Mapping Alcator C-Mod's EDA H-Mode Stability Boundaries with BOUT++

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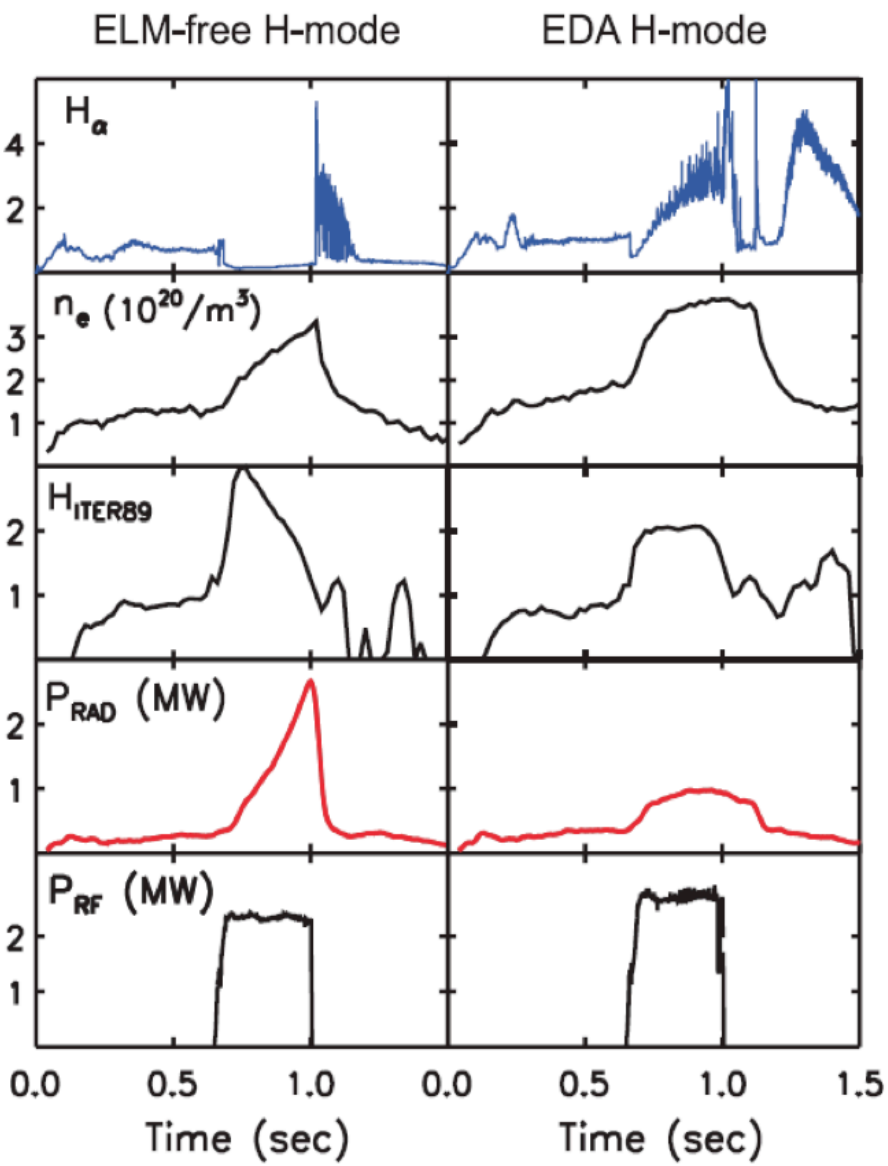
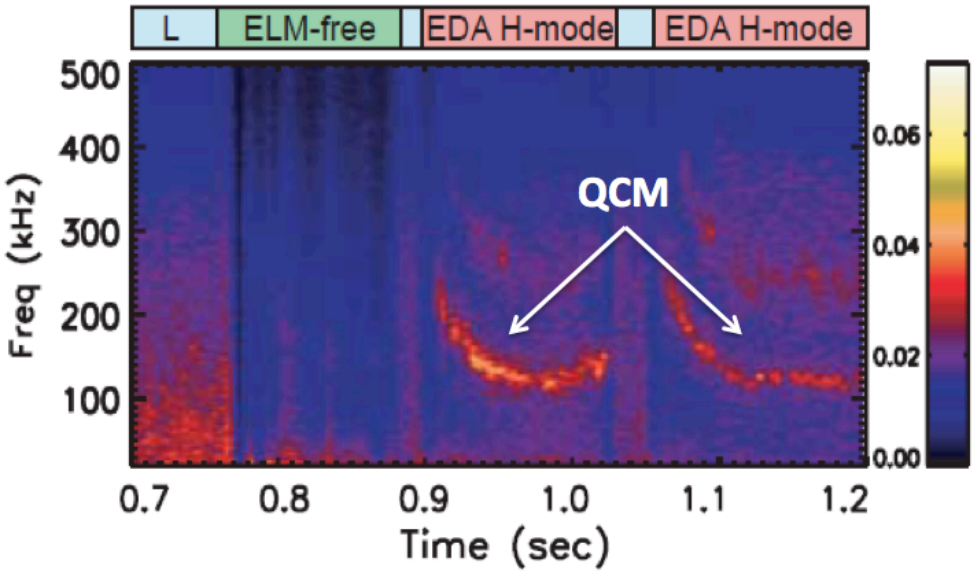
Outline

- Motivation
  - Enhanced D_α (EDA) H-Mode
  - Peeling-Ballooning (PB) modes
- BOUT++ framework and capabilities
- BOUT++ computed linear stability boundaries
  - Ideal
  - Diamagnetic (FLR) effects
  - Resistivity
- Initial nonlinear simulations
- Conclusions and future work

Motivation

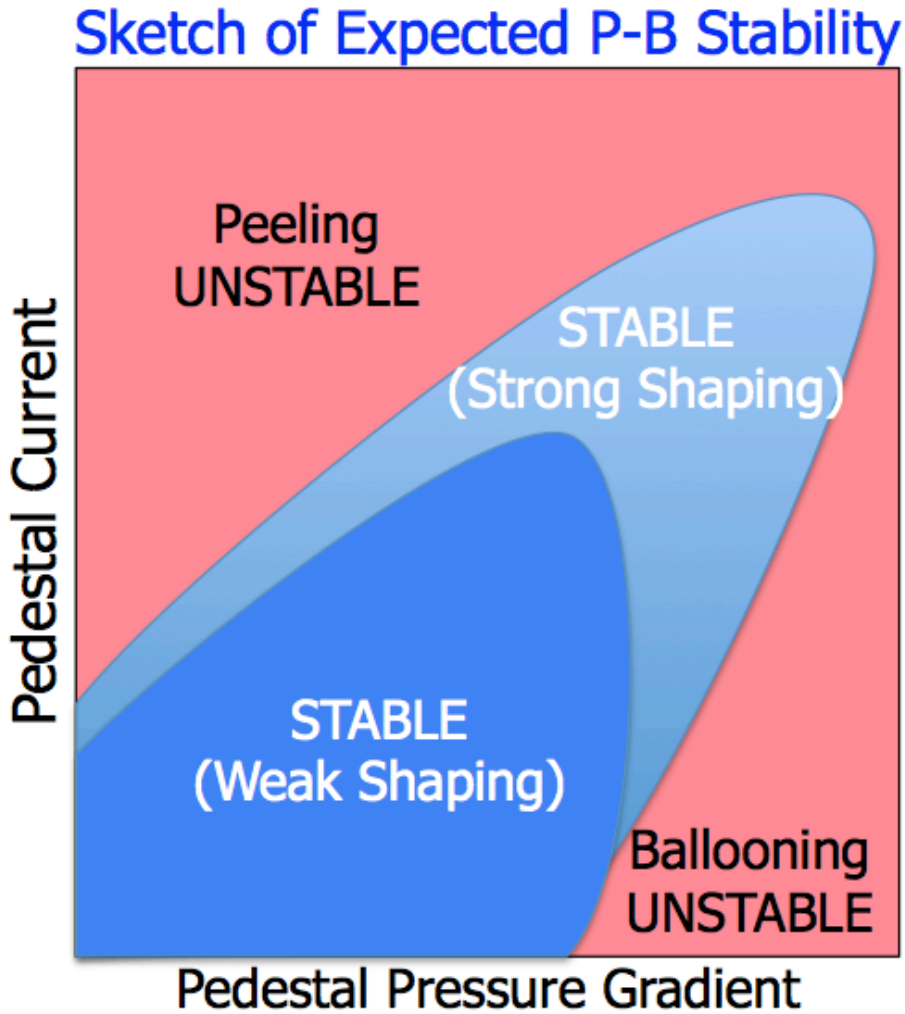


- The Enhanced D_α (EDA) H-mode[1,2] exhibits:
  - Excellent energy confinement
  - Reduced impurity confinement
- EDA pedestal regulated by a quasi-coherent mode (QCM) oscillation ~100 kHz
- $\nu^* > 1$



[1]M. Greenwald et al. *Phys. Plasmas* **6** 1943 (1999).
[2]A. Mazurenko et al. *Phys. Rev. Lett.* **89** 225004 (2002).

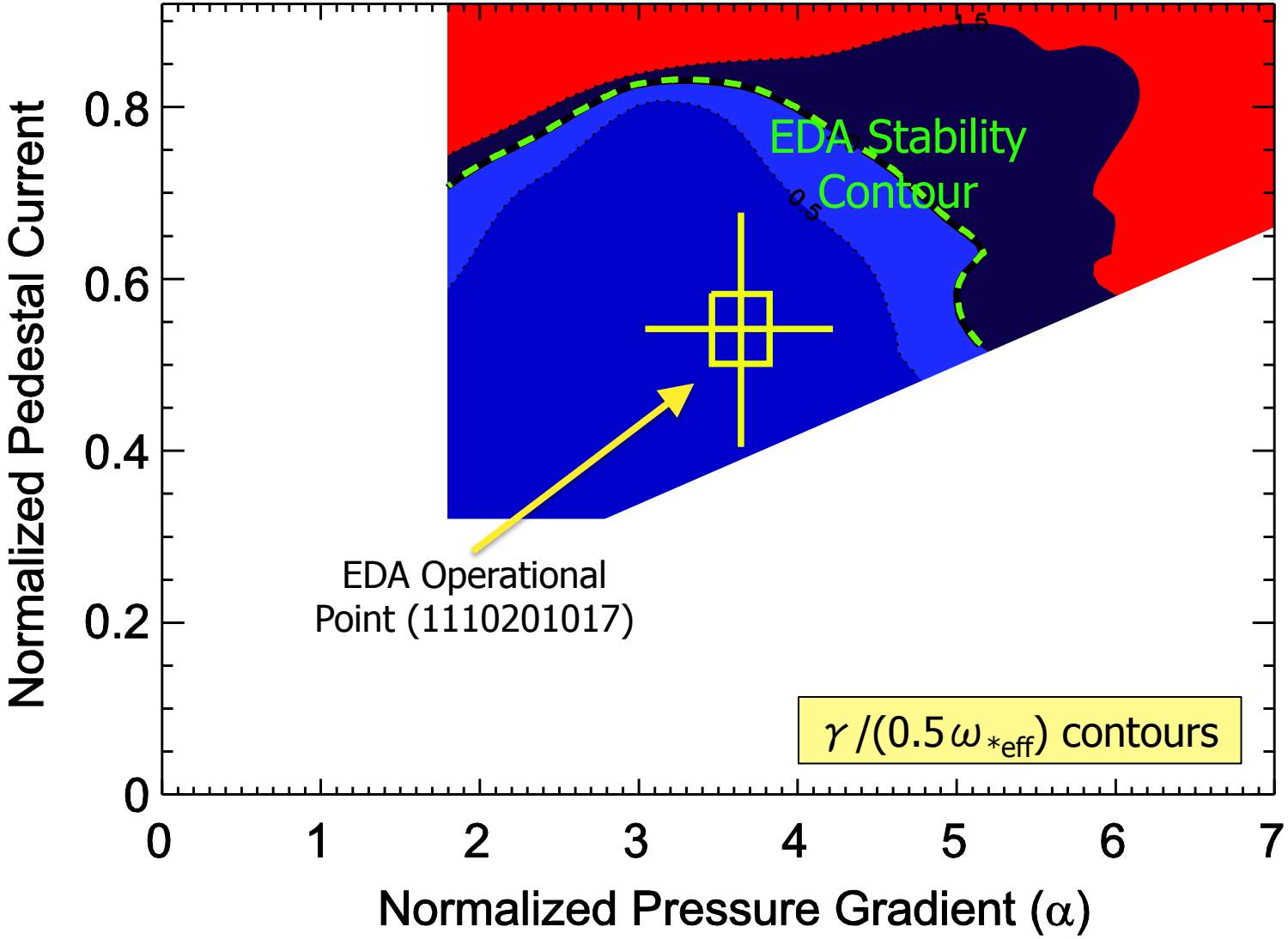
Peeling-Ballooning (PB) modes believed to constrain ELMy pedestals



- Peeling and ballooning modes *couple* at intermediate $5 \leq n \leq 25$ to drive ELMs
  - Ideal MHD instability
- Experimentally, ELMs are routinely observed when crossing the PB threshold
- Codes such as ELITE[3] can assess stability to PB modes

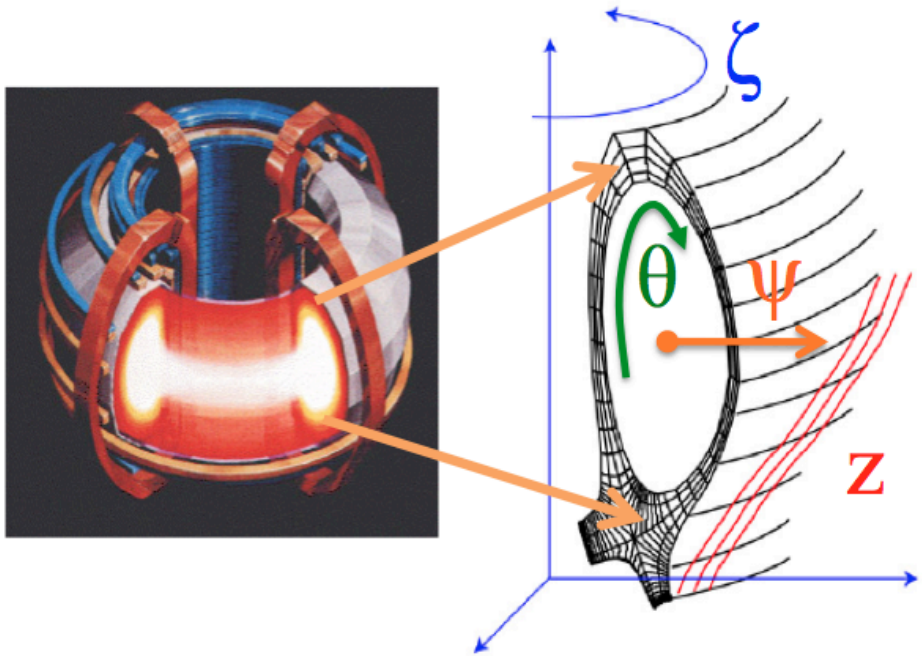
[3]P.B. Snyder et al. *Phys. Plasmas* **9** 2037 (2002).

ELITE calculations indicate ideal PB modes do **not** constrain EDA pedestals



Nonideal and nonlinear physics can be investigated with the BOUT++ code[4]

- 3D, nonlinear, initial value *fluid* code in a general geometry
  - Realistic X-point geometry
- Nonideal affects (resistivity, FLR, etc) can easily be implemented
- MPI parallelization allows ideal strong scaling to ~10,000 cores



BOUT++'s Field-Aligned Coordinate System

[4]B.D. Dudson et al., *Comput. Phys. Commun.* **180**, 1467 (2009)

The nonideal reduced MHD equations[5] solved in BOUT++

Reduced MHD Equations

Vorticity

$$\frac{\partial \varpi}{\partial t} + v_E \cdot \nabla \varpi = B_0^2 \nabla_{\parallel}\left(\frac{j_{\parallel}}{B_0}\right) + 2 b_0 \times \kappa \cdot \nabla p,$$

Pressure

$$\frac{\partial P}{\partial t} + v_E \cdot \nabla P = 0,$$

Ohm's

$$\frac{\partial A_{\parallel}}{\partial t} = -\nabla_{\parallel}\left(\varphi + \Phi_0\right) + \frac{\eta}{\mu_0}\nabla_{\perp}^2 A_{\parallel},$$

Non-ideal physics
✓Include resistivity
✓After gyroviscous cancellation, the diamagnetic drift modifies the vorticity
✓Using force balance and assuming no net rotation, $E_{r0} = (1/N_i Z_i e)\nabla_{\perp} P_{i0}$

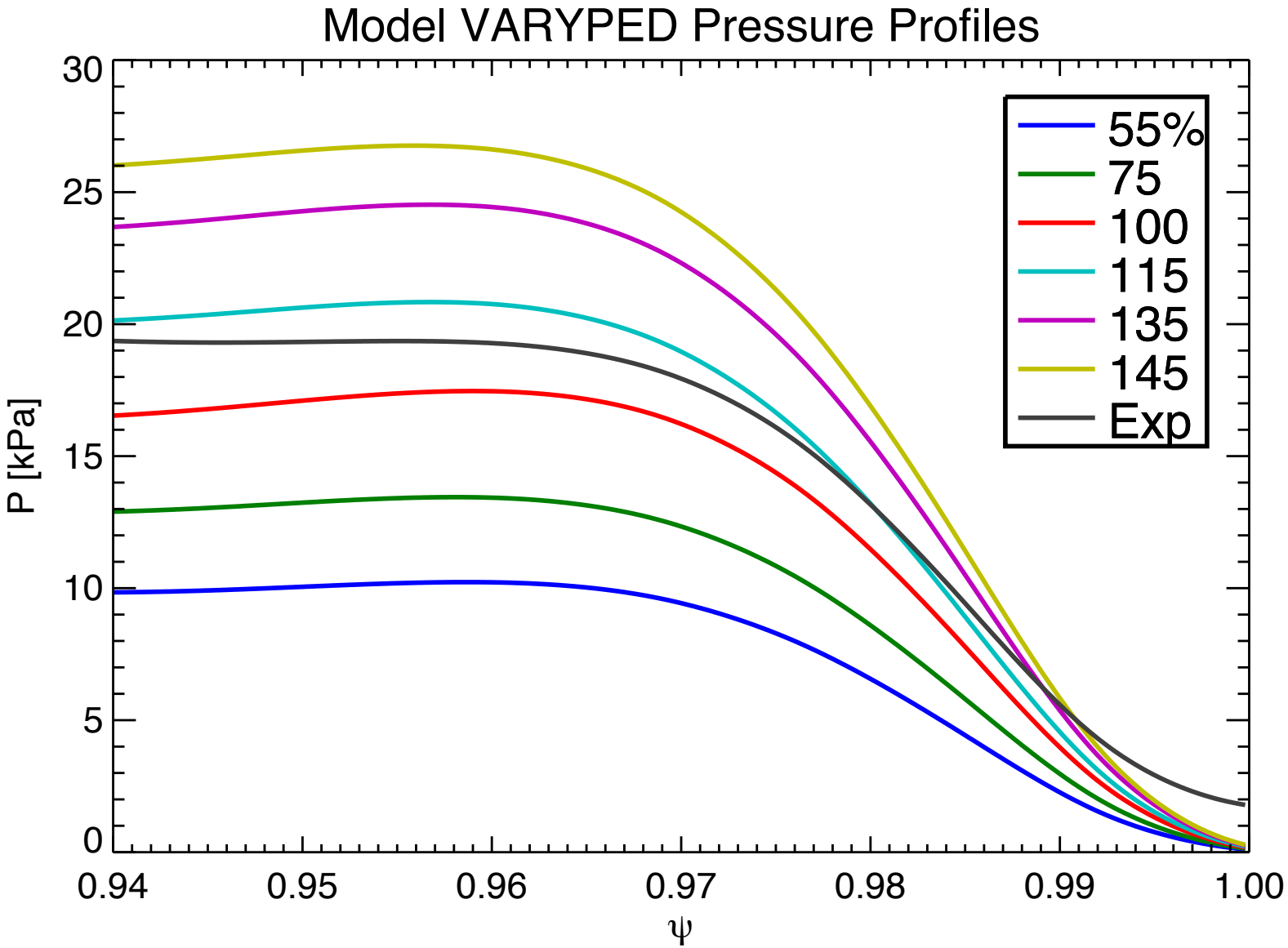
Definitions

$$\varpi = \frac{n_0 M_i}{B_0}\left(\nabla_{\perp}^2 \varphi + \frac{1}{n_0 Z_i e}\nabla_{\perp}^2 p_i\right), \quad P = P_0 + p$$

$$j_{\parallel} = J_{\parallel 0} - \frac{1}{\mu_0}\nabla_{\perp}^2 A_{\parallel}, \quad v_E = \frac{1}{B_0} b_0 \times \nabla\left(\varphi + \Phi_0\right)$$

[5]B.D. Hazeltine and J.D. Meiss, *Plasma Confinement* (Dover, Mineola, NY, 2003)

Profiles with self-consistently varied pressure gradient used as BOUT++ input



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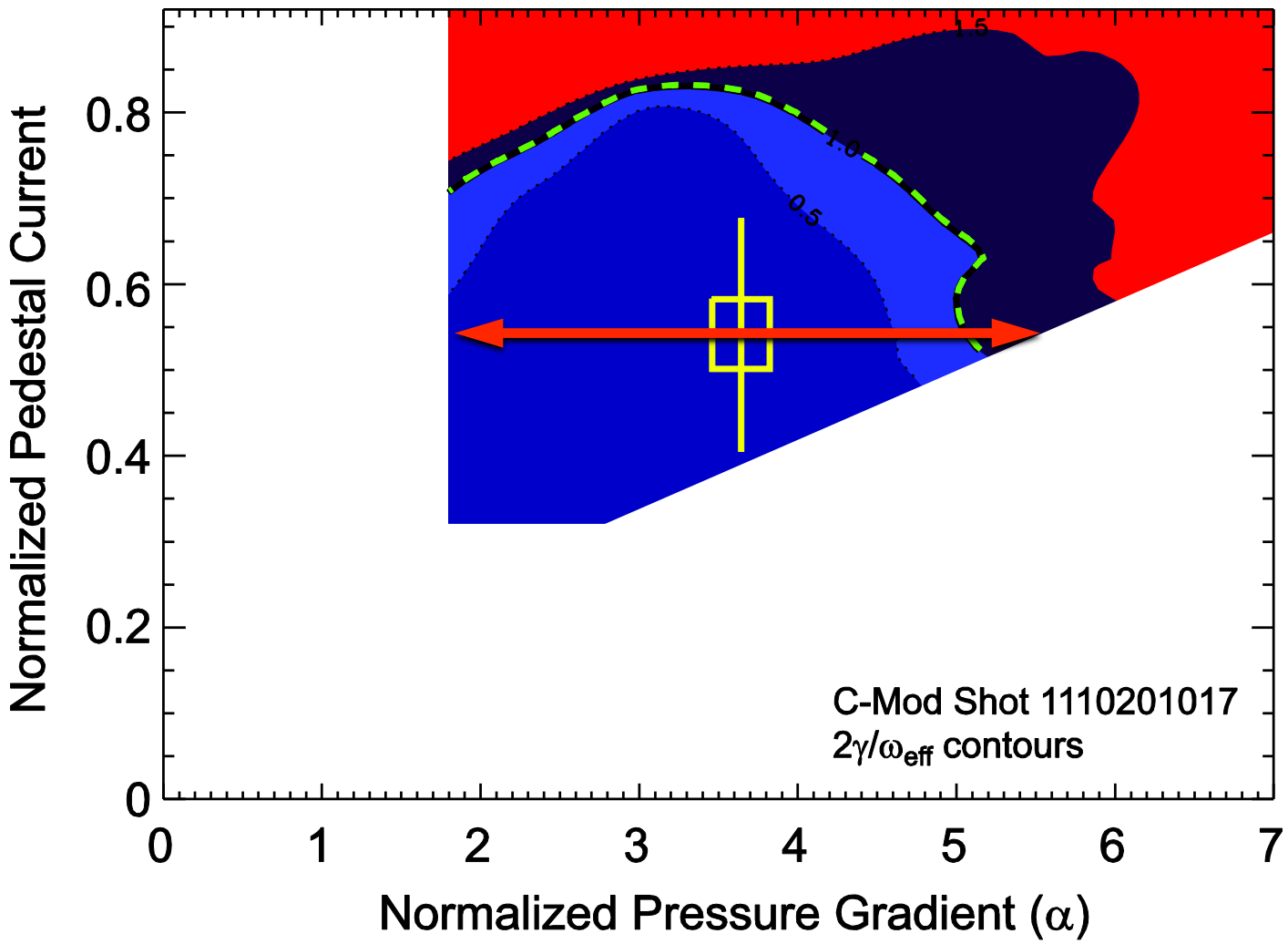
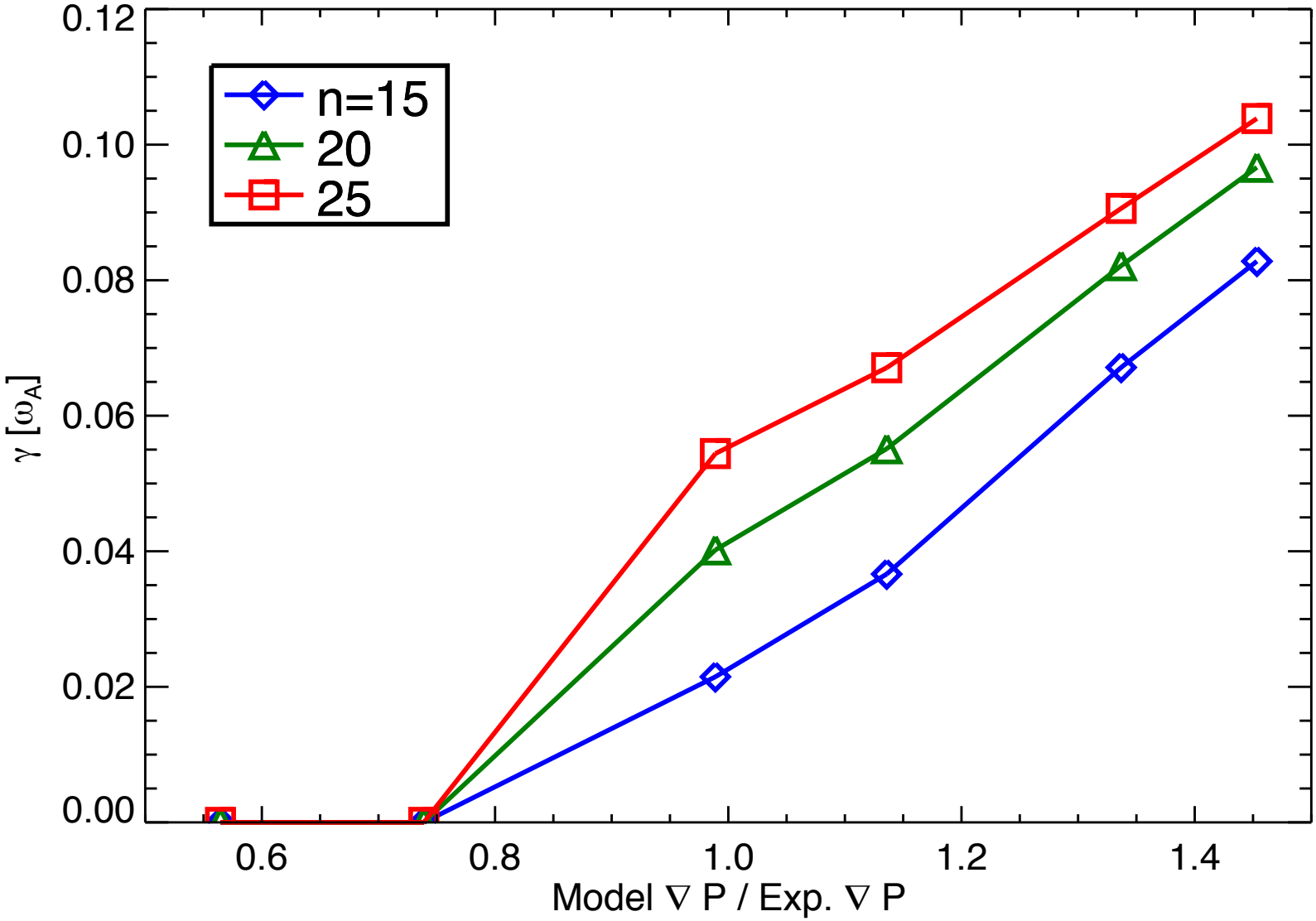
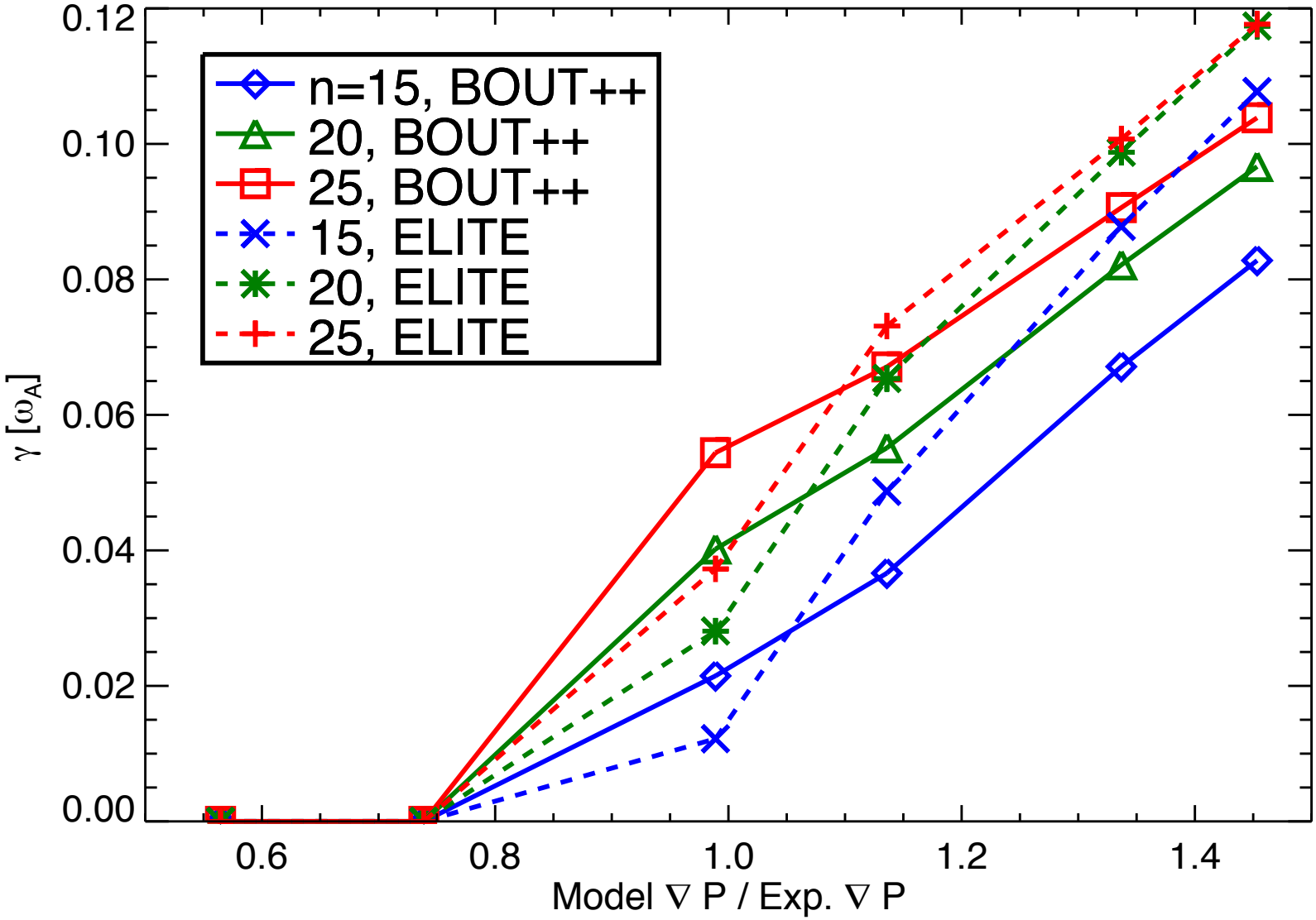


BOUT++ indicates a "growing" mode at experimental values of ∇P…



BOUT++ marginal stability thresholds and growth rate trends agree with ELITE



However, FLR effects can stabilize these ideal MHD modes[6]

- Kinetic theory gives

$$\gamma_{MHD}^2 = -\omega\left(\omega - \omega_{*eff}\right), \quad \omega_{*eff} = \frac{\omega_{*i,\max}}{2}$$

- The ideal MHD mode will be *stabilized* when

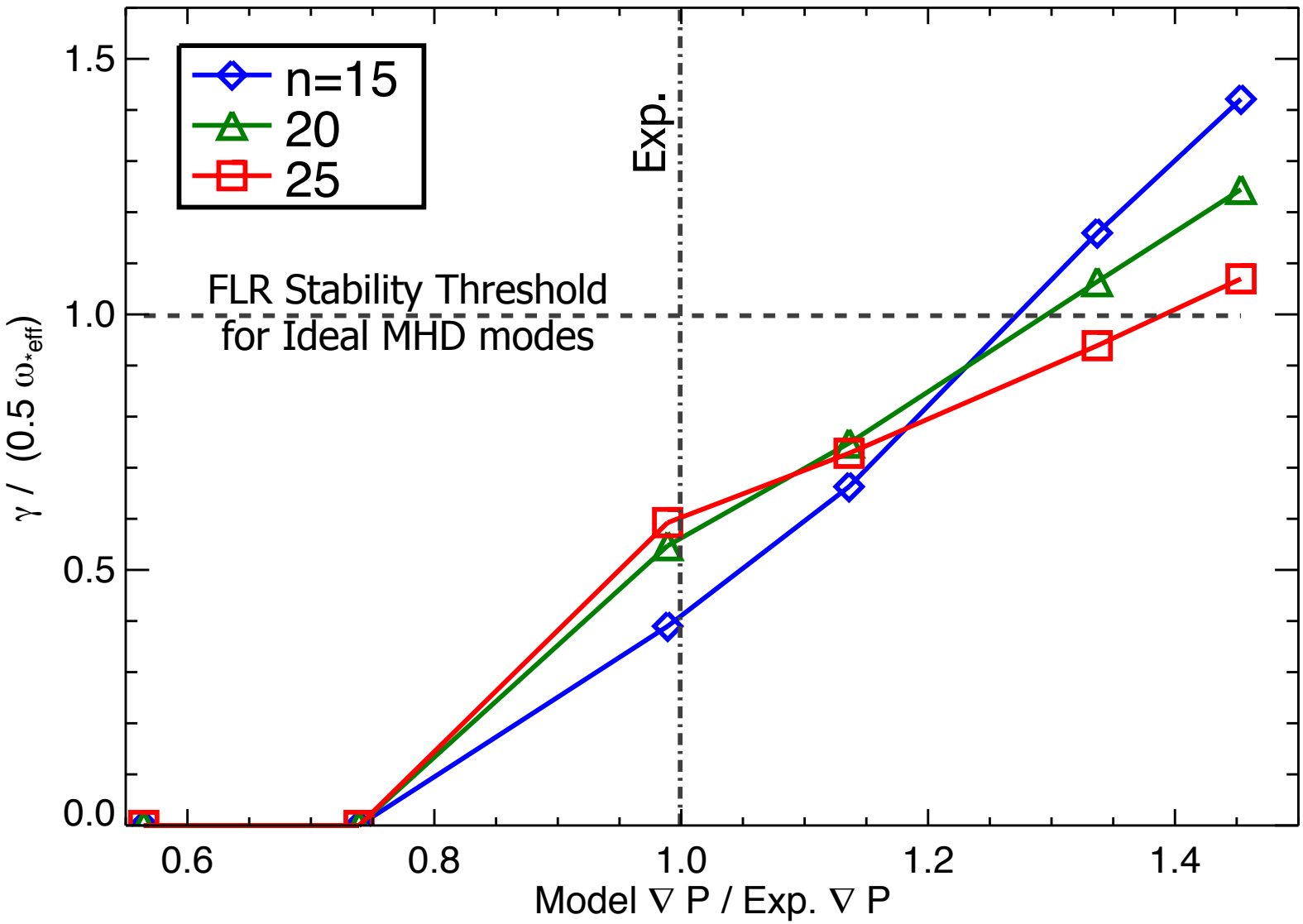
$$\gamma_{MHD} < \frac{\omega_{*eff}}{2}$$

- The diamagnetic frequency can be roughly calculated as

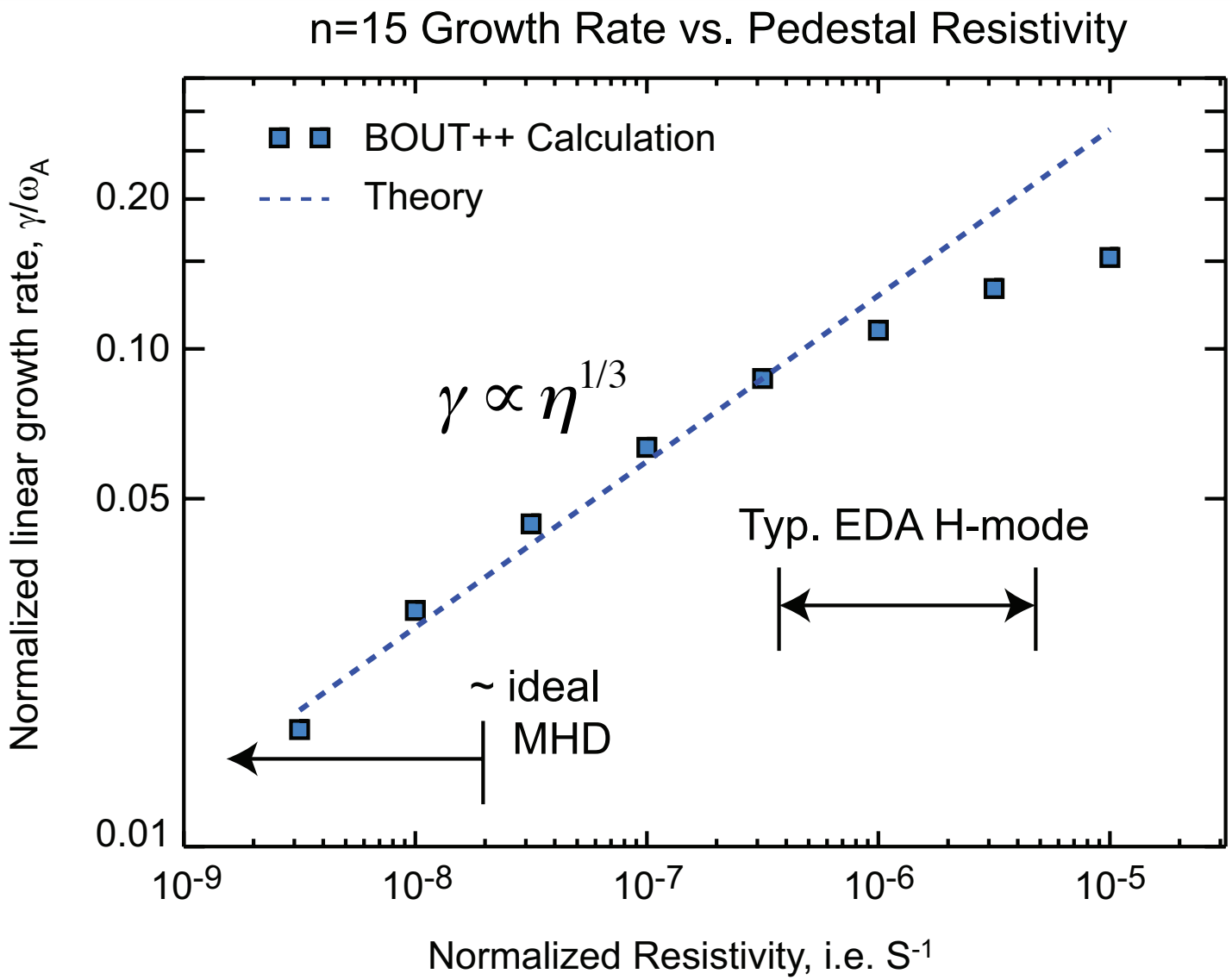
$$\omega_{*i} = \vec{k} \cdot \vec{V}_{di} = \vec{k} \cdot \left(\frac{\hat{b} \times \vec{\nabla} p_i}{e n_i B} \right) \approx \frac{nq\left|\vec{\nabla} p\right|}{2\sqrt{\kappa}\, a n_i e B_\phi}$$

[6]P.B. Snyder et al., *Nucl. Fusion* **51**, 103016 (2011)

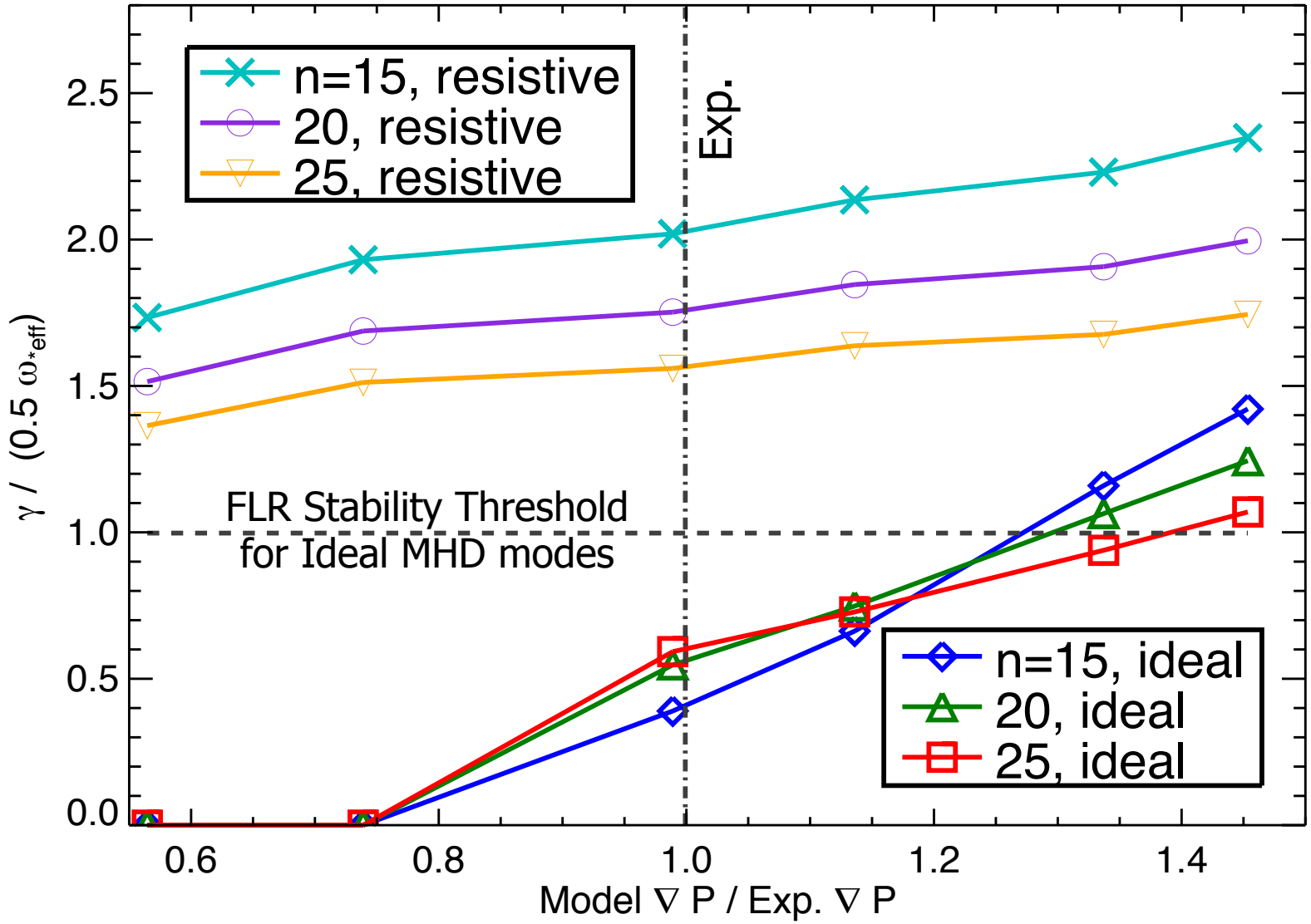
The diamagnetic shearing stabilizes the modes at experimental ∇P



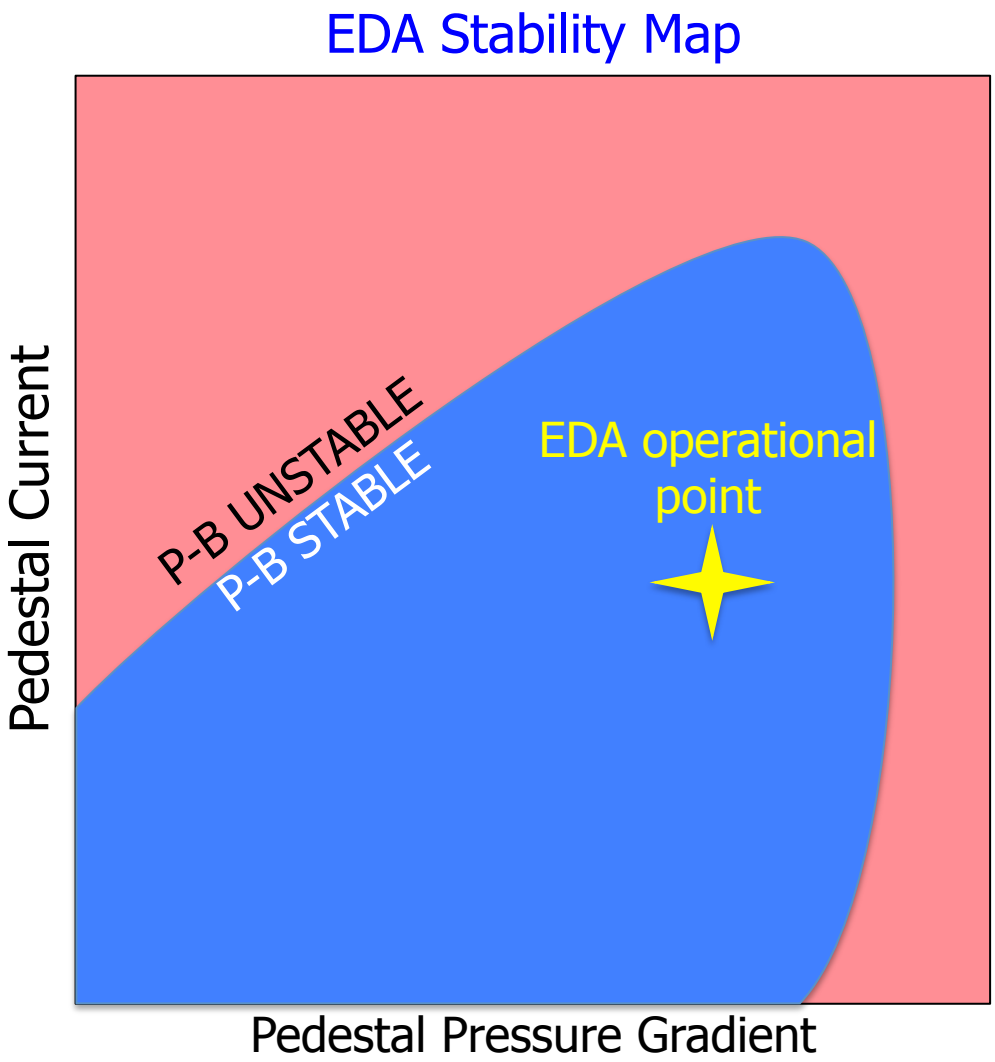
Resistivity can drive Instability



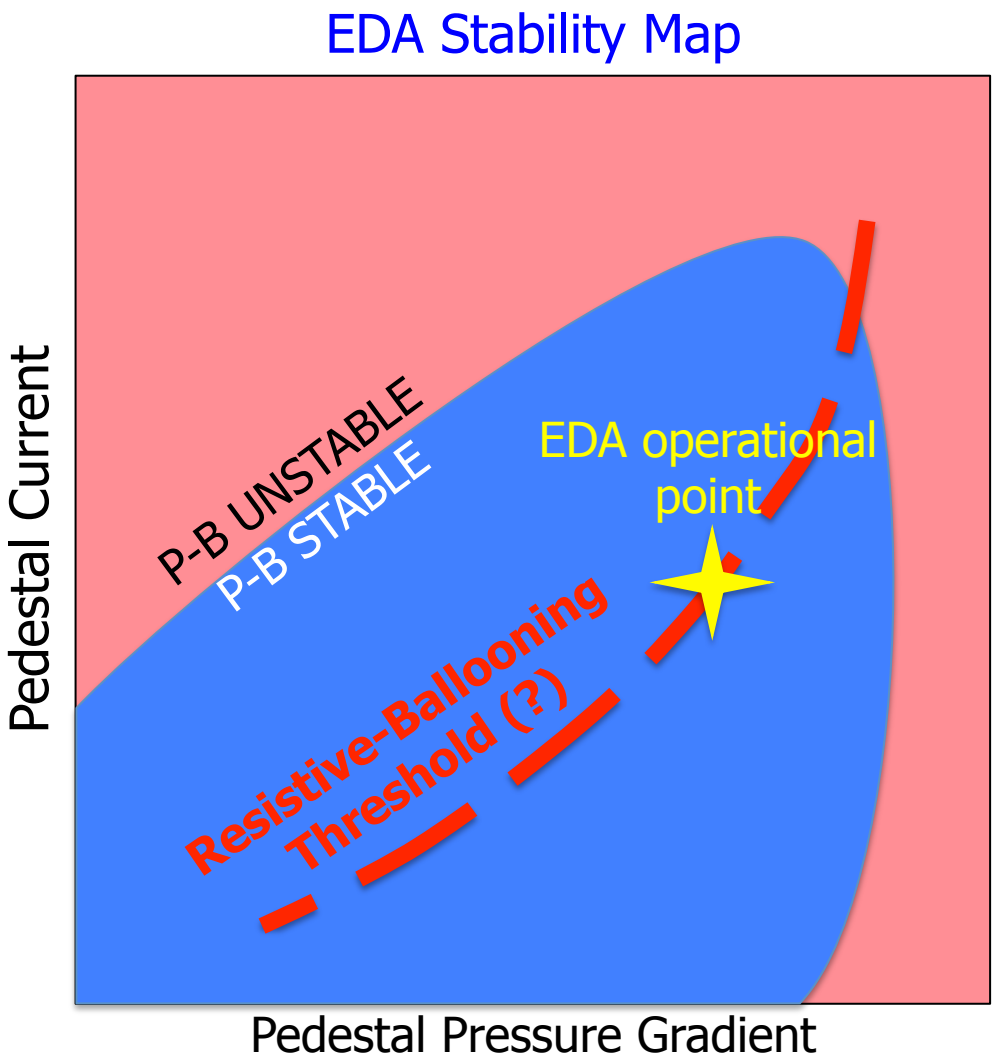
Resistivity substantially enhances growth rates above the FLR stability criterion



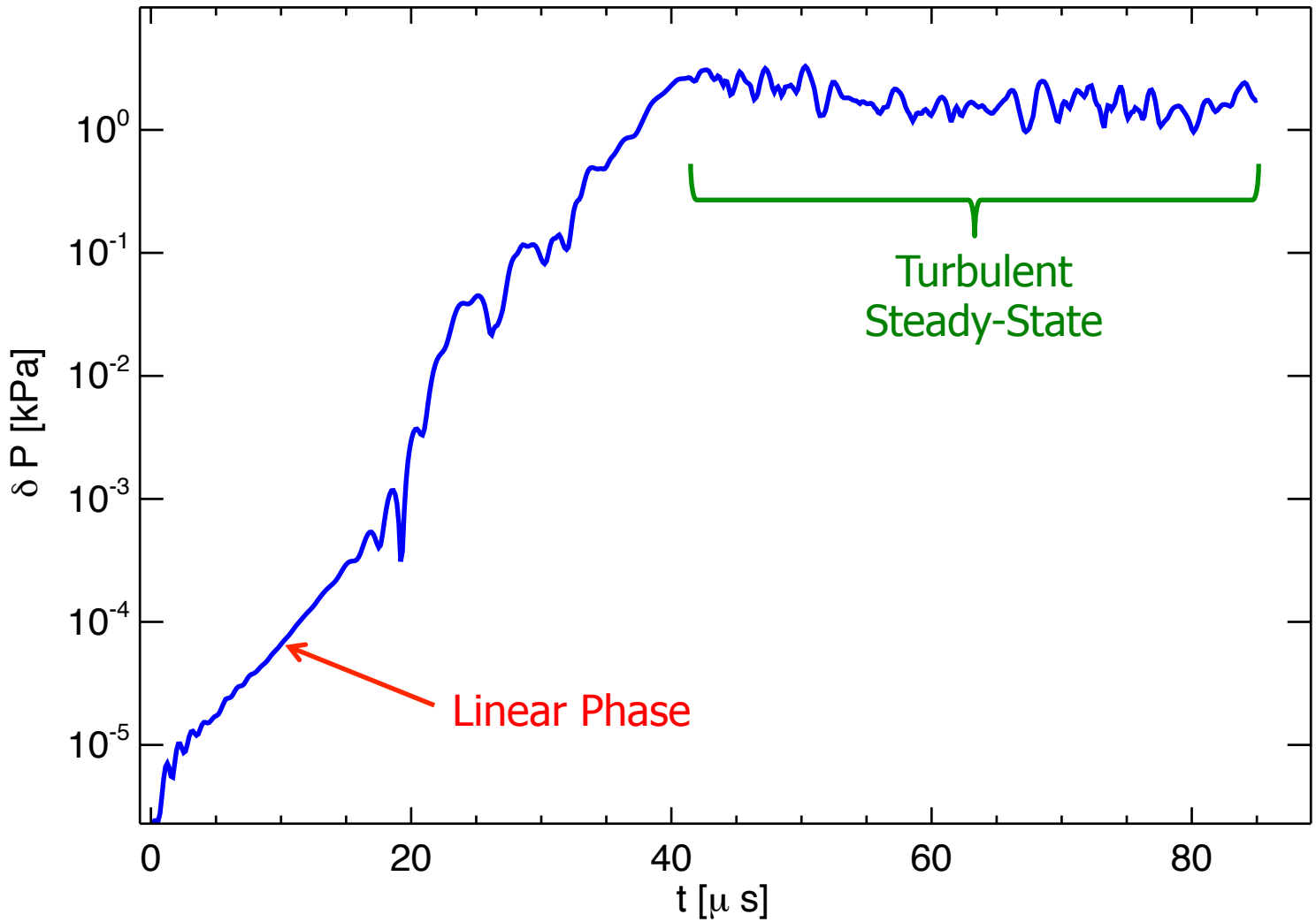
Stability picture if PB modes constrained the EDA Pedestal



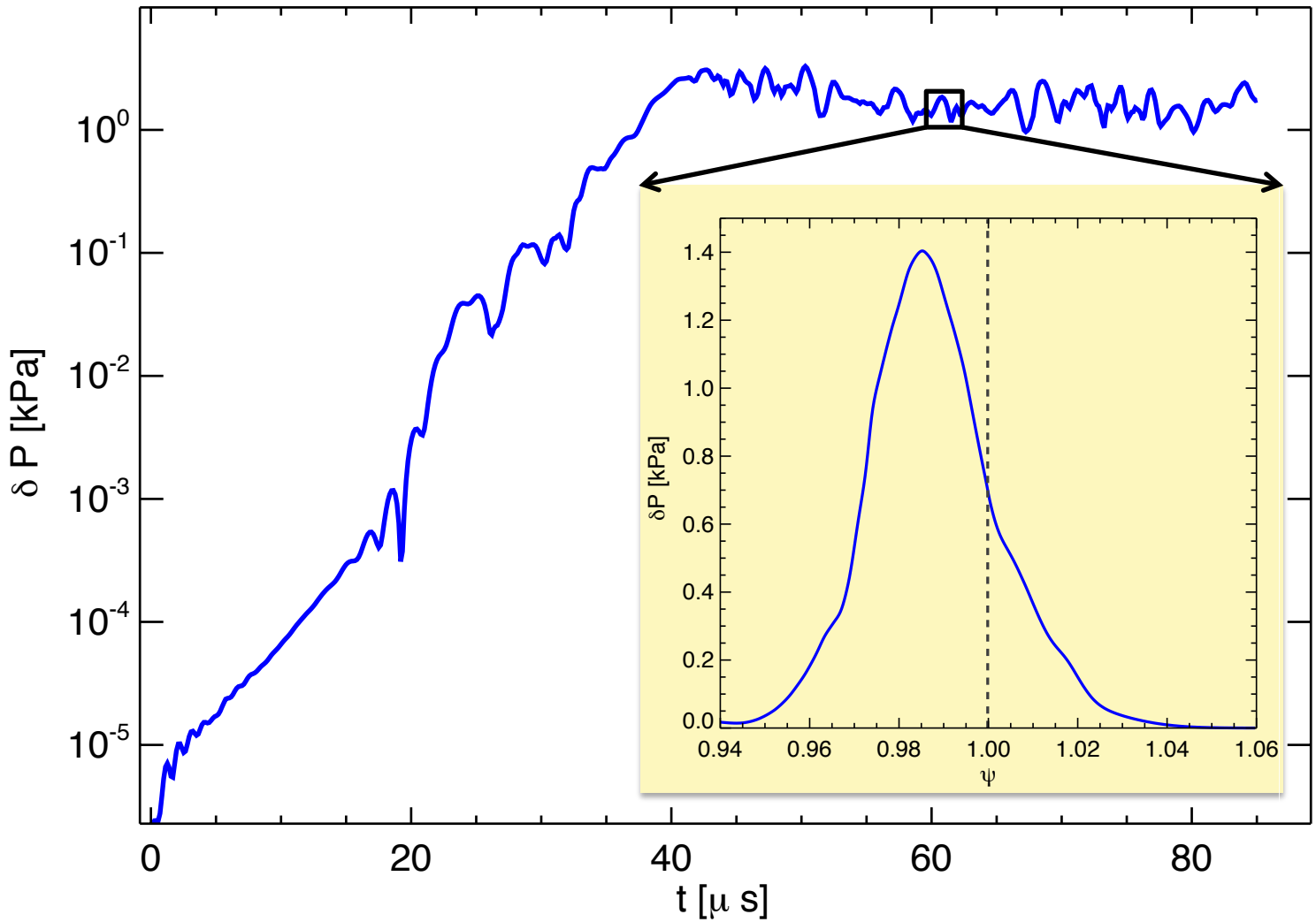
Stability picture if resistive-ballooning modes constrain the EDA pedestal



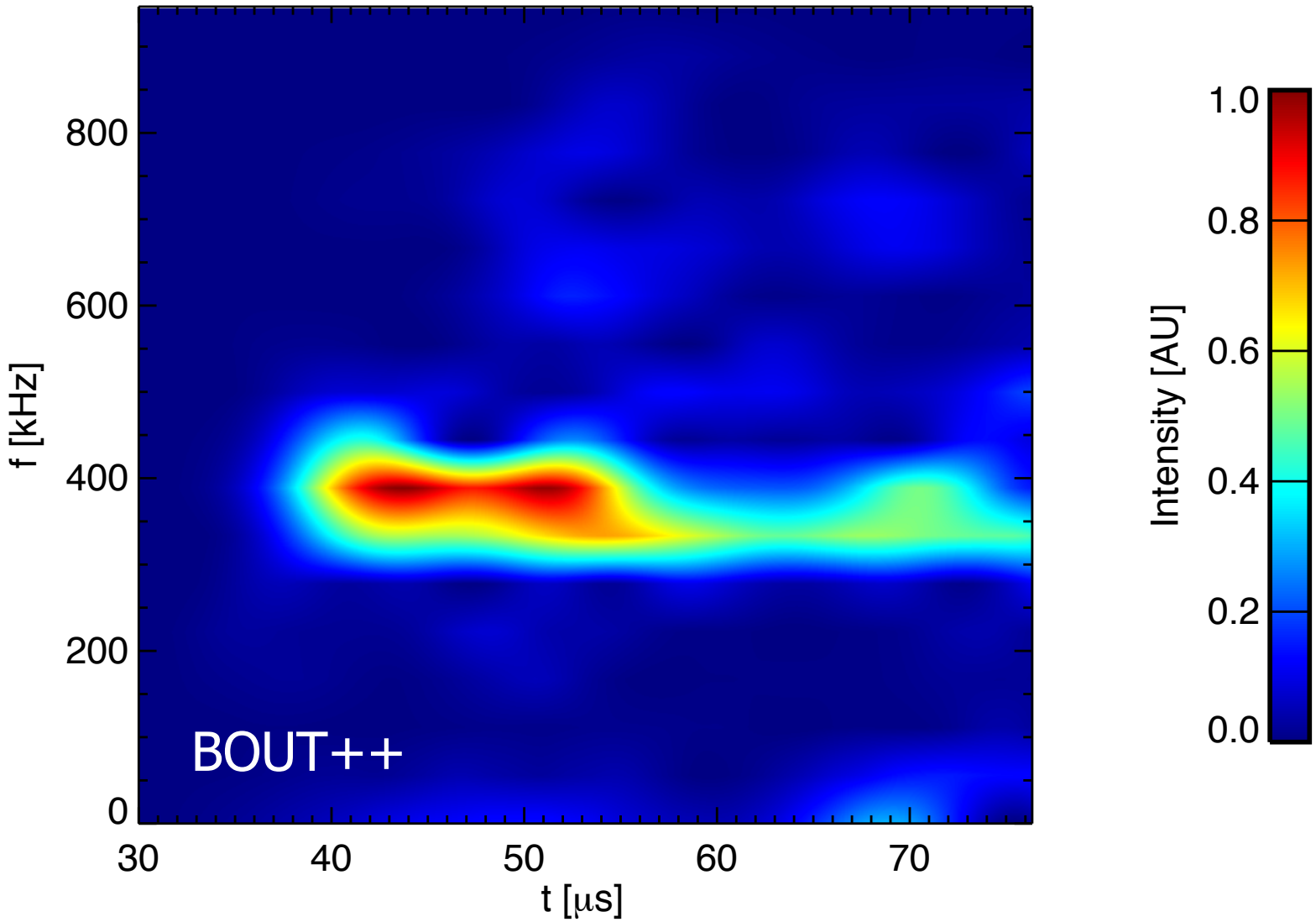
Nonlinear simulations have reached turbulent steady-state



The mode spans the separatrix and exists in the high gradient region at the outboard midplane



Nonlinear simulations show a quasi-coherent oscillation *qualitatively* similar to EDA's QCM



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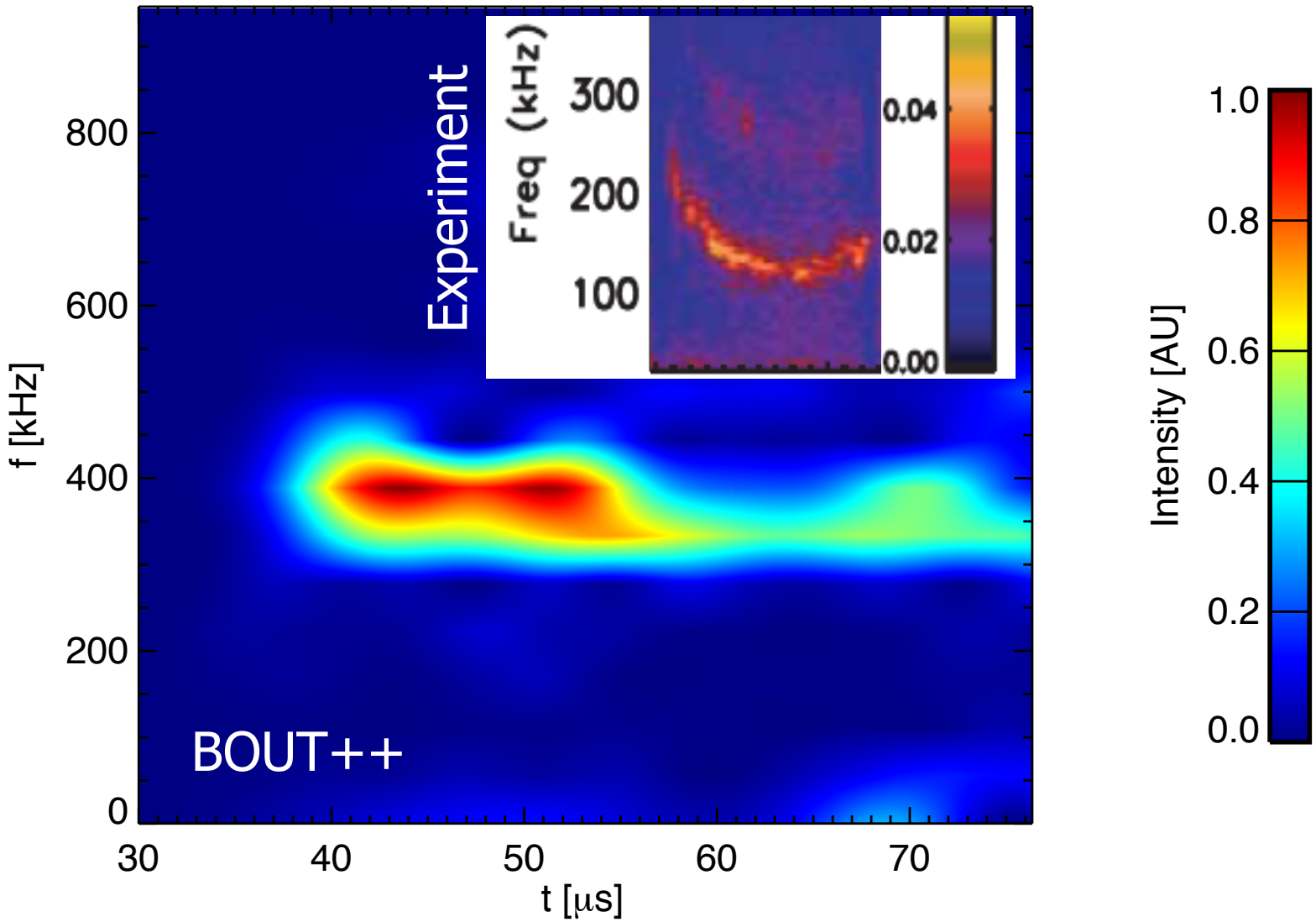
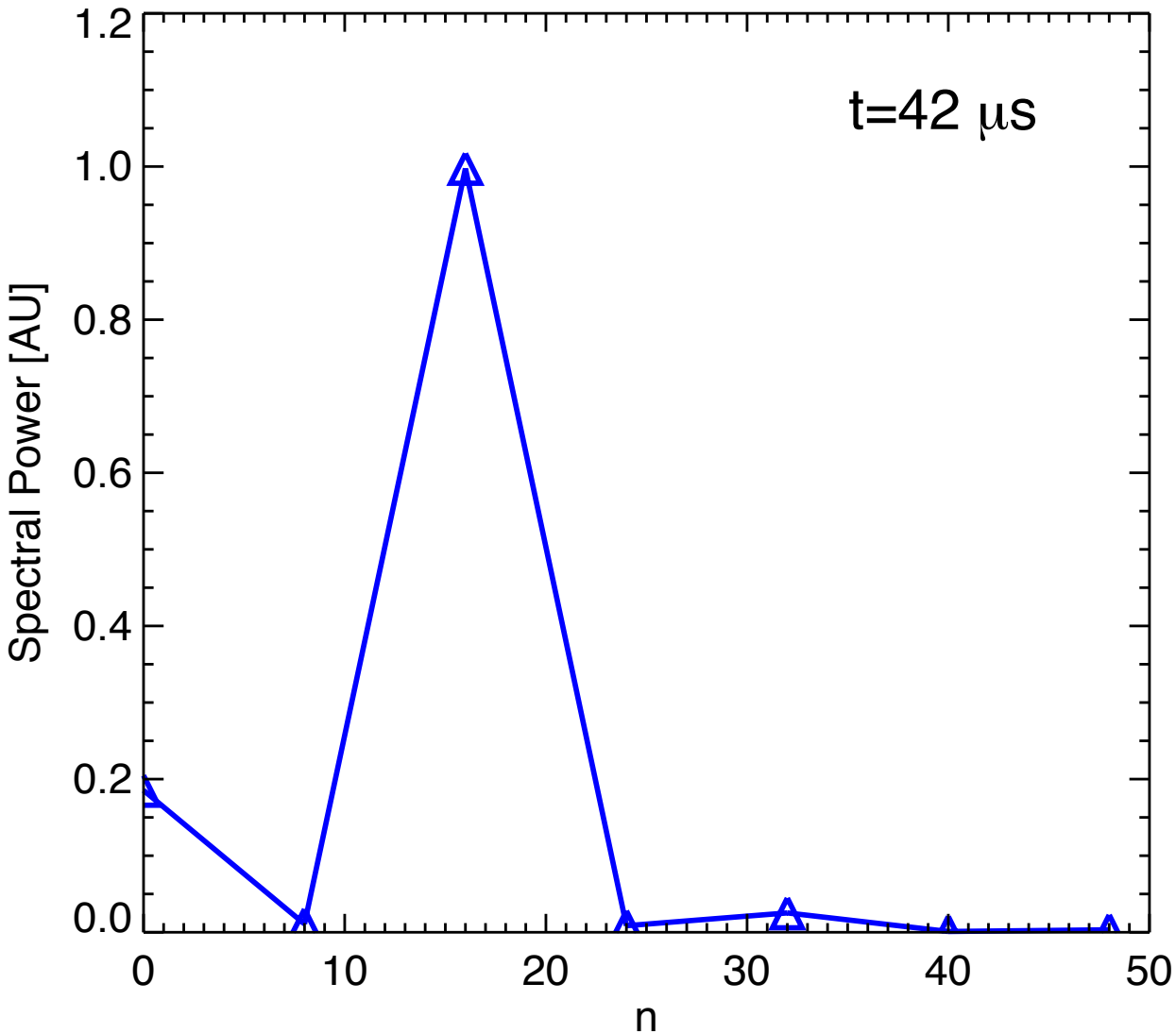
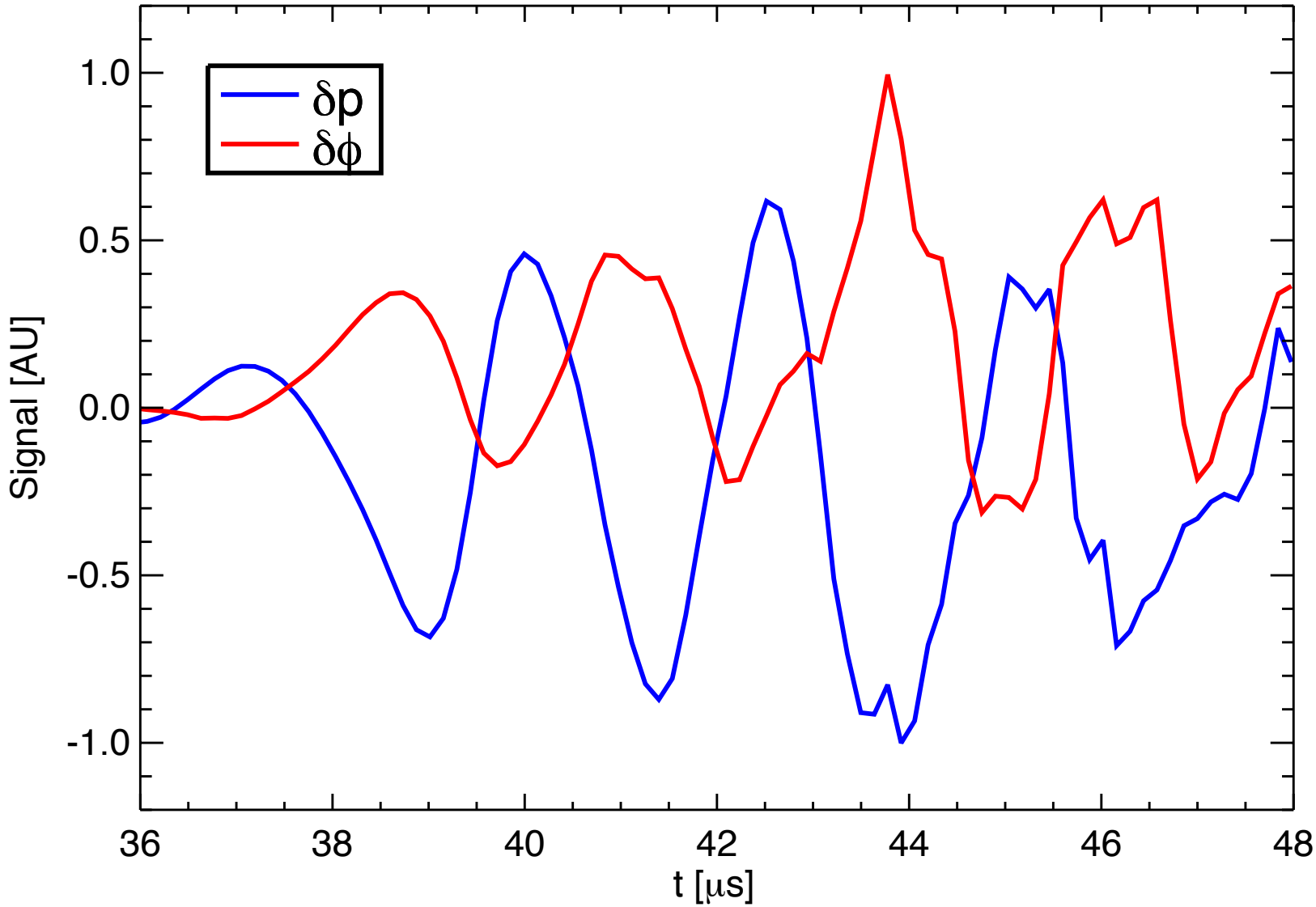


The nonlinear quasi-coherent oscillation is peaked about n~16, similar to EDA's QCM



The pressure and potential fluctuations are *out* of phase, in contrast to recent QCM measurements



Conclusions

- EDA H-mode is a steady-state high performance operational regime
- PB theory fails to constrain the EDA pedestal
- BOUT++ is an extensible nonlinear fluid code suitable for investigating the EDA H-mode
- BOUT++ ideal linear growth rates are in good agreement with those from ELITE
- Inclusion of realistic pedestal resistivity drives RBMs that may ultimately constrain EDA
- Nonlinear simulations are ongoing and share *some* qualitative features with EDA's QCM