INTERPRETATION OF EDGE MEASUREMENTS VIA BOUT++ SIMULATIONS

G. McKee

University of Wisconsin-Madison

Acknowledgements:

D. Smith, Z. Yan

University of Wisconsin-Madison

J. Boedo, C. Holland, G. Tynan

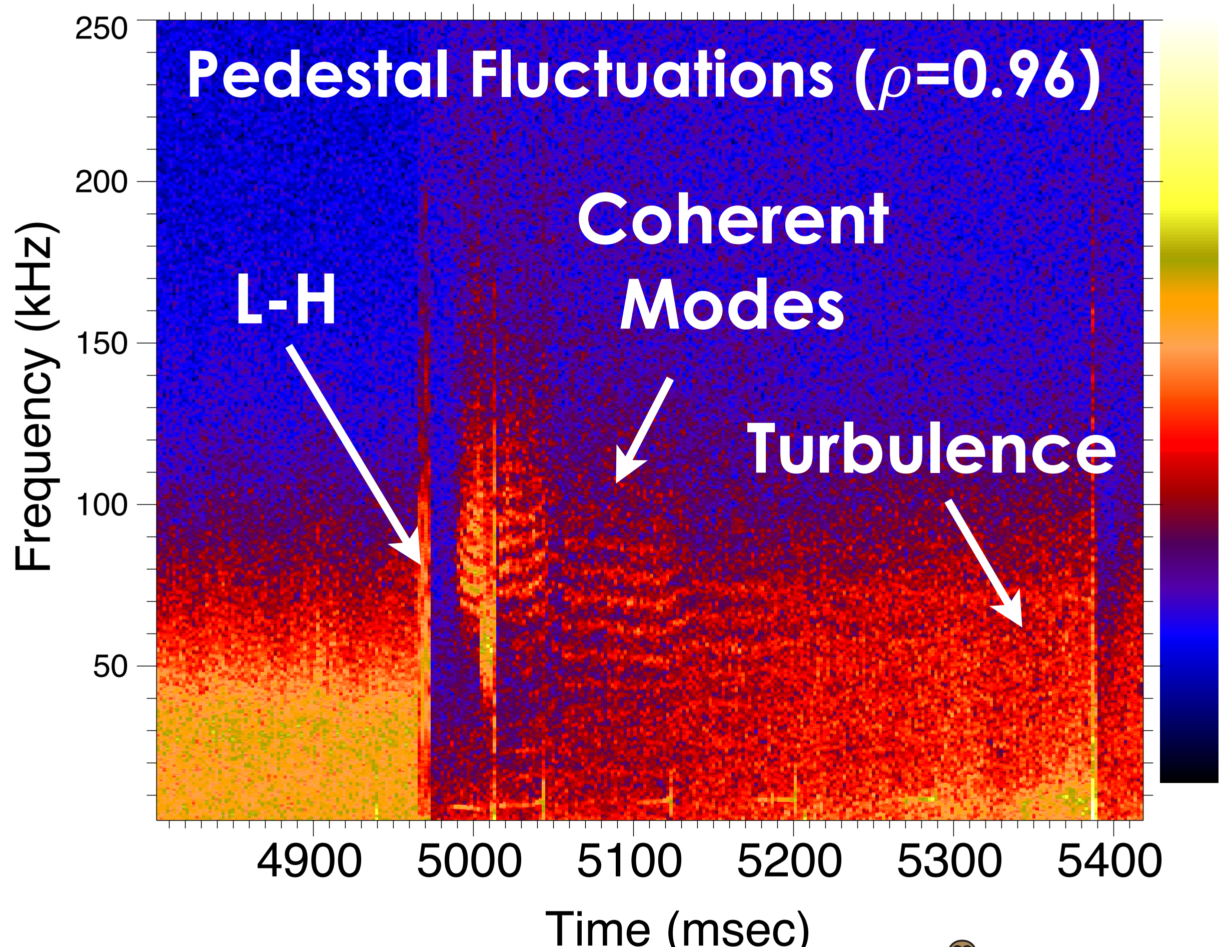
Univ. California-San Diego

L. Schmitz, T.L. Rhodes

Univ. California-Los Angeles

T. Osborne

General Atomics



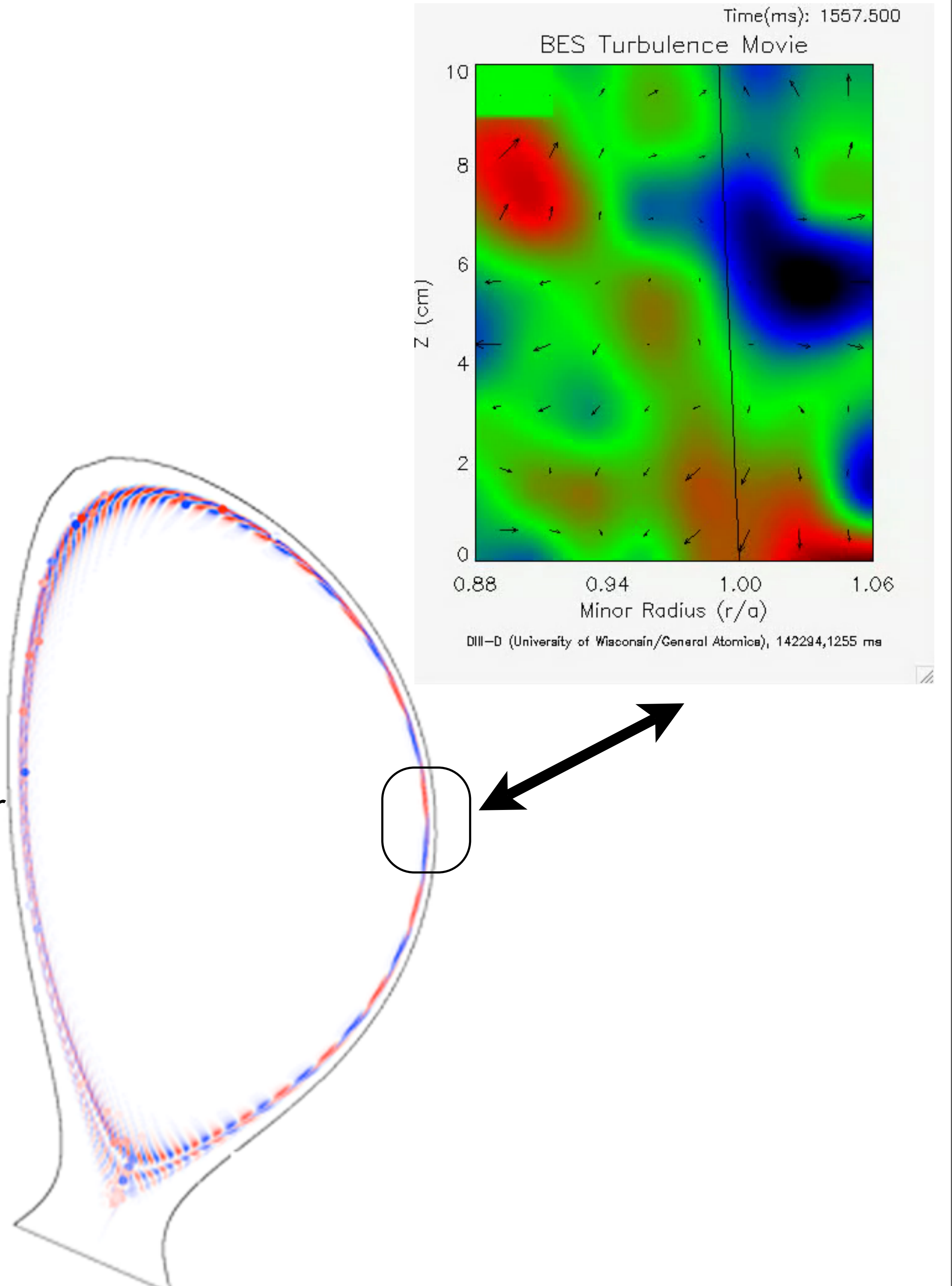
BOUT++ Workshop
Livermore, California
September 5, 2013

DIII-D NATIONAL FUSION FACILITY

THE UNIVERSITY of WISCONSIN MADISON

Seeking to Identify Fundamental Processes and Instabilities in the Edge of Tokamak (or other!) Plasmas

- **Observations of edge plasma behavior reveal wide array of interesting and important phenomena**
- **Understanding and extrapolating will require close interaction of experiment, theory and simulation**
  - Test, challenge, refine models
- **Goal: Identify experimental observations that perhaps can be explained through BOUT++ simulation**
  - Aid improvement and ultimately validation (or rejection) of various models for edge turbulence
- **Interpret, Understand, Extrapolate Physics behind observations**



Can we identify ballooning modes (kinetic, resistive, current diffusive...)

BOUT++ Simulations can Elucidate Physics Behind Several Specific Edge Experimental Observations

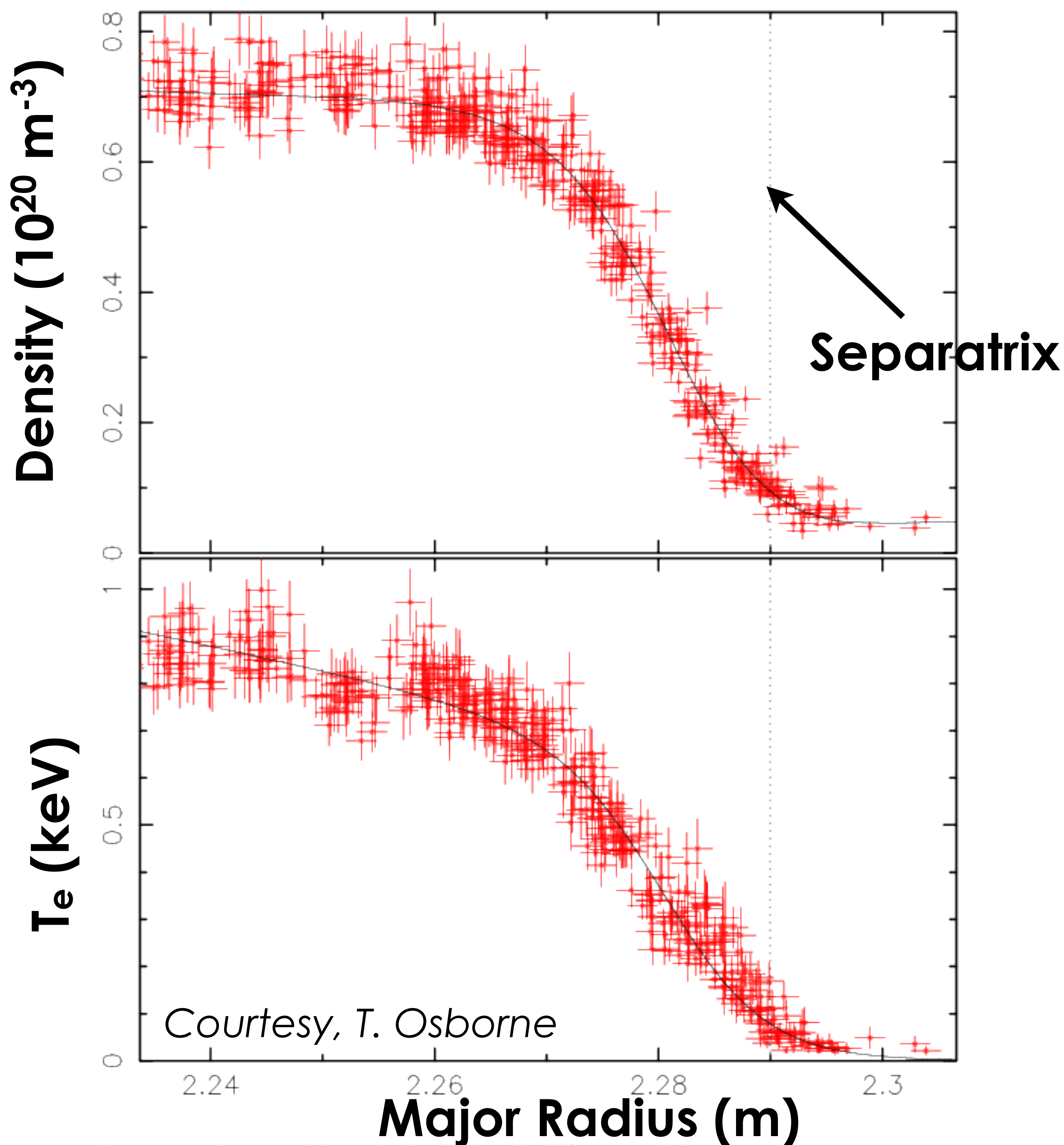
- **L-H Transition physics**
  - Nature of L-mode turbulence approaching the transition
  - Identifying trigger mechanism
  - Understanding threshold behavior: B_T, n_e, A, V_{TOR}, boundary shape
- **H-Mode Pedestal Instabilities**
  - Inter-ELM evolution: coherent and broadband structures, saturation
  - Edge Harmonic Oscillation, High-Frequency-Coherent Modes (QH plasmas)
  - Quasi-Coherent Mode (EDA plasmas on C-MOD)
- **ELM Dynamics**
  - Precursors
  - Nonlinear evolution
- **ELM Suppression methods**
  - Radial Magnetic Perturbations, turbulence, transport, pedestal stability
- **Intrinsic rotation**
- **Blob Dynamics: Density scaling, particle transport**
- **I_P scaling of SOL width, implications for ITER**

Pedestal Profiles Well Characterized via Multiple Diagnostics

- **Charge Exchange Recombination Spectroscopy**
  - T_i, V_{TOR}, V_{POL}, n_C, E_r
- **Thomson Scattering**
  - n_e, T_e
- **Electron Cyclotron Emission**
  - T_e
- **Lithium Beam Spectroscopy**
  - Current density (*challenging!)
- **Motional Stark Effect**
  - Pitch angle/current density
- **Gradients measured via time-averaging, phase-averaging**
  - Crucial for simulations

Spatial and Temporal Resolution Limits

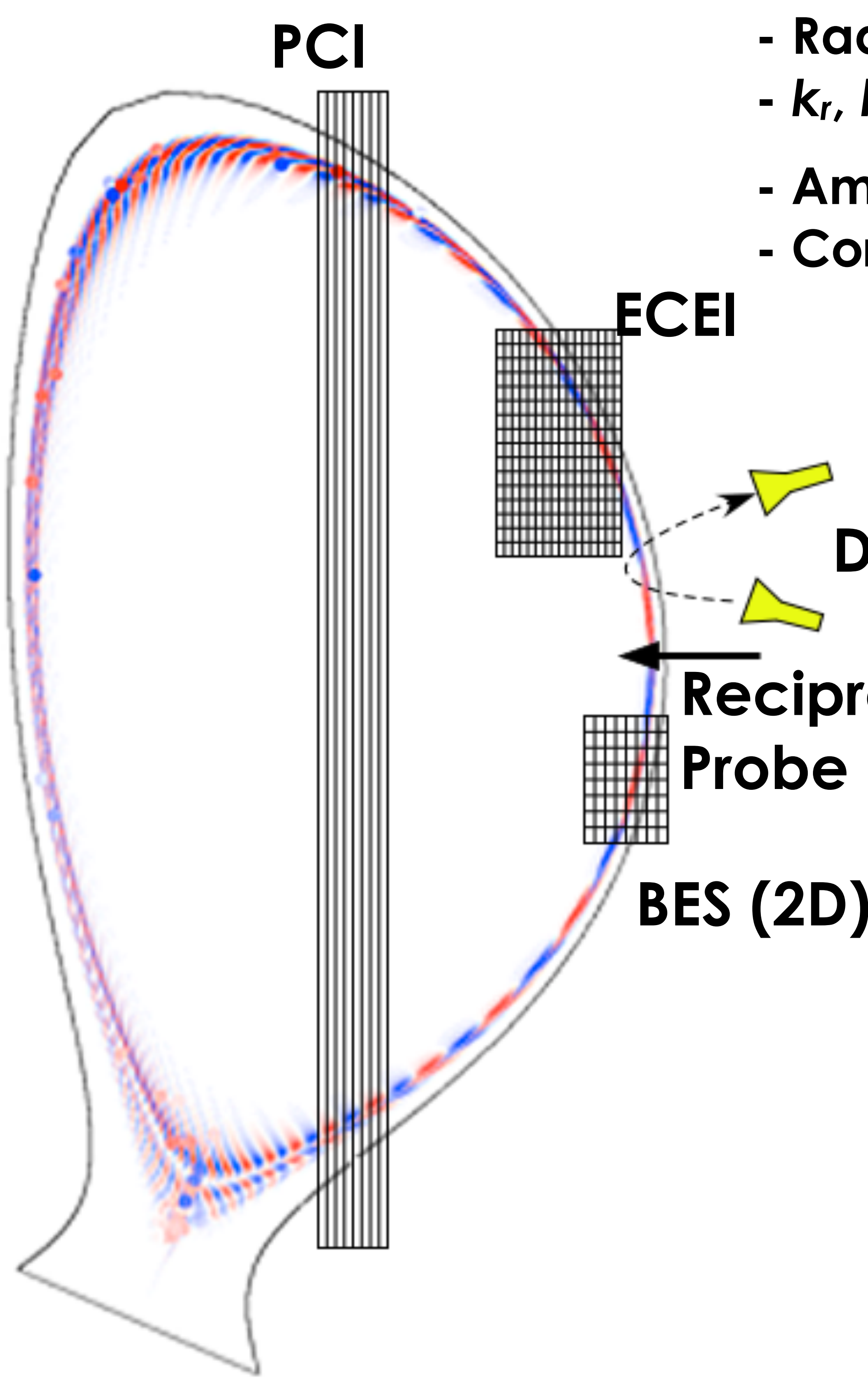
Pre-ELM H-Mode Pedestal Profiles
(assembled from multiple TS pulses)



Fluctuation Diagnostics Measure Multiple Fields at Relevant Temporal, Spatial and Wavenumber Resolution

- **Reciprocating probes**
  - n_e, T_e, φ, E_r, Mach #,
  - Reynolds Stress (low/med-k)
- **Beam Emission Spectroscopy**
  - n (2D), V_{POL}, (low-k)
- **Correlation Reflectometry**
  - n, correlation lengths, (low/med-k)
- **Doppler Backscattering**
  - n, V_{pol} (low/med-k)
- **ECE Imaging**
  - T_e (low-k)
- **Gas-Puff-Imaging**
  - n_e, (T_e) (2D, low-k)
- **UF-CHERS**
  - Ti, V_{TOR} (low-k)
- **Polarimetry (n, B)**

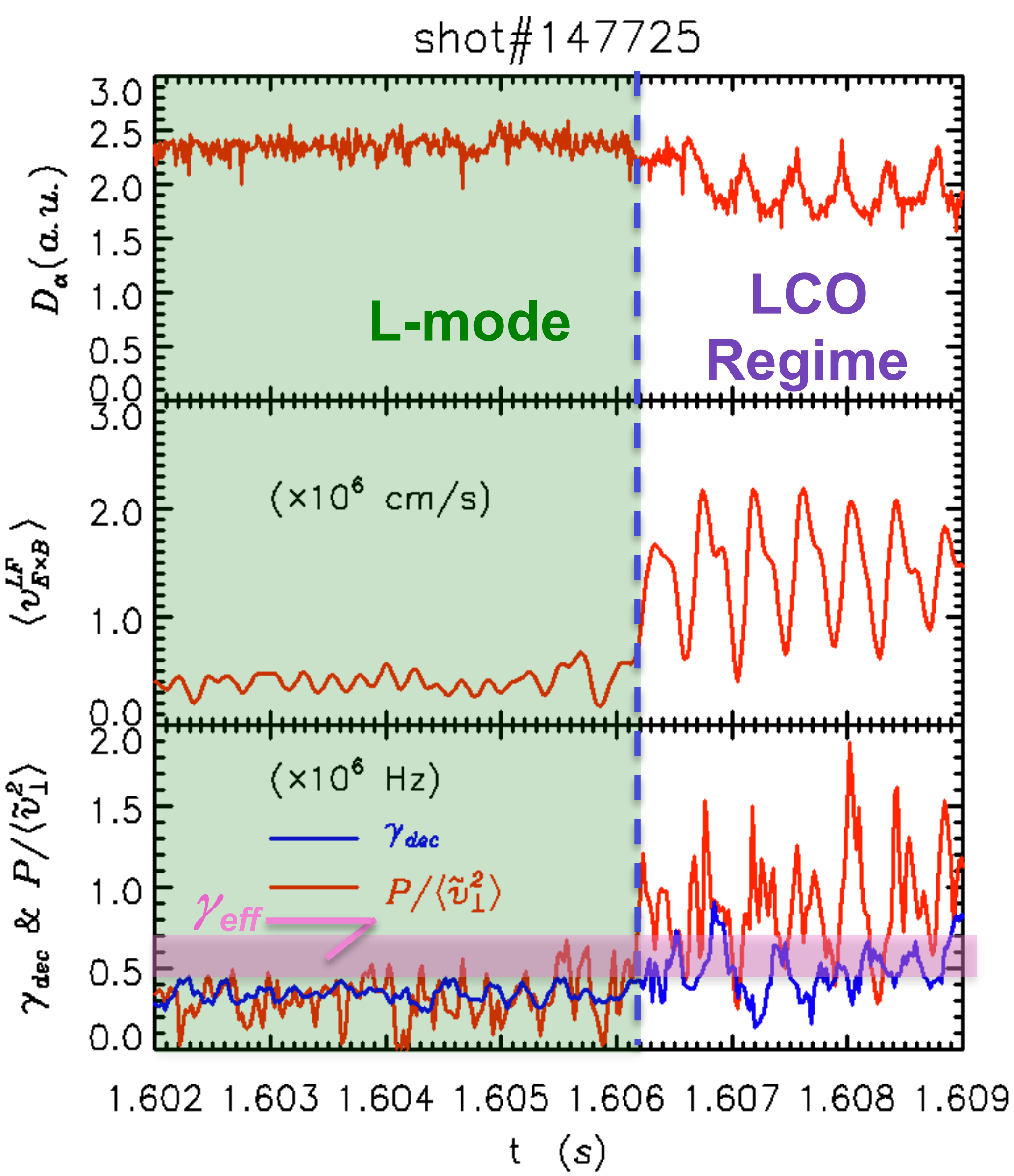
Measurables:
- Radial profile
- k_r, k_θ
- Amplitude
- Correlations

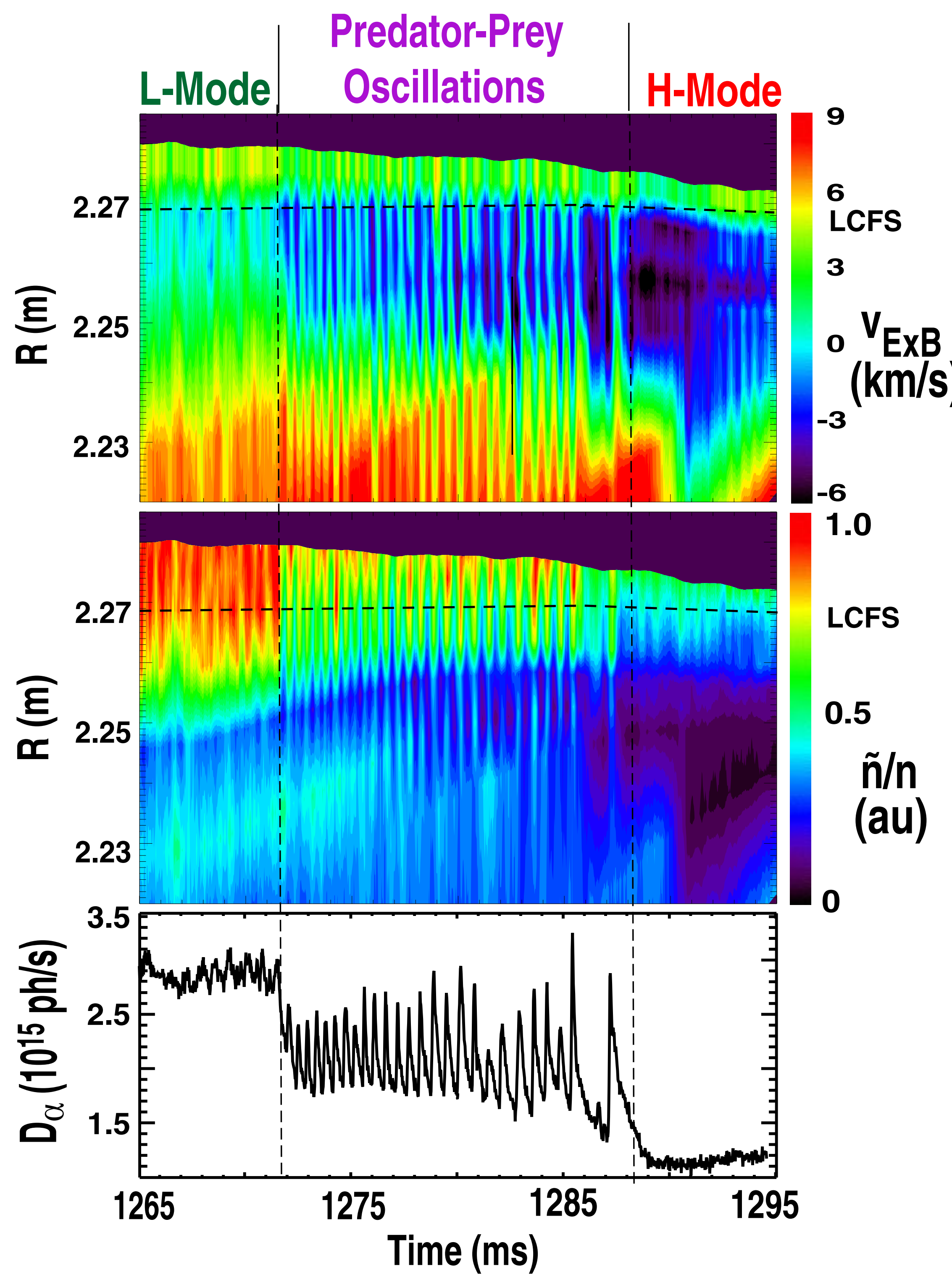


Identifying the L-H Transition Trigger Mechanism

- **Substantial progress in detailed investigations of L-H process**
  - Observe critical changes in phase leading up to transition
- **Theoretical mechanisms proposed**
  - Predator-prey model
  - Mean-shear flow
- **Strong dependencies on macroscopic parameters**
- **BOUT++ simulations can help unravel the physics behind these observations**
- **Apply same analysis techniques to simulation and experimental data**
  - Nevins tools
  - 2D data readily affords opportunity for detailed dynamical investigations of velocity, energy transfer, cascades
    - *Inferred flow field reveals ZF, GAM, turbulent fluxes…*
  - Quantitative comparison with <u>*nonlinear*</u> simulations

Limit Cycle Oscillations During L-I-H Demonstrate Predator-Prey Relationship between Turbulence and Zonal Flows





- **Transfer of energy from turbulence to zonal flows**

G. Tynan, NF (2013)

L. Schmitz, PRL (2011)

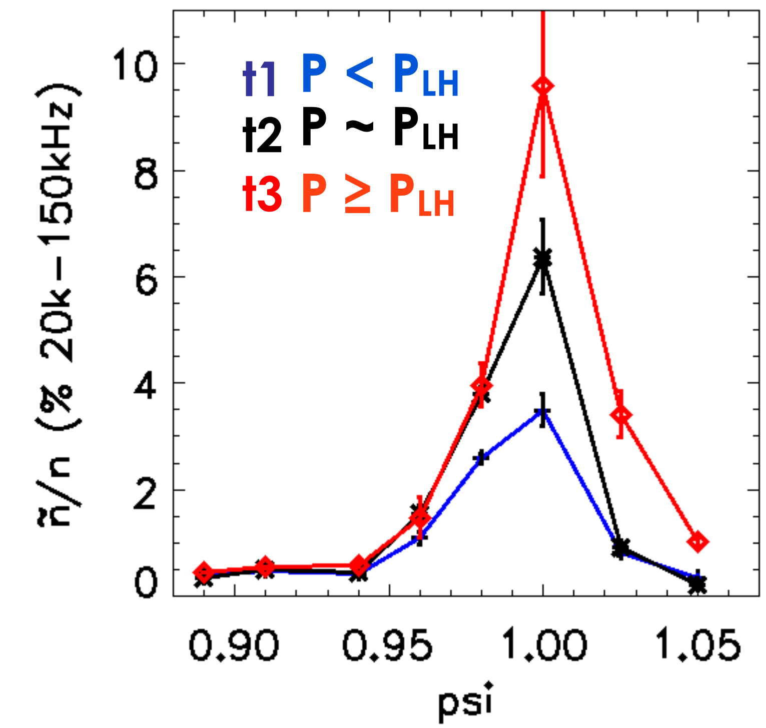
Evolution of L-Mode Edge Plasma Towards L-H Transition

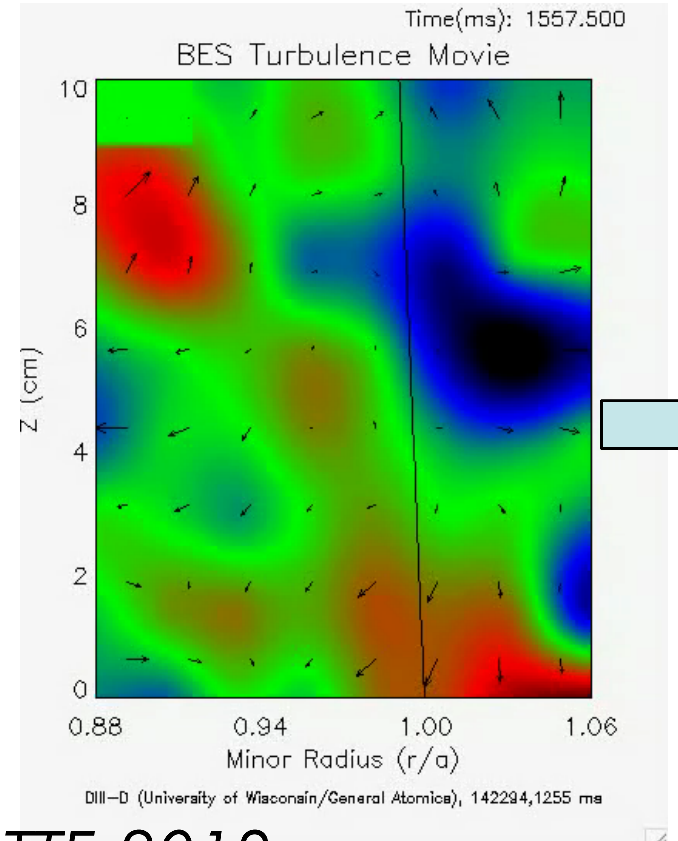
- **Emerging picture of turbulence/flow evolution:**
  - Increasing power flux across separatrix: increased turbulence, ñ/n, just inside separatrix
  - Increasing turbulence alters and increases Reynolds stress drive
  - Increasing RS drives increased zonal flow
  - Transfer of internal energy from turbulence to ZF
  - ZF shearing rate increases, competes with turbulence decorrelation rate

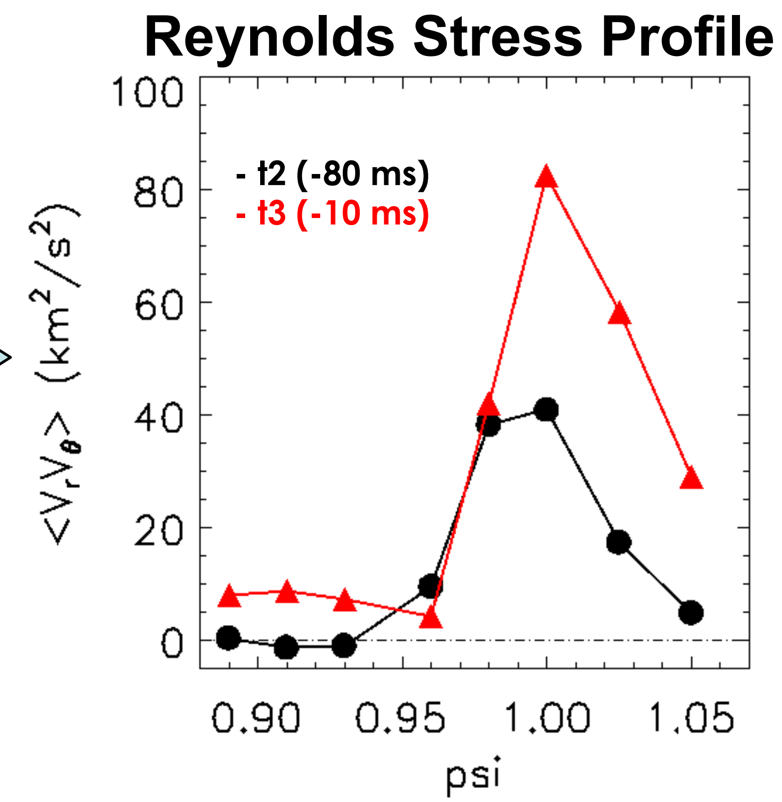
$$\omega_s \sim \tau_c$$

- **L-H Transition!**

Can BOUT++ simulations unravel the unique characteristics of L-mode turbulence on verge of L-H transition?







Z. Yan, IAEA-2012, TTF-2013

L-H Power Threshold Depends on Numerous Parameters

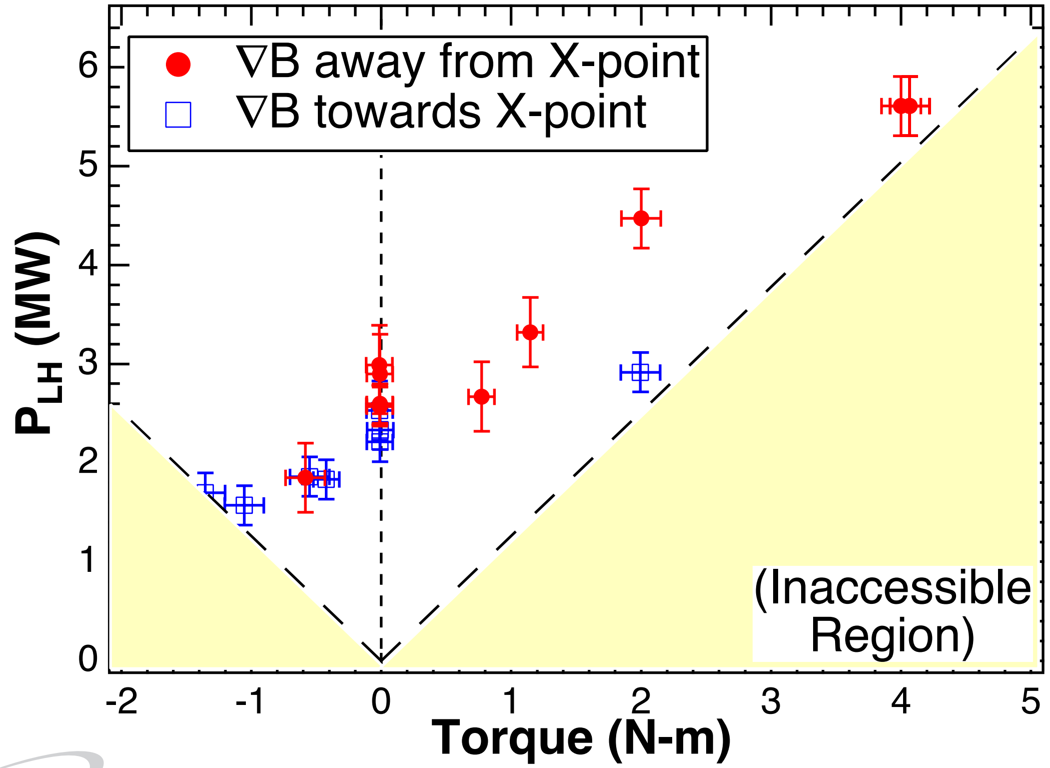
$$P_{LH} = 0.042 n_{20}^{0.73} B_t^{0.74} S^{0.98} \ (MW)$$

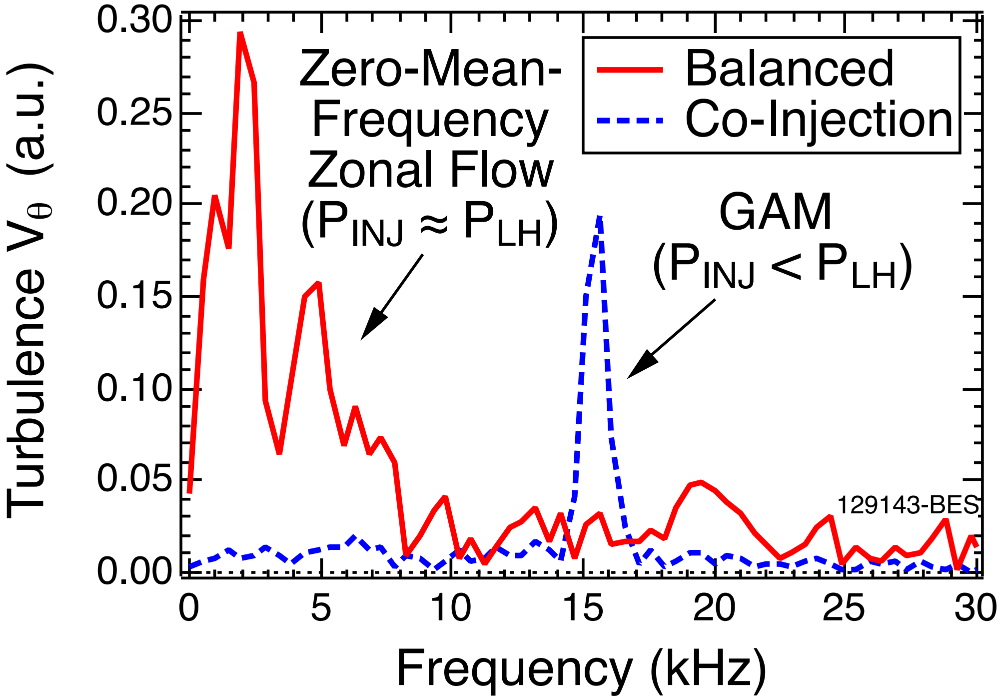
"There are known knowns, known unknowns, and unknown unknowns…" - D.R., 2002

- **Known knowns:**
  - Density, toroidal field, surface area, isotope mass
- **Known unknowns:**
  - Toroidal velocity,
  - Magnetic geometry: ion ∇B drift, SND/DND, triangularity, X-point height,
  - Plasma current
  - Magnetic perturbations (RMP)
- **Unknown unknowns:**
  - Wall material (C, Be/W, Li)
    - *JET ILW*
    - *NSTX*
  - ??

Why does P_{LH} Increase with Toroidal Rotation?

- **Found on DIII-D that P_{LH} increases with toroidal rotation in plasmas with ion ∇B drift directed towards and away from X-point**
  - P_{LH} continues to reduce with counter-injection
- **Equilibrium and turbulence-flow effects play a role**
  - Er and Er' increase at lower rotation
    - *Competition between v_{TOR} and pressure gradient terms*
  - Turbulence mode structure and zonal flow/GAM behavior favors transition at lower rotation



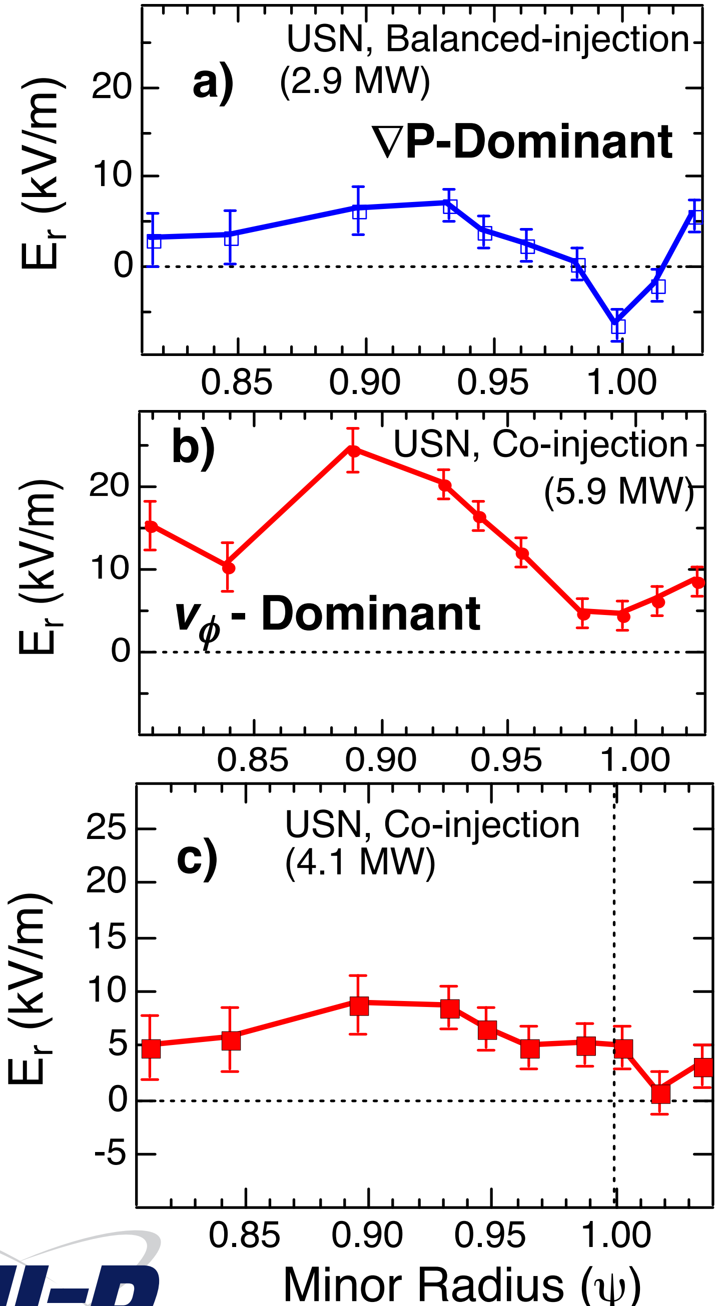


McKee, NF (2009)

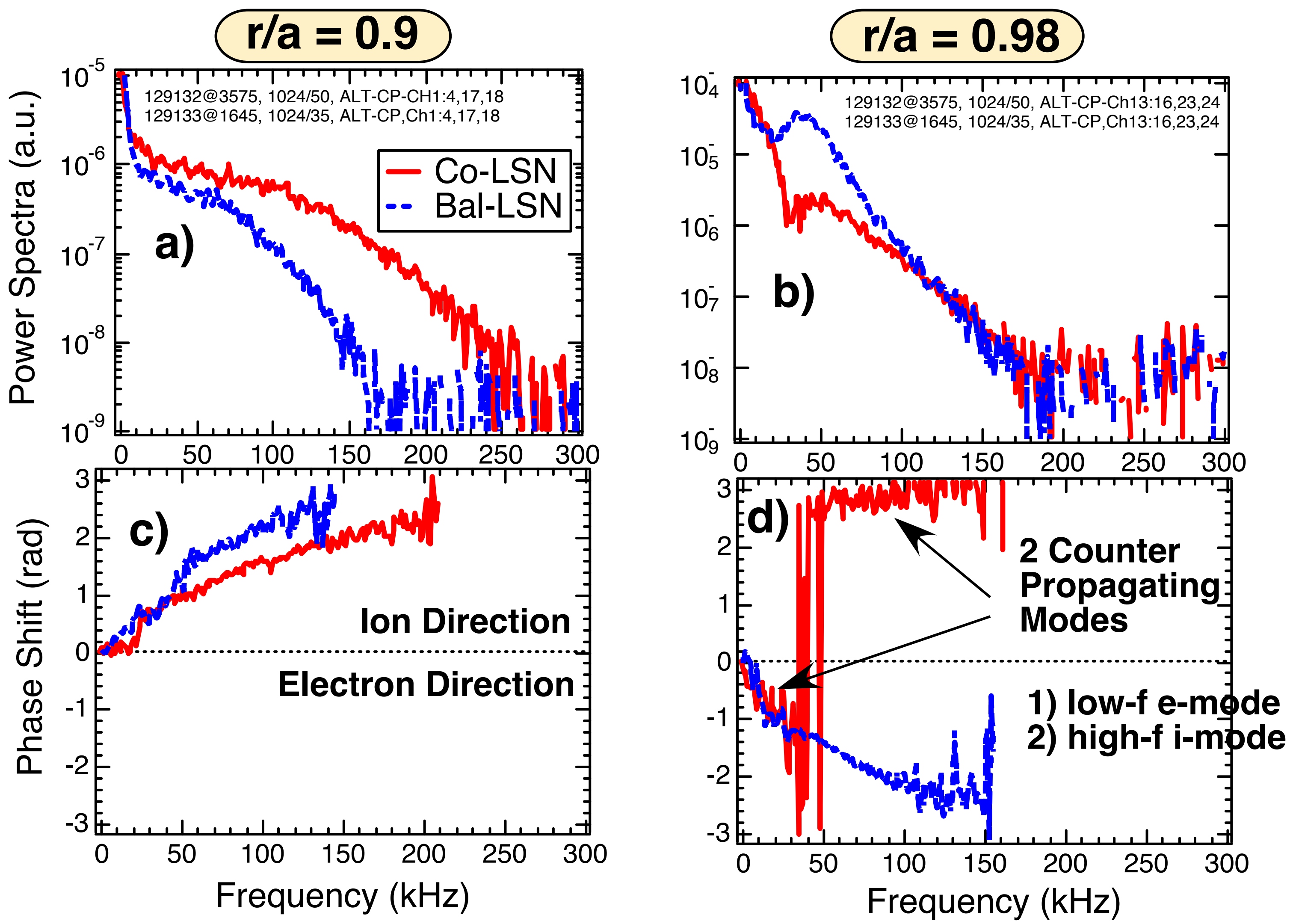
Why does P_{LH} Increase with Toroidal Rotation?

- **Combination of equilibrium and turbulence/zonal flow effects**
  - Multiple turbulence bands sometimes observed in near edge region
    - *Suggests different underlying instabilities co-existing*

L-Mode E_R Profiles



Edge fluctuation spectra reveal sheared flows and multiple bands



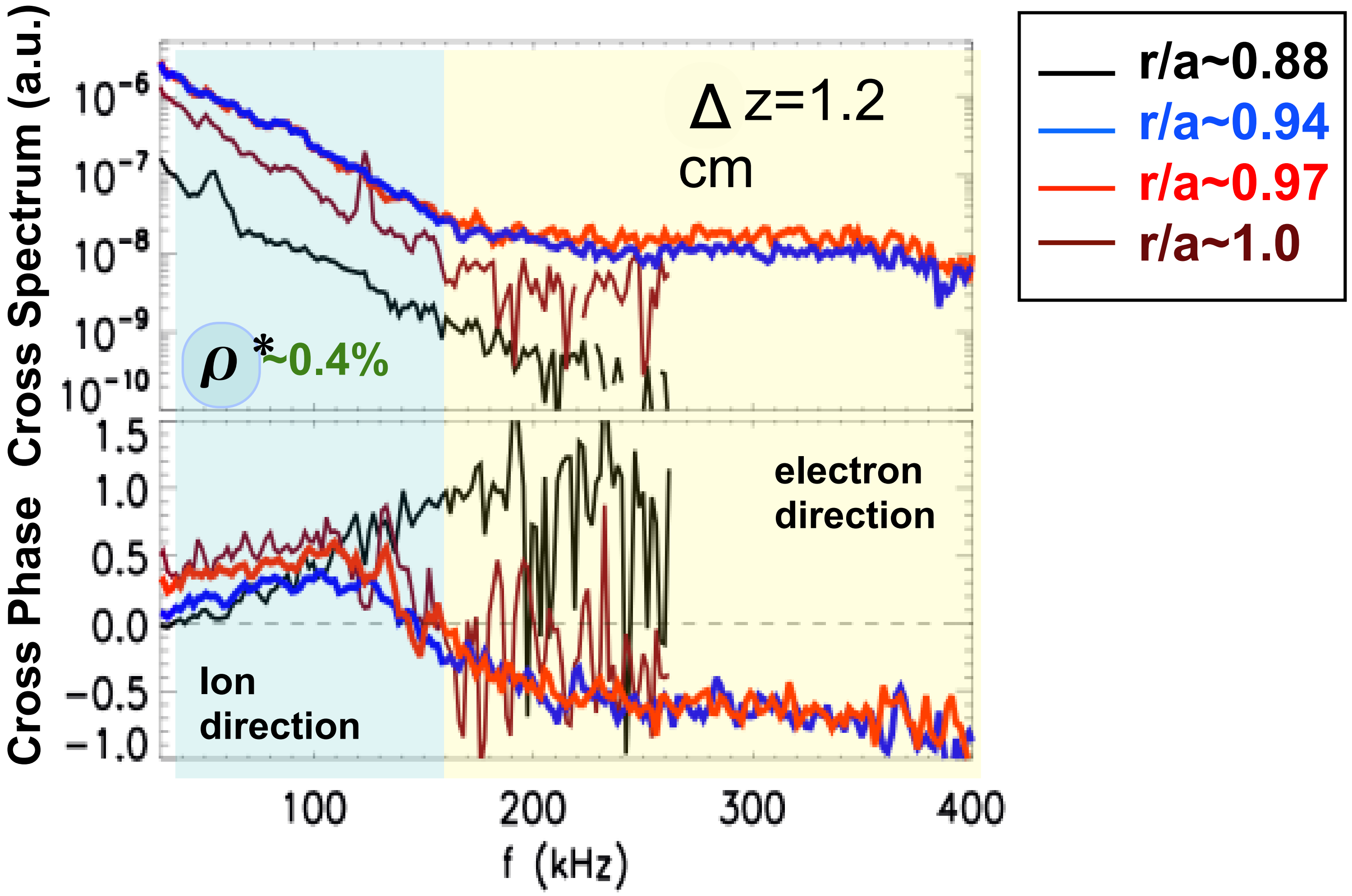
Questions on L-H Transition Physics

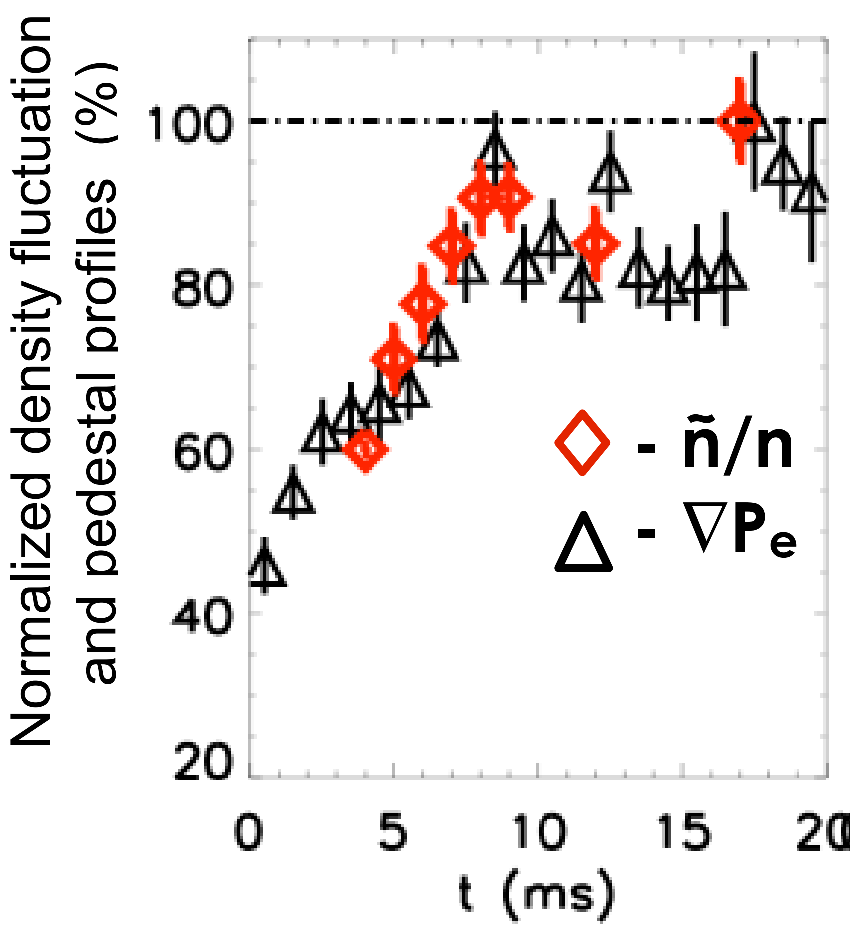
- **Can the Limit-Cycle-Oscillation be reproduced via simulation?**
- **Can a "conventional" (single step) L-H transition be simulated?**
  - What characteristics of the L-mode turbulence differ between a plasma far from L-H vs. one on verge of L-H transition?
- **What determines dependencies on global parameters?**
  - Appears to result from a strong interplay between edge and SOL turbulence and flows
- **What governs hysteresis and back-transition physics?**
  - Impacts operational scenarios (inductance, power supply requirements)
- **Can methods to reduce P_{LH} be identified?**
- **BOUT++ capability to include full diverted, shaped magnetic geometry and interaction of edge and SOL turbulence and flows is key strength**

H-Mode Pedestal Physics

Do Broadband Pedestal Fluctuations Reflect Pressure Gradient-Limiting Instabilities?

- **Two counter-propagating fluctuation bands observed near maximum pressure gradient in ELMing H-Mode**
  - one in electron diamagnetic direction, one in ion
  - Strong spatial dependence
- **Amplitude increases rapidly then saturates during inter-ELM phase**
- **Behavior consistent with expectations for KBM-type modes (low-f)**

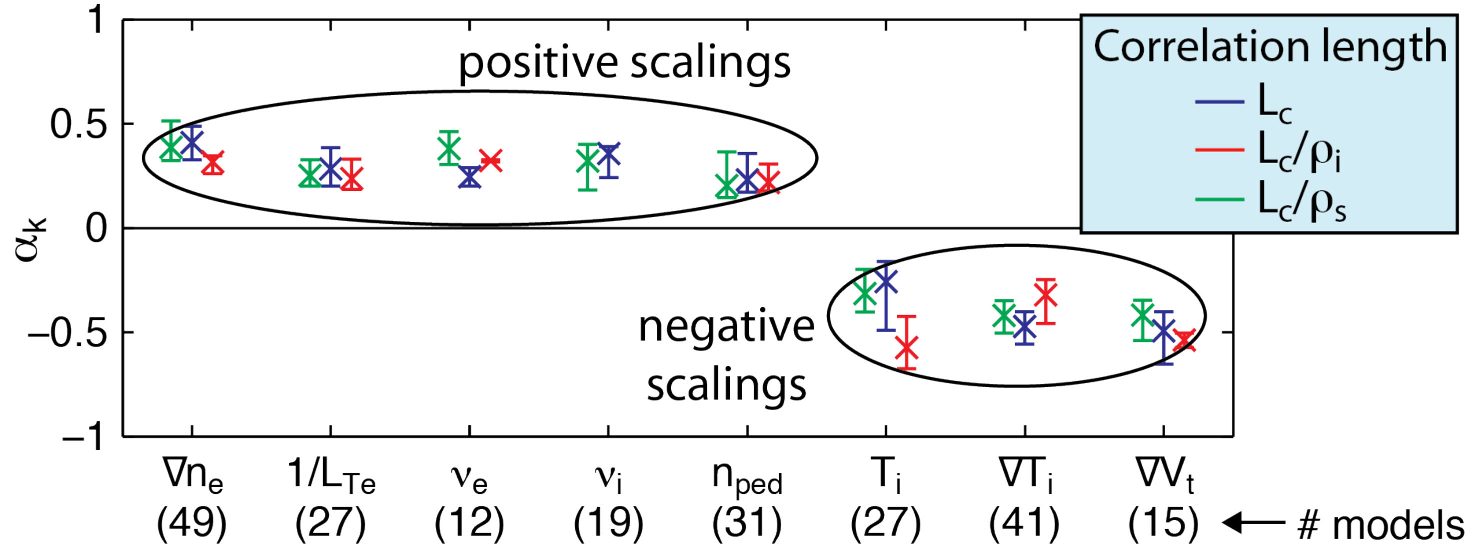




Z. Yan, Phys. Plasmas (2011)

Pedestal Turbulence on NSTX Exhibits Clear Dependencies on Local Parameters and Gradients

L_c scalings



BES Measurements of pedestal turbulence - similar for *k*, tau_c

- **Relations between specific turbulence characteristics (L_{cr}, k, t_c, $\tilde{n}/n$) determined from multiple-shot database**
  - Correlation length exhibits positive scalings with:
    - *Density gradient, Te gradient, collisionality, pedestal density*
  - Negative correlations with: Ti, grad-Ti, grad-Vt
- **Most consistent with TEM-driven turbulence**
  - Somewhat consistent with KBM, micro-Tearing-mode
  - Least consistent with ITG-driven turbulence
- **Qualitative consistency with GEM simulations**
- **Initial BOUT++ simulations (Braginskii) haven't captured relations**
  - Could be related to specific model chosen

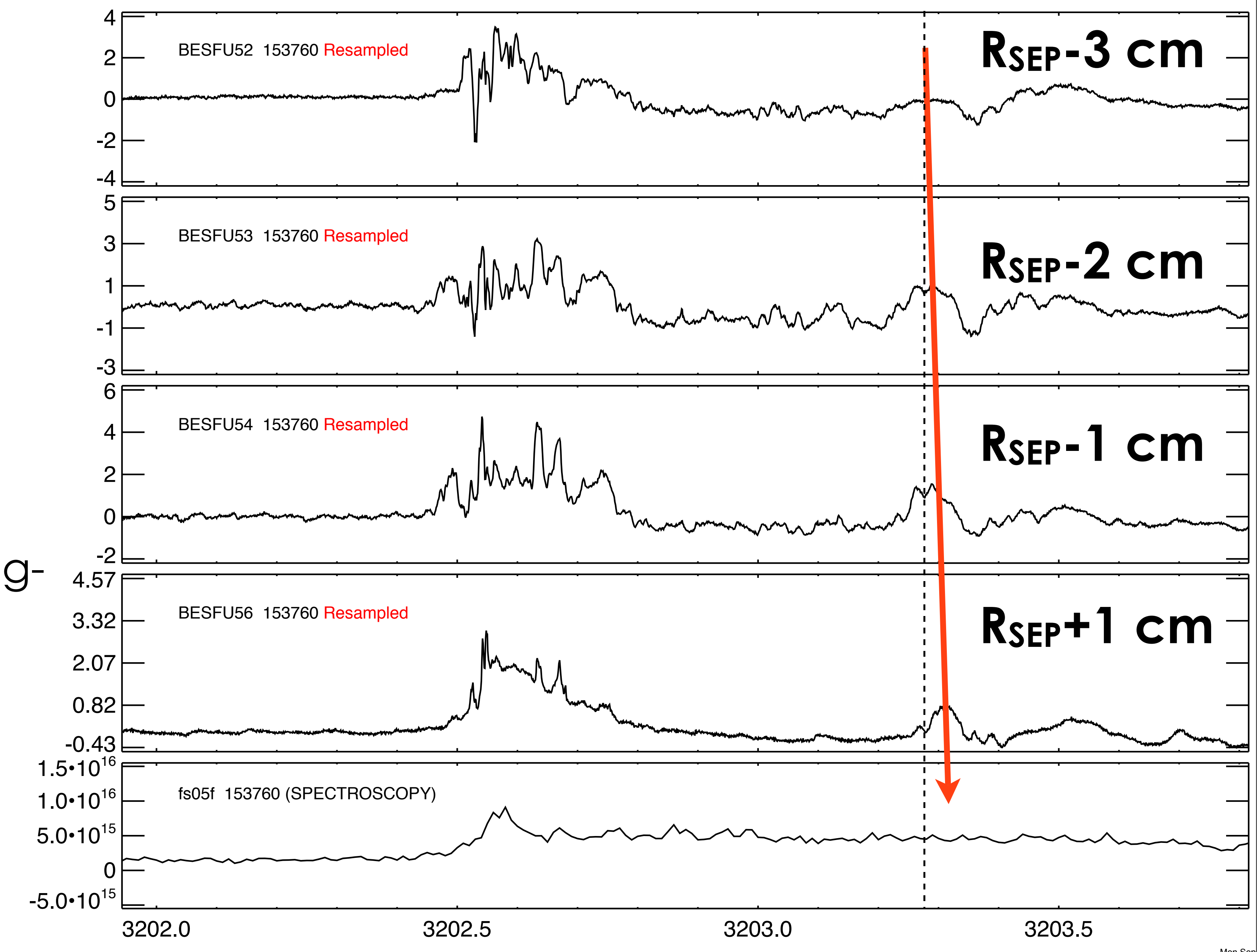
D. Smith, PoP (2013) (poster this workshop)

NSTX-U

Explain the Growth and Nonlinear Evolution of ELMs

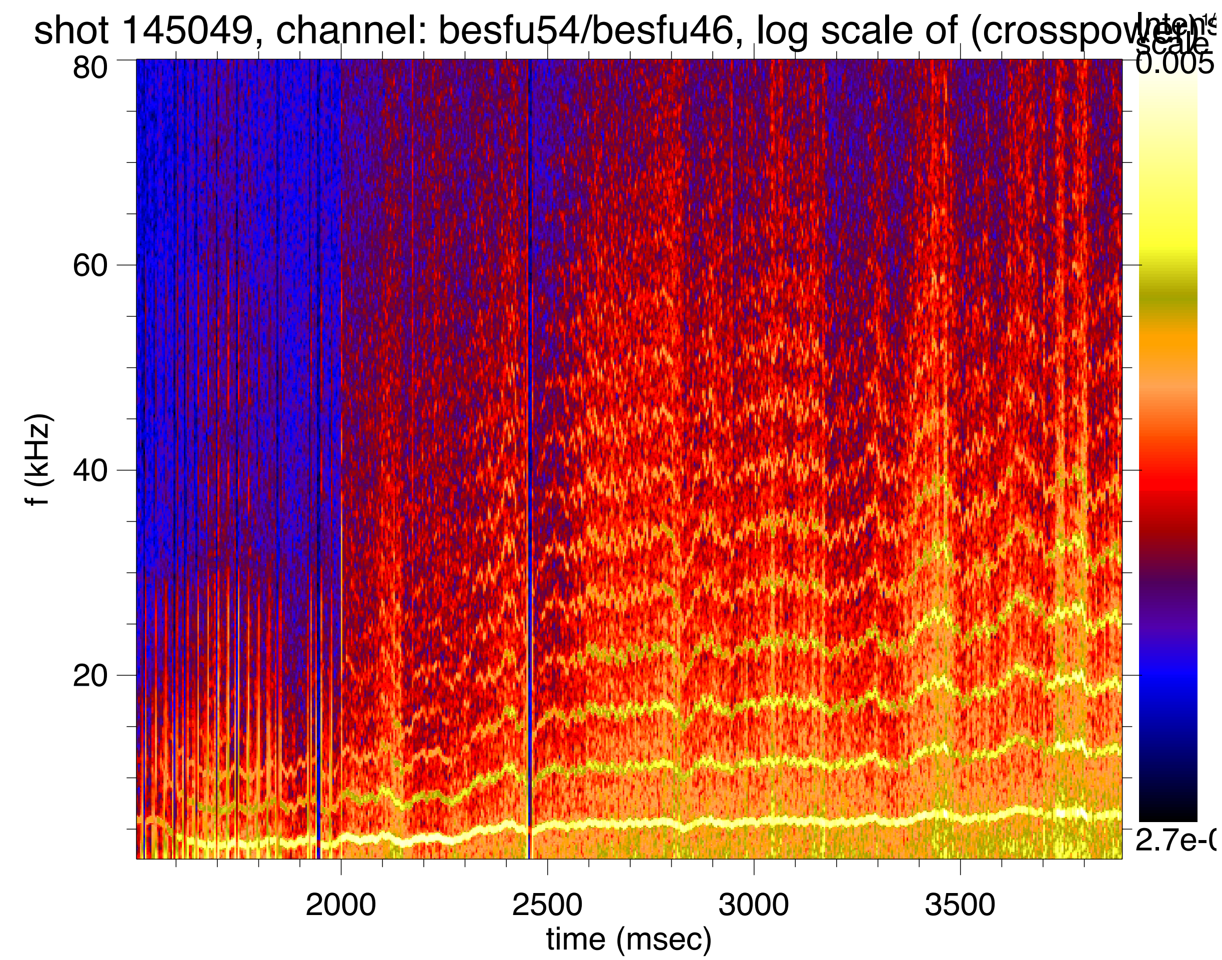
- **Why are precursors evident in some plasma conditions, not others?**
  - Coherent oscillations, can persist for many ms
- **Why does ELM size and frequency depend on collisionality, edge parameters?**
  - Evolution from low-n peeling-ballooning mode to medium-high-n? KBM?
-

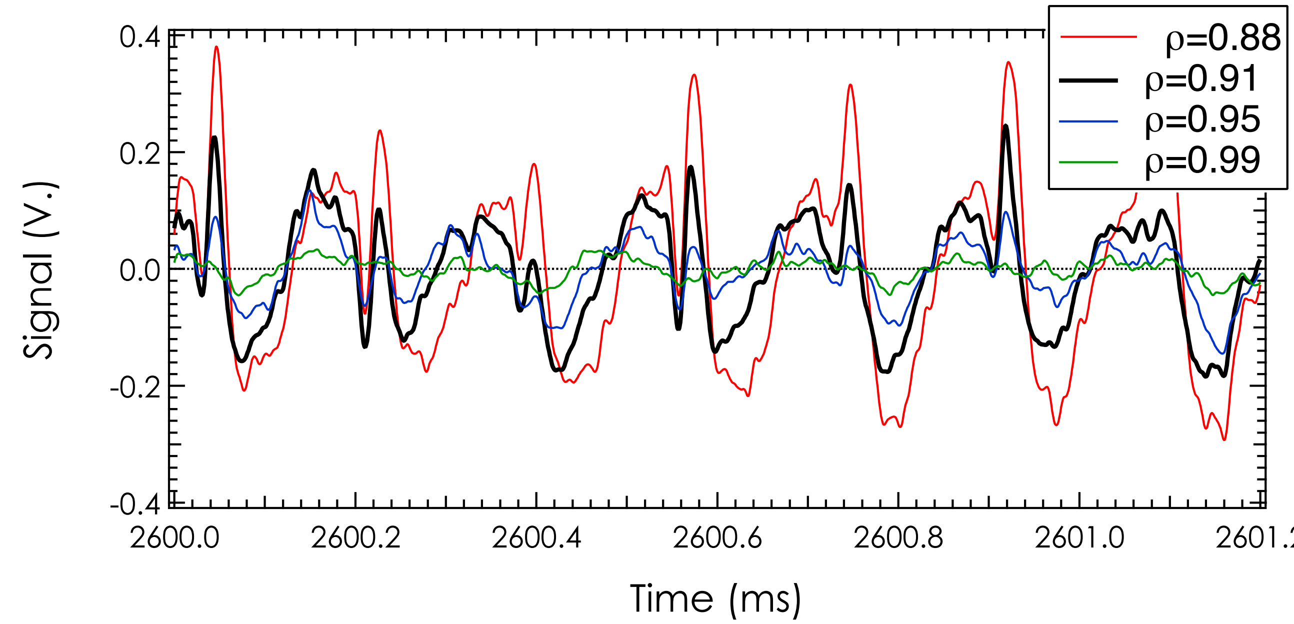
Example of Type-1 ELM Evolution



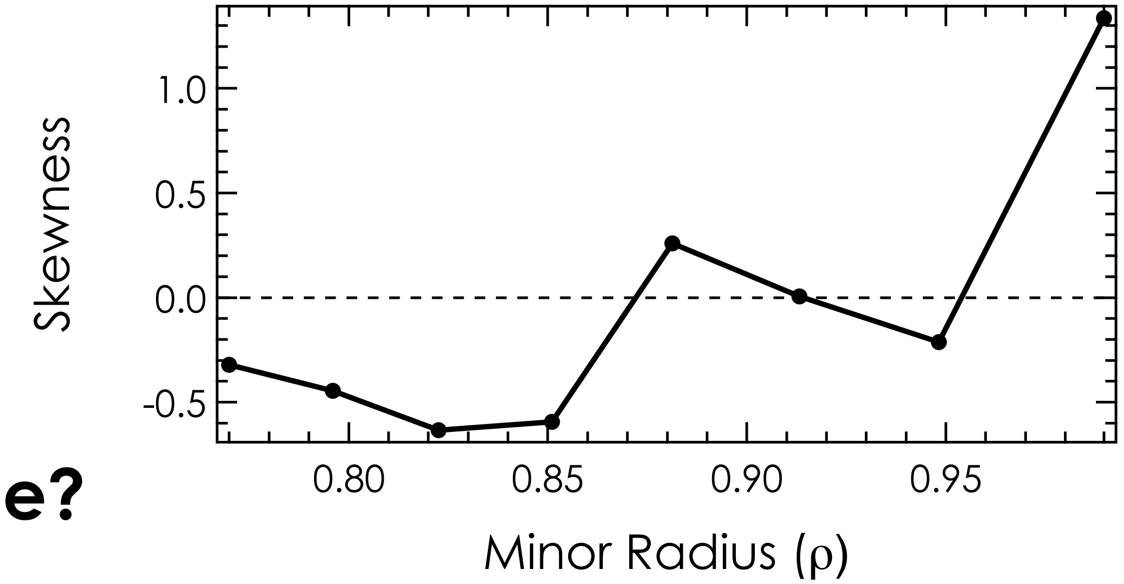
What is Underlying Instability Behind the EHO and how Does It Prevent ELMs?

- **Multiple harmonics (>10) observed**
- **Localized to pedestal vicinity**
- **Quasi-steady, ELM-free**





Radially increasing skewness consistent with outward particle transport

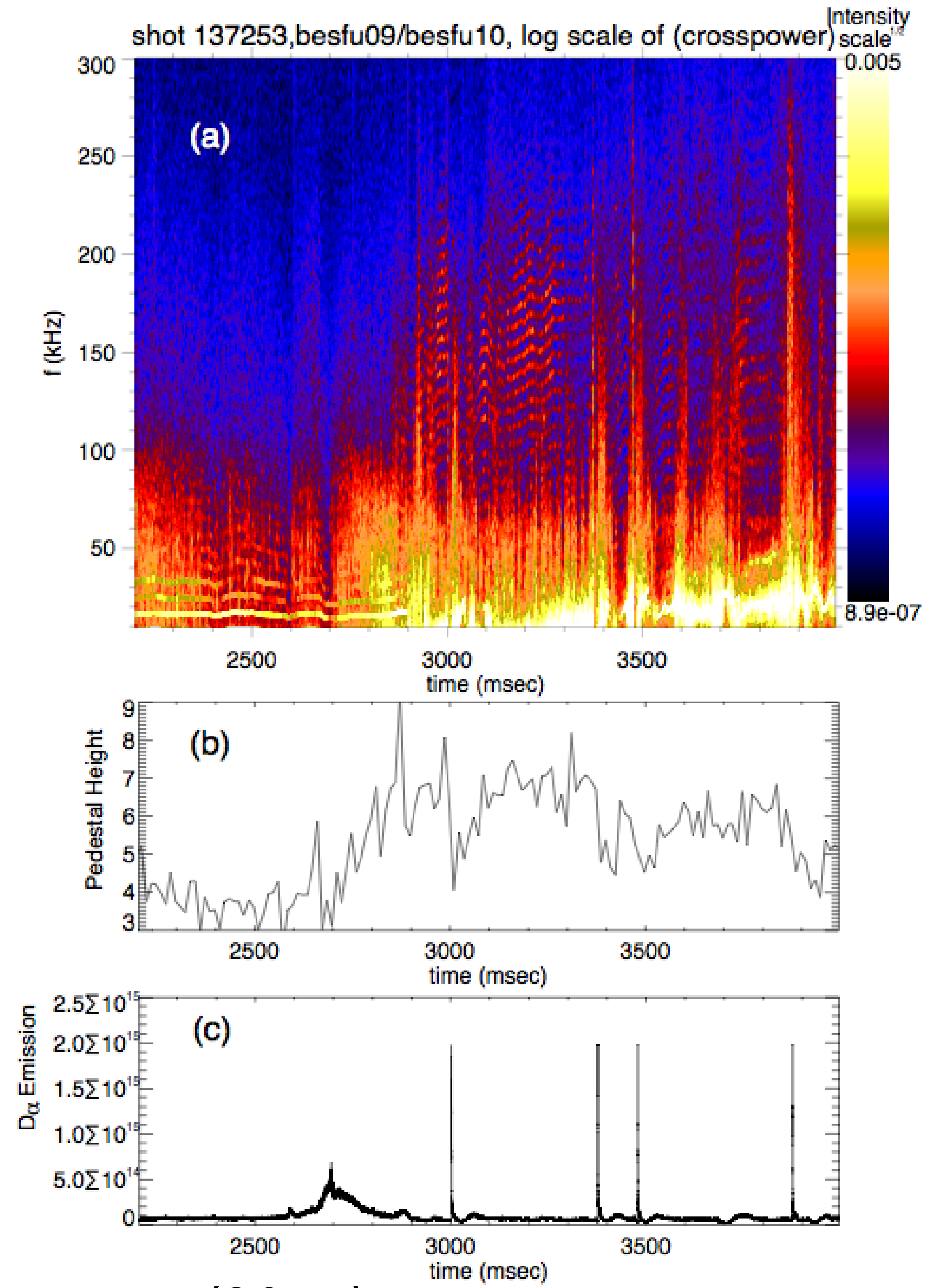


Is EHO a saturated Kink-Peeling Mode?

P. Snyder, NF (2007)

Do High-Frequency Coherent Modes Reflect Kinetic Ballooning Mode Instability?

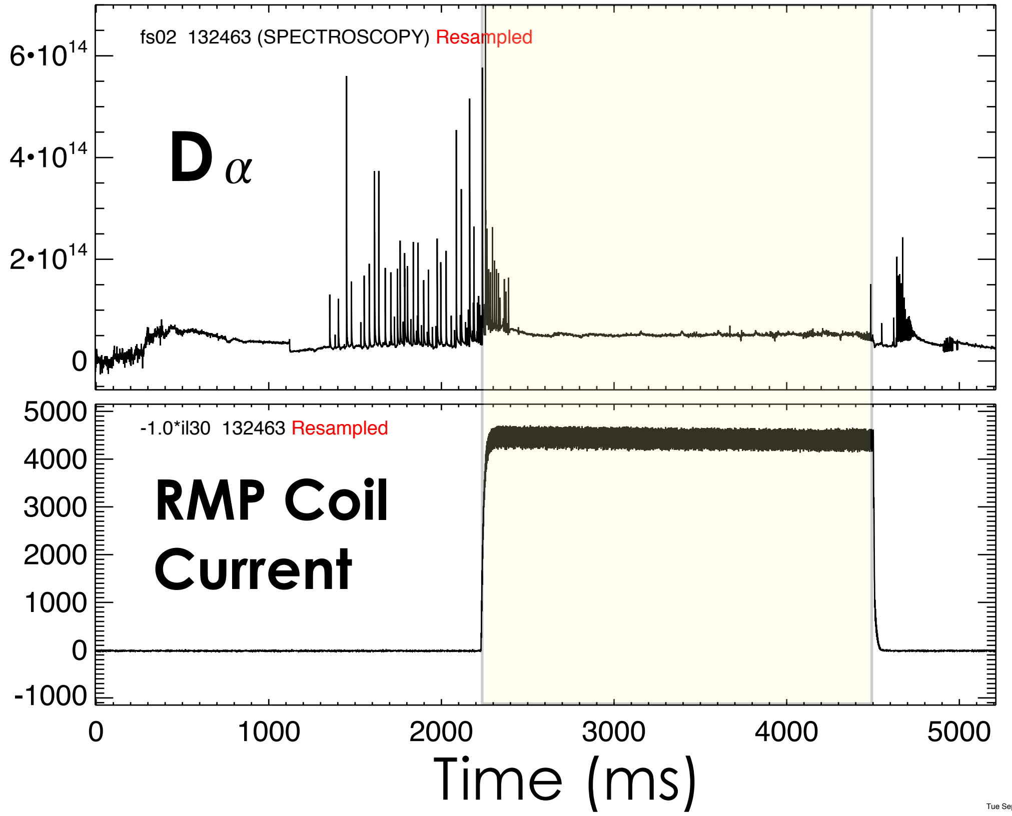
- **Observed in high pedestal-pressure QH-mode plasmas**
- **Exhibit several features predicted for kinetic ballooning modes:**
  - Frequency: 80-250 kHz
  - Dominant n-modes: 10-20
  - Propagate in ion diamagnetic direction
  - $f \sim 0.2\text{-}0.3\ f_{DIA}$
  - High decorrelation rates ($\sim \omega_s$)
- **Coincide with saturation of pedestal pressure**
- **Understanding the transition from EHO-dominant to HFC-dominant pedestal may aid achievement of high-performance ELM-free regimes**



Yan, PRL (2011)

How Do Resonant Magnetic Perturbations Suppress ELMs?

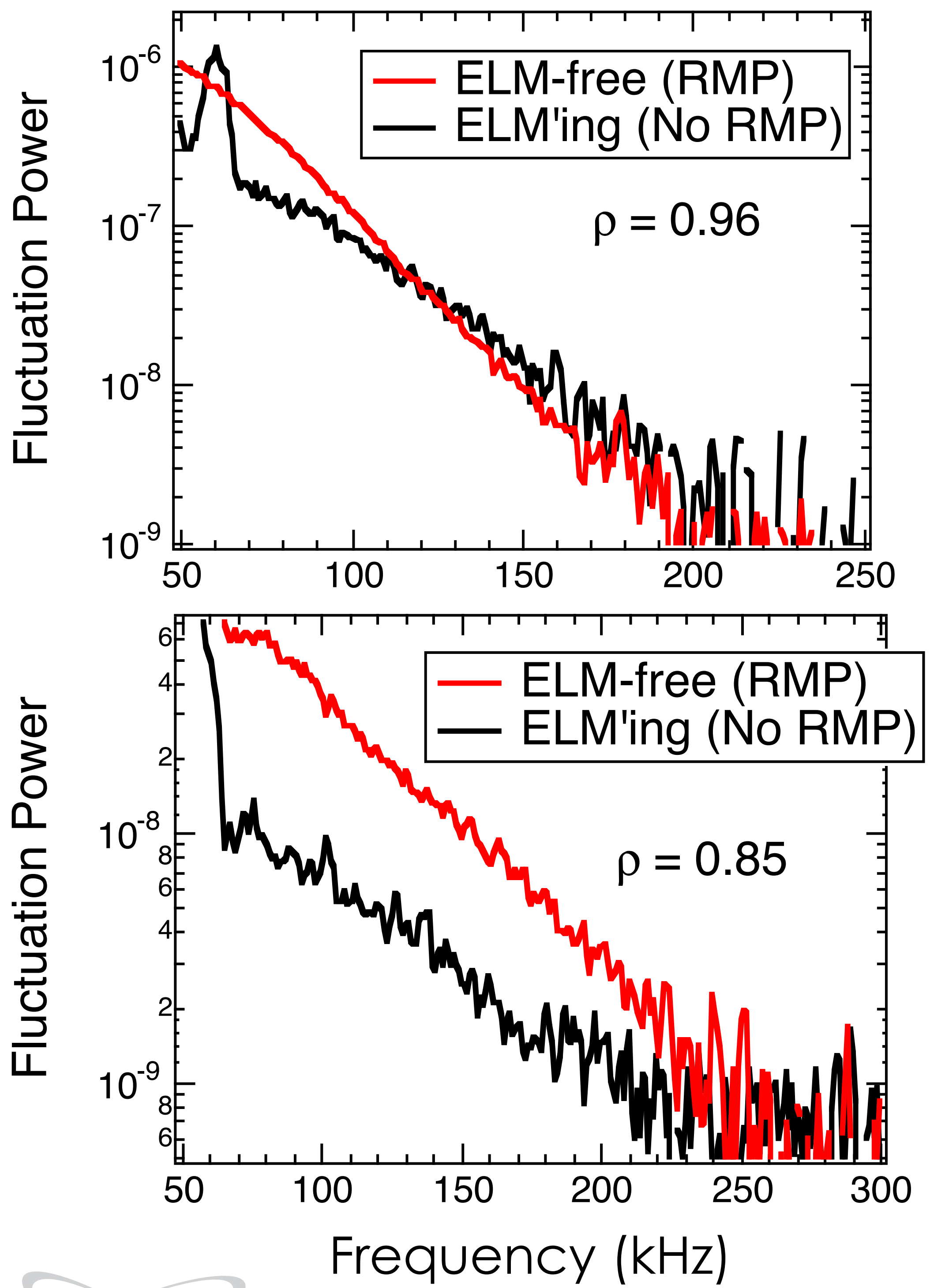
- **RMP successfully suppress ELMs in certain operational regimes**
  - DIII-D: low to moderate collisionality, resonant q-profile (q_{95}~3.5 for n=3)
  - AUG: high density, non-resonant condition (ELM mitigation)
- **RMP increase transport in pedestal (and core)**
  - Density pump-out
  - Reduction in toroidal rotation
  - Energy confinement reduction (usually)
- **Pedestal operational point reduced below P-B stability threshold**
  - Reduced pressure height
- **Main questions:**
  - Why do RMPs increase transport?
    - *Increased turbulence?*
    - *Magnetic flutter?*
  - How is pedestal growth arrested?
    - *Magnetic islands?*
    - *Effects of plasma screening*



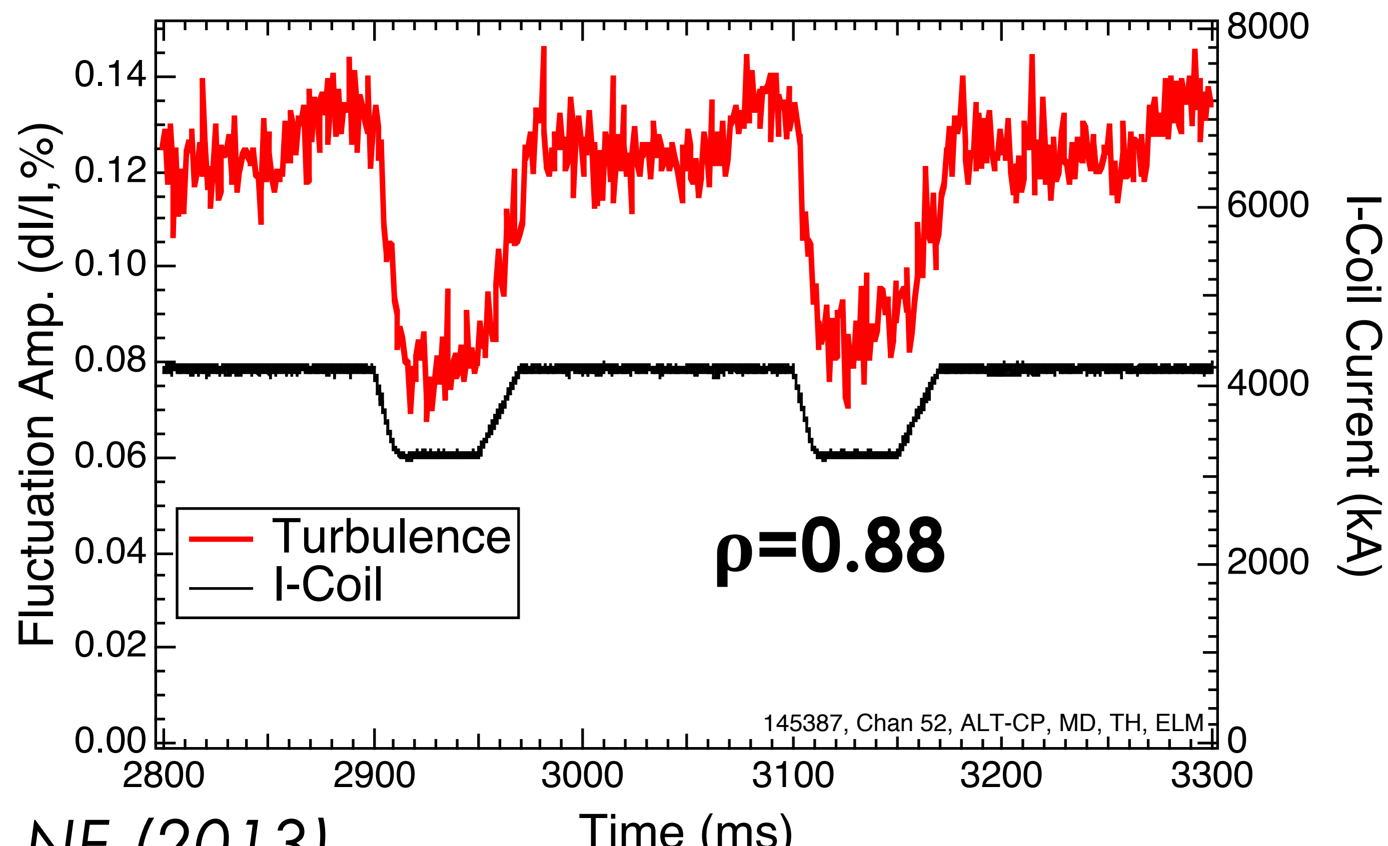
DIII-D NATIONAL FUSION FACILITY

How Does Increased Turbulence Affect Pedestal Stability?

Density Fluctuation Spectra



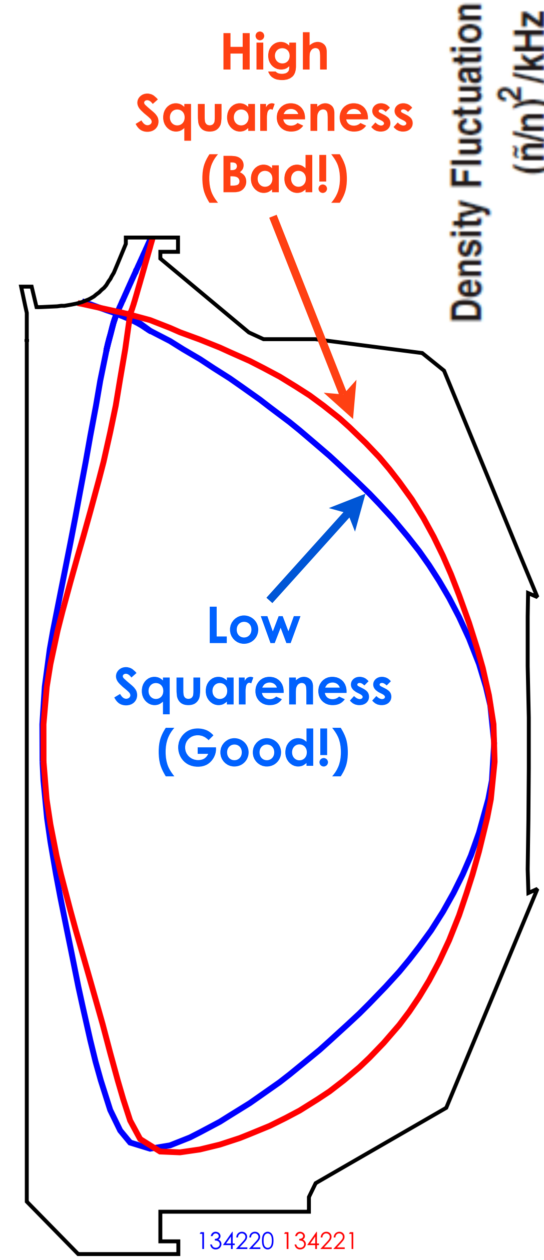
- **Turbulence increases significantly across outer plasma with application of RMP field**
  – Most significant just inside pedestal
- **Responds rapidly to modulated fields**
  – Faster than local gradients/parameters
- **Connected with increased transport**

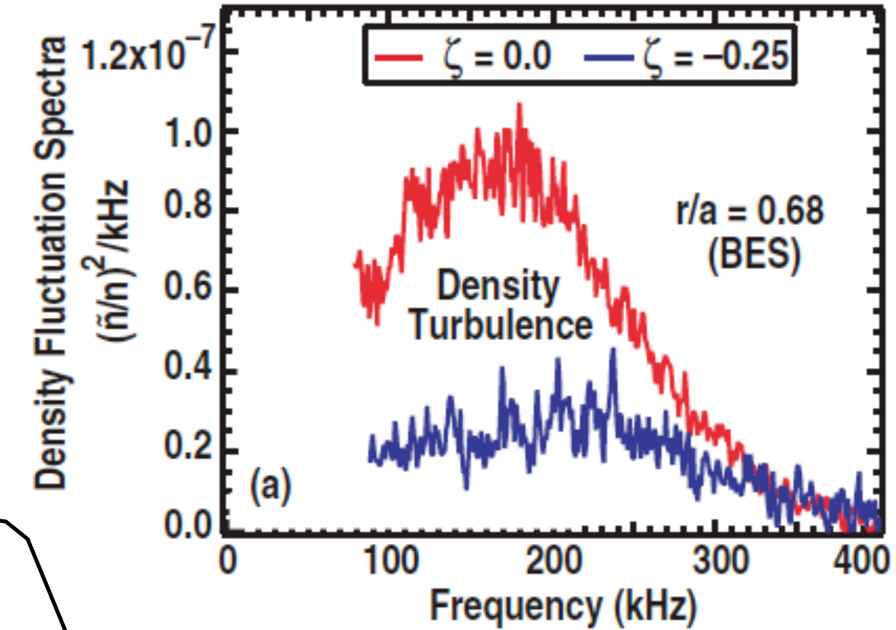


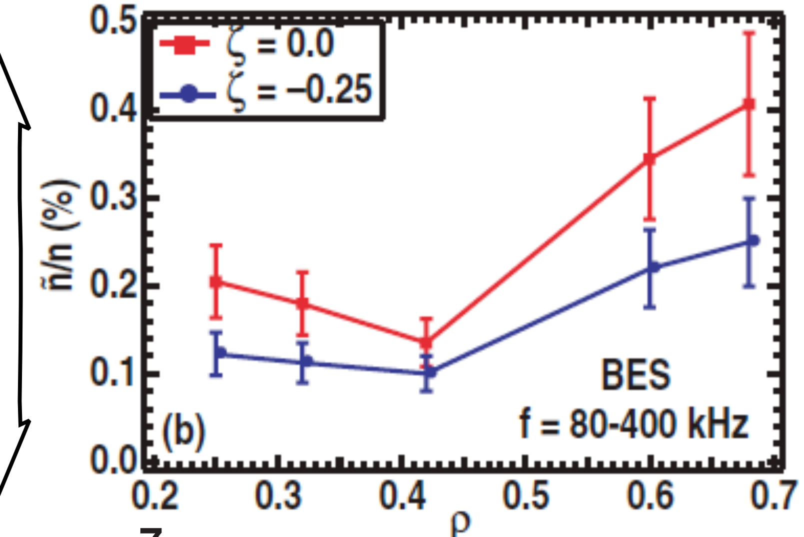
McKee, NF (2013)

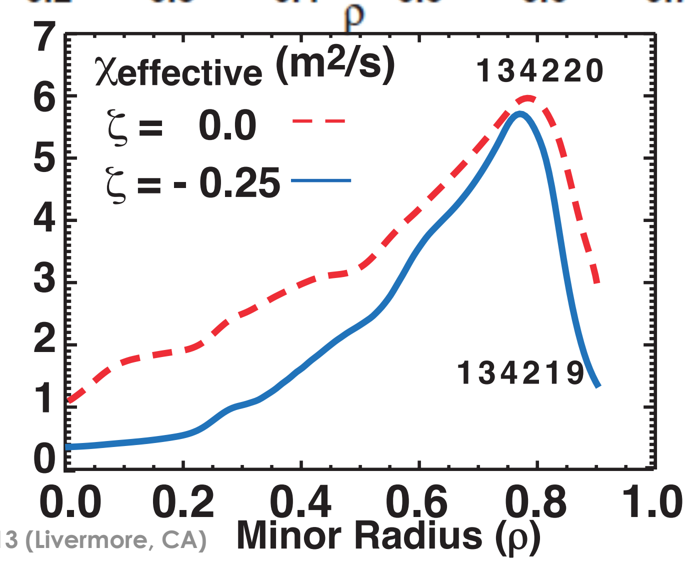
Shape Matters! How does the Tail Wag the Dog?

- **Modest changes to plasma "squareness" shaping parameter dramatically alter core performance:**
  - Increases turbulence
  - Increases ion thermal transport
  - Reduces confinement
- **Pedestal height also impacted**
- **Can we determine underlying causes for transport and pedestal variations with shape?**
- **Can more optimized shapes be developed via simulation?**
  - A la "Super-H" - P. Snyder









C. Holcomb, PoP (2009)

DIII-D
NATIONAL FUSION FACILITY

A few other interesting and important topics ...

- **What is the torque source for intrinsic rotation?**
  - C-MOD, DIII-D other machines have seen large "intrinsic" (external torque-free) toroidal rotation
  - Scalings differ markedly, major impacts on ITER
  - What is the mechanism?
    - *Thermal ion loss near X-point creates radial electric field*
    - *Turbulence-driven Reynolds stress*
- **Why does the Scrape-Off-Layer Width Scale with I_P?**
  - Projections indicate ITER SOL width at midplane ~1-2 mm
  - Extremely high local power flux
- **Scaling of "blobby" transport with density**
  - Implications for L-mode transport in ITER/BP operating near max. density

Summary

- **Greater understanding of experimentally observed behavior will increase confidence in extrapolating the physics to ITER and burning plasmas**
- **Several experimental observations warrant fundamental understanding**
  - L-H transition physics: trigger, parametric dependencies
  - Pedestal instabilities: coherent, broadband fluctuations
  - ELM-free operation: Edge Harmonic Oscillation (QH), Quasi-Coherent Mode (EDA)
  - Nonlinear ELM evolution, collisionality dependence
  - Resonant Magnetic Perturbation ELM-suppression mechanism
  - Shaping effects
  - Intrinsic rotation
- **Strengths of BOUT++ in simulating turbulence, transport and flows, in realistic shapes and accounting for edge/SOL interactions can greatly benefit experimental investigations to understand behavior and optimize performance**

Quantitative Comparisons of Edge Measurement Phenomena Will Advance Validation of Simulations and Reveal Physics

- **Extrapolate current knowledge to ITER and Burning Plasmas**
  - ITER will most likely have significantly less capability to measure detailed edge and pedestal phenomena given harsh environment and diagnostic limitations
- **Focus on experimentally observed phenomena that are:**
  - Unexpected theoretically
  - Important (possibly...)
  - Scientifically interesting
  - Fun!
- **What would we like to measure vs. what we can measure**
  - Diagnostics: finite spatial, k-resolution, limited signal-to-noise
  - Simulations: computational time, mesh-size, "plasma" time
  - Using synthetic diagnostics for quantitative comparison (C. Holland)
- **What can the experimental community learn from BOUT++ simulations?**
- **What new measurements would be desired by theory and simulation community?**