Beta Limits in Stellarators

H. Strauss, NYU

L. Sugiyama, MIT

G.-Y. Fu, W. Park, M. Zarnstorff, J. Breslau, PPPL

Outline

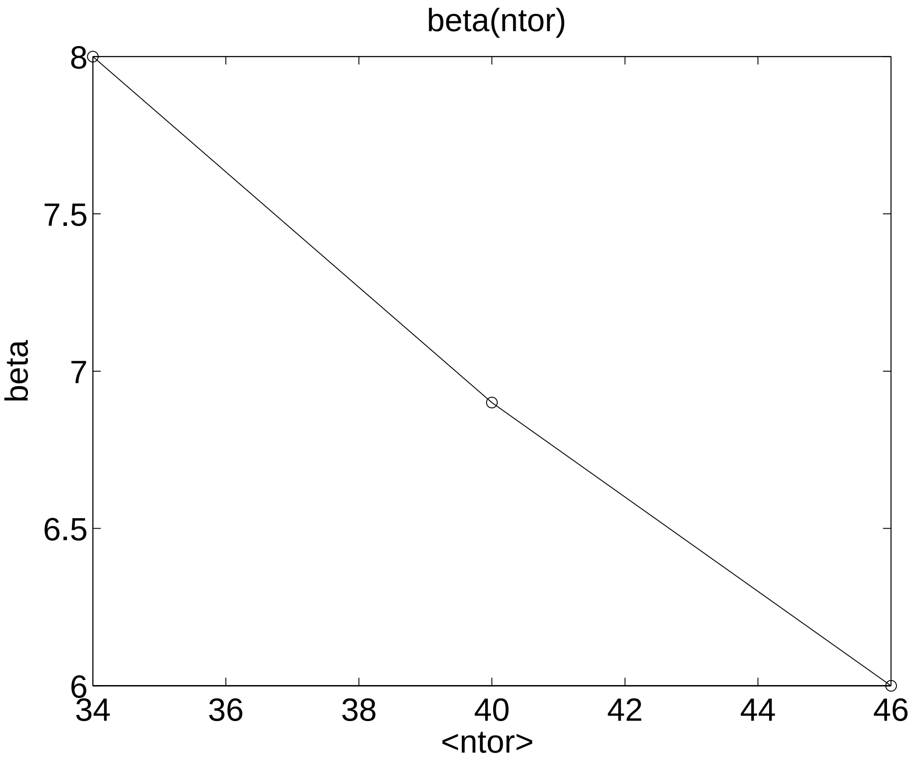
- M3D code
- Ideal MHD stability: internal modes
- Resistive ballooning stability
- Two fluid drift stabilization
- Equilibrium Islands
- Free Boundary Stability

M3D code

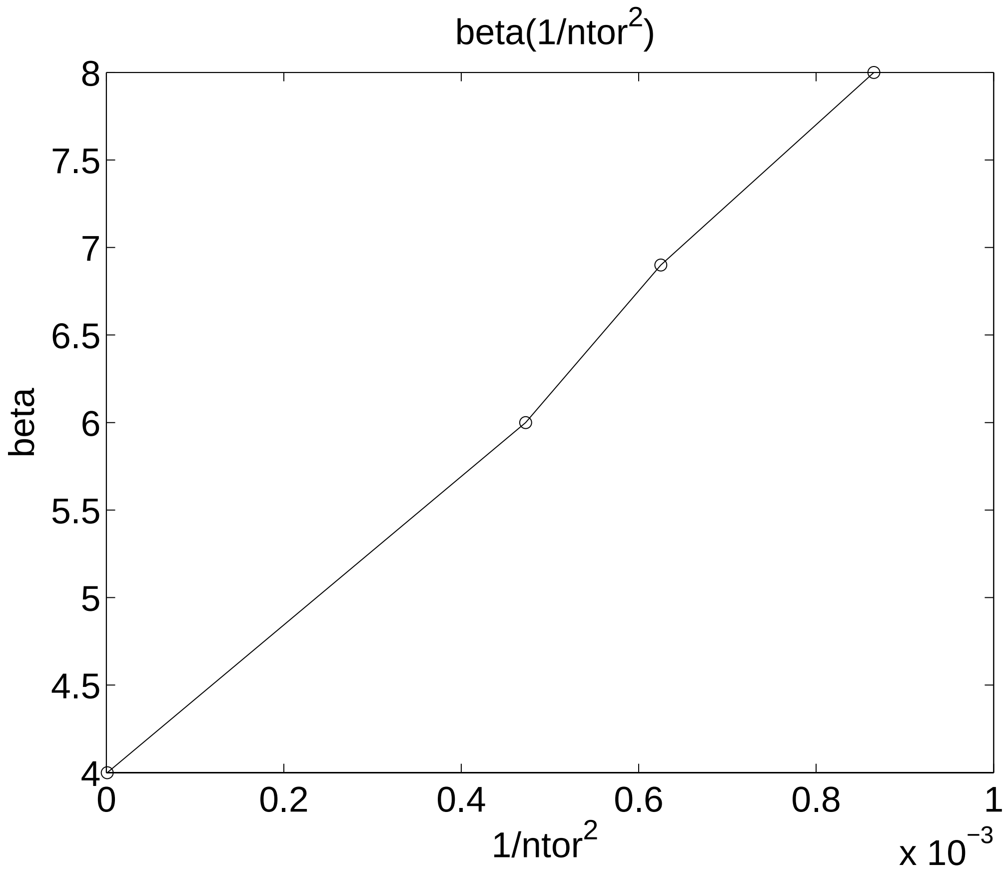
- Extended MHD physics model
  - Ideal and resistive MHD
  - 2 fluid drift model (Sugiyama & Park, PoP 2000)
    - Ion Gyroviscous stress
    - Electron pressure in Ohm’s Law
    - Parallel thermal conduction model
  - Gyrokinetic energetic ions
- Massively parallel
  - Computations still very time consuming
- Finite element unstructured mesh discretization

Ideal Stability: internal modes

- Tokamaks: lowest n (=1) has lowest beta threshold
- Stellarators: highest n is most unstable (Terpsichore: G.-Y. Fu)
- 2 fluid drift more important in stellarators than in tokamaks



Ideal Ballooning stability depends on toroidal mode number n

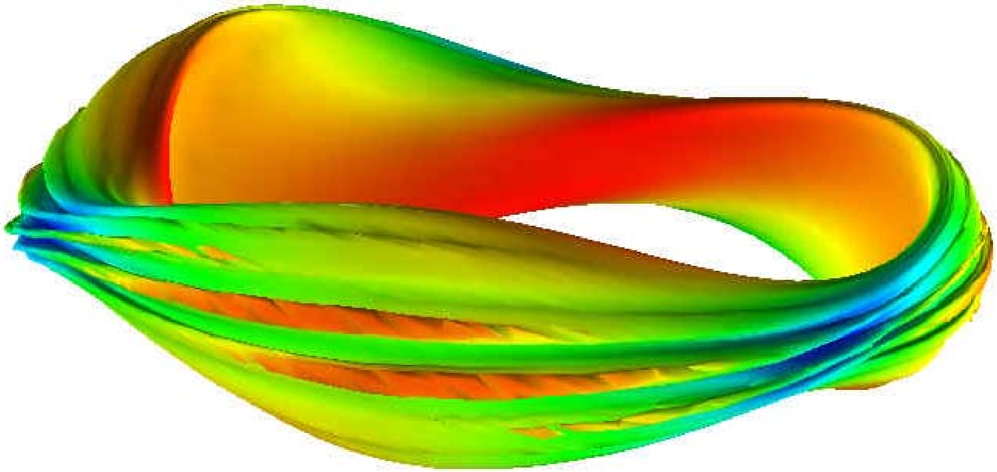


Scaling with n - Terpsichore

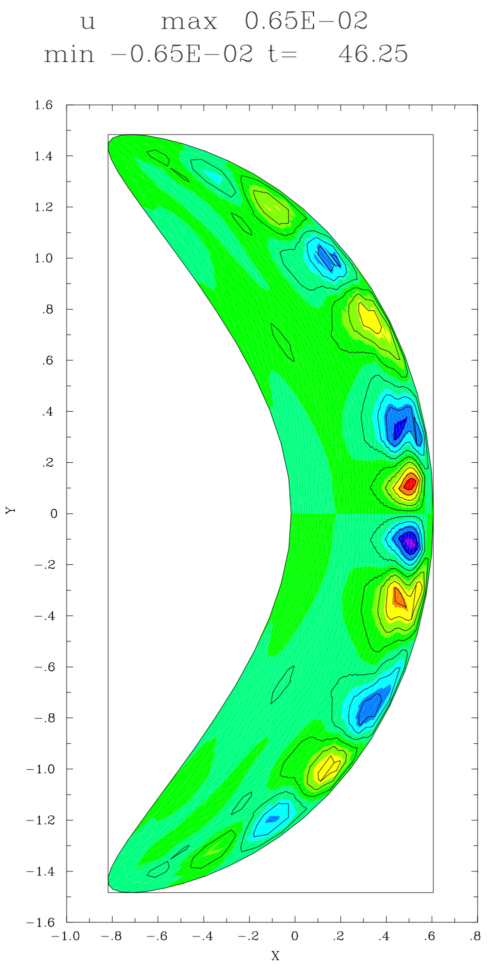
$$\beta_c = \beta_o + \frac{\alpha}{n^2}$$

M3D Nonlinear internal mode

Pressure isosurface, NCSX li383
Beta = 8%

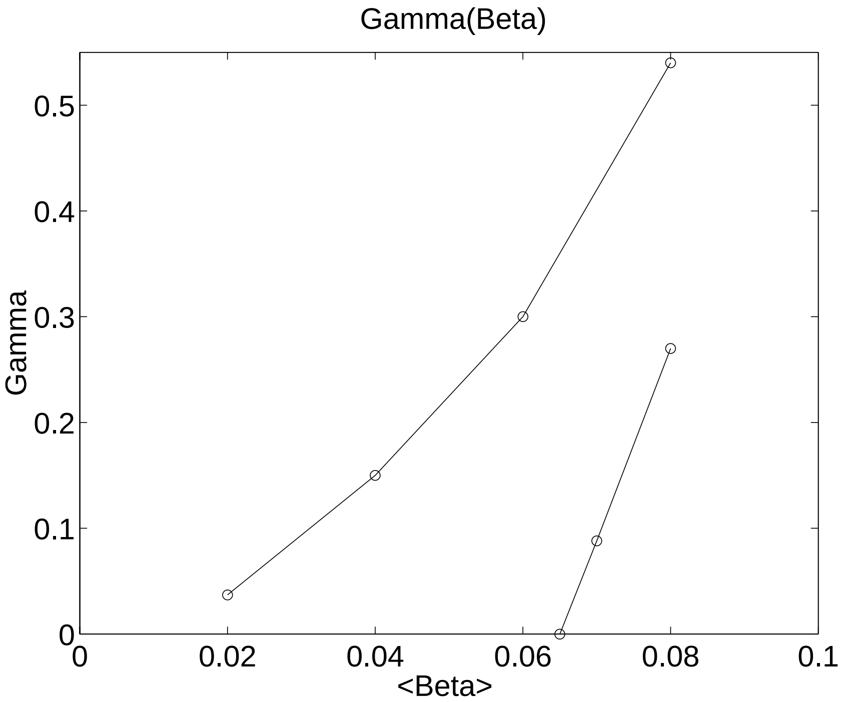


Velocity streamfunction



Resistive Stability

- Stellarators tend to be resistive interchange unstable
- Resistive ballooning modes not stabilized by coupling to interchange, unlike tokamaks
- Stellarators unstable to resistive ballooning for all beta
- M3D may be more unstable than Terpsicore – newer computations agree better
- 2 Fluid stabilizes RBM



2 fluid stabilization

- Stabilizing n > 40 gives beta > 7% for ideal internal modes with

  Hall parameter H = 2%

- Infinite n ballooning limit is "irrelevant"

$$H = \frac{c}{\omega_{pi} R} \approx .01$$

$$\omega(\omega + \omega_{*i}) = -\gamma_{MHD}^2$$

$$\omega_* \frac{R}{v_A} = Hn \frac{\beta_p}{q}$$

RBM stabilization

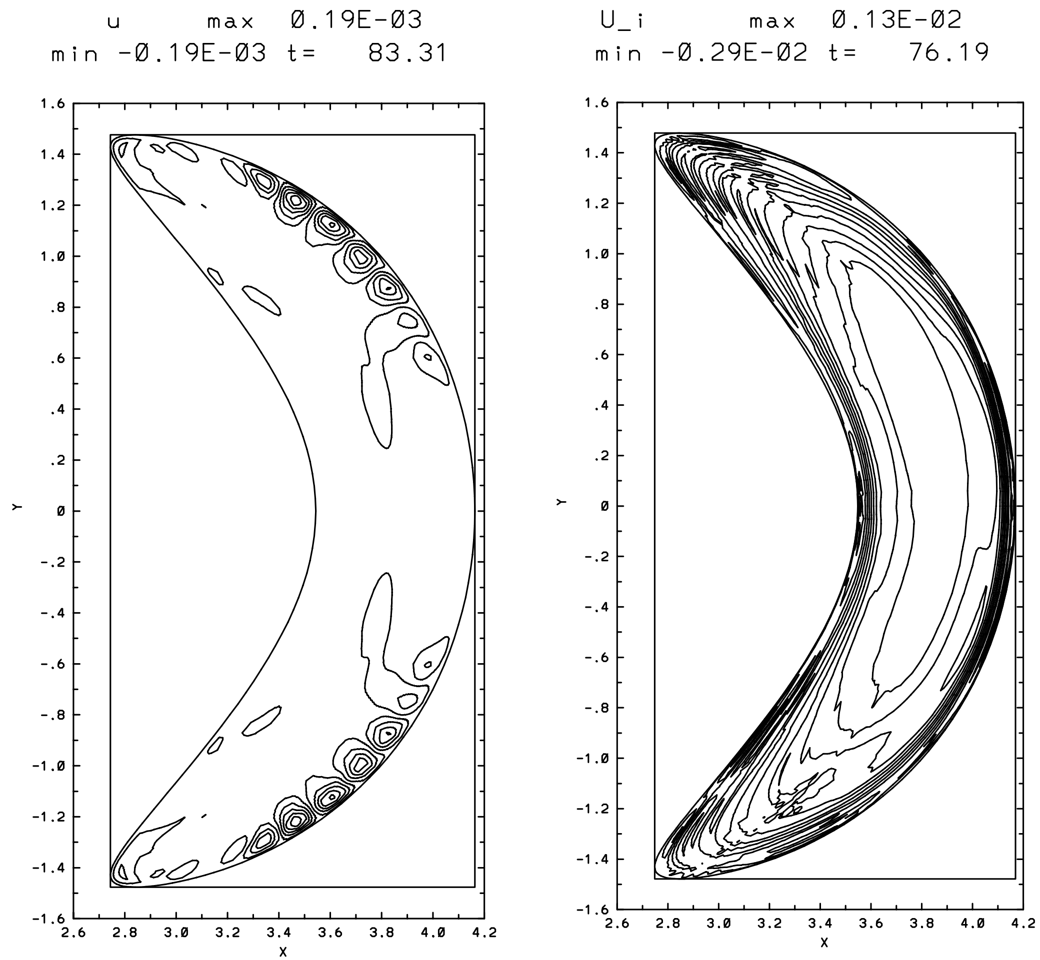
$$\omega(\omega+\omega_{*i})(\omega-\omega_{*e}) = \eta^3 \Delta'^4 \frac{v_A}{qR}$$

H can be lower because growth rate is usually small compared to ideal MHD

Drifts are large where pressure gradient is large

Ion flow may be important for stabilization

W7AS – possibly observe RBM in cold high density shots



Island growth

- Islands can give soft beta limit
- Parallel electron pressure gradient in Ohm's Law enhances island growth

$$\frac{\partial A_{\parallel}}{\partial t} = \nabla_{\parallel}\Phi - \frac{\nabla_{\parallel} p_e}{en} - \eta J_{\parallel}$$

$$p_e = nT_e$$

$$\frac{\partial T_e}{\partial t} = -v_e \bullet \nabla T_e - (\Gamma - 1) T_e \nabla \bullet v_e + \chi_{\parallel} \nabla_{\parallel}^2 T_e + \chi_{\perp} \nabla_{\perp}^2 T_e$$

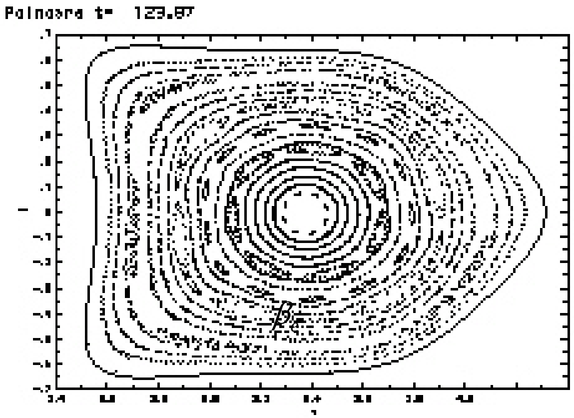
$$\frac{\partial n}{\partial t} = -\nabla \bullet (n v_i) \approx 0$$

Density evolution turned off

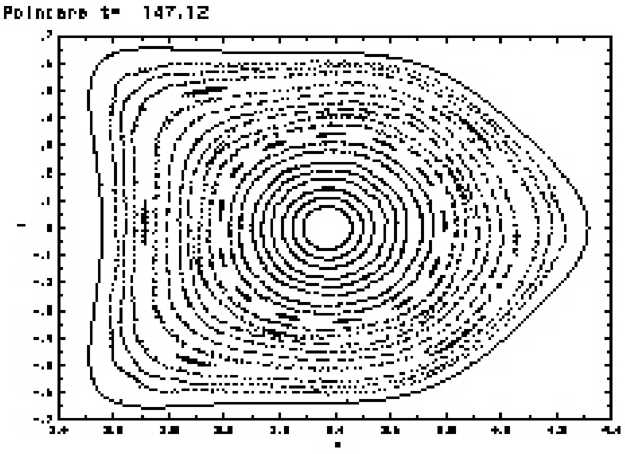
Island growth depends on β_e

- Beta = 7%
- H = .02
- L. Sugiyama, APS03

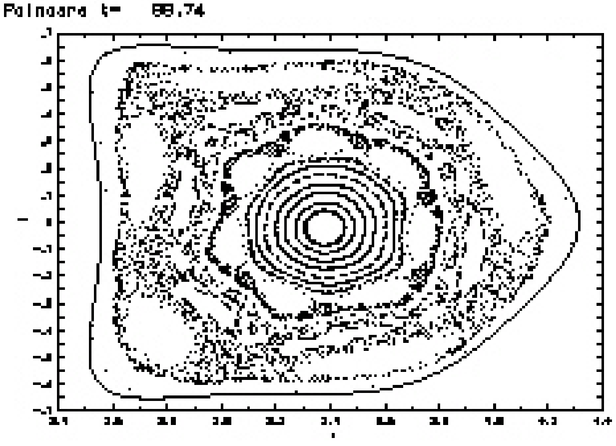
$p_e/p = 0.5$



$p_e/p = 0.05$



$p_e/p = 0.95$

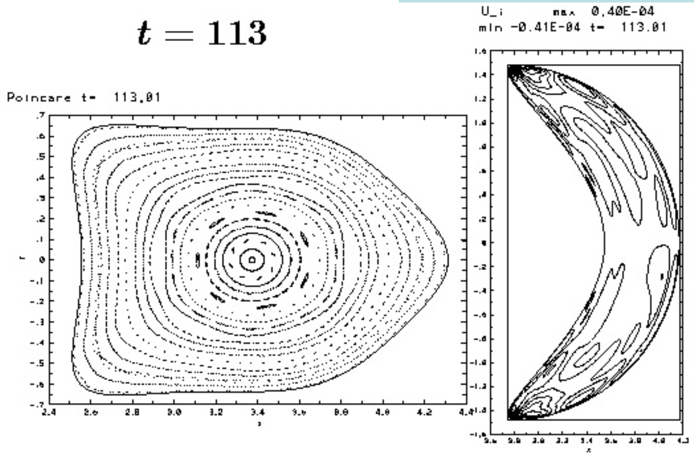


Island growth depends on H

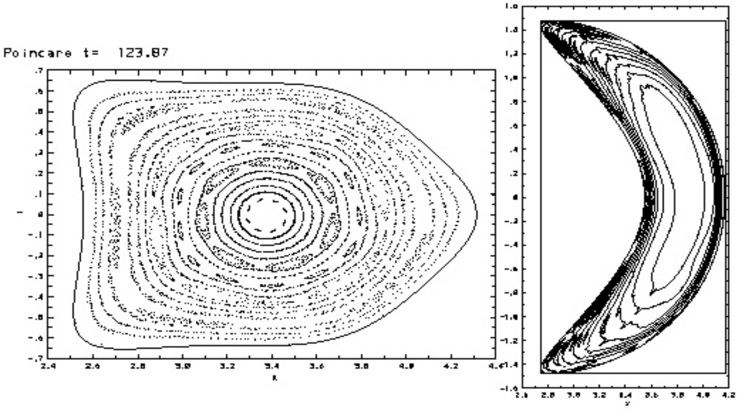
- H = .02, .00002(!?)
  - S = 100,000
  - Density evolution turned off
  - too much parallel smoothing of pressure by thermal conduction
  - Density parallel smoothing by sound waves
  - Density evolution may cause more island growth
  - More modeling and theory needed

Ion flow streamfunction

$t = 113$



$t = 124$



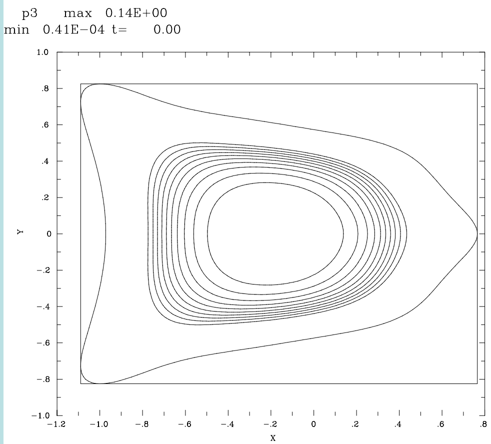
Free boundary modes

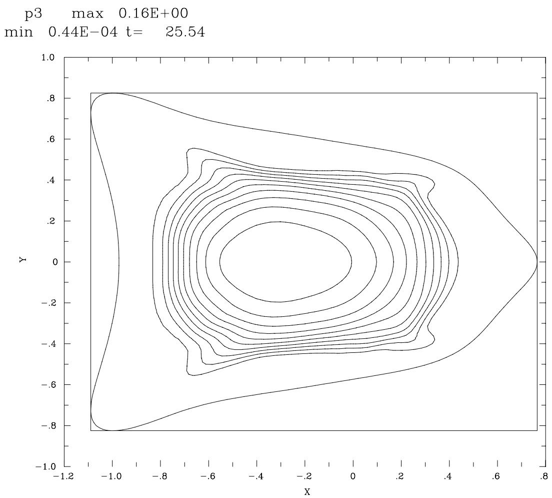
- Free boundary modes
  - Limit beta
  - Resistive halo model $10^5 > S > 10^2$

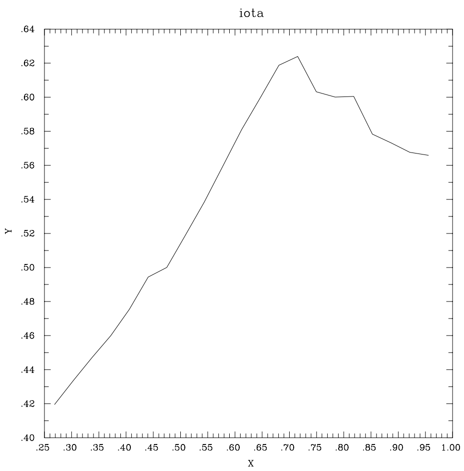
  (vacuum modeled as high resistivity region)
- Moderate n external kinks
  - Beta = 4% in NCSX
  - Tokamak ELMS?
- M3D
  - Double tearing mode

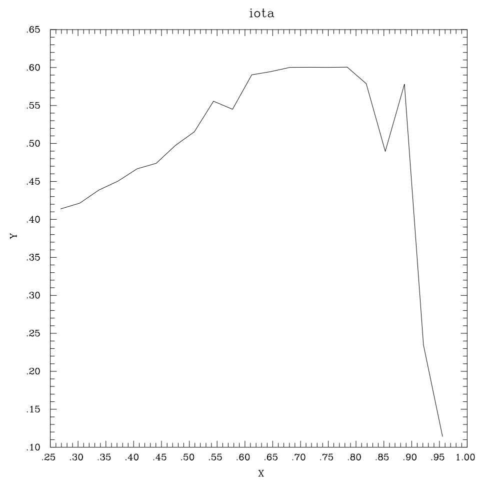
NCSX li383 5% beta

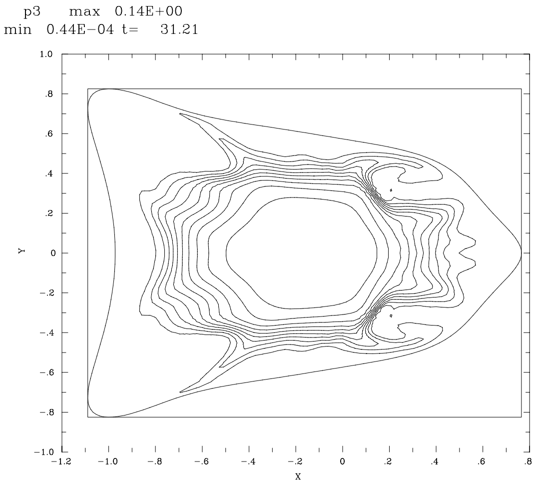
- Cold halo region
- 5/3 island in plasma and in halo
- Double tearing mode





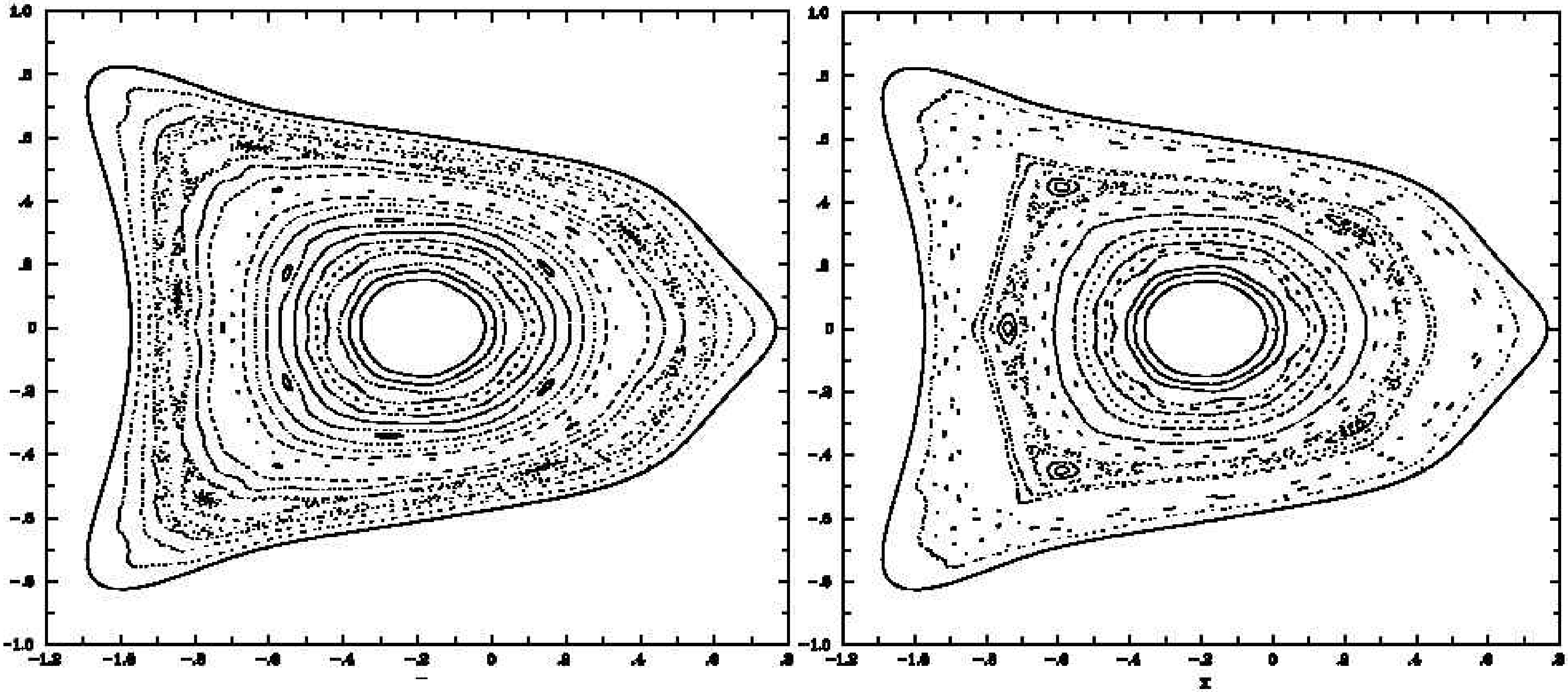






plasma resistivity caused 5/3 double tearing mode to grow faster than ideal free boundary edge kink

5/3 edge mode



Conclusions

- Ideal mode beta limit determined by intermediate n
  - 2 fluid (H = .02) raises beta by stabilizing n>20
  - Beta = 7% rather than 4% in NCSX
  - M3D convergence study needed
- Resistive ballooning stabilized by 2 fluid
  - Resistive model (H = 0) unstable for all beta
- Equilibrium islands depend on $H\,\beta_e$
  - Sensitive to details of model
  - Islands can give soft beta limit
- Free boundary
  - Modeling vacuum as resistive halo
  - Need cases without islands near plasma vacuum boundary