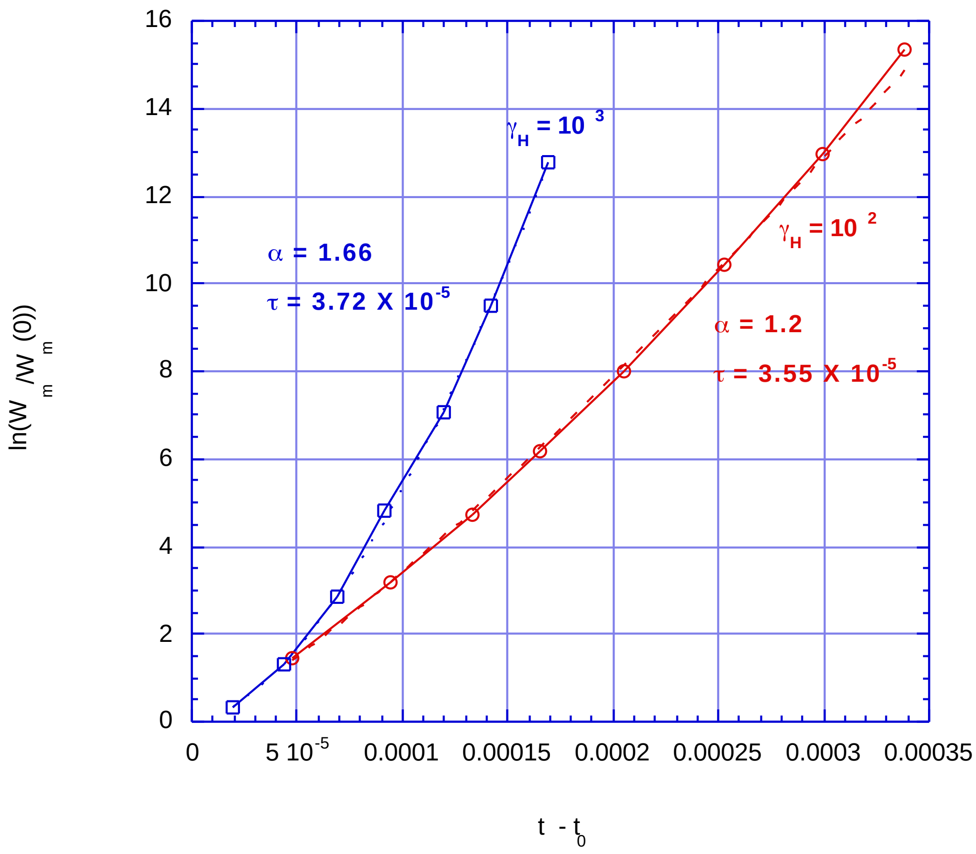


t = 2.2 X 10^{-4} sec



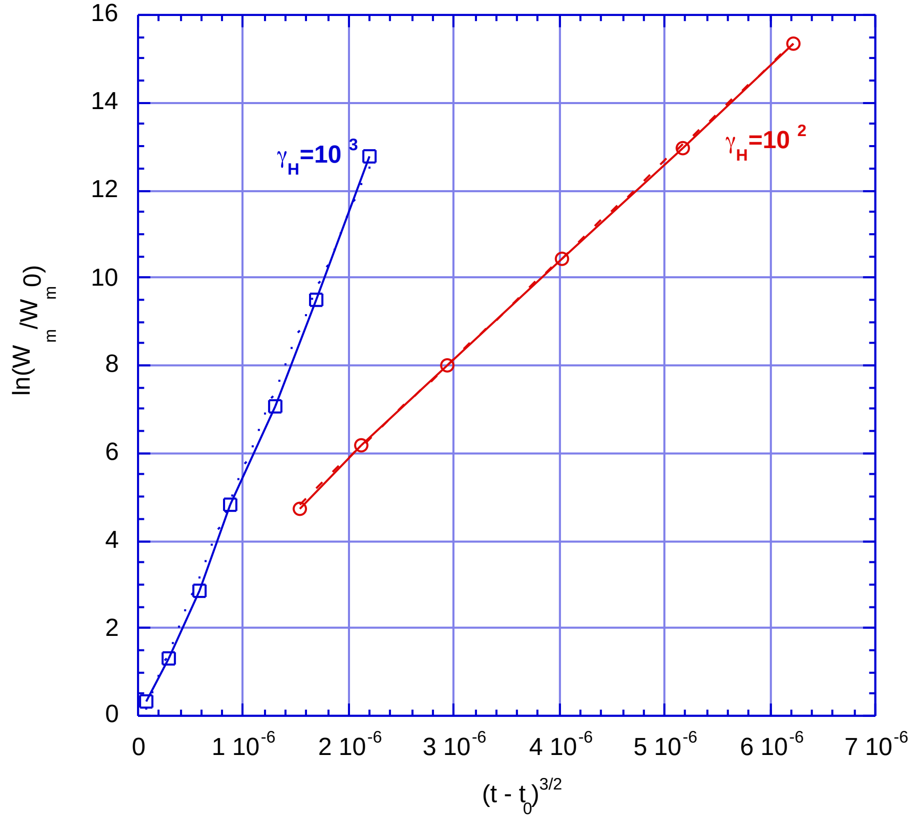
EFFECT OF HEATING RATE

$\xi \sim \exp[(t - t_0)/\tau]^{\alpha}$, α (theory) = 3/2, $\tau \sim \gamma_{MHD}^{-2/3} \gamma_H^{-1/3}$



ASSUME α = 3/2 DEPENDENCE

$$\xi \sim \exp[(t - t_0)/\tau]^{3/2}, \quad \tau \sim \gamma_{MHD}^{-0.72}\gamma_H^{-0.28}$$



DISCUSSION

- **Direct comparison with experiment difficult because of high β-limit due to presence of conducting wall**
- **Theory predicts** $\xi = \xi_0 \exp\left(\frac{t - t_0}{\tau}\right)^{3/2}, \quad \tau = \left(\frac{3}{2}\right)^{2/3} \hat{\gamma}_{MHD}^{-2/3} \gamma_H^{-1/3}$
- **NIMROD finds** $\xi = \xi_0 \exp\left(\frac{t - t_0}{\tau}\right)^{\alpha(\gamma_H)}, \quad \tau \sim const.$
- **When fit to α = 3/2, NIMROD yields scaling** $\tau \sim \gamma_{MHD}^{-0.72} \gamma_H^{-0.28}$
- **Possible explanations**
  - **Initial conditions actually above critical β, then $\gamma_H \rightarrow 0$ would imply $\alpha \rightarrow 1$ (exponential growth)**
  - **Non-ideal effects are important**
- **Stochastic field lines in saturated state ==> degraded confinement**
  - **Self-consistent calculations with anisotropic heat flux underway**