Saturated *n*=1 Mode in NSTX

Josh Breslau

Acknowledgements: M.S. Chance, J. Chen, G.Y. Fu,
S. Gerhardt, N. Gorelenkov, S.C. Jardin, J. Manickam
PPPL

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Outline

I. Observation of untriggered NTM in NSTX

II. Identification of internal kink mode

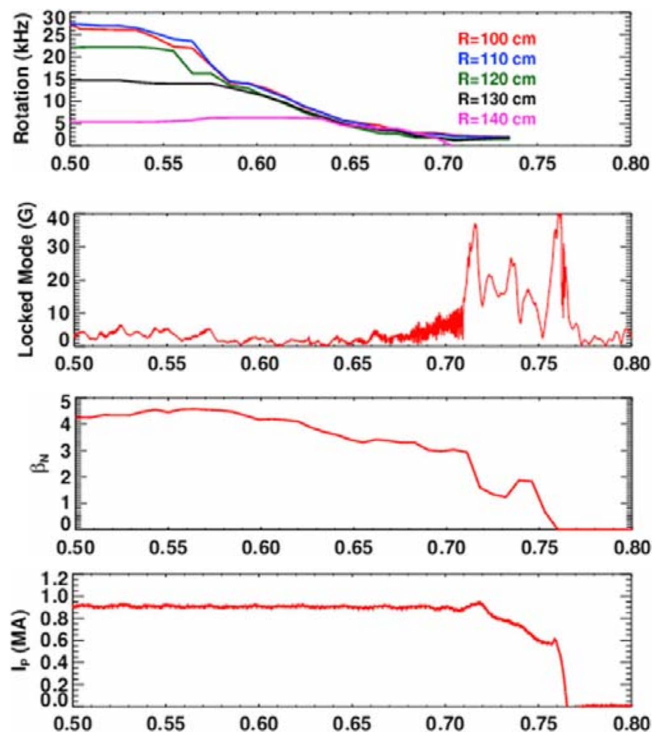
III. Linear stability analysis
   A. Ideal: PEST, NOVA
   B. Resistive: M3D, M3D-C^1
   C. Kinetic: NOVA-K

IV. Nonlinear analysis with M3D
   A. Mode saturation
   B. Scalings

V. Conclusions & plans for future work

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

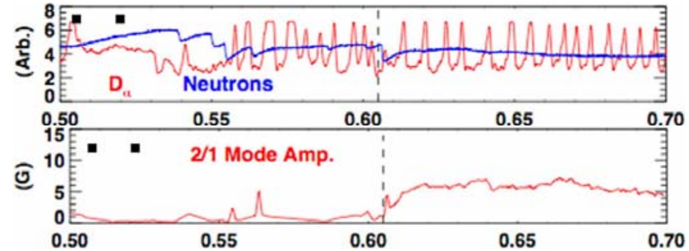
- Island width is proportional to β_p.
- Deleterious effects include
  - Rotation damping
  - Mode locking
  - Confinement degradation
  - Disruption



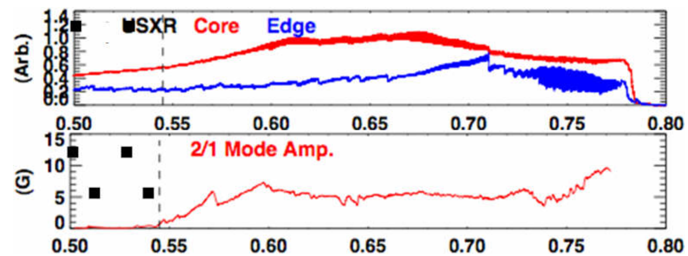
Gerhardt

Triggers Have Been Identified for Some NTMs

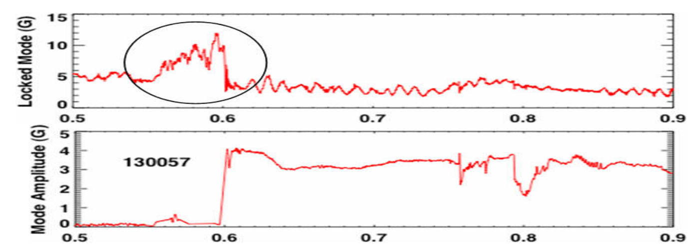
- Energetic particle modes



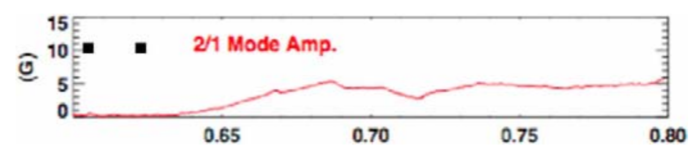
- Edge localized modes



- Locked modes

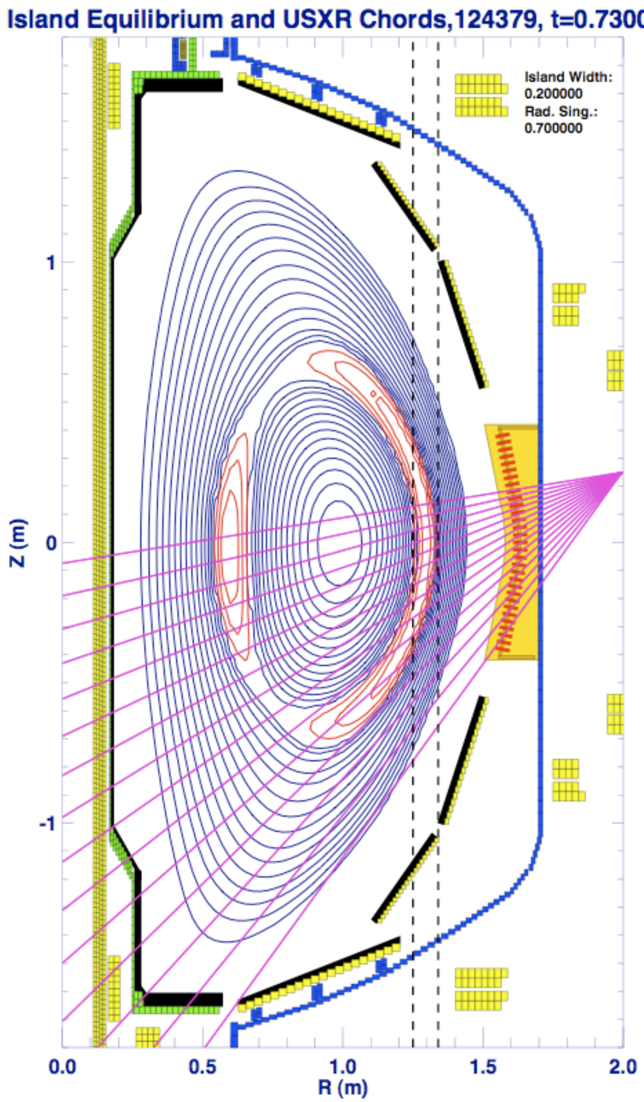


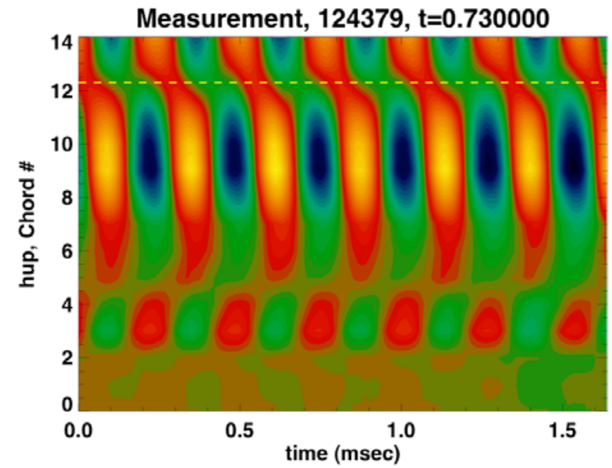
- <u>Others have no clear trigger…</u>

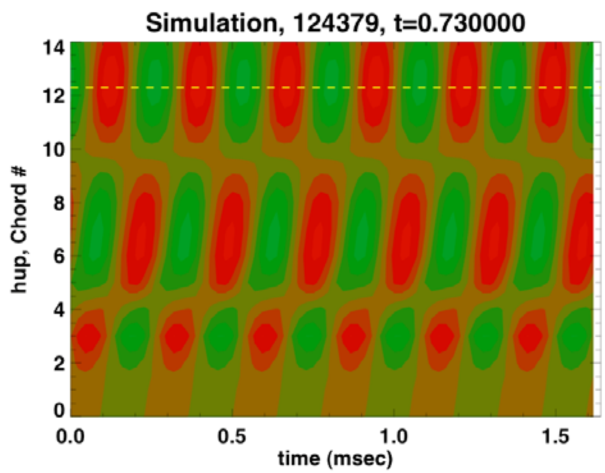


Gerhardt

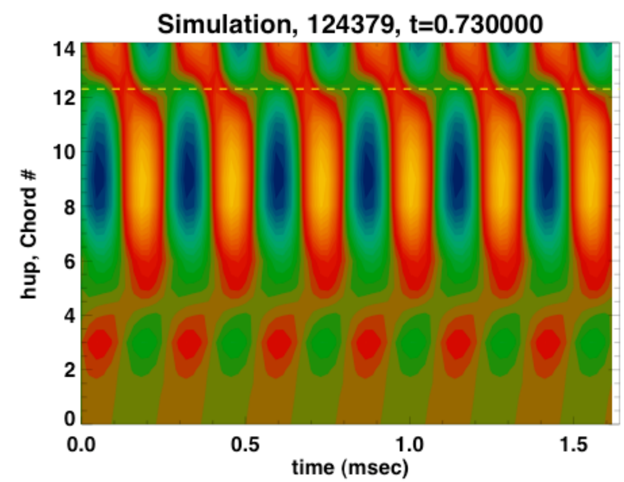
Eigenfunction Analysis of Multichord Data Suggests Coupling to 1,1 Ideal Kink







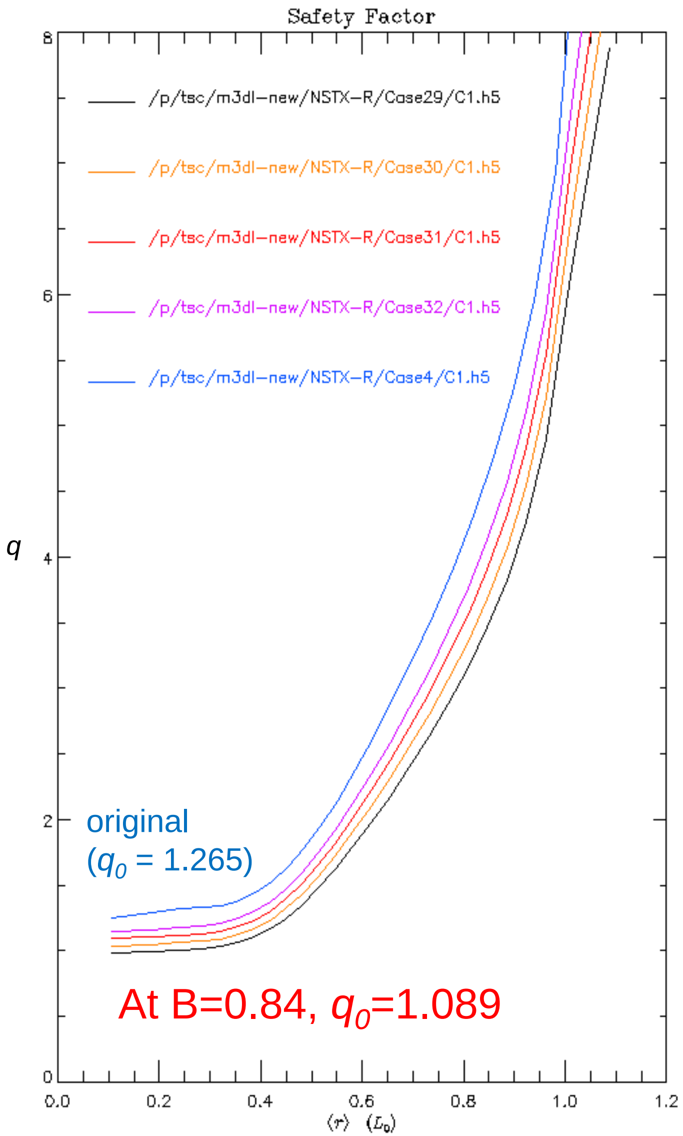
2,1 only



2,1 + 1,1 pert

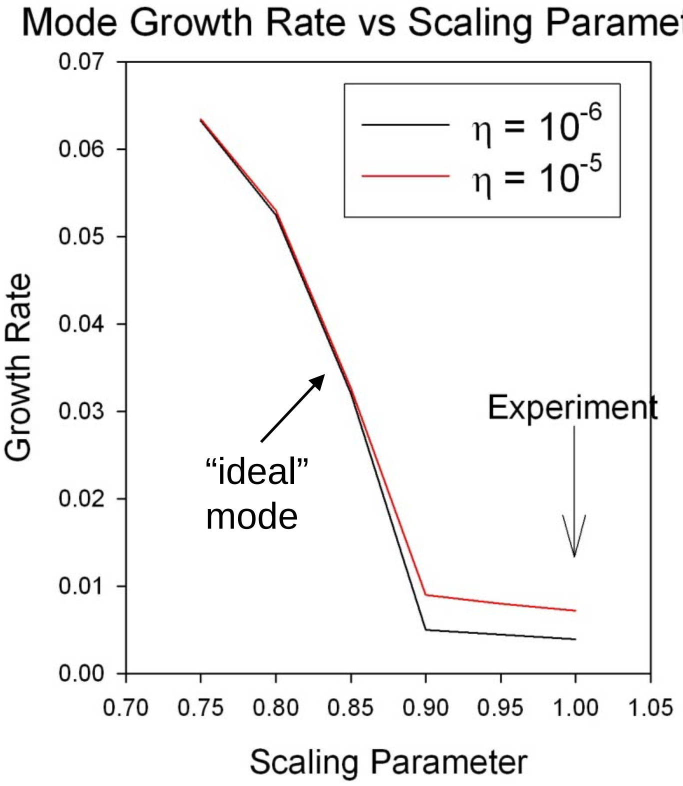
Gerhardt

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



Toroidal field was scaled down, keeping current density constant.

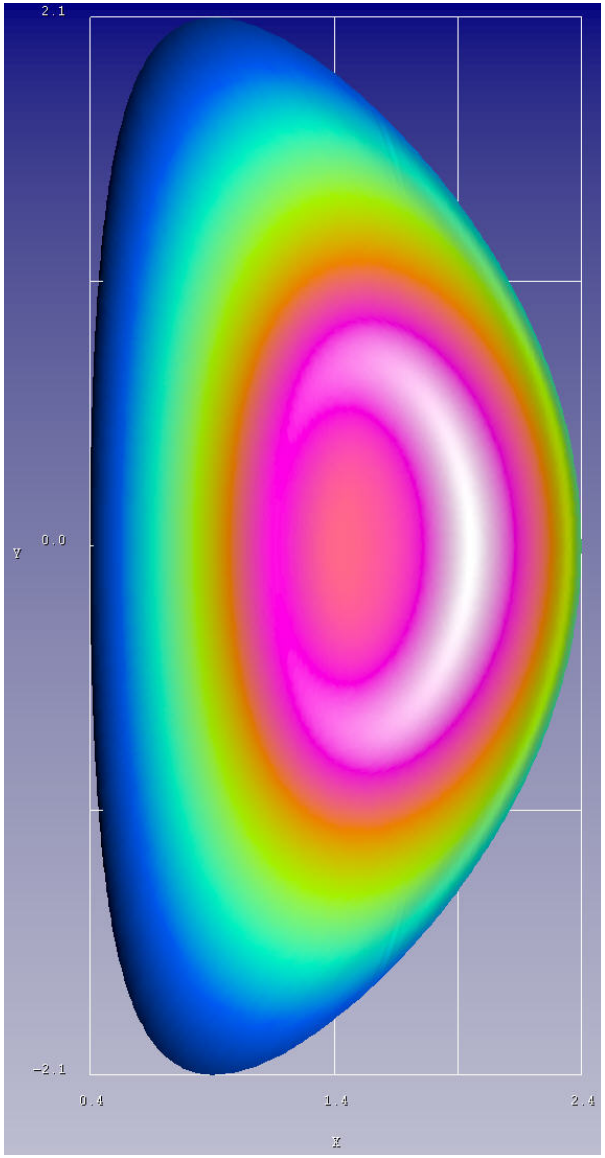
q is proportional to Bateman scaling factor B.



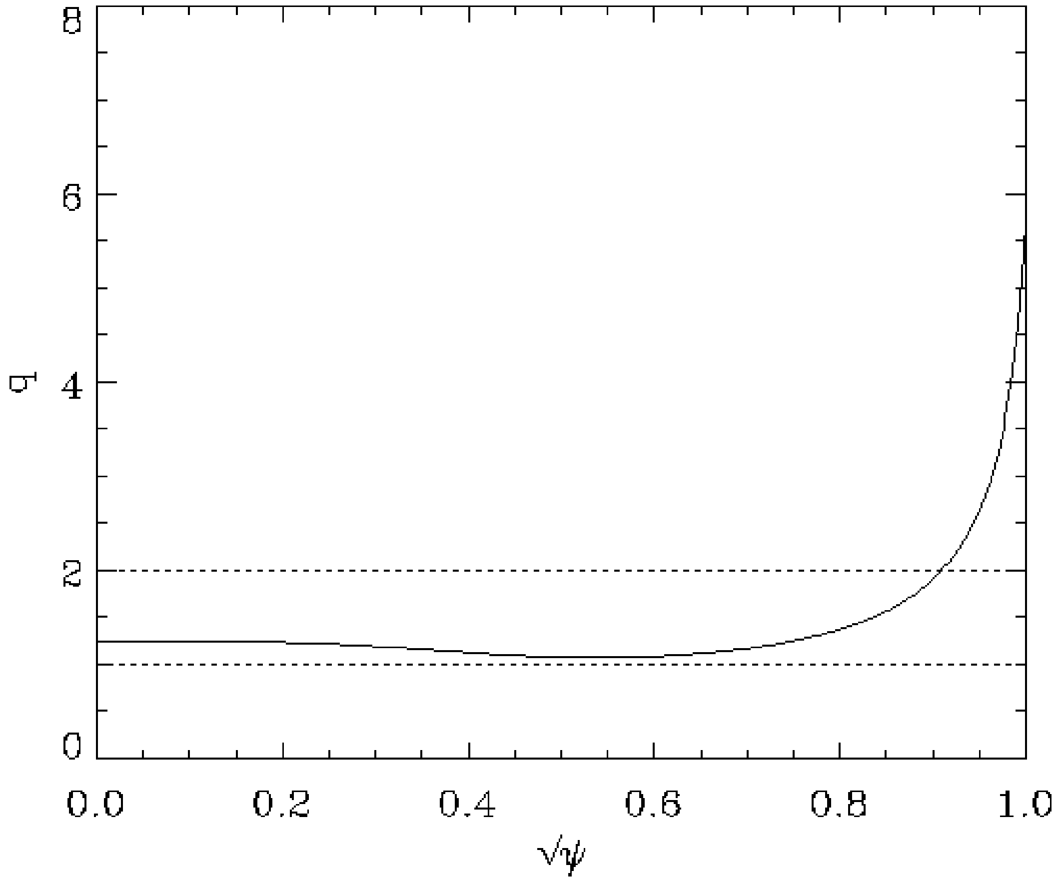
Jardin

Typical reversed shear NSTX equilibrium

RJ_φ

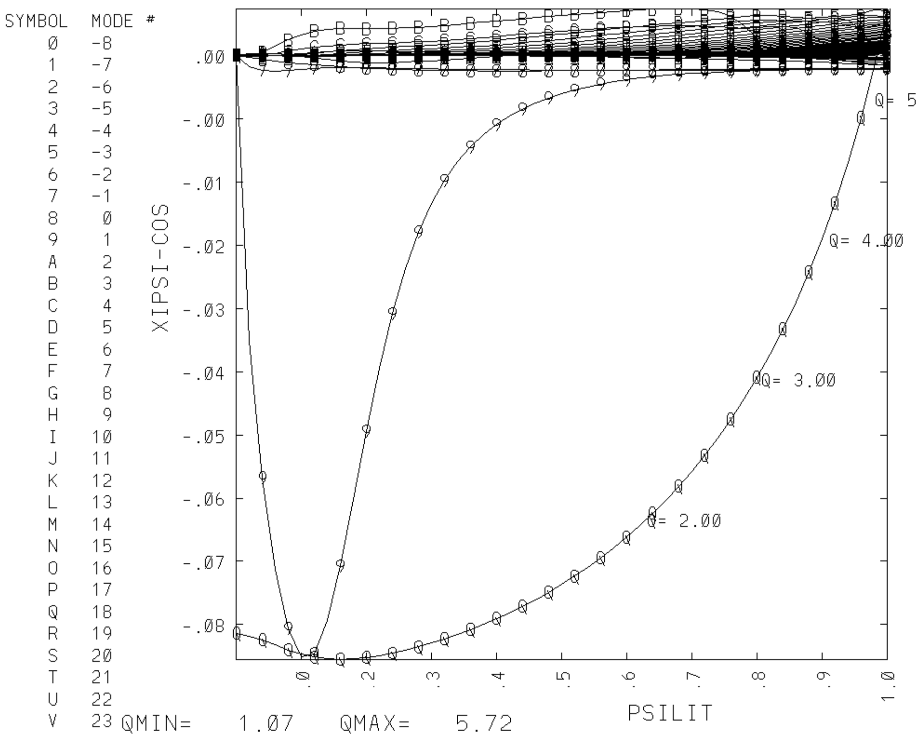


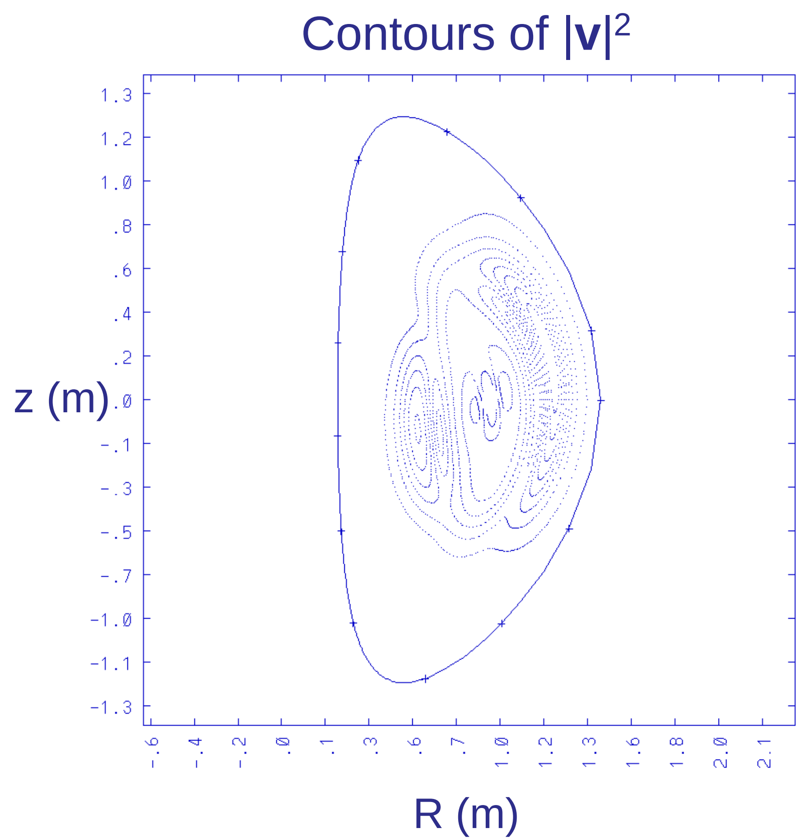
- Aspect ratio = 1.425; elongation = 2.15; tri=0.52
- q_0 = 1.25; q_{min}=1.074; q_a=5.715
- β_N = 3.32; β_0 = 0.54
- I_p = 2 MA



Linear Stability Analysis

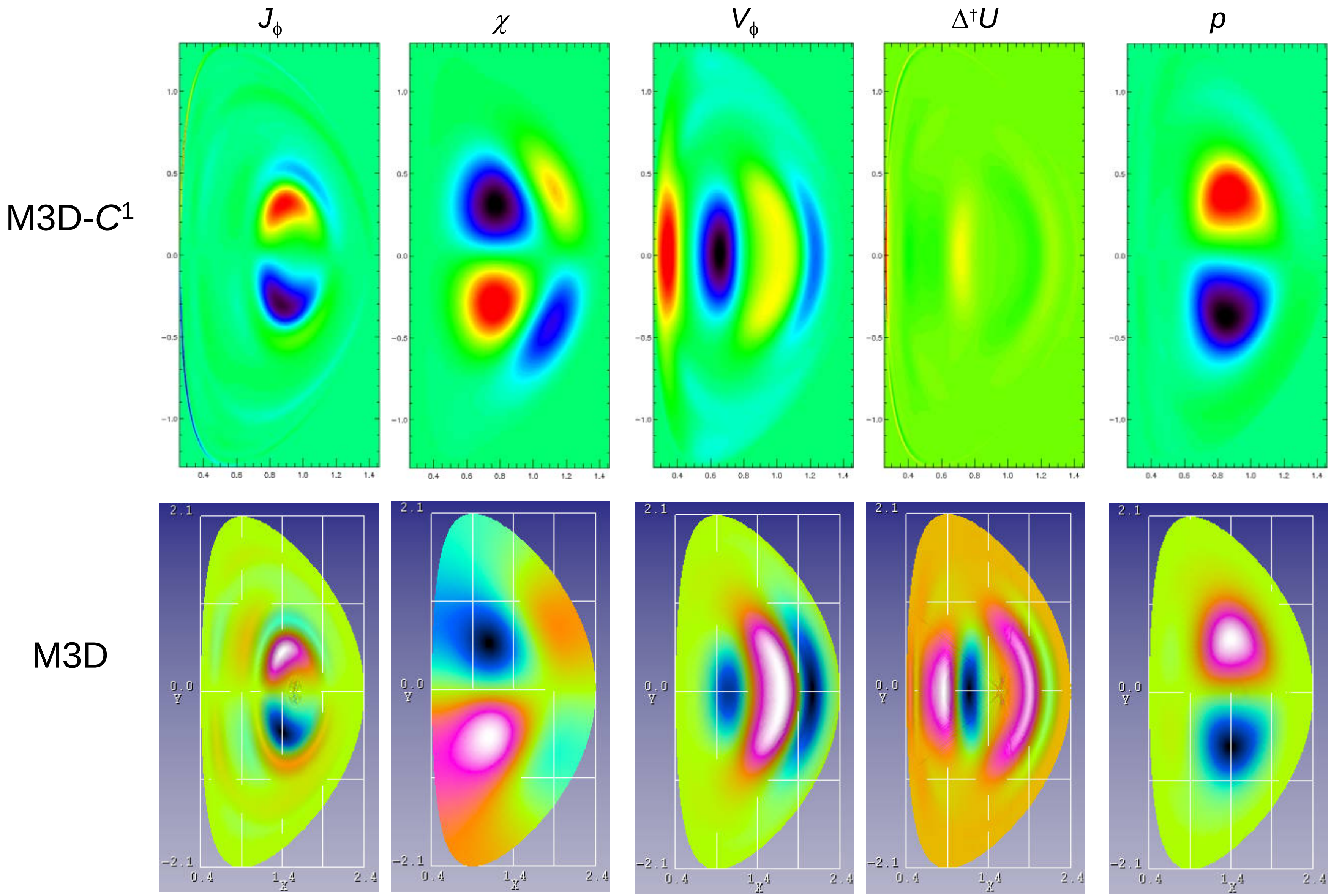
- Ideal stability of low-*n* modes analyzed with PEST-1 and NOVA.
- n=1 eigenvalue $\lambda \equiv (\omega\tau_A)^2 = -4.56 \times 10^{-3}$.
- n=2, 3 are stable.





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

Higher n modes are stable



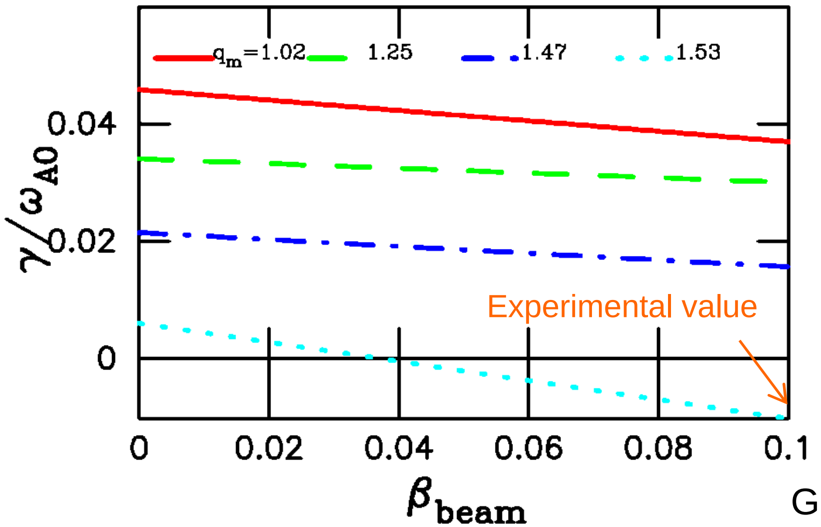
Kinetic Effects computed using NOVA-K

- 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:

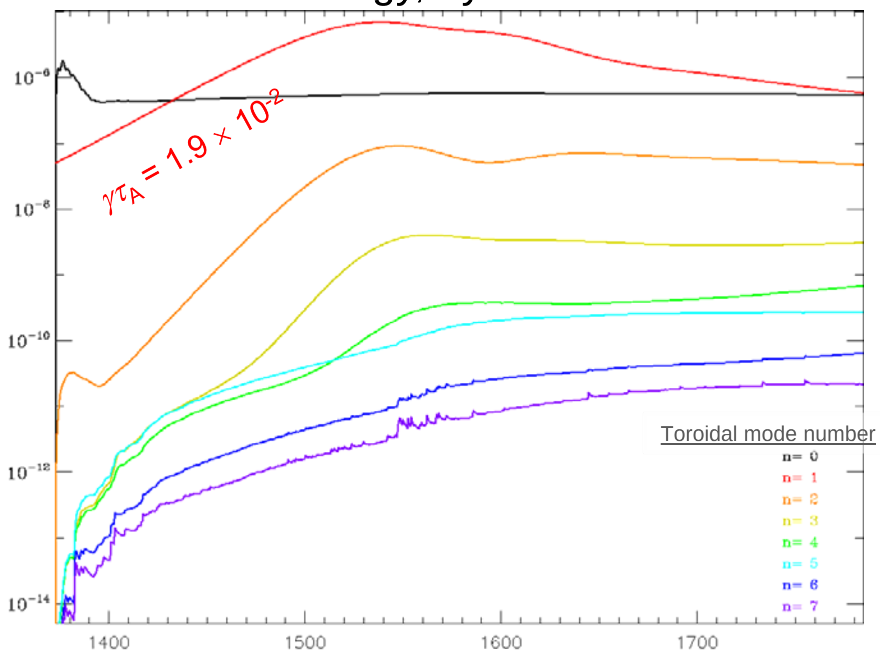


- Growth rate is very sensitive to q_{min}.
- Energetic beam ions can have a significant stabilizing effect near instability threshold.

Gorelenkov

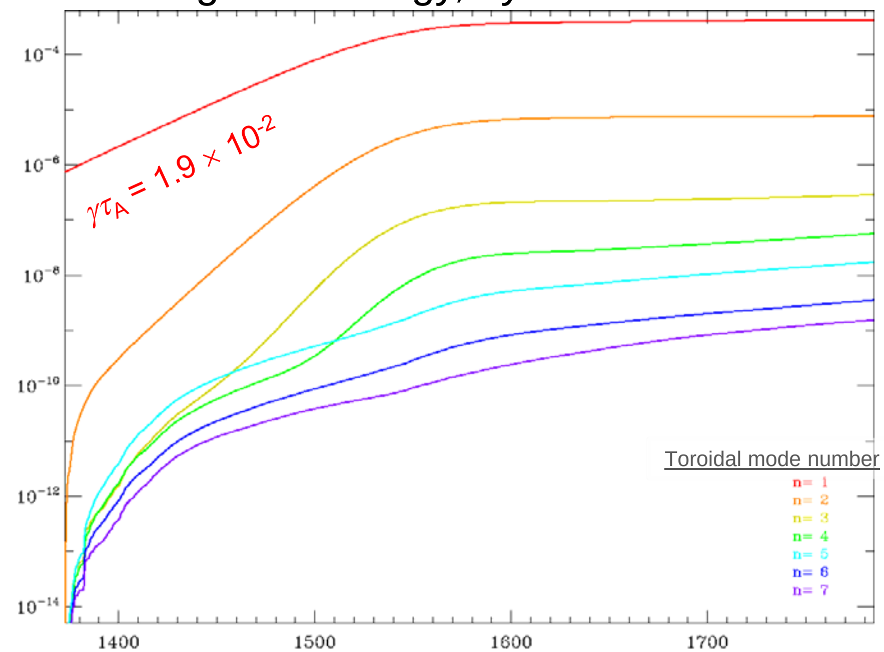
Internal mode saturates nonlinearly

Kinetic Energy, by mode number



Time

Magnetic Energy, by mode number



Time

$B = 1.05$

$\eta = 6.25 \times 10^{-6}$

$\mu = 5 \times 10^{-4}$

$\kappa_\perp = 5 \times 10^{-5}$

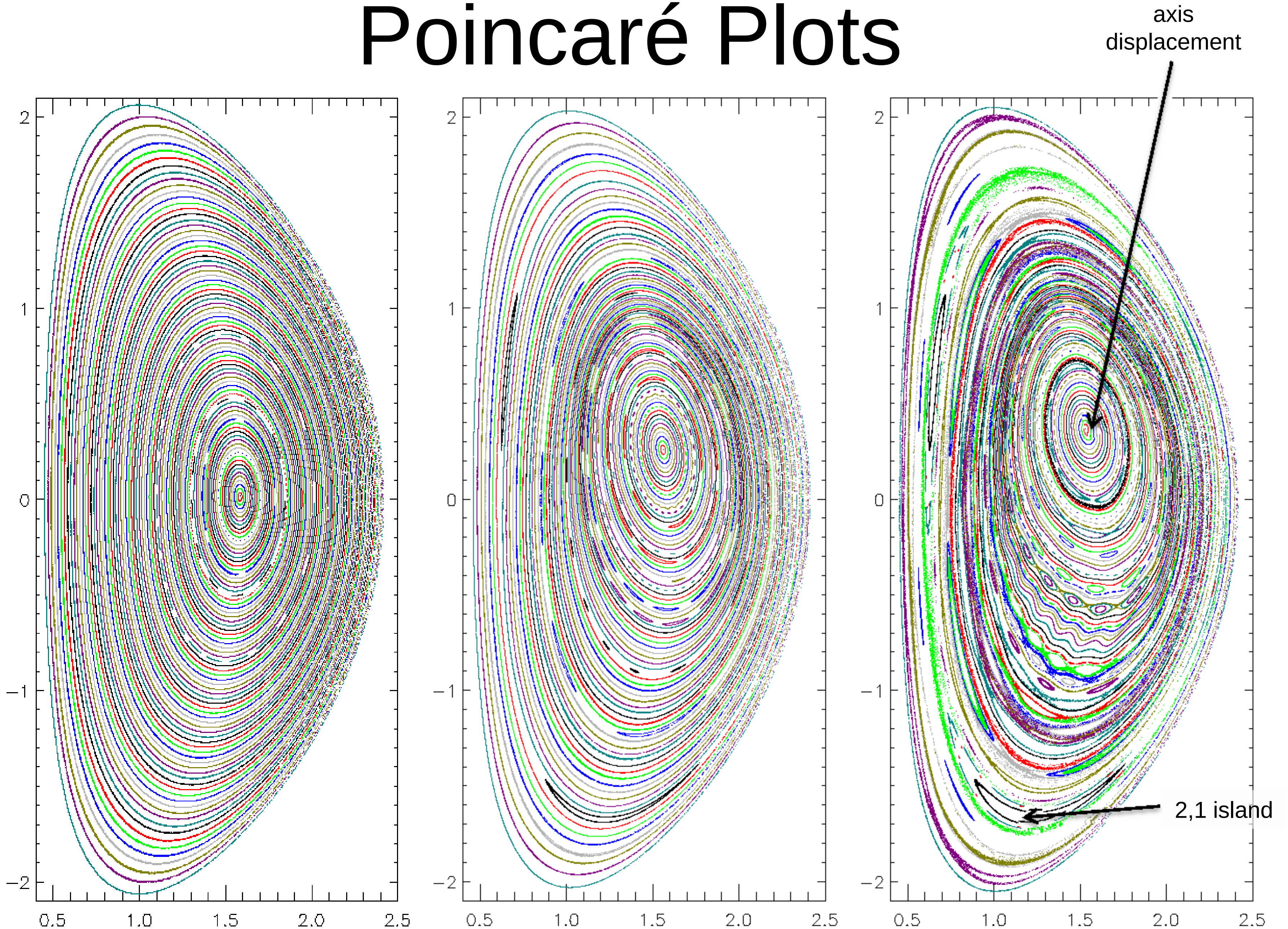
$\kappa_{||} = 5 \times 10^{-1}$

$H_\mu = 10^{-3}$

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

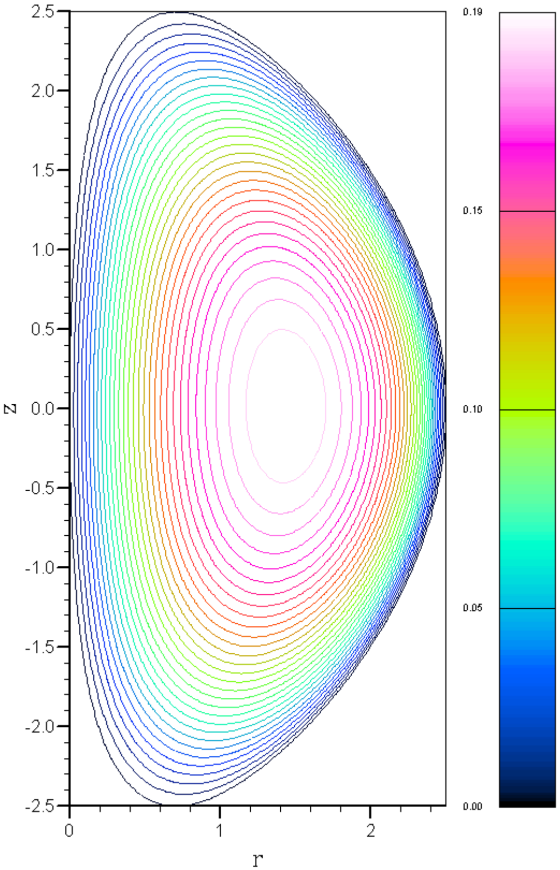
24 planes × 101 radial × symmetry 5 = 606,024 vertices on 96 processors.

Poincaré Plots

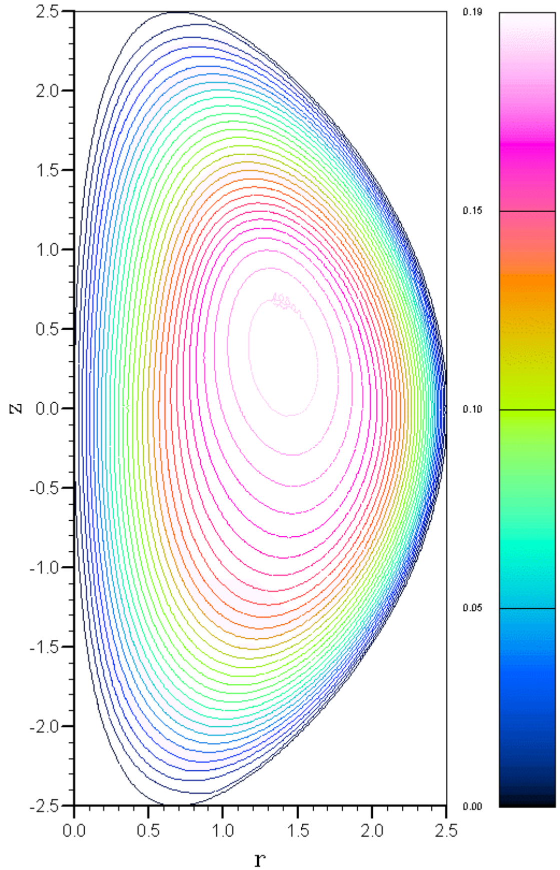


t =1372.60 *t* =1539.00 *t* =1784.60

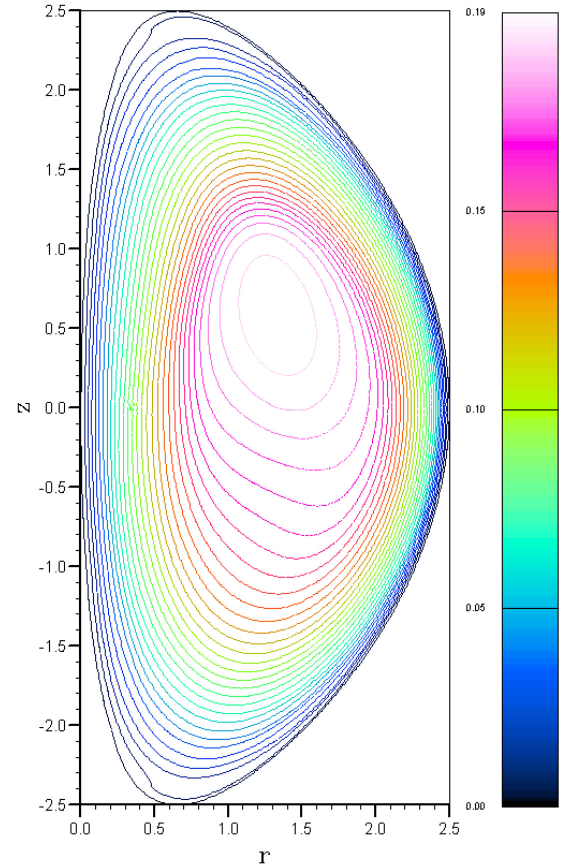
Temperature Contours



t = 1372.60

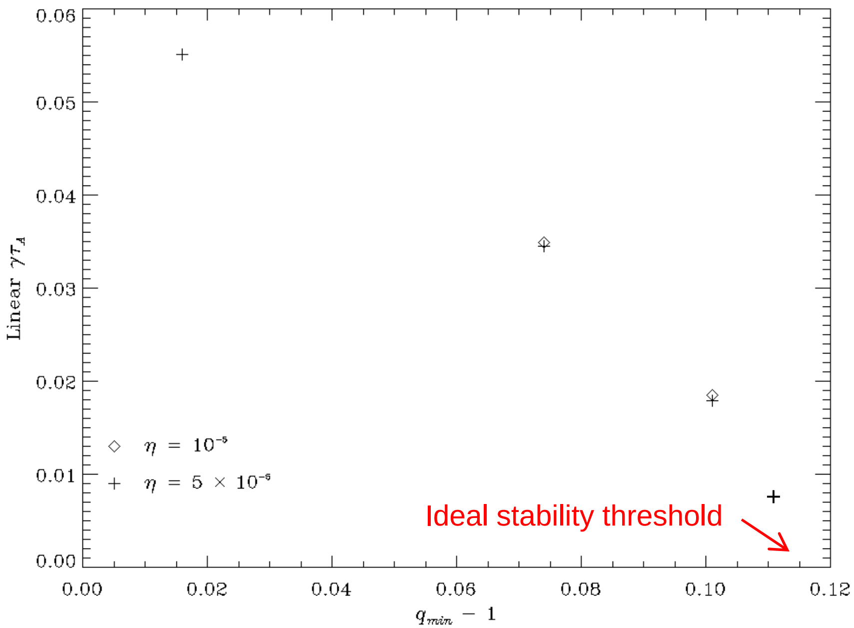


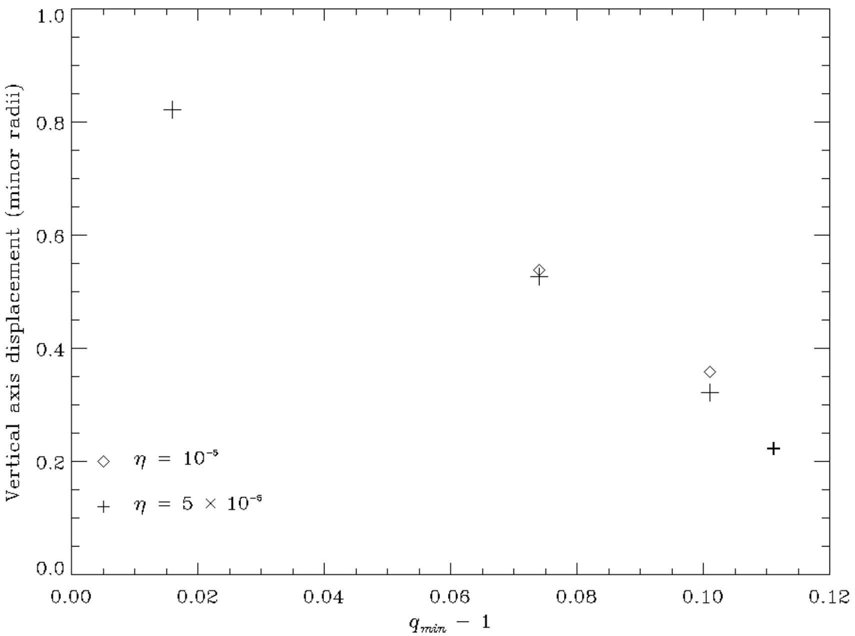
t = 1539.00

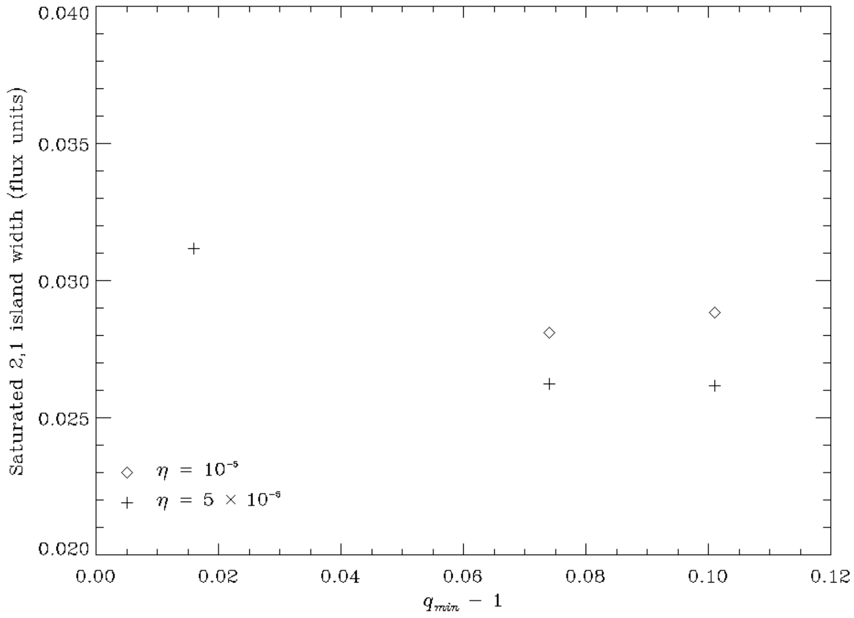


t = 1784.60

Scaling of mode amplitude with δq and η







- 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.