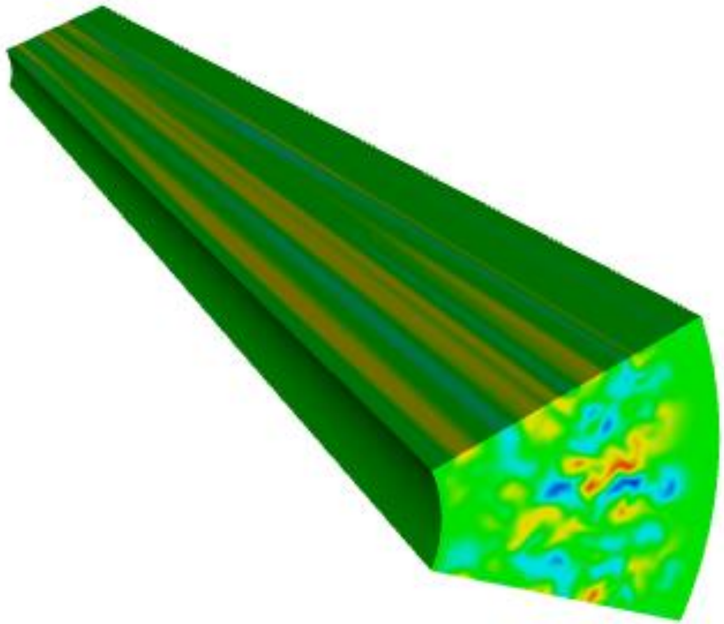
Energy Dynamics in a Simulation of LAPD Turbulence



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Summary

- **A two fluid plasma model is used to simulate zero mean flow density gradient driven drift wave turbulence in the LArge Plasma Device (LAPD). The code used is BOUT++.**

- **Spectral energy dynamics are used to show where energy is injected and dissipated in the simulation, revealing a picture very different from what one would expect based on linear drift wave properties.**

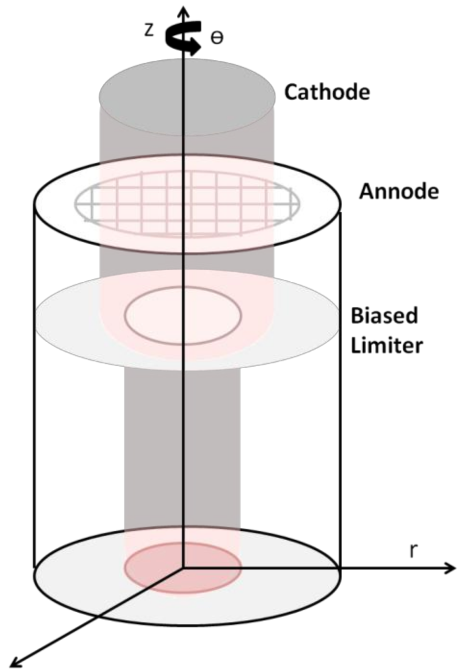
- **We find that although a linear drift wave instability exists in the system, a nonlinear instability provides the dominant turbulent drive mechanism in the standard simulation. The nonlinear instability relies upon axial wavenumber transfer between finite and infinite wavelength modes.**

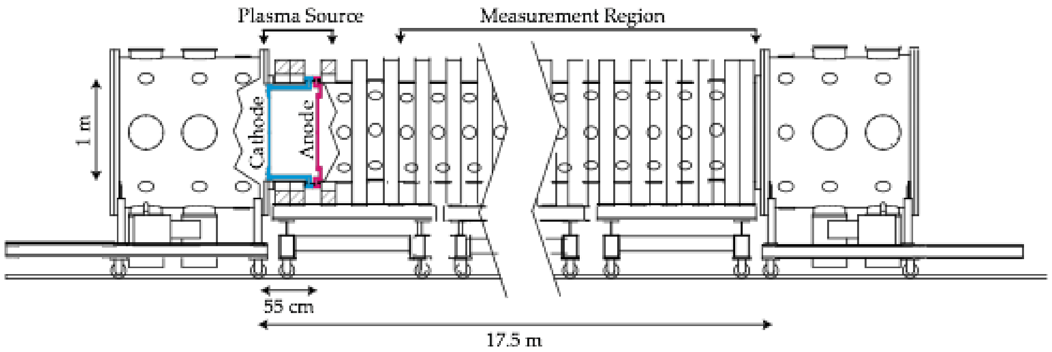
LAPD is Suitable for Collisional Plasma Fluid Model

Machine and plasma size:
Plasma column length $\sim 17\ m$
Plasma radius $\sim 30\ cm$

Typical LAPD operational parameters:
$0.4 < B_0 < 2\ kG$
$10^{11} < n_e < 4 \times 10^{12}\ cm^{-3}$
$0.5 < T_e < 8\ eV$
$0.5 < T_i < 1.5\ eV$
$f_{ci} \sim 400\ KHz$
$\nu_{in} \sim 2\ KHz$
$\nu_{ei} \sim 5\ MHz$
$\frac{\omega}{k_{\parallel}} \leq v_{the}$
$\nu_i/\omega_{ci} \sim 1$

$\lambda_{ei}/L_{\parallel} \sim 0.01$
$k_{\perp}\rho_i \sim 0.1$





Model Equations as Written for BOUT++

Continuity equation

$$\frac{\partial N}{\partial t} = -\mathbf{v}_E \cdot \nabla N_0 - N_0 \nabla_{\|} v_{\|e} + \mu_N \nabla_{\perp}^2 N + S_N + \{\phi, N\}$$

Parallel electron momentum equation

$$\frac{\partial v_{\|e}}{\partial t} = -\frac{m_i}{m_e}\frac{T_{e0}}{N_0}\nabla_{\|} N + \frac{m_i}{m_e}\nabla_{\|}\phi - \nu_e v_{\|e} + \{\phi, v_{\|e}\}$$

Energy balance equation

$$\frac{\partial T_e}{\partial t} = -\mathbf{v}_E \cdot \nabla T_{e0} - 1.71\tfrac{2}{3} T_{e0} \nabla_{\|} v_{\|e} + \tfrac{2}{3N_0}\kappa_{\|e}\nabla_{\|}^2 T_e - \tfrac{2m_e}{m_i}\nu_e T_e + \mu_T \nabla_{\perp}^2 T_e + S_T + \{\phi, T_e\}$$

Charge conservation / Vorticity equation

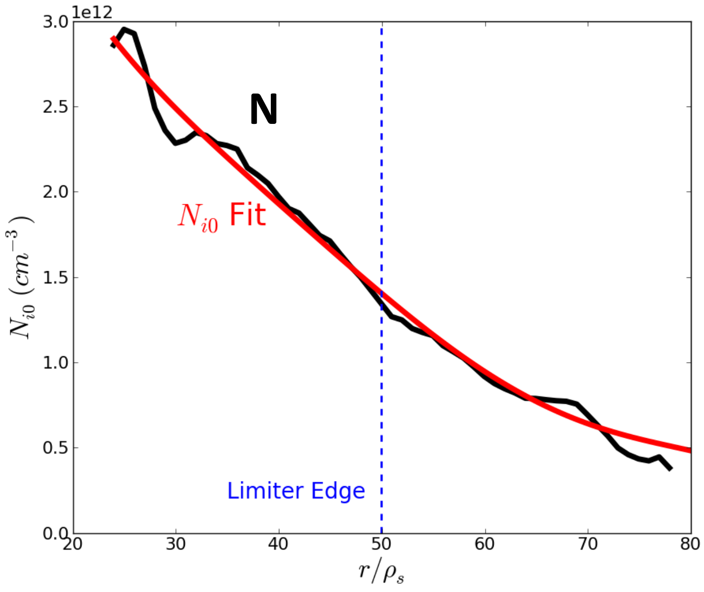
$$\frac{\partial \varpi}{\partial t} = -N_0 \nabla_{\|} v_{\|e} - \nu_{in}\varpi + \mu_\phi \nabla_{\perp}^2 \varpi + \{\phi, \varpi\}$$

$$\varpi = \nabla_{\perp} \cdot (N_0 \nabla_{\perp}\phi)$$

- **Electrostatic**
- **Only advective nonlinearities**
- **Artificial diffusions and viscosity.**

Verification and validation studies:
Popovich et al 2010, Umansky et al 2011
Grid convergence study
Friedman et al 2012

Experimental Profiles Used in Simulation

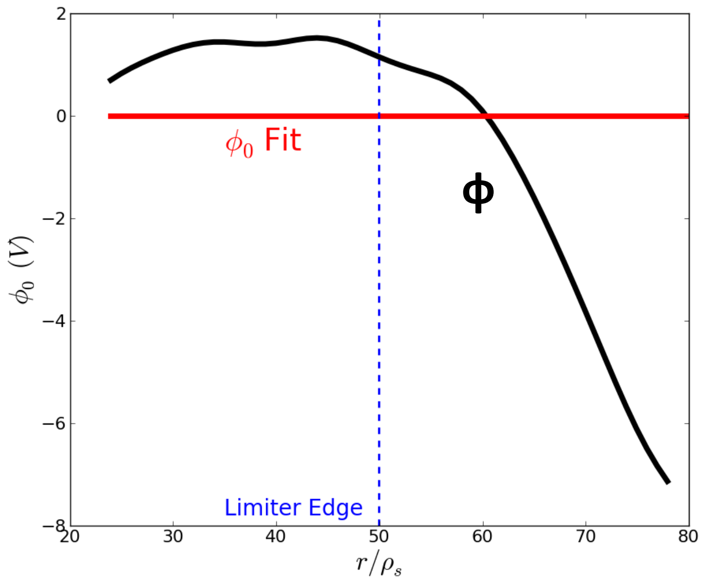


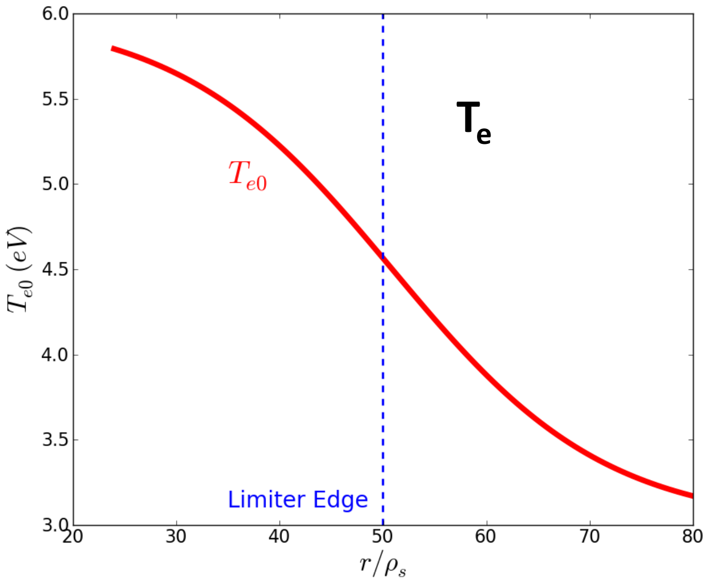
- **Density equilibrium profile fit to experiment.**
- **Density source – subtracts m=0 density fluctuation component.**

- **T_e is a typical looking tanh fit**
- **T_i = 0 eV**

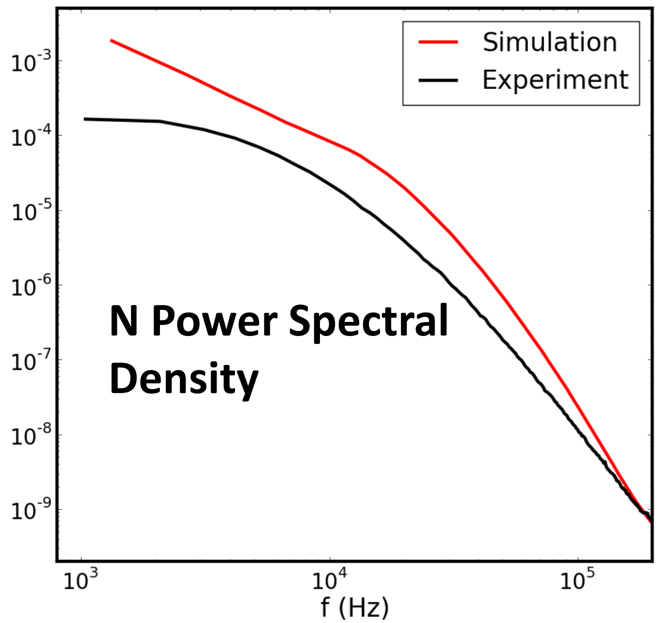
- **Zero mean potential profile.**
- **Zonal flows evolved.**

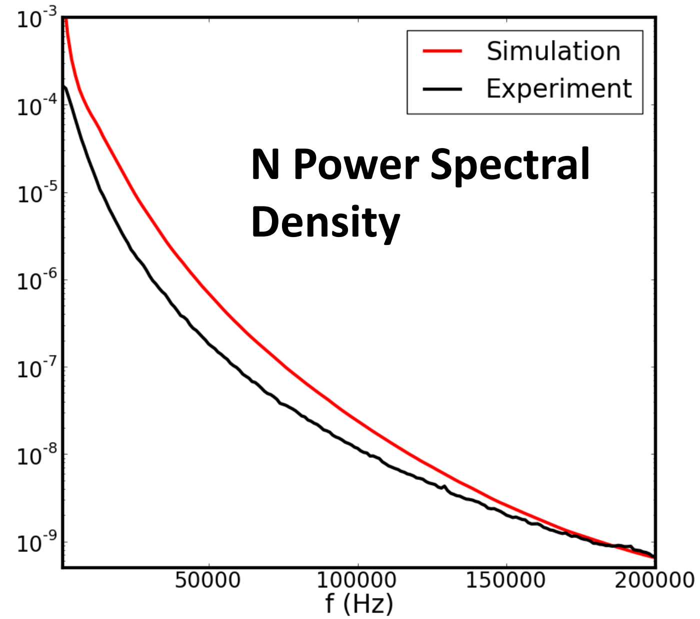
- **Periodic axial BC. Dirichlet radial BC.**

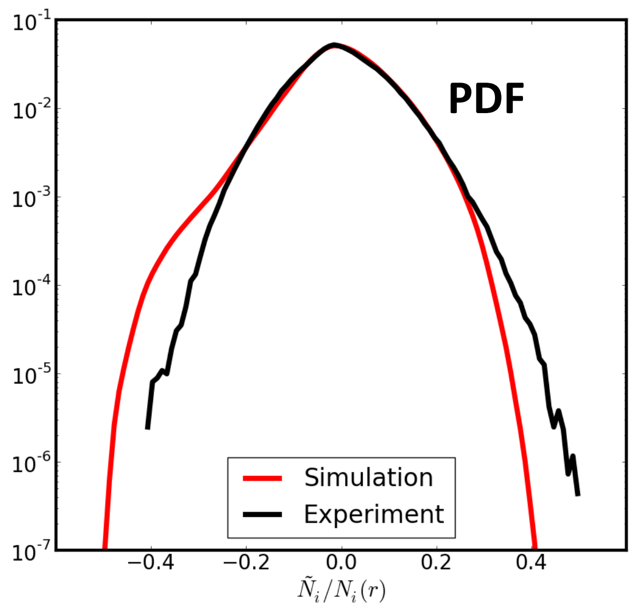


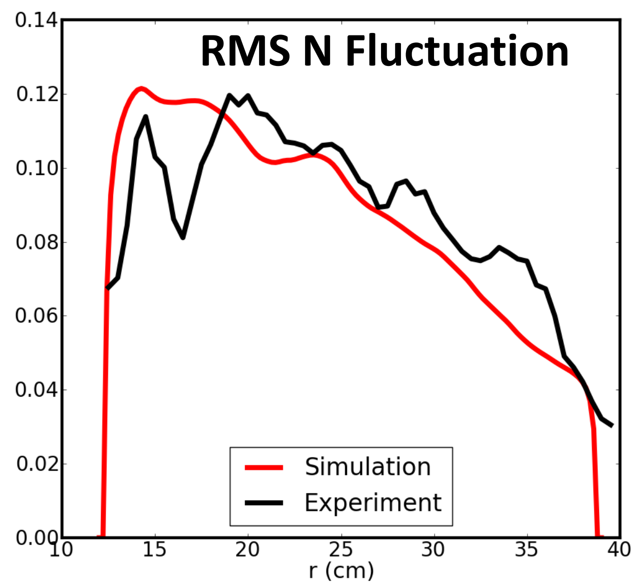


BOUT++ and LAPD Experimental Density Fluctuations Have Similar Statistical Properties

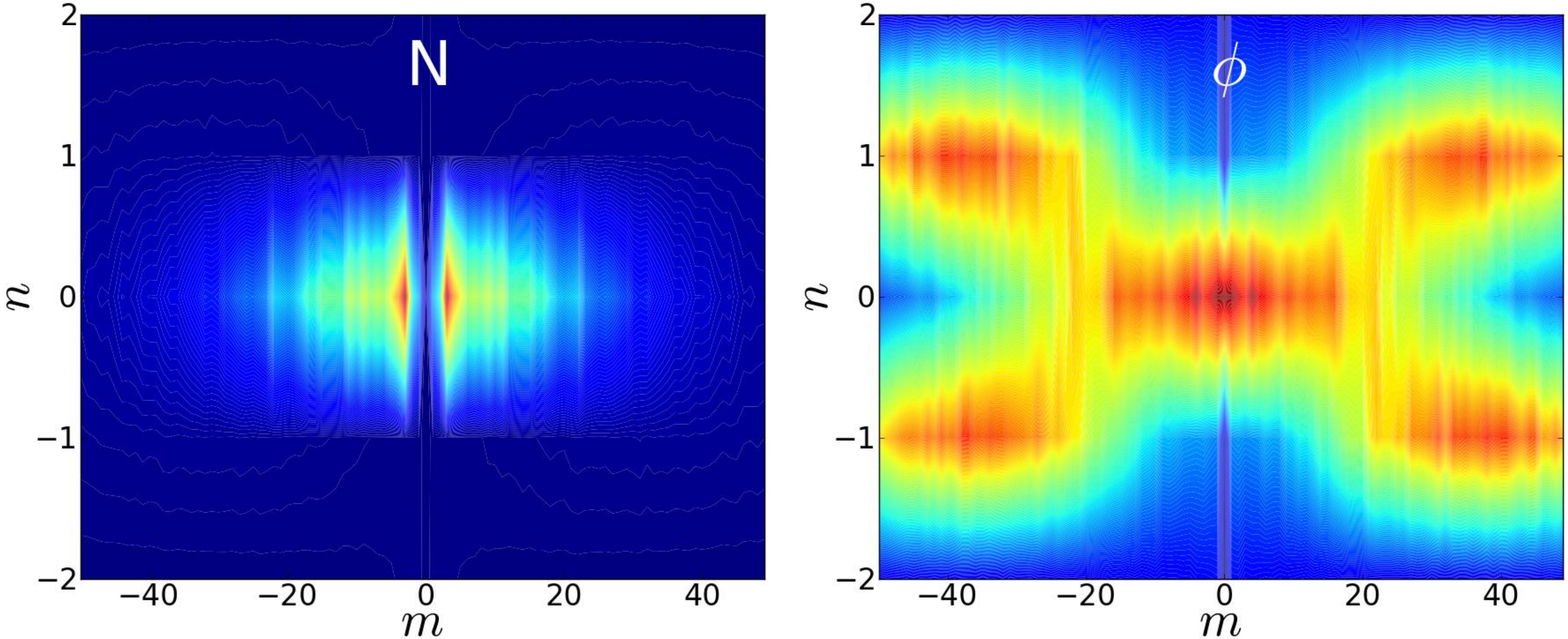








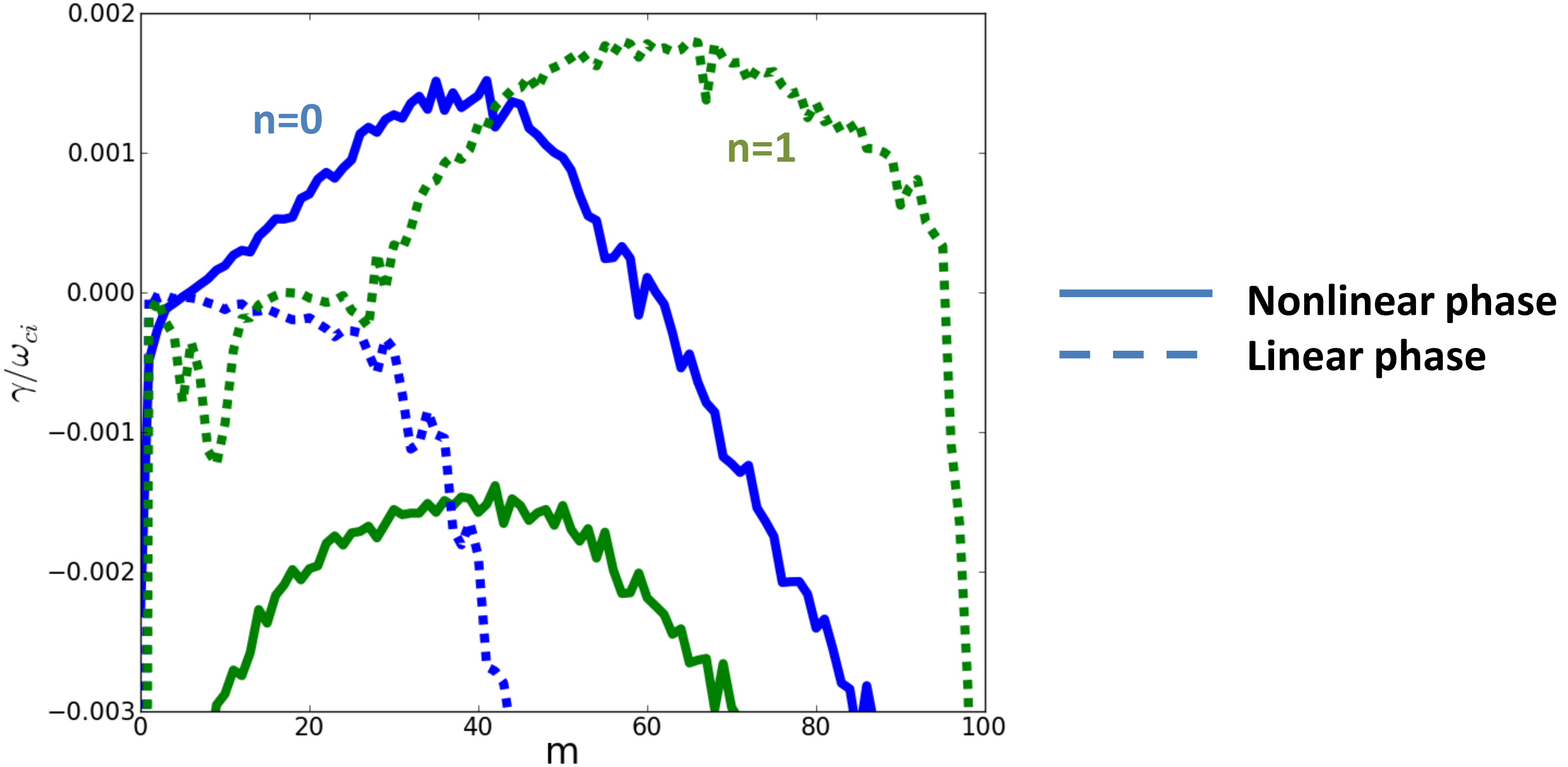
Energy Clusters in n=0 Flute Structures Due to a Nonlinear Instability that Overcomes the Linear Drift Wave Instability



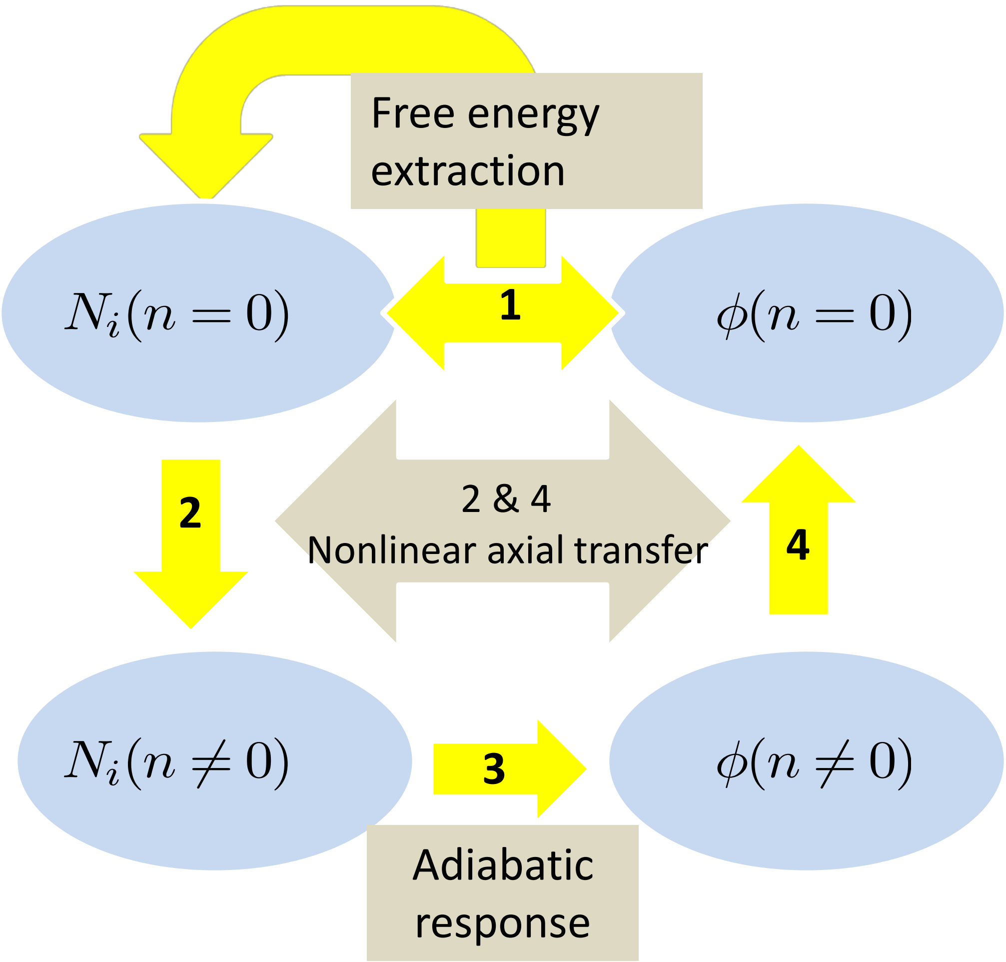
- Linear drift waves only inject energy at finite n
- n=0 flute modes are not a result of secondary instability, interchange instability, or KH instability. They are driven by a primary nonlinear instability

Total Nonconservative Energy Dynamics Show that Linear Stability Properties are Dominated by Self-Sustained Turbulent Dynamics

$$\gamma(\mathbf{k}) = \frac{\partial \mathbf{E_{tot}}(\mathbf{k})/\partial \mathbf{t}}{\mathbf{2E_{tot}}(\mathbf{k})}$$



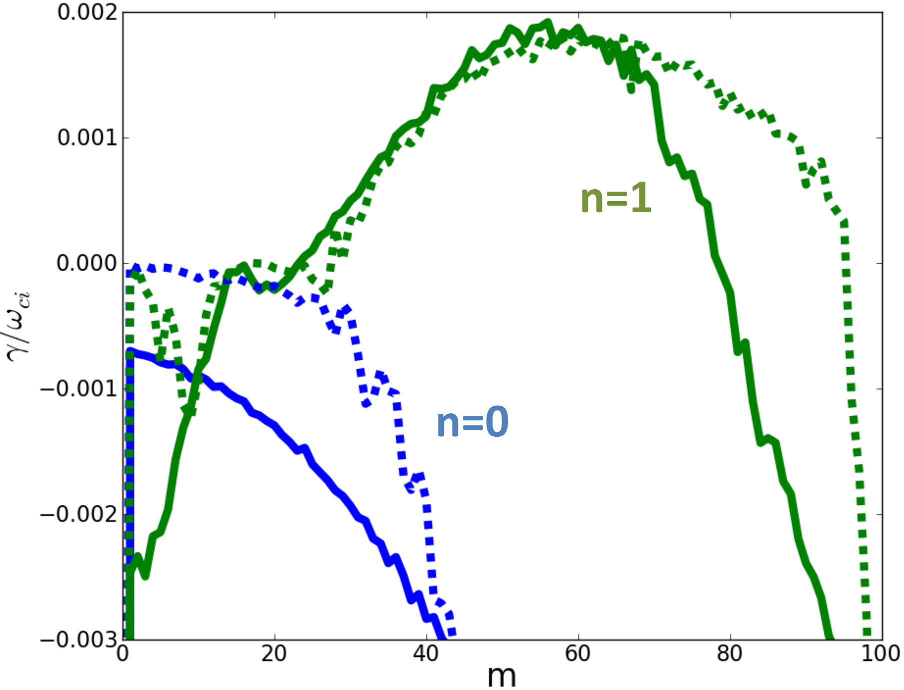
Main Energy Dynamic Mechanism Involves an Interplay of Density and Potential Fluctuations with Both n=0 and n≠0. Temperature Fluctuations Are Unimportant.



Biskamp et. al. 1995

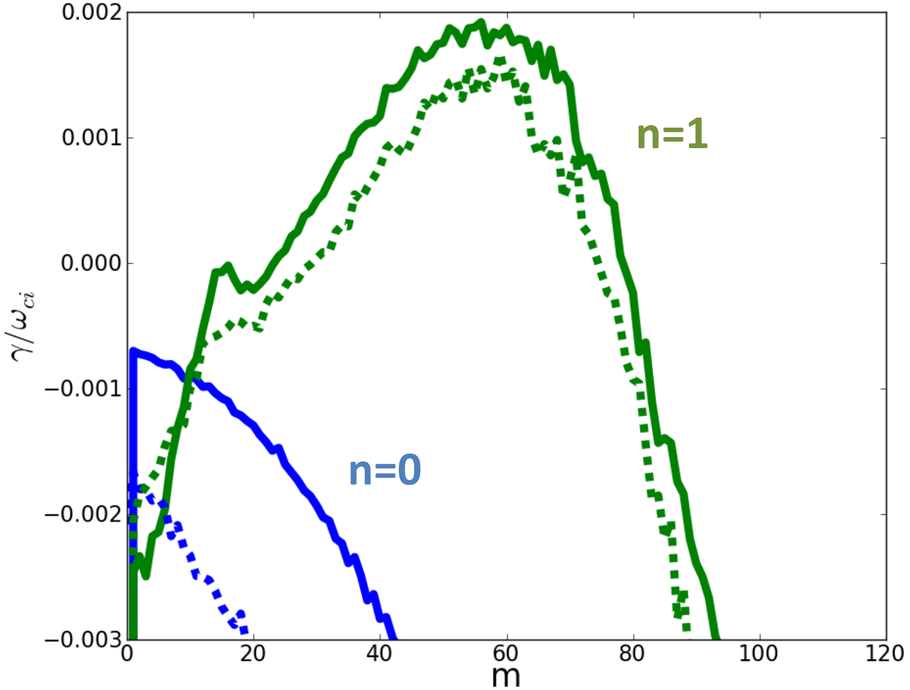
The Removal of n=0 Modes Causes the Linear Instability to Dominate the Dynamics

n=0 removed at each timestep



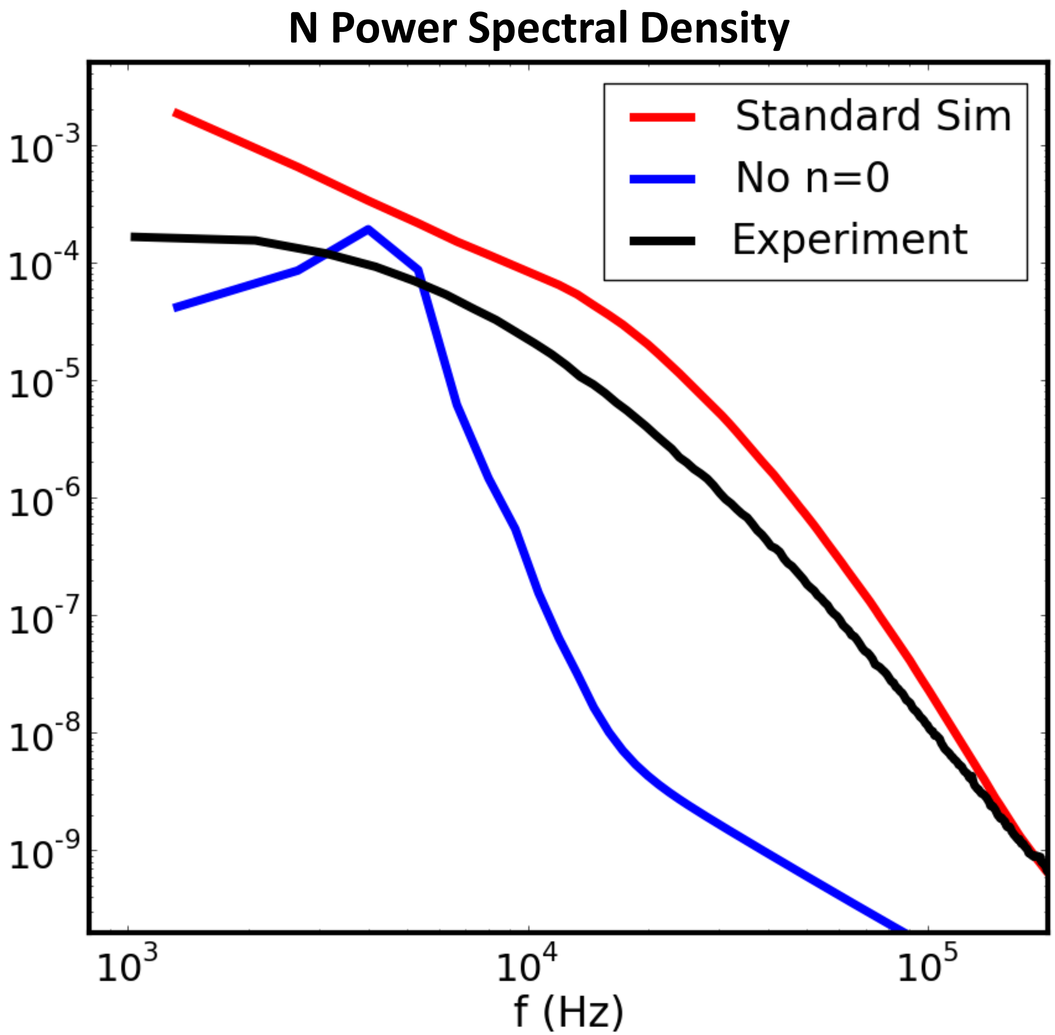
Nonlinear phase
Linear phase

n=0 removed, but zonal flow retained



Without ZF
With ZF

The Removal of n=0 Modes Causes an Experimentally Inconsistent Peak in the Frequency Spectrum

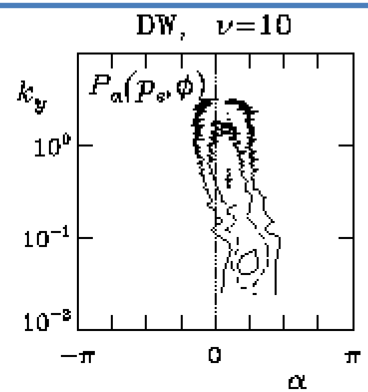


Nonlinear Instabilities Can Overwhelm Linear Instabilities, Affecting Turbulent Characteristics

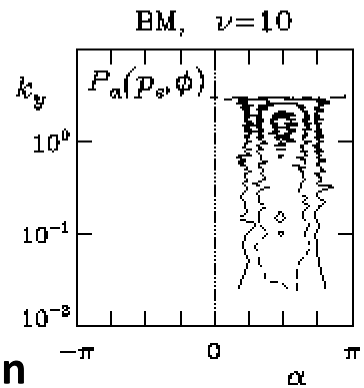
$$\alpha_{p\phi}(l) = \mathrm{Im}\,\ln(\tilde{p}^*_{e_l}\tilde{\phi}_l)$$

Cross phase - measure of the instability drive and transport.

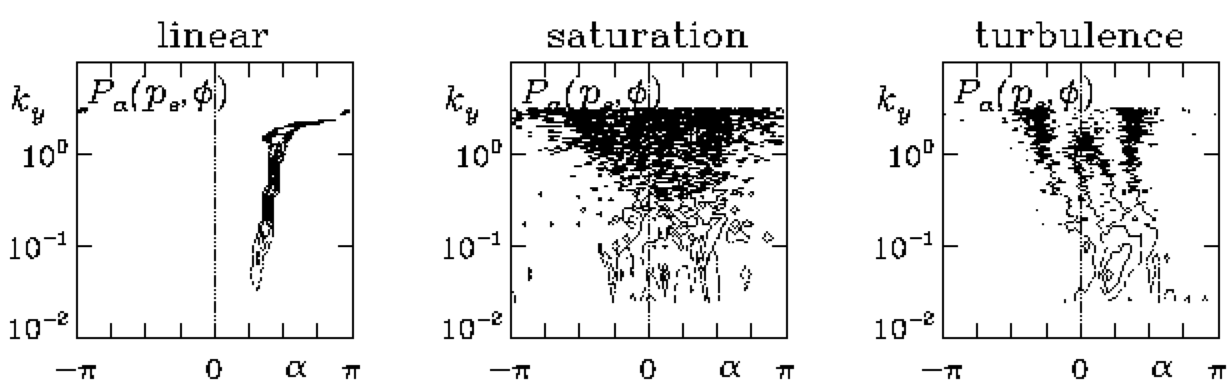
Pure drift wave turbulence



Pure ballooning mode turbulence



Drift-ballooning physics starting from small perturbation



B.D. Scott (2005)

Conclusion

- **A nonlinear instability provides the dominant turbulent drive mechanism. The instability preferentially drives n=0 structures, but relies upon the nonlinearities and n=1 structures to access the adiabatic response.**

- **Removal of the n=0 modes causes the linear instability to dominate, but the turbulent frequency spectrum is more coherent, which is inconsistent with experiment .**

- **Nonlinear instability can be relevant in tokamak edge turbulence and linear growth rate calculations can be misleading when nonlinear instabilities are present.**