Sheared flow dynamics in edge turbulence*

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Introduction

- Core confinement in tokamaks is sensitive to edge profile gradients.
- The edge profiles are set by turbulence, so it is important to understand the mechanisms of turbulence saturation and how these influence the edge gradients.
- For typical edge profiles, there is no scale separation between background and turbulence, $k_\perp L_n \sim 1$.
- Edge turbulence studies require a “global” code (with edge and SOL profiles free to evolve), not a “local” or flux-tube code. Here, we use the 2D SOLT (SOL turbulence) code.
- We are studying the roles of
  - *pressure profile modification*
  - *Reynolds stress and sheared flows*
  - *radial variation in geometry and physics (open and closed field lines, drift wave, curvature driven and sheath regions)*

Outline

- *Quasi-linear calculations for Kelvin-Helmholtz (KH) and interchange modes*
- *Overview of SOLT turbulence simulations*
- *Comparison of quasi-linear theory with simulations*
- *Conclusions*

Quasi-linear model

- **Interchange and Kelvin-Helmholtz (KH) stability is given by**

$$(\omega - k_y v_y)(\Phi'' - k_y^2)\Phi + k_y v_y''\Phi + \frac{k_y^2 n_0'}{n_0(\omega - k_y v_y)}\Phi = 0$$

- **BCs: $\Phi \to 0$ as $x \to \pm\infty$**
- **Inputs: k_y and profiles $n_0(x)$ and $v_y(x) \Rightarrow$ scalelengths L_n and L_v**

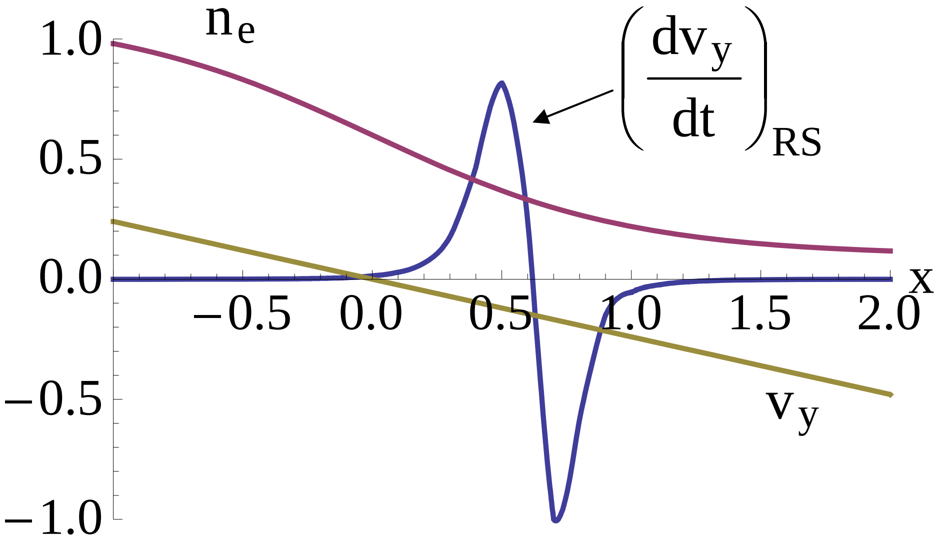
- **Compute the Reynolds' stress (RS)-generated $dv_y(x)/dt$.**

  $\Rightarrow$ the *sign* of $dv_y(x)/dt$ depends on $k_y L_n$ and L_v/L_n.

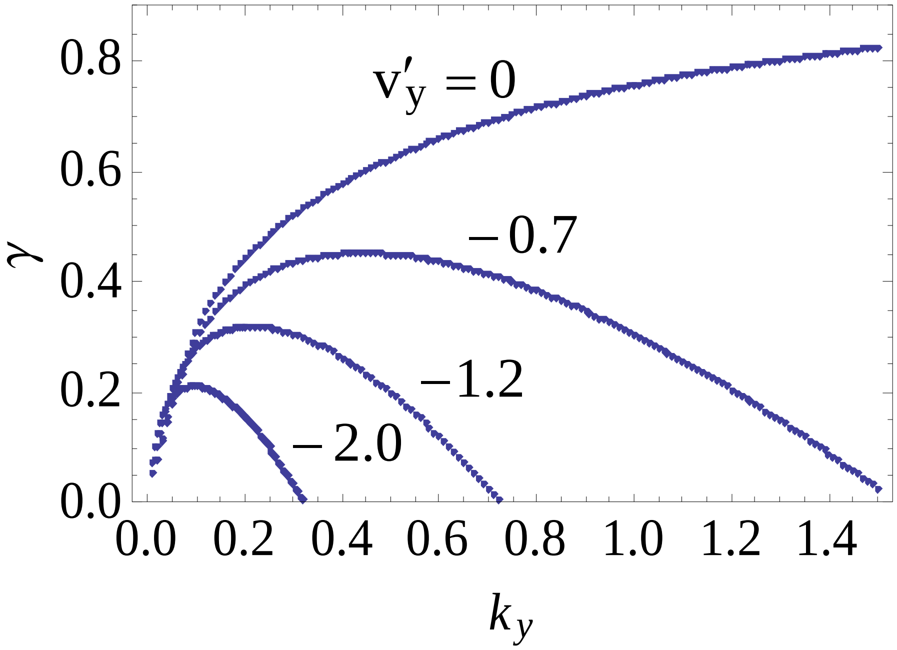
- **Let $L_n = 1$ so that length scales are normalized to L_n.**

Constant velocity shear ($L_v >> L_n$)

$k_yL_n = 0.6$



Interchange growth rate γ vs k_yL_n

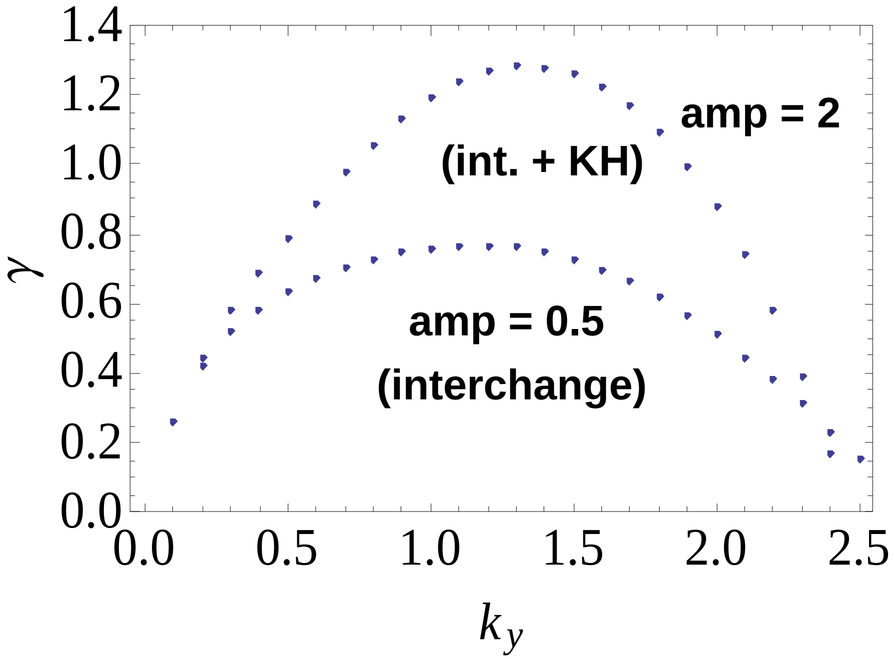


RS tries to increase the v_y gradient at the mode center ⇒ ZF instability

Constant v_y shear ⇒ no KH mode.

Shear stabilizes the interchange mode and is most effective at high k_y.

Localized v_y shear ($L_v \sim L_n$)



The amp = 0.5 case is largely interchange driven.

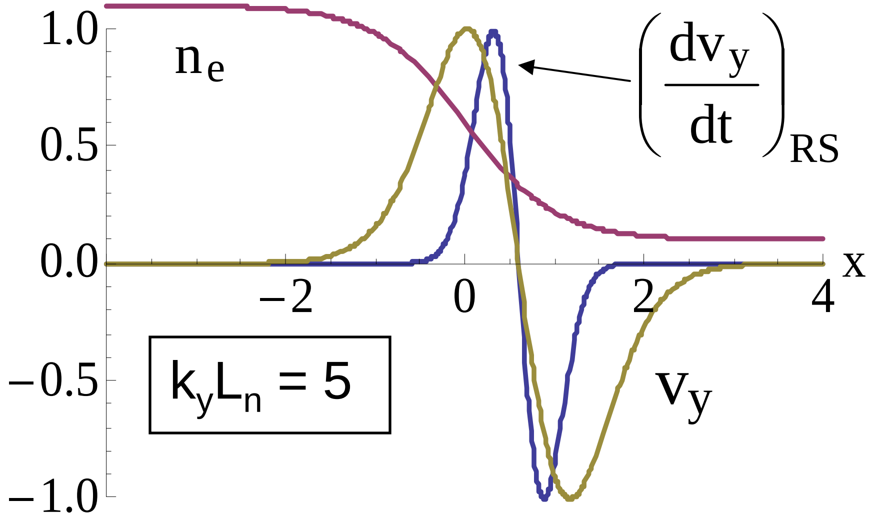
Note dependence of growth rate on k_yL_n:

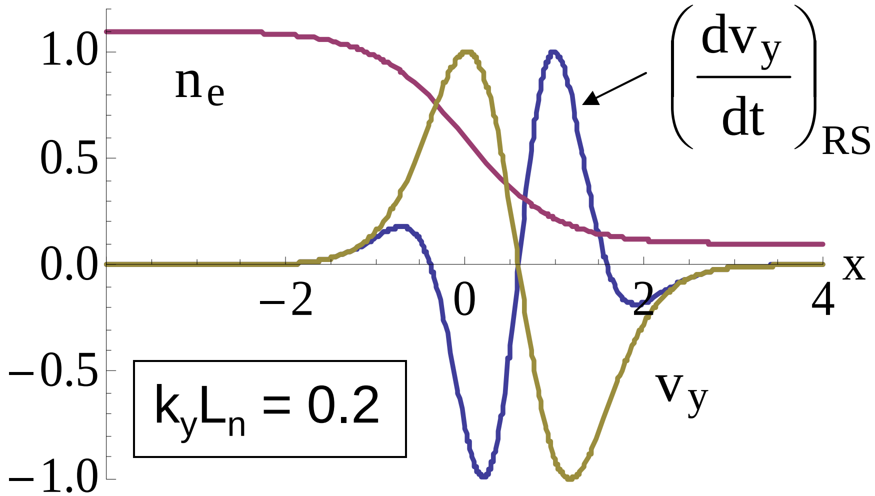
(a) small k_yL_n ⇒ $\gamma \to 0$ for all instability drives (flows are not important)

(b) intermediate k_yL_n ⇒ flows are destabilizing (KH mode)

(c) large k_yL_n ⇒ flows stabilize interchange mode

Effect of the RS depends on k_yL_n





amp << 1 for both cases ⇒ pure interchange instability drive

$k_yL_n >> 1 \Rightarrow$ RS tries to increase the gradient in v_y at the mode center, enhancing the flow that was present.

$k_yL_n \leq 1 \Rightarrow$ The RS opposes the existing flow.

Quasi-linear picture

From these and other cases, varying the shapes of the profiles and the scale lengths, we obtain the following picture of how curvature-driven interchange modes interact with sheared flows:

- Pure KH modes act to reduce the v_y shear driving them (at least locally, although this may increase the shear elsewhere).
- Shear in v_y stabilizes the interchange mode and is most effective on the high k_y modes.
- The Reynolds Stress (RS) from pure interchange modes acts to enhance the imposed flows if the flows are large-scale with respect to the mode's radial variation, while the RS opposes the seed flows if those flows are small scale.

Quasi-linear picture - 2

- An important implication of this work is that long wavelength modes (with respect to the pressure gradient) cannot be stabilized by self-generated sheared flows; instead, they must be stabilized by pressure profile modification (wave-breaking, plateau formation). This agrees with the SOLT simulations described subsequently.

- Finally note that these results suggest that the inverse cascade in k_y may be responsible for this behavior:
  - Large k_y, associated with small-scale radial mode structure, feeds the (larger-scale) flow.
  - Small k_y, associated with large-scale radial mode structure, saps the (smaller-scale) flow.

- This picture is in qualitative agreement with SOLT simulations of turbulence saturation as a function of radial gradients

Quasi-linear picture - 3

For comparison with the SOLT turbulence simulations, summarize the results of the quasi-linear calculations for curvature-driven interchange modes in the following table:

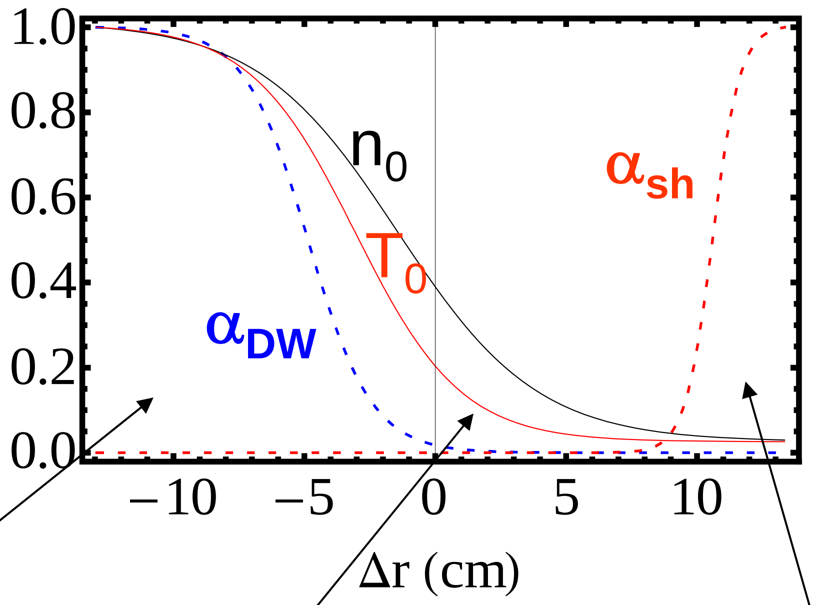
	$L_v \leq L_p$	$L_v >> L_p$
$k_y L_p >> 1$	RS+	RS+
$k_y L_p \leq 1$	RS–	RS+

where RS+ (RS–) $\Rightarrow$ the Reynolds Stress (RS) acts to increase (decrease) the flow shear at the mode center.

RS+ is the usual ZF instability found in flux-tube (local) simulations.
RS– requires a global turbulence code (e.g. SOLT).

SOLT turbulence studies

input profiles:



source region,
DW physics

curvature-driven
turbulence

sheath region

Definitions:

$$\alpha_{dw} = \frac{2\rho_s m_i c_s}{L_{\|e}^2 \nu_{ei0} m_e}$$

$$\beta = \frac{2\rho_s}{R} \qquad \alpha_{sh} = \frac{2\rho_s}{L_{\|s}}$$

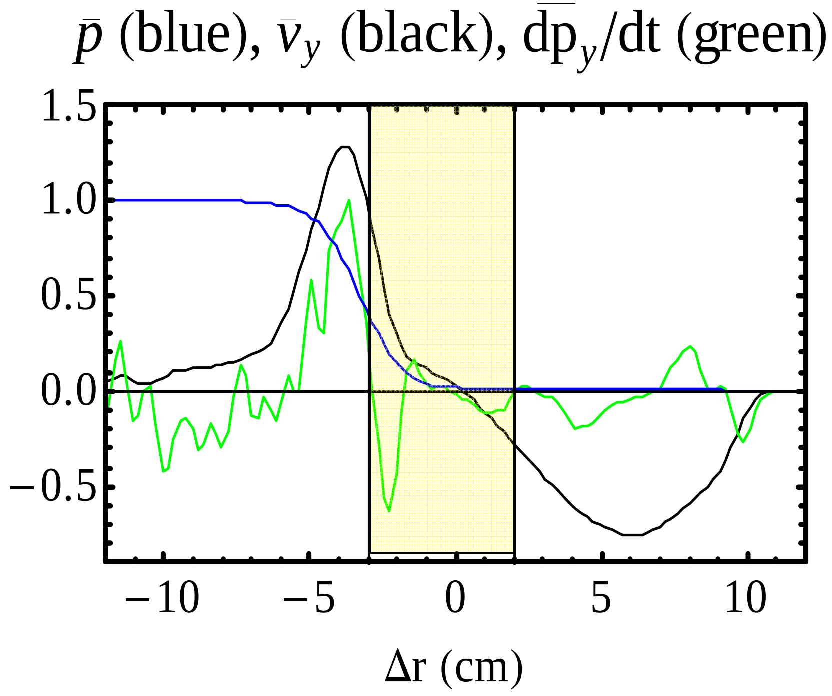
$$\gamma_0 \equiv \left(\frac{\beta}{n}\frac{dP}{dx}\right)^{1/2}$$

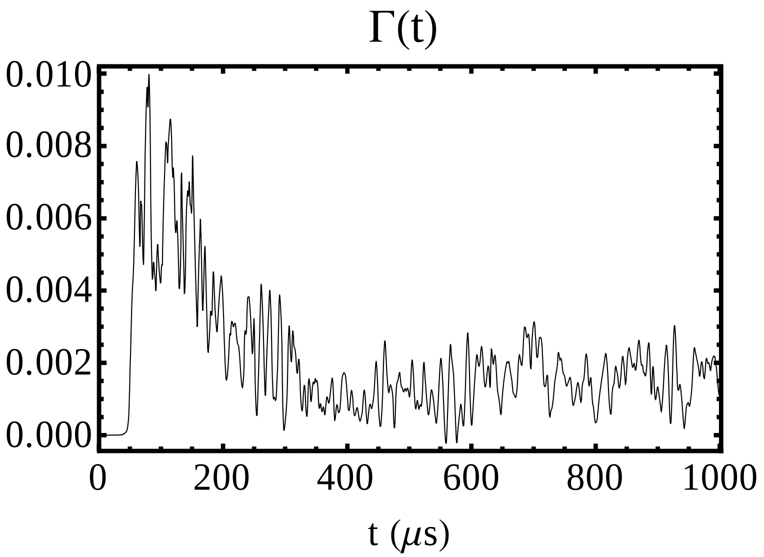
We have done a study of the saturation of the turbulence as a function of the instability drive $\gamma_0 \propto dP/dx$ ($P = n T$)

Large gradient case

run32 Quasi-steady state:

Below: shaded area indicates FWHM of **particle flux Γ = <n v_x>**


$\bar{p}$ (blue), v_y (black), $d\bar{p}_y/dt$ (green)


$\Gamma(t)$

⇒ **RS- regime near max Γ**

⇒ **flows are not strong enough to stabilize interchange modes)**

$$\langle v'_y \rangle_{y,t} / \langle \gamma_{mhd} \rangle_{y,t} \approx 0.6$$

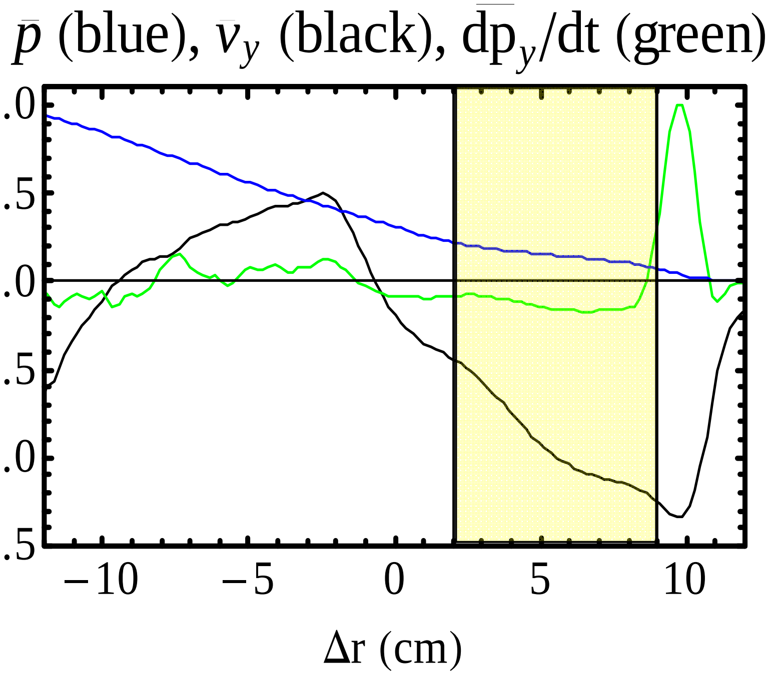
$$\boxed{\langle k_y L_p \rangle_{y,t} \approx 1.2}$$

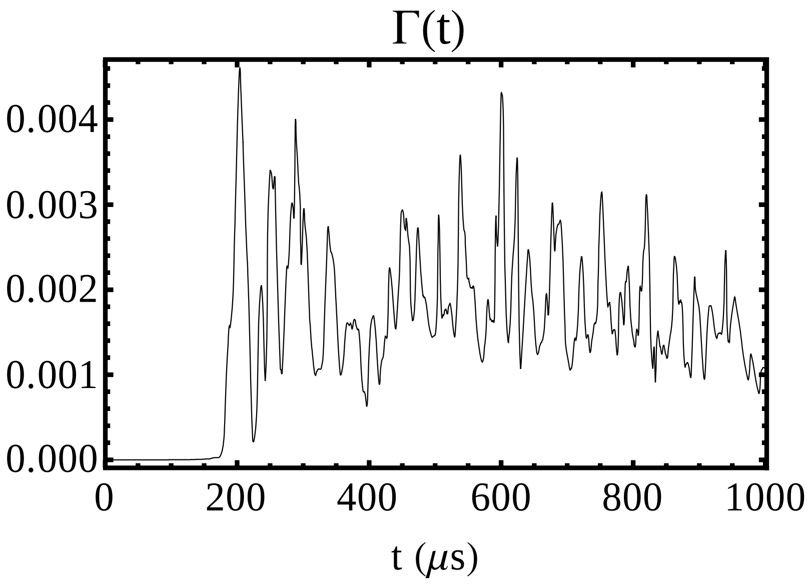
Small gradient case

run33

Right: note different initial transient and fluctuation behavior than in run32

Below: shaded area indicates FWHM of **particle flux $\Gamma = \langle n\, v_x \rangle$**





⇒ **RS+ regime near max Γ**

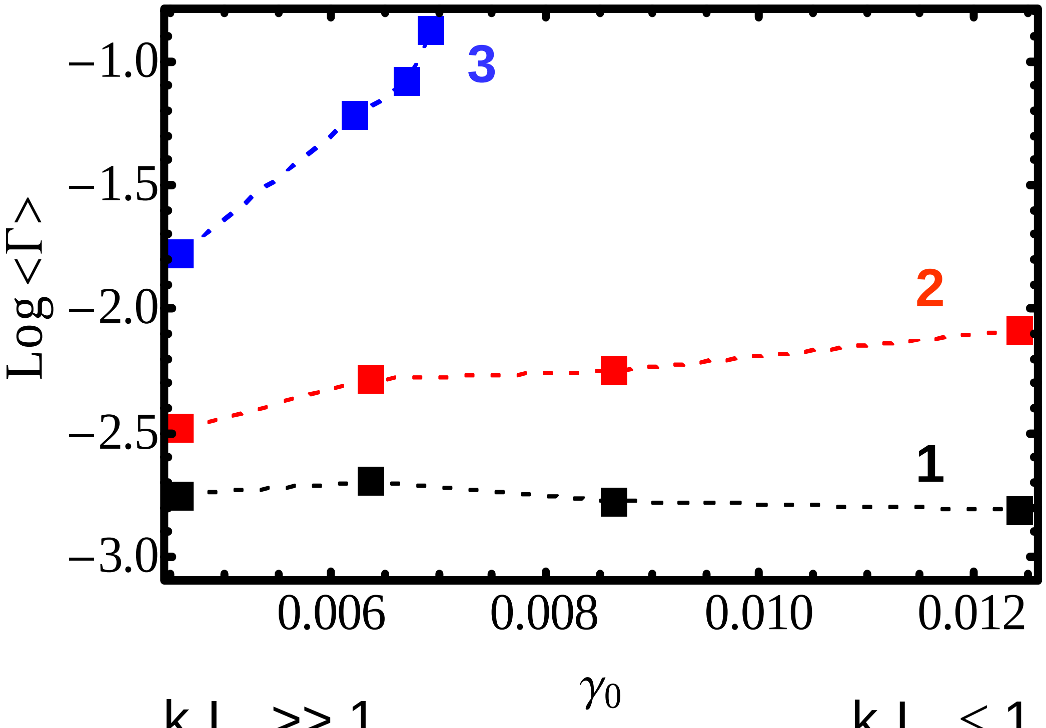
⇒ **sheared flows help stabilize interchange modes**

$$\langle v'_y \rangle_{y,t} / \langle \gamma_{\mathrm{mhd}} \rangle_{y,t} \approx 2.4$$

$$\boxed{\langle k_y L_p \rangle_{y,t} \approx 7.5}$$

Regime diagram for SOLT study

Plot of particle flux Γ vs interchange growth rate γ_0 (see p. 11)



$k_y L_p >> 1$ $k_y L_p \leq 1$

Saturation mechanisms

1 ⇒ flow + profile mod

2 ⇒ profile mod only

3 ⇒ flow only (frozen profiles)

- y- and t-averaged flux
- evaluated at radial location of max flux Γ

blue curve ⇒ stabilizing effect of sheared flow decreases rapidly as grad-P increases and k_y L_p decreases (agrees with the quasi-linear model)

Conclusions: emerging picture

- Here we have studied curvature-driven interchange turbulence in the edge plasma, saturated by a combination of
  - sheared poloidal flows
  - radial profile flattening
- The dominant saturation mechanism depends on the radial gradients.
- The experimental geometry (changing topology of magnetic field lines) sets the natural radial scale L_x of the edge turbulence.
- The radial mode structure of the turbulence, and profiles, determine the k_y spectrum, and $k_y L_x$ determines the evolution of the sheared flows.
- The relative ordering of k_y, L_p, and L_v (pressure and sheared velocity scale lengths) influences the sign of the Reynolds Stress (RS) and whether it causes the sheared flows to grow (RS+) or damp (RS-)
  - this may be related to the inverse cascade
  - see pp. 8 – 10 for details

Conclusions (cont.)

- The RS regime influences the saturation mechanism for the interchange turbulence
  - RS+ ⇒ shear flow stabilization
  - RS- ⇒ profile flattening

- When the mode significantly overlaps with the DW region inside the edge or the sheath-connected region in the far SOL, additional physics enters:

  - DW ⇒ directionality, poloidal flows
  - sheath ⇒ sink for particles, heat and momentum;
    Bohm sheath-potential-driven flows

- Preliminary comparisons with SOLT turbulence simulations are encouraging but more work is needed to obtain optimal simulations for this comparison.