

Progress Towards Analyzing the Dynamic Behavior of Peeling-Ballooning Modes in a Shifted-Circle Tokamak Equilibrium

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Edge Localized Modes (ELM's) limit H-mode plasmas

- Linear, ideal MHD (ELITE) successful in explaining some of the experimental ELM observations
 - ✦ ELM onset and growth has been linked to the coupling between ideal kink and ballooning modes (peeling-ballooning)
 - *more linear non-ideal analysis needed and may be useful*
 - ✦ Many unresolved questions require going beyond linear MHD
 - How type I ELMs relate to type 3 ELMs? How do RMP's stabilize ELM's? How does heat flux go to wall? How localized is the heat flux on the divertor? How does the linear stability correspond to the observed structures? (some filaments, some not, etc.) How does this scale to ITER?
- The extended MHD code NIMROD can expand the ideal studies
 - ✦ NIMROD can include:
 - diffusivities: resistivity, viscosity, thermal diffusivities
 - 2-fluid physics: Hall terms, gyroviscosity, electron stress tensor
 - closure physics: parallel heat flux, gyrokinetics



Two-step approach to nonlinear (NL) dynamics

- I) Comprehensive linear stability analysis of peeling-ballooning modes
 - Reproduce established linear ideal-MHD results (ELITE & GATO)
 - Ensures accurate physical representation in NIMROD
 - Perform linear ideal background scans
 - Isolate ideal & vacuum effects
 - Compare linear ideal and non-ideal behavior
 - Generate resolution requirements and initial mode structure for subsequent NL studies



Two-step approach to nonlinear (NL) dynamics

2) Phenomenological study of NL peeling-ballooning evolution

- Preliminary studies performed in **Final Report on the OFES ELM Milestone for FY2006**, *UW-CPTC 06-4*, www.cptc.wisc.edu
- Direct comparison to recent intermediate NL ballooning theory
(*P. Zhu, et al. **WI5.00003** Tues. 11:45am*)
- Develop analytic NL peeling-ballooning edge-specific theory, compare with NIMROD results
- Establish framework for representing the physics of peeling-ballooning modes in NL simulations



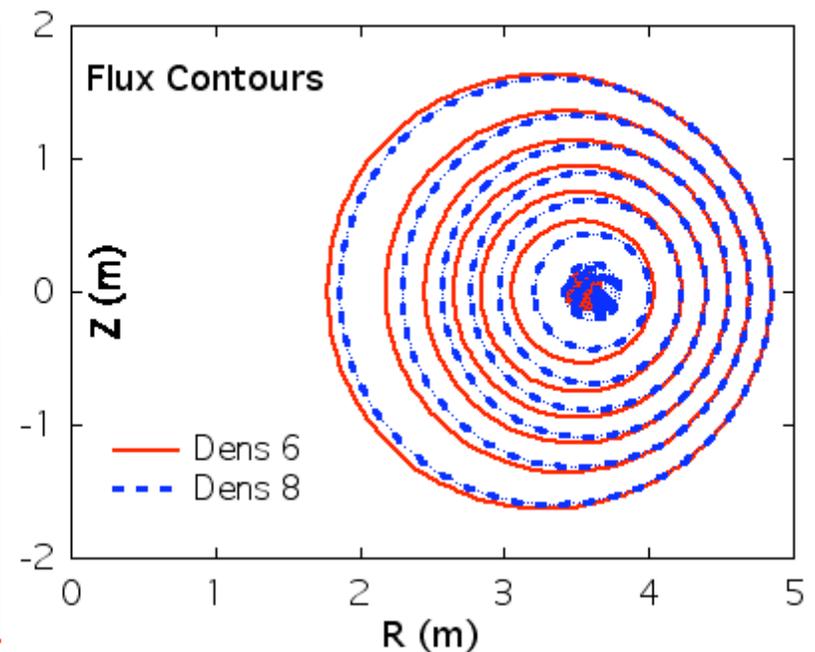
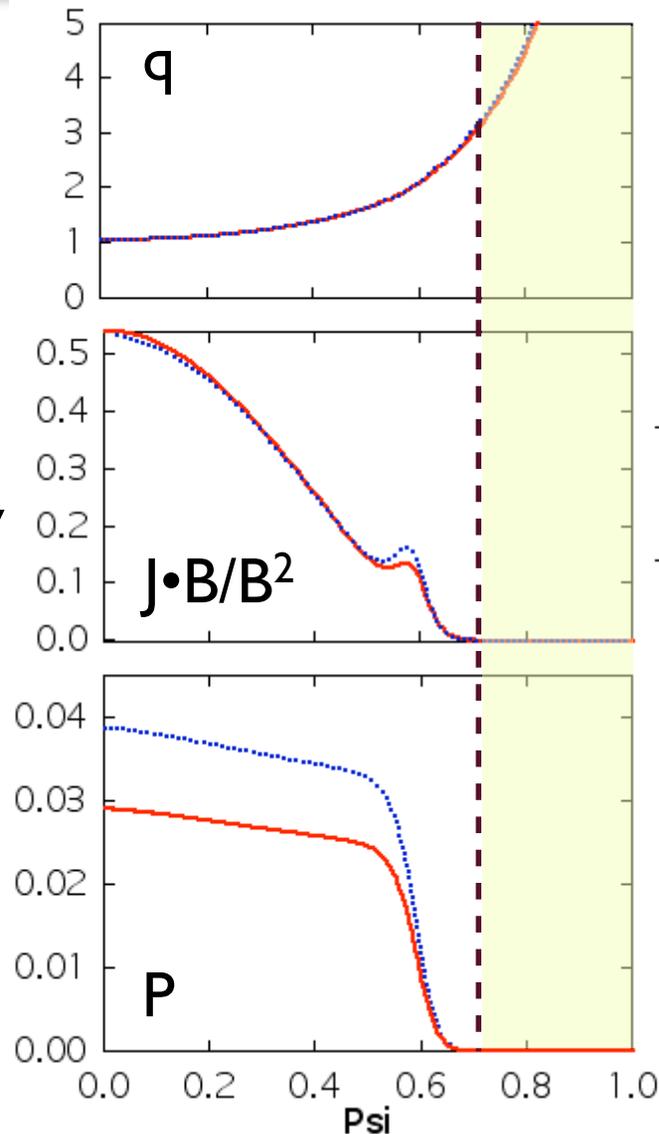
General Outline

- ELITE & GATO benchmarks with NIMROD
 - ✦ 2 ballooning-dominated equilibria
- “Ideal-like”/ “Halo” defined in NIMROD
- Peeling-Ballooning equilibrium examined as precursor to NL studies
 - ✦ equilibrium has both peeling and ballooning drives
- Technique developed to isolate ballooning and kink drives
- Preliminary nonlinear results guide future analysis
- Summary



Two ballooning unstable equilibrium generated by TOQ for benchmark

- Ballooning instability isolated for benchmark
- Equilibria scan across stability boundary
- ELITE: spectrum is weakly sensitive to vacuum location

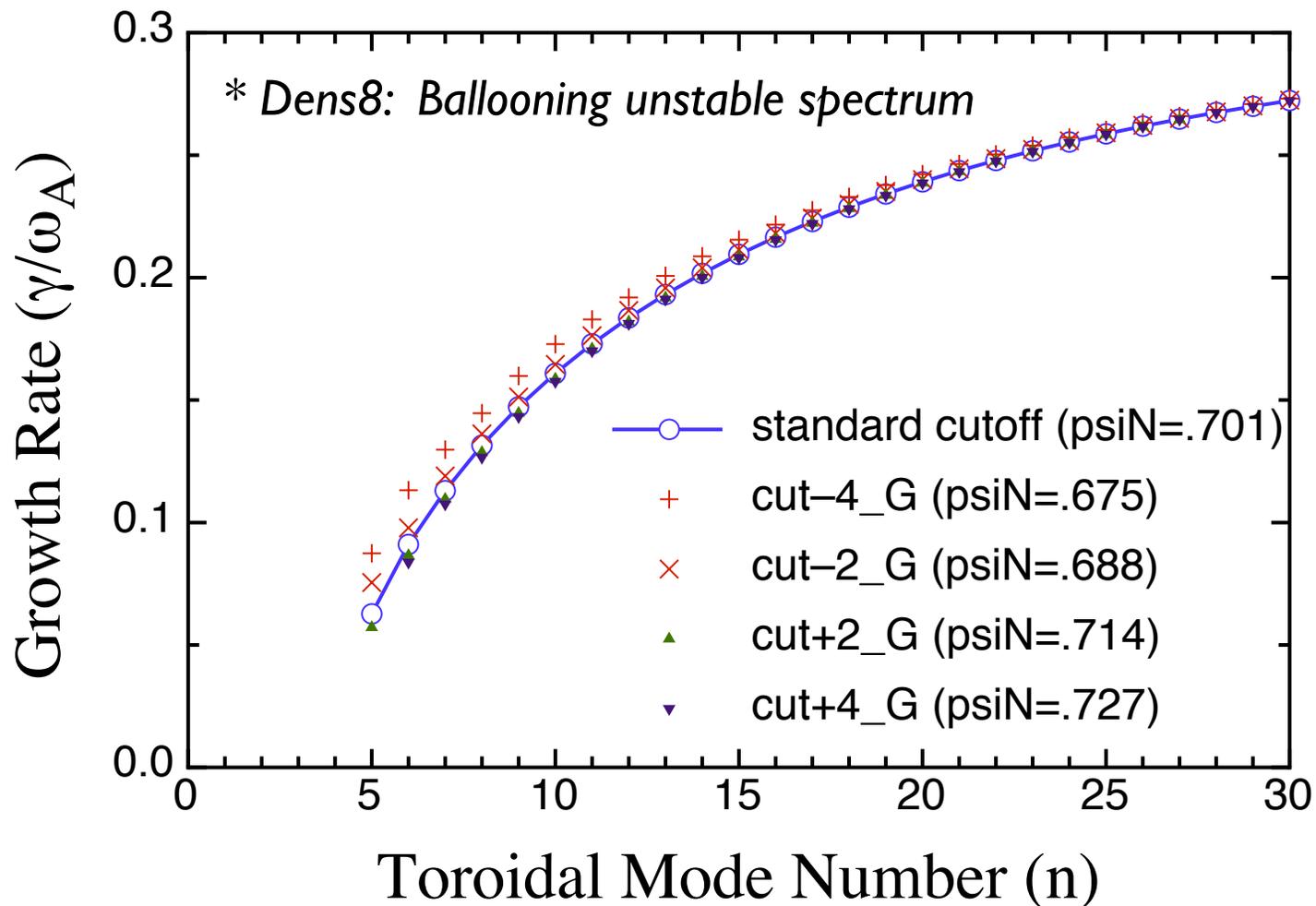


- shape = simple circle
- pedestal is wide
- vacuum interface at $\Psi_{IN} \sim 0.7$ (P' and $J_{||} = 0.0$)



Equilibria dominated by ballooning modes

- Low n modes marginally affected by vacuum location





The ideal limit must be carefully defined in the nonideal code NIMROD

Ideal values

* ELITE &
GATO

Vacuum

Halo
Vacuum-like

NIMROD

$$S=0$$

$$\eta = \infty$$

$$S=\text{Low}$$

$$\eta = \text{High}$$

Ideal
 $S=\infty$

Ideal-like
 $S=\text{High}$

$$\frac{e_{\text{vac}}}{e_{\text{plasma}}} = 0$$

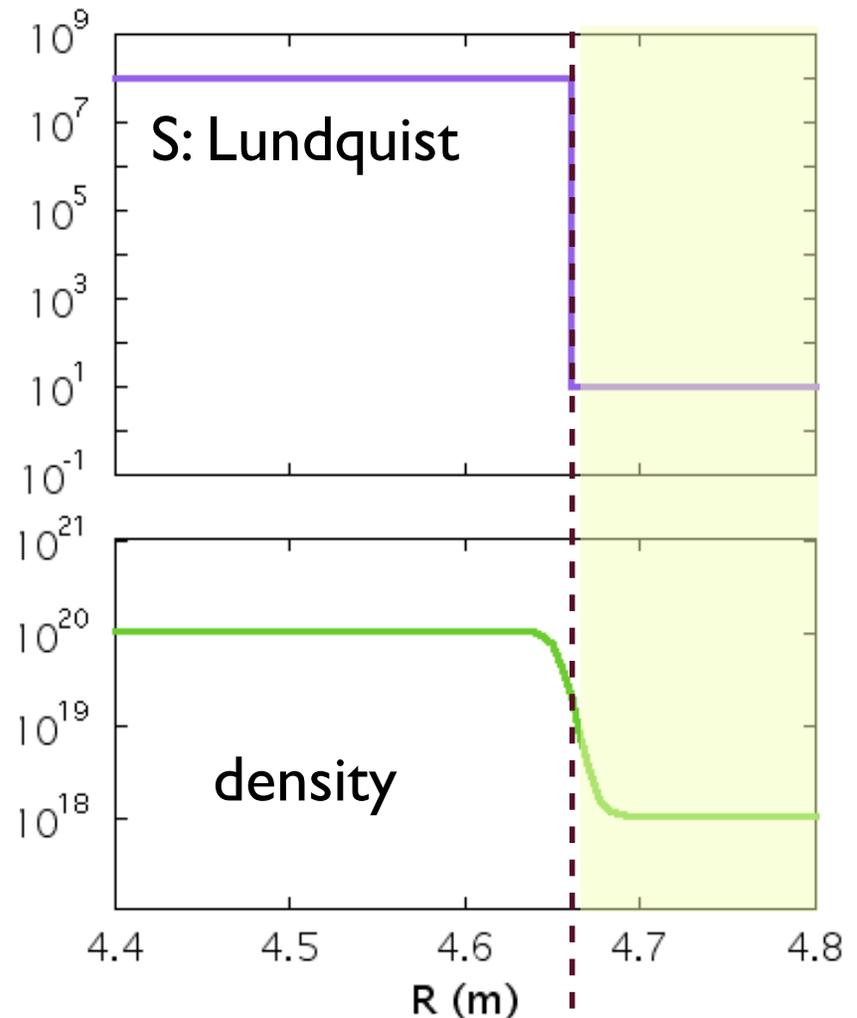
$$\frac{e_{\text{halo}}}{e_{\text{plasma}}} = 0.01$$

conducting wall



Halo region defined with an imposed resistivity and density transition

- η transitions from low, “ideal” to a large value at a specified ρ_{Halo}
 - ✦ Step-like, sharp transition
 - ✦ Eliminates transition overlap in pedestal region
- Density decreased by a factor of 100, at a specified ρ_{dens}
 - ✦ Tanh function used, sharp transition not possible
- ρ_{Halo} & ρ_{dens} are placed at the same location
 - ✦ Chosen to exactly match vacuum location of ELITE & GATO
 - ✦ $R \approx 4.66\text{m}$

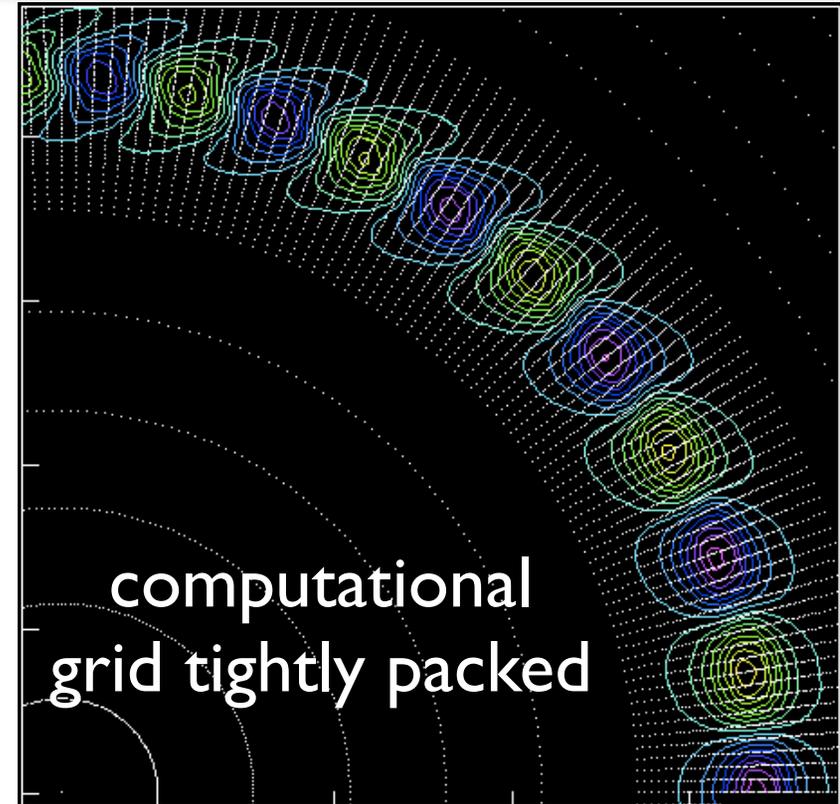
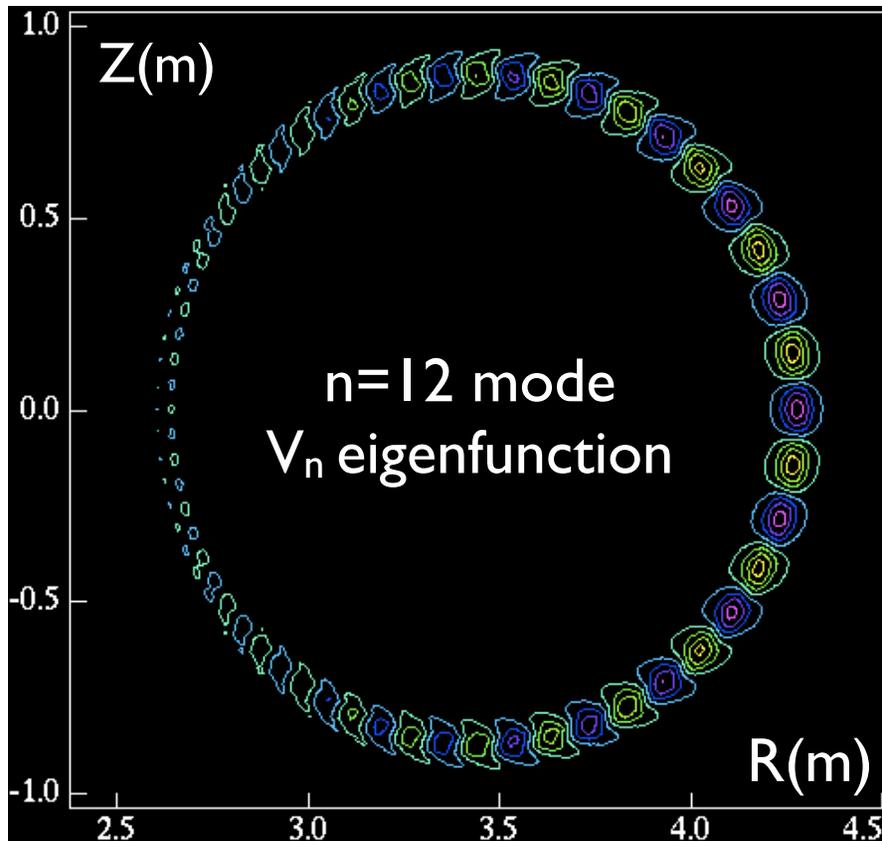


*ELITE vacuum location



Quantifying “Ideal” in NIMROD requires high spatial resolution

- Start with purely ideal case
 - ✦ $S = \infty$ everywhere
 - *no halo region*

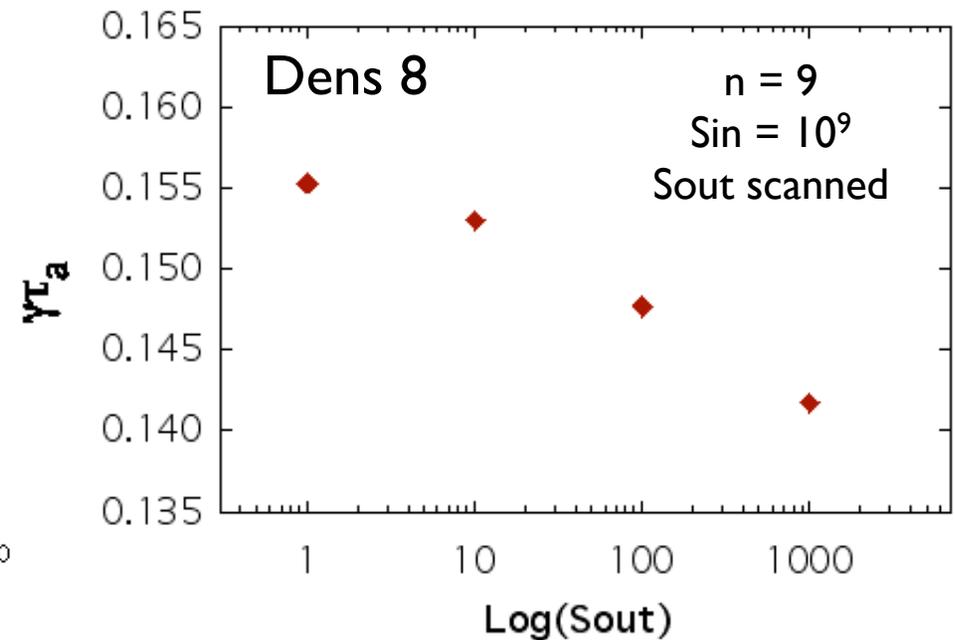
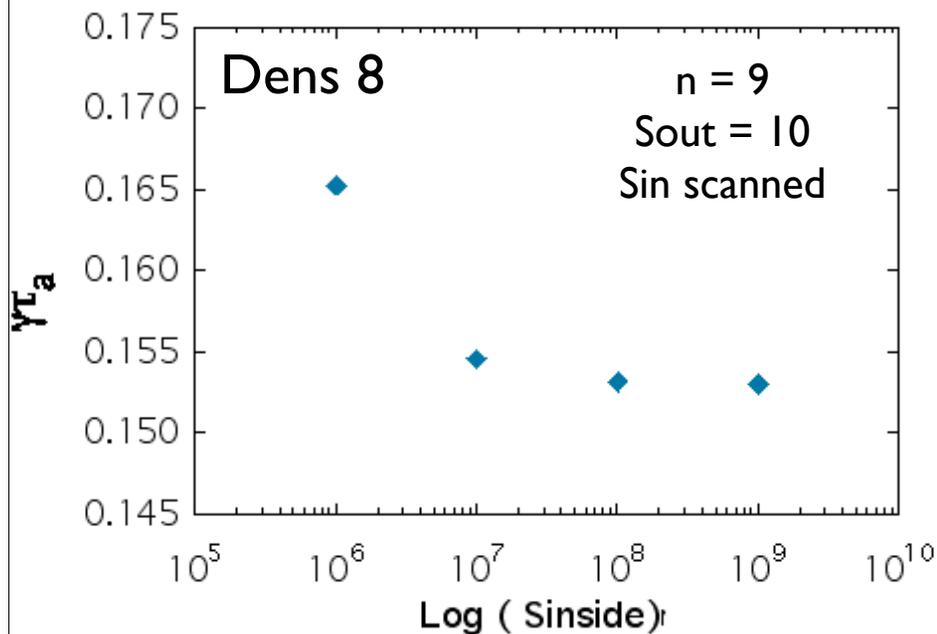


- ✦ linear ideal MHD, $n = 12$
- ✦ no dissipation in system
- ✦ $k_{\text{visc}}, k_{\text{perp}} = 0$



Lundquist scans identify the ideal and halo parameters

- Equilibrium specific: Dens6 and Dens8
 - ✦ critical ideal-like and halo Lundquist values are determined

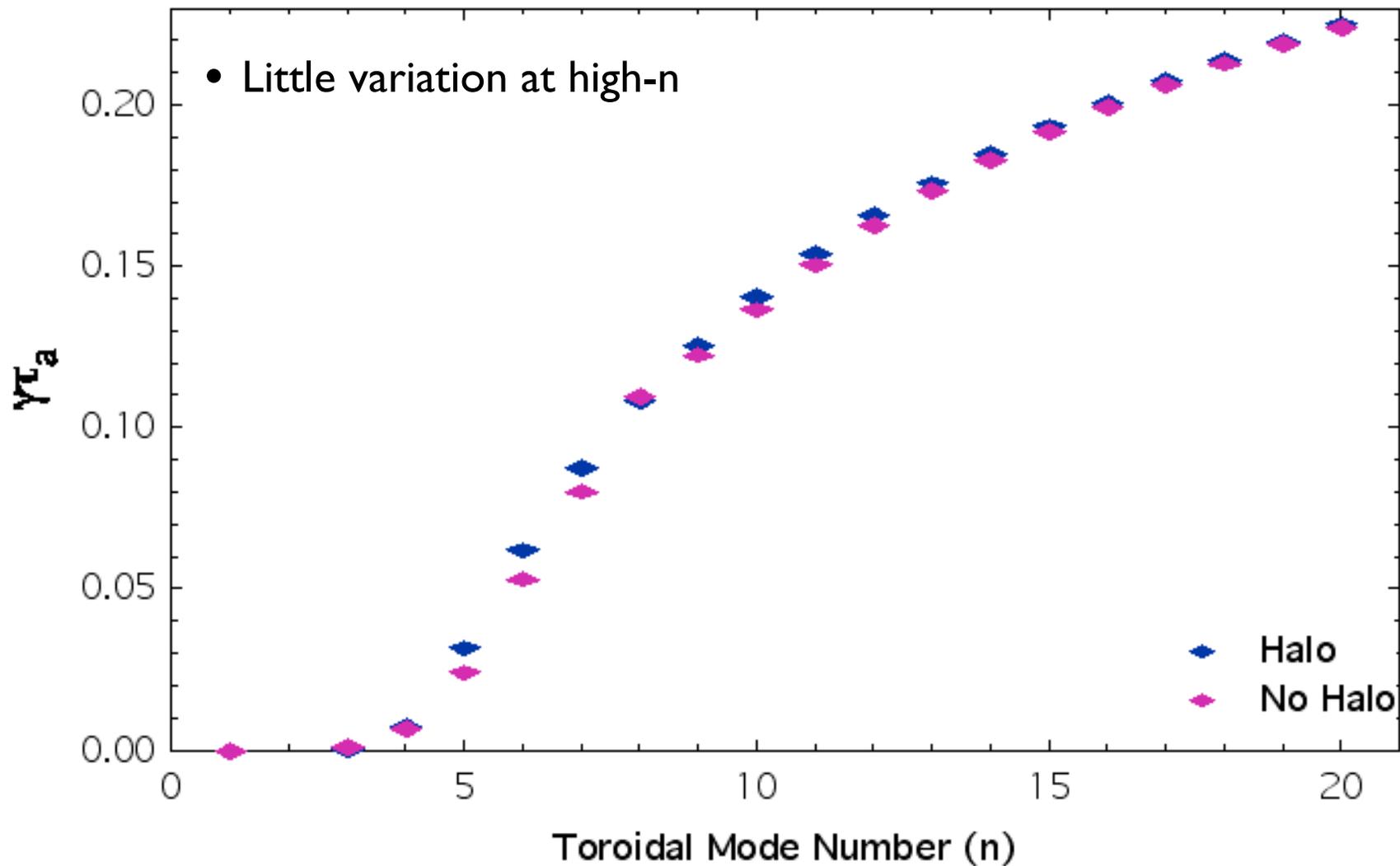


- For both equilibriums these Lundquist values are: $S_{in} \sim 10^8$ & $S_{out} \sim 10$,



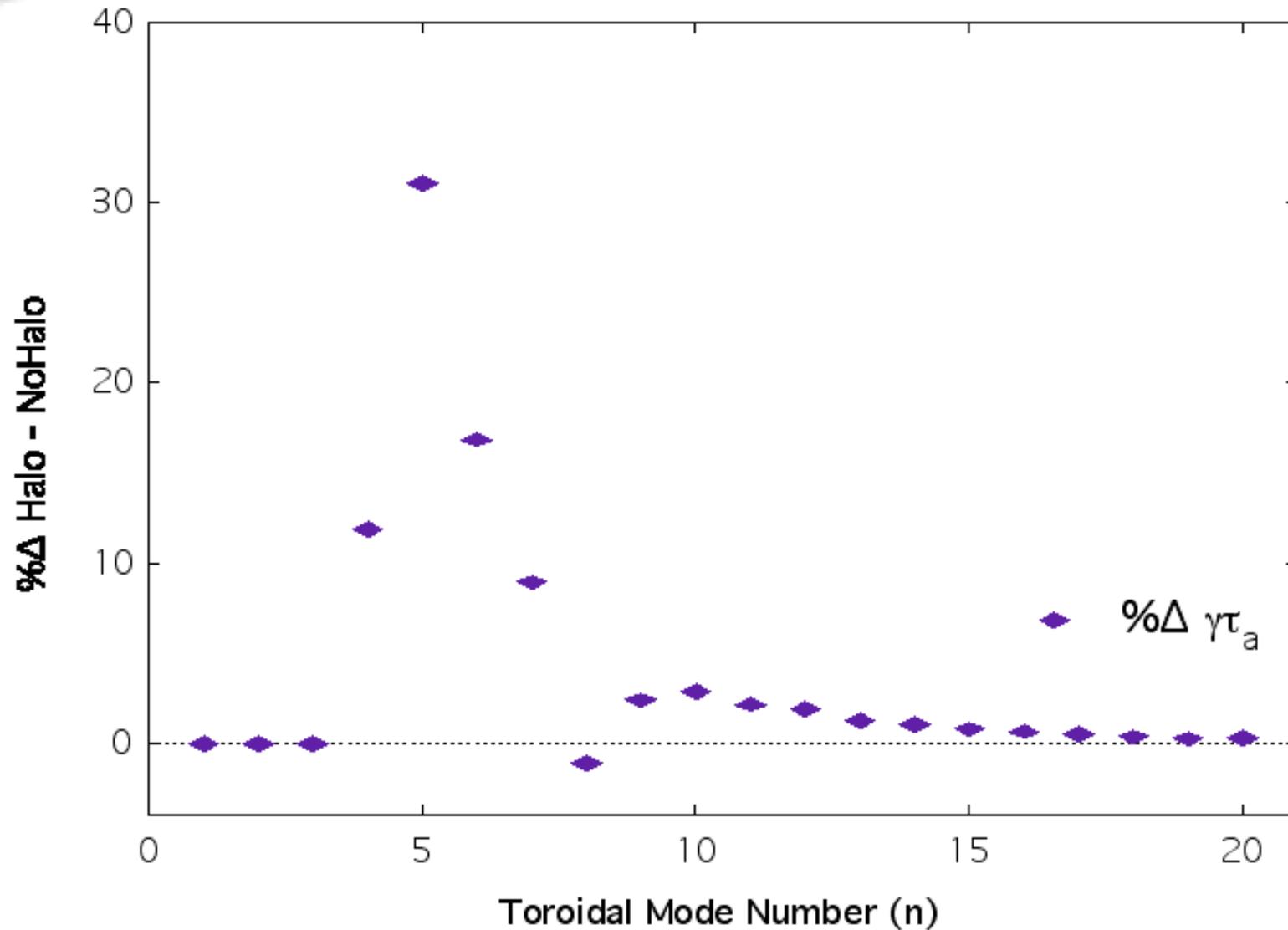
Background halo-free spectrum shows extent of vacuum influence

Dens8





Largest variation occurs at low n

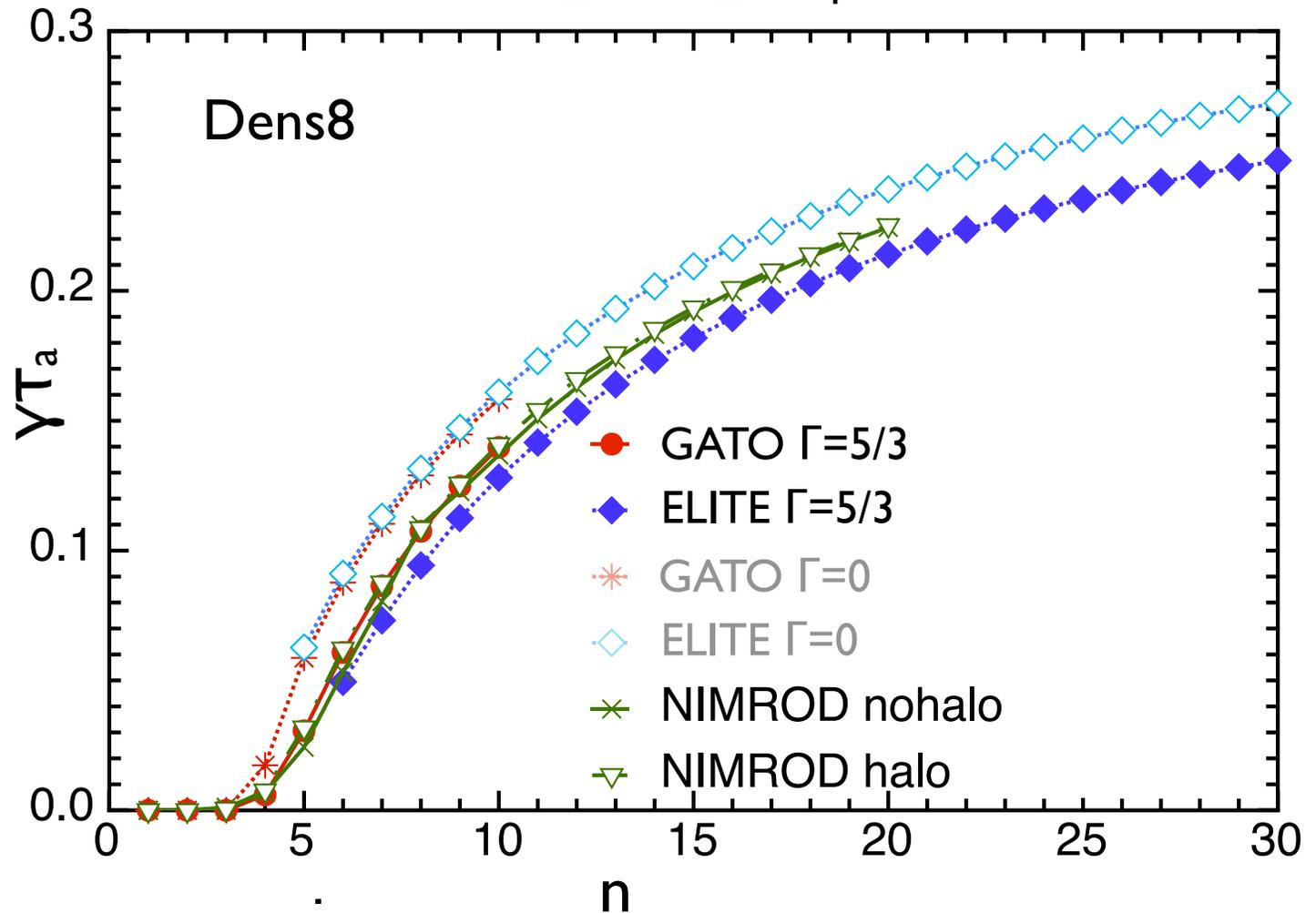




NIMROD obtains excellent agreement with GATO and ELITE

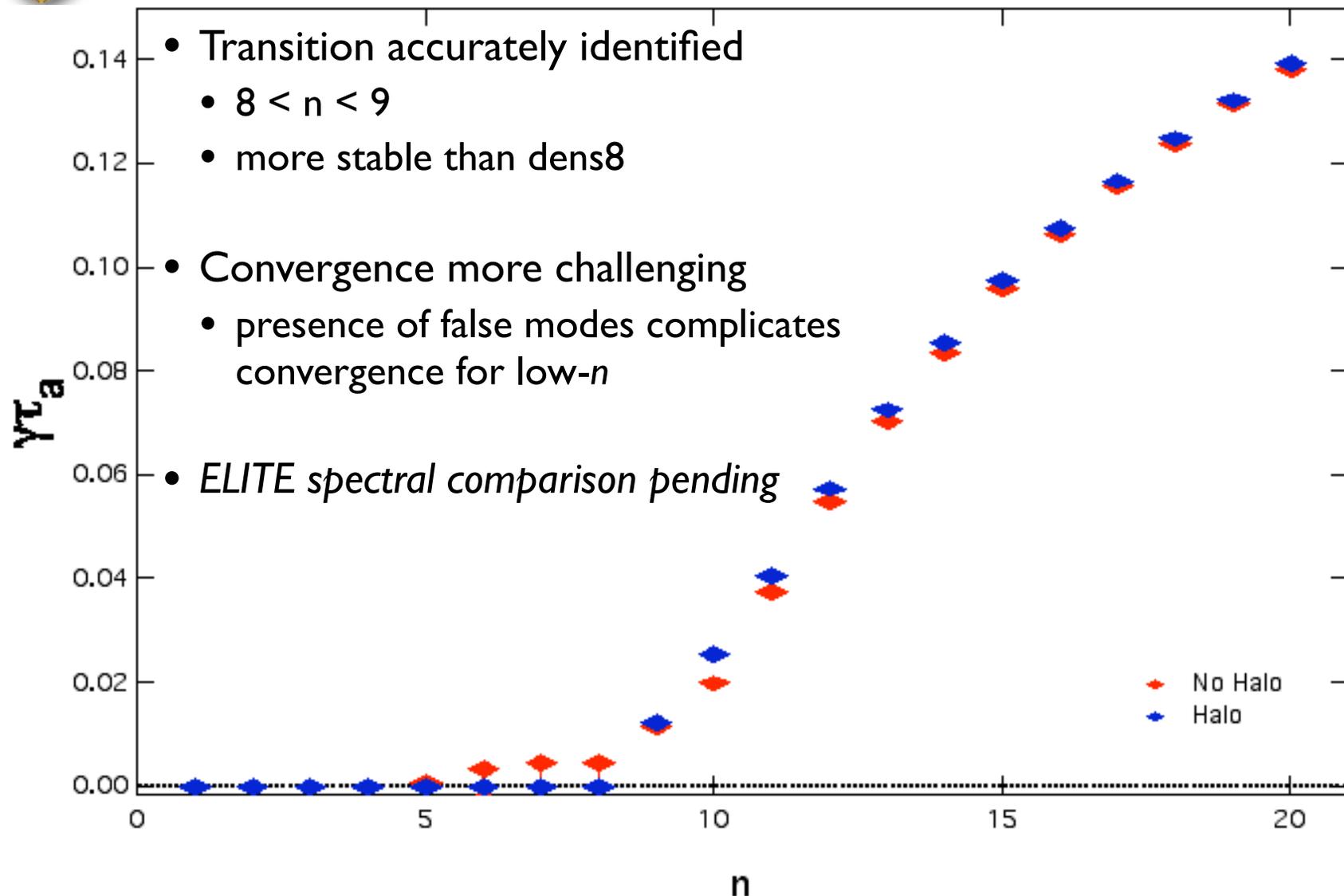
cbm18_dens8_comp.data

- Transition to instability accurately identified
 - ✦ $3 < n < 4$
- Toroidal mode spectrum reproduced
 - ✦ Exact match with GATO





Dens 6 spectrum complete & stability threshold identified





New equilibrium allows the study of peeling & ballooning mode drives

TOQ-generated shifted-circle tokamak equilibrium

~S. Kruger & P. Snyder

$$R_o = 3\text{m}, a = 1\text{m}$$

$$\mathbf{B}_o = 2\text{T}$$

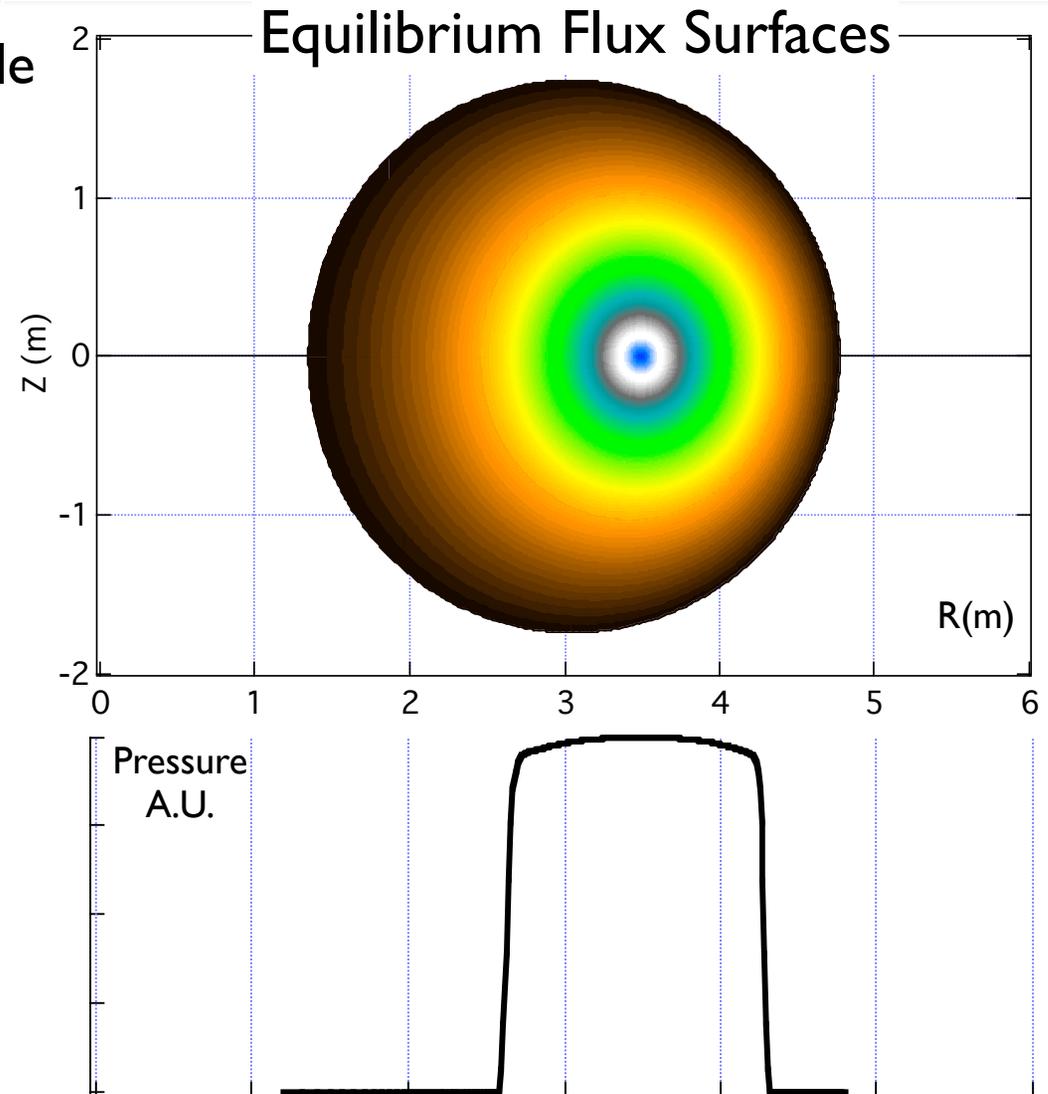
$$\beta_{to} = .005$$

$$n = 1.06 \times 10^{20} (\text{m}^{-3})$$

- no density transition

- Modified TOQ

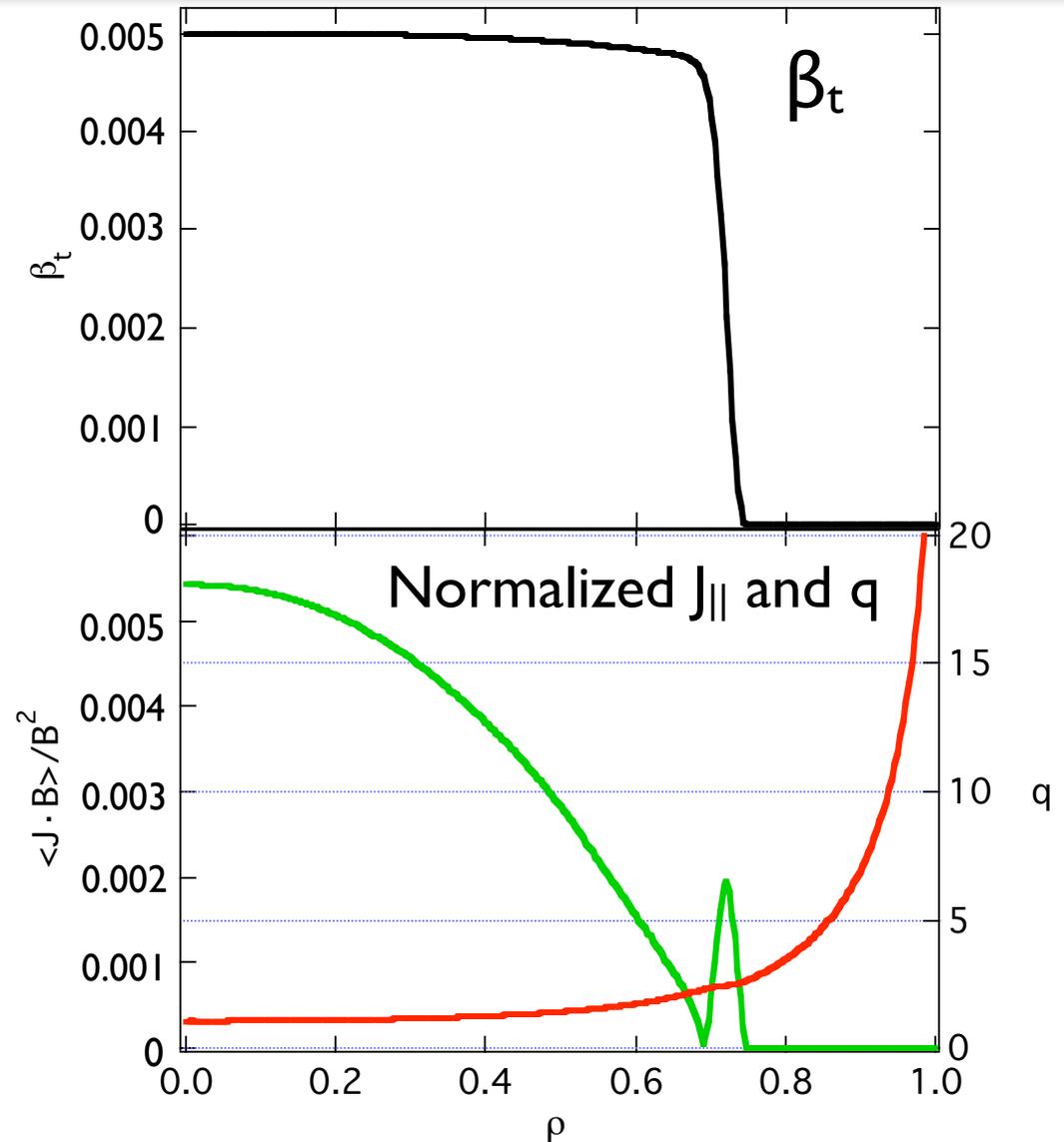
- ✦ currents in edge set to 0
- ✦ minimizes numerical errors (no separatrix)
- ✦ pedestal region
- ✦ ~67-75cm on midplane





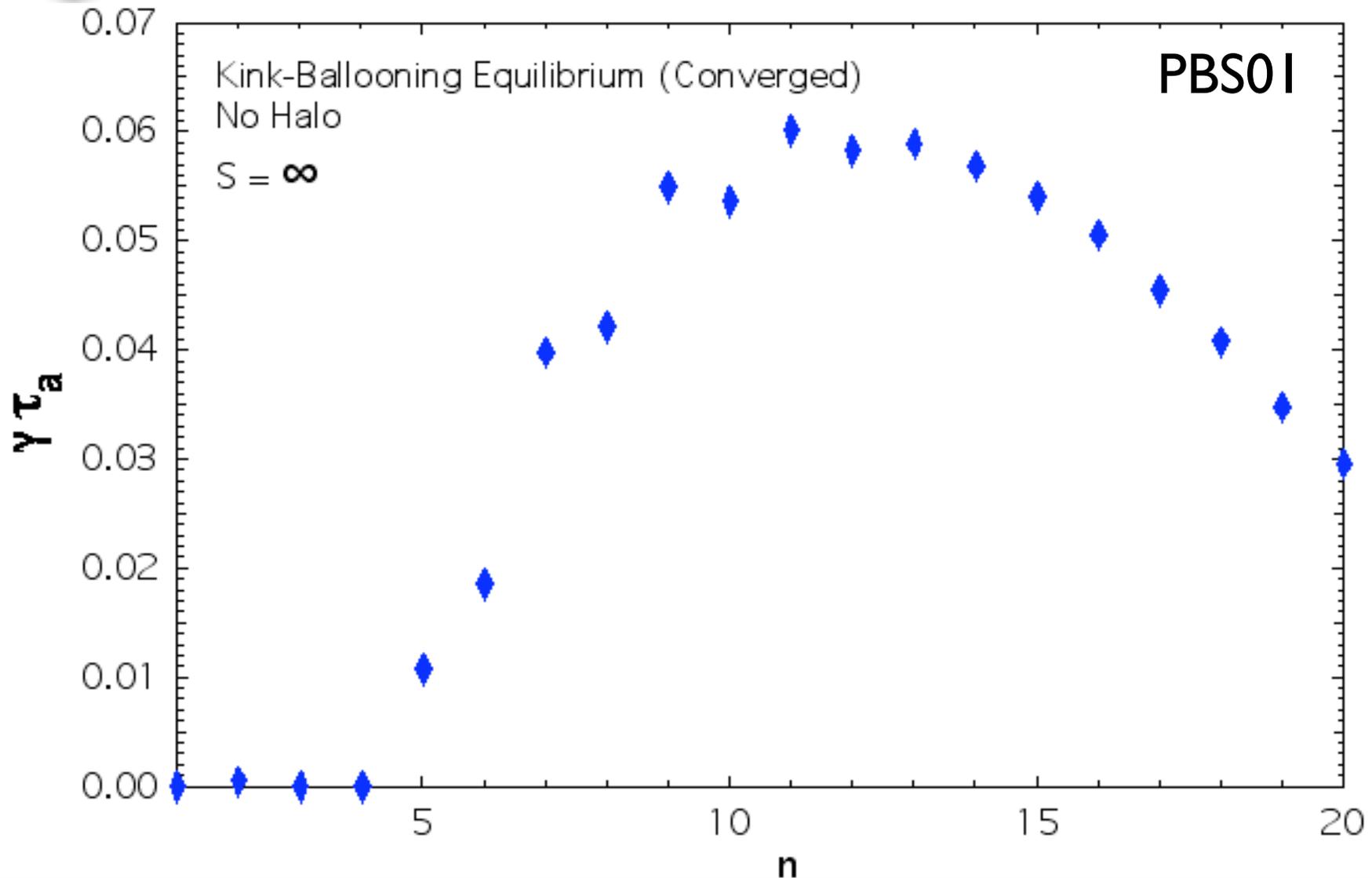
Equilibrium profiles show peeling-ballooning instability drive source

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





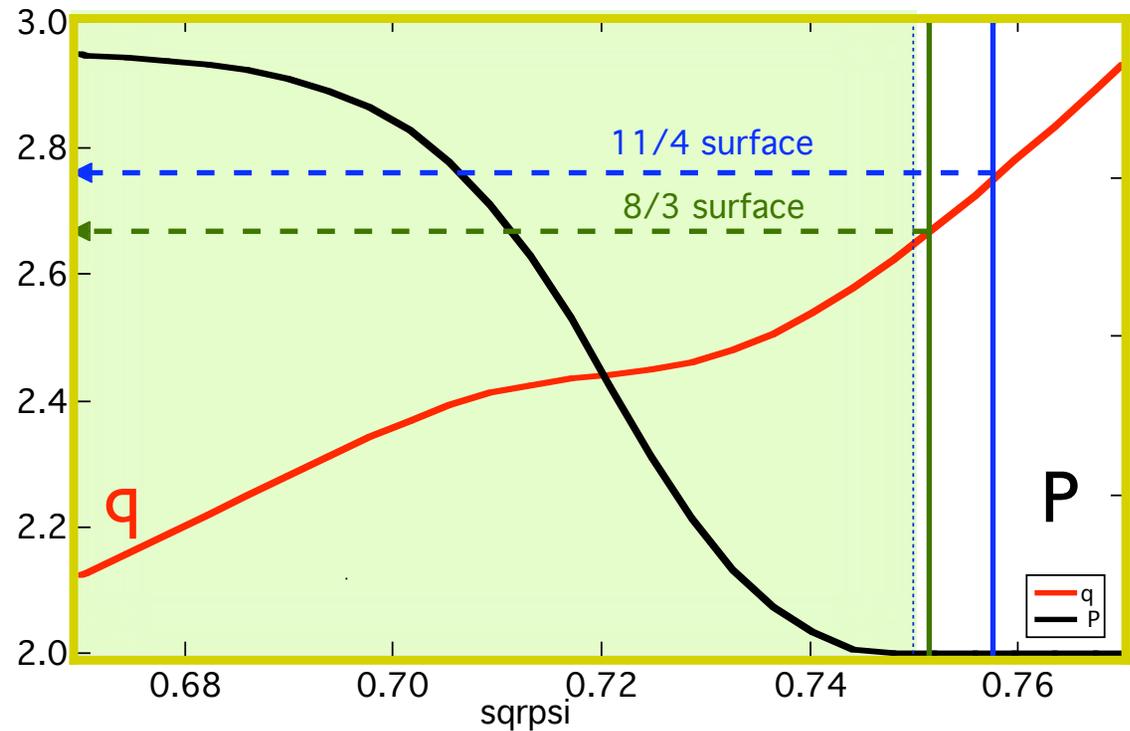
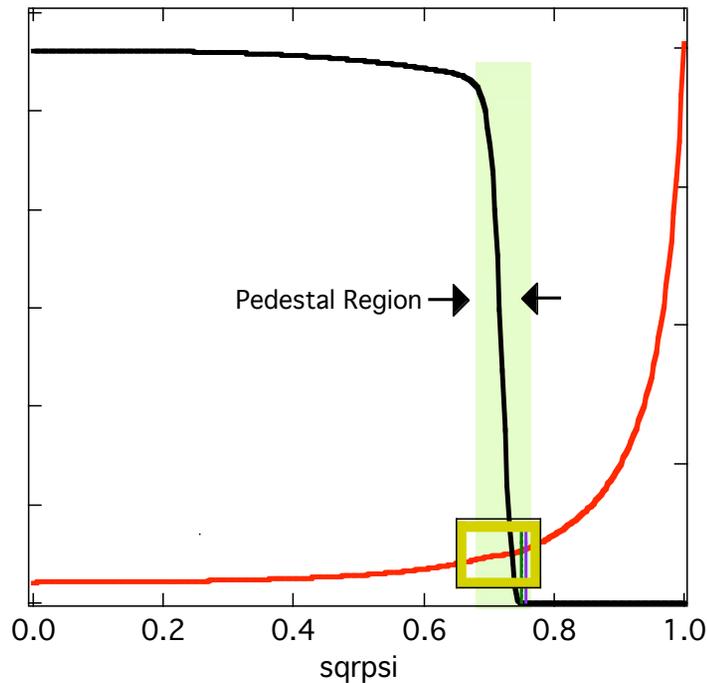
Ideal background spectrum completed (no halo)





Halo location relative to the q rational surfaces affects instability drives

- using q profile identify mode rational surfaces

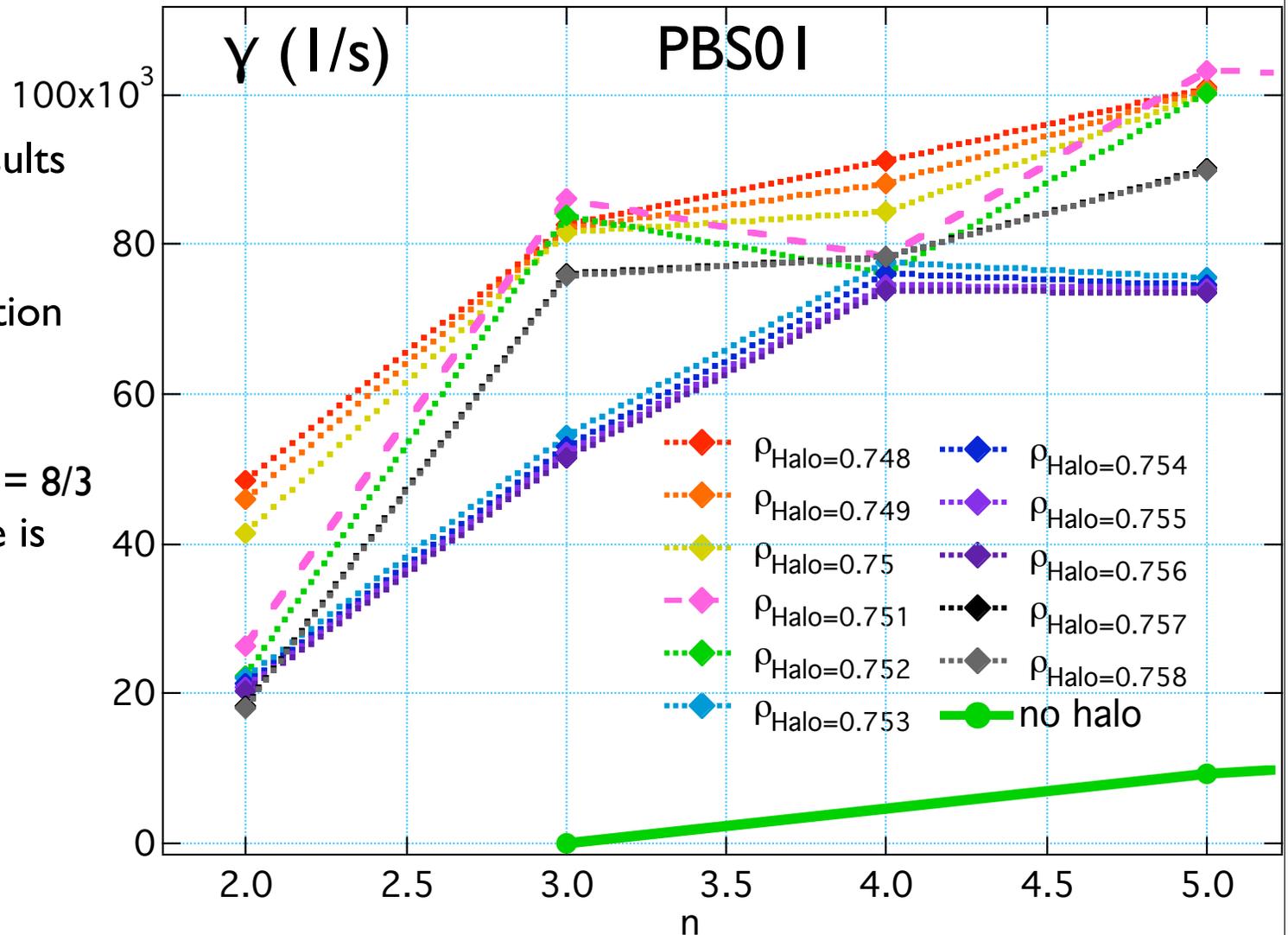


- adjusting the halo location “dials in” kink, ballooning, & peeling-ballooning behavior



Preliminary scans show low-n modes are sensitive to halo location

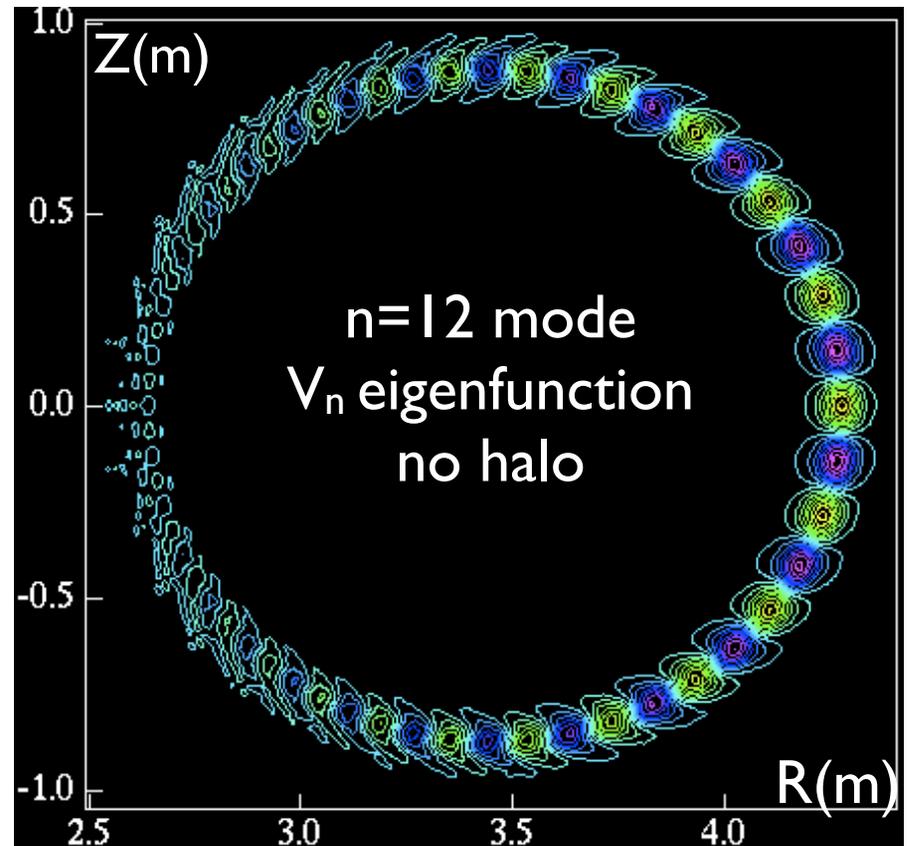
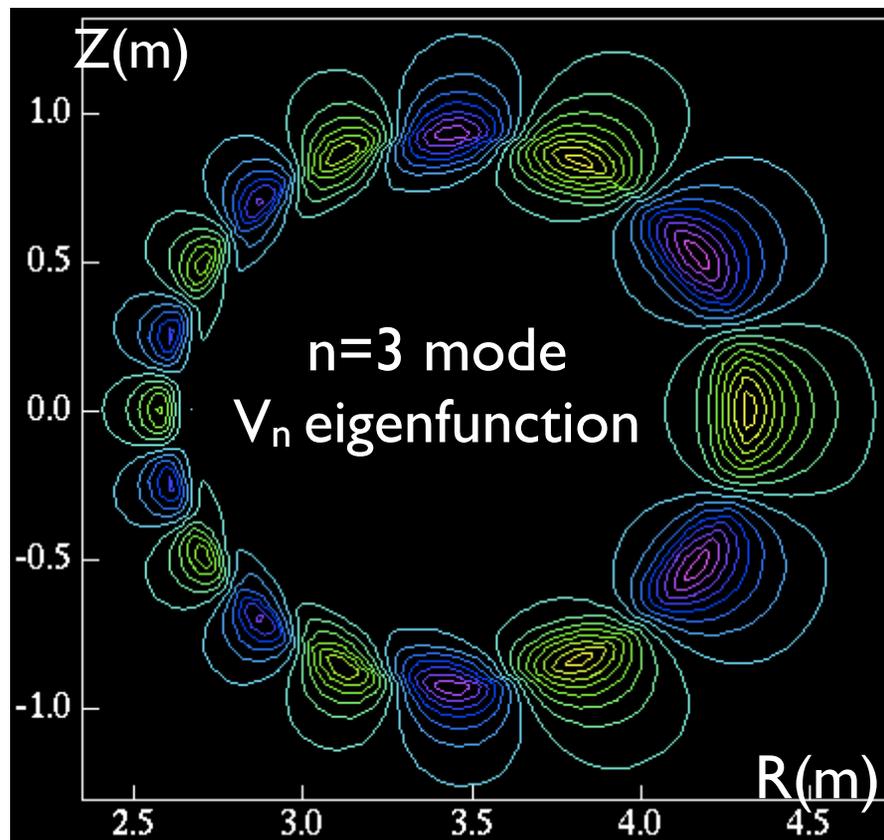
- Preliminary... results found prior to established halo transition definition
- When $\rho_{ped} < \rho_{Halo} < \rho_{rat} = 8/3$ $n = 3$ kink mode is driven
- convergence challenging





Eigenfunctions have peeling-ballooning structure

- $n=12$ Halo-free mode structure, ballooning
- $n=3$ $\rho_{vac}=0.751$ mode structure, peeling-ballooning





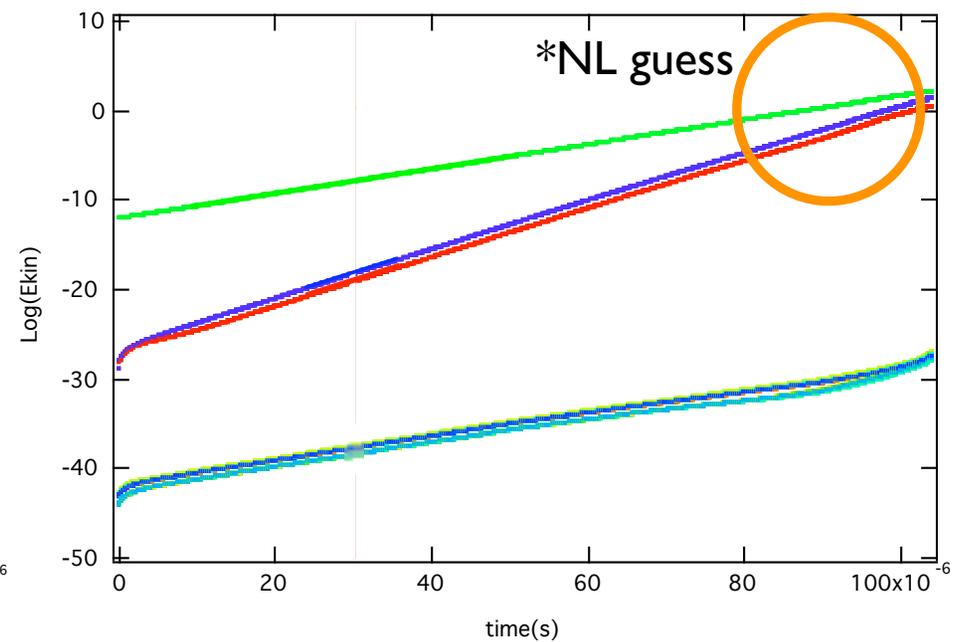
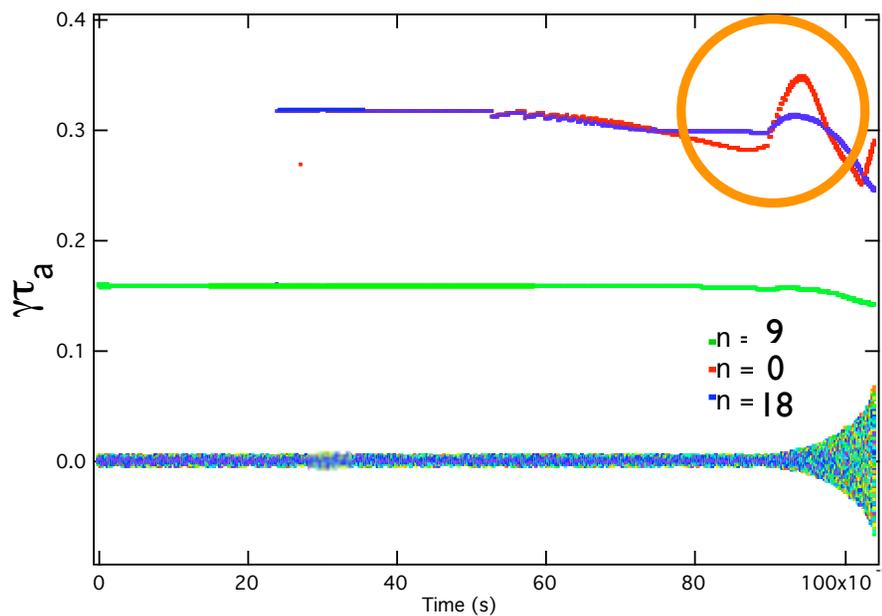
Preliminary NL calculations in NIMROD

- In addition to the linear, began preliminary NL calculations in NIMROD
- Ballooning-dominated, Dens8 equilibrium
- Purely a demonstration of technique
 - ✦ Minimal dissipation
 - ✦ $X_{||} \sim X_{\perp} \sim 10^{-2}$
 - ✦ $v \sim 10^{-3}$
 - ✦ $S = 10^8$
- Used to:
 - ✦ guide future studies
 - ✦ use results to design analysis tools
 - develop method to estimate transition between NL stages (*ongoing P.Zhu*)
 - determine growth regime to compare with analytic studies



Nonlinear calculations of $n = 9$ duration $\sim 100\tau_A$

- 22 modes included: $n=0-21$, initialized with linear $n=9$ mode
- nonlinear $n=9$ & $n=18$ mode growth at twice linear $n=9$ rate expected
- The transition to nonlinear dynamics is expected when $\frac{\xi}{\Delta x} \sim O(1)$





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
 - Equilibrium specific
 - * Peeling Ballooning: $S_{\text{crit-ideal}} \sim 5 * 10^7$; $S_{\text{crit-halo}} \sim 0.5$
 - * Dens6 & 8: $S_{\text{crit-ideal}} \sim 10^8$; $S_{\text{crit-halo}} \sim 10$
 - 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 $\rho_{\text{Halo}} \sim \rho_{\text{qmn}}$)*
 - edge kink effects can be “dialed in” by using a sharp resistivity transition region located at relevant flux positions



Summary

- Preliminary NL results show qualitatively needed resolution and expected energy growth rates for a single NL filament growth
 - ✦ promising for future analysis
 - compare with current NL ballooning theory
 - * (*P. Zhu and C.C. Hegna, Phys. Plasmas 15, 092306 (2008)*)
 - compare and contrast nonlinear peeling vs ballooning components
 - extend analytic modeling of nonlinear peeling-ballooning modes to be compared with calculated results
- Additionally, currently working on background linear scans for experimentally relevant parameters
 - $\eta = \eta_{sp}$
 - $T \sim 900\text{eV (core)} \sim 40\text{eV (edge)}$
 - n decreases by factor of 4 - 10