Physics 218c

Lecture 8a: Density Limit and Greenwald Scaling, SOL Width and Heatloads

Edges & Separatrix

(Monday) 8b: Sheaths and PWI (Tynan)

→ All good things must come to an end....

- Monday is last class
- Still missing 6⁺ write-ups....!

→ Loose Ends — Rotation and Momentum Transport

- for details on symmetry breaking, see P.D. review 2013
- for details on 'momentum pinch' see Hahm, et. al. '07
- For unifying Physical Picture, see Kosuga, P.D., Gurcan and refs. therein (especially Ozawa)

approach is entropy production —
due Q_i, ∇T_i, ITG etc.

vs.

entropy destruction — Zonal flow and intrinsic rotation drive

⇒ Engine Paradigm ...

— for phenomenology OV, see review by Ida, Rice

— for the physics of boundary effects on intrinsic rotation, see ??

⇒ major issue! Most works (theory) have no-slip B.C.

La Bombard

⇝ Many papers posted.

Density Limits — RTT, $\beta = \frac{nT}{B^2}$

why? high n

Fueling → gas, pinch

$\Gamma = -D\nabla n + Vn$, $V < 0$ Thermo TEP

Surprise

↳ Density

Greenwald ← '88

$\bar{n}_g \sim I_p/\pi a^2$ → fundamental constraint

$\bar{n} \sim I_p$

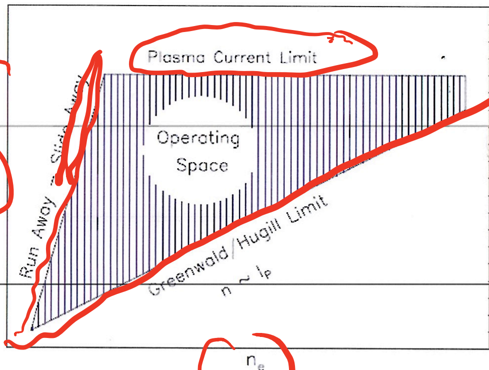
Stell — n Limit
Carlos Hidalgo
TJ II

n — Limit → edge

Density Limits: Some Basic Aspects

- Not a review!
- Greenwald density limit:

$$\bar{n} = \bar{n}_g \sim \frac{I_p}{\pi a^2}$$



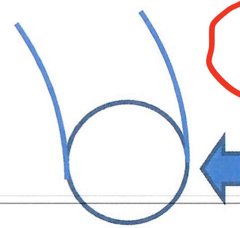
Constrains tokamak Operating Space

- Manifested on other devices
  - See especially RFP ($n \sim I_p$ scaling)

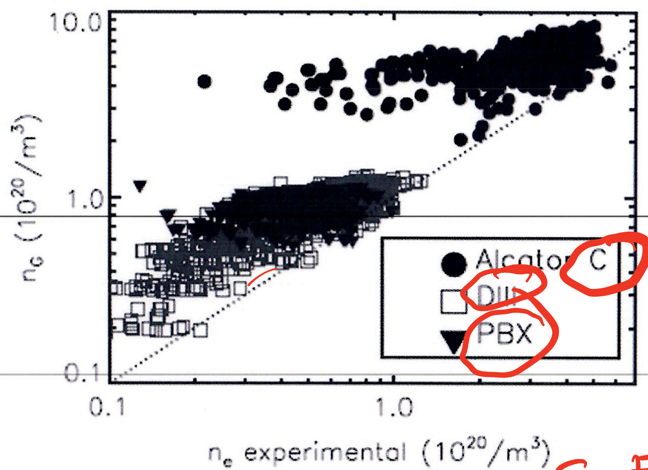
- Line averaged limit
- (Too) simple dependence!?
- Begs origin of I_p scaling?!

Stellarators?

- Most fueling via edge → edge transport critical to $\bar{n}$ limits



- Trends well established



works

Greenwald '88

G. Field

Drake

DJ

- Often (but not always!) linked to:
  - MARFE (radiative condensation instability) ←→ Impurity influx
  - MHD disruption
  - Divertor detachment
  - H→L Back-transition

radiation → condensation → cooling → DJ ↑ → Tearing → disruption

N.B. HDL (H-mode Density Limit) ≡ $\bar{n}$ s/t back transition.

→ usually $\bar{n}_{HDL} \leq \bar{n}_G$.

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→ Edge

Core ≡ closed field lines as discussed

SOL ≡ open field lines → connect to limiter, plate

– What is the Edge?

Core

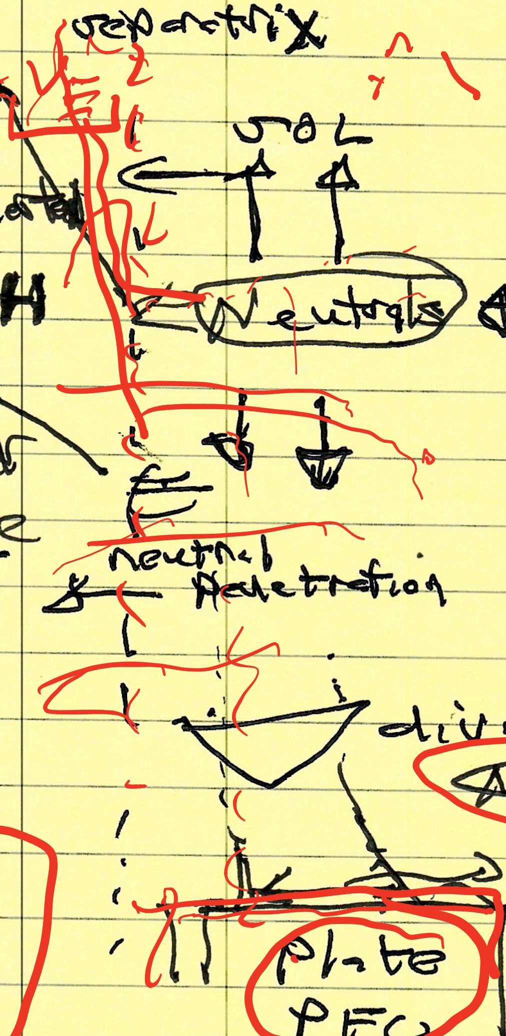
✓ Q ⇒ 'No Man's Land'

√ Γ ⇒ Pedestal

Π ⇒ L H

– pedestal, shear layer at edge in L, H

Shear Layer



Wall

Science

recycling

Tynan

blobs

$\Gamma_n \sim e^{-x/\Delta}$

Neutral Pressure

λ → heat load

sheath

Tynan

Plate PFC

(Pin → here)

– in L mode, edge turbulence is strong

$\frac{e\phi}{T}, \frac{\tilde{n}}{n} \gtrsim .1 \to 1$

D, χ

rising profile

Drop in H-mode

or

Langmuir probes often used to study edge.

→ "Which" Edge? transition L→H

n_e ? → soft

⇓ P_{th}.

~ density limit	L-mode	H-mode
very strong turbulence	strong turbulence	weak turbulence
collapse of shear layer	Shear Layer ⇓ (Reynolds stress, Neoclassical)	Strong Shear ⇓ $(\nabla P/n)'$ + . . .
D_r ↑	High Transport	ELMs ↔ MHD events (Turbulence)
density outflow	Pinch	D, χ_i, χ_ϕ ⇓ χ_e up. Pinch (?) (don't take too far)

~ Order Parameter

0 ← $V_E' / \Delta\omega_k$ → high

→ How determine E_r ?

– Core → $\underline{\nabla} \cdot \underline{J} = 0$, with mainly
(closed)

$\partial_r J_{pol} \cong 0$

⟺ Radial force balance

– SOL → $\underline{\nabla} \cdot \underline{J} = 0$ with $\partial_r J_r + \nabla_\parallel J_\parallel = 0$
(open)

⇓

sheath b.c.

→ What about the edge?

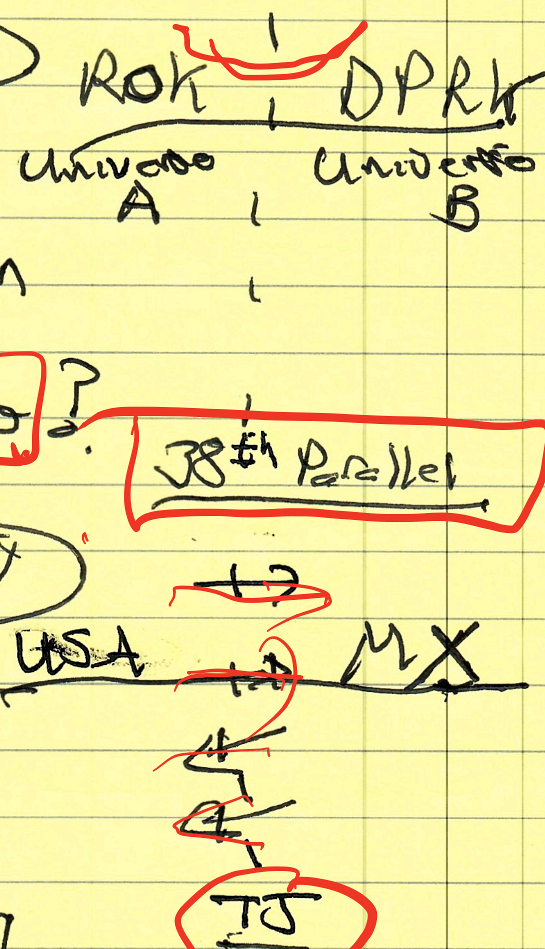
– Stupidity ⇔ Core–SOL Boundary

Core | SOL

sep

What people think

→ →



Key: transition layer.

How big – ρ_0?

(k-mode)

What it's really like?

∇P

Core: $\langle E_r \rangle$ → radial force balance

Edge: $\langle E_r \rangle \to \langle \phi \rangle \to$ Sheath

$$\langle \phi \rangle \simeq \frac{T}{|e|} \sim T \sim e^{-x/\lambda}\, T_{sep}$$

so $$V_E' \simeq \frac{1}{\lambda^2} \frac{T_{sep}}{|e|}$$

↑ SOL width

- In SOL

$\nabla \cdot \Gamma^{t} = Q \Rightarrow \nabla_{\perp} \Gamma^{t}_{\perp} + \nabla_{\parallel} \Gamma^{t}_{\parallel} = 0$

parallel losses

In core

$\nabla \cdot \Gamma^{t} = 0$

$\rightarrow \Gamma^{t} = \text{const.}$ (fixed flux)

For Density Limit, first ask:

→ What of L-mode ? → base state

- lots of Info → Langmuir probes '58 (since Zeta → Robinson + Rusbridge)
- intensities, direct measurement of fluxes → $\langle \tilde{v}_r \tilde{n} \rangle$ $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ especially

$\tilde{T}$ harder !

$E \quad E$ cross phase

- interestingly, frequently see:

$\tilde{n}/n \sim \frac{|e|\tilde{\phi}}{T}$ (but $\alpha \lesssim 1$?)

non-adiabatic

— Candidates → see Zoo

[CDW, DTEM, [ITG RBM [DM (CRGDT) continues

(α > 1, k << 1 continuous)

— "Drift Waves", extended to hydrodynamic electron regime

$\frac{k_{\parallel}^2 v_{the}^2}{\omega \nu} < 1$

does it matter?

Non adiabatic behavior is not surprising → "MHD-like" candidates

— What does matter? — Shear Layer

— L-mode tokamak stellarator (1990's) edges support a shear layer — universal

— Observed first TEXT — mid 80's.

Exhibited effects on eddys, etc. linked to turbulence control. →

[redacted] Ritz 1990.

Evidence for Confinement Improvement by Velocity-Shear Suppression of Edge Turbulence

Ch. P. Ritz, H. Lin, T. L. Rhodes, and A. J. Wootton
Fusion Research Center, The University of Texas, Austin, Texas 78712
(Received 10 April 1990)

The electrostatic fluctuations are decorrelated in the region of a naturally occurring $\mathbf{E}_r \times \mathbf{B}$ velocity shear close to the outermost closed flux surface of regular Ohmic TEXT discharges. The concomitant local steepening of the density profile and suppression of the fluctuations are consistent with theoretical predictions. The high-confinement mode (*H* mode) found in other tokamaks shows in exaggerated form similar characteristics and could thus be related to the same mechanism leading to a locally improved confinement.

PACS numbers: 52.55.Fa, 52.25.Gj

Quantitative comparisons on the TEXT tokamak demonstrate that electrostatic fluctuations are a major cause of the anomalous particle and energy transport[1] in Ohmic discharges as suggested previously by other experiments.[2,3] In addition, a radial electric field E_r has been shown to modify the global confinement[4] as well as the edge turbulence and electrostatic-fluctuation-induced transport.[2,5] Most recently a series of experiments has been conducted on the Constant Current Tokamak (CCT) using a highly biased emissive electrode.[6] The biasing triggered a transition to a regime with the characteristics of the high-confinement mode (*H*-mode regime first reported on ASDEX[7]), which is one of the most successful paths to improve the plasma confinement in tokamaks. Associated with the transition on CCT was a measured increase in E_r, and thus in the rotation velocity $\mathbf{v}_E \equiv \mathbf{v}_{\mathbf{E}_r \times \mathbf{B}}$. Such changes in E_r have also been observed on DIII-D, a large tokamak, at the transition to the *H* mode.[8] Since the physics of *H* modes is not well understood, this is a motivation for further experimental studies.

The above experiments suggest that one possible mechanism for improved confinement is a change in the edge electric field, and concomitant change in the $\mathbf{E} \times \mathbf{B}$ rotation velocity v_E and the fluctuation levels. Theoretical work[9–14] shows that, if changes in radial electric field result in an angular-velocity shear, then turbulence can be reduced leading to a decreased outward transport. In this paper we examine the theoretical predictions of turbulence suppression by sheared plasma rotation. Based on results from TEXT we demonstrate a clear correlation between velocity shear, reduction of the turbulence, and local improvement of the confinement.

A velocity shear due to a peaking plasma potential close to the outermost closed flux surface has been characterized on TEXT[15] and other devices.[16,17] The mean velocity of the fluctuations perpendicular to $\mathbf{B}$ measured with a two-point correlation technique in the laboratory frame of reference,

$$v_{\rm ph} = \sum_{k>0,\omega} [\omega/k_\theta(\omega)] S(k,\omega) \Big/ \sum_{k>0,\omega} S(k,\omega) \,,$$

is dominated by $v_E = E_r/B$ effects,[18] as shown in Fig. 1(a), where v_{de} is the diamagnetic drift velocity. (The contribution to v_E from ∇p is thus small and only slowly varying with radius.) The density and floating potential fluctuations, $\tilde{n}$ and $\tilde{\varphi}$, are reduced in a region shifted to larger r/a from the shear region by roughly half the radial shear width, as shown in Fig. 1(b). The mean density is slightly steepened in the region of maximal shear, as

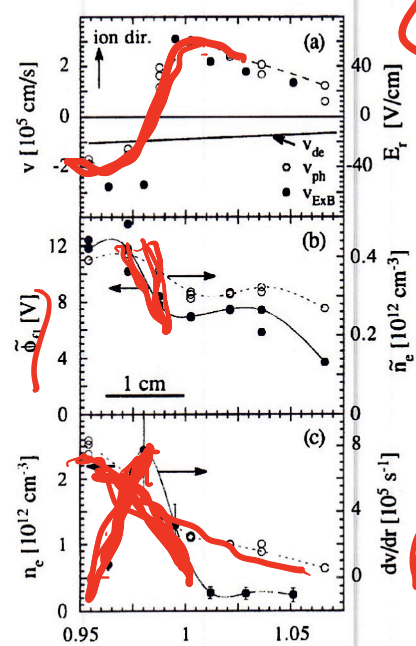


FIG. 1. Radial profiles for a discharge with $B_\phi = 2$ T, plasma current of 200 kA, and chord-averaged density of $n_{\rm chord} = 2\times10^{13}$ cm^{-3}. (a) Phase velocity of the fluctuations $v_{\rm ph}$ (closed circles), $v_{\mathbf{E}_r \times \mathbf{B}}$ plasma rotation (open circles), and drift velocity v_{de}. (b) Density and floating potential fluctuations. (c) Density and velocity shear. The statistical error for individual shots is of order the symbol size and shot-to-shot reproducibility is given by the individual symbols. The systematic error in the plasma position is 0.5 cm or $r/a \simeq 0.02$.

shown in Fig. 1(c). The steepening is not pronounced, but consistently found on reproducible discharges.

The (one-point) correlation time τ_c^{lab} of the fluctuations measured in the laboratory frame of reference is obtained from the e-folding time τ of the autocorrelation function $R(\tau,\mathbf{r})\equiv\langle x(t,\mathbf{r})x(t+\tau,\mathbf{r})\rangle$. The fluctuation quantity $x(t,\mathbf{r})$ is the ion saturation current (proportional to density) and the angular brackets represent averaging over a temporal interval large compared to τ and ensemble averaging over several realizations. From Fig. 2 we find $\tau_c^{lab}=10\pm1.5$ μs behind the velocity shear ($r/a\simeq1$), 2 ± 0.4 μs at the location of maximal shear, and 5 ± 1 μs on the bulk plasma side of the shear layer ($r/a\simeq0.95$).

Similarly we compute the normalized cross-correlation function between two points $\mathbf{r}$ and $\mathbf{r}+\delta\mathbf{r}$,

$$\gamma(\tau,\mathbf{r},\delta\mathbf{r})\equiv C(\tau,\mathbf{r},\delta\mathbf{r})/[R(\tau=0,\mathbf{r})R(\tau=0,\mathbf{r}+\delta\mathbf{r})]^{1/2},$$

where the cross-correlation function is

$$C(\tau,\mathbf{r},\delta\mathbf{r})\equiv\langle x(t,\mathbf{r})y(t+\tau,\mathbf{r}+\delta\mathbf{r})\rangle.$$

By varying the Langmuir-probe separation $\delta\mathbf{r}$ we obtain the correlation lengths in the radial, poloidal, and toroidal directions from the separations for which the peak values of $\gamma(\tau,\mathbf{r},\delta\mathbf{r})$ decrease to $1/e$ of the values at $\delta\mathbf{r}=0$. The resulting correlation lengths on the bulk plasma side of the velocity shear ($r/a=0.95$) are $\sigma_r\simeq0.5$ cm, $\sigma_\theta\simeq1$ cm, and $\sigma_\phi\simeq100$-200 cm.[19] To study the dependence of the correlation length on the velocity shear we measured the fluctuations simultaneously with an array of four probes separated poloidally and toroidally by a fixed distance of $\delta r=3$ mm. As shown in Fig. 3 the peak values of the normalized cross-correlation function decrease in the shear layer with respect to the values on either side for both radially and poloidally separated probes. (The decrease is not large since the probe spacing is within a correlation length.) Furthermore, the τ dependences of $\gamma(\tau,\mathbf{r},\delta\mathbf{r})$ in the poloidal and radial directions are similar in the shear layer.

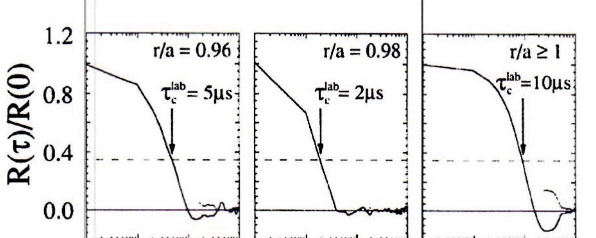


FIG. 2. Normalized one-point correlation function for two positions on either side of the shear layer and in the velocity shear. Dotted curve is the absolute value. Arrow indicates e-folding time τ_c^{lab}.

The turbulence is thus isotropic perpendicular to the magnetic-field direction, in contrast to the turbulence on either side of the shear layer where the decorrelation is faster in the radial direction than in the poloidal direction, consistent with the correlation-length measurements.

Relating the experimental observations to theoretical models, we can form three groups of questions: (i) What causes the peaking plasma potential leading to the strongly nonuniform electric field? (ii) Can the free energy in the velocity shear drive instabilities? (iii) Can the velocity shear suppress turbulence and thus improve the confinement? The first two questions are only briefly addressed for completeness.

On TEXT the width of the plasma potential peak which is connected with the velocity shear is typically 2 cm and thus approximately of the width of a poloidal ion Larmor radius (banana orbit width) for the hot-ion tail with $v^*(v)\leq1$. The positive peak of the plasma potential causing the nonuniform radial electric field is thus possibly due to a differential orbit loss mechanism at the outermost closed flux surface.[11,20,21] Mechanisms causing a nonambipolar transport may also generate such effects.

For the strong velocity shear measured here, the Kelvin-Helmholtz (KH) instabilities[22] must be examined. The radial extent over which significant fluctuation levels are observed experimentally is much larger than the velocity-shear region. Further the fluctuation level is reduced and not enhanced in the velocity-shear region. Based on these experimental results, the KH instability is not expected to dominate the edge turbulence. A theoretical study also comes to the conclusion that the edge plasma of TEXT is KH stable because of the stabilizing role of the magnetic shear.[9]

Before the velocity shear is sufficient to destabilize KH instabilities it is already capable of reducing the ambient turbulence level due to the fissuring of fluid elements subject to a velocity shear:[12] A *nonuniform* radial electric field ($E_r'=\partial E_r/\partial r\neq0$) causes in a slab a velocity dif-

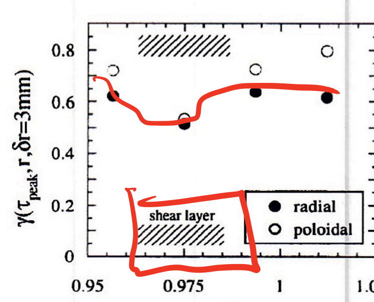


FIG. 3. Peak values of the normalized two-point correlation function for poloidally and radially separated probes with fixed separations of $\delta r=3$ mm.

Kinks

- L→H transition builds on base state of OH shear layer (Hidalgo)

- Shear Layer accountable from turbulent Reynolds stresses.

Shear layer regulating L-mode

Now back to Density Limit ...

- Edge particle transport crucial to density limit

Shear Layer Collapse

- Greenwald small pellet relaxation

Perturbative Transport Exp.

⇒ Edge sheds excess density without disruption

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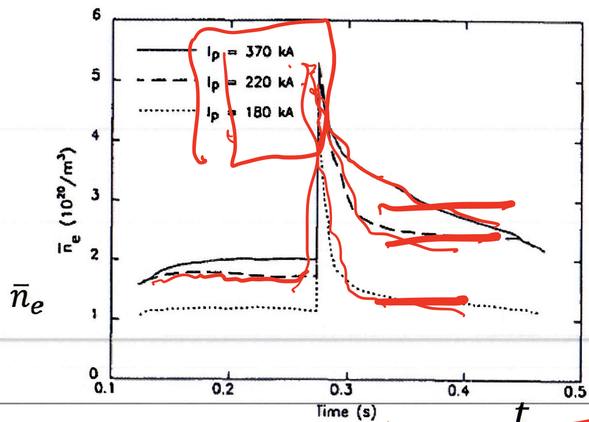
⇒ Density limit linked to intrinsic physics of L-mode edge transport.

- 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

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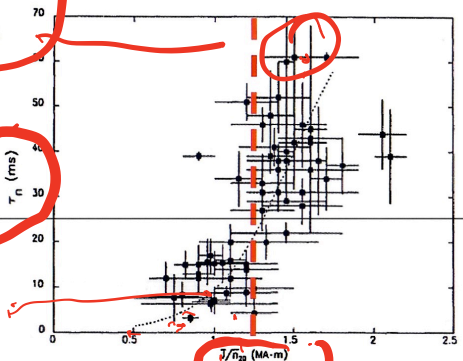
- More Evidence for Role of Edge Transport

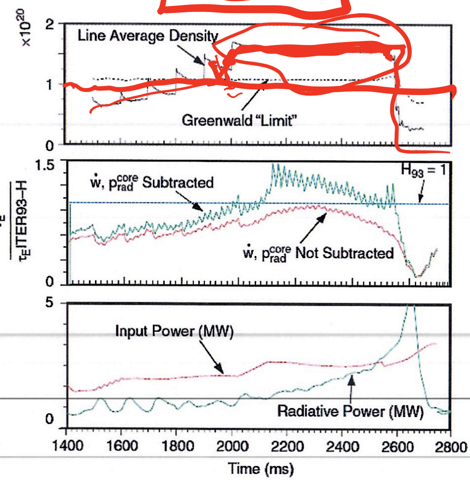


Pert.

- 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 ?!)

$\bar{J}/\bar{n}$

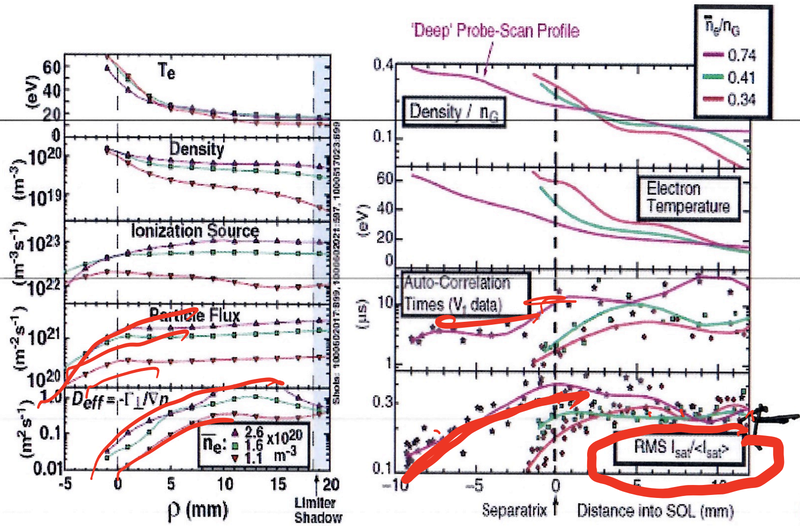


- Pellet in DIII-D beat $\bar{n}_g$
- Peaked profiles ←→ enhanced core particle confinement (ITG turbulence reduced?)
- Reduced particle transport → impurity accumulation — issue with Pellet.

(N.B. Deeper deposition)

— advantage ELMy H-mode (Grassy) QH

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, $\chi_\parallel \sim 1/n$)
⇒ detachment?

Greenwald, Review

Edge cooling

Cooling → increased ExB transport.

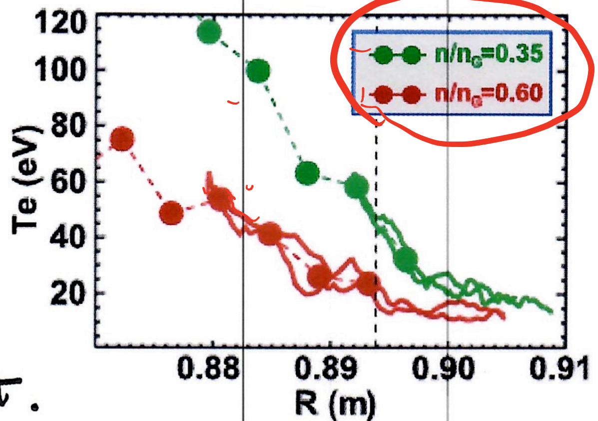
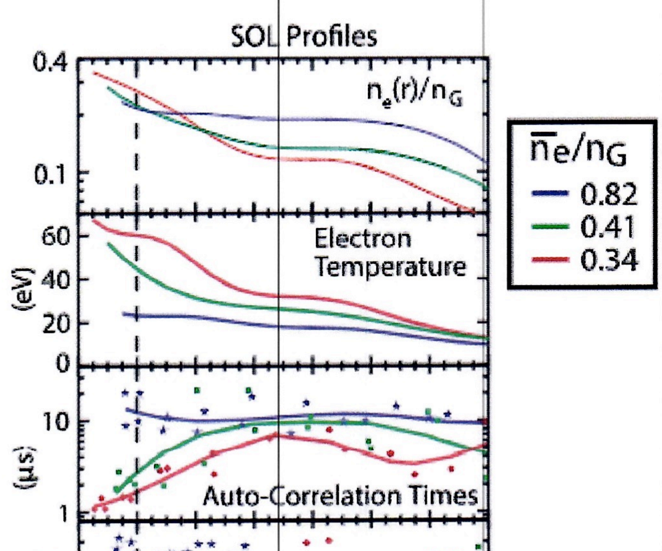


FIG. 17. Edge temperature profiles show the progressive edge cooling as the normalized density is increased toward n_G.

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.

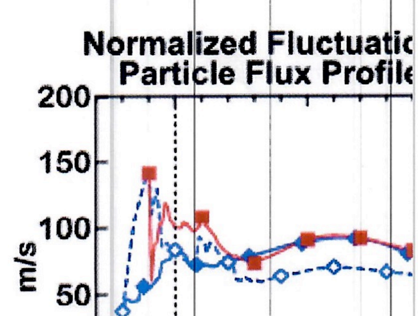
C-Mod carried out experiments to measure the change in edge temperature along with any changes in fluctuations that accompany the approach to the density limit.[87,104] Well before the limit was reached, changes in the time-averaged SOL density profiles were observed, with progressive increases in the 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. V 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 signific given the low upstream temperatures, transport channel is starved. This contra at lower density where all power is lost nel to the divertor. In that case, the ups 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 turbulenc cause of the density limit, work remains 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 r

2. Poloidally asymmetric transport a flows

An important prediction of turbu transport would have a significant ball is, the turbulence would be stronger o (LFS) of the plasma, which has a bad cu the high-field side (HFS) with its good diction was tested on C-Mod using scanning probe, mounted on the inner w 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

n $\bar{n}$

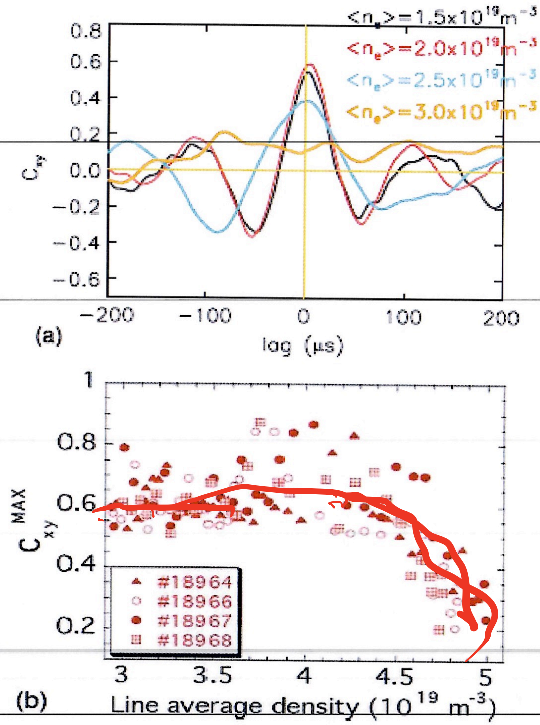
⇒

– Shear Layer collapse scenario.

Recent Experiments - 1

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

LRC → Long range correlation → ZF.



LRC vs $\bar{n}$

- Decrease in maximum correlation value of LRC (i.e. ZF strength) as line averaged density 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.

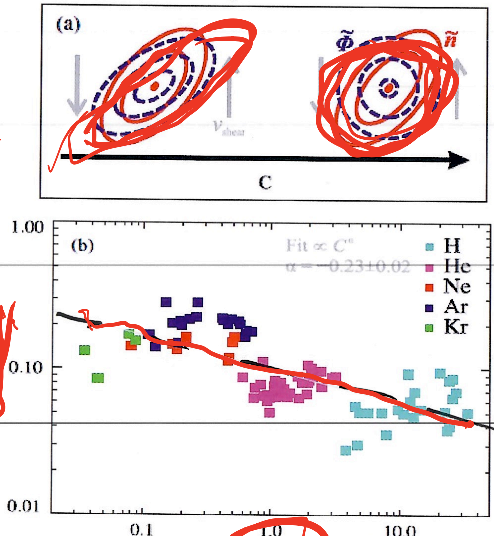
TJ II

Recent Experiments - 2

Eddy Tilt

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

(not 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*.

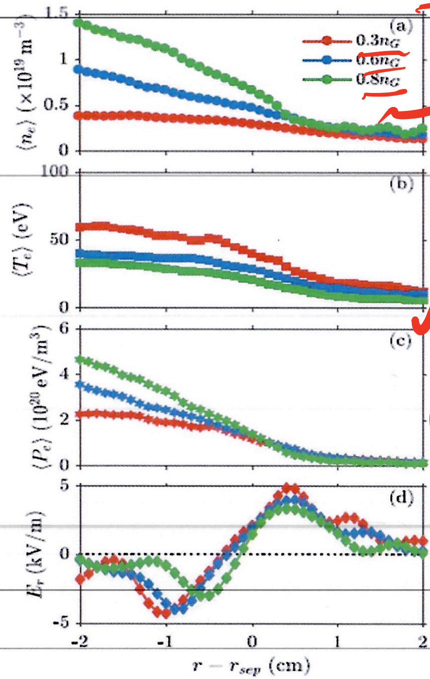
a) Increase in decoupling between density (red) and potential (blue) coupling with collisionality C.
b) Increase in ZF contribution to the spectrum in the adiabatic limit (C→0)

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

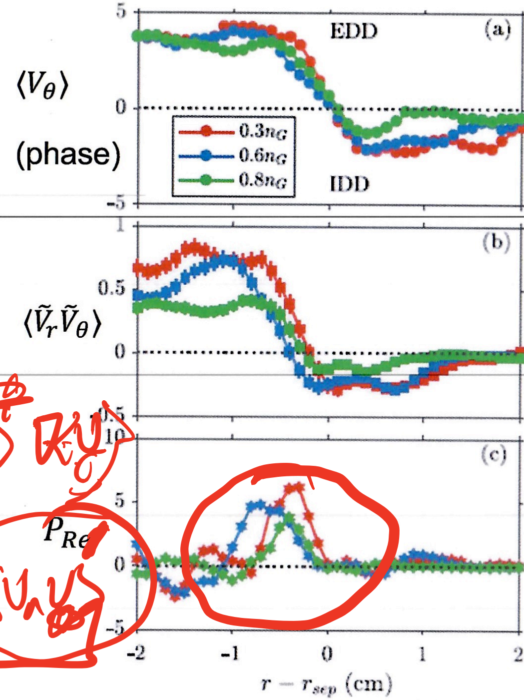
Basic Results

- 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

HL-2A



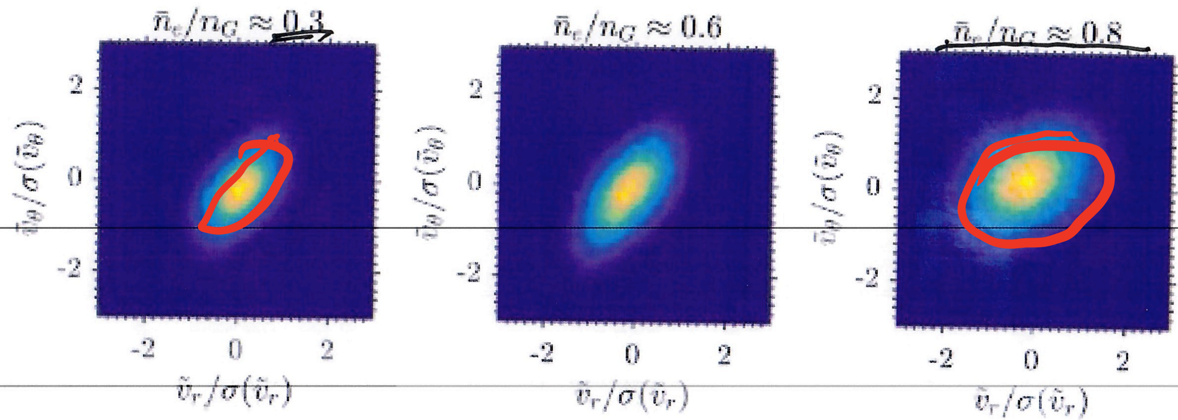
- Fluctuation Properties



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

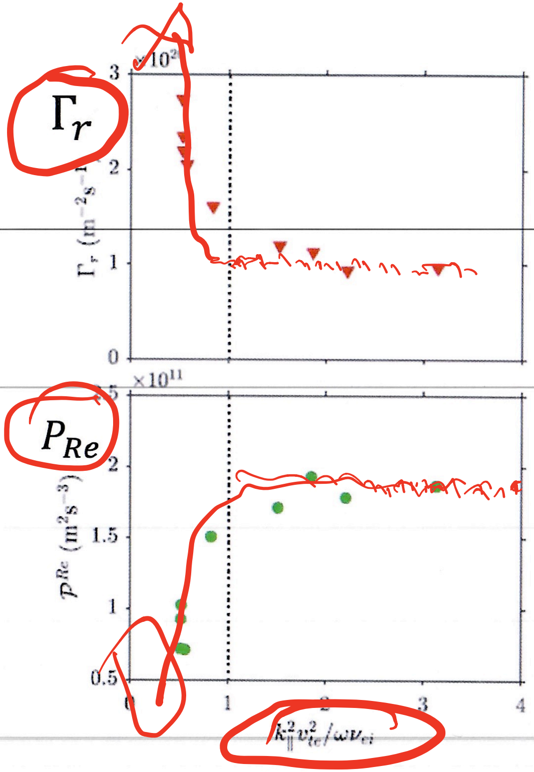
DROPS as $\bar{n} \rightarrow \bar{n}_g$

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



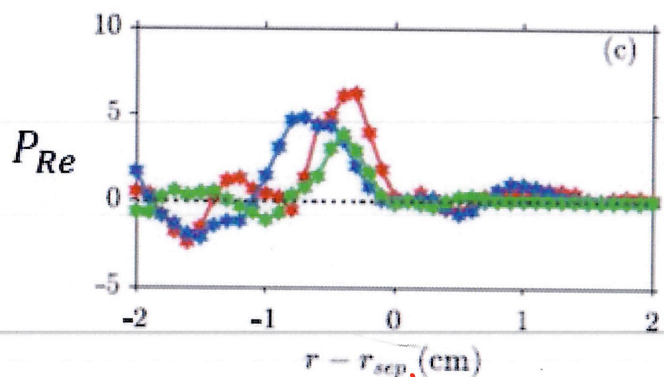
- Joint pdf of $\tilde{V}_r, \tilde{V}_\theta$ for 3 densities, $\bar{n} \to n_g$
- $r - r_{sep} = -1cm$
- Note:
  - Tilt lost, symmetry restored as $\bar{n} \to \bar{n}_g$ ➔ Weakened shear flow production by Reynolds stress
  - Consistent with drop in P_{Re}

Key Parameter: Electron Adiabaticity



adiabaticity

- Electron adiabaticity $\alpha = \frac{k_\parallel^2 v_{th}^2}{|\omega|\nu_{ei}}$ emerges as interesting local parameter. α~3 → 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

$\beta \sim nT$

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Synthesis of the Experiments

- Shear layer collapse and turbulence and D (particle transport) rise as $\frac{\bar{n}}{\bar{n}_G} \to 1$.
  → Key microphysics of density limit !?
- ZF collapse as $\alpha = \frac{k_{||}^2 v_{th}^2}{|\omega| \nu_c}$ drops from $\alpha > 1$ to $\alpha < 1$.
  → 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 : { shear layer → barrier; turbulence }

Density Limit: strong turbulence ← { shear layer, turbulence }

➔ 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.

Advertisement: Singh PRL, NF

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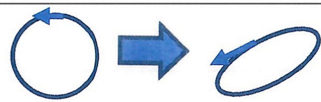
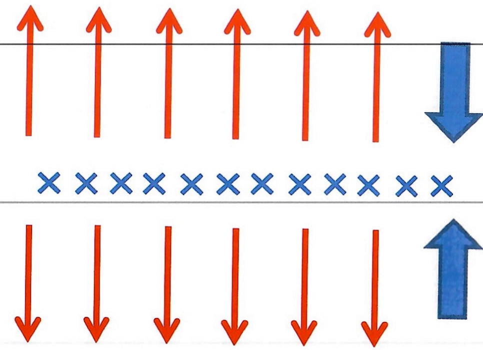
Step Back: Zonal Flows Ubiquitous! Why?

- 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. 



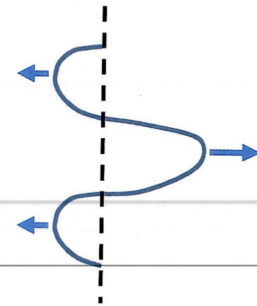
$\omega_k = -\beta\, k_x / k_\perp^2$: (Rossby)

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

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

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 flow convergence! ➔ Shear layer spin-up

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 not arise as direct consequence of causality

➔ ZF generation not '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 $\hat{\alpha} \ll |\omega|$)

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

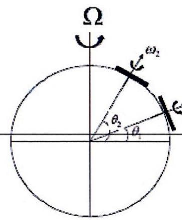
Convective Cell

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

ZF Collapse ←→ PV Conservation and PV Mixing?

Back to to the start.

How reconcile?

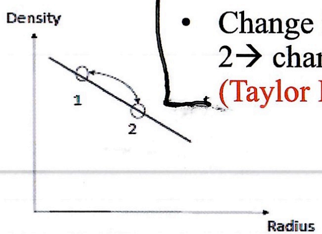


Rossby waves:

- $PV = \nabla^2\phi + \beta y$ 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)



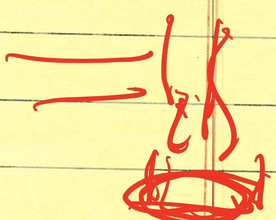
Quantitatively

- 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, Fluxes

The rest — Ongoing .....

HDL → SOL width



LeBombard $\lambda \sim 1/B_\theta$

→ Goldston 1/2

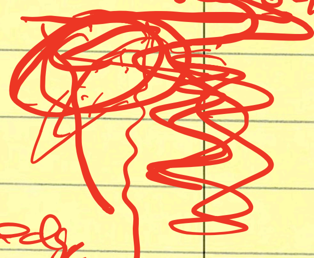
$\lambda \sim v_D \tau_\parallel \sim \frac{1/m_i}{R} \frac{R}{v_{thi}} \sim \rho_i \frac{B_T}{B_\theta} \frac{r}{R}$

SOL

$\frac{D_\perp}{(\lambda_\theta)^2}$ $\lambda \sim \rho_\theta$

1/n

turbulence



edge

HDL

HDL → onset of SOL turbulence high?

Turb. spreading

$\langle \tilde{v}_r \tilde{v}_\theta \rangle \Leftrightarrow v_{\theta n} \sim \frac{\chi_{turb} \partial_x^2 v_\theta}{1 + k_\perp^2 \rho_s^2}$

$\alpha \langle E \rangle$

$\omega_r \sim \omega_{\ldots}$