Studies of the Tokamak Edge with Self Consistent Turbulence, Equilibrium, and Flows

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Physical Situation of the Tokamak Edge

- scale ratios: $R \gg L_T$

$$\hat{\mu} = \frac{m_e}{M_D}\left(\frac{qR}{L_T}\right)^2 > 1 \qquad\qquad \hat{\beta} = \frac{4\pi p_e}{B^2}\left(\frac{qR}{L_T}\right)^2 > 1$$

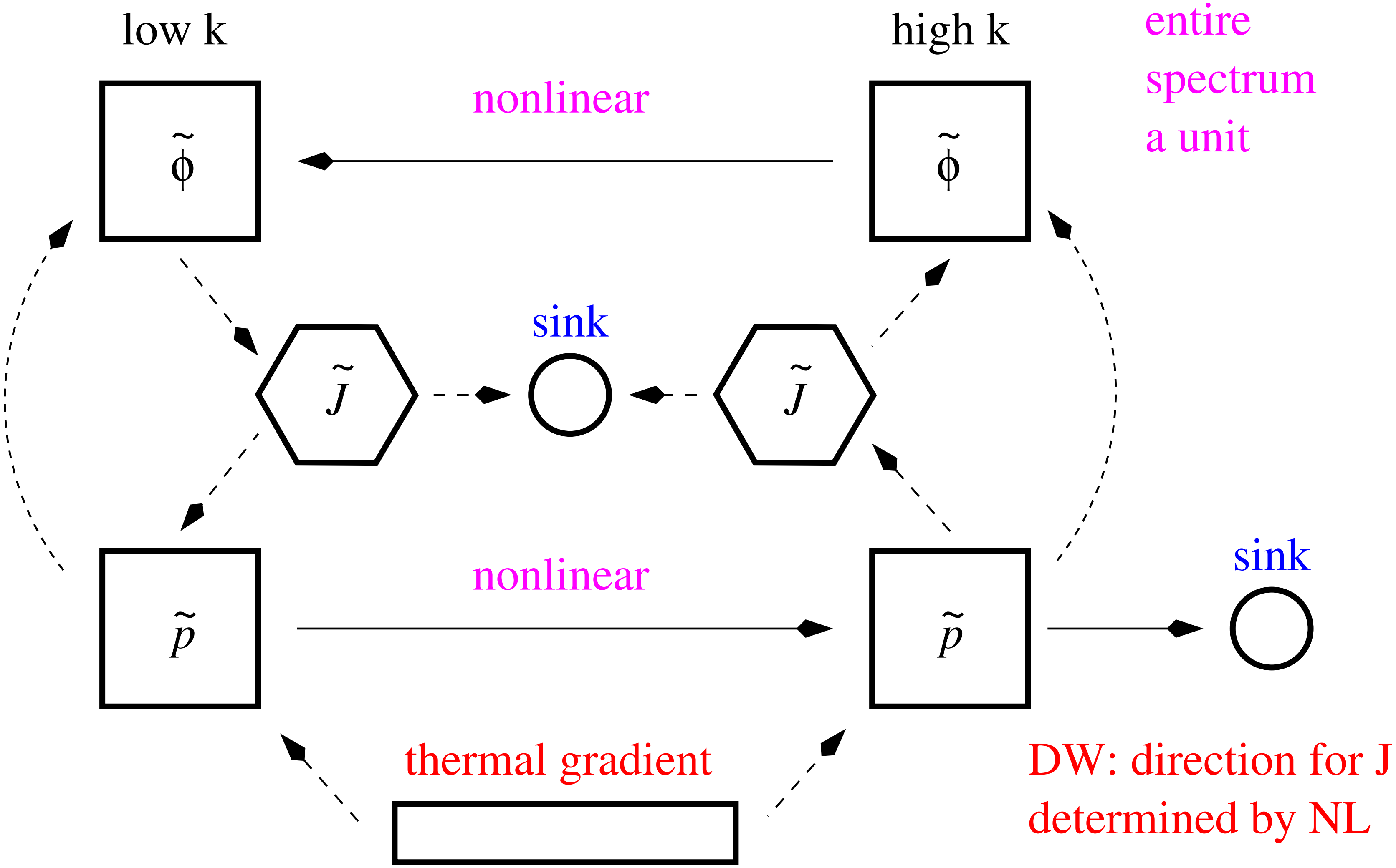
- gradients and transcollisionality (ions mostly collisionless)

$$\eta_{e,i} = \left.\frac{d\log T}{d\log n}\right|_{e,i} \sim 2 \qquad\qquad \hat{\nu} = \frac{\nu_e L_T}{c_s} \sim 1$$

- adiabatic response: $\nabla_\parallel \widetilde{p}_e \quad \leftrightarrow \quad \nabla_\parallel \widetilde{J}_\parallel \quad \leftrightarrow \quad n_e e \nabla_\parallel \widetilde{\phi}$

cannot be described by MHD

Energy Transfer: electromagnetic turbulence



(B Scott Phys Fluids B 1992, Plasma Phys Contr Fusion 1997)

(S Camargo et al Phys Plasmas 1995 and 1996)

L-Mode Base Case

- generic ASDEX Upgrade (AUG) L-Mode conditions

- $n_e = 2.0 \times 10^{13}\,\mathrm{cm}^{-3}, \quad T_e = T_i = 100\,\mathrm{eV}, \quad B = 2.5\,\mathrm{T}, \quad R = 165\,\mathrm{cm}, \quad q = 3.5$
  ◦ profile scale $L_\perp = L_T = 3.5\,\mathrm{cm}$ with $L_n/L_T = 2$

- set x-domain width $L_x = 64\rho_s \sim L_\perp$ and drift-direction extent $L_y = 4L_x$

- GEM: electromagnetic 6-moment gyrofluid for both electrons, ions

(B Scott, Phys Plasmas Oct 2005) — details at poster

- broad band turbulence, energetic range $0.1 < k_y\rho_s < 1$

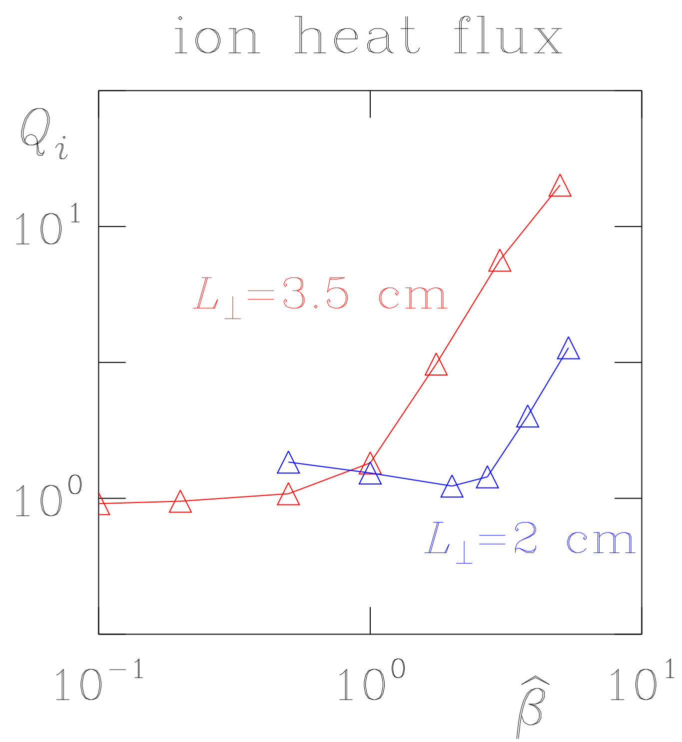
- scales and transport commensurate with observations NB: no H-Mode

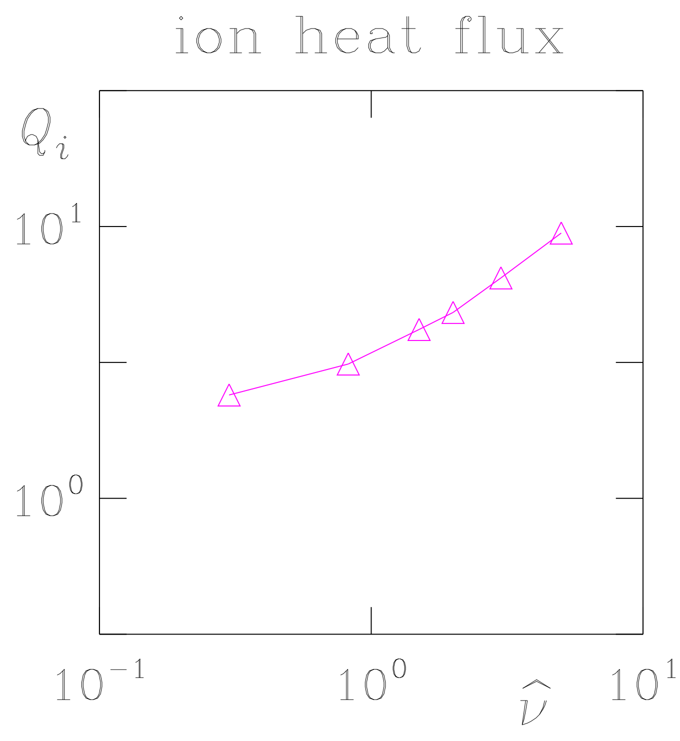
- DED: dynamic ergodic divertor (3-band magnetic field perturbation)
  ◦ main effect: 3D perturbed equilibrium, stronger ExB transport

(D Reiser et al, Phys Plasmas 2005) — details at poster

Basic Parameter Scaling

- total ion ExB thermal transport (electron is very similar)

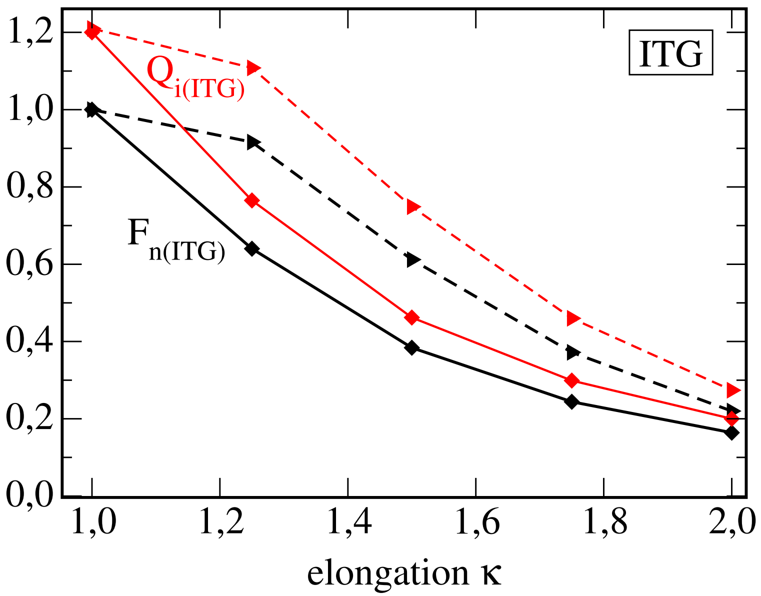


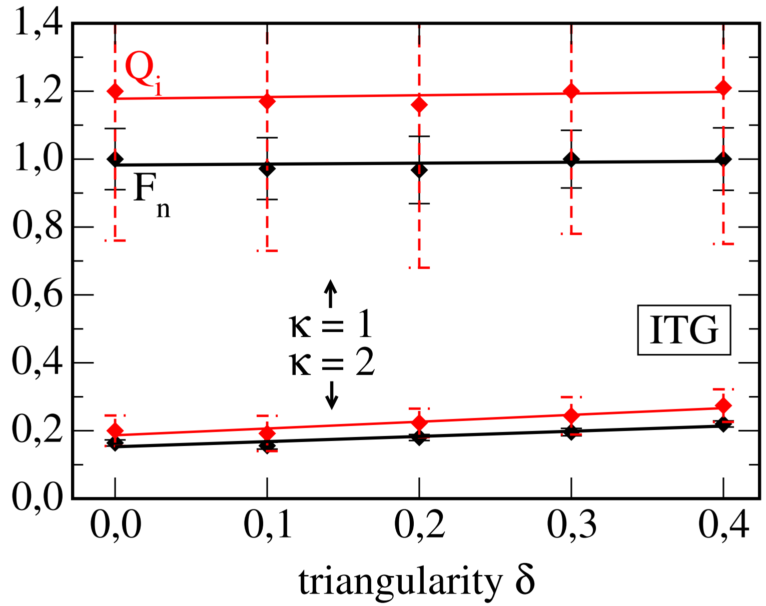


- mangetic flutter: small and negative — dynamic EM, transport ES
- delta-f gyrokinetic result is similar with differences (IAEA TM Instabilities, 2005)
- on top of this: rho-star scaling $D, \chi \sim \rho_s^2 c_s / L_\perp$ (nominal: $0.66\,\mathrm{m}^2/\mathrm{sec}$)

Flux Surface Shaping Effects

- ITG transport versus elongation and triangularity





- elongation: direct effect on local and global shear, shorter effective field lines

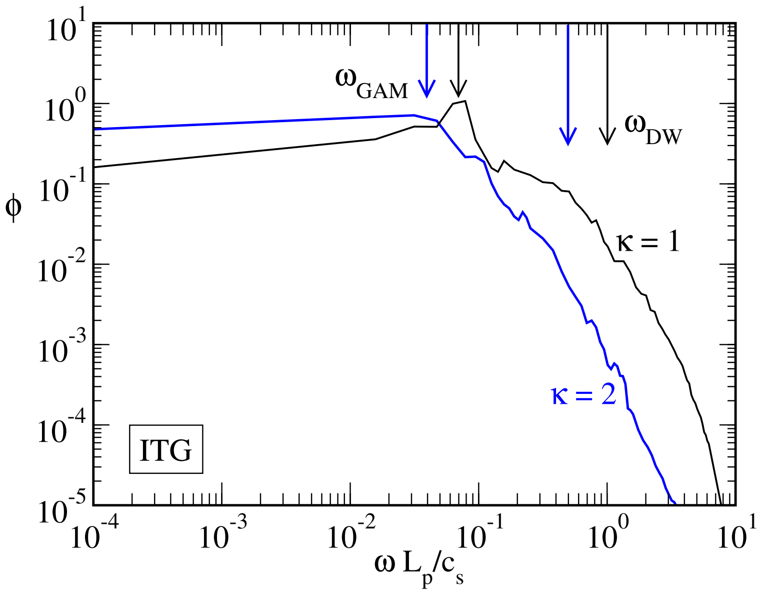
- triangularity: weak effect assuming parameters and elongation held fixed

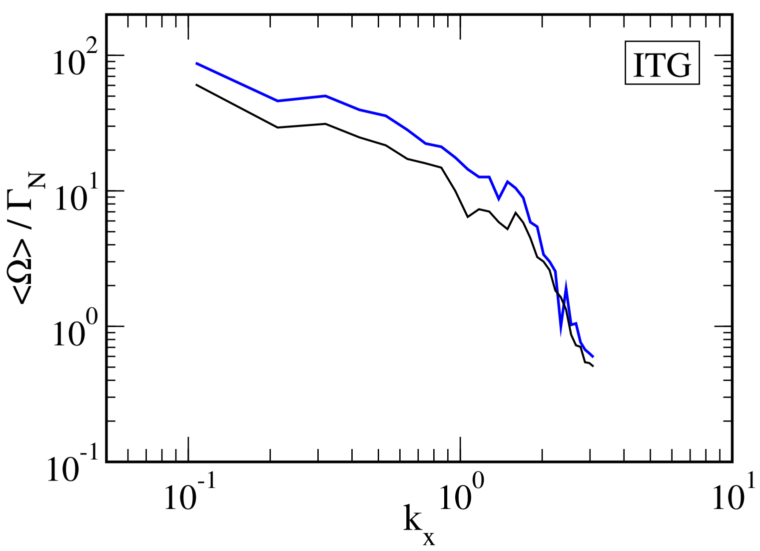
(A Kendl et al, Phys Plasmas 2006)

Zonal Flow Energetics

- zonal potential frequency spectrum

zonal vorticity radial-k spectrum





- elongation: sharper decay, but stronger at lower frequencies
- elongation: enhancement of zonal vorticity at all radial scales
- more detail: poster

(A Kendl et al, Phys Plasmas 2006)

Equilibrium

(B Scott, Contrib Plasma Phys 2006)

- description by gyrofluid equations
  - sidebands in quasistatic equilibrium e.g., $\langle p \sin\theta \rangle$ and $\langle u_\parallel \cos\theta \rangle$
  - dissipation free overall fluxes, force balance
  - slow evolution of zonal state variables e.g., $\langle p \rangle$ and $\langle \phi \rangle$
- Braginskii (collisional fluid equations) correspondence in collisional limit
  - collisional damping of heat fluxes: conduction
  - collisional damping of T anisotropy: parallel viscosity
- Braginskii breakdown for $\omega > c_s/qR$
  - affects zonal flows and turbulence

main point: zonal flows are compressible
even equilibrium is outside the Braginskii limit

Self Consistent Equilibrium — Logic

- turbulence, zonal profiles, and zonal flows
- flows to geodesic curvature to poloidal sidebands ($n = 0$ and $m = \pm 1$)

$$\langle \phi \rangle \quad \leftrightarrow \quad \nabla \cdot \mathbf{v}_E \quad \leftrightarrow \quad \langle p \sin \theta \rangle$$

- sideband pressure and zonal pressure (diamagnetic compression, “neoclassical”)

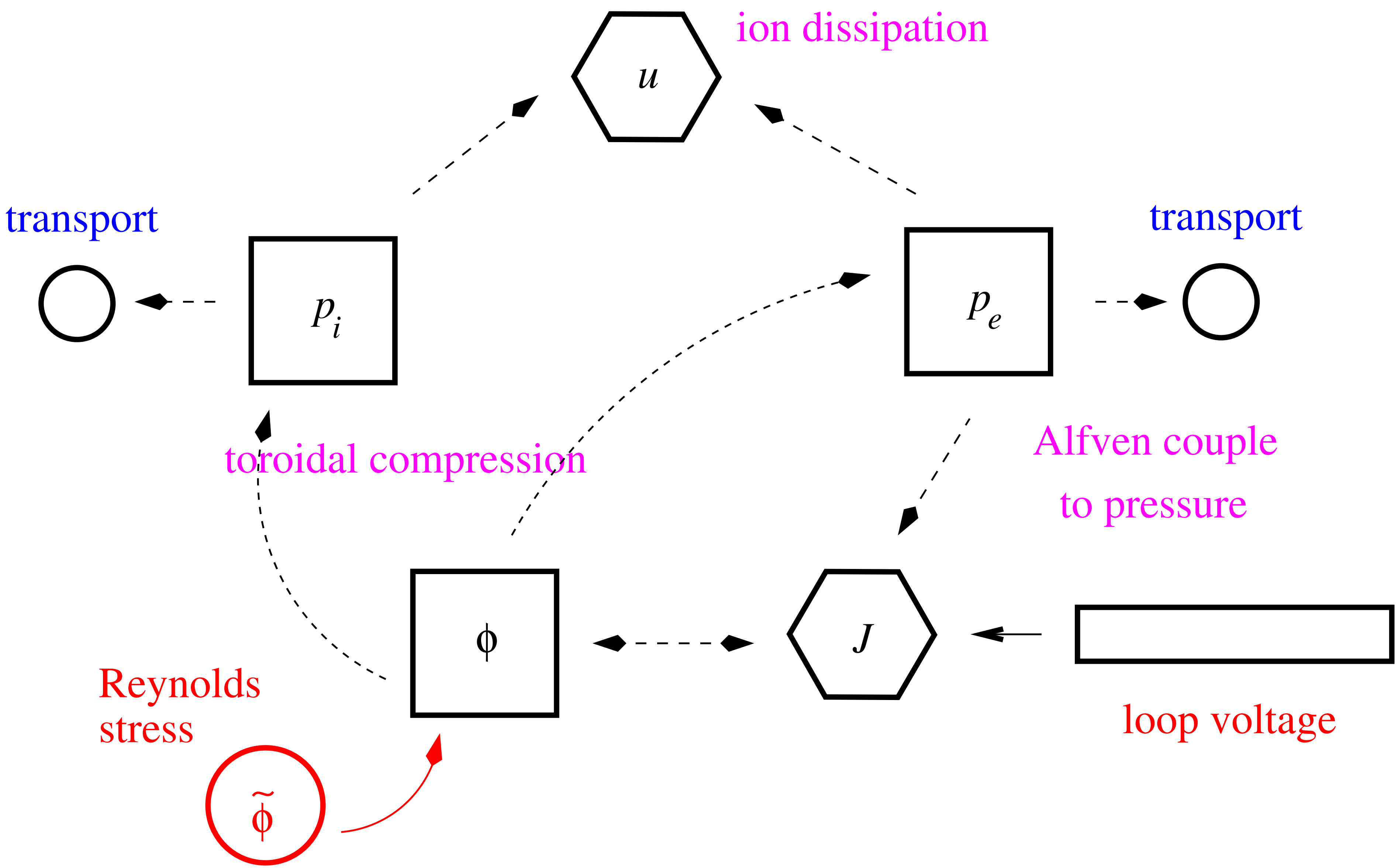
$$\langle p \sin \theta \rangle \quad \leftrightarrow \quad \nabla \cdot \mathbf{u}_* \quad \leftrightarrow \quad \langle p \rangle$$

- sideband pressure and sideband current (adiabatic compression, “Pfirsch-Schlüter”)

$$\langle p_e \sin \theta \rangle \quad \leftrightarrow \quad \nabla_\parallel \quad \leftrightarrow \quad \left\langle J_\parallel \cos \theta \right\rangle$$

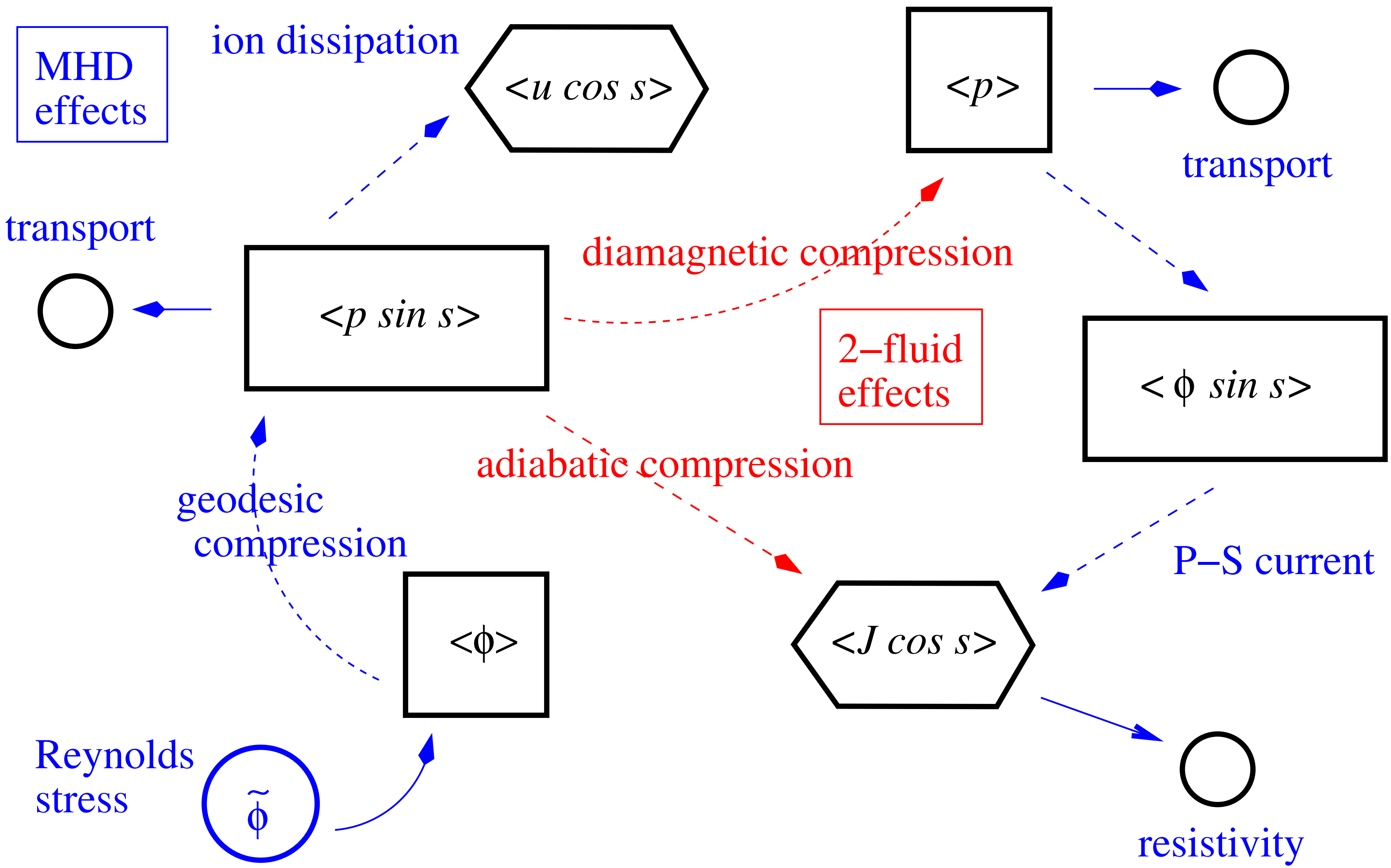
keep evolving profiles, keep evolving equilibrium

Energy Transfer: equilibrium



(B Scott Phys Plasmas 2003)

Energy Transfer: flows and currents



(B Scott Phys Lett A 2003, New J Phys 2005)

Basic Flow Equilibrium Statements

- ion continuity → sideband divergence equilibrium
  - ($\omega_B \sin\theta$ is geodesic curvature, W_i is ion force potential)

$$(\text{time dependence}) + B\nabla_\parallel(u_\parallel/B) = \mathcal{K}\left(\phi_G + \frac{\Omega_G}{2} + \tau_i \frac{p_{i\parallel} + p_{i\perp}}{2}\right) \equiv \mathcal{K}(W_i)$$

$$\left\langle u_\parallel \cos\theta \right\rangle = -\omega_B \frac{\partial}{\partial x} \left\langle W_i \sin^2\theta \right\rangle \approx -\frac{\omega_B}{2} \frac{\partial}{\partial x} \langle W_i \rangle$$

- parallel momentum → sideband force balance
  - ($p = [p_\parallel + 2p_\perp]/3$ and $\delta p = p_\parallel - p_\perp$ with $p = p_i + p_e$)

$$\left\langle p_{i\parallel} \sin\theta \right\rangle + \langle \phi \sin\theta \rangle = (\text{FLR,mass ratio})$$

$$\langle p \sin\theta \rangle = \frac{2}{3} \langle \delta p \sin\theta \rangle \equiv (\text{parallel viscosity})$$

- requirement: $\omega \ll c_s/qR$

Pfirsch-Schlüter Currents

- flow equilibrium in both species, eventually the vorticity, $= (n_e - n_i)$

$$\left\langle u_\parallel \cos\theta \right\rangle = -\frac{\omega_B}{2} \frac{\partial}{\partial x} \langle W_i \rangle$$

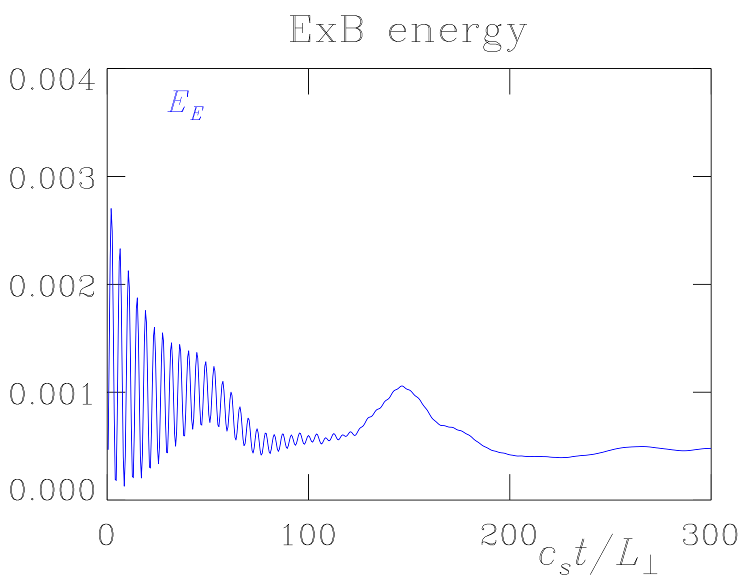
$$\left\langle v_\parallel \cos\theta \right\rangle = -\frac{\omega_B}{2} \frac{\partial}{\partial x} \langle W_e \rangle$$

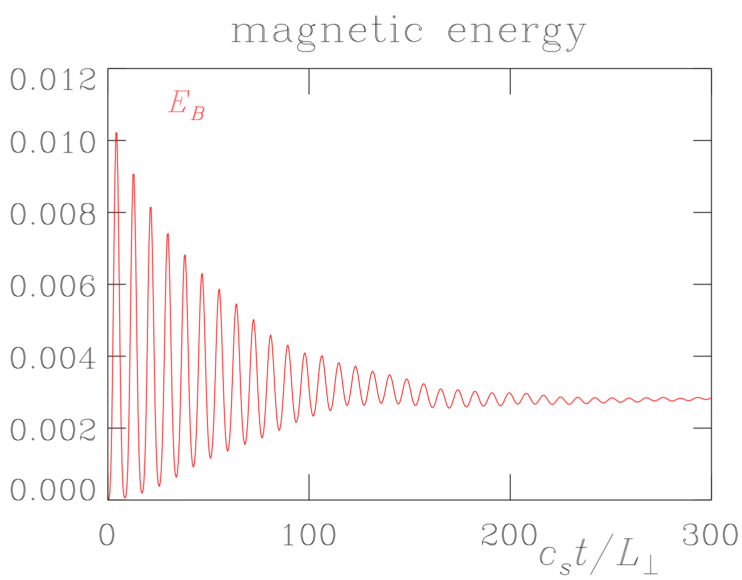
- hence the current $J_\parallel = (u_\parallel - v_\parallel)$

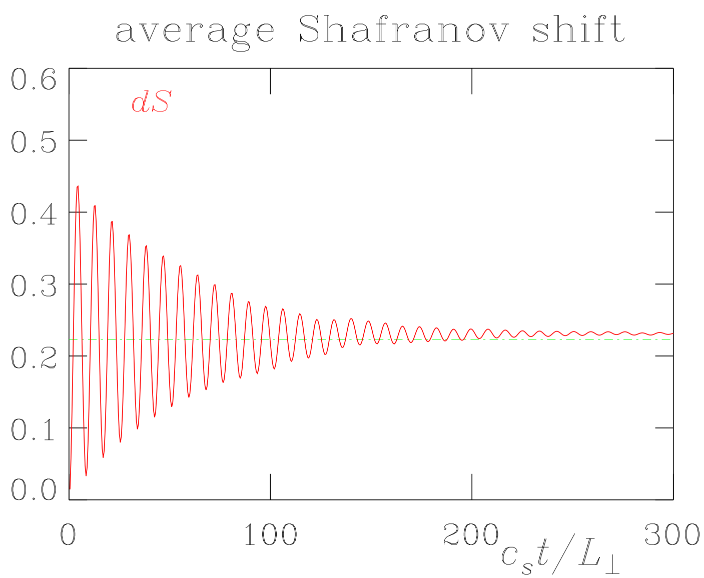
$$\left\langle J_\parallel \cos\theta \right\rangle = -\frac{\omega_B}{2} \frac{\partial}{\partial x} \langle p \rangle + (\mathrm{FLR})$$

neither flow nor MHD equilibrium is assumed by GEM equations
largest scales fall into equilibrium naturally, when $\omega_t \sim \omega_* \ll c_s/qR$

Initial Time Traces — L-Mode Base Case



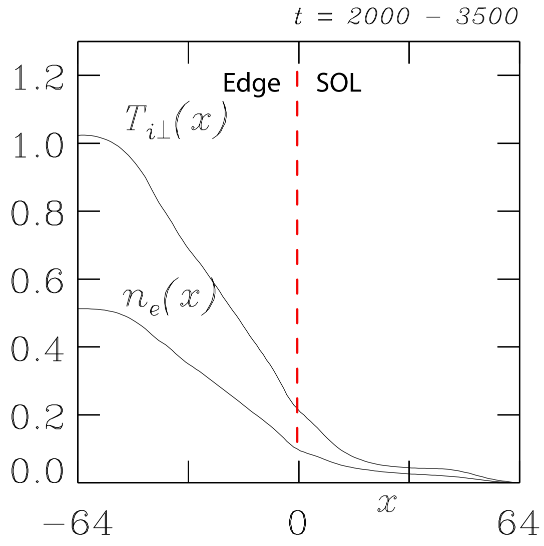


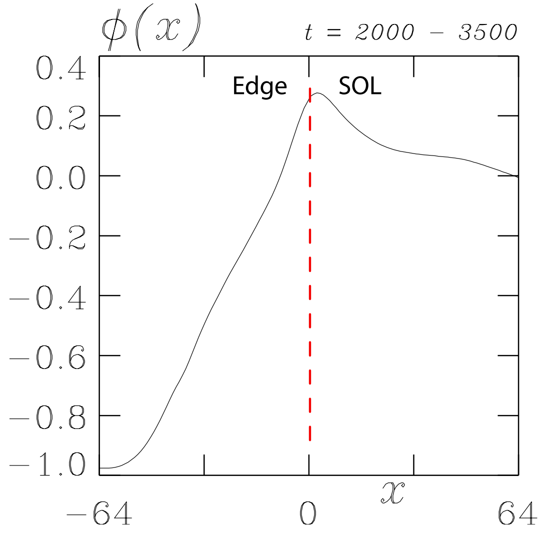


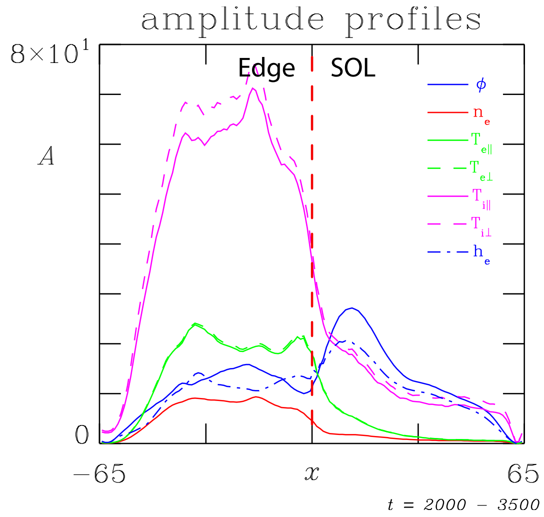
- global Alfvén oscillation
- stable transient relaxing to MHD (P-S current) equilibrium
- necessary ingredient of any electromagnetic computation

Basic Edge/SOL Situation

- profiles, equilibrium ExB shear layer, radial edge/SOL mode structure transition





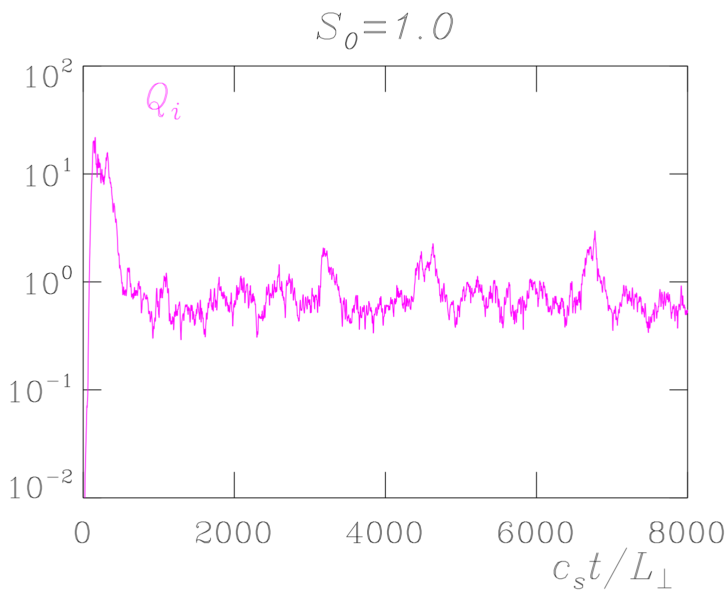


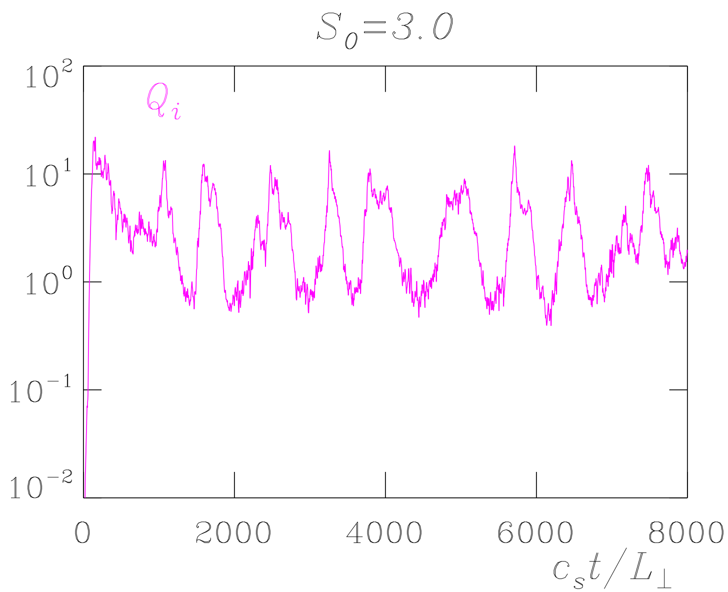
- shear layer: neoclassical balances in edge, Debye sheath coupling in SOL
- turbulence: ITG (see $\widetilde{T}_i$) in edge, interchange (see $\widetilde{\phi}$) in SOL
- edge/SOL transition: about $10\rho_s$
- more detail: poster

(T Ribeiro et al, Plasma Phys Contr Fusion 2005)

Global Bursts in the Self Consistent Equilibrium

- ion heat flux time traces, fixed source on inner (radial) boundary

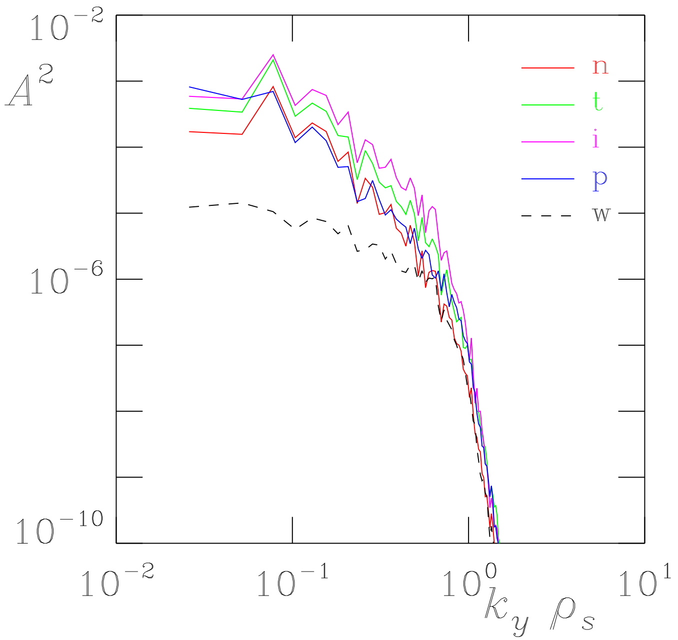


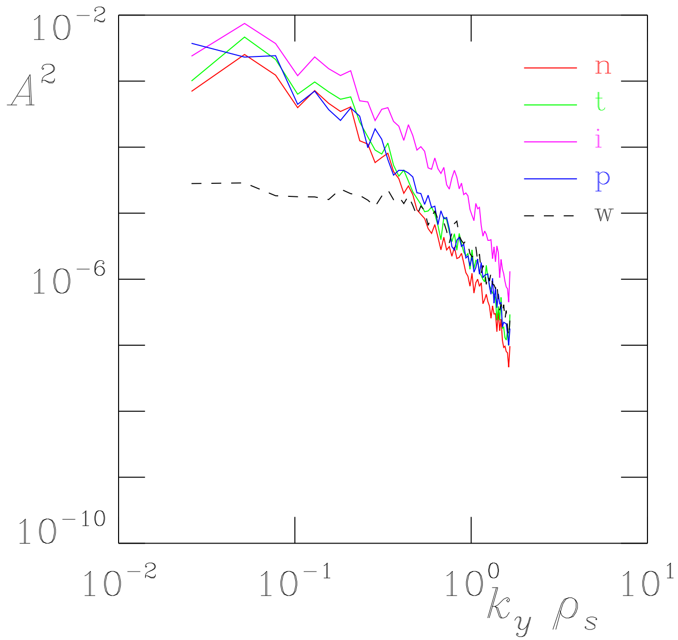


- total run length $8000L_\perp/c_s$ (gyro-Bohm times) or about 4 msec
- bursty turbulence for moderate drive levels, global bursts for stronger ones
- many full cycles, compare to saturation time *ca.* $200L_\perp/c_s$

Turbulence Spectra

- between (left) and during (right) global bursts for $S_0 = 3.0$

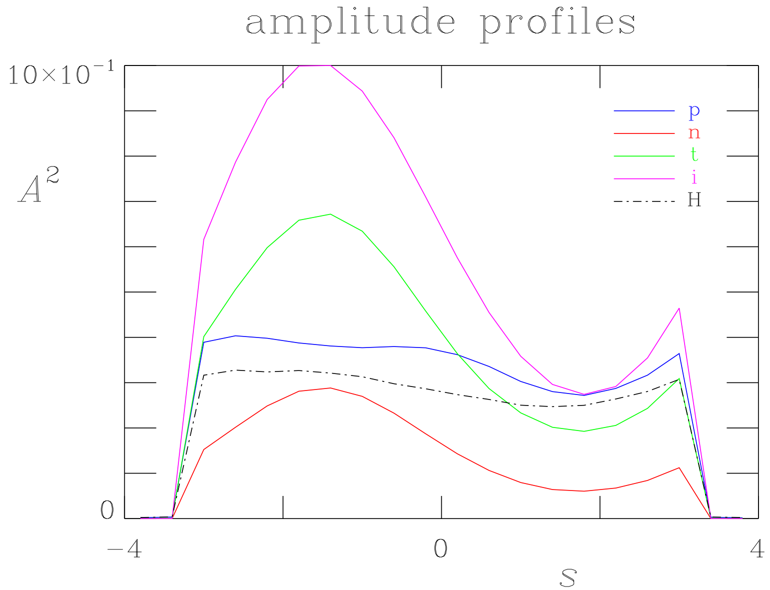


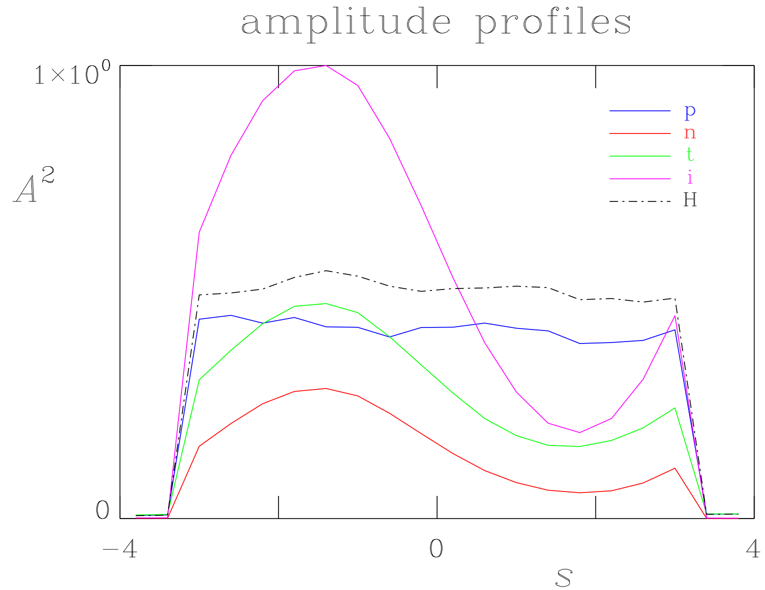


- n, t, i, p, w are $\widetilde{n}_e$, $\widetilde{T}_e$, $\widetilde{T}_i$, $\widetilde{\phi}$ and vorticity $\widetilde{\Omega}$, extending to ion gyroradius
- spectra (especially $\widetilde{\Omega}$) flatter in bursts, reflects basic nonlinearity
- no signature of “new mode” (would affect relative amplitudes)

Turbulence Parallel Envelopes

- between (left) and during (right) global bursts for $S_0 = 3.0$





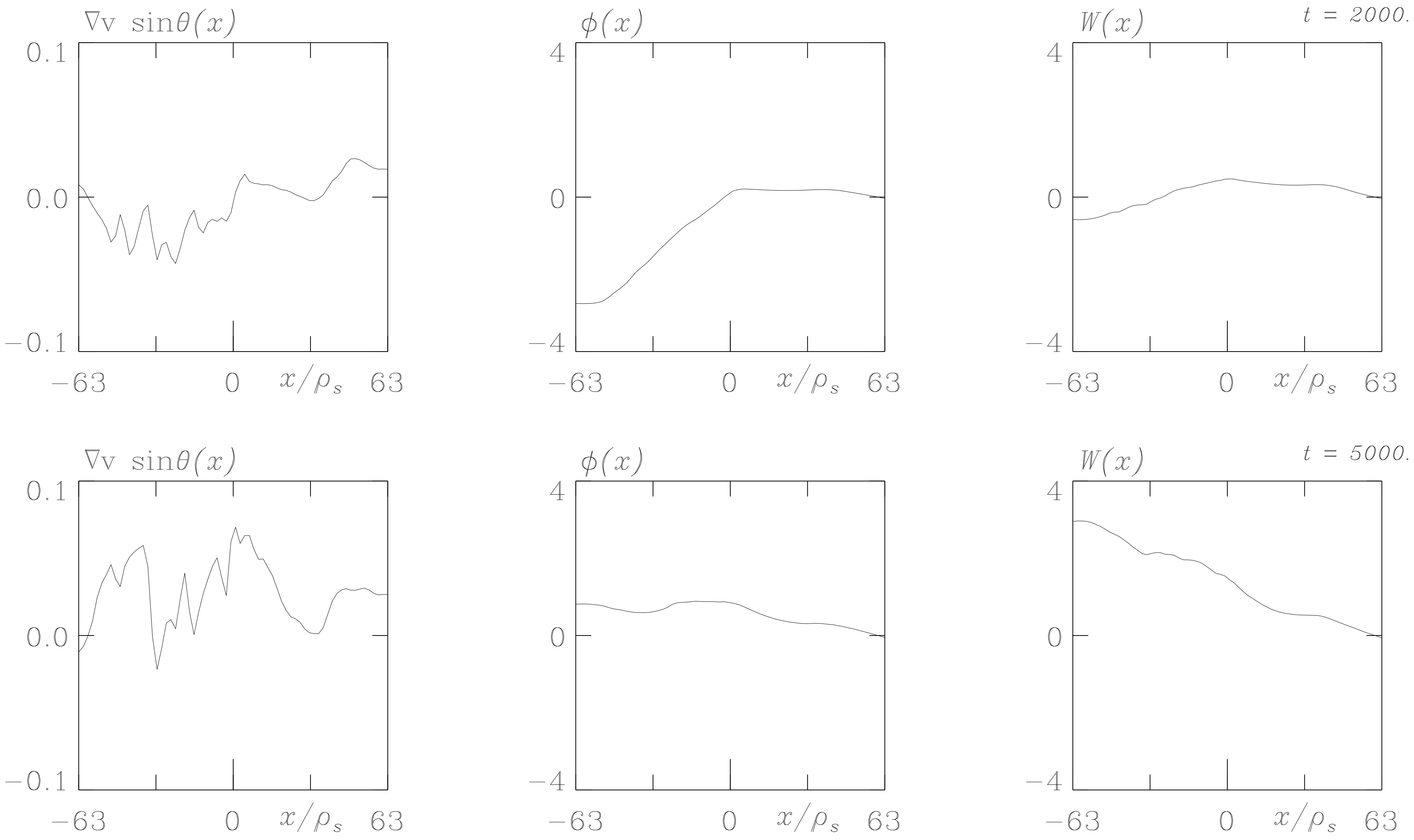
- n, t, i, p, H are $\widetilde{n}_e$, $\widetilde{T}_e$, $\widetilde{T}_i$, $\widetilde{\phi}$ and nonadiabaticity $\widetilde{h}_e$

- ITG signature: $\widetilde{T}_i$ largest, most strongly ballooned
  - ◦ shear Alfvén signature: flat $\widetilde{\phi}$ curve

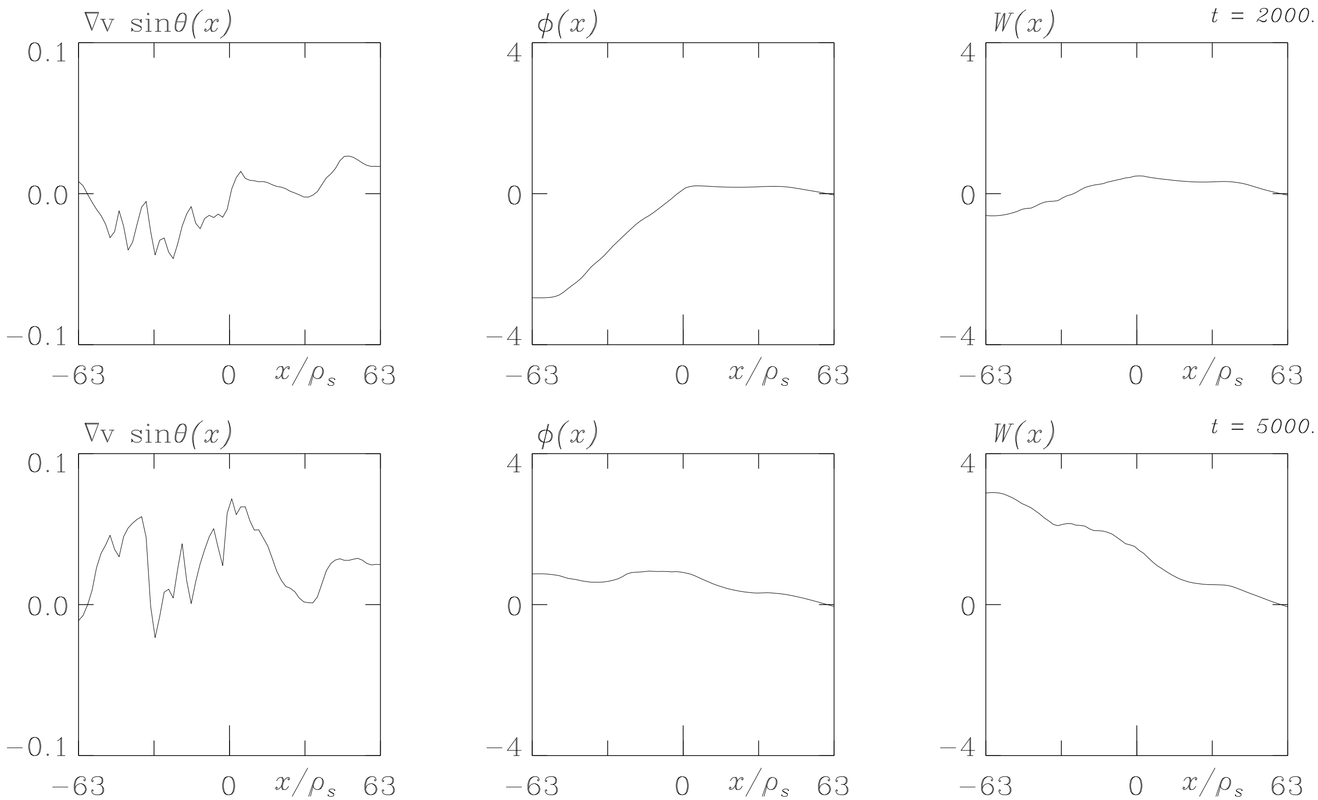
- no signature of "new mode" (only stronger nonadiabaticity)

Sideband Divergence and Potential Profiles

- between (top) and during (bottom) global bursts for $S_0 = 3.0$



Sideband Divergence and Potential Profiles



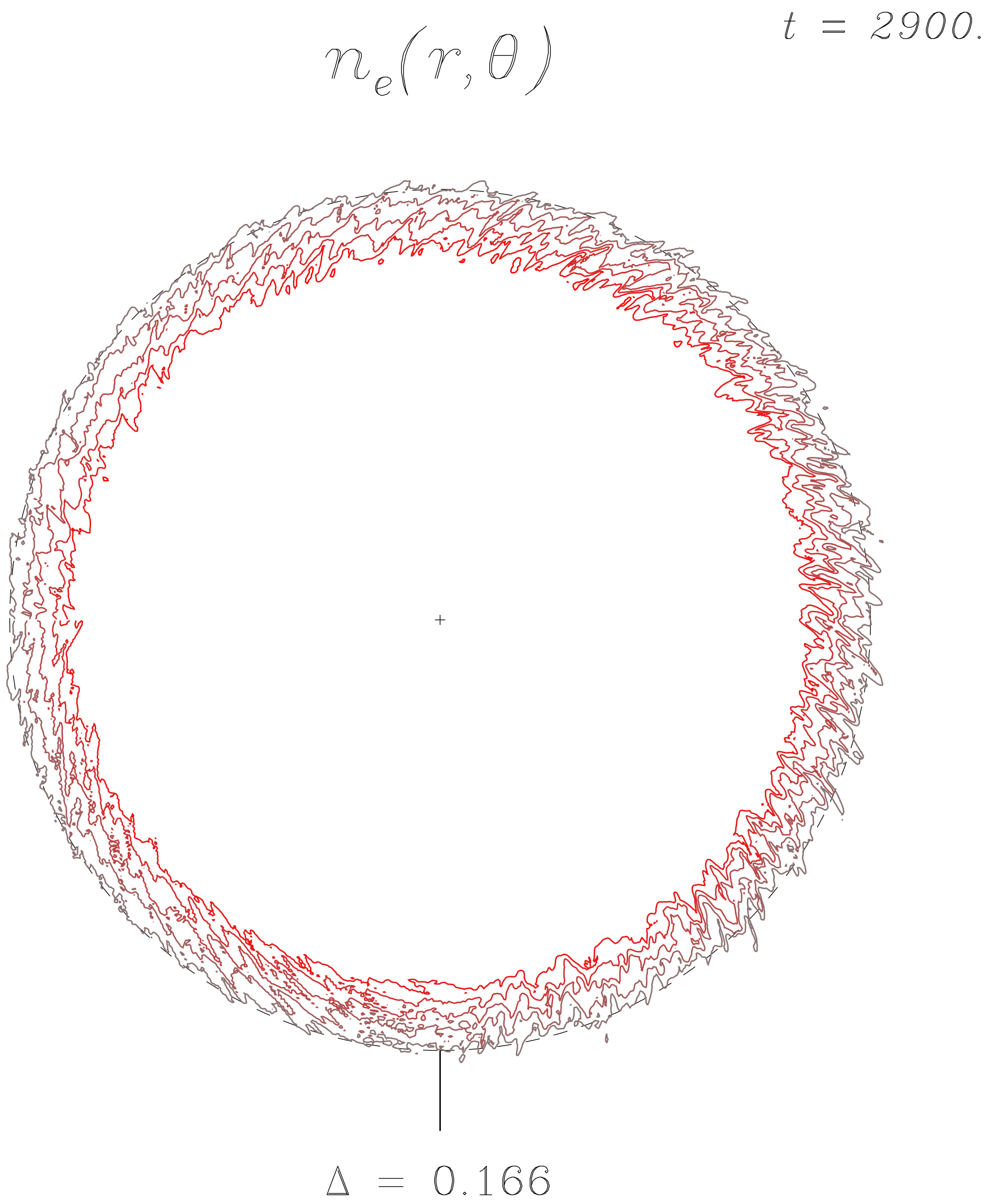
- (top) quiescent: slow growth, well formed equilibrium in ϕ (shear layer) and W_i
- (bottom) bursts: collapse of equilibrium, large divergence, no shear layer
  - ◦ basic strength of turbulence suddenly overshoots as compensation disappears

this is the main cause of the global burst

quiescent structure

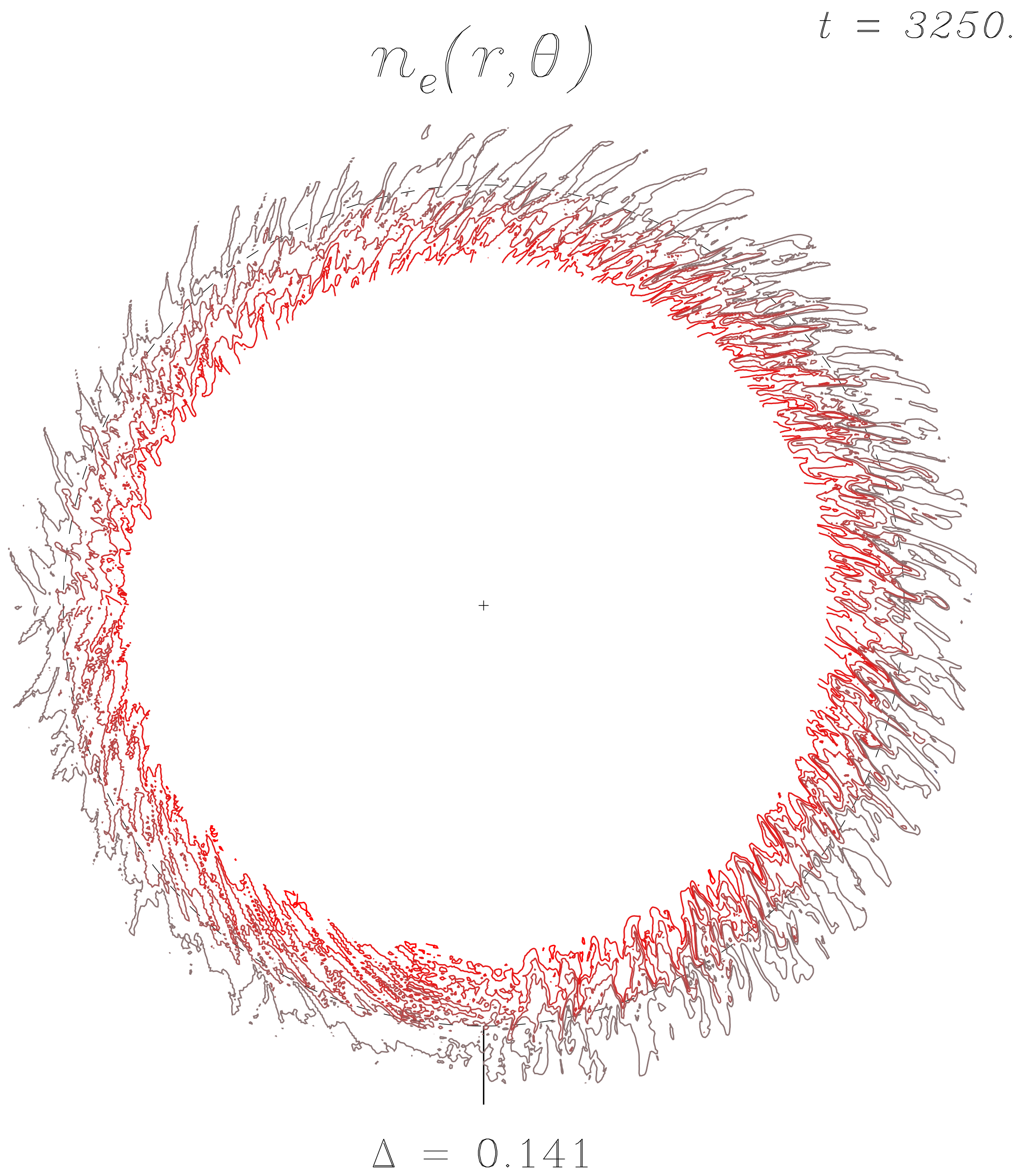
- between bursts
  (full flx sfc case, 1024 y-nodes)
  (equiv 3600 poloidal nodes)
- profile/turbulence mostly
  on edge region (inward of LCFS)
- weak fingers onto SOL
- remember this is still
  strong EM-ITG turbulence

$$\widetilde{p}_e/p_e \sim 5\%$$



burst structure

- global bursts reach across SOL
- "fluctuation" amplitude $O(1)$
- Alfvén dynamics ($\widetilde{\phi}$) carry burst to high-field side (burst still more strongly ballooned than is apparent)
- remember all this is is stronger EM-ITG turbulence



IBM Blowout Case

- standard case: AUG #17151 H-mode deuterium

(L Horton etal, Nucl Fusion 2005)

$$n_e = 2.5 \times 10^{13}\,\mathrm{cm}^{-3} \qquad T_e = 300\,\mathrm{eV} \qquad T_i = 360\,\mathrm{eV}$$

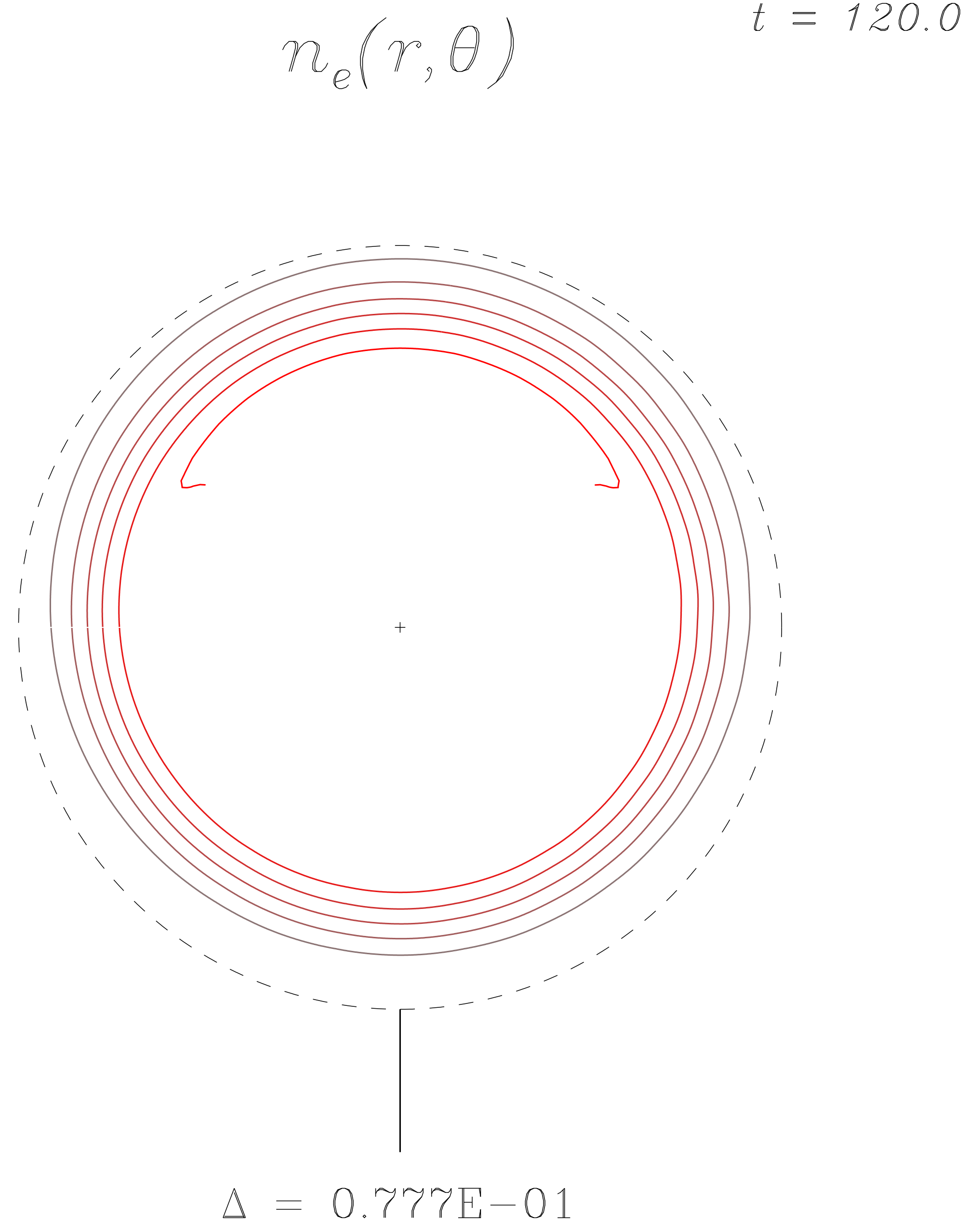
$$B = 2\,\mathrm{T} \qquad R = 165\,\mathrm{cm} \qquad L_\perp = 3\,\mathrm{cm} \qquad q = 5$$

- mid-pedestal values for parameters, pedestal width is $3\,\mathrm{cm} = 24\rho_s$
- set x-domain width $L_x = L_\perp = 3\,\mathrm{cm}$ and use entire flux surface
- main linear mode near toroidal mode $9 - 10$
- violent overshoot, cascade, crash
- at no point is there more than a linear instability
  - (then segue into remnant turbulence)

Equilibrium Structure

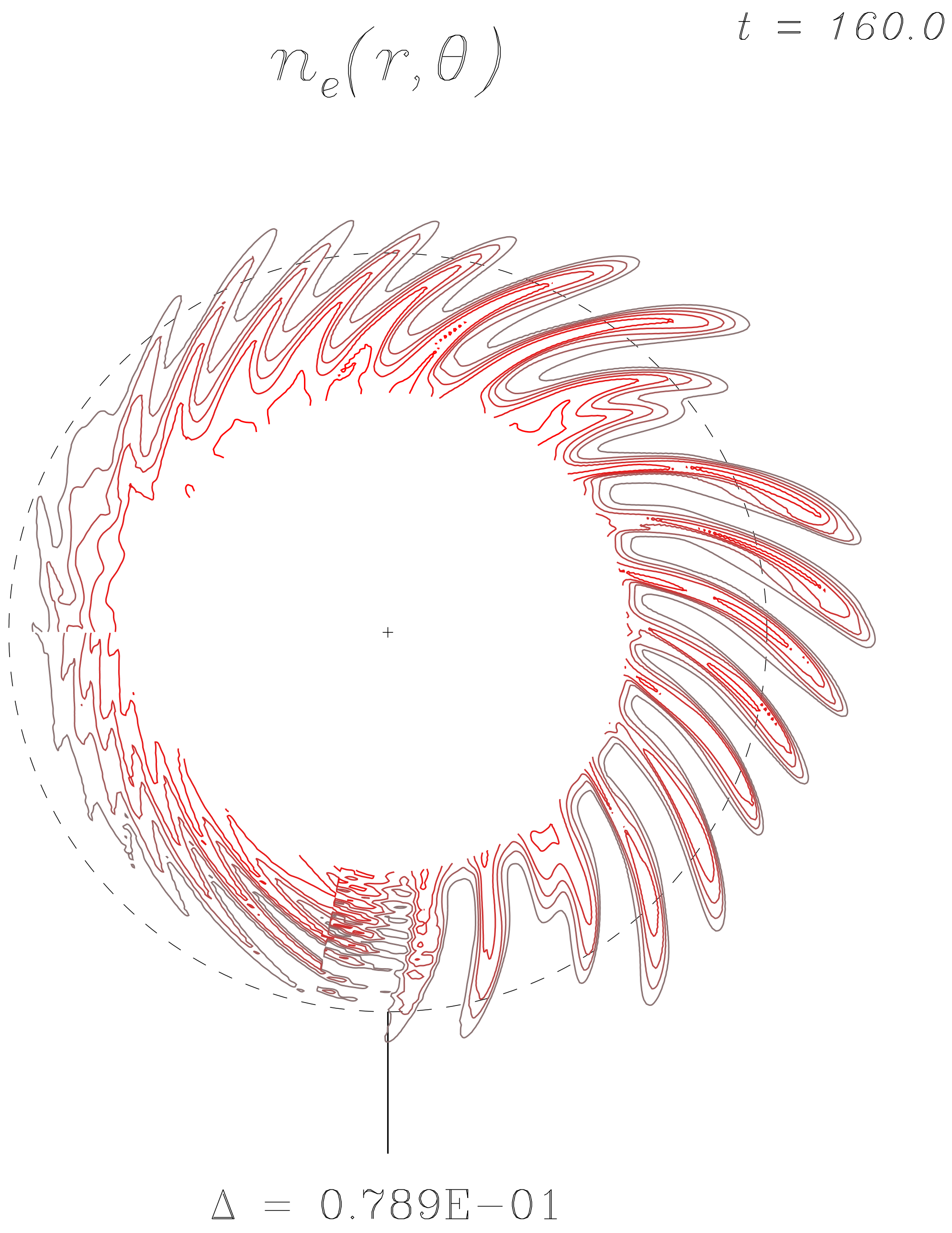
- neoclassical structure:
  dense on top, hot on bottom

- instability rocketing up,
  yet unseen

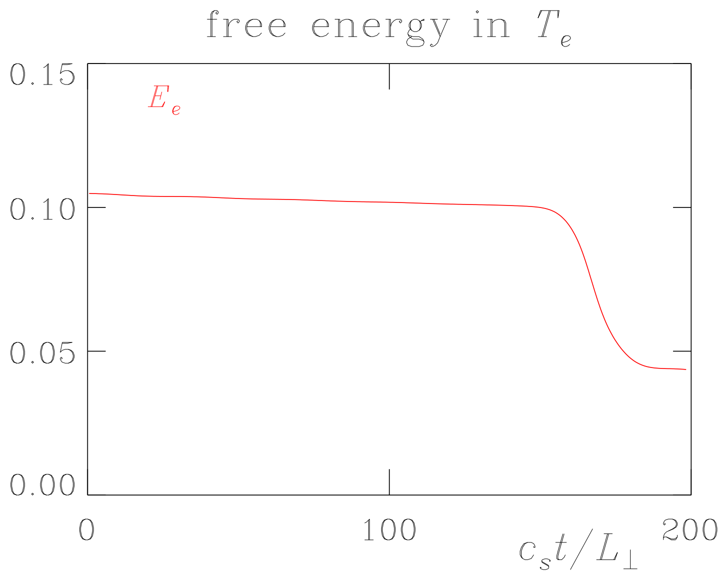


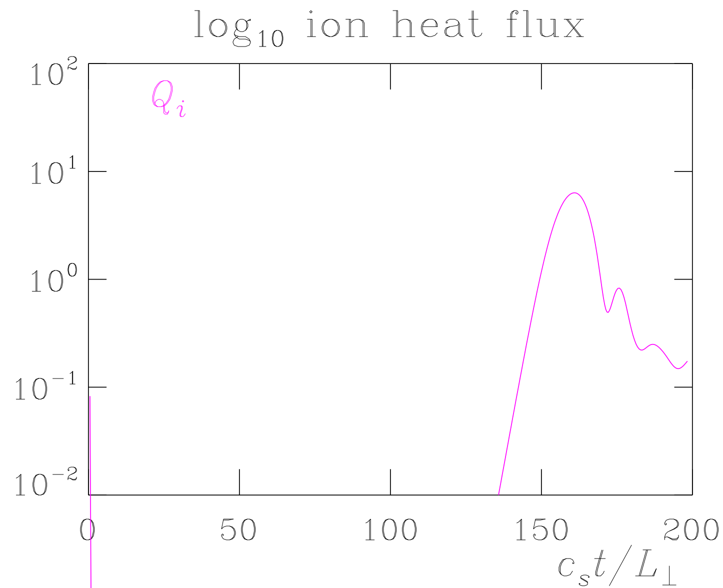
Blowout

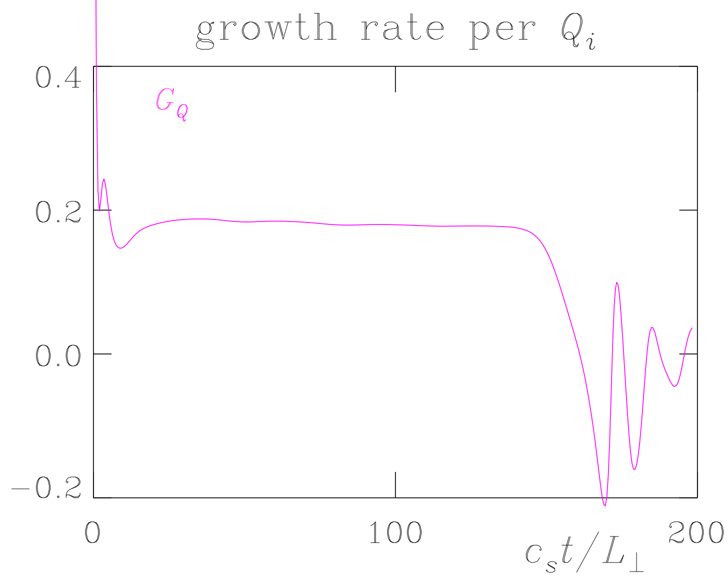
- 20 μsec after previous frame
- profile blown away
- finger structure obvious (and trivial)



Blowout Time Traces



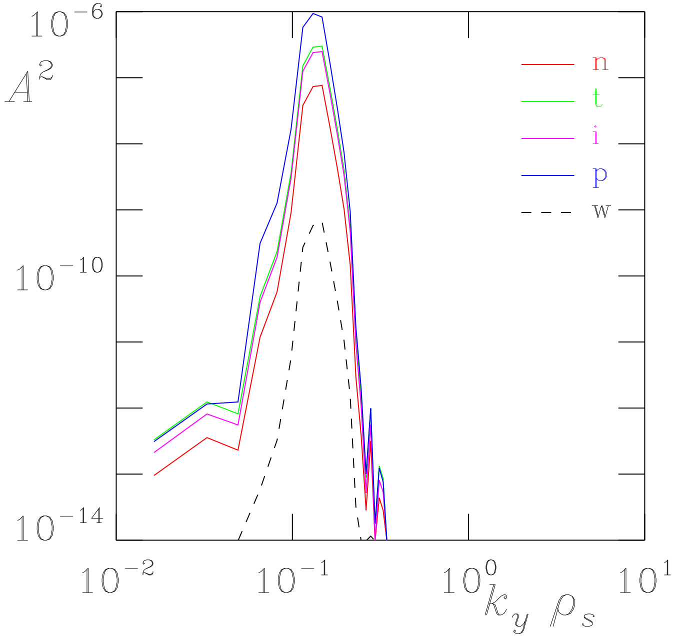


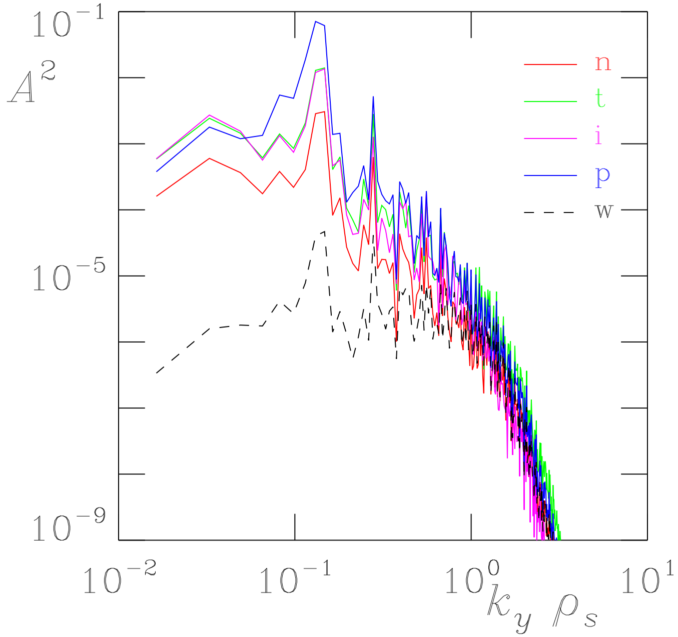


- energy, *ca.* 2/3 lost in blowout
- flux, short event ($< 40\,\mu$sec)
- growth rate as per flux, linear then segue into turbulent aftermath

Blowout Spectra

- linear growth (left) and peak-flux (right) phases





- linear growth: peak modes are $n = 9$ and 10 (MHD: $e\widetilde{\phi}/T_e$ largest)

- peak-flux: vorticity already flat to ion gyroradius scale

crash phase is outside not only MHD but also Braginskii regime

Main Points

- Basic Nature of edge turbulence: electromagnetic ion grad-T
  - basic scaling incompatible with H-Mode (no local explanation is tenable)

- Zonal Flow Energetics: influence of geodesic curvature
  - energy transfer mechanism, not "GAMs"

- Ergodic Field Perturbations — 3D equilibrium

- Self Consistent Equilibrium: flows, heat fluxes, currents, MHD structure
  - global Alfvén oscillation, time dependent Shafranov shift as profiles evolve

- •• Bursty Turbulence (basic) and then Global Bursts (equilibrium breakdown)
  - loss of shear layer leads to very strong overshoot

- IBM Blowout: perhaps not as good an ELM model as the bursts themselves
  - basic MHD instability, but lacking pre-state, and H-Mode is not that quiescent

- Development: nonlocal gyrofluid (GEMX) and gyrokinetic (FEFI) codes
  - GEMX: basic turbulence plus equilibrium OK, including Alfvén oscillation
    currently developing temperature physics
  - FEFI: still trouble with Alfvén oscillation, investigating symplectic methods