Dynamic Behavior of Peeling-Ballooning Modes in a Shifted-Circle Tokamak Equilibrium

B. Squires[1], S.E. Kruger[2], C.C. Hegna[1], E. Held[3], P.B. Snyder[4], C.R. Sovinec[1], P. Zhu[1]

1) University of Wisconsin-Madison
2) Tech-X Corporation, Boulder Colorado
3) Physics Department, Utah State University
4) General Atomics, San Diego

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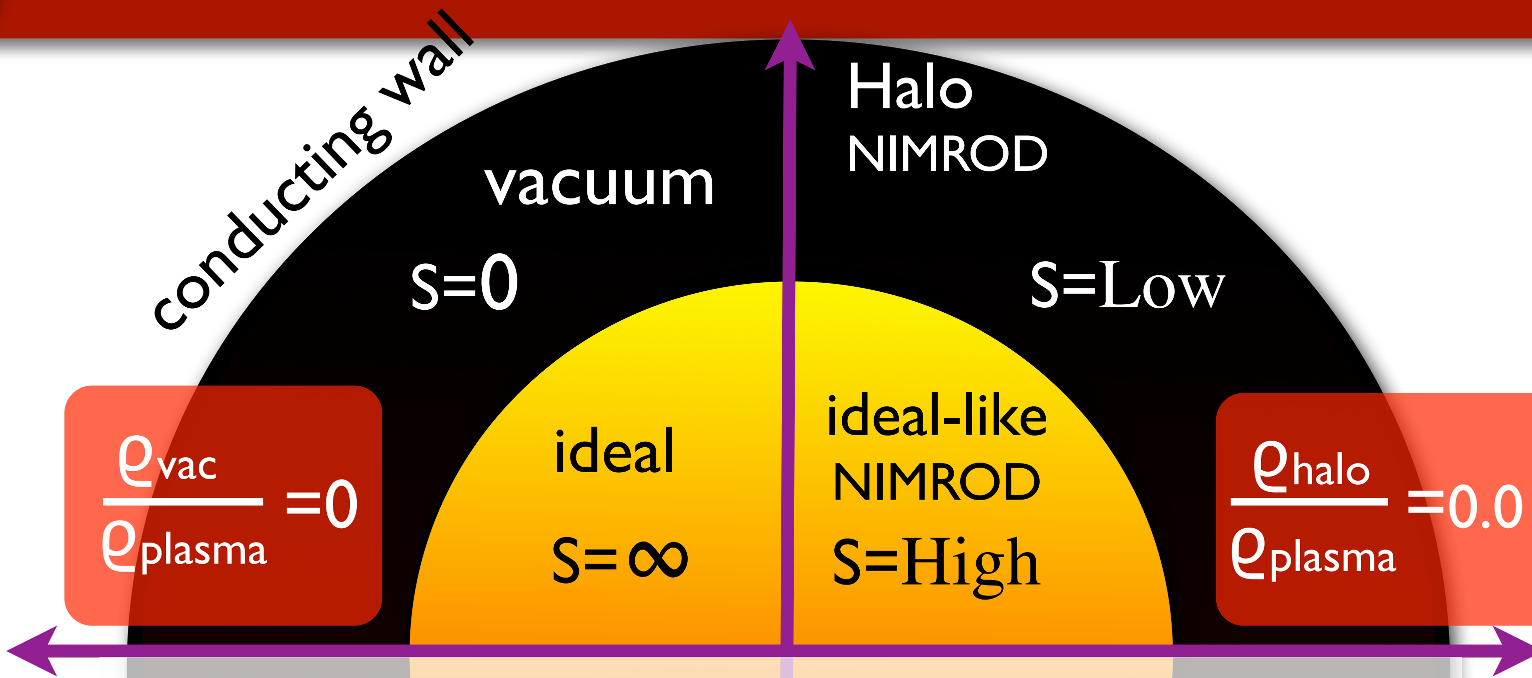
*The research was performed under appointment to the Fusion Energy Sciences Fellowship Program administered by Oak Ridge Institute for Science and Education under a contract between the U.S. Department of Energy and the Oak Ridge Associated Universities.
*Research supported by U. S. DOE under grant no. DE-FG02-86ER53218

November, 2008 APS-DPP Dallas, Texas

ELM onset and growth linked to the coupling between ballooning and kink modes

- “Ideal-like”/ “Halo” defined in NIMROD
- ELITE benchmarks with NIMROD
- Single Linear case examined as precursor to NL studies
- Technique developed to isolate ballooning and kink drives
- Preliminary nonlinear results guide future analysis
- Summary

Detailed “ideal” study in NIMROD

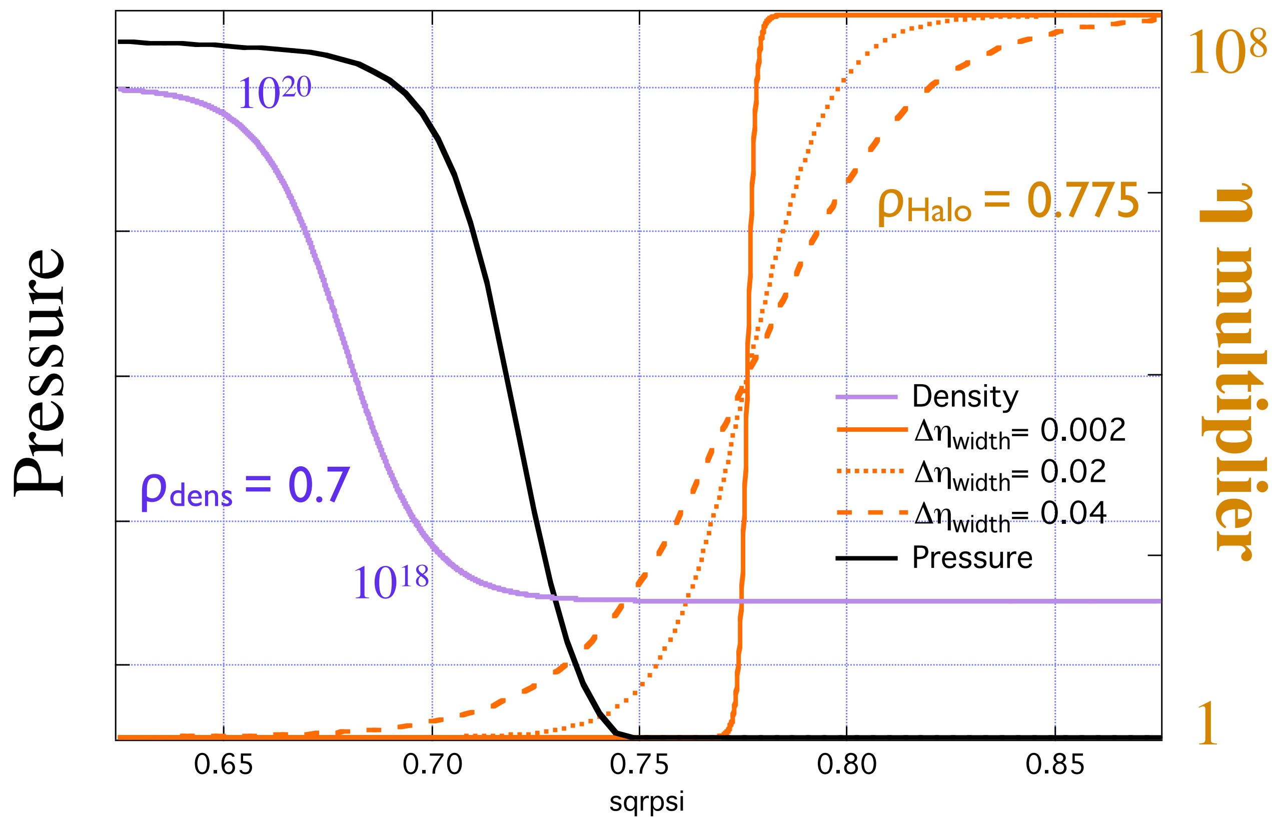


define ideal and halo in NIMROD with the intent of using the halo placement to “dial in” kink/ballooning drive

1) kink: halo region just outside pedestal
2) ballooning: halo region far from pedestal

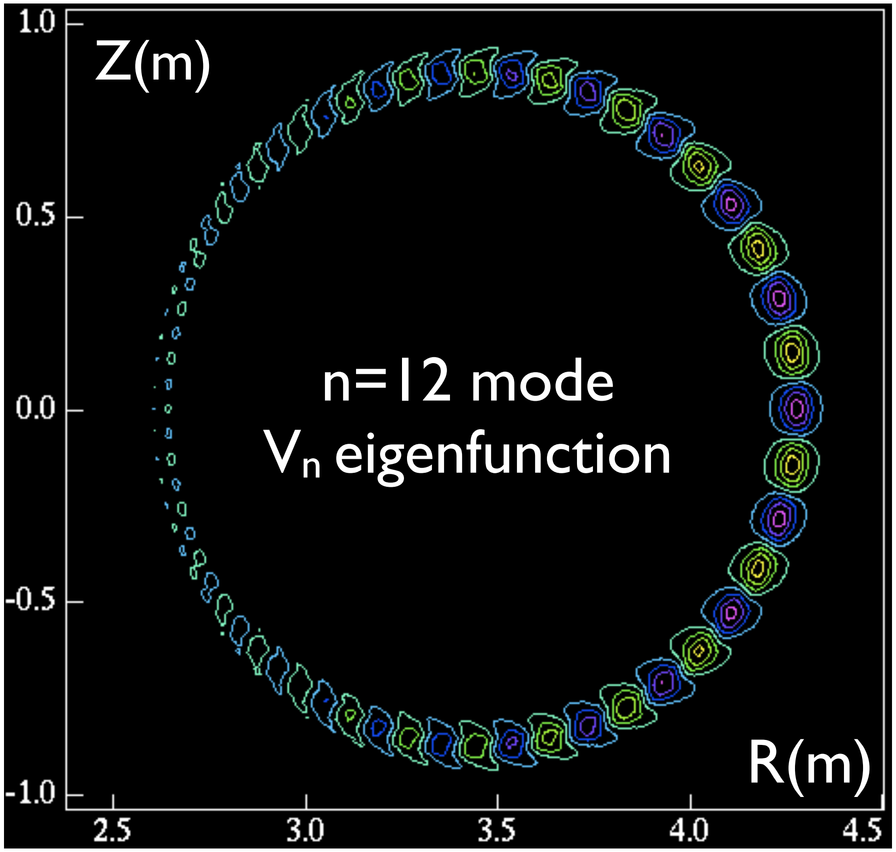
Halo region defined with an imposed resistivity and density transition

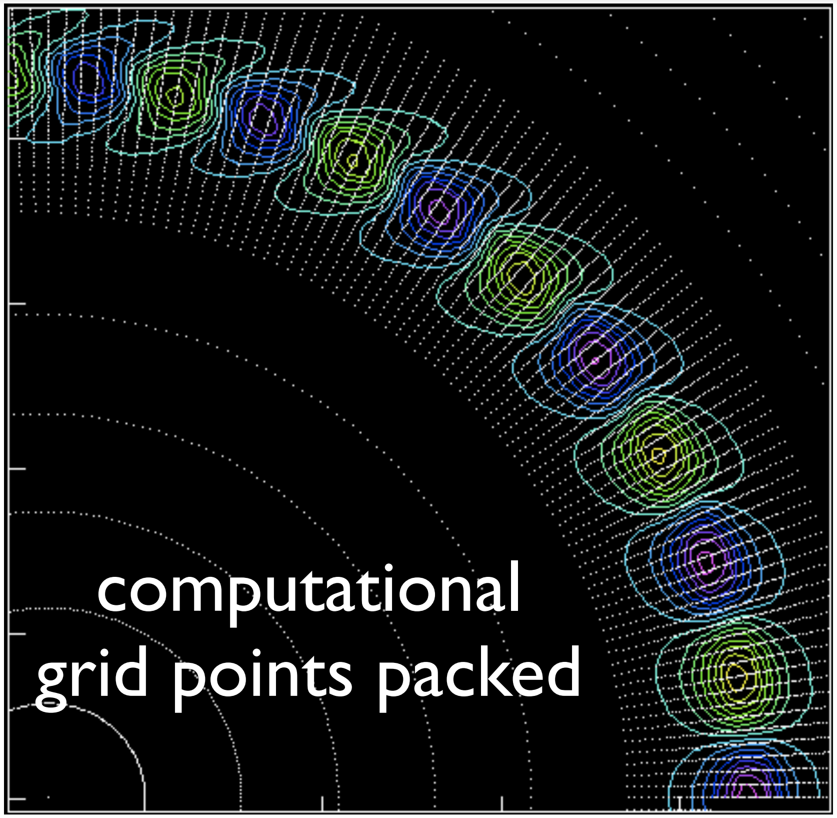
- η transitions from low, "ideal" to a large value at a specified ρ_{Halo}
  - Tanh function used as an η multiplier
- Density decreased by a factor of 100, transitions at a specified ρ_{dens}
  - Tanh function also used, sharp transition not possible



Quantifying "Ideal" in NIMROD requires high spatial resolution

- Start with purely ideal case
  - S = ∞ everywhere
    - *no halo region*

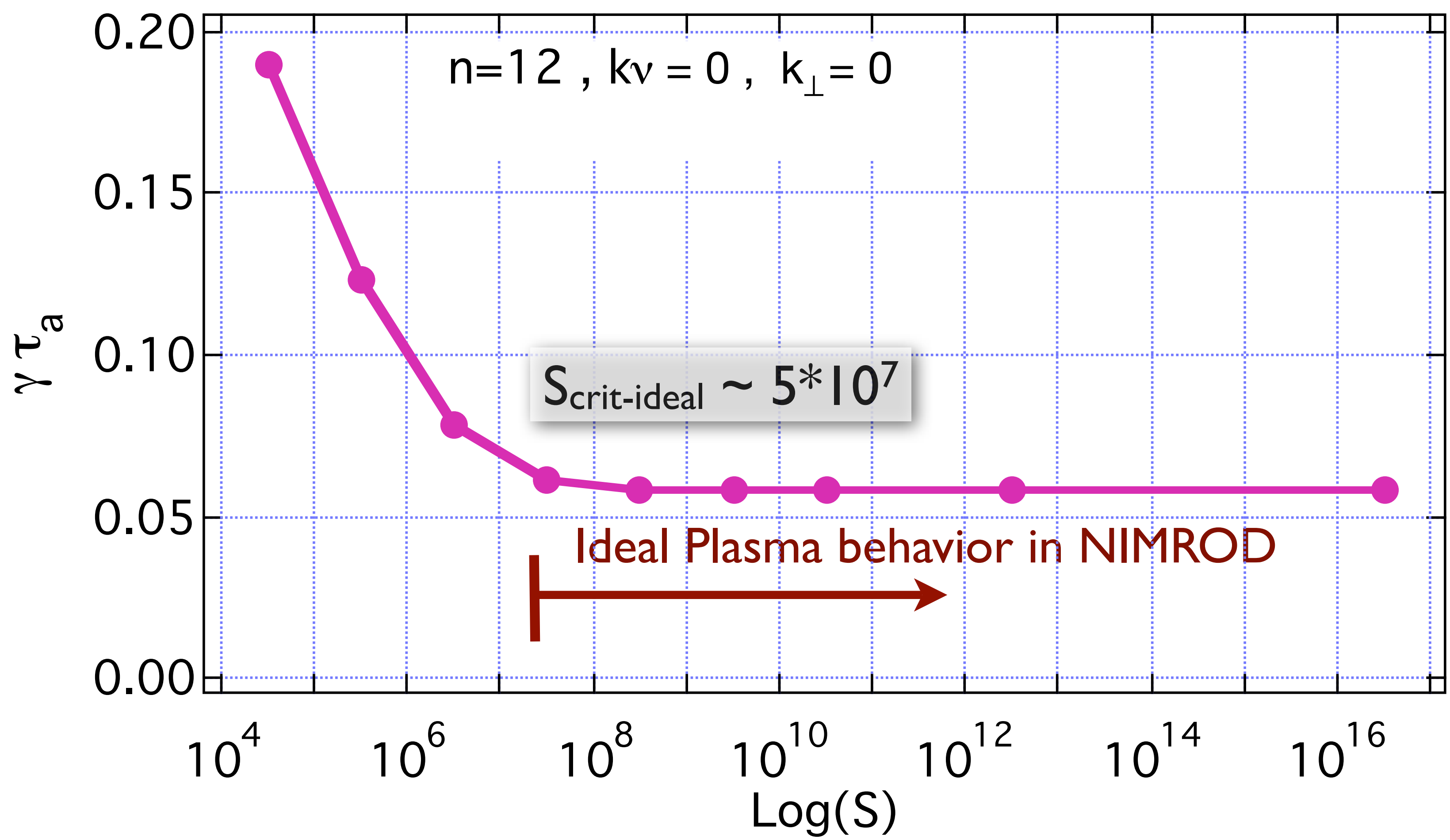




- linear ideal MHD, n = 12
- no dissipation in system
- k_{visc}, k_{perp} =0

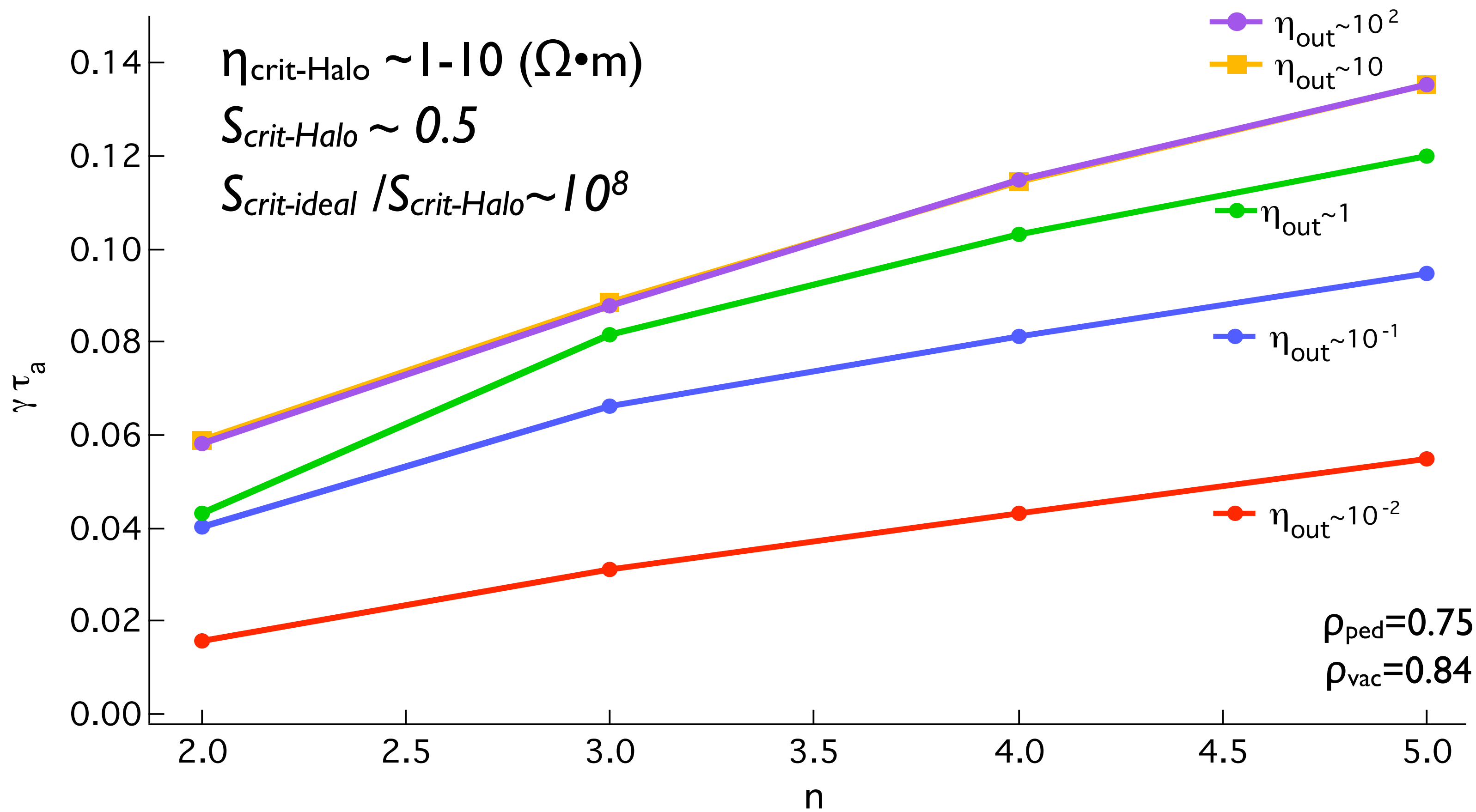
Lundquist scans define critical, “ideal-like” value in NIMROD

- systematically decreased S from ∞
- critical value defined, below which plasma behaves ideally



Beyond a critical halo-resistivity the modes are not affected

- Define $S_{crit\text{-}Halo}$: increase vacuum resistivity until no effect is produced
  - Lundquist ratio not a good characterization parameter
  - Introduction of halo region doesn't affect $S_{crit\text{-}ideal}$



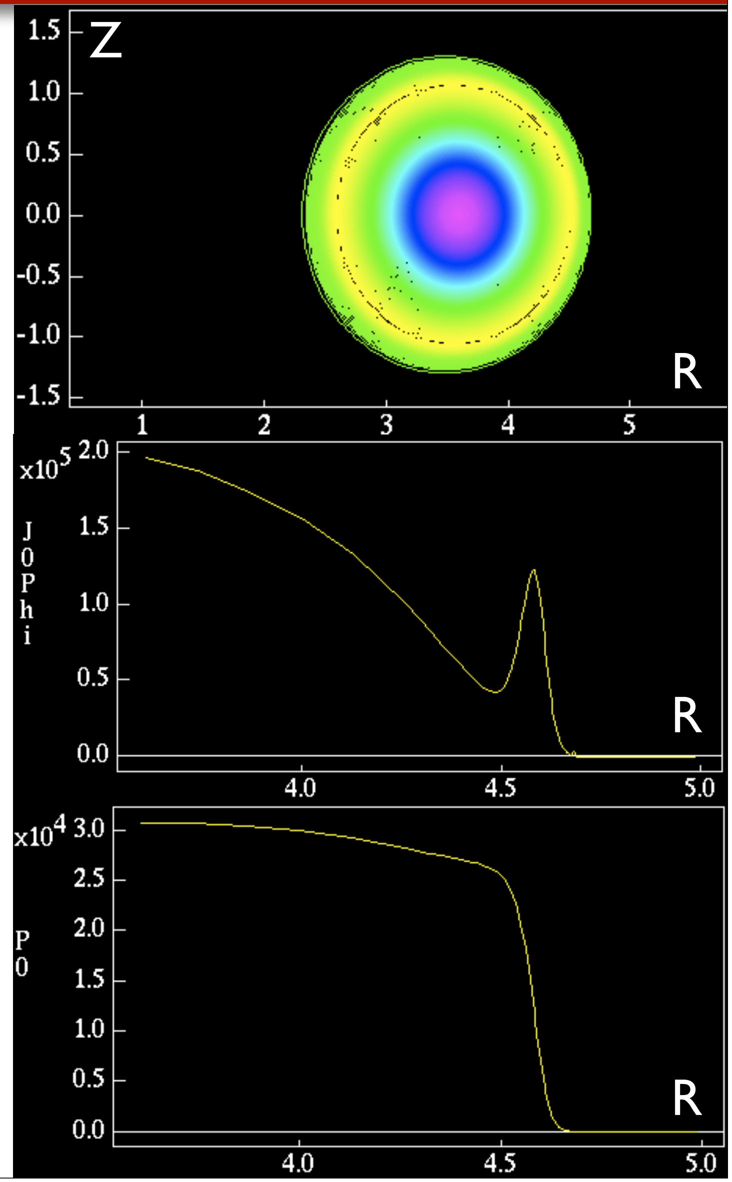
Ballooning unstable equilibrium generated for ELITE benchmarking

- TOQ-generated series of equilibria scanning across stability boundary

- shape = simple circle
- pedestal is wide
- interface at Psi_N ~0.7 (P' and $J_{||}$ = 0.0)

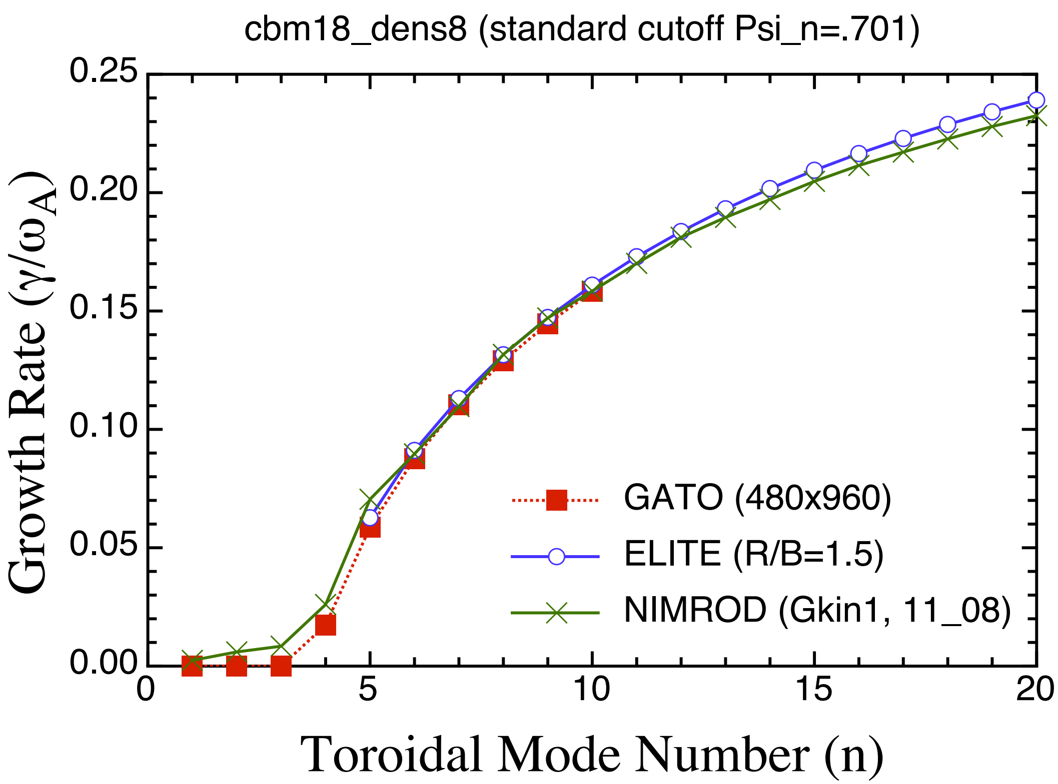
- plasma vacuum interface has 0 pressure and current

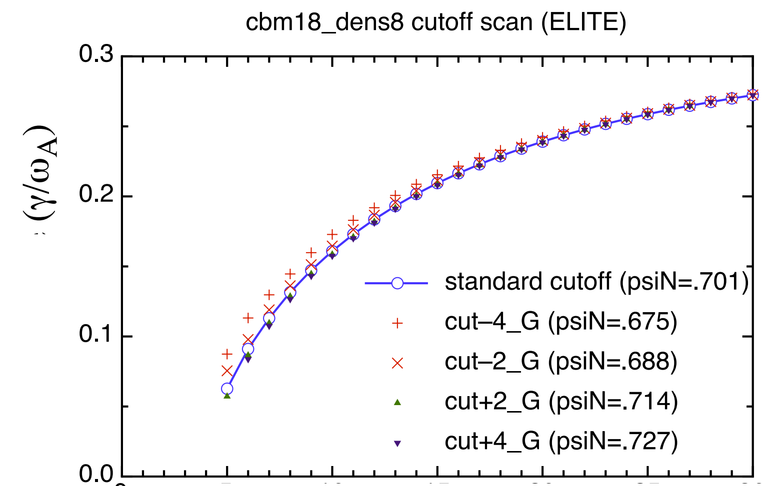
- ELITE growth rates weakly sensitive to vacuum location

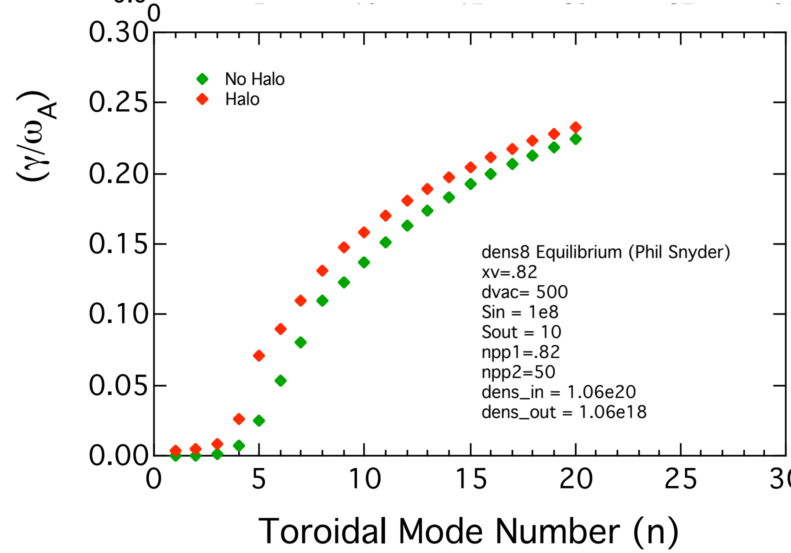


Results show excellent spectral agreement with ELITE

- Equilibrium generated to have little variation with vacuum placement
- results without halo region show little variation at high-n

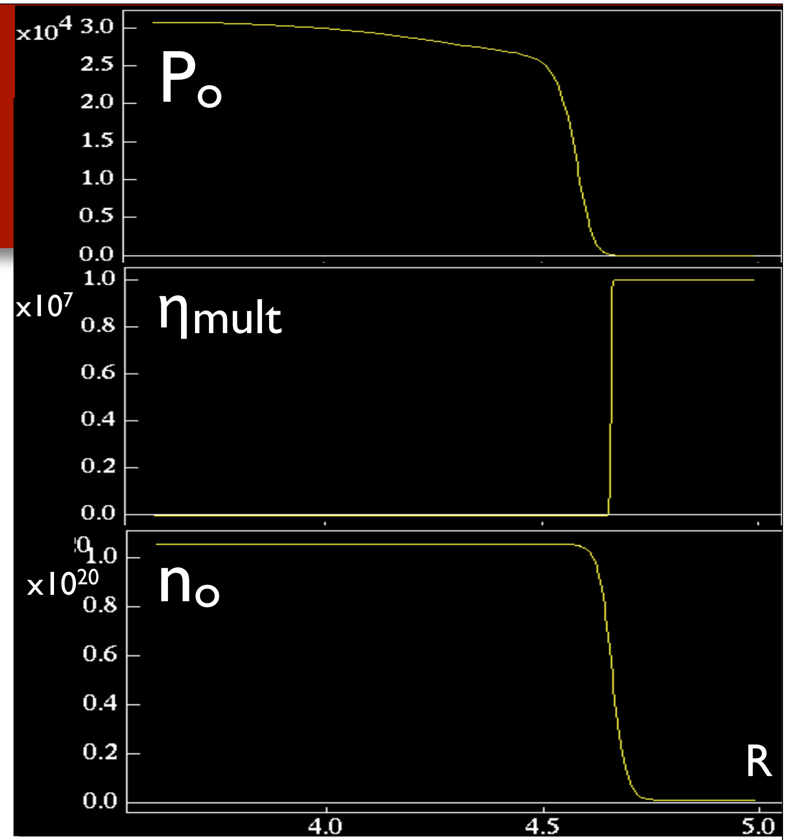




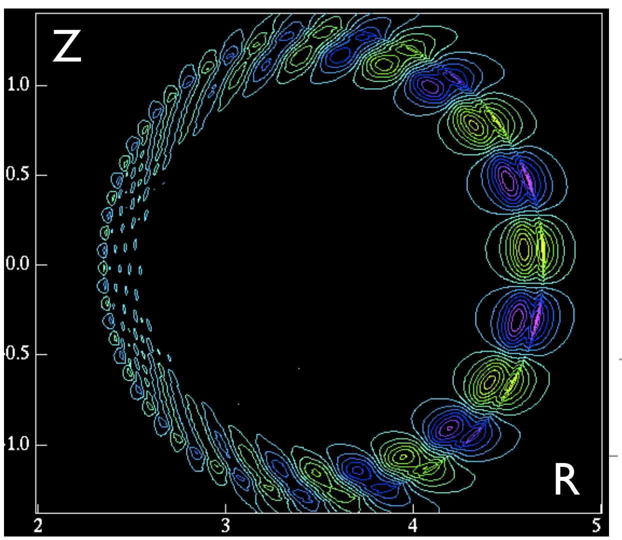


n = 8 mode structure in NIMROD and ELITE

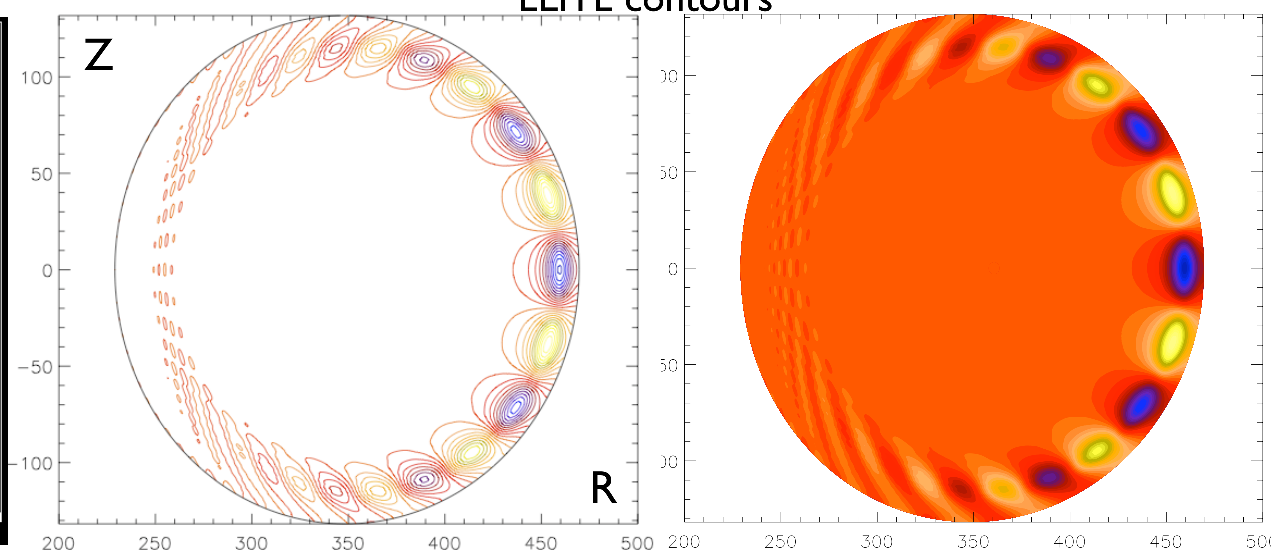
- $\gamma\tau_{aELITE} \sim 0.132$
- $\gamma\tau_{aNIMROD} = 0.132$
- S_{in}=1e8, S_{out}=10
- ρ_{halo} = 0.82, dvac = 500
- ρ_{dens} = 0.82, npp(1) = 50
- $k_{perp} = k_{visc} = 0$



Vn contours NIMROD

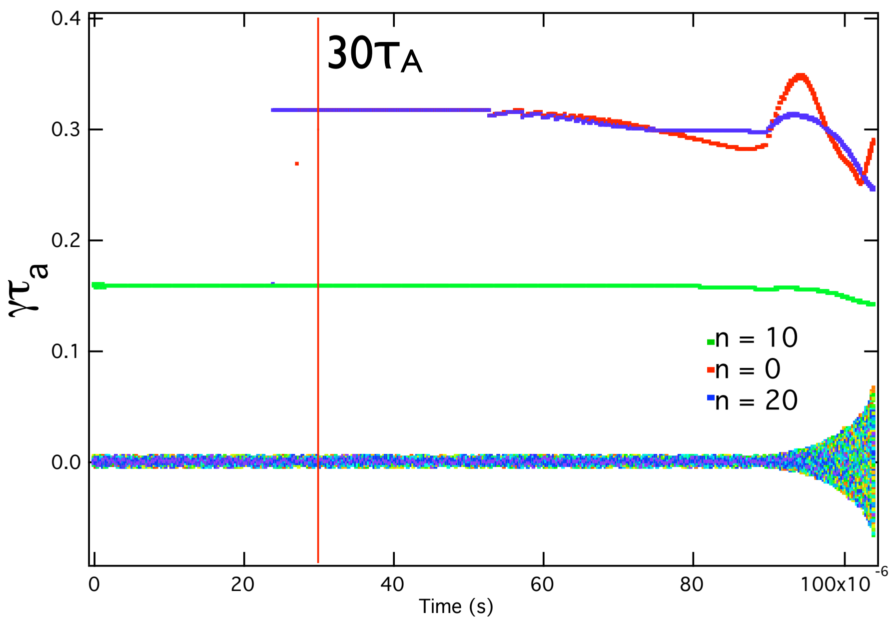


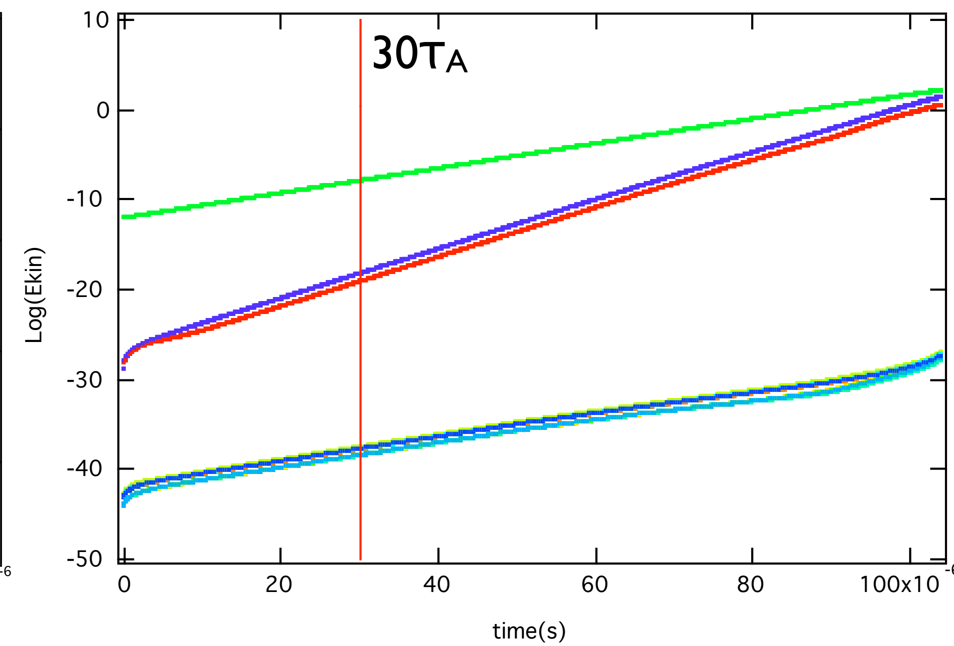
ELITE contours



Nonlinear calculations of n = 10 duration = $100\tau_A$

- 22 modes included: n=0-21, initialized with linear n=10 mode
- nonlinear n=0 & n=20 mode growth at twice linear n=10 rate expected
- The transition to nonlinear dynamics is expected when $\frac{\xi}{\Delta x} \sim O(1)$
  - For an initial velocity perturbation $V_o \sim 1\times10^{-4}$ this occurs after $\sim 30\tau_A$

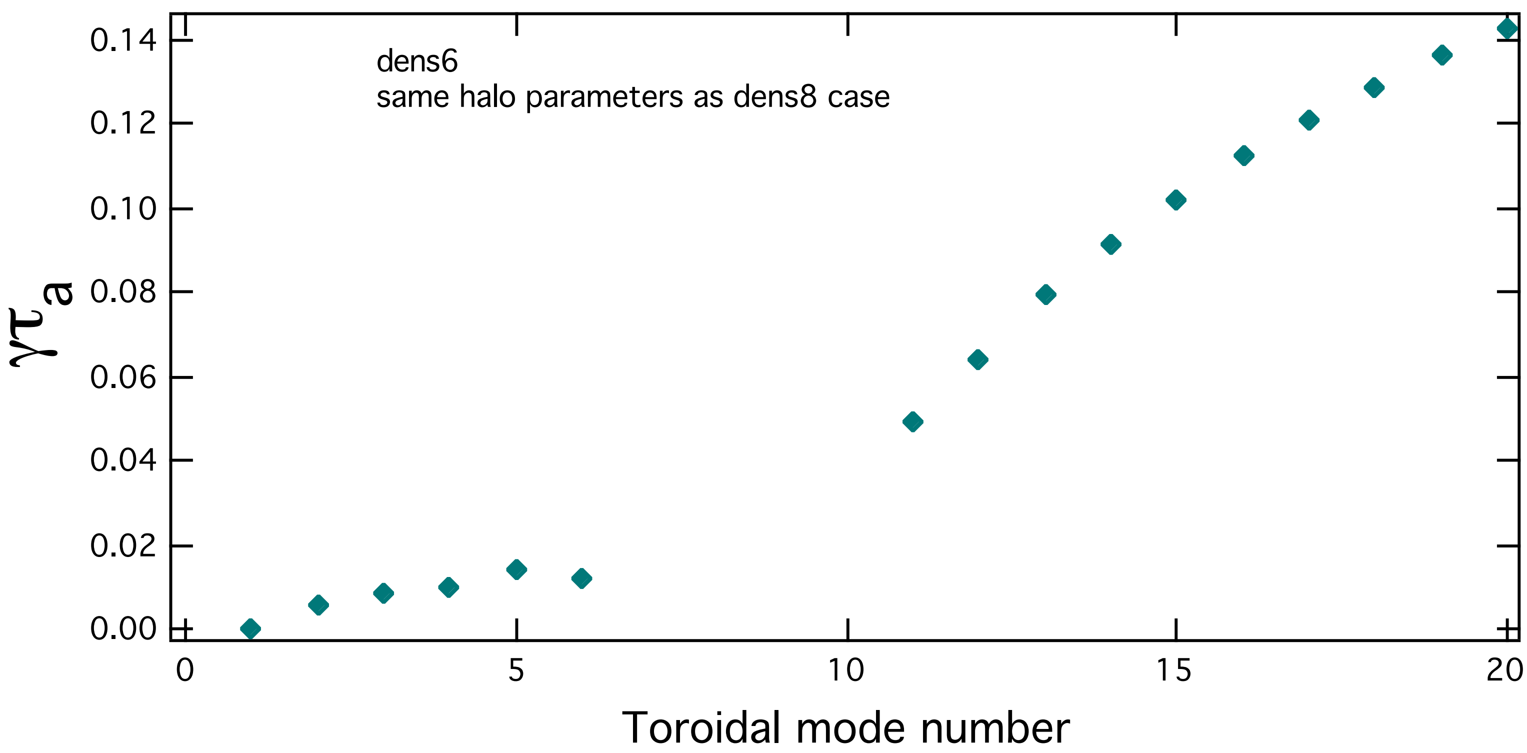




- Results show linear growth rates well into NL regime,
  - (as expected, Ping Zhu -- see APS poster)

Currently working on benchmarking the stability threshold with ELITE

- Similar equilibrium
- Lower pedestal pressure and edge current
- n > 10 converged
- n (1-10) appears to be slowly growing oscillating modes... in progress



New equilibrium allows the study of peeling & ballooning mode drives

TOQ-generated shifted-circle tokamak equilibrium

~S. Kruger & P. Snyder

R_o = 3m, a=1m

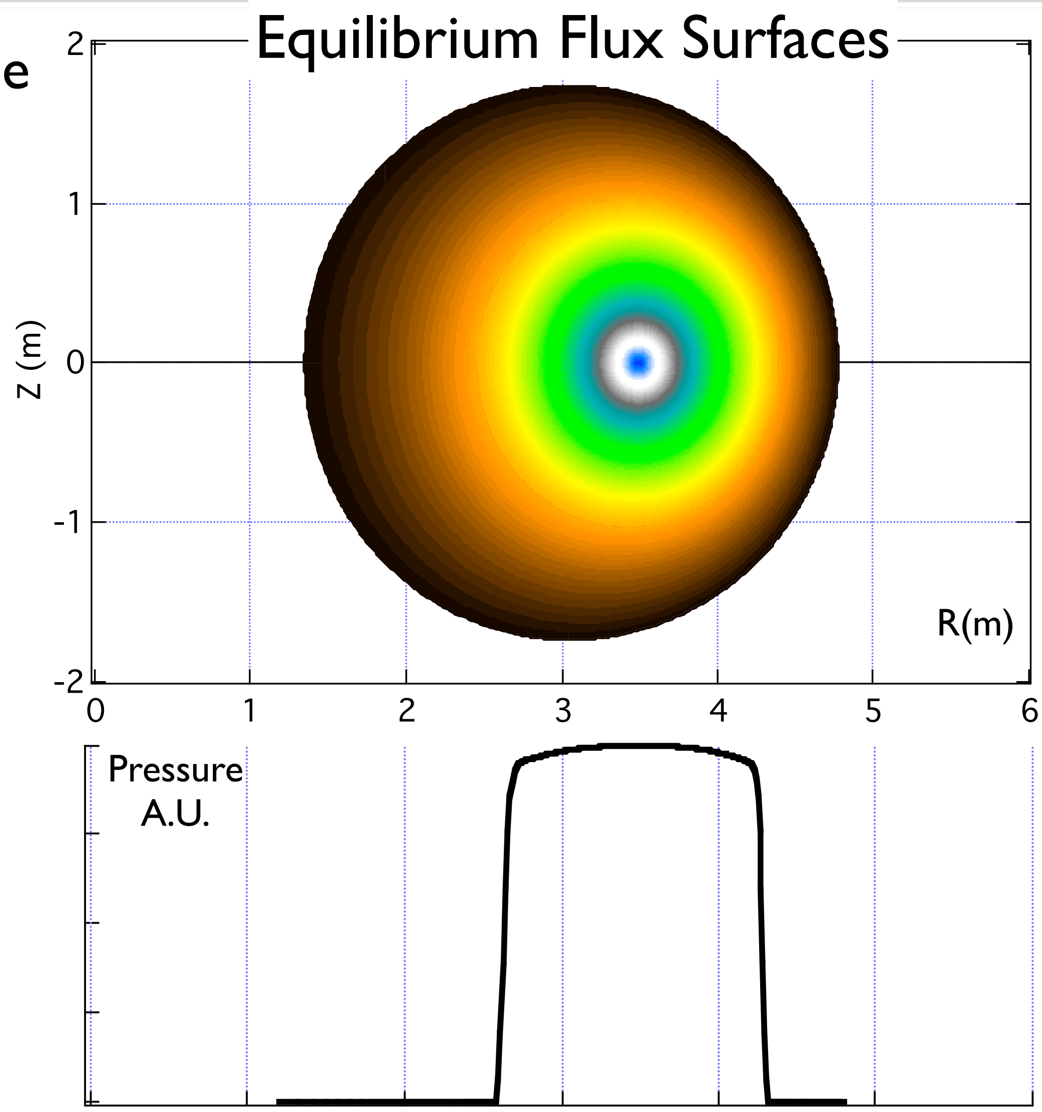
$\mathbf{B}_o$ = 2T

β_{to} = .005

n = $1.06\times10^{20}(m^{-3})$

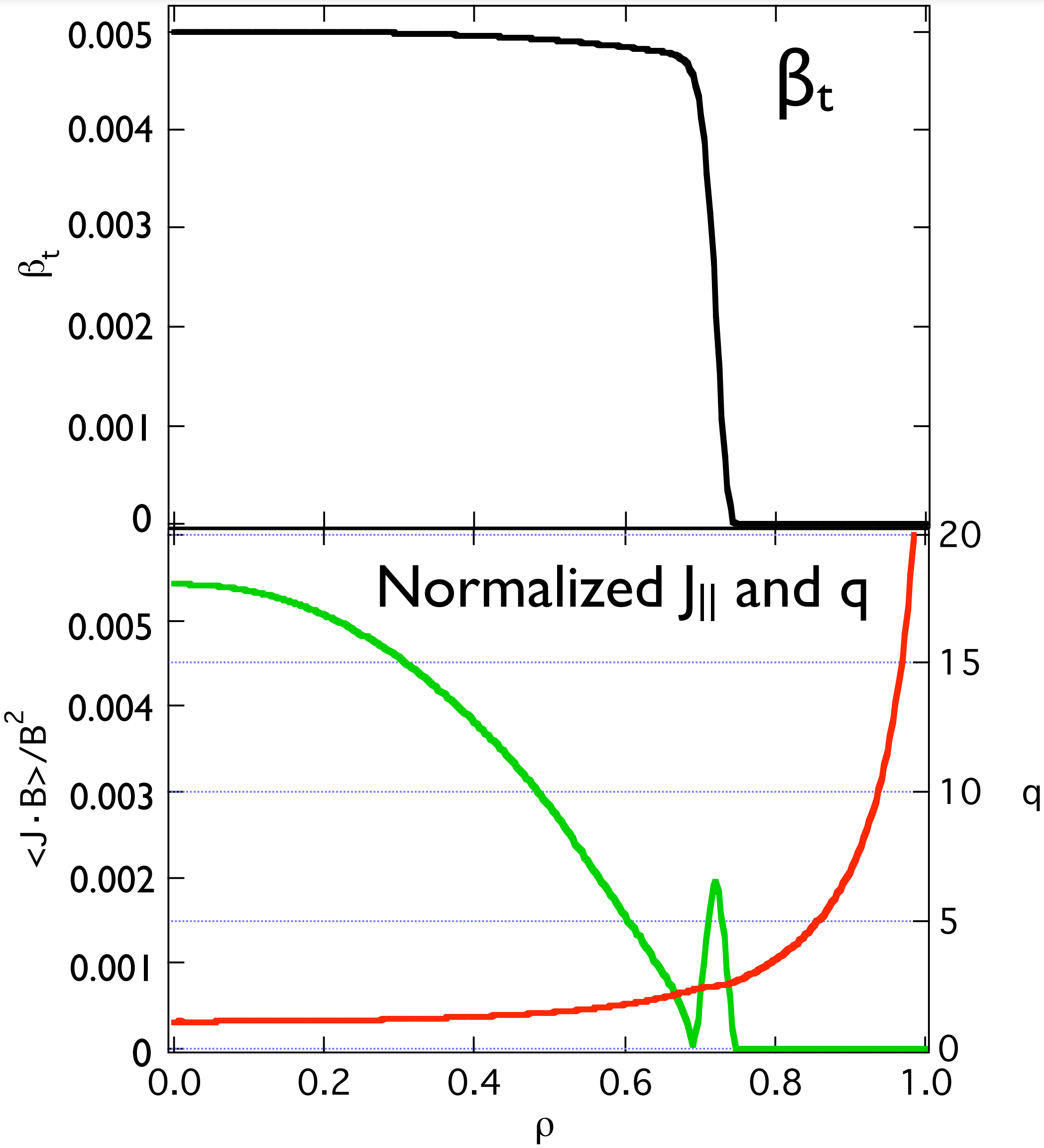
- no density transition

- Modified TOQ
  - currents in edge set to 0
  - minimizes numerical errors (no separatrix)
  - pedestal region
  - ~67-75cm on midplane



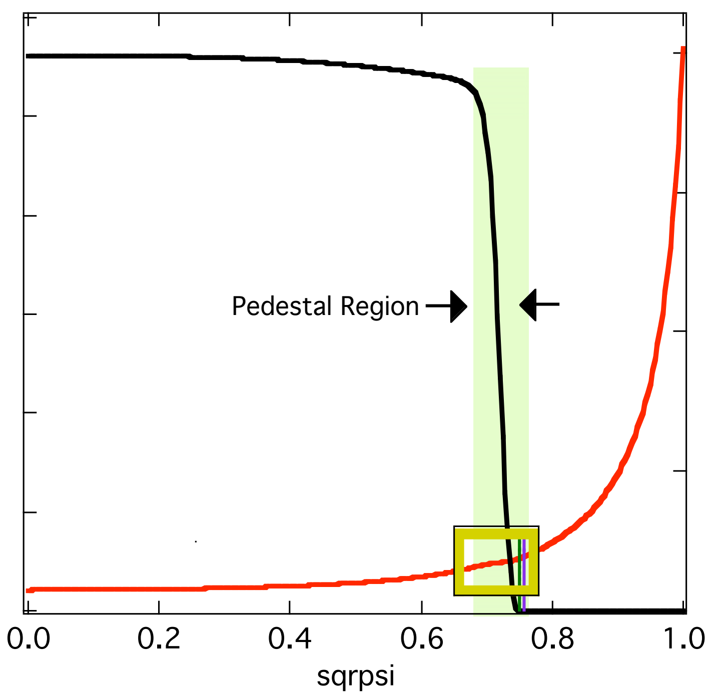
Equilibrium profiles show peeling-ballooning instability drive source

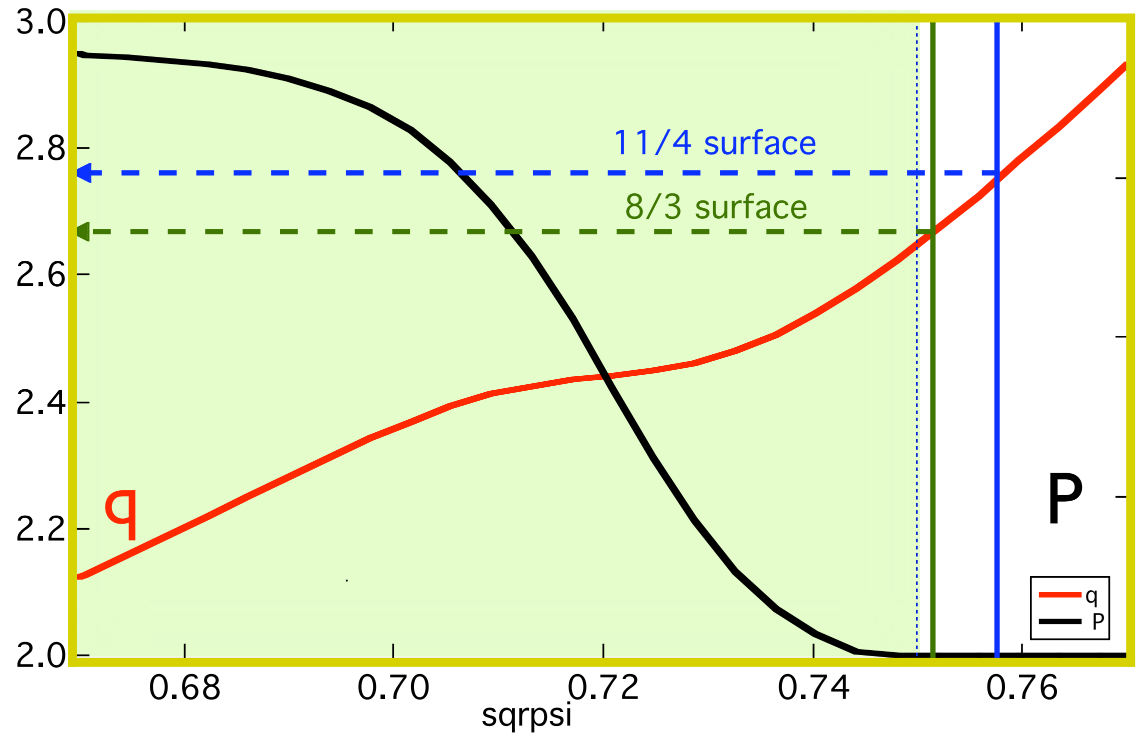
- Steep pressure gradients drive ballooning modes (DCON)
  - *Pedestal width twice experimental value, simplify vacuum transition region*
- Self-consistent edge currents & $2 < q_{edge} < 5$ to provide increased kink drive
  - comparable to ballooning drive



Halo location relative to the q rational surfaces affects instability drives

- using q profile identify mode rational surfaces

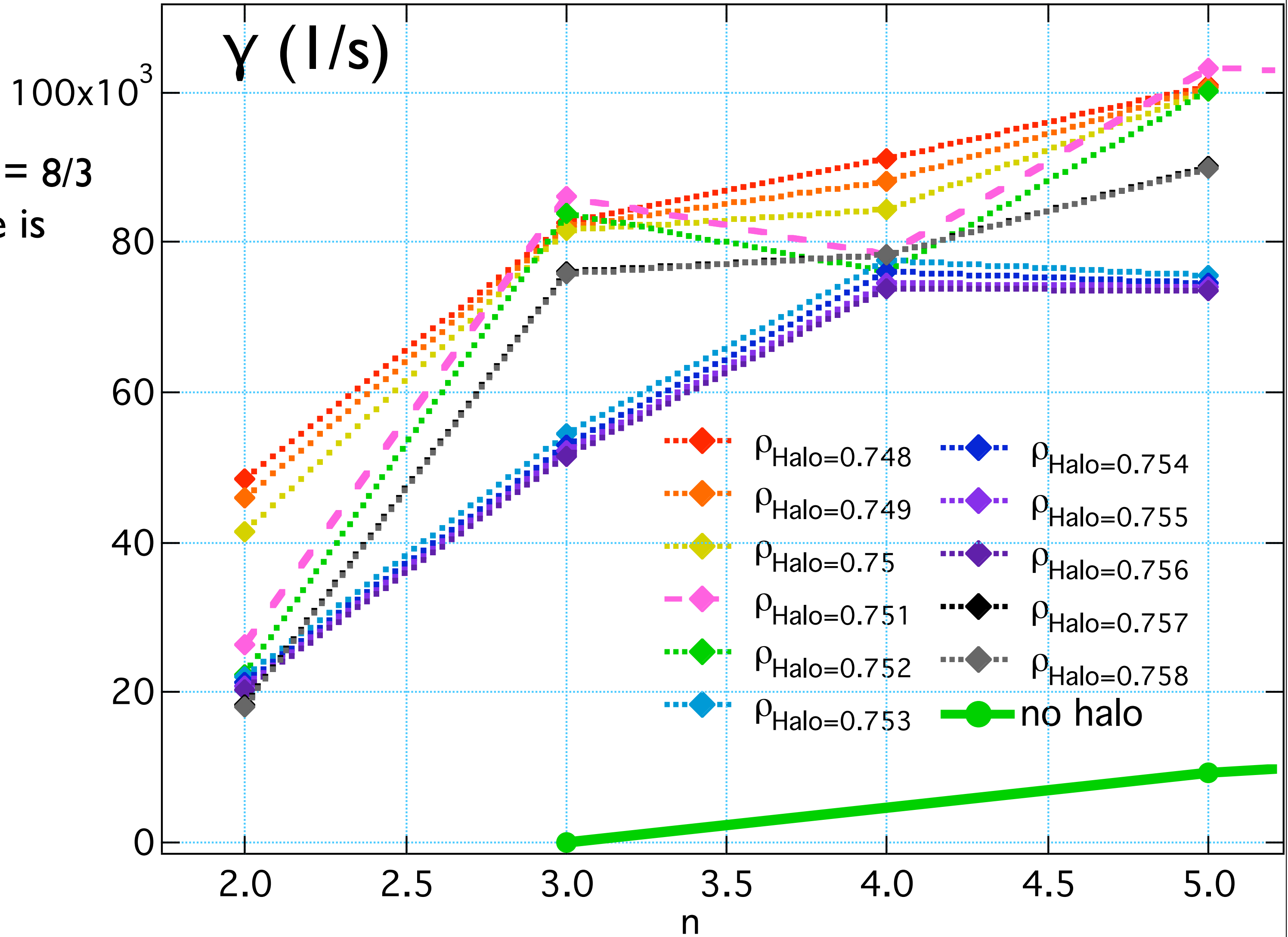




- adjusting the halo location "dials in" kink, ballooning, & peeling-ballooning behavior

Low-n modes are sensitive to location of halo transition

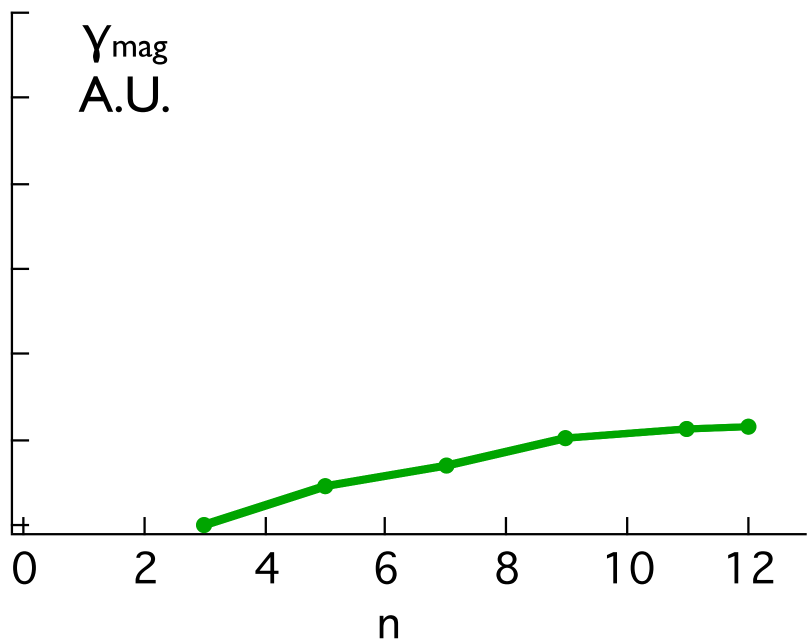
- When $\rho_{ped} < \rho_{Halo} < \rho_{rat} = 8/3$ n = 3 kink mode is driven
- compared to ideal spectrum: more clearly ballooning dominant
- convergence challenging



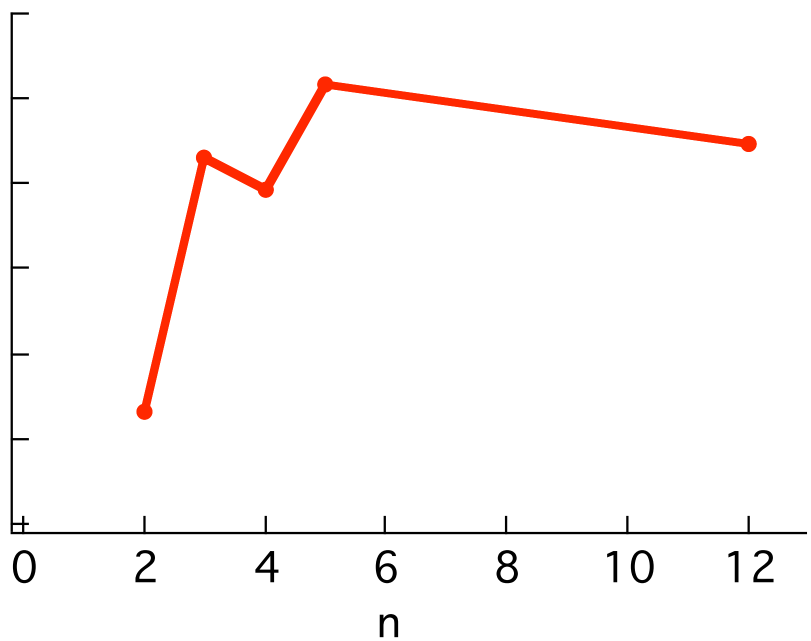
Kink & ballooning drives are adjusted within a single equilibrium

- Developed a technique where relative rates of ballooning / kink drive are changed by adjusting the location of the halo region relative to the plasma pedestal region
  - *actual NIMROD calculations*

No Halo: Ballooning Dominant Spectra



Halo: Increases Low-n Kink Drive

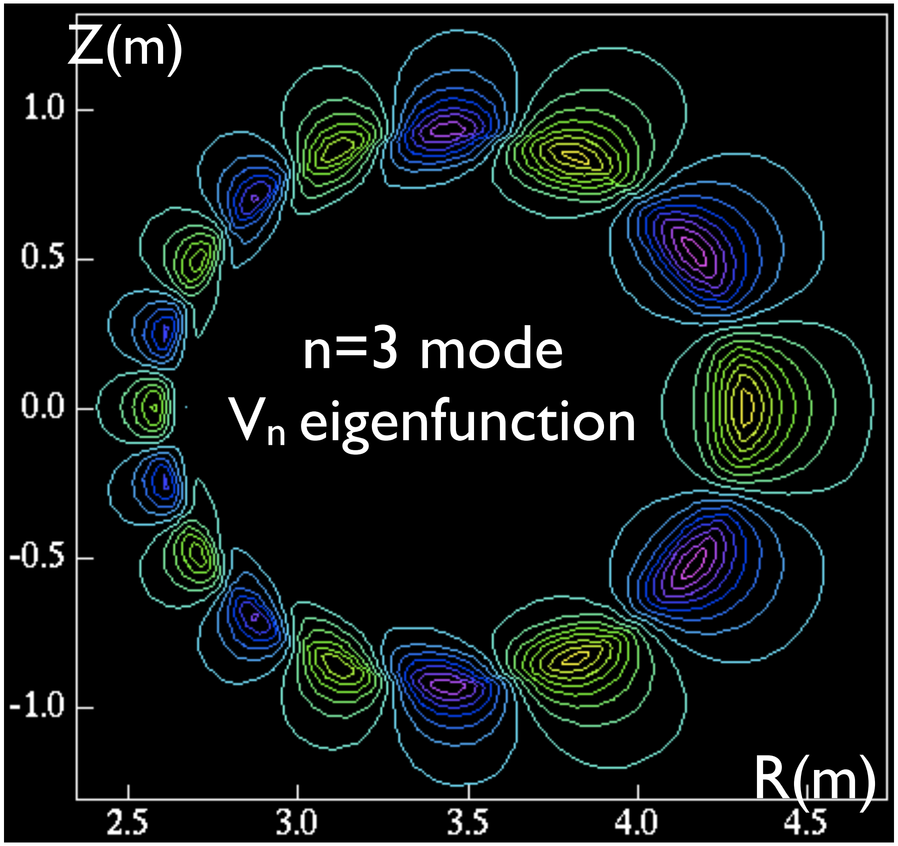


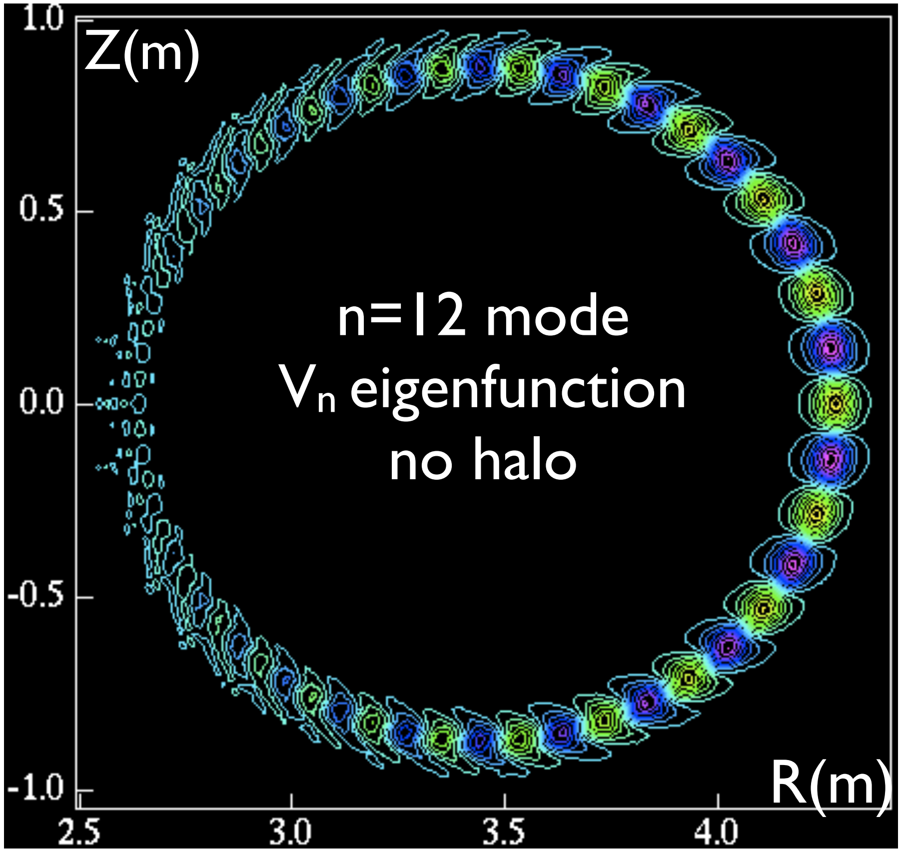
Summary

- Currently developing/documenting detailed linear peeling-ballooning analysis in NIMROD
  - Defined critical Lundquist values for defining an "ideal-like" plasma and halo region in NIMROD
    - ($S_{crit\text{-}ideal} \sim 5 * 10^7$; $S_{crit\text{-}halo} \sim 0.5$)
    - Ratio of these values are greater than in experiment
  - Demonstrated a technique that varies the linear spectral properties of a single equilibrium
    - scans show extreme spectral sensitivity to halo location
      - convergence in this region is quite challenging
        (especially when $\rho_{Halo} \sim \rho_{qmn}$)
    - edge ballooning & kink effects can be "dialed in" by using a sharp resistivity transition region located at relevant flux positions
- Preliminary NL results show qualitatively needed resolution and expected energy growth rates for a single NL filament growth

Eigenfunctions have peeling-ballooning structure

- n=12 Halo-free mode structure, ballooning
- n=3 ρvac=0.751 mode structure, peeling-ballooning



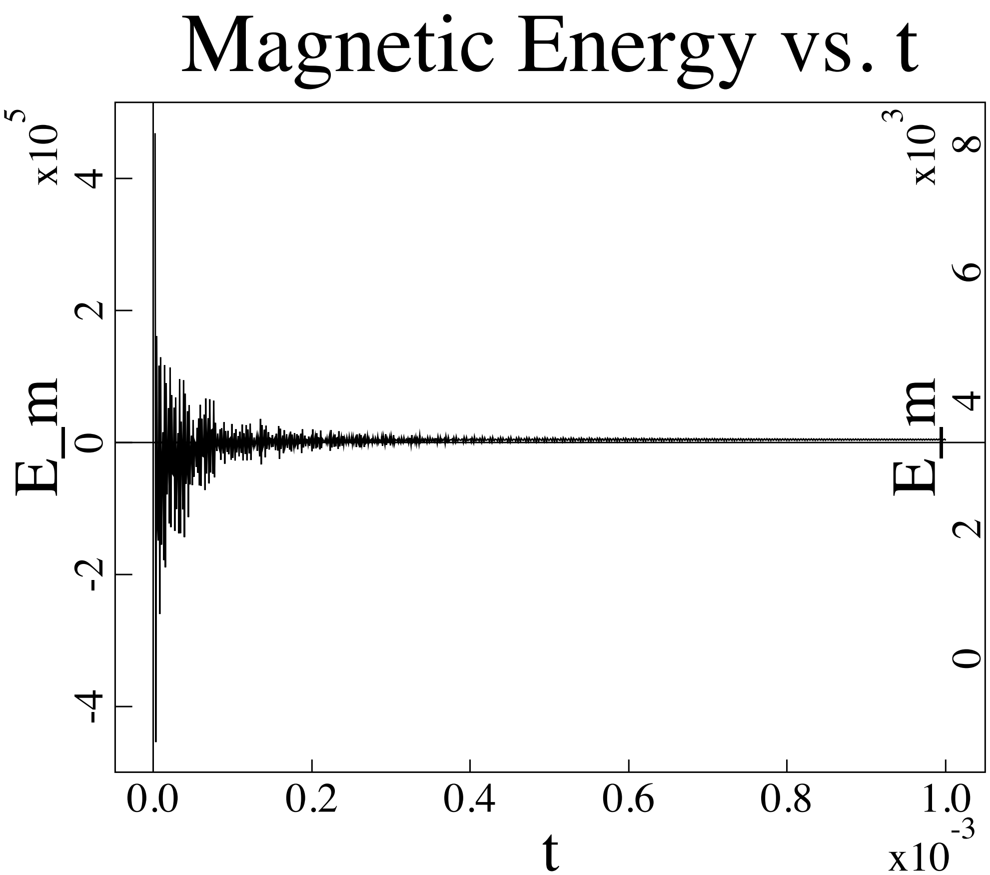


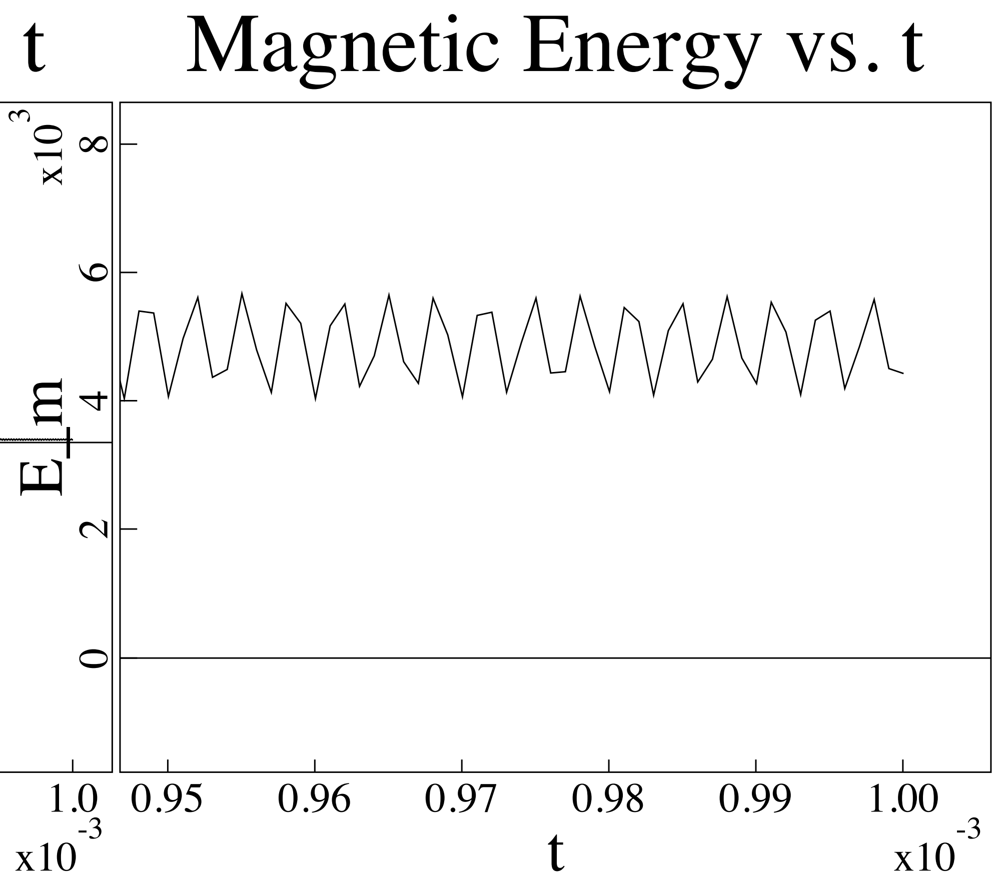
Preliminary NL runs in NIMROD

- In addition to the linear, began preliminary NL calculations in NIMROD
- Purely a demonstration of technique
  - not ideal S_{crit}: $S_{in} \sim 5*10^5$
  - not resistivity independent halo: $\eta_{out} \sim 10^{-2}$ (Ω•m)
    - *$S_{out} \sim 5*10^2$*
  - $\rho_{vac} = 0.84$
  - calculation grid points not packed
- Used to:
  - guide future studies
  - use results to design analysis tools
    - develop method to estimate transition between NL stages
    - determine growth regime to compare with analytic studies

Increasing S (constant) increases problem

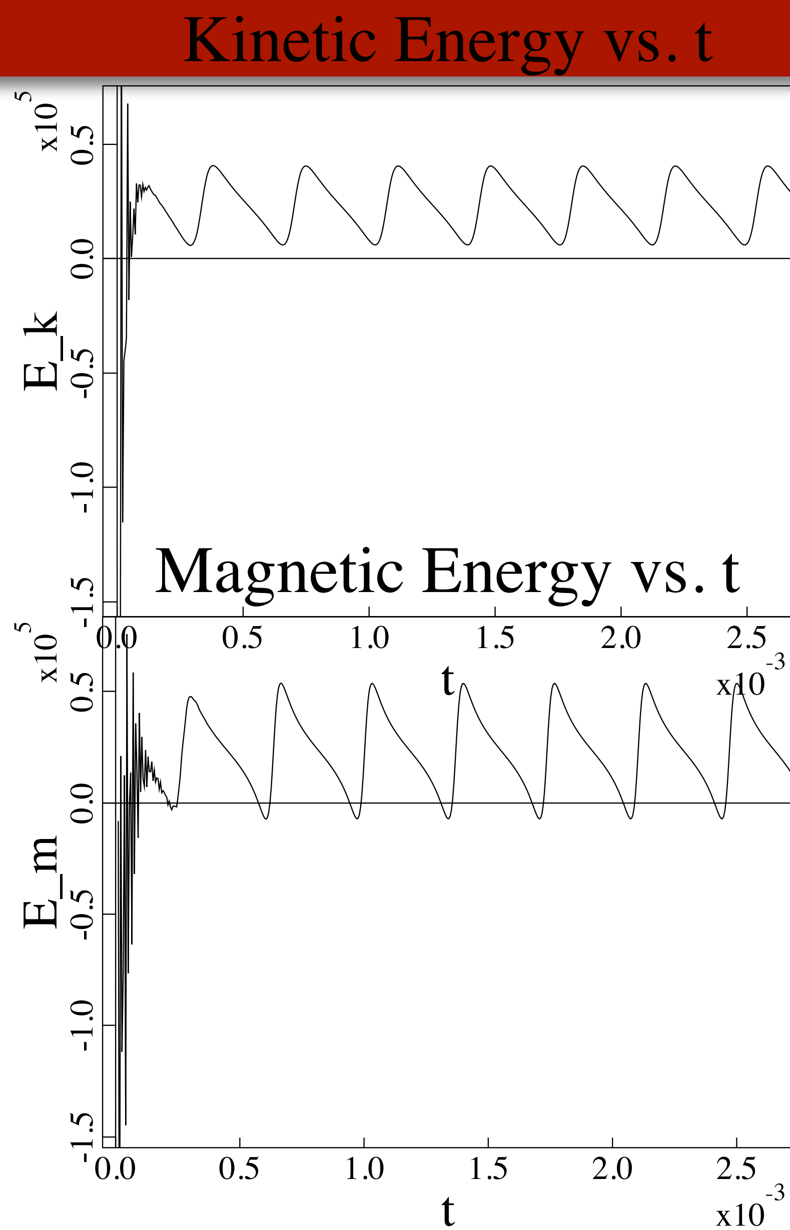
- For S = 10^6 the sawtoothing is seen up to n = 3 mode
- Not entirely sure if it is the exact same behavior
- Ping and Chris believe this is converged growth, I am not sure





Low-n modes have oscillatory behavior

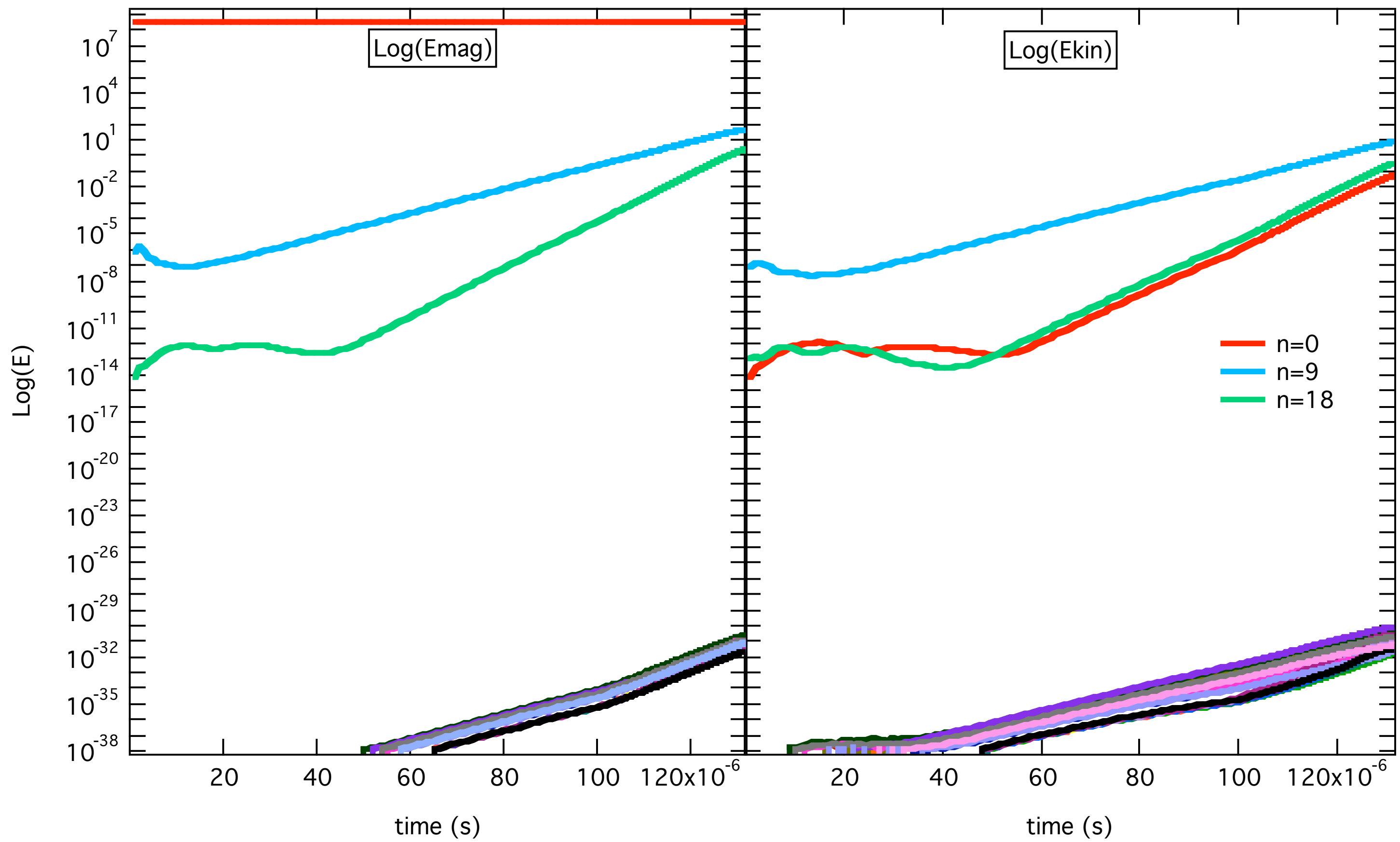
- Strange “saw-tooth-like” growth
  - occurs in low-n (stable?) modes
  - may be real physics
    - two modes (resistive & ideal) may simultaneously exist
    - Scott also saw this sawtoothing
    - perhaps nimrod bounces between two solutions
  - Moving the vacuum region out seems to eliminate the issue...
    - without a vacuum modes don’t grow
  - Modes appear to be rotating/ oscillating?



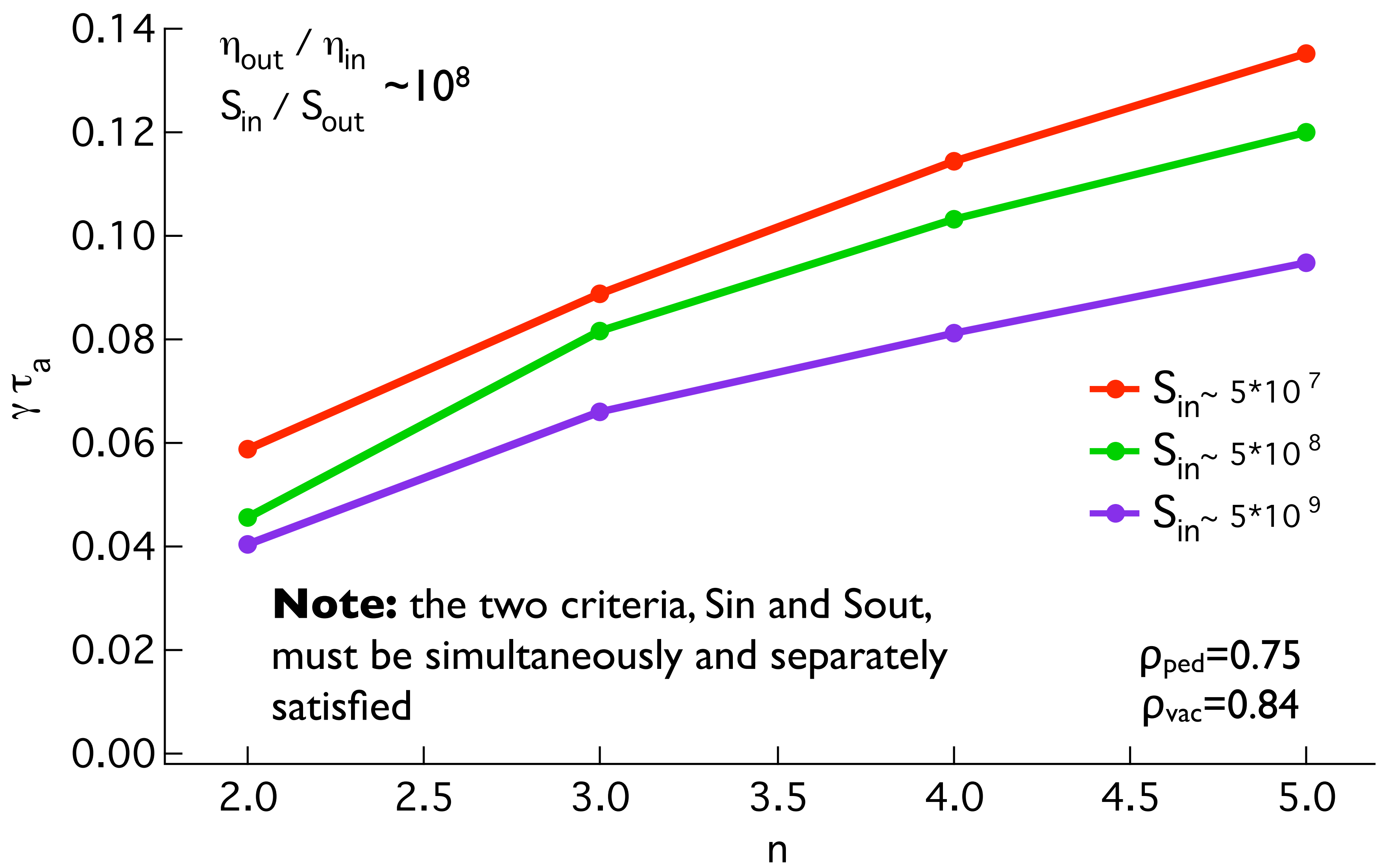
Linear n=9 eigenmode used to excite NL growth

- 22 modes included: n=0-21
- initialized with linear n=9

- nonlinear beating expected to produce n=0 & n=18 mode growth at twice linear n=9 rate



Lundquist/Resistivity ratio is not a good characterization parameter



Note: the two criteria, Sin and Sout, must be simultaneously and separately satisfied