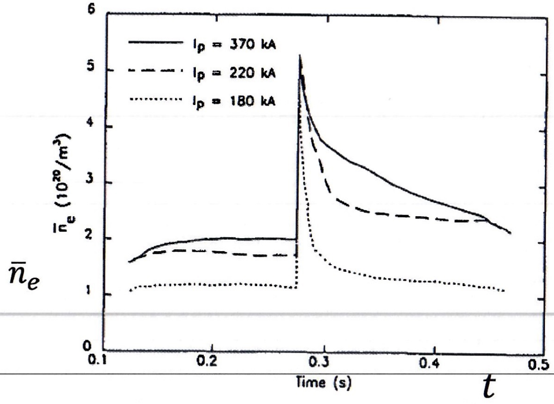
- Argue: Edge Particle Transport is crucial
  - ‘Disruptive’ scenarios secondary outcome, largely consequence of edge cooling, following fueling vs. increased particle transport
  - $\bar{n}_g$ reflects fundamental limit imposed by particle transport
- A Classic Experiment (Greenwald, et. al.)

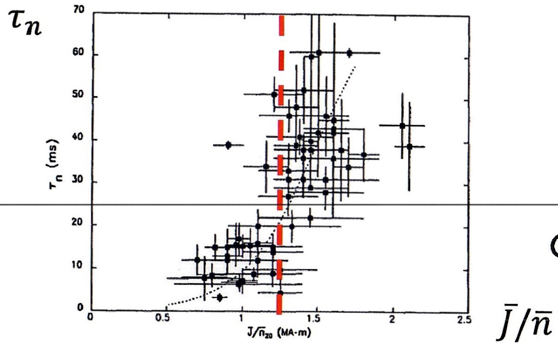


(Alcator C)

- Density decays without disruption after shallow pellet injection
- $\bar{n}$ asymptote scales with I_p ←
- Density limit enforced by transport-induced relaxation
- Relaxation rate not studied (?)

T.B.D

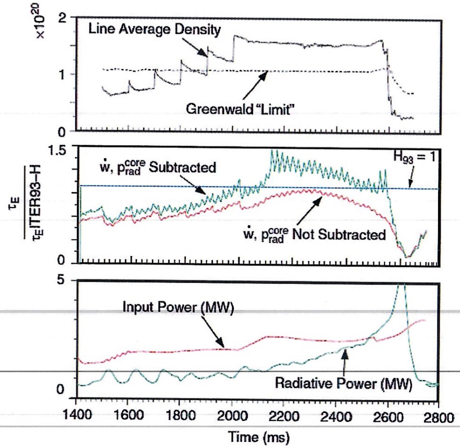
- More Evidence for Role of Edge Transport



- Post-pellet density decay time vs $\bar{J}/\bar{n}$.
- Increase in relaxation time near (usual) limit: $\bar{J}/\bar{n} \sim 1+$

C-Mod

(Fluctuations ?!)

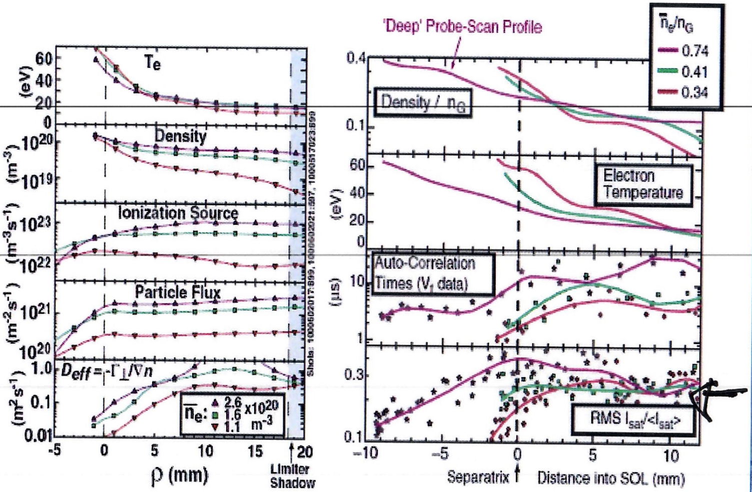


- Pellet in DIII-D beat $\bar{n}_g$
- Peaked profiles ←→ enhanced core particle confinement (ITG turbulence reduced?)
- Reduced particle transport ➔ impurity accumulation – issue with Pellet.

(N.B. Deeper deposition)

-advantage ELMy H-mode (Grassy) Q.H

Density limit ←→ Fluctuation Structure



C-Mod profiles,
Greenwald et al, 2002, PoP

- Average plasma density increases as a result of edge fueling → edge transport crucial to density limit.
- As *n* increases, high ⊥ transport region extends ~~inward~~ and fluctuation activity increases.
- Turbulence levels increase and perpendicular particle transport increases as $n/n_G \to 1$.

Why?

N.B. Increase in $D_\perp$ relative to $\chi_\parallel$ (n.b. high n, $\chi_\parallel \sim 1/n$)
⇒ detatchment?

18

Greenwald, Review

Edge cooling

Cooling → increased $\tilde{E} \times B$ transport.

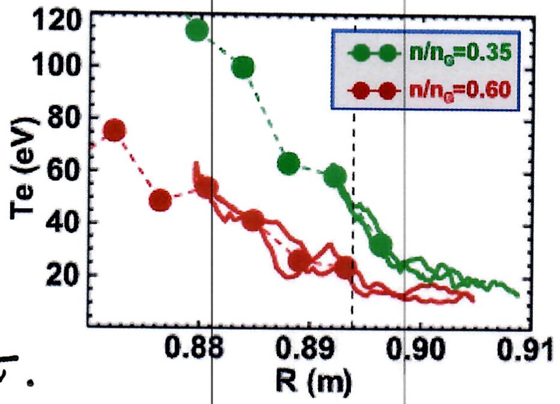
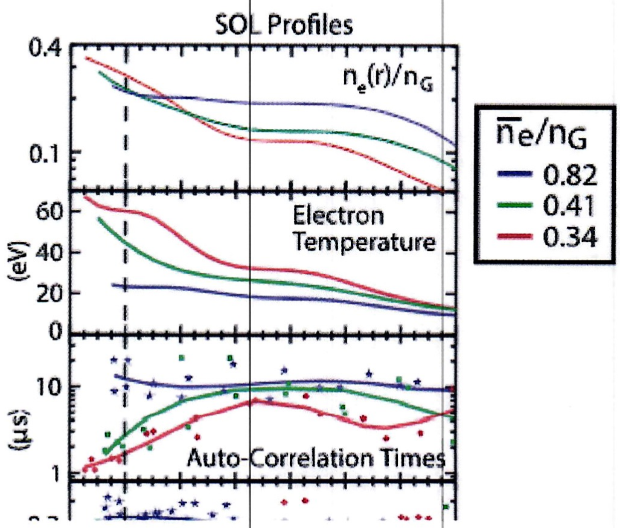


FIG. 17. Edge temperature profiles show the progressive edge cooling as the normalized density is increased toward n_G.

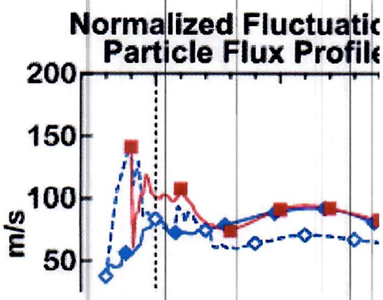
down at the end of a plasma shot is often at the rate required to stay just below the density limit.[5] That is, the discharge sheds particles during ramp-down to keep n/n_G just below 1.

C-Mod carried out experiments to measure the change in edge temperature along with any changes in fluctuations that accompany the approach to the density limit.[87,104] Well before the limit was reached, changes in the time-averaged SOL density profiles were observed, with progressive increases in the far-SOL density and overall flattening of the profiles even with modest increases in the separatrix density as shown in Fig. 9. At the same time, the amplitude, frequency, and velocity of blob production increased.[103,108] This picture is supported by fluid models, which predict very strong transport under these conditions.[90,109] At still higher densities, the boundary between the near-SOL and far-SOL moved inward, with the region of colder plasma, intermittent fluctuations and blob creation[110] eventually crossing the separatrix and intruding onto regions of closed field lines as seen in Figs. 17 and 18. The net cooli exchange between warm plasma convec fueling gas entering to replace it. \ reaches roughly to the position of 0.8 movement of about 3 cm on C-Mod), a tion is triggered. As the density limit is dicular transport of energy is signifi given the low upstream temperatures, transport channel is starved. This contr at lower density where all power is lost nel to the divertor. In that case, the up pinned to a narrow range, typically t boundary between open and closed fie close to the limit, perpendicular transp open field lines and the temperatures ca values. The appearance of Marfes or d then inevitable—if the plasma has not d sities, it will certainly detach near the no power is available in the parallel observations coupled to the predictions make a compelling case for turbulen cause of the density limit, work remain tive model. What is required is a model change in the equilibrium temperature is raised, which will require, at a minim lution to equations for turbulence an transport coupled to a neutral transport



2. Poloidally asymmetric transport flows

An important prediction of turbu transport would have a significant ball is, the turbulence would be stronger (LFS) of the plasma, which has a bad c the high-field side (HFS) with its good diction was tested on C-Mod using scanning probe, mounted on the inner tokamak's strong toroidal field crosse small coil in the probe mechanism.[97,1] the more remarkable in requiring that t



→ Why does the particle transport increase as $n \to n_G$?

→ If V_E' regulates transport → look at the shear layer

→

— Shear Layer collapse scenario.

Q

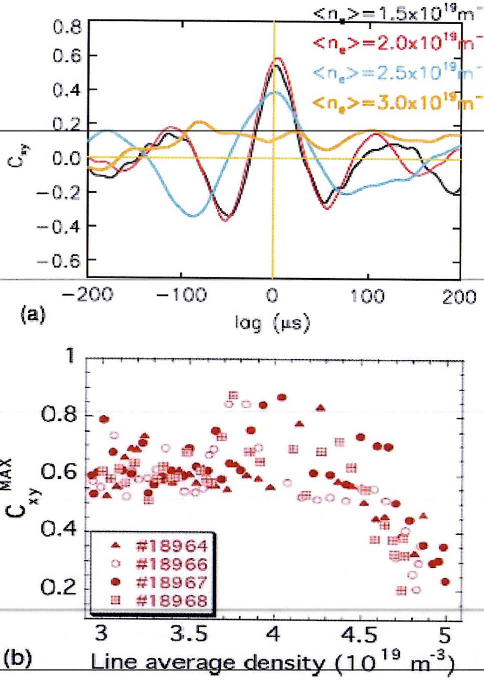
Recent Experiments - 1

(Y. Xu et al., NF, 2011)

LRC → Long range correlation

LRC vs $\bar{n}$

→ ZF. !



- Decrease in maximum correlation value of LRC (i.e. ZF strength) as line averaged density $\bar{n}$ increases at the edge (r/a=0.95) in both TEXTOR and TJ-II.
- At high density ($\langle n_e \rangle > 2 \times 10^{19}\ m^{-3}$), the LRC (also associated with GAMs) drops rapidly with increasing density.
- The reduction in LRC due to increasing density is also accompanied by a reduction in edge mean radial electric field (Relation to ZFs).

Is density limit related to edge shear decay?

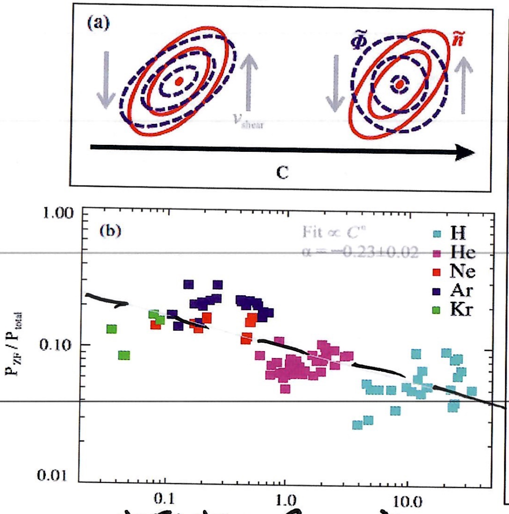
see also M. Pedrosa 2007
C. Hidalgo 2006.

Recent Experiments - 2

Eddy Tilt

(Schmid, Mans et al., PRL, 2017) – stellarator experiment

(not ~~an~~ density limit exp.)



- Experimental verification of the importance of collisionality for large-scale structure formation in TJ-K.
- Analysis of the Reynolds stress shows a decrease in coupling between density and potential for increasing collisionality → hinders zonal flow drive (Bispectral study)

  collisionality — density

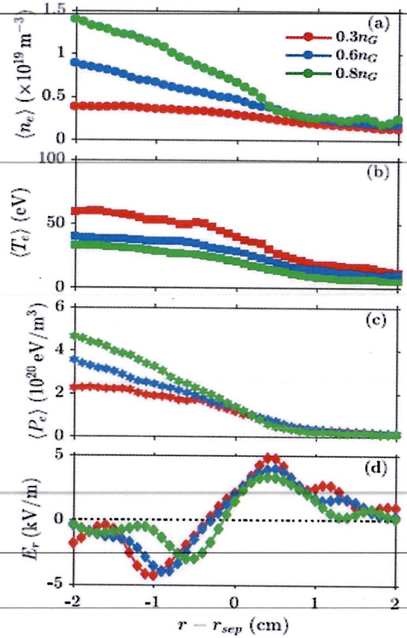
- Decrease of the zonal flow contribution to the total turbulent spectrum with collisionality *C*.

a) Increase in decoupling between density (red) and potential (blue) coupling with collisionality C.
b) Increase in ZF contribution to the spectrum in the adiabatic limit (C→0)

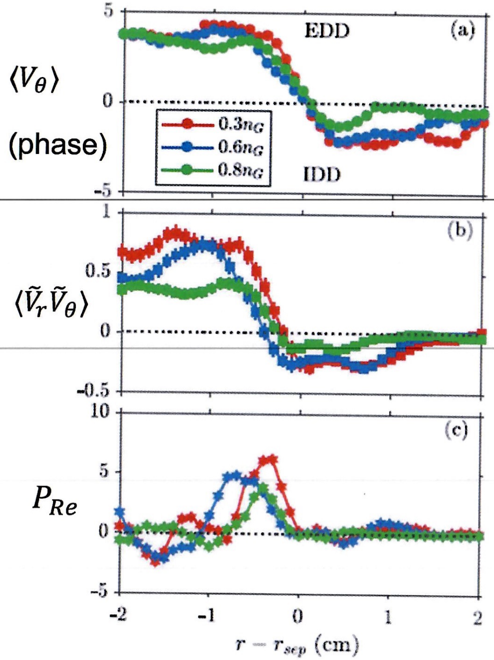
C ⇔ adiabaticity $k_{\parallel}^2 V_{th}^2/\omega\nu$

Basic Results

- OH, $I_p \sim 150kA$, $B_T = 1.3T$, $q = 3.5 \rightarrow 4$
- $\bar{n} = 0.25 \rightarrow 0.9\,\bar{n}_g$
- Profiles



- Fluctuation Properties

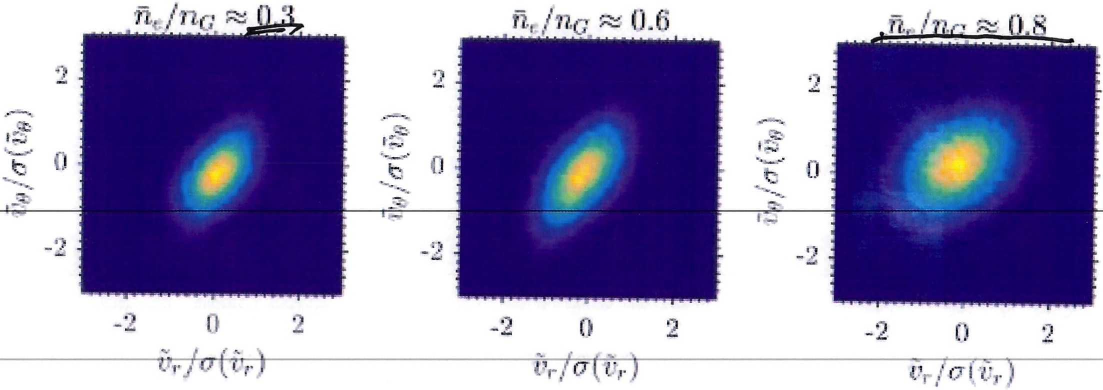


$P_{Re} = -\langle V_\theta \rangle \partial_r \langle \tilde{V}_r \tilde{V}_\theta \rangle$ → energy gained by low-f flow

DROPS as $\bar{n} \rightarrow \bar{n}_g$

2/9,

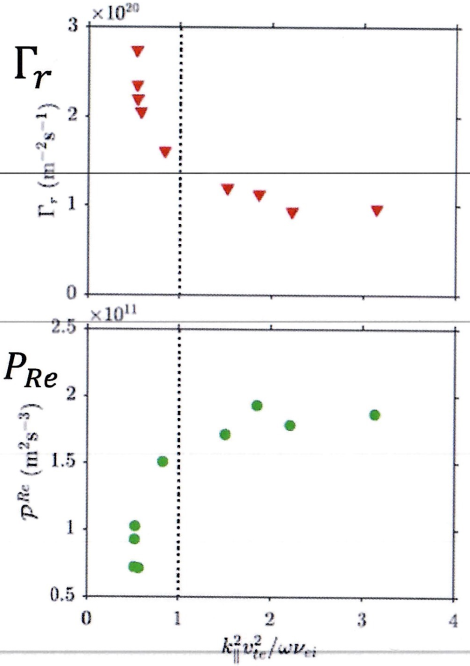
Recent Studies, Hong, et. al. (NF 2018)



- Joint pdf of $\tilde{V}_r, \tilde{V}_\theta$ for 3 densities, $\bar{n} \rightarrow n_g$
- $r - r_{sep} = -1cm$
- Note:
  - Tilt lost, symmetry restored as $\bar{n} \rightarrow \bar{n}_g$ ➔ Weakened shear flow production by Reynolds stress
  - Consistent with drop in P_{Re}

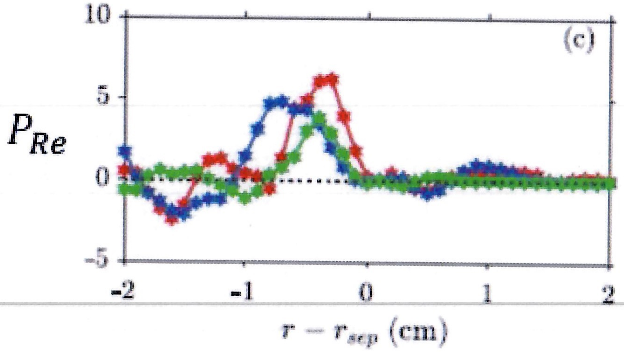
!?

Key Parameter: Electron Adiabaticity



adiabaticity

- Electron adiabaticity $\alpha = \frac{k_{\|}^2 v_{th}^2}{|\omega| \nu_{ei}}$ emerges as interesting local parameter. $\alpha \sim 3 \rightarrow 0.5$ during $\bar{n}$ scan!
- Particle flux ↑ and Reynolds power $P_{Re} = -\langle V_\theta \rangle \partial_r \langle \tilde{V}_r \tilde{V}_\theta \rangle$ ↓ as α drops below unity.



N.B. Plasma beta remained very low → kills the RBM scenario

Synthesis of the Experiments

- Shear layer collapse and turbulence and *D* (particle transport) rise as $\frac{\bar{n}}{\bar{n}_G} \rightarrow 1$.

  → Key microphysics of density limit !?

- ZF collapse as $\alpha = \frac{k_{||}^2 v_{th}^2}{|\omega| \nu_e}$ drops from $\alpha > 1$ to $\alpha < 1$. (or via ZF damping)

  → Effect on production

- Degradation in particle confinement at density limit in L-mode is due to breakdown of self-regulation by zonal flow

- Note that β in these experiments is too small for conventional Resistive Ballooning Modes (RBM) explanation.

➡ How reconcile all these with our understanding of drift wave-zonal flow physics?

The Key Questions

- What physics governs shear layer collapse (or maintanance) at high density?

⇔ 'Inverse process' of familar L→H transition !?

i.e. L→H : $\begin{cases}\text{shear layer} \rightarrow \text{barrier} \\ \text{turbulence}\end{cases}$

Density Limit: strong turbulence $\leftarrow \begin{cases}\text{shear layer,} \\ \text{turbulence}\end{cases}$

➔ In particular, what is the fate of shear flow for hydrodynamic electrons: $k_{\parallel}^{2}V_{th}^{2}/\omega\nu < 1$?

More generally → strong collisionality.

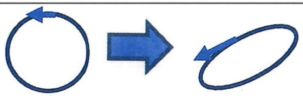
Step Back: Zonal Flows Ubiquitous! Why?

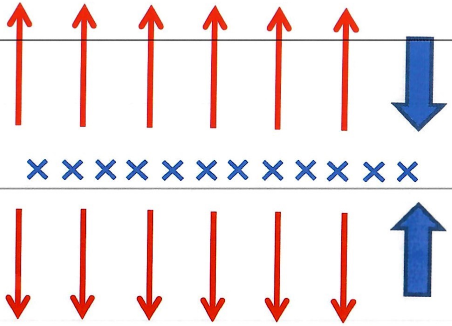
- Direct proportionality of wave group velocity and wave energy density flux

  to Reynolds stress ←→ spectral correlation $\langle k_x k_y \rangle$

  Causality ←→ Eddy Tilting

i.e.





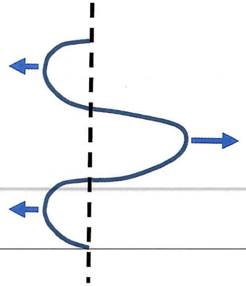
$\omega_k = -\beta\, k_x / k_\perp^2$: (Rossby)

➔ $V_{g,y} = 2\beta\, k_x k_y / (k_\perp^2)^2$

➔ $\langle \tilde{V}_y \tilde{V}_x \rangle = -\sum_k k_x k_y |\phi_k|^2$

same

So: $V_g > 0\ (\beta > 0)$ ⟷ $k_x k_y > 0$ ➔ $\langle \tilde{V}_y \tilde{V}_x \rangle < 0$



- Outgoing waves generate a <u>flow convergence</u>! ➔ <u>Shear layer spin-up</u>

But NOT for hydro convective cells:

- $\omega_r = \left[\frac{|\omega_{*e}|\hat{\alpha}}{2k_\perp^2\rho_s^2}\right]^{1/2}$ → for convective cell of H-W
- $V_{gr} = -\frac{2k_r\rho_s^2}{k_\perp^2\rho_s^2}\,\omega_r$ ←??→ $\langle\tilde{V}_r\tilde{V}_\theta\rangle = -\langle k_r k_\theta\rangle$; direct link broken!

→ Energy flux NOT simply proportional to Momentum flux →

↓

→ Eddy tilting ($\langle k_r k_\theta\rangle$) does <u>not</u> arise as direct consequence of causality

→ ZF generation <u>not</u> 'natural' outcome in hydro regime!

→ Physical picture of shear flow collapse emerges

Dispersion Relation for $\alpha < 1$ and $\alpha > 1$

Dispersion relation: $\omega = \frac{1}{2}\left(-i\frac{\hat{\alpha}(1+k_\perp^2\rho_s^2)}{k_\perp^2\rho_s^2} + \sqrt{\frac{4i\omega^\star\hat{\alpha}}{k_\perp^2\rho_s^2} - \left(\frac{\hat{\alpha}(1+k_\perp^2\rho_s^2)}{k_\perp^2\rho_s^2}\right)^2} \right)$

$$\hat{\alpha} = -\frac{v_{th}^2}{\nu_{ei}}\nabla_\parallel^2$$

$$\alpha = \frac{k_\parallel^2 V_{the}^2}{\nu_{ei}|\omega|}$$

Adiabatic Limit:
($\alpha \gg 1$ and $\hat{\alpha} \gg |\omega|$)

$$\omega_{adiabatic} = \frac{\omega^\star}{1+k_\perp^2\rho_s^2} + i\frac{\omega^{\star 2}k_\perp^2\rho_s^2}{\hat{\alpha}}$$

Wave + inverse dispersion

(Classic Drift Wave)

Hydro Limit:
($\alpha \ll 1$ and $\hat{\alpha} \ll |\omega|$)

$$\omega_{hydrodynamic} \simeq \sqrt{\frac{\omega^\star\hat{\alpha}}{2k_\perp^2\rho_s^2}}(1+i)$$

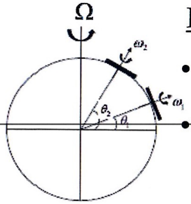
Convective Cell

key: $\alpha < 1$ → drift wave converts to convective cell

ZF Collapse ←→ PV Conservation and PV Mixing?

Back to
to the start.

How reconcile?

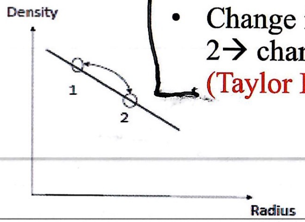


Rossby waves:

- $PV = \nabla^2\phi + \beta y$ is conserved from θ_1 to θ_2.
- Total vorticity $2\vec{\Omega} + \vec{\omega}$ frozen in→ Change in mean vorticity Ω leads to change in local vorticity ω → Flow generation (Taylor's ID)

Drift waves:

- In HW, $q = \ln n - \nabla^2\phi = \ln n_0 + h + \tilde{\phi} - \nabla^2\phi$ conserved along the line of density gradient.
- Change in density from position 1 to position 2→ change in vorticity → Flow generation (Taylor ID)



Quantitatively

- Total PV flux $\Gamma_q = \langle \tilde{v}_x h \rangle - \rho_s^2 \langle \tilde{v}_x \nabla^2\phi \rangle$
- Adiabatic limit $\alpha \gg 1$:
  +Particle flux and vorticity flux are tightly coupled (both prop. to $1/\alpha$)
- Hydrodynamic limit $\alpha \ll 1$:
  - Particle flux proportional to $1/\sqrt{\alpha}$.
  - Residual vorticity flux proportional to $\sqrt{\alpha}$.
- PV mixing still possible without ZF formation → Particles carry PV flux
- Branching ratio changes with α!

Flow, Fluctns

The rest – Ongoing ......

→ Discuss SOL
HD Mode
HOL.