CDXU Benchmark Case

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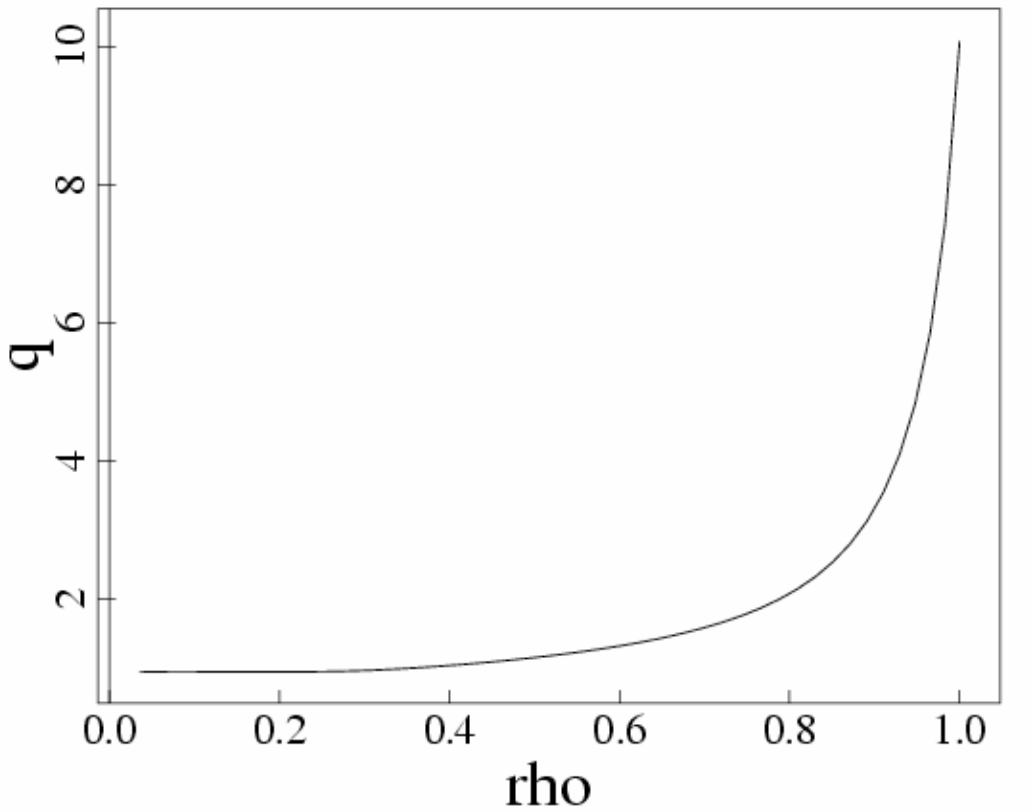
SAIC

CDXU is Low Aspect Ratio Tokamak



- Equilibrium produced from TSC calculation (*jsolver* file)
- $R/a = 1.4$
- $q(0) = 0.95$
- $q(a) \sim 10$
- Benchmark with M3D:
  - Linear growth rate and eigenfunction
  - Nonlinear evolution

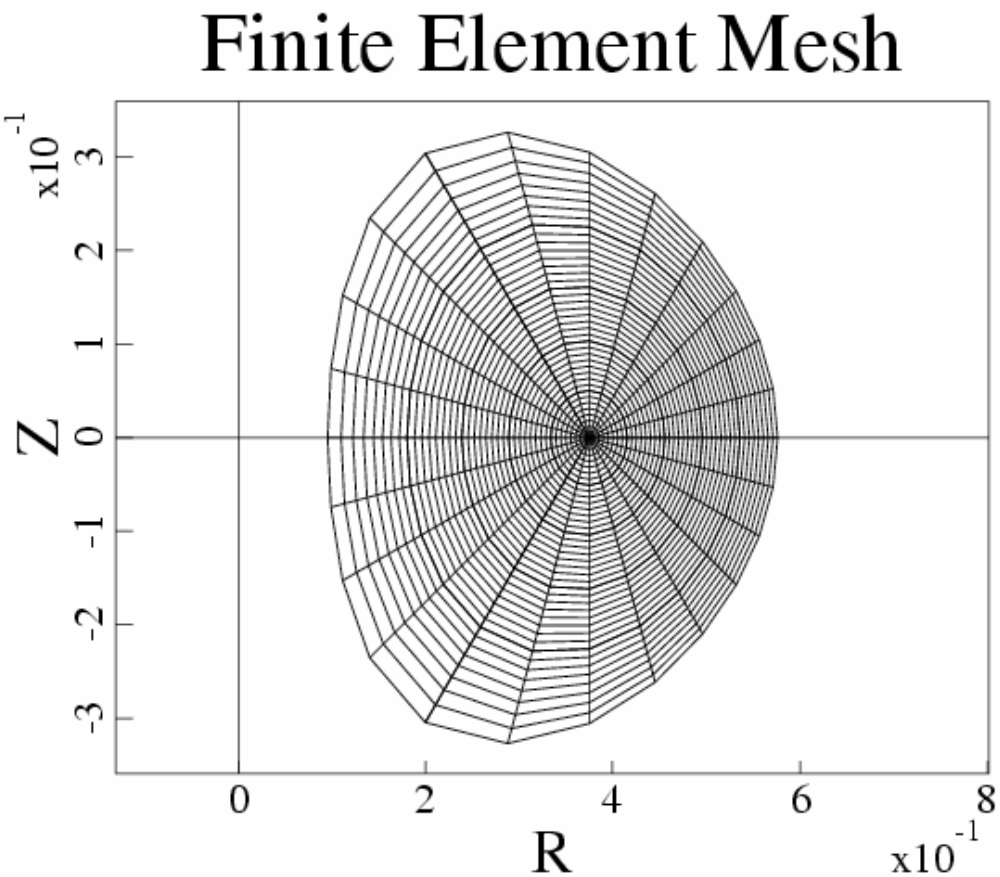
Benchmark Parameters

- $S(0) = 1.97 \times 10^4$
- $\beta \sim 10^{-2}$ (low-β)
- $\eta \sim T_{eq}^{-3/2}$: fixed profile ($\eta(\mathbf{r},t)$ also considered)
- Pr = 10 : flat profile (Pr = 100 and shaped profiles also considered)
- Density evolution:
  - Fixed equilibrium profile for linear case (little or no effect on NIMROD results)
  - Full 3-D evolution for non-linear cases
- Thermal conduction:
  - Isotropic: $\kappa_\perp = 200$ m^2/sec (CDXU confinement time)
  - Anisotropic: $\kappa_\parallel = 10^8$ m^2/sec
  - Adiabatic and $\kappa_\perp = 1$ m^2/sec cases also considered

Benchmarking Issues

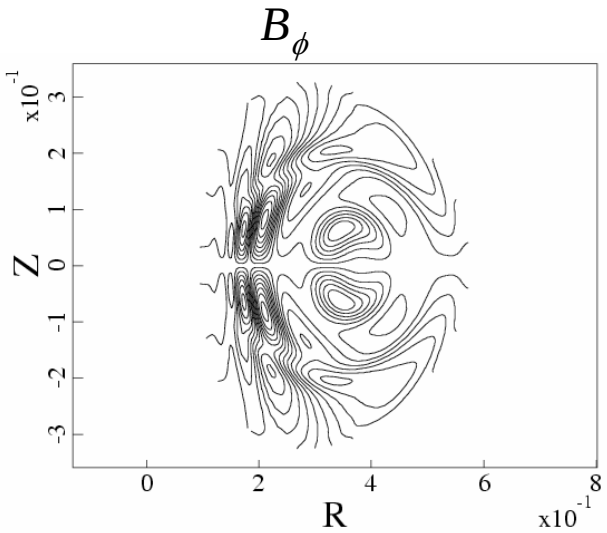
- Units
- Codes don’t produce the same output
- Evolution of “Equilibrium”
- Results strongly dependent on dissipation *parameters* and *profiles*
- $n = 1$ is not a “standard” 1/1 sawtooth mode
  - Strong $m > 1$ components appear at inboard edge
- Higher-n modes are more unstable than $n = 1$
  - Low n
    - Localized at inboard edge
  - High n
    - Move toward outboard edge
- Role of resistivity evolution?
- Is sufficient toroidal resolution possible?
- Is there a better benchmark case?

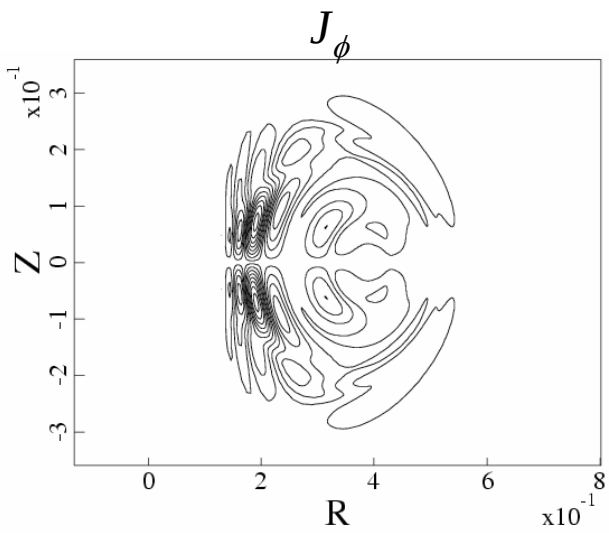
The NIMROD Poloidal Grid

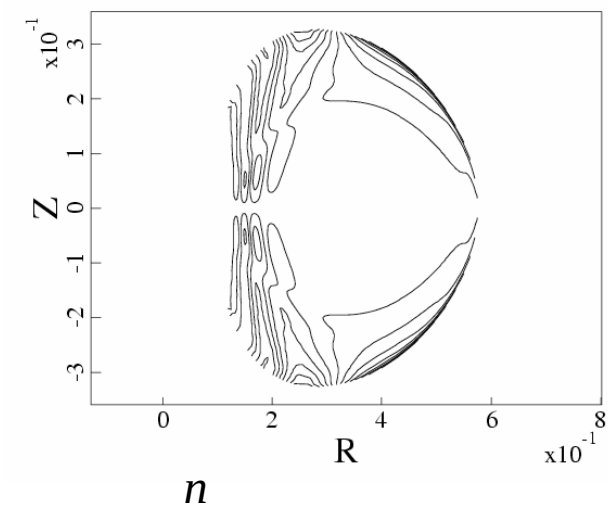


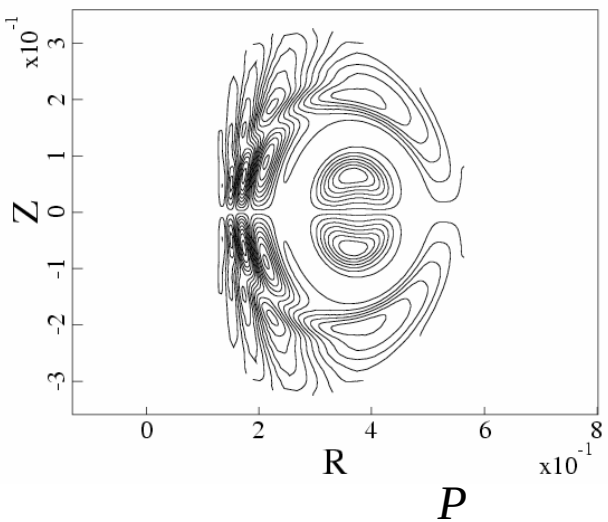
- 40 × 24 grid
- 4th order finite elements
- Conducting wall

The "Standard" Case









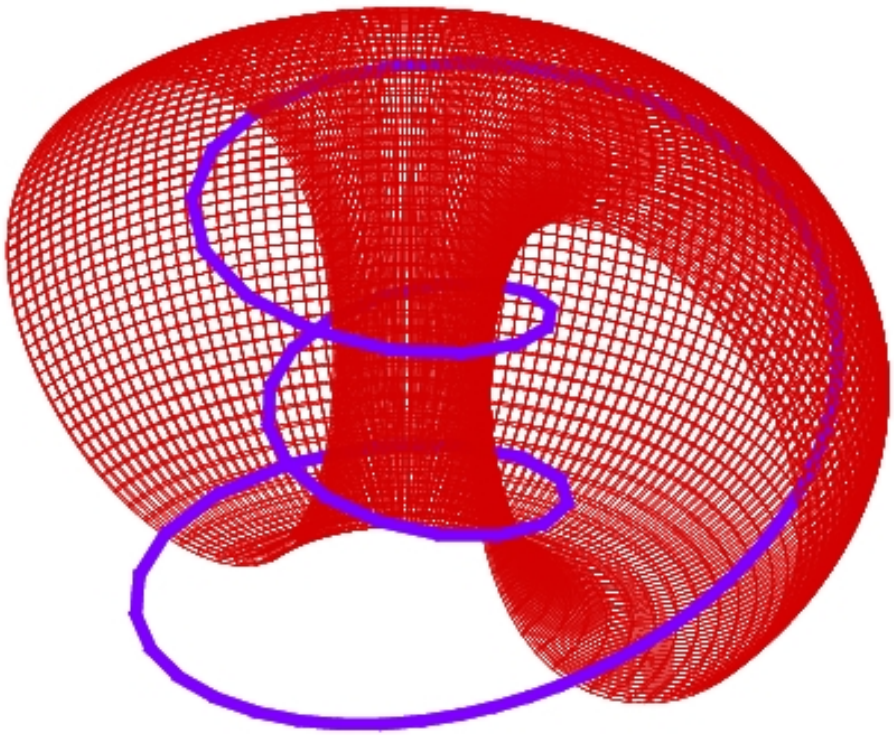
- $n = 1$
- Pr = 10
- ν = const.
- $\eta \sim T_{eq}^{-3/2}$ (fixed)
- Isotropic heat flux:
  - $\kappa_\perp = 200$ m^2/sec
- Small $m = 1$
- Higher m components at inboard edge
- Density evolution (no effect on linear behavior)

$\gamma\tau_A = 3.7 \times 10^{-4}$

The Variations

- "Standard" case: Pr = 10 (flat), $\kappa_\perp = 200$ m^2/sec (isotropic)
  - $\gamma\tau_A = 3.7 \times 10^{-4}$
- Variation 1: Pr = 10 (flat), $\kappa_\perp = 1$ m^2/sec (isotropic)
  - $\gamma\tau_A = 1.8 \times 10^{-3}$
- Variation 2: Pr = 10^2 (flat), $\kappa_\perp = 200$ m^2/sec (isotropic)
  - *Stable!*
- Variation 3: Pr = 10^2 (flat), $\kappa_\perp = 1$ m^2/sec (isotropic)
  - $\gamma\tau_A = 4.5 \times 10^{-4}$
- Variation 4: Pr = 10 (flat), $\kappa_\perp = 200$ m^2/sec, $\kappa_\parallel = 10^8$ m^2/sec
  - *Marginal*
- Variation 5: Pr = 10 (flat), $\kappa_\perp = 1$ m^2/sec, $\kappa_\parallel = 10^8$ m^2/sec
  - *Marginal*
- Variation 6: Pr = 10^2 (flat), adiabatic pressure
  - $\gamma\tau_A = 1.7 \times 10^{-4}$
- Variation 7: Pr = 10 (flat), adiabatic pressure
  - $\gamma\tau_A = 2.4 \times 10^{-3}$

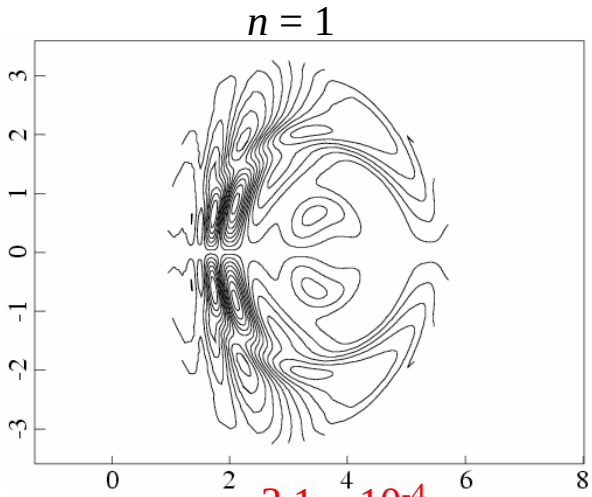
Mode Structure?

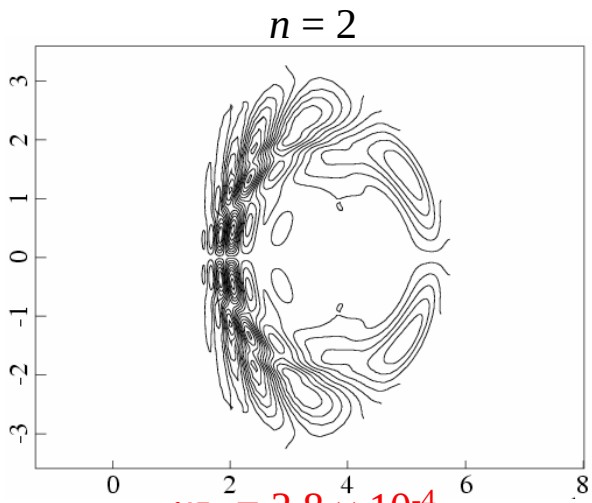


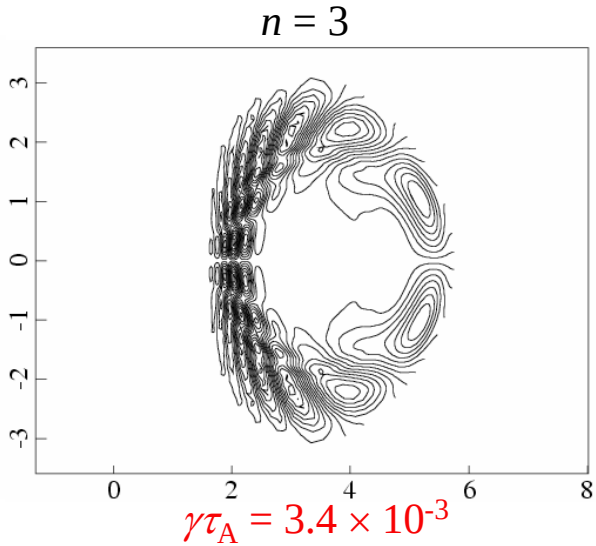
Equilibrium field line with pitch
$m = 3, n = 1$

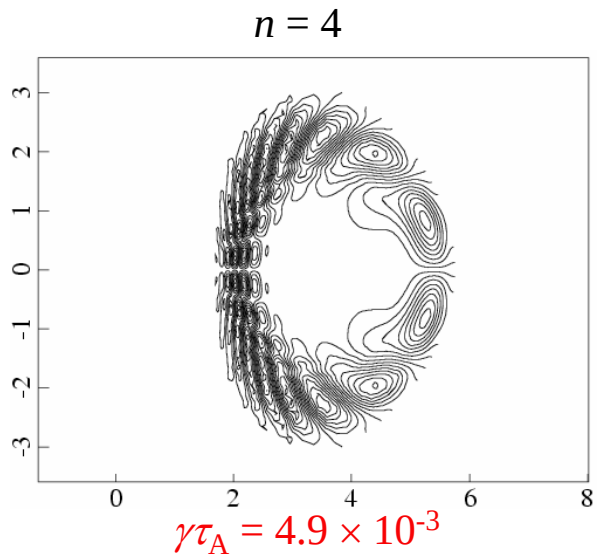
- Low aspect ratio
- Low-*n* field lines make more turns on inboard side
- Mode localized along equilibrium field line will have more structure on inboard side
- Higher-*n* ?????

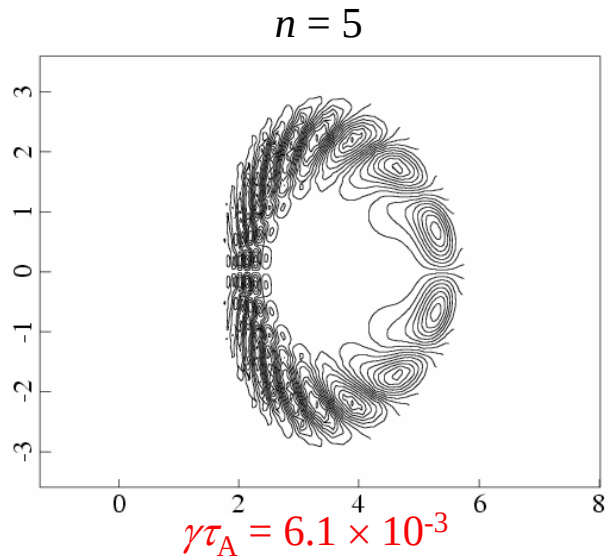
Effect of toroidal mode number *n*





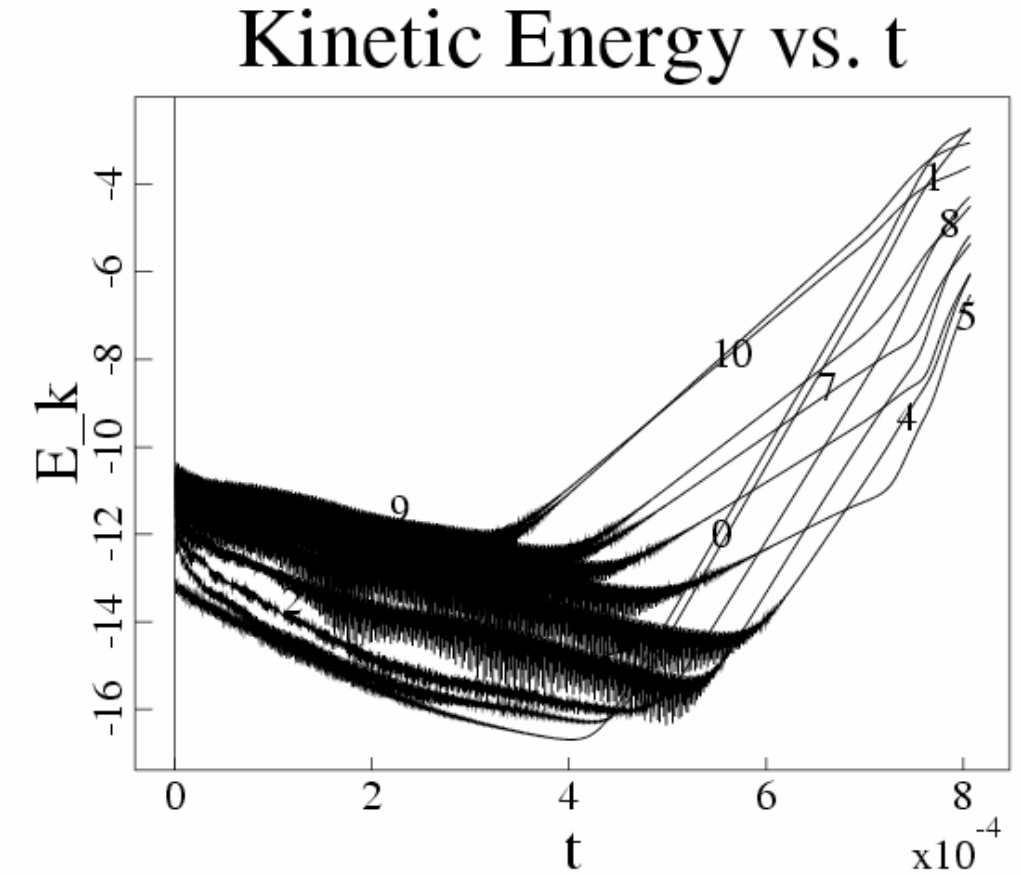






- Edge of discharge
- Move slightly outboard with increasing *n*
- Growth rate increases with *n*

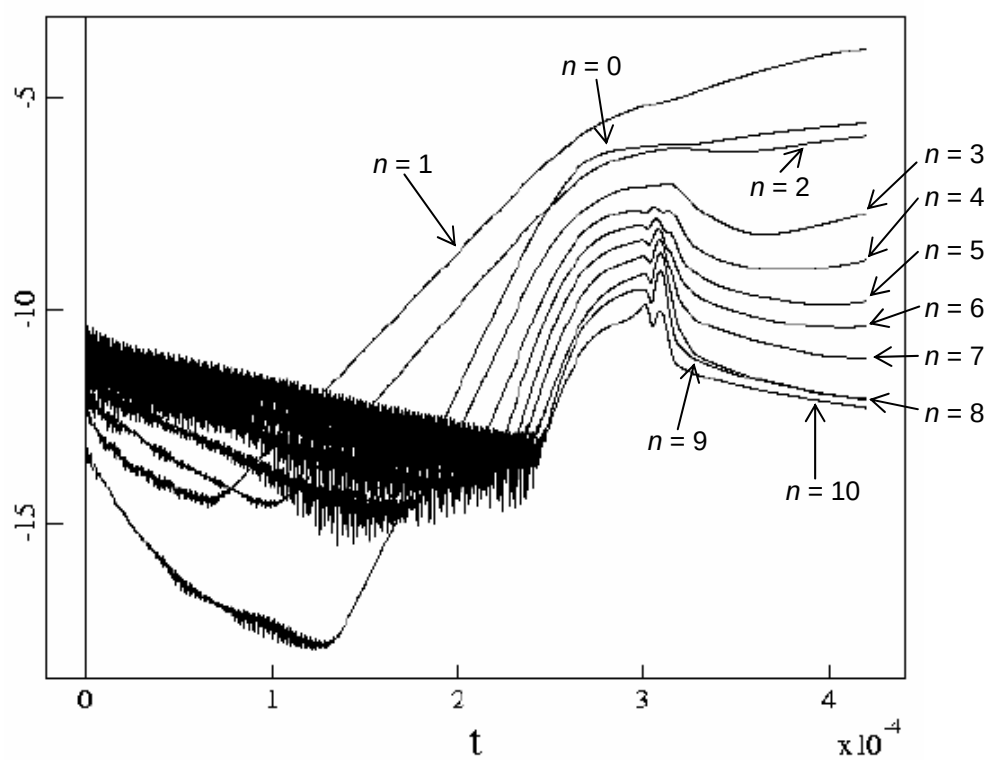
Nonlinear “Standard” Case



- n = 10, 9,… most unstable
- Lower n (e.g., n = 1) now *nonlinearly driven*:

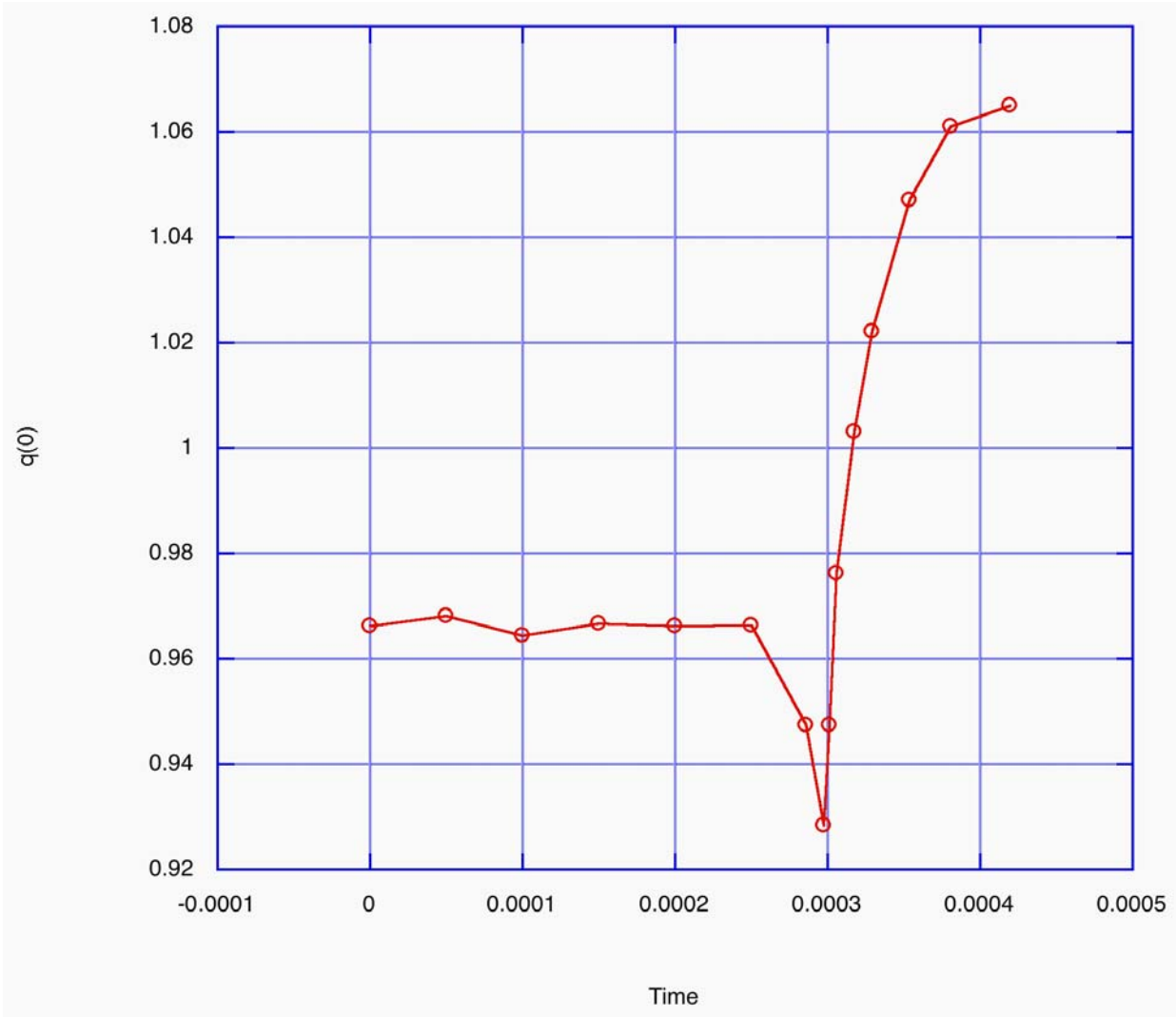
  $\gamma_{n=1} \sim \gamma_{n=9} + \gamma_{n=10}$
- Completely different from linear picture
- Can there ever be enough toroidal resolution?

“Alternative” Nonlinear Case: $q(0)=0.97$



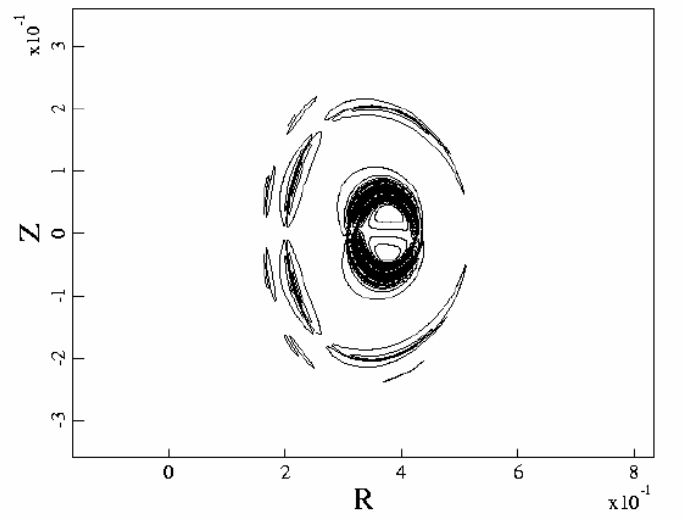
- *Linear n* = 1 is dominantly 1/1 (“sawtooth”)
- *Nonlinear n* = 1 changes from 1/1 to 2/1
- Finite sized 2/1 mode growth nonlinearly in Rutherford regime
- No indication of high-*n* instabliity

Evolution of $q(0)$



n = 1 mode Changes After Reconnection

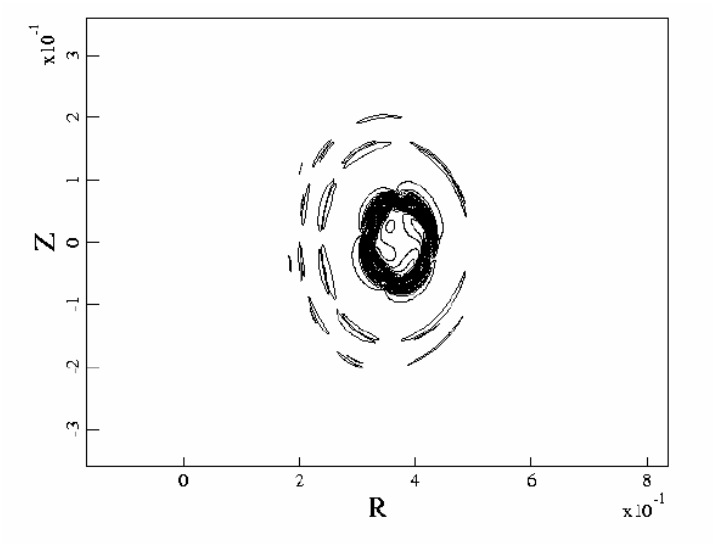
Before sawtooth saturation



t = 2.5 X 10^{-4} sec.

1/1 with harmonics

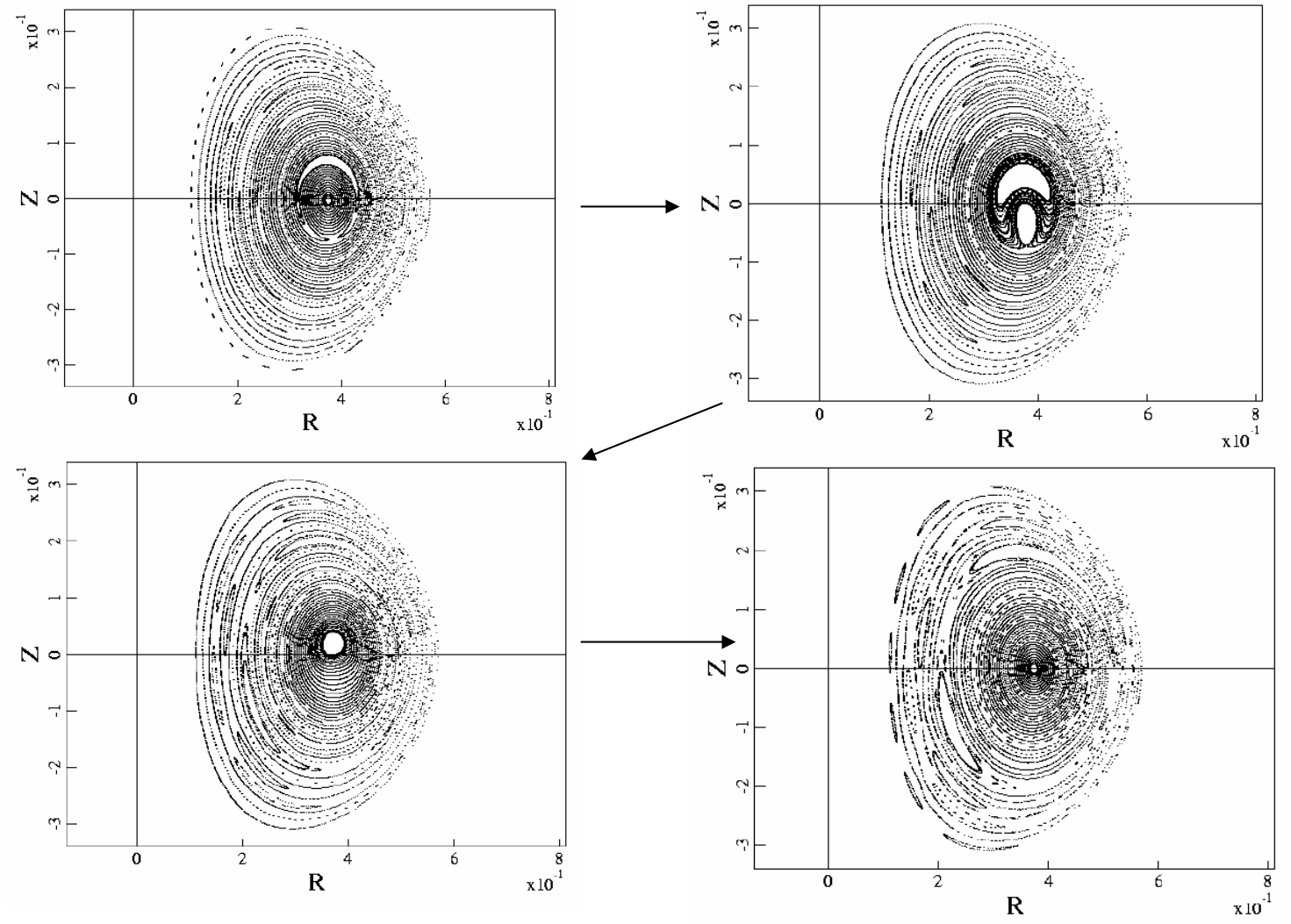
After sawtooth saturation



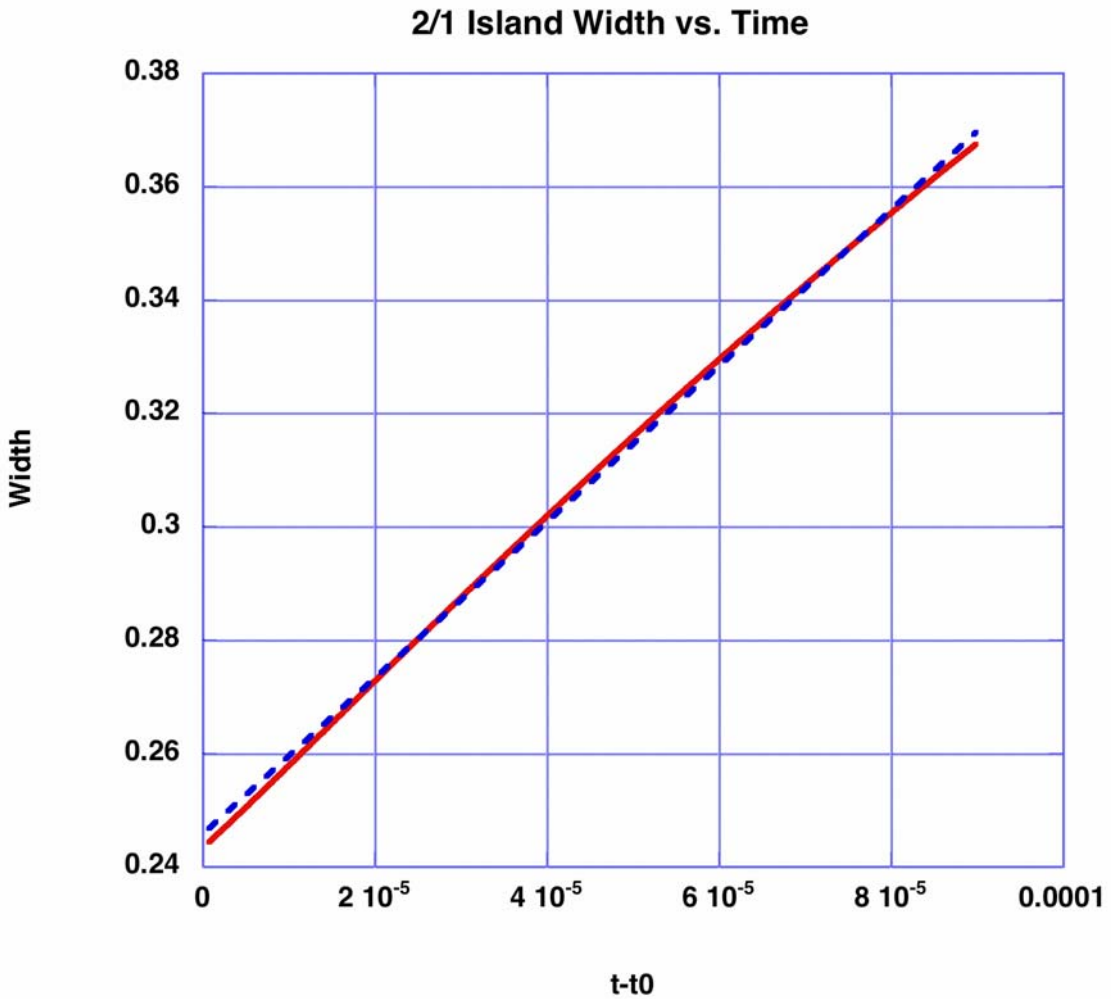
t = 4.20 X 10^{-4} sec.

2/1 with harmonics

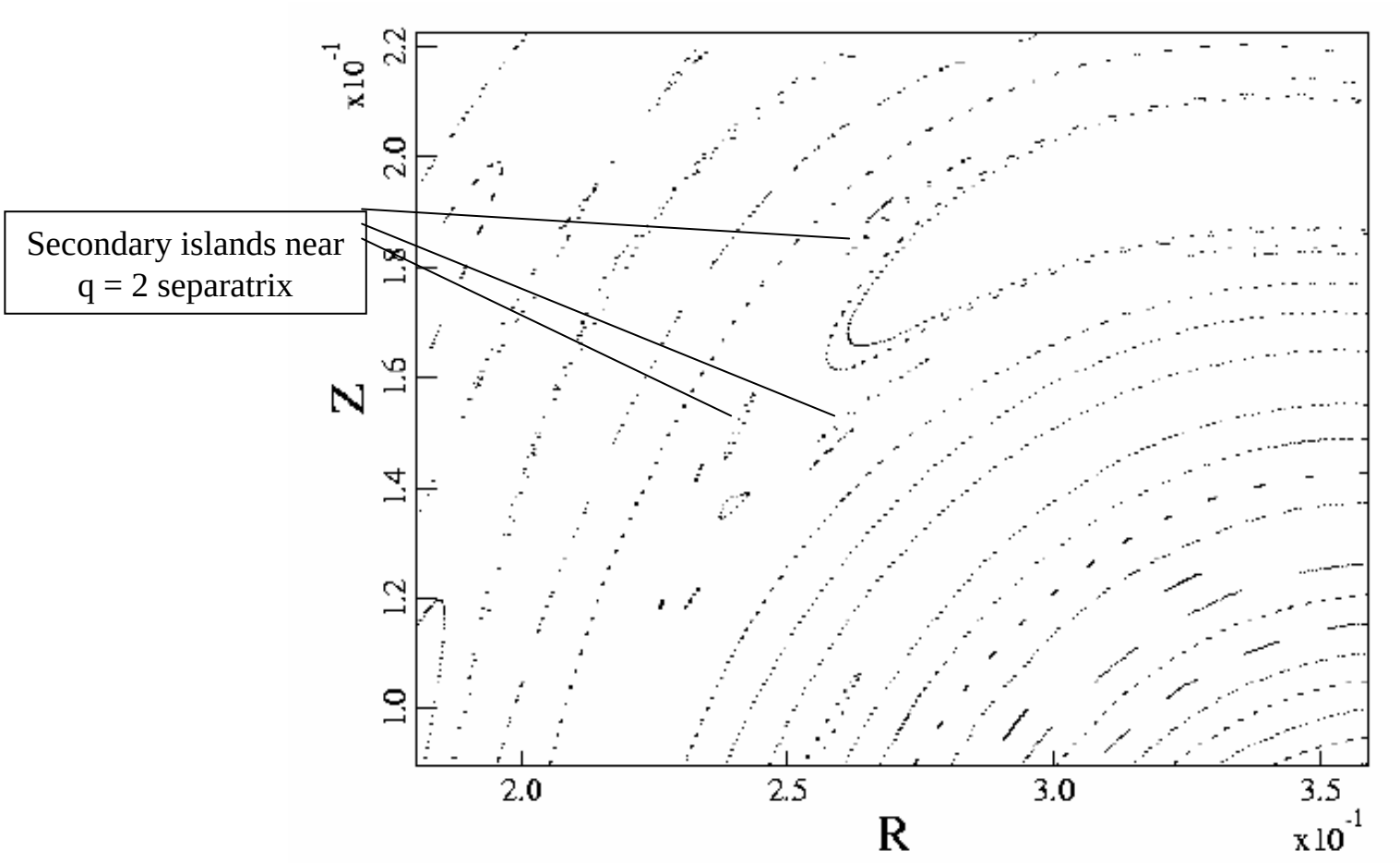
1/1 Reconnection and 2/1 Growth



Growth of 2/1 Island after 1/1 Reconnection



Field Line Structure near $q = 2$ Surface



Remarks

- At agreed parameters, low-$q(0)$ CDXU profile has non-standard stability properties:
  - "Sawtooth mode" (1/1) is at best marginally unstable
  - Outer parts of q-profile drive instability at higher m
  - Growth rate increases with increasing n, mode structure becomes more complex
- Can we ever achieve sufficient toroidal resolution for this case for nonlinear calculation?
- Poor case to study non-linear sawtooth evolution?
- Is $q(0) = 0.95$ physically relevant to CDXU?
  - $q(0) = 0.97$ case exhibits beautifully dominant sawtooth, no high-n instability, rich nonlinear dynamics
  - Would CDXU ever achieve $q(0)= 0.95$?