Onset and Saturation of a Non-Resonant Internal Mode in NSTX and Implications for AT Modes in ITER

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Abstract

Motivated by experimental observations of apparently triggerless tearing modes, we have performed linear and nonlinear MHD analysis showing that a non-resonant mode with toroidal mode number $n=1$ can develop in the National Spherical Torus eXperiment (NSTX) at moderate normalized β_N when the shear is low and the central safety factor q_0 is close to but greater than one. This mode, which is related to previously identified "infernal" modes, will saturate and persist, and can develop poloidal mode number $m=2$ magnetic islands in agreement with experiments. We have also extended this analysis by performing a free-boundary transport simulation of an entire discharge and showing that, with reasonable assumptions, we can predict the time of mode onset.

NSTX Discharges are Severely Degraded in the Presence of Neoclassical Tearing Modes

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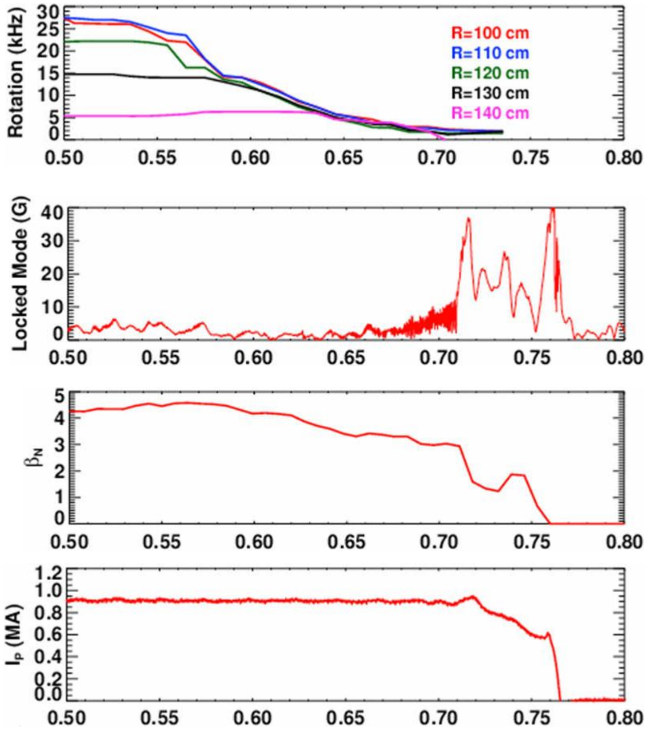
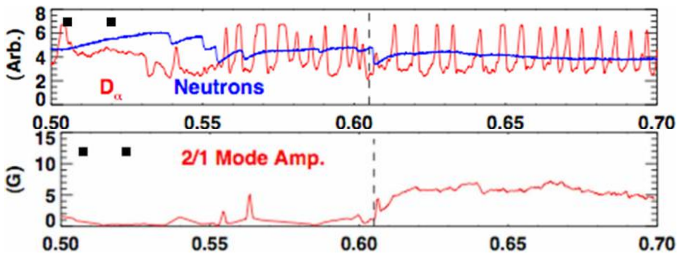
- Island width is proportional to β_p.
- Deleterious effects include
  - – Rotation damping
  - – Mode locking
  - – Confinement degradation
  - – Disruption

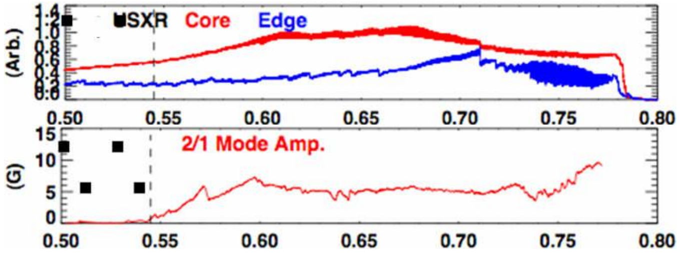


Triggers Have Been Identified for Some NTMs

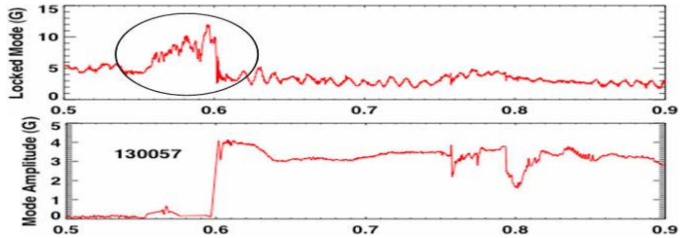
- Energetic particle modes



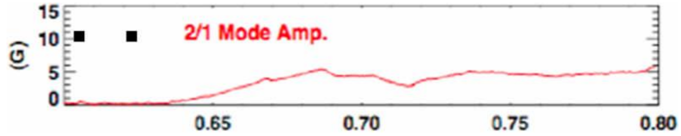
- Edge localized modes



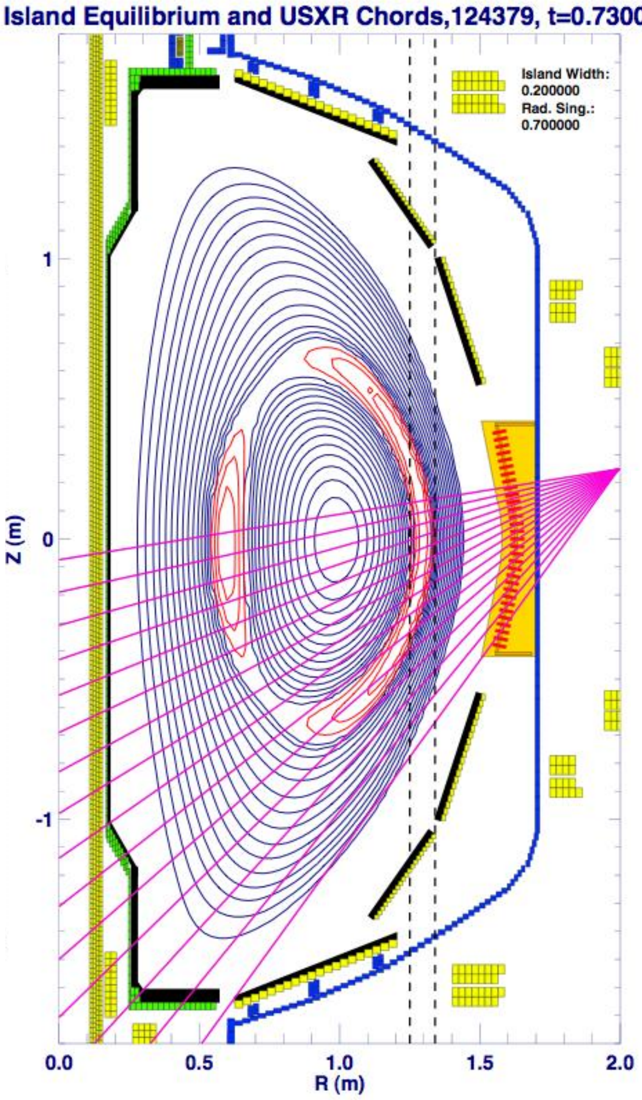
- Locked modes

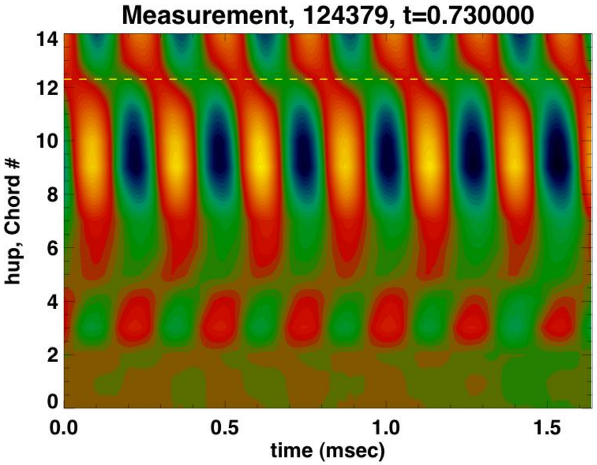


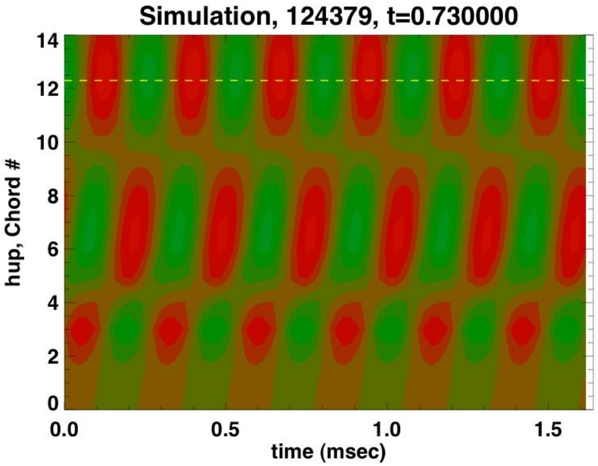
- <u>Others have no clear trigger…</u>



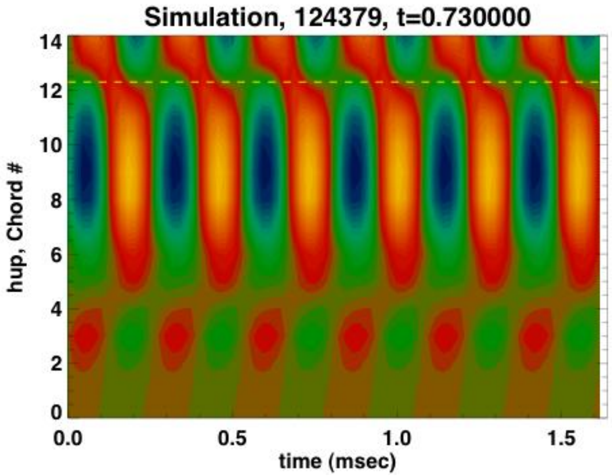
Eigenfunction Analysis of Multichord Data Suggests Coupling to 1,1 Ideal Kink


Island Equilibrium and USXR Chords,124379, t=0.730000


Measurement, 124379, t=0.730000

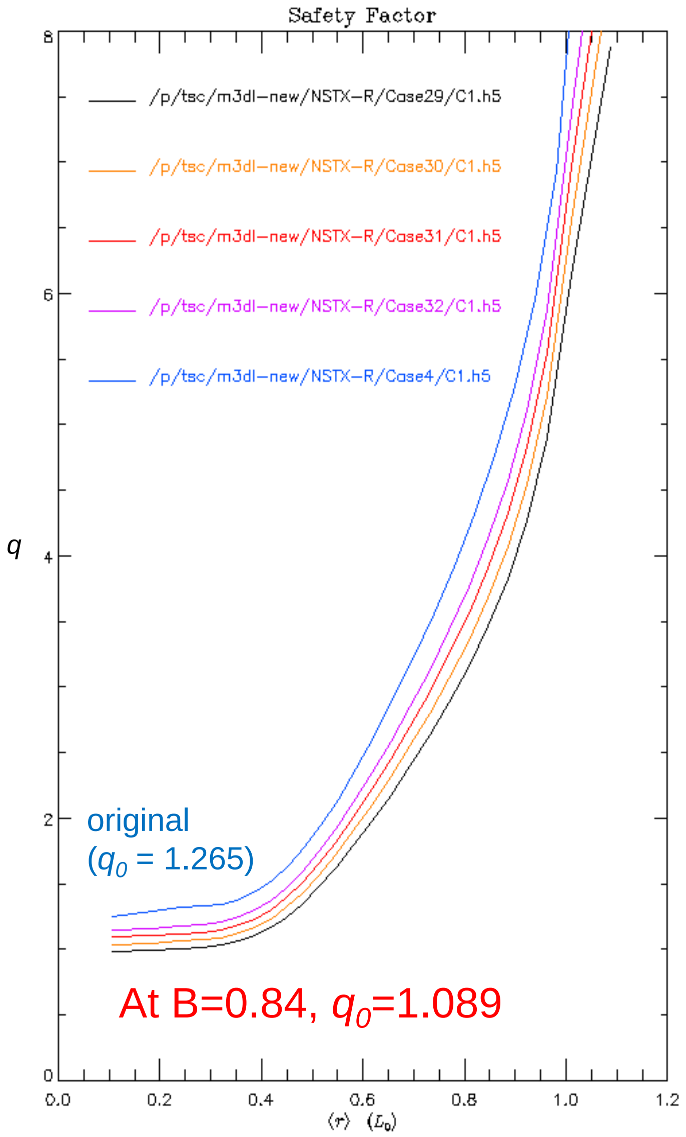

Simulation, 124379, t=0.730000

2,1 only


Simulation, 124379, t=0.730000

2,1 + 1,1 pert

Scan of Nearby Equilibria with M3D-C^1 Shows Marginal Stability to Ideal n=1 Mode

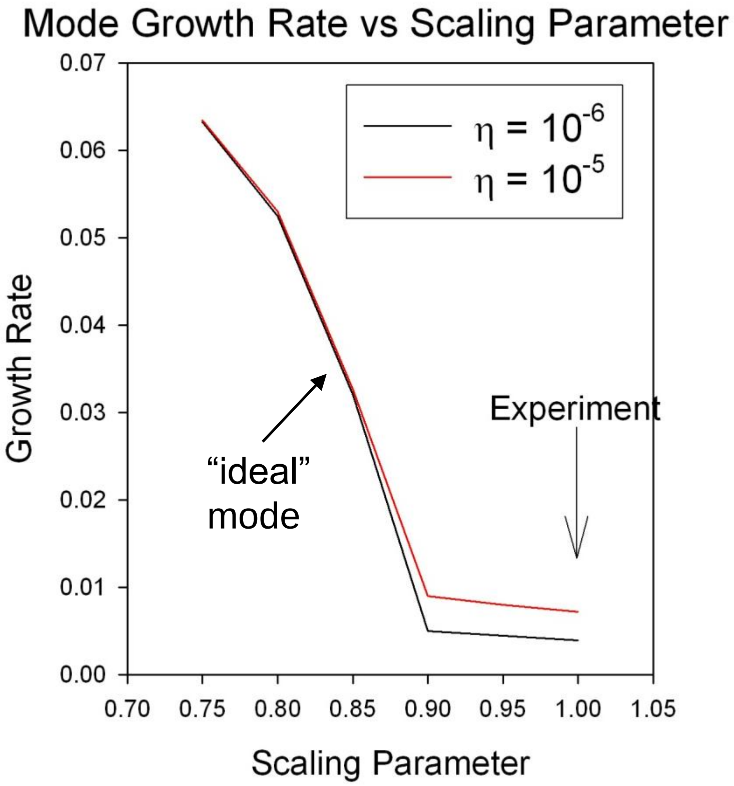


original (q_0 = 1.265)

At B=0.84, q_0=1.089

Toroidal field was scaled down, keeping current density constant.

q is proportional to Bateman scaling factor B.

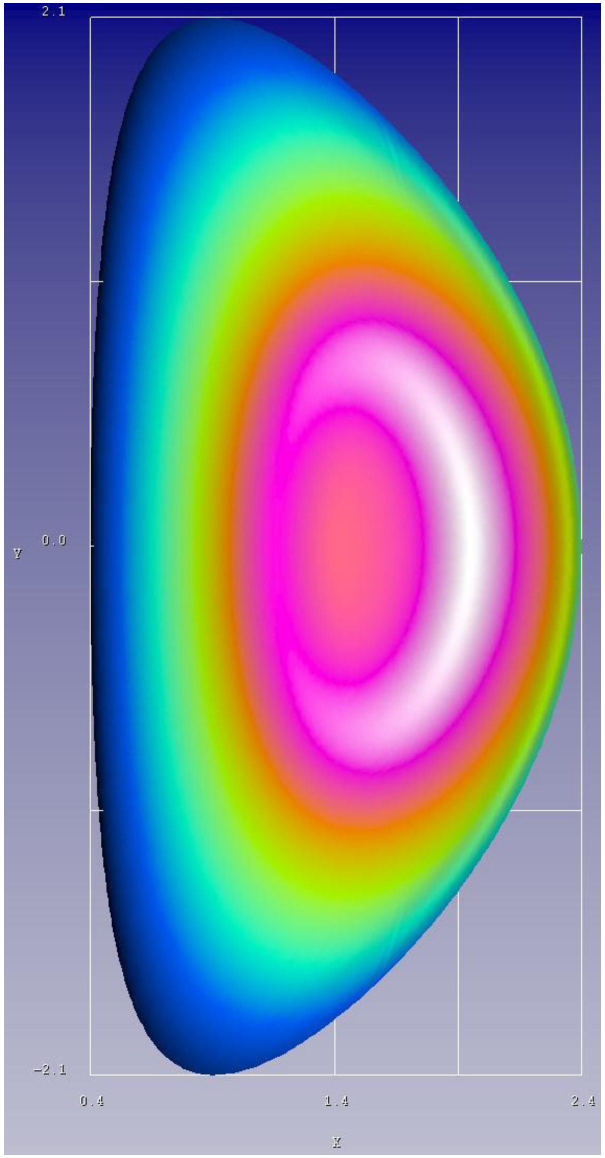


“ideal” mode

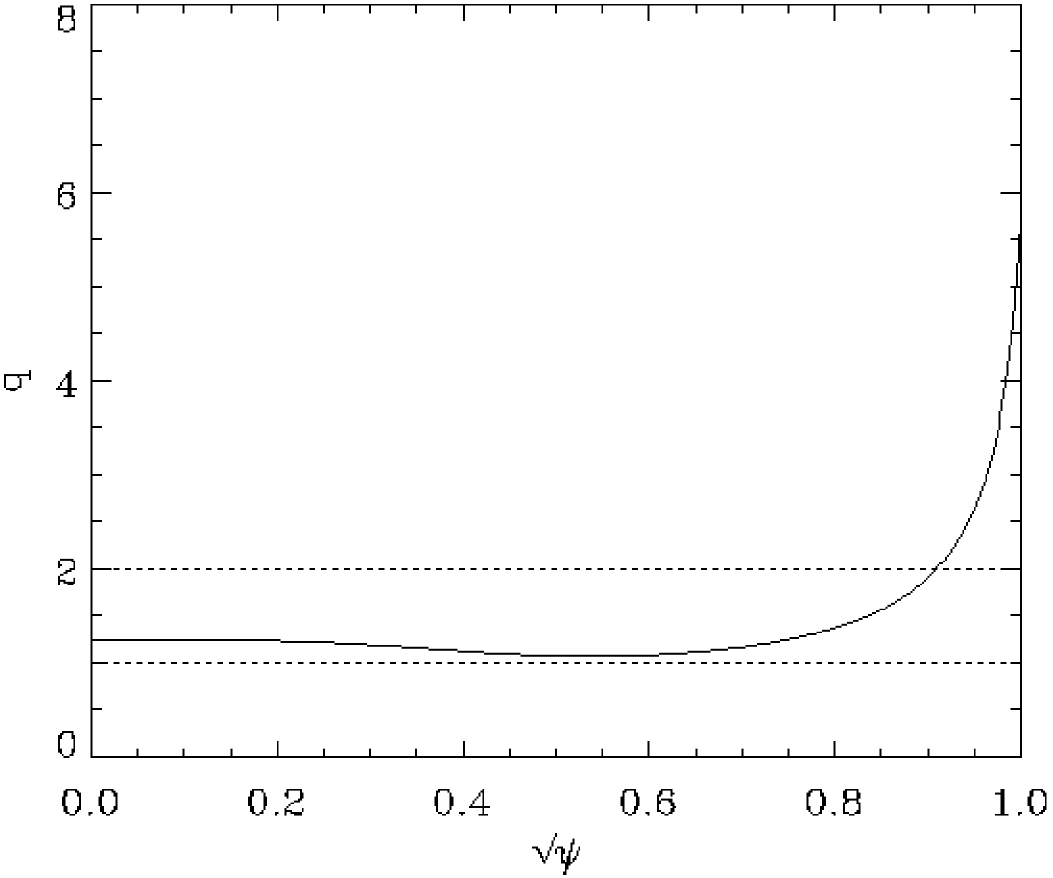
Experiment

Typical reversed shear equilibrium

C

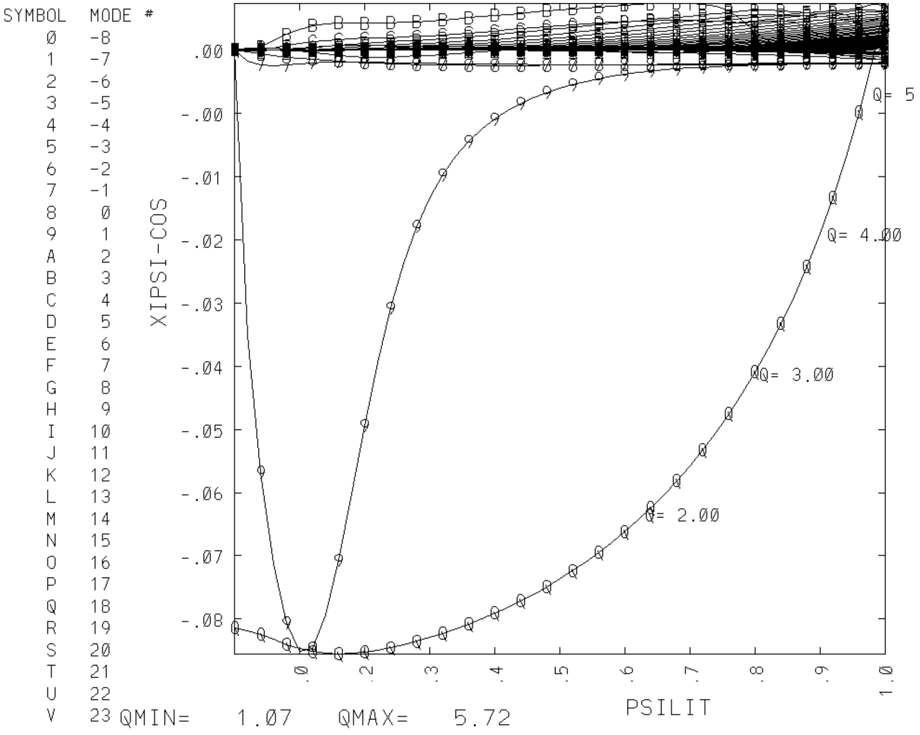


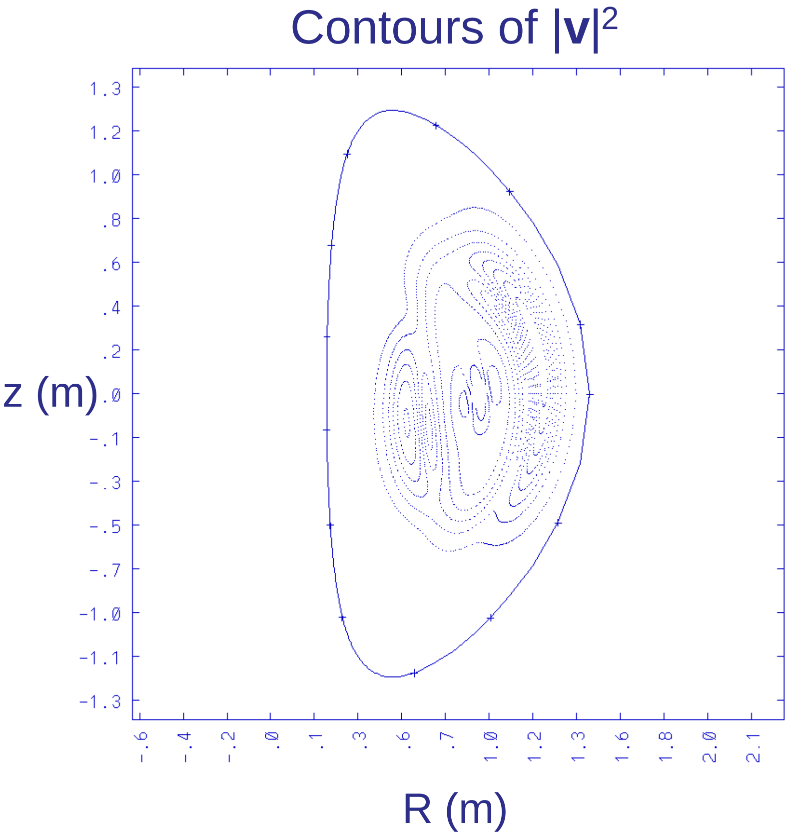
- Aspect ratio = 1.425; elongation = 2.15; tri=0.52
- $q_0 = 1.25$; $q_{\min}=1.074$; $q_a=5.715$
- $\beta_N = 3.32$; $\beta_0 = 0.54$
- $I_p = 2$ MA



Linear Stability Analysis

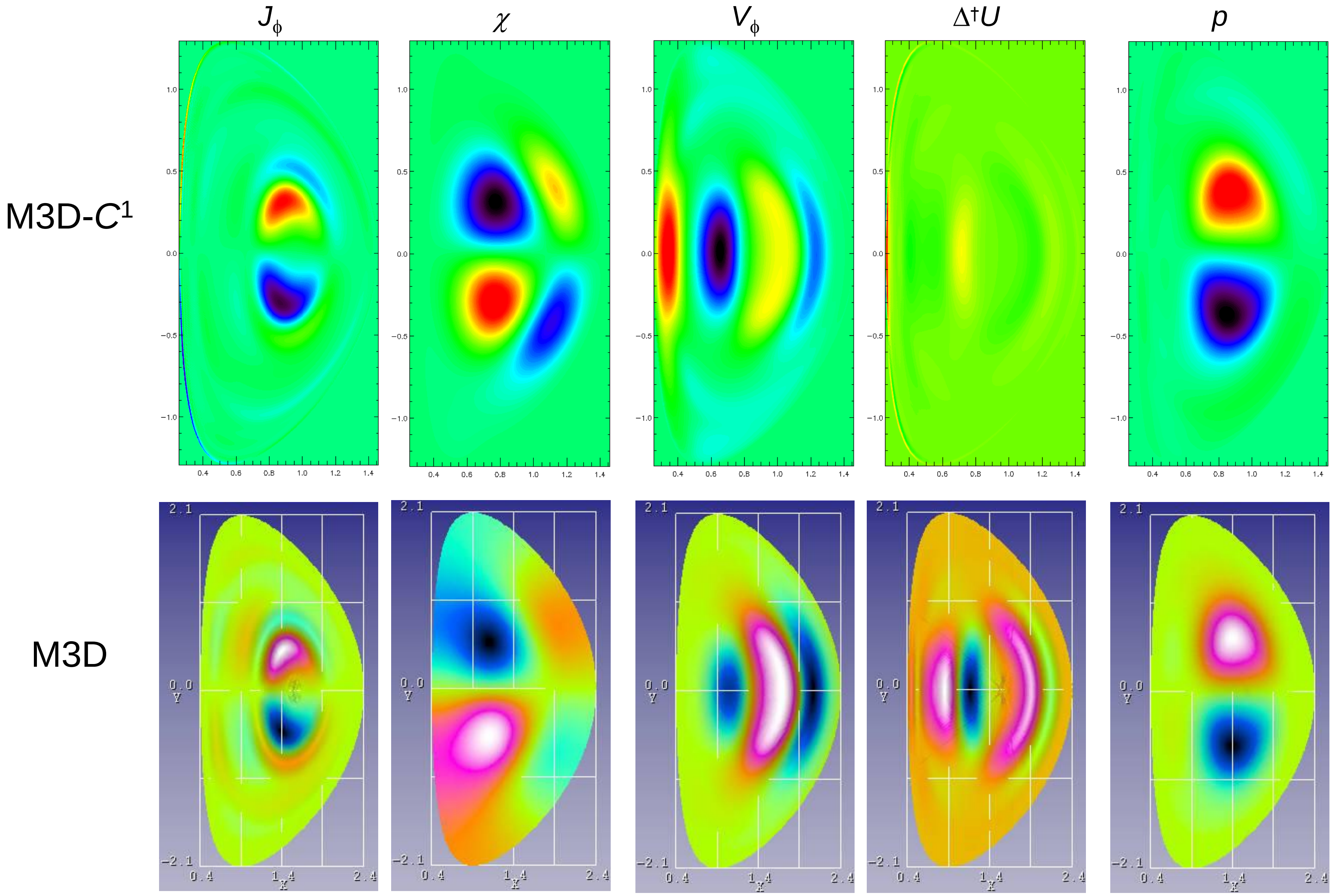
- Ideal stability of low-*n* modes analyzed with PEST-1 and NOVA.
- n=1 eigenvalue $\lambda \equiv (\omega\tau_A)^2 = -4.56 \times 10^{-3}$.
- n=2, 3 are stable.




Contours of $|\mathbf{v}|^2$

n=1 eigenmode: $\gamma\tau_A = 4.144\times10^{-2}$

Higher *n* modes are stable



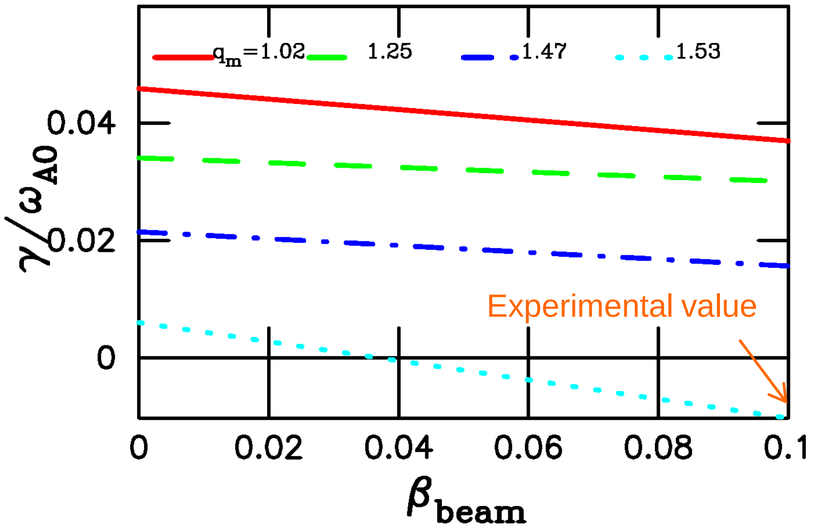
Kinetic Effects computed using NOVA-K

- Determines beam ion contribution to δW based on ideal n=1 mode structure from NOVA:

$$\delta W_{kbeam} = -(2\pi)^2 e_\alpha c \int dP_\varphi d\mu d\mathcal{E}\tau_b \sum_{m,m',l} \frac{X^*_{m,l}(\omega-\omega_*)X_{m',l}}{\omega-\overline{\omega_d}} \frac{\partial F_{beam}}{\partial \mathcal{E}},$$

where the integration is performed over the particle phase space $P_\varphi, \mu, \mathcal{E}$ in general tokamak geometry, τ_b is the particle bounce time, $X_{m,l}$ gives the wave-particle interaction power exchange, F_{beam} is the fast particle equilibrium distribution function, $\omega_* = -i \frac{\partial F/\partial P_\varphi}{\partial F/\partial \mathcal{E}} \frac{\partial}{\partial \varphi}$, and ω_d is the particle toroidal drift frequency.

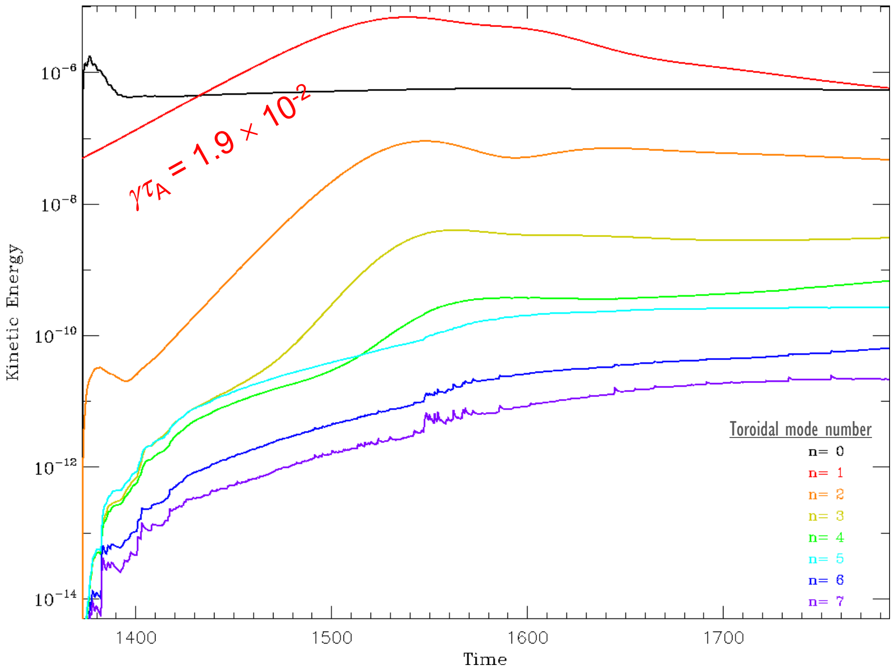
- Use TRANSP profiles similar to those above, Lorentz collision operator with injection pitch angle χ_0 = 0.55 and pitch angle distribution width $\Delta\chi$ = 0.3:



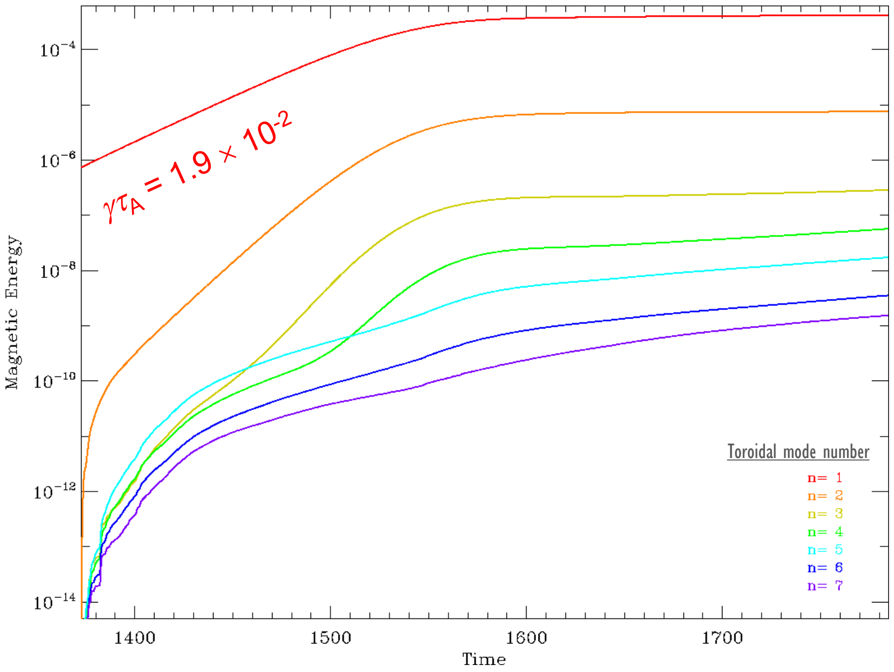
Experimental value

- Growth rate is very sensitive to q_{min}.
- Energetic beam ions can have a significant stabilizing effect near instability threshold.

Internal mode saturates nonlinearly



$\gamma\tau_A = 1.9 \times 10^{-2}$



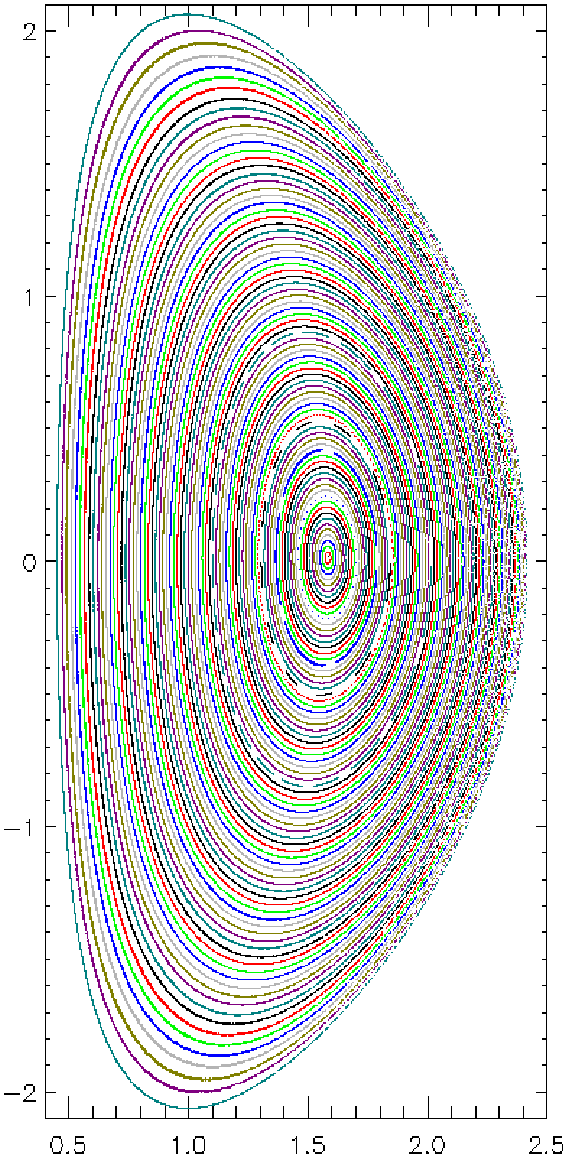
$\gamma\tau_A = 1.9 \times 10^{-2}$

$B = 1.05$
$\eta = 6.25 \times 10^{-6}$
$\mu = 5 \times 10^{-4}$
$\kappa_\perp = 5 \times 10^{-5}$
$\kappa_{||} = 5 \times 10^{-1}$
$H_\mu = 10^{-3}$

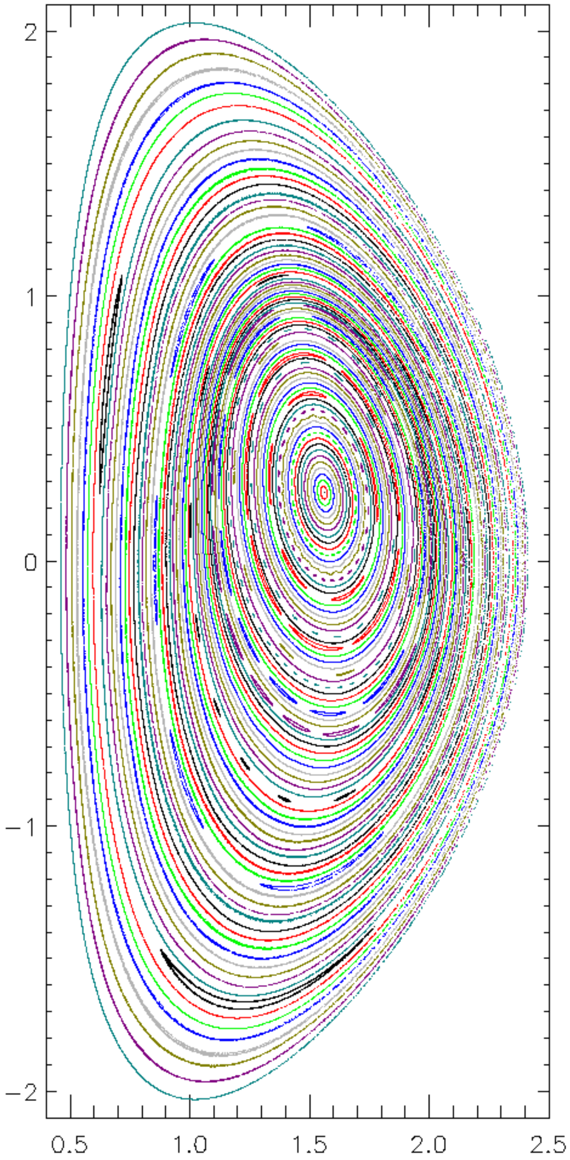
$$\frac{\partial \mathbf{v}}{\partial t} = \cdots - \mathcal{H}_\mu \frac{\partial^4 \mathbf{v}}{\partial \varphi^4}$$

24 planes × 101 radial × symmetry 5 = 606,024 vertices on 96 processors.

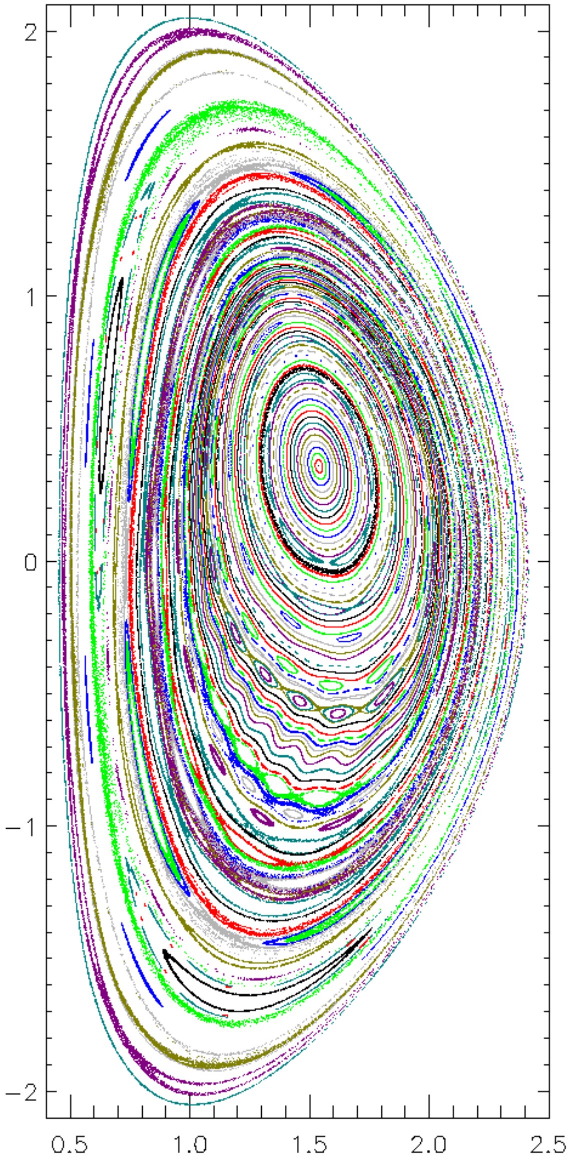
Poincaré Plots



t =1372.60

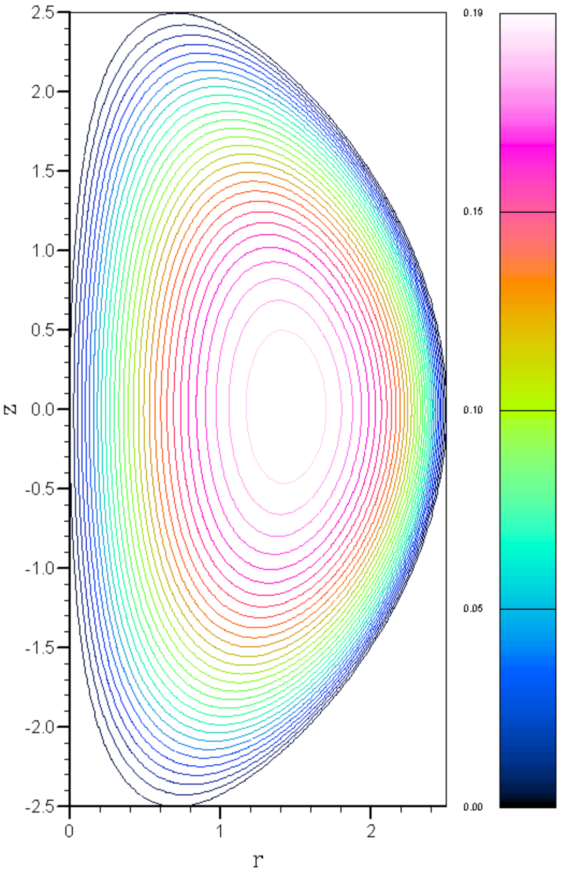


t =1539.00

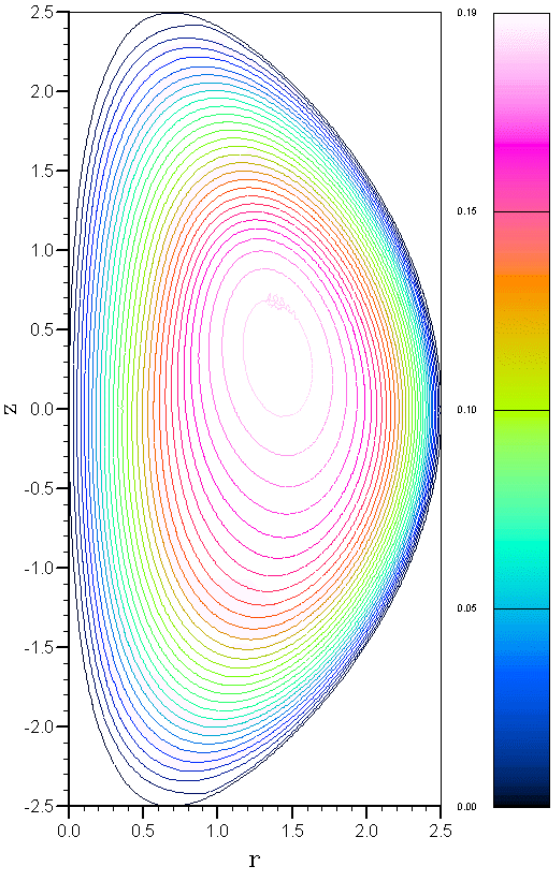


t =1784.60

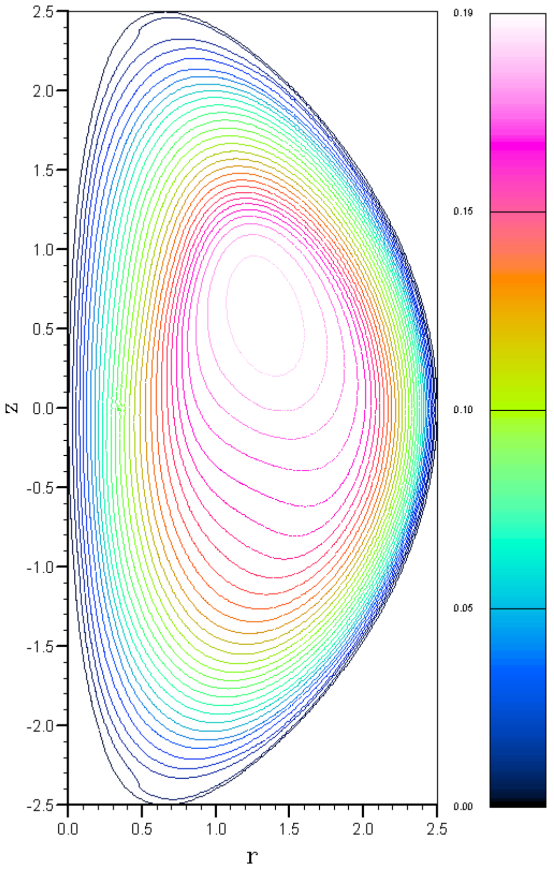
Temperature Contours



t = 1372.60

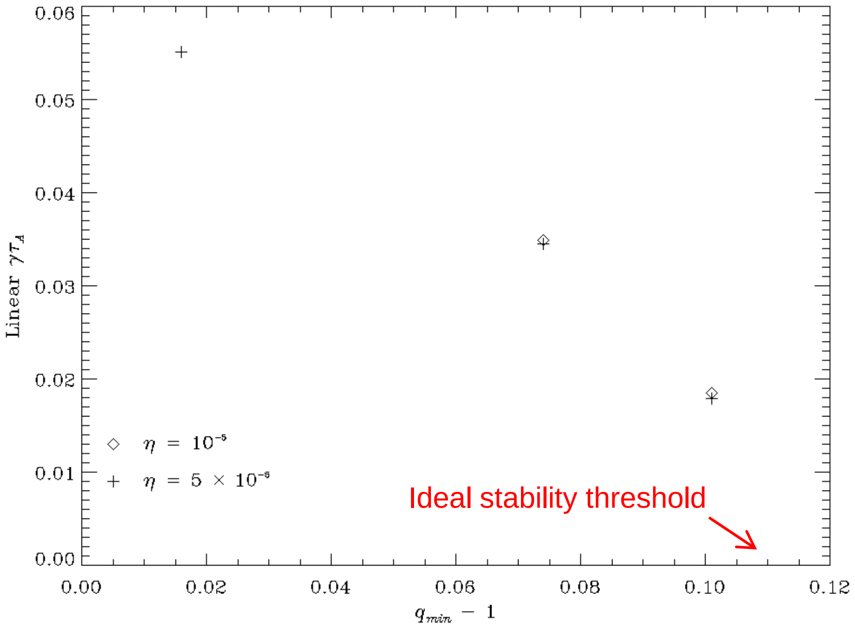


t = 1539.00

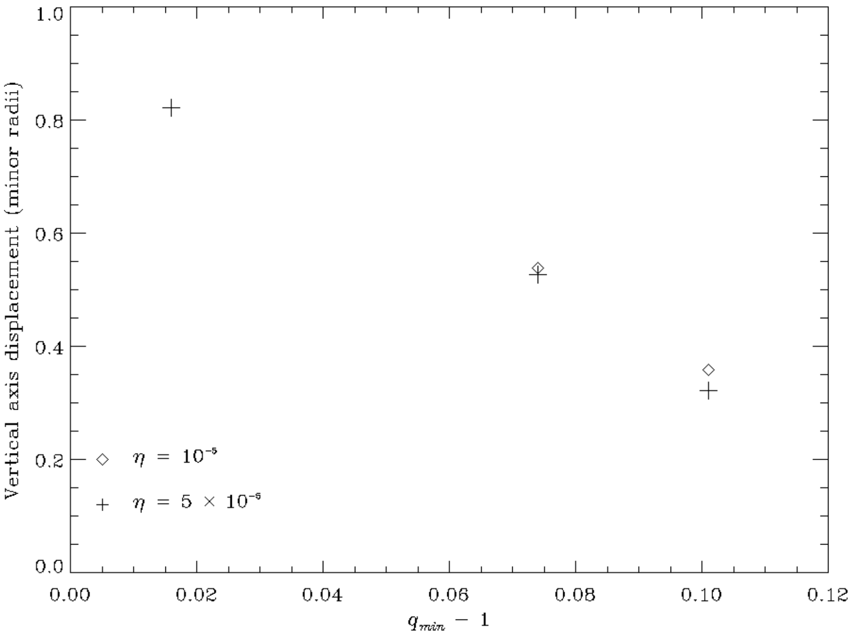


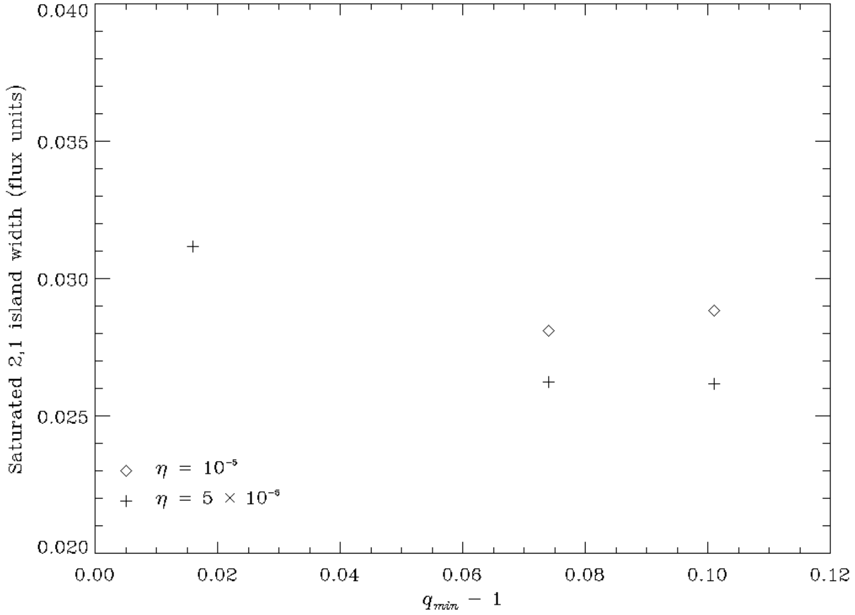
t = 1784.60

Scaling of mode amplitude with δq and η



Ideal stability threshold





- Growth rate is insensitive to resistivity.
- Final displacement is strongly correlated with growth rate.
- Final island width is more sensitive to resistivity.

Conclusions and Plans

- The untriggered NTMs seen in NSTX are the result of an ideal n=1 instability (“infernal mode”) arising as q_0 approaches (but remains greater than) one.

- High β_{beam} has a stabilizing effect on the mode near the stability threshold.

- Recreating the precise equilibrium from magnetics measurements is challenging; a limited parameter scan over candidate equilibria finds a narrow range of q_0 for which n=1 is unstable but higher n modes are stable.

- Nonlinear resistive MHD studies with selected equilibria show development of m=2, n=1 islands and eventual mode saturation, sensitive to q_{min}.

- Higher-n modes can be destabilized by higher resistivity; these should be investigated further for possible ballooning character.

- Further effort is needed in converging the existing nonlinear studies, exploring parameter space further, and including neoclassical and kinetic effects in the model.