SOL Broadening by Edge Turbulence: Experiment and Theory

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Outline

- Background: SOL Width Problem and the Physics of the Boundary Layer
- Turbulence Production Ratio and its Implications
- Calculating the Scale of the Spreading-Driven SOL
- Open Issues and Future Plans

Background

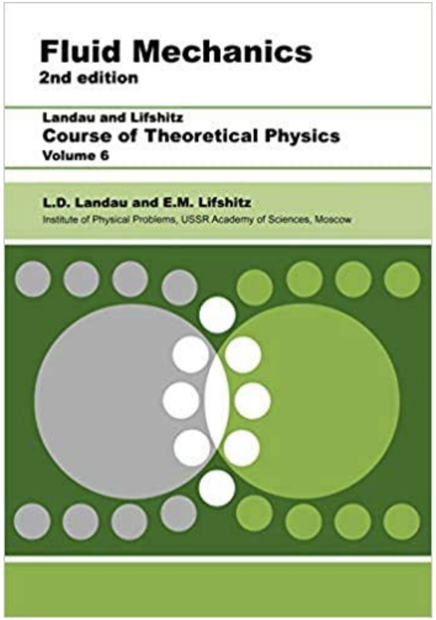
- Conventional Wisdom of SOL:

  (cf: Stangeby...)

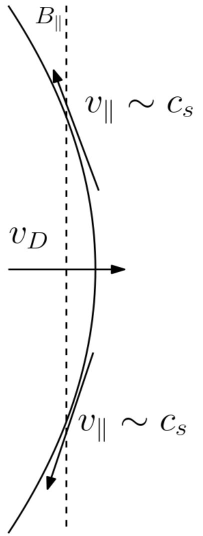
  - Turbulent Boundary Layer, ala' Blasius
  - $\delta \sim (D\tau)^{1/2}, \tau \approx L_c/V_{th}$
  - $D \leftrightarrow$ local production by SOL instability process

    → usual approach

- Features:
  - Open lines → dwell time τ limited by transit, conduction
  - Intermittent → "Blobs" etc.



Background, cont'd



- But... Heuristic Drift (HD) Model (Goldston +)
  - $V \sim V_{\text{curv}}$, $\tau \sim L_c/V_{thi}$, $\lambda \sim \epsilon\, \rho_{\theta i}$
  - Pathetically small
  - Pessimistic B_θ scaling
  - Fits lots of data.... (Brunner '18, Silvagni '20)
- Why does neoclassical work? → ExB shear suppresses SOL modes i.e. $\gamma_{\text{interchange}} \sim \frac{c_s}{(R_c\lambda)^{\frac{1}{2}}} - \frac{3T_{edge}}{|e|\lambda^2}$

shearing ←→ strong λ^{-2} scaling

Background, cont’d

- The Existential Problem... (Kikuchi, Sonoma TTF):

Desire ⟨ Confinement → H-mode ←→ ExB shear
Power Handling → broader heat load, etc

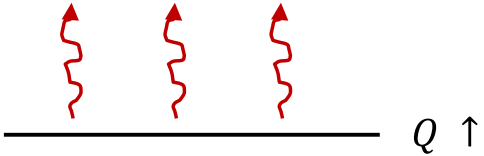
→ Both to be good !

How reconcile?

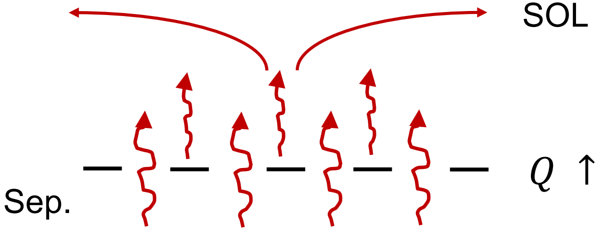
- Spurred:
  - Exploration of turbulent boundary states with improved confinement: Grassy ELM, WPQHM, I-mode, Neg. D ...   N.B. What of ITB + L-mode edge?
  - Simulations, Visualizations (XGC, BOUT...)
- But... What’s the Physics ??

SOL BL Problem

- NOT ala' Landau + Lifshitz



Surface



Classic: Heat flux driven BL, Plumes etc

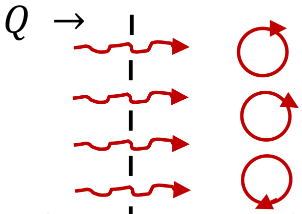
SOL: Turbulent Energy Flux and Heat Flux Drive

➔ Turbulence Spreading (Hahm, P.D., Gurcan, ...)

N.B.: Includes "blobs" c.f. Manz + Grenfell + for direction flux

- SOL Excitation:
  - Turbulence energy influx from pedestal
  - Local production

Ratio?



spreading from pedestal + local production

Physics Issues – Part I

- Measure and Characterize Turbulence Energy Flux at LCFS
- Determine Relative Contributions of :
  - – Influx/Spreading thru LCFS
  - – SOL Production

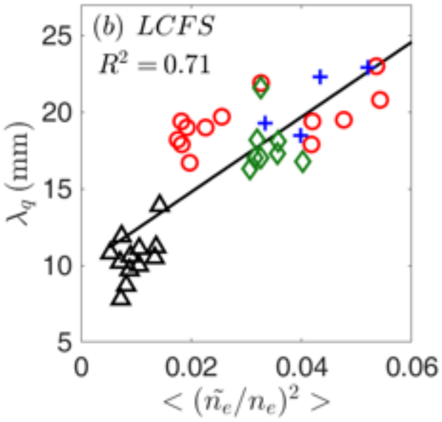
  R_a → Production Ratio
- Trends in λ_q vs : ExB shear, 'Blob' Fraction...
- Question: Is SOL turbulence usually spreading driven?

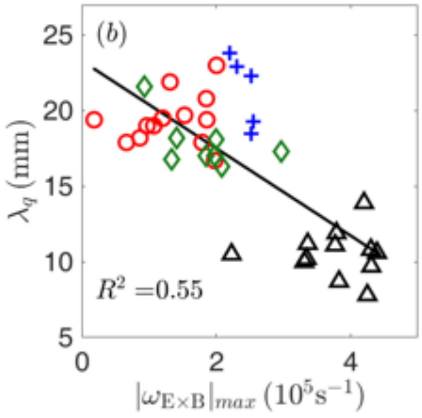
→ Phenomenology... (see Ting Wu +, in preparation)

Experiments and Data Set

- HL-2A limited OH plasmas
- Reciprocating probe array ←→ Outboard mid-plane
- $q_{\|} = \gamma J_{sat} T_e$, $\gamma \equiv$ sheath transmission coefficient
- Database: 'Garden Variety OH' ~ 150 kA, 1.4T
- 4 parameter subgroups ○ red circle + blue cross ◇ green diamond △ black triangle
- Similar, with $\lambda_q \gg \lambda_{HD}$, except: black triangles △
  - $\lambda_q > \lambda_{HD}$, not $\gg$
  - Significant GAM activity → stronger ExB shear

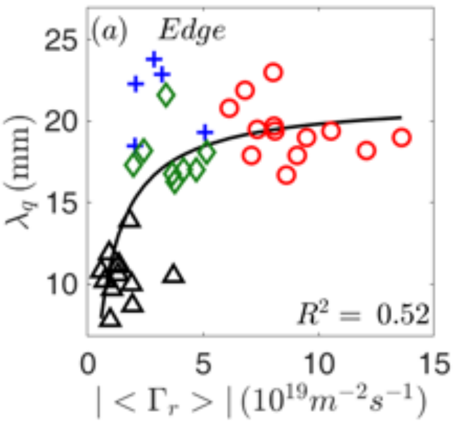
λ_q Trends 1 – Fluctuation Levels and Shearing

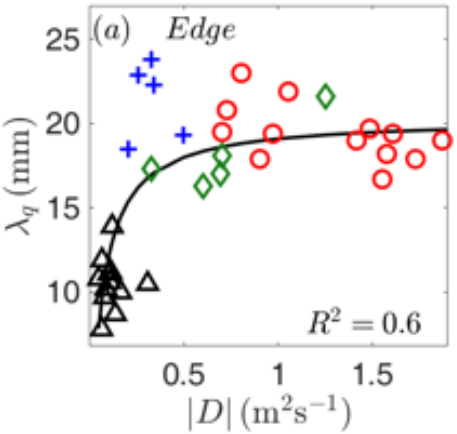




- λ_q increases for increasing fluctuation intensity at lcfs
- λ_q decreases for increasing ExB shear at lcfs

λ_q Trends 2 – Particle Flux and Diffusion

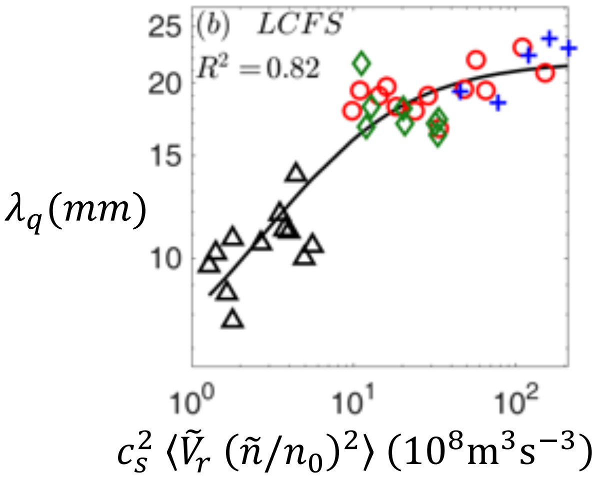




- λ_q increases for increasing edge Γ_n
- λ_q decreases for increasing edge D

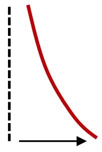
? Saturation

λ_q Trends 3 – Spreading



- $\Gamma_\varepsilon = c_s^2 \langle \tilde{V}_r (\tilde{n}/n_0)^2 \rangle$ → flux of turbulence internal energy thru lcfs
- Direct measurement of <u>local</u> spreading flux
- Consistent with expected trend of expanded SOL width due to spreading across lcfs

SOL Fluctuation Energy – Production Ratio



1 Fluid • $\rho\left(\frac{\partial\vec{V}}{\partial t}+\vec{V}\cdot\nabla\vec{V}\right)=-\nabla P+\frac{1}{c}\vec{J}\times\vec{B}+\rho g\hat{r}$

$\nabla\cdot\vec{V}=0,\ \tilde{P}+\frac{\vec{B}_0\cdot\tilde{\vec{B}}}{4\pi}\approx 0$

SOL interchange

• $\partial_t(KE)_{SOL}=-\int_0^{\lambda}dr\,\nabla\cdot\Gamma_E+\int_0^{\lambda}dr\left[\frac{c_s^2}{R}\left\langle\frac{\tilde{V}_r\tilde{n}}{n_0}\right\rangle-\langle\tilde{V}_r\tilde{V}_\perp\rangle\frac{\partial}{\partial r}\langle V_\perp\rangle\right]$

$=-\Gamma_E|_{\lambda_q}+\Gamma_E|_{\mathrm{lcfs}}+[\text{SOL Integrated local production}]$

Fluctuation Energy Influx to SOL

• $\Gamma_E=\langle\tilde{V}_r\tilde{V}^2\rangle\approx c_s^2\langle\tilde{V}_r(\tilde{n}/n_0)^2\rangle$ → amenable to measurement

Take: KE flux ~ Int. Energy Flux

this gives ...

Production Ratio, Cont'd

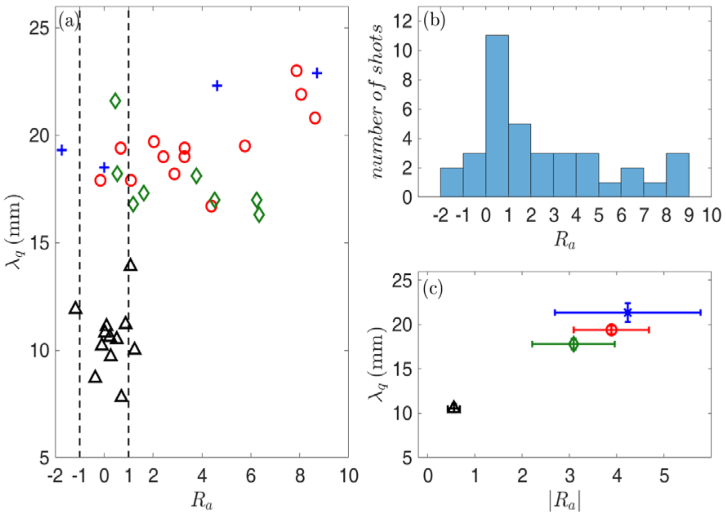
How important is spreading ?

$$R_a = c_s^2 \langle \tilde{V}_r \, (\tilde{n}/n_0)^2 \rangle \Big|_{\mathrm{lcfs}} \Big/ \int_0^{\lambda} dr \, \frac{c_s^2}{R} \langle \tilde{V}_r \tilde{n}/n_0 \rangle$$

- – Ratio of fluctuation energy influx from edge i.e. spreading drive - to net production in SOL
- – $R_a < 1$ → SOL locally driven
- – $R_a \gg 1$ → SOL is spreading driven

- Quantitative measurement by Langmuir probes
- N.B. very simple; likely low estimate

Production Ratio - Measurements



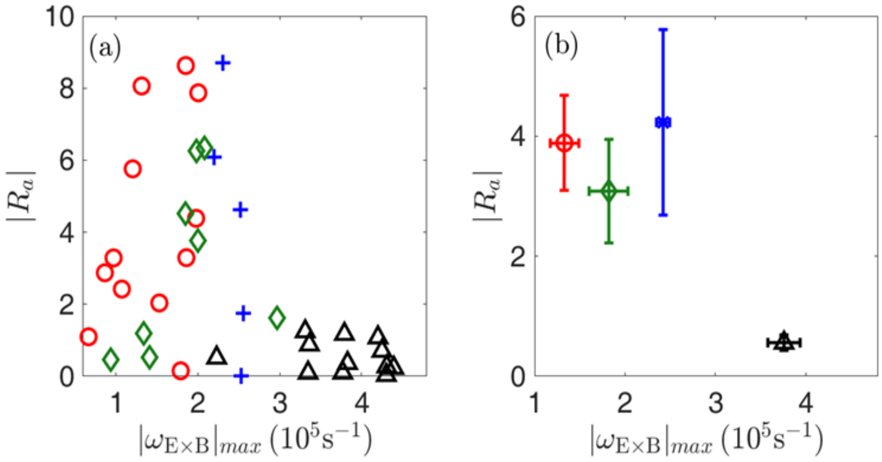
$$R_a = \frac{\text{Fluctuation Energy Influx}}{\text{SOL Local Production}}$$

- Observe:
  - λ_q increases with R_a
  - Most cases R_a > 1
  - Broad distribution R_a values
  - Low R_a values ↔ strong ExB shear

  N.B. Non-trivial, as shear ↔ production, also

- Also:
  - Some $R_a < 0$ cases → inward spreading ↔ local measurement trend outward
  - Some very large R_a values

Production Ratio vs ExB Shear 1

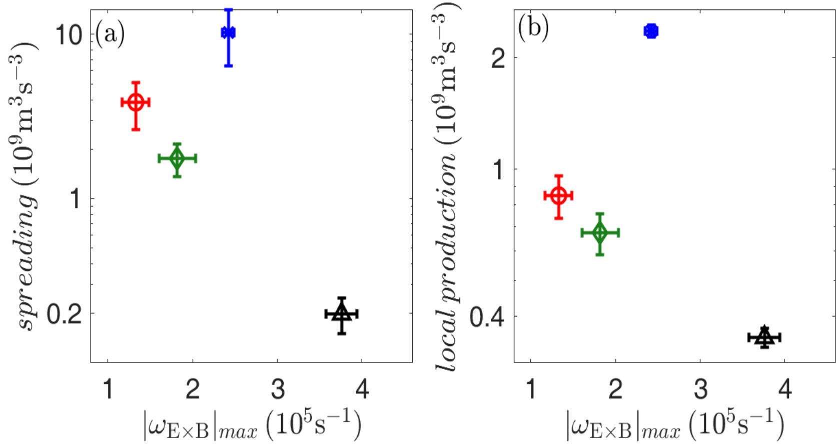


- Low values of $|R_a|$ at high V_E'
- But why?

$$R_a = c_s^2\,\langle \tilde{V}_r\,(\tilde{n}/n_0)^2\rangle|_{\text{lcfs}}\ \Big/\ \int_0^\lambda dr\,\frac{c_s^2}{R}\,\langle \tilde{V}_r\tilde{n}/n_0\rangle$$

→ Expect shear inhibits both spreading and transport flux?

Production Ratio vs ExB Shear 2



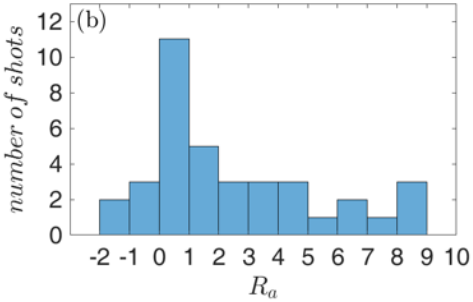
- Both spreading and local production drop due high V_E'
- But spreading x (1/8) vs Production x (1/2)

➔ Spreading flux significantly more sensitive to V_E' than transport flux

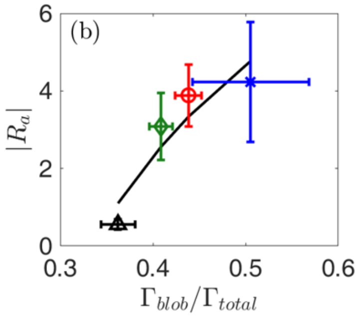
←→ Triplet vs quadratic ➔ Phases?

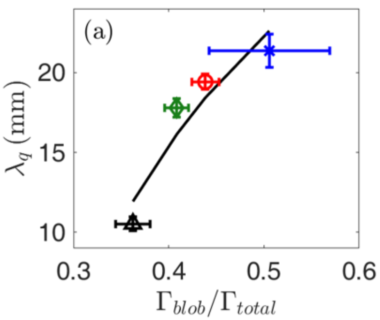
Large R_a → 'Blobs' ?!

- What of the large R_a values?
- Suspect – Structure Emission i.e. "blobs" !?
- Test:
  - Conditional averaging (i.e. threshold $\tilde{n} > 2\tilde{n}_{rms}$ → "blob")
  - Threshold arbitrary → setting based upon previous studies
  - Compute R_a, Γ etc. with conditionally averaged quantities

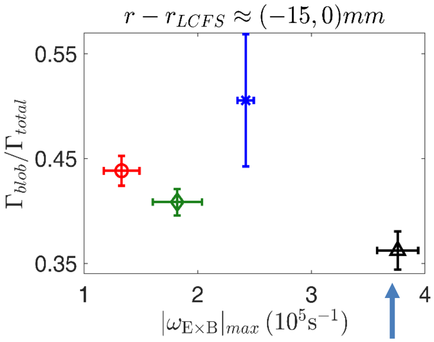


Large R_a → λ_q increases with 'blob' fraction





- Large R_a cases ←→ larger 'blob fraction' of flux
  ←→ spreading encompasses 'blobs' (c.f. Manz +)
- λ_q increases with Γ_b/Γ_{Tot}



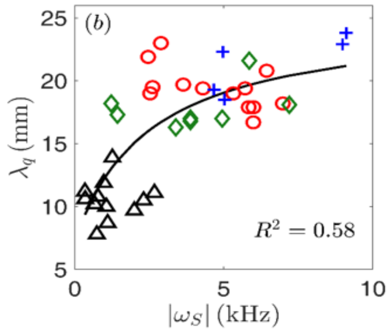
- High ExB shear cases ➔ low 'blob' fraction

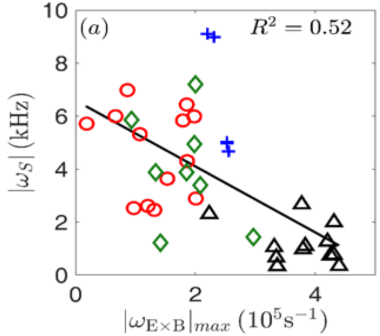
Time Scales

- Spreading rates: $\omega_s \approx -\partial_r \langle \tilde{V}_r \tilde{n}\tilde{n} \rangle / \langle \tilde{n}^2 \rangle$

  characteristic rate of spreading (Manz +)

- Shearing rate V_E'





- λ_q broadens for large ω_s
- Stronger shear reduces spreading rate

Partial Summary

- Significant, mostly outward, spreading measured at lcfs
- Identified and calculated production ratio

  $R_a =$ (spreading influx) / (local production)

- Most cases: $R_a > 1$ ➔ spreading dominant player in SOL energetics
- ExB shear reduces R_a ←➔ spreading more sensitive to V_E' than transport and production
- High R_a, spreading ←➔ 'blob' dominated dynamics

YES ➔ SOL turbulence usually spreading driven!

"The conventional wisdom is little more than convention" - JKG

Physics Issues – Part II

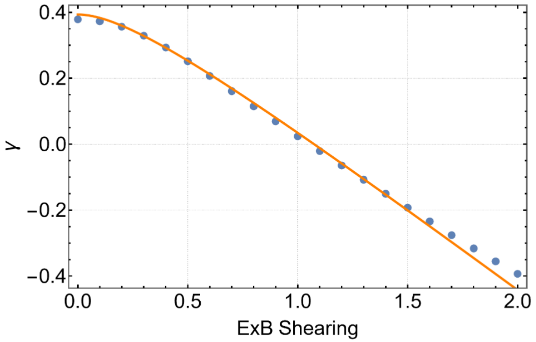
N.B. Simulations need theoretical guidance!

- How calculate SOL width for turbulent pedestal but stable SOL?
  - – spreading penetration depth?
  - – recover HD in turbulence → 0 limit
- Scaling and cross-over of λ_q vs HD model?
- Effect Barrier?
- Question: Reconcile SOL Broadening and Confinement?

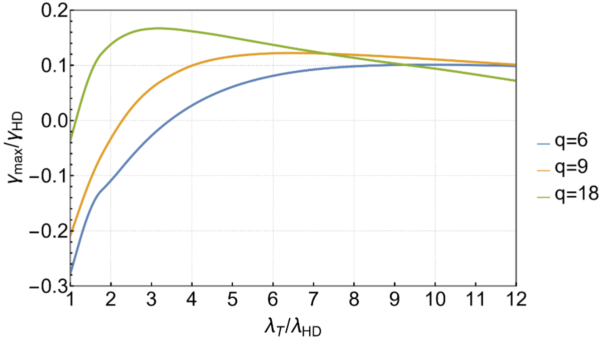
➔ Theory (Chu, P.D., Guo NF 2022)

Model 1 – Stable SOL

- Standard drift-interchange with sheath boundary conditions + ExB shear (after Myra + Krash.)



Linear Growth Rate of a specific mode (fixed k_y) v.s. $E \times B$ shear at $q = 5, \beta = 0.001, k_y \cdot \lambda_{HD} = 1.58$.



Maximal Linear Growth Rate of Interchange Mode in the SOL v.s. normalized pedestal width λ_D/λ_{HD} at different SOL safety factor q (with $\beta = 0.001$)

- Relevant H-mode ExB shear strongly stabilizing
- Need $\lambda/\lambda_{HD} \gg 1$ for SOL instability. $V_E' \approx \frac{3T_e}{|e|\lambda^2}$

Model 2 – Multiple Adjacent Regions

- "Box Model" – see Z.B. Guo, P.D.

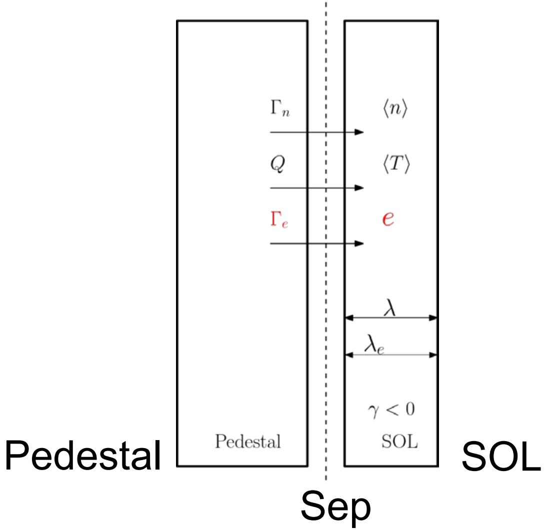


Illustration of Two Box Model: SOL driven by particle flux, heat flux and intensity flux (Γ_e) from the pedestal. The horizontal axis is the radial direction, and vertical axis is the poloidal direction.

- Key Point:
  - Spreading flux from pedestal can enter stable SOL
  - Depth of penetration ➔ extent of SOL broadening

Width of Stable SOL

- Fluid particle: $\frac{dr}{dt} = V_{Dr} + \tilde{V}$

  drift — fluctuating velocity

- Dwell time: $\tau_{\parallel}$

- $\delta^2 = \langle (\int (V_D + \tilde{V})dt)(\int (V_D + \tilde{V})dt) \rangle$

  $\langle (\text{step})^2 \rangle$

  $= V_D^2 \tau_{\parallel}^2 + \langle \tilde{V}^2 \rangle \tau_c \tau_{\parallel}$

  correlation time
  modest turbulence $\leftrightarrow \tau_c \geq \tau_{\parallel}$

  $= \lambda_{HD}^2 + \varepsilon \tau_{\parallel}^2$

  turbulence energy density

  See also Fokker-Planck analysis

- So $\lambda = \left[\lambda_{HD}^2 + \varepsilon \tau_{\parallel}^2\right]^{1/2}$ → SOL width [Effects add in quadrature]

- How compute ε ? → turbulence energy !

Calculating the SOL Turbulence Energy 1

N.B.: Can explore different NL processes

- $\kappa - \epsilon$ type model:
- $\partial_t \varepsilon = \gamma\varepsilon \; - \sigma\varepsilon^{1+\kappa} - \partial_x \Gamma_e$ → spreading – turbulence energy flux (cf Part1)

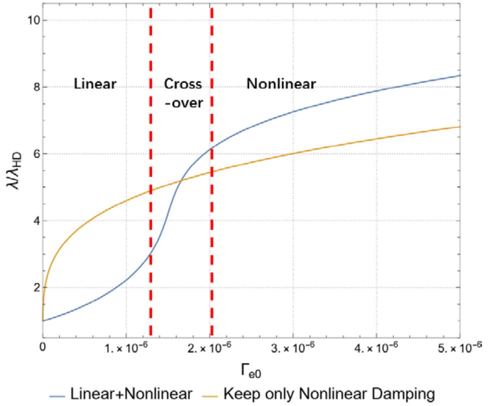
  growth $\gamma < 0$ here

  NL transfer $\gamma_{NL} \sim \sigma\varepsilon^{\kappa}$
- Integrate $\int_0^\lambda \cdots$ (Quantities – layer averaged)
- $\Gamma_{e,0} = \lambda_e \, |\gamma|\varepsilon + \sigma\varepsilon^{1+\kappa}$ → Linear + NL damping ($\gamma < 0$)

  separatrix intensity flux
- $\Gamma_{e,0}$ specifies SOL turbulence drive

SOL width Broadening vs $\Gamma_{e,0}$

- SOL width broadens due spreading



(blue) (orange)

λ/λ_{HD} plotted against the intensity flux Γ_{e0} from the pedestal at $q = 4, \beta = 0.001, \kappa = 0.5, \sigma = 0.6$

Variation indicates need for detailed scaling analysis

- Clear decomposition into
  - Weak broadening regime → shear
  - Cross-over regime
  - Strong broadening regime
  - ➔ NL damping vs spreading

- Cross-over for:

  $\langle \tilde{V}^2 \rangle \sim V_D^2$ ➔ minimal $\Gamma_{0,e}$

Computing the Turbulence Energy Flux 1

- Need consider pedestal to compute $\Gamma_{e,0}$

- Two elements

Does another trade-off loom?

-- Pedestal Turbulence: Drift wave? Ballooning?

-- Effect of transport barrier ←→ ExB shear layer

- Key Point: shearing limits correlation in turbulent energy flux

i.e. $\Gamma_{e,0} \approx -\tau_c \, \kappa \, \partial_x \, \kappa \approx \tau_c \, \kappa^2 \, / w_{\mathrm{ped}}$ (Hahm, PD +)

ped turbulence intensity (κ)

correlation time (τ_c) → strongly sensitive to shearing

Computing the Turbulence Energy Flux 2

- Familiar analysis:
  - Kubo formalism for D
  - $\tau_c \leftrightarrow \omega_s$, + scattering ➔ $\Gamma_{0,e}$ (Pedestal Intensity)

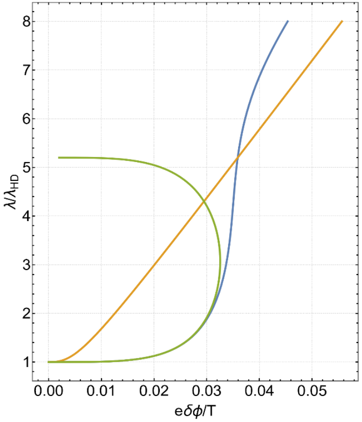
    shearing rate
  - $\omega_s \approx \partial_x \nabla P / n_0 |e| \sim \frac{\rho_i^2}{w_{ped}^2} \Omega_i$

- Bottom Line:

blue – all damping

non-

orange – linear only



➔ λ/λ_{HD} vs $|e|\hat{\phi}/T_e$ (pedestal)

➔ Can broaden layer at acceptable fluctuation level

Computing the Turbulence Energy Flux 3

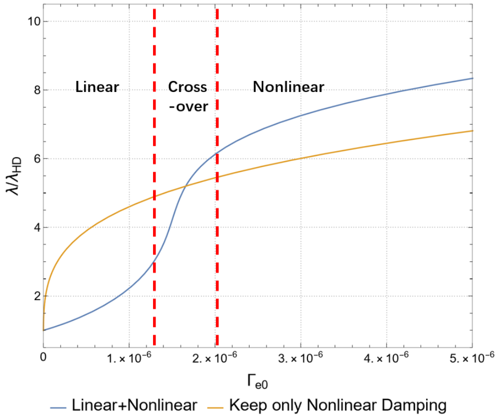
- SOL broadening achieveable at tolerable pedestal fluctuation levels
- DW levels required scale ~ $(\rho_i/R)^{1/2}$ → favorable
- Grassy ballooning turbulence also can broaden SOL
- Sensitivity analysis → <u>Cross-over</u> determined primiarly by <u>linear damping</u>. Conclusion not sensitive to NL saturation.

Partial Summary

- Turbulent scattering broadens stable SOL

$$\lambda = \left(\lambda_{HD}^2 + \varepsilon\tau_{\parallel}^2\right)^{1/2}$$

- Separatrix turbulence energy flux specifies SOL turbulence drive



$$\Gamma_{0,e} = \lambda_e|\gamma|\varepsilon + \sigma\varepsilon^{1+\kappa}$$

Broadening increases with $\Gamma_{0,e}$
cross-over for $\langle\tilde{V}^2\rangle \sim V_D^2$

Non-trivial dependence

- $\Gamma_{0,e}$ must overcome shear layer barrier

Yes – can broaden SOL to $\lambda/\lambda_{MHD} > 1$ at tolerable fluctuation levels

Further analysis needed

Broader Messages

- Turbulence spreading is important – even dominant – process in setting SOL width. $\Gamma_{0,e}$ is critical element. $\lambda = \lambda(\Gamma_{0,e}, \text{parameters})$
- Production Ratio R_a merits study and characterization
- Spreading is important saturation meachanism for pedestal turbulence
- Simulation should stress calculation and characterization of turbulence energy flux over visualizations and front propagation studies.

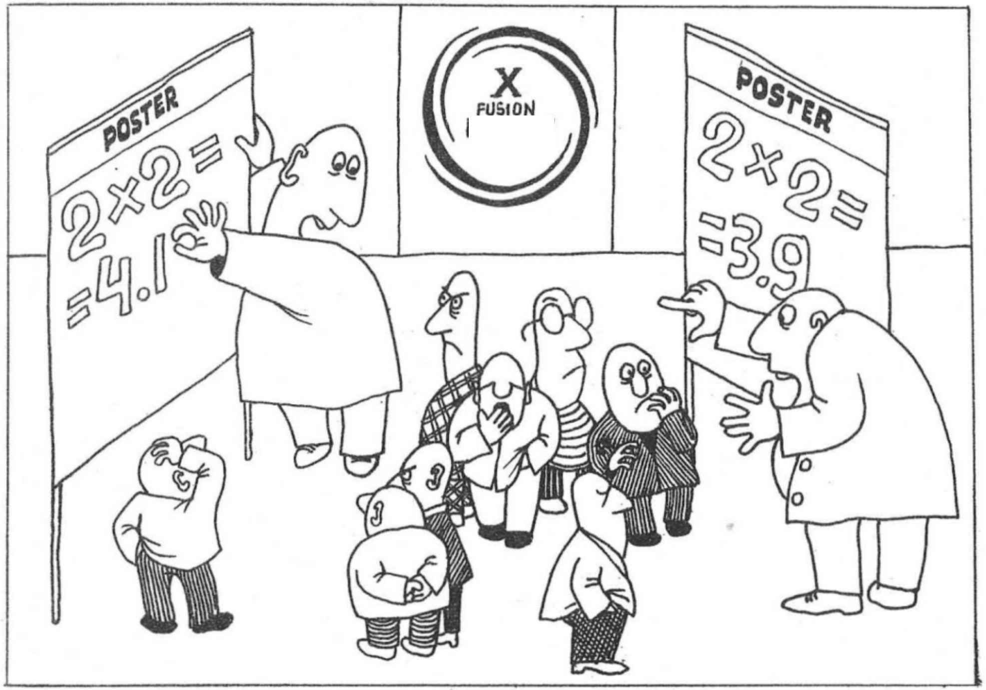
Critical questions include local vs FS avg, channels and barrier interaction.

Open Issues

- Quantify $\lambda = \lambda\left(\left.\frac{|e|\hat{\phi}}{T}\right|_{ped}\right)$ dependence
- Structure of Flux-Gradient relation for turbulence energy?
- Phase relation physics for intensity flux? – crucial to ExB shear effects
- Kinetics → $\langle \tilde{V}_r \delta f \delta f \rangle$, Local vs Flux-Surface Average, EM
- SOL Diffusive? → Intermittency('Blob'), Dwell Time ?
- SOL → Pedestal Spreading ? ←→ HDL (Goldston) ?

  i.e. Tail wags Dog ? Both wagging ? → Basic simulation, experiment ?

  Counter-propagating pulses ?



Thank You !
Good to be back in person !

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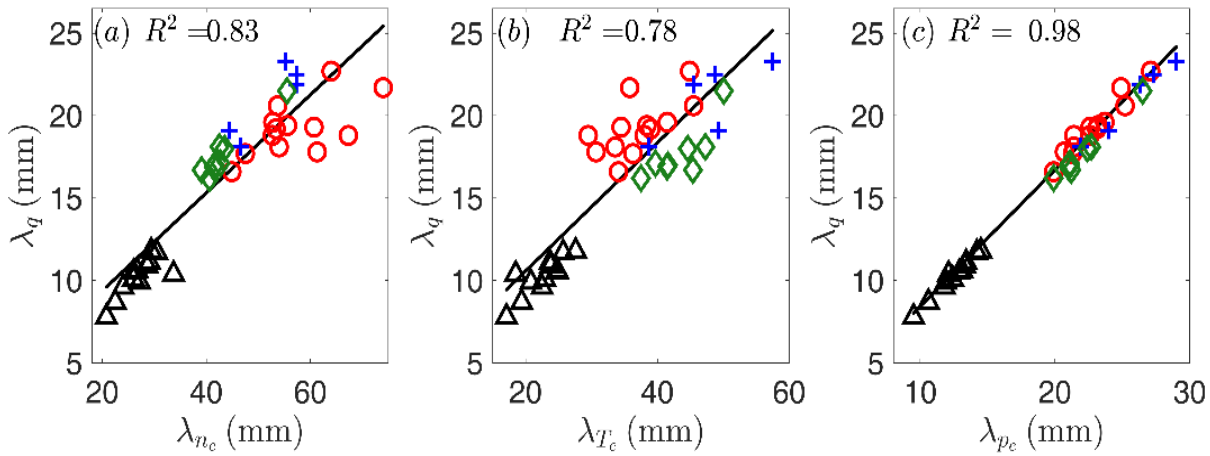
Back-Up

$$\lambda_{n_e} \sim \lambda_{T_e} \sim \lambda_{P_e}$$



All SOL profiles scales comparable