SOL Broadening by Edge Turbulence: Experiment and Theory

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- Experiment: Ting Long, Ting Wu (SWIP), Filipp Khabanov, Rongjie Hong, G. Mckee, Zheng Yan, G. Yu, G. Tynan (DIII-D → Frontiers Exp.), Xi Chen (GA)

Outline

- Brief Primer on the Edge and SOL
- SOL Width Problem and the Physics of the Plasma Boundary Layer
- Some Data: Turbulence Production Ratio and its Implications
- Some Theory: Calculating the Scale of the Spreading-Driven SOL
- Some Computation: A Closer Look at Turbulence Spreading
- Open Issues and Future Plans

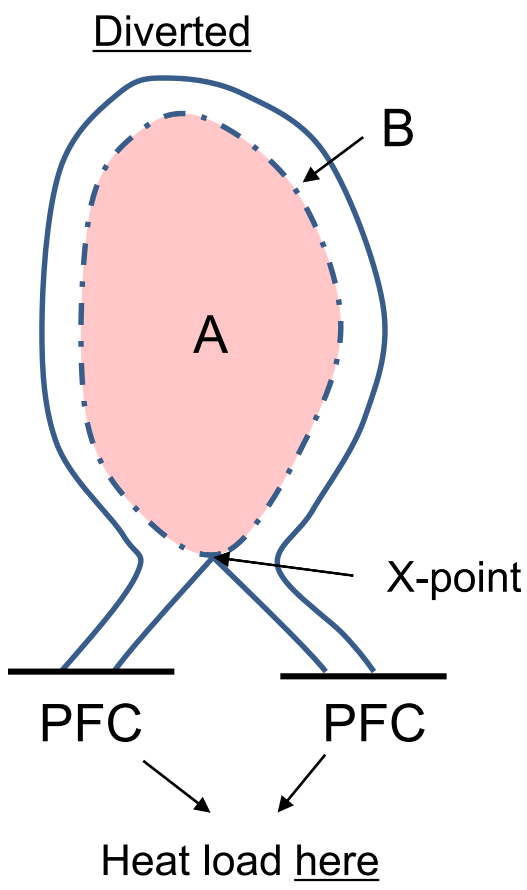
Primer (Brief)

- All confinement devices have an edge and SOL (scrape-off layer)

  Fueling at Edge

- Define:
  - – Confined plasma boundary
  - – Connection to plasma facing components
  - – SOL as confined plasma ‘boundary layer’

A – confined plasma
B – SOL
Dashed – separatrix



NB: Magnetic field lines are perp to plane, with slight tilt

Primer, cont'd

- SOL: $\nabla \cdot \vec{\Gamma} = \nabla \cdot \vec{Q} = 0$ (open lines)

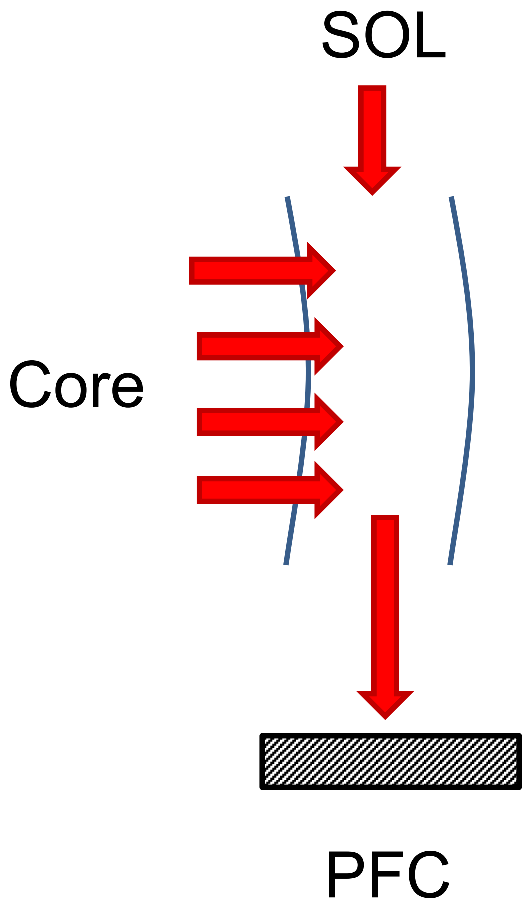
$\Gamma_\perp \approx -D\partial_r n$ (?) $\qquad \nabla_\perp \sim \partial_r \sim 1/\lambda_\perp$

$\Gamma_\parallel \approx \alpha\, c_s\, n \qquad \nabla_\parallel \sim 1/L_c \sim 1/Rq$

➔ $D\,\partial_r^2 n \sim \alpha n/L_c \qquad \tau_\parallel \approx Rq/c_s$

$\lambda_\perp \sim (D\tau_\parallel)^{1/2}$ ~ crude SOL width

⇔ $1/\tau_\parallel \sim \chi_\parallel/L_c^2$ conduction, high density



Background

- Conventional Wisdom of SOL:

  (cf: Stangeby...)

  – Turbulent Boundary Layer, ala' Blasius, with D due turbulence

  – $\delta \sim (D\tau)^{1/2}, \tau \approx L_c/V_{th}$

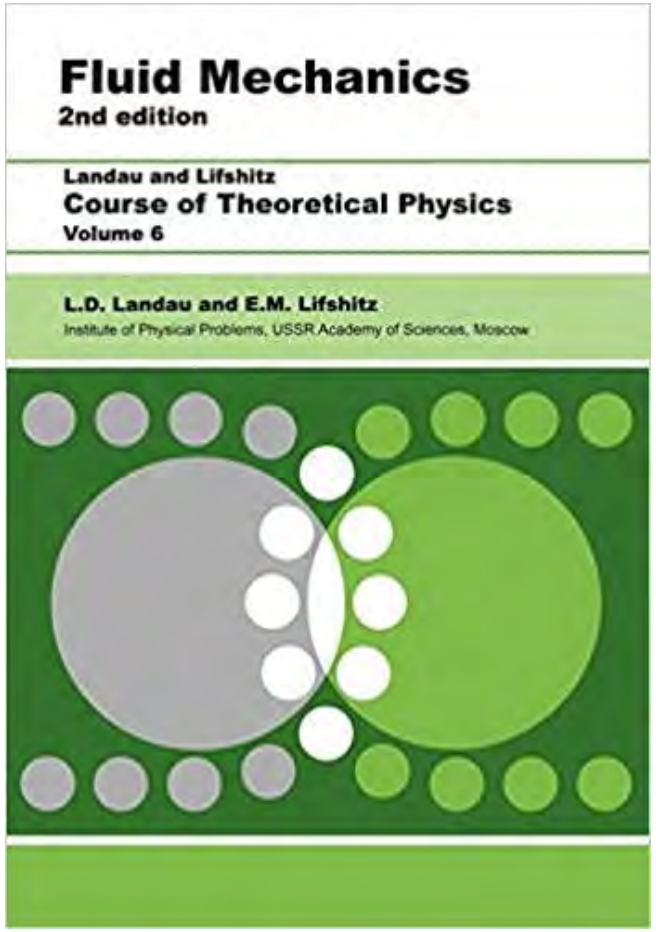
  – $D \leftrightarrow$ local production by SOL instability process

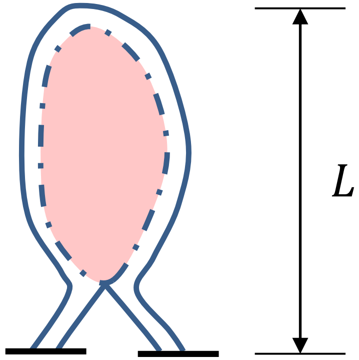
  → familiar approach, D ala' QL, …

- Features:

  – Open magnetic lines → dwell time τ limited by transit, conduction, ala' Blasius

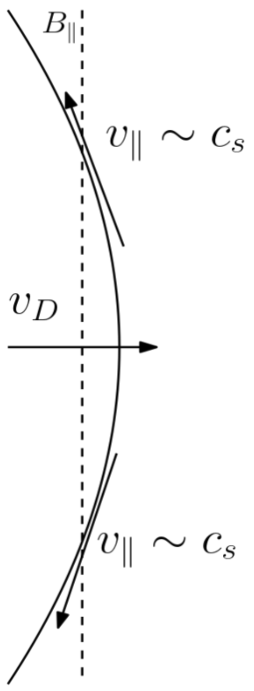
  – Intermittency → "Blobs" etc. Observed. Physics?





Background, cont'd

- But... Heuristic Drift (HD) Model (Goldston +)
  - $V \sim V_{\mathrm{curv}}$, $\tau \sim L_c/V_{thi}$, $\lambda \sim \epsilon\, \rho_{\theta i}$ → SOL width
  - Pathetically small
  - Pessimistic B_θ scaling, yet high I_p for confinement
  - Fits lots of data.... (Brunner '18, Silvagni '20)



- Why does neoclassical work? → ExB shear suppresses SOL modes i.e.

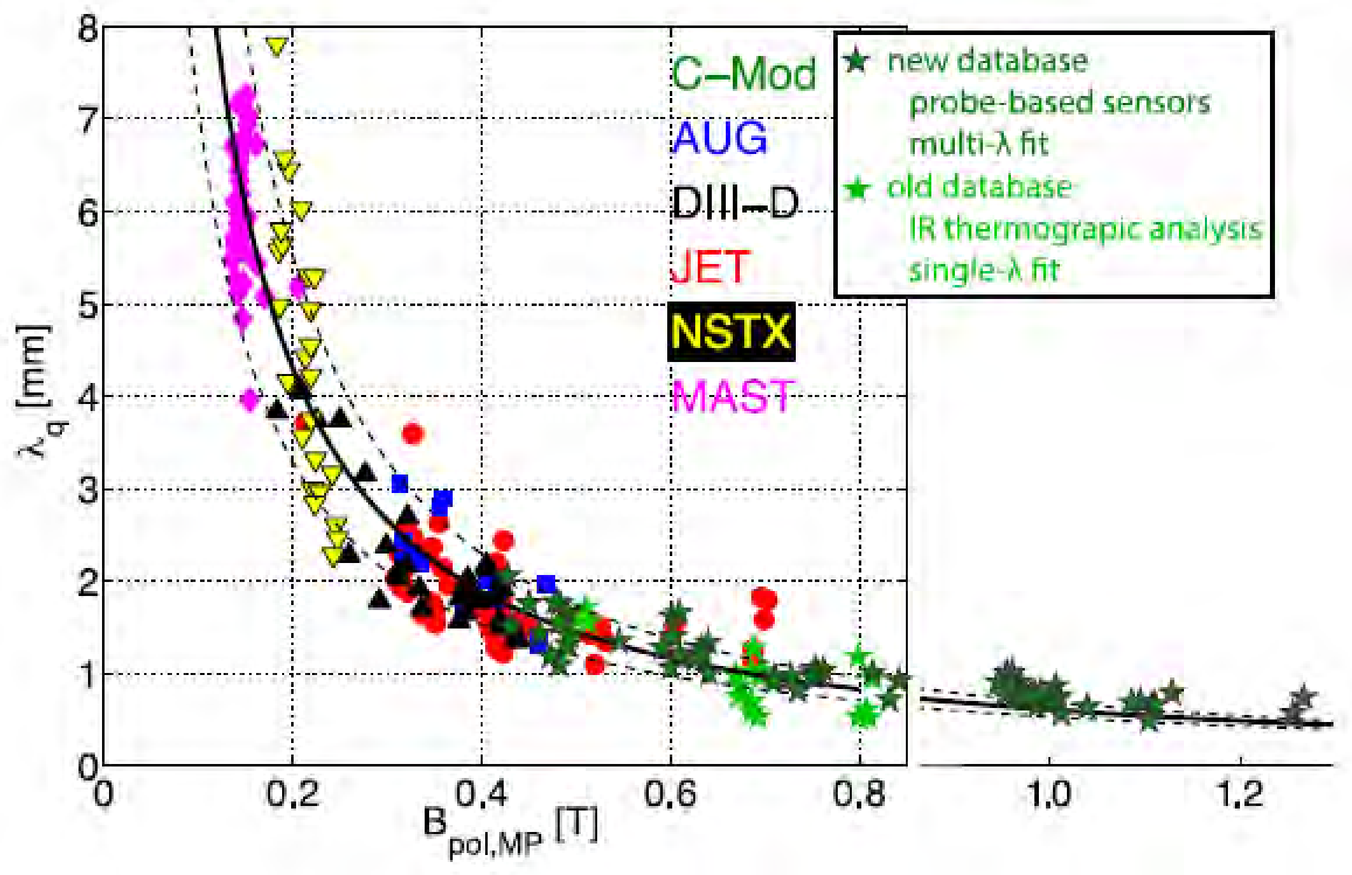
$$\gamma_{\mathrm{interchange}} \sim \frac{c_s}{(R_c\lambda)^{\frac{1}{2}}} - \frac{3T_{edge}}{|e|\lambda^2}$$

shearing ←→ strong λ^{-2} scaling

from: $\frac{c_s}{(R_c\lambda)^{\frac{1}{2}}} - \langle V_E\rangle'$

Feedback Loop:
$\lambda \downarrow \;\rightarrow\; \gamma \downarrow \;\rightarrow\; D \downarrow$

Background: HD Works in H-mode



HD is Bad News…

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? – Pay for power mgmt with confinement ?!

- Spurred:
  - Exploration of turbulent boundary states with improved confinement: Grassy ELM, WPQHM, I-mode, Neg. D ... N.B. What of ITB + L-mode edge?
  - SOL width now key part of the story
  - Simulations, Visualizations (XGC, BOUT...) ~ "Go" to ITER and all be well
- But... What's the Physics ?? How is the SOL broadened?

SOL Boundary Layer:

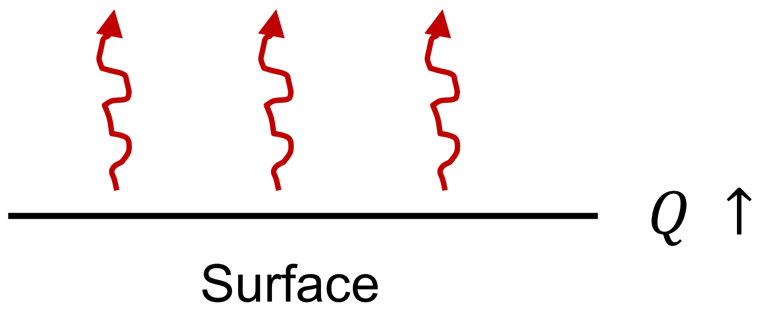
Turbulence Production Rate and the Role of Spreading

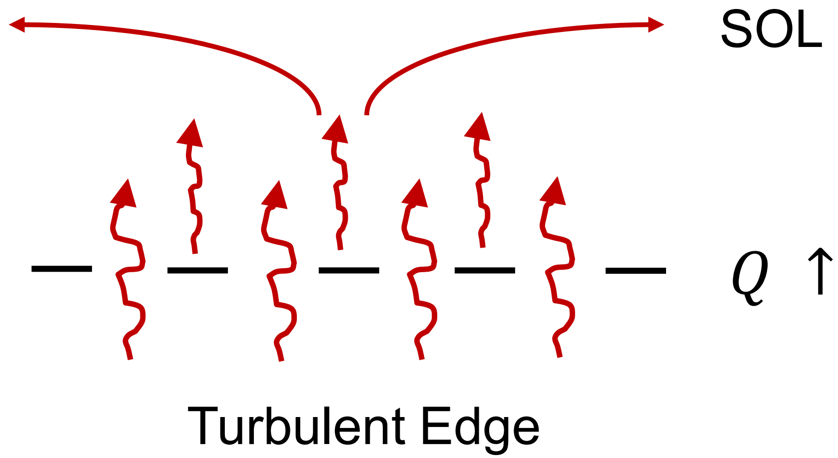
SOL BL Problem

- Classic flux-driven BL problem
  - Heat flux at surface drives
  - Production $= gQ \quad \tilde{V}_E \sim (gQz)^{1/3}$ etc
  - Plumes

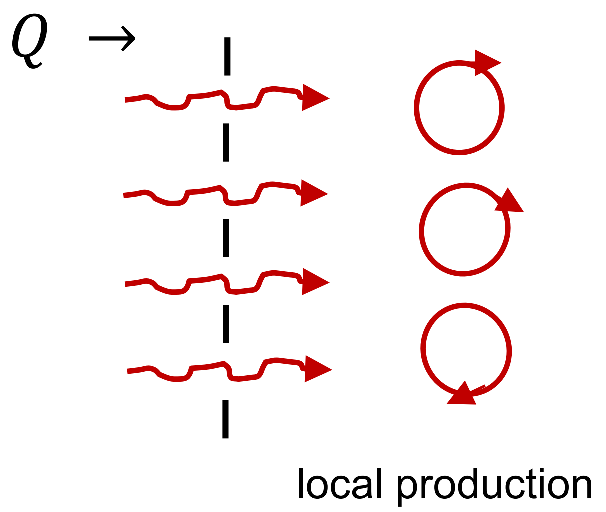
  Adapt to SOL ?

- SOL
  - Open field lines
  - Turbulent energy flux and heat flux, etc drive
  - Turbulence spreading (Garbet, P.D., Hahm, …)
  - Includes 'blobs' – c.f. Manz, 2015





SOL BL Problem



- SOL Excitation
  - Local production (SOL instabililties)
  - Turbulence energy influx from pedestal
- Key Questions:
  - Local drive vs spreading ratio → Ra
  - Is the SOL usually dominated by turbulence spreading?
  - How far can entrainment penetrate a stable SOL → SOL broadening?
  - Effects ExB shear, role structures ?

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 and R_a vs : ExB shear, 'Blob' Fraction...
- Question: To what extent is SOL turbulence usually spreading driven?

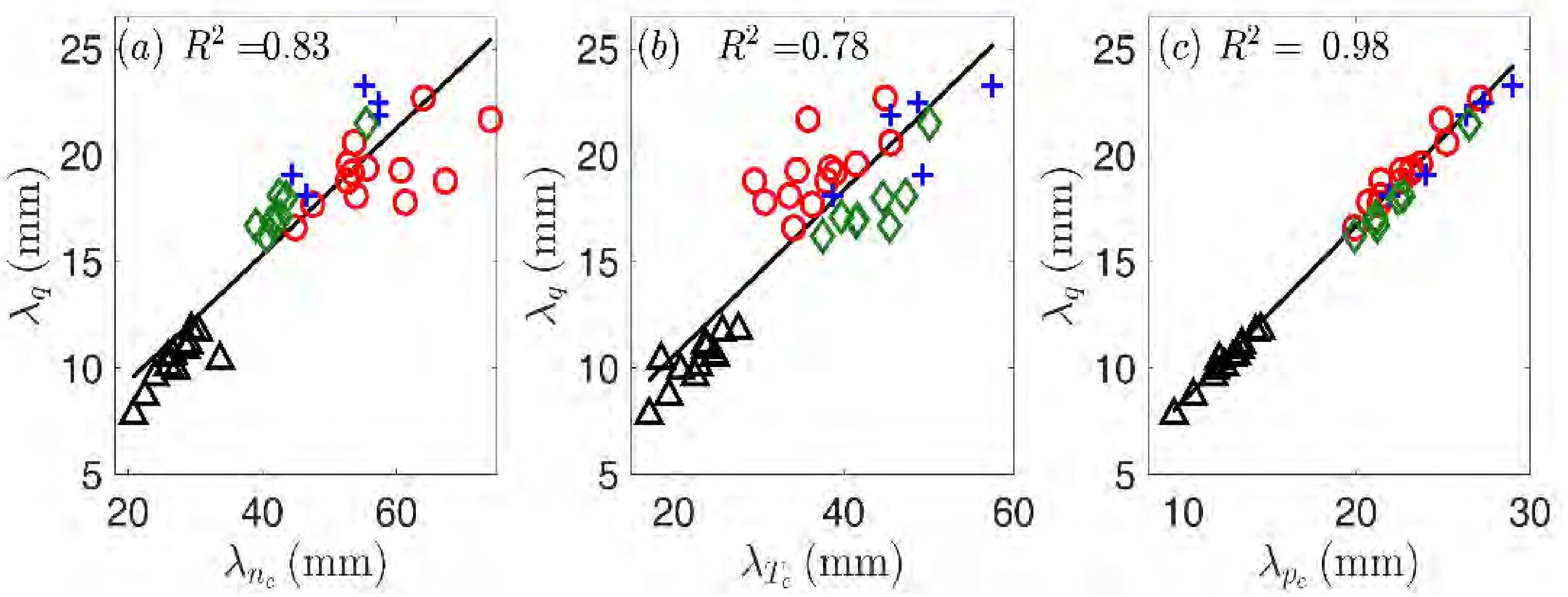
→ Phenomenology... (see Ting Wu +, NF 2023)

Experiments and Data Set

N.B.:
λ_q → SOL width

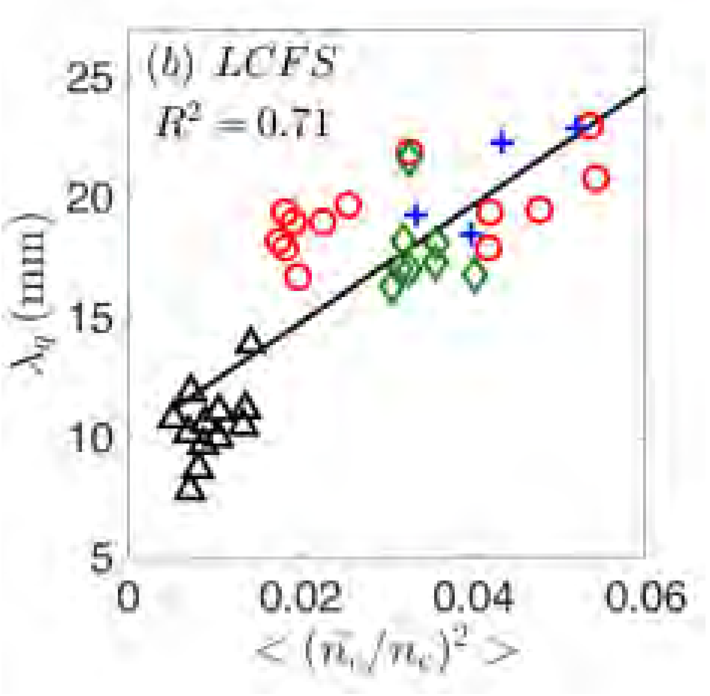
- HL-2A limited OH plasmas – classic “boring plasmas”
- Reciprocating probe array ←→ Outboard mid-plane
- $q_{\parallel} = \gamma J_{sat} T_e$, $\gamma \equiv$ sheath transmission coefficient
- Database: ‘Garden Variety OH’ ~ 150 kA, 1.4T
- 4 parameter subgroups ○ red circle, + blue cross, ◇ green diamond,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

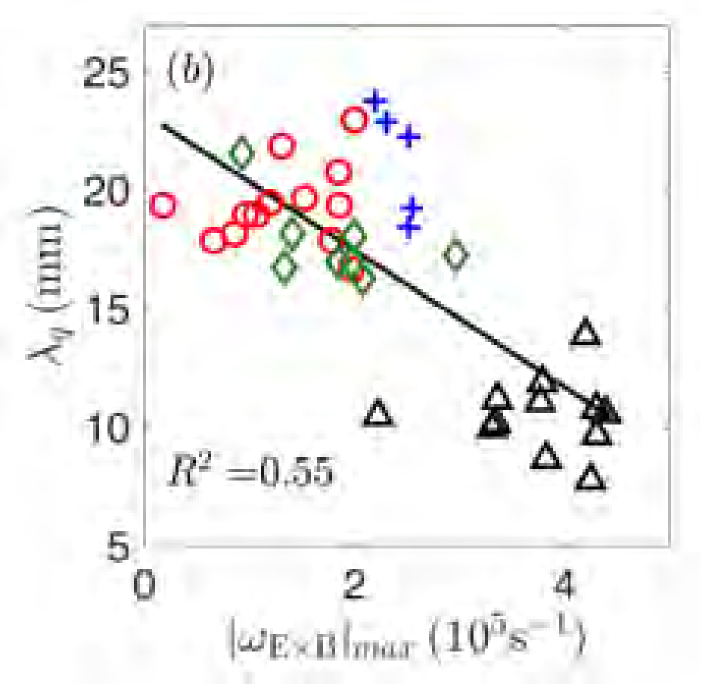
$$\lambda_{n_e} \sim \lambda_{T_e} \sim \lambda_{P_e}$$



All SOL profiles scales comparable

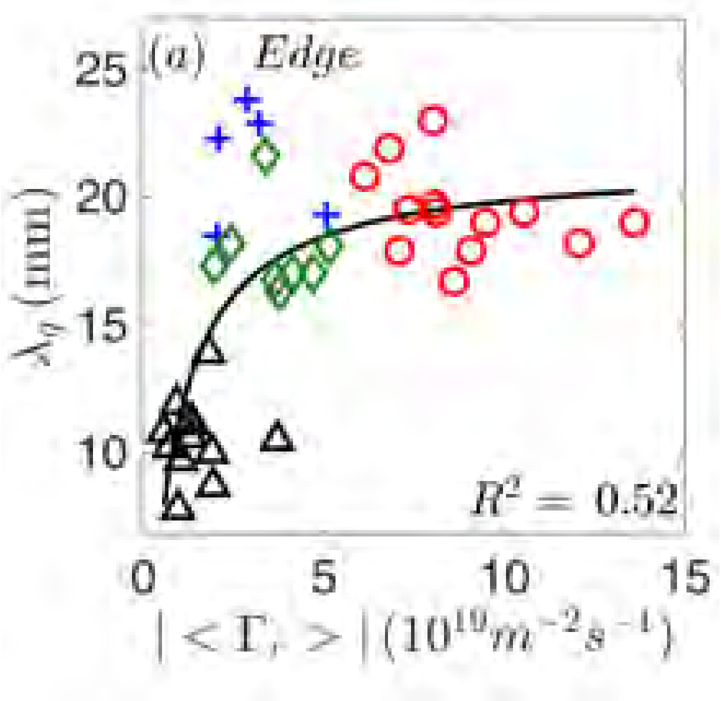
λ_q Trends 1 – Fluctuation Levels and Shearing

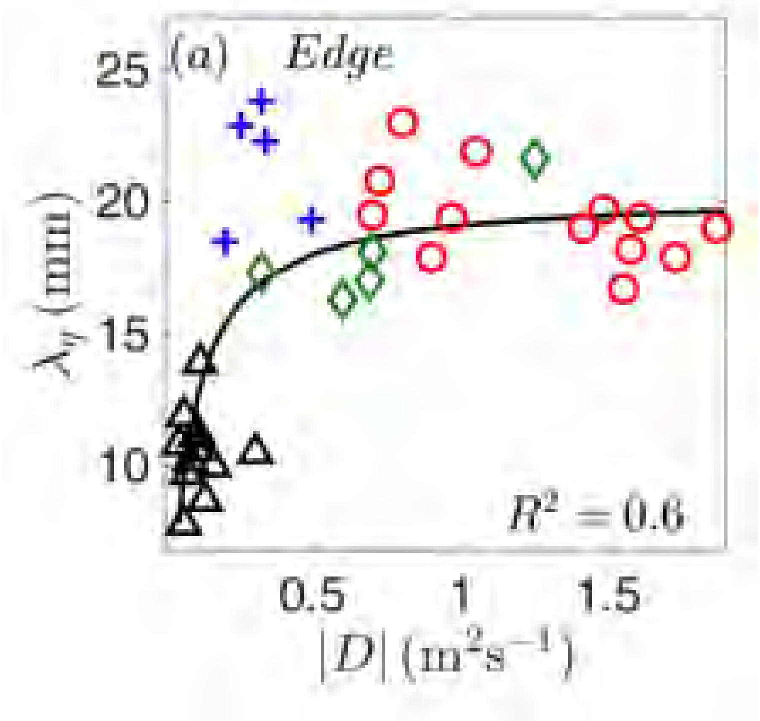




- λ_q increases for increasing fluctuation intensity at lcfs
- λ_q decreases for increasing ExB shear at lcfs
- Max $\omega_{E\times B}$ at shear layer ~ lcfs

λ_q Trends 2 – Particle Flux and Diffusion



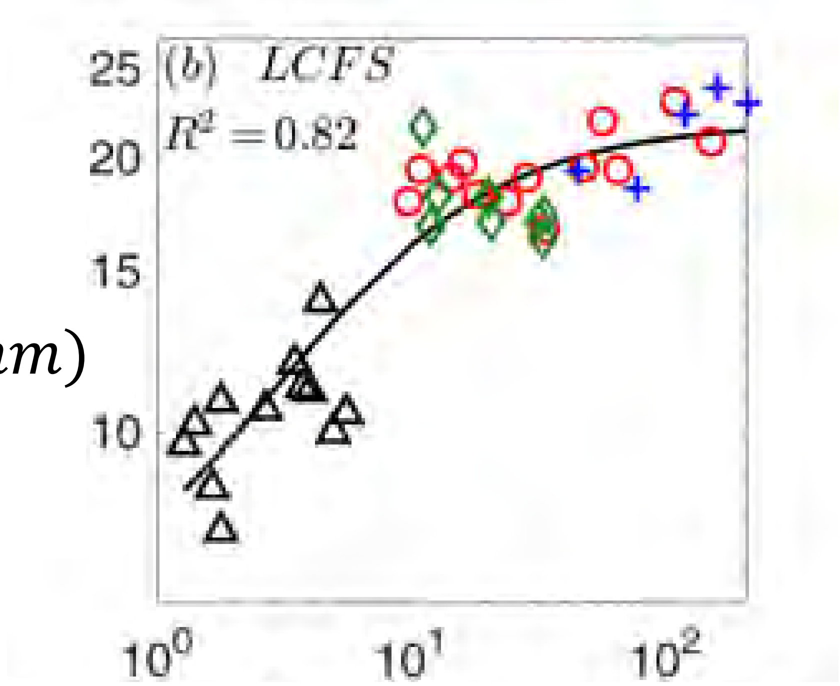


- λ_q increases for increasing <u>edge</u> Γ_n
- λ_q increases for increasing <u>edge</u> D

? Saturation – might expect $\lambda \sim (D\tau)^{1/2}$ scaling …

λ_q Trends 3 – Spreading !

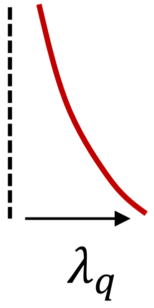
$\lambda_q(mm)$



$c_s^2 \langle \tilde{V}_r (\tilde{n}/n_0)^2 \rangle \, (10^8 \mathrm{m}^3 \mathrm{s}^{-3})$ → at lcfs

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

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

Take: KE flux ~ Int. Energy Flux (✓ for drift-interchange)

this gives ...

Aside: On Calculating the Spreading…

- Why perturbed pressure balance?
  - Else, $\langle \vec{V} \cdot \nabla P \rangle$ and $\langle \rho \nabla \cdot \vec{V} \rangle$ enter energy balance. Acoustic energy propagation irrelevant on $\tau \gg \tau_{MS}$
  - Can eliminate via vorticity eqn, $\vec{V} = \vec{E} \times \vec{B}$ etc.
- Interchange drive: $\kappa P \quad \rightarrow \quad \kappa \langle \tilde{V}_r \tilde{P} \rangle \approx g c_s^2 \langle \tilde{V}_r \tilde{n} \rangle$

  as cannot measure $\tilde{P}$ fluctuations

Production Ratio, Cont'd

How important is spreading ?

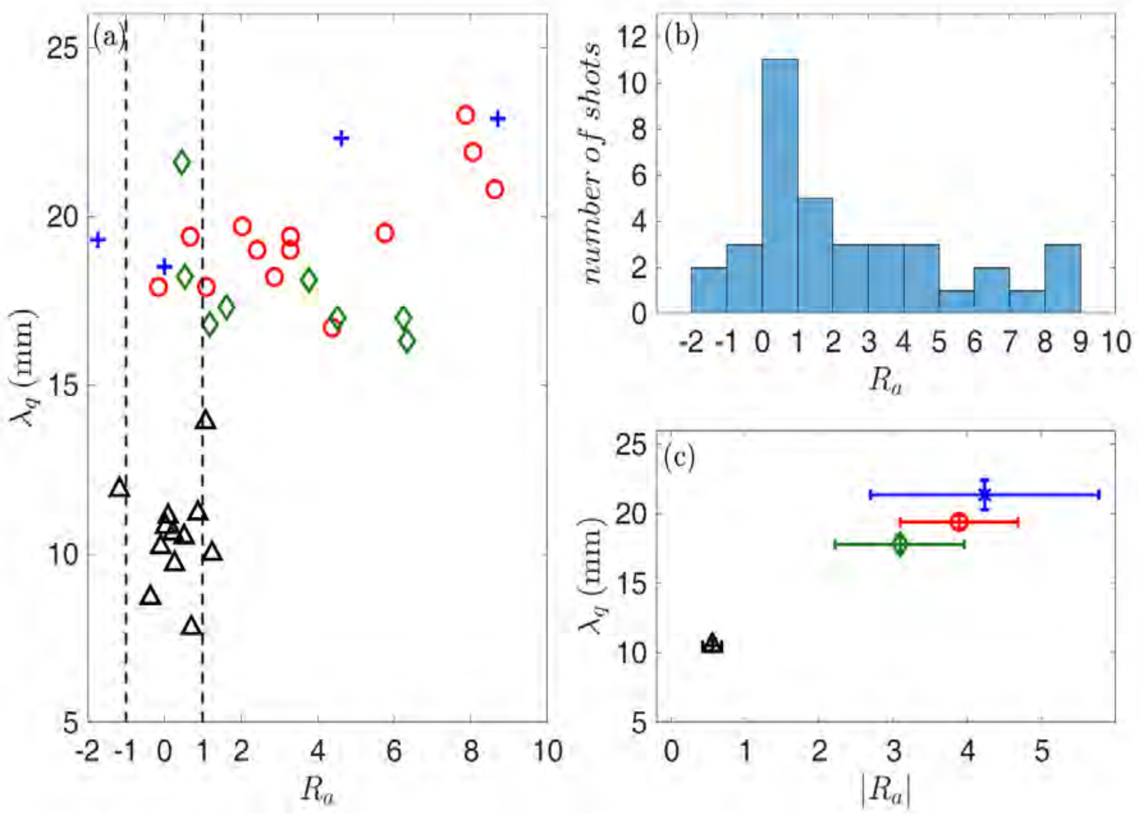
$$R_a = c_s^2 \langle \tilde{V}_r (\tilde{n}/n_0)^2 \rangle \Big|_{\text{lcfs}} \Big/ \int_0^{\lambda} dr \frac{c_s^2}{R} \langle \tilde{V}_r \tilde{n}/n_0 \rangle$$

- 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 lower bound, as local production smaller

Production Ratio - Measurements



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

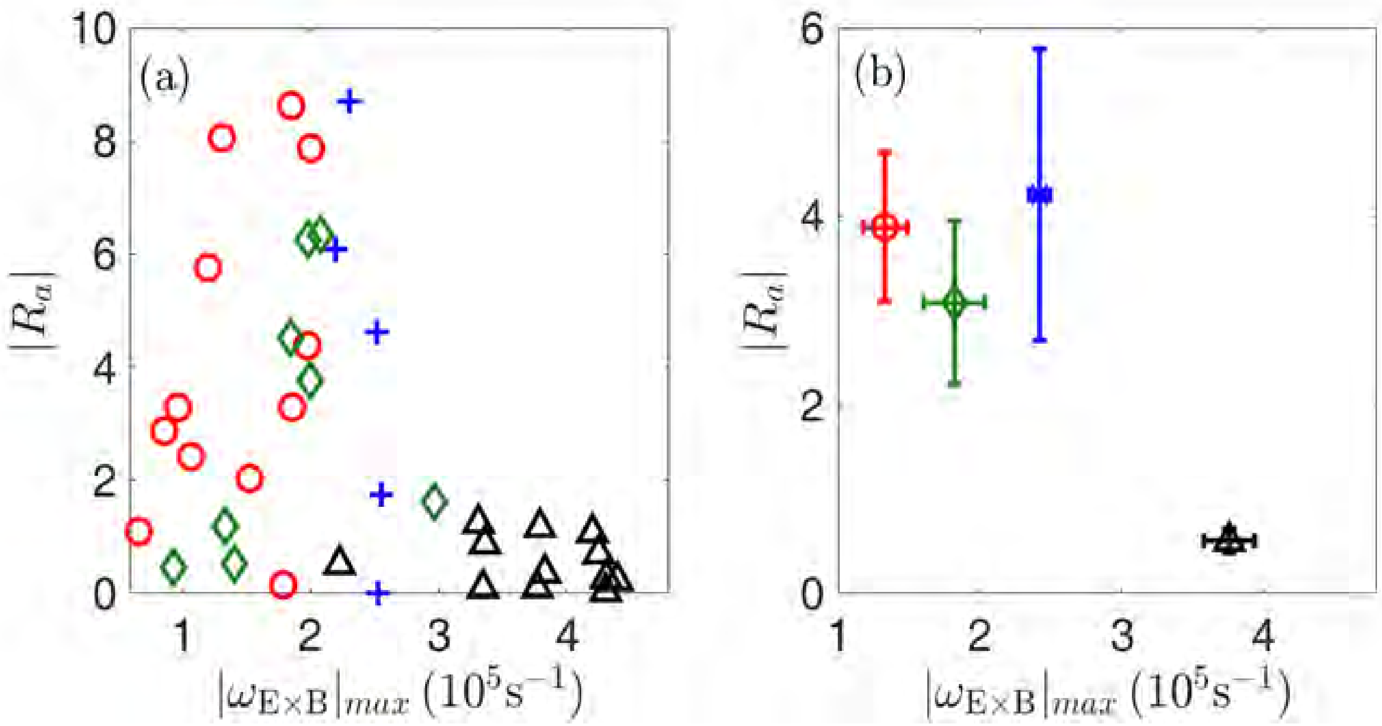
- Observe:
  - λ_q increases with R_a
  - Most cases R_a > 1
  - Broad distribution R_a values
  - Low R_a values ↔ strong ExB shear

  N.B. Non-trivial, as shear enters production, also via cross phase

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

  What is happening?

Production Ratio vs ExB Shear 1



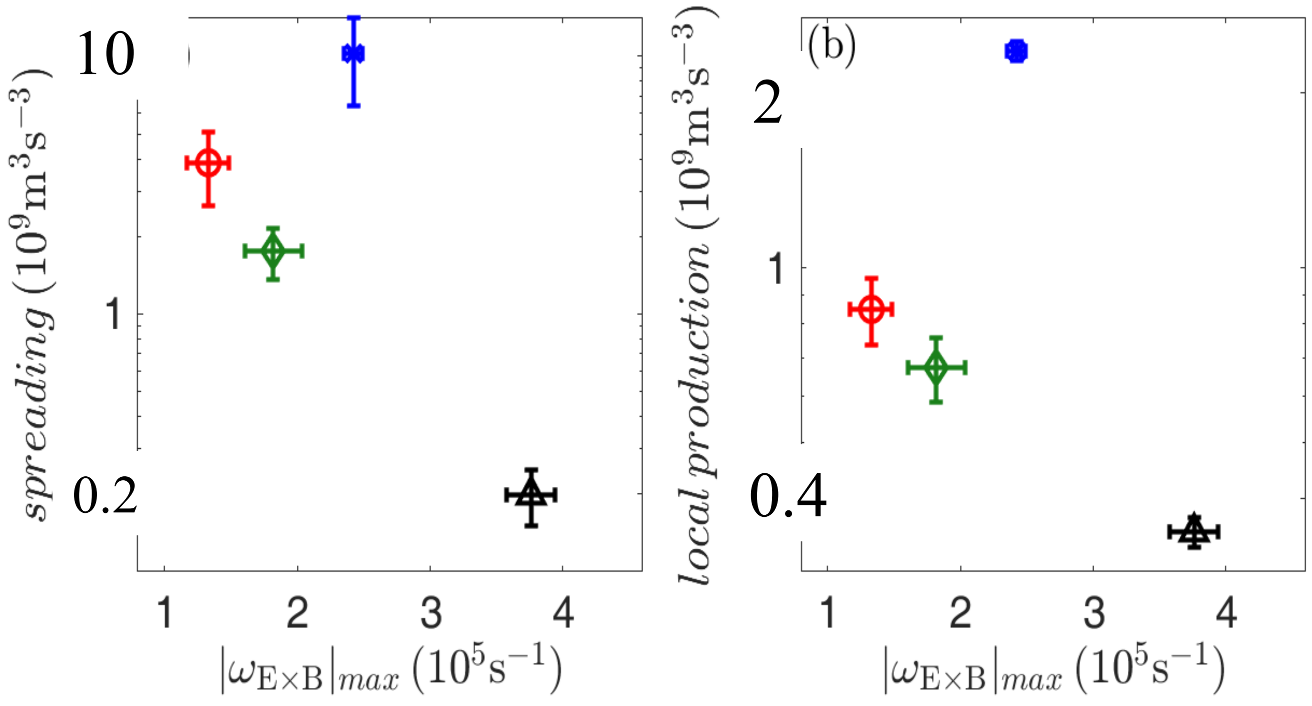
- Low values of $|R_a|$ at high V_E'
- But why?

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

→ Expect shear inhibits both spreading and transport flux?

←→ ExB shear enters phase relation in both

Production Ratio vs ExB Shear, cont'd



- Both spreading and local production drop due high V_E'
- But spreading x (1/10) vs Production x (1/2)

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

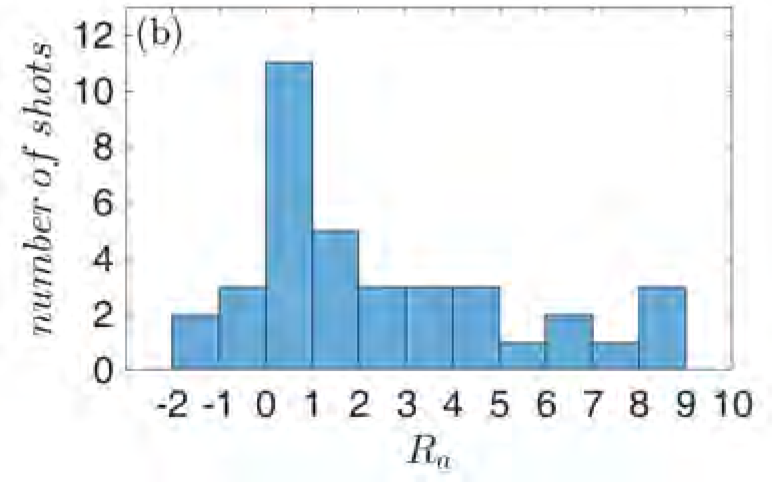
←→ Triplet vs quadratic ➔ Phases?

Large R_a → 'Blobs' ?!

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

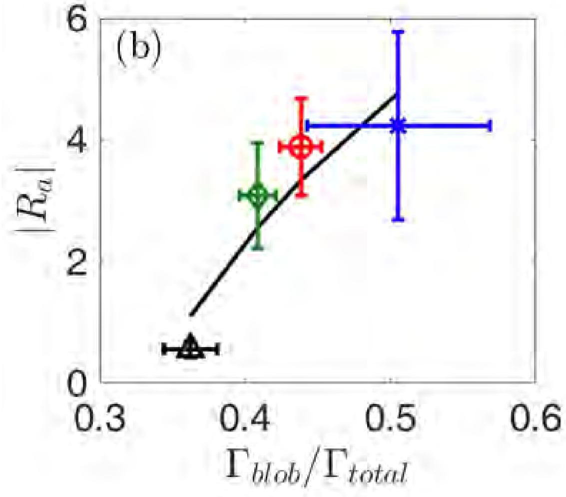
Especially: $\Gamma_{blob} / \Gamma_{total}$

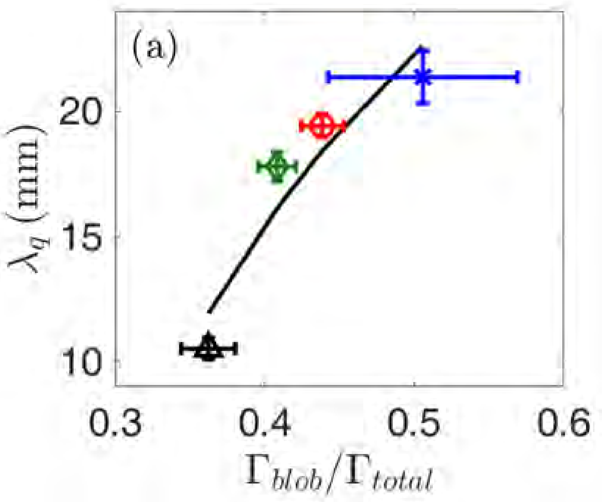
Flux carried by "blobs"



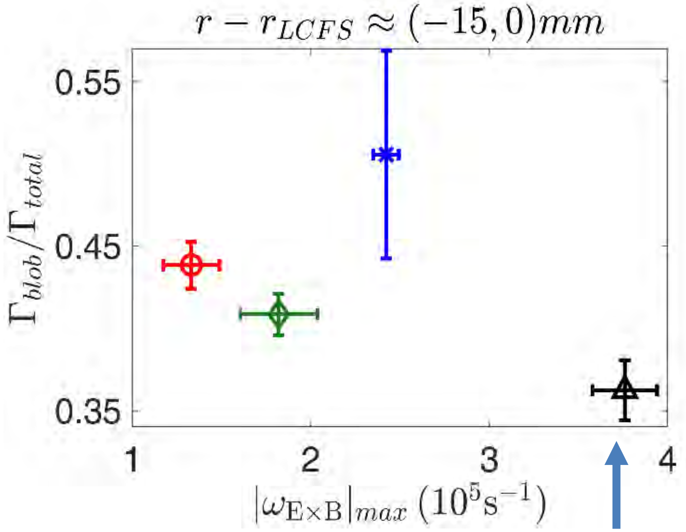
Physics of the "2" ?

Large R_a → λ_q increases with 'blob' fraction





- Large R_a cases ←→ larger 'blob fraction' of flux
  ←→ spreading encompasses 'blobs' (c.f. Manz +) → $\langle \tilde{V}_r \tilde{n}^2 \rangle$
- λ_q increases with Γ_b/Γ_{Tot}



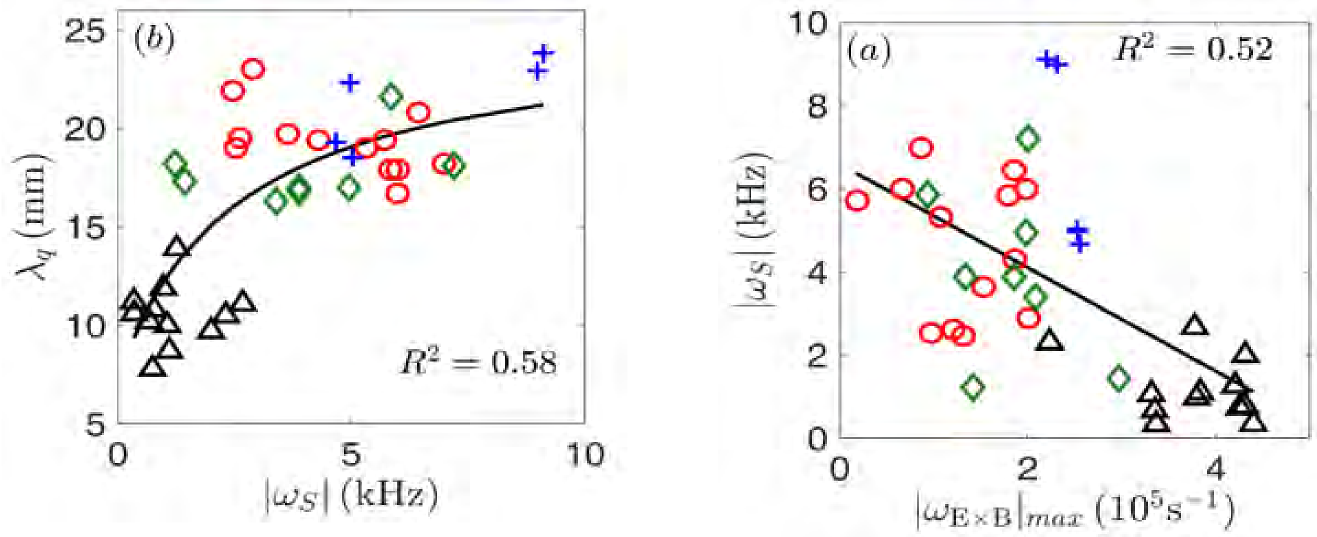
- High ExB shear cases ➔ low 'blob' fraction
  (Consistent with Bodeo+, '03)

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 – phases ?
- High R_a spreading ←➔ 'blob' dominated dynamics ➔ how calculate?

YES ➔ SOL turbulence usually spreading driven!

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

N.B. No use of closure of spreading flux

Calculating the Width of the Spreading-Driven SOL

Physics Issues – Part II

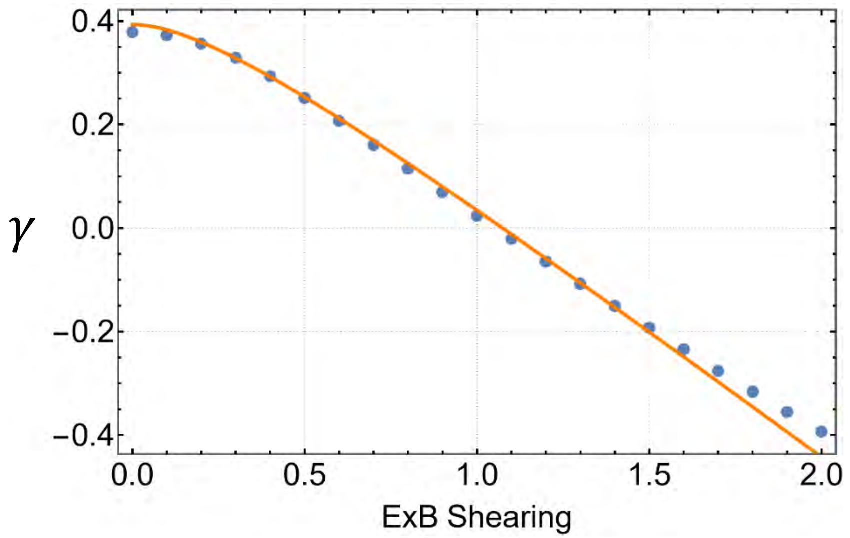
[C.f. Chu, P.D., Guo, NF 2022

P.D.+ IAEA ‘23]

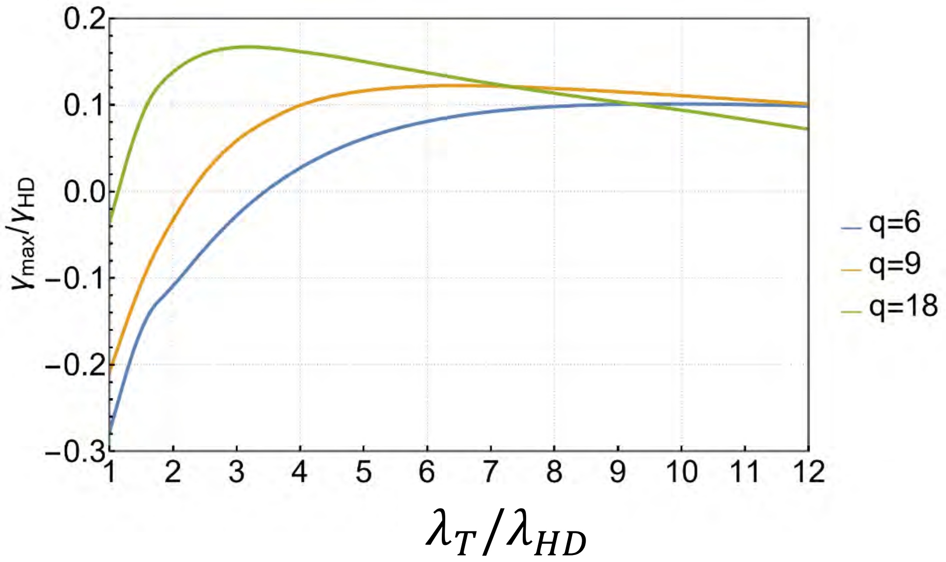
- How calculate SOL width for turbulent pedestal but a locally stable SOL?
  - spreading penetration depth
  - must recover HD in WTT limit
- Scaling and cross-over of λ_q relative HD model
- What is effect/impact of barrier on spreading mechanism?
- Can SOL broadening and good confinement be reconciled ?

Model 1 – Stable SOL – Linear Theory

- 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 layer width λ_D/λ_{HD} at different SOL safety factor q (with $\beta = 0.001$)

- Relevant H-mode ExB shear strongly stabilizing $\quad \gamma_{HD} = c_s/(\lambda_{HD} R)^{1/2}$
- Need λ/λ_{HD} well above unity for SOL instability. $V_E' \approx \frac{3T_e}{|e|\lambda^2}$ → layer width sets shear

Model 2 – Two Multiple Adjacent Regions

- “Box Model” – after Z.B. Guo, P.D.

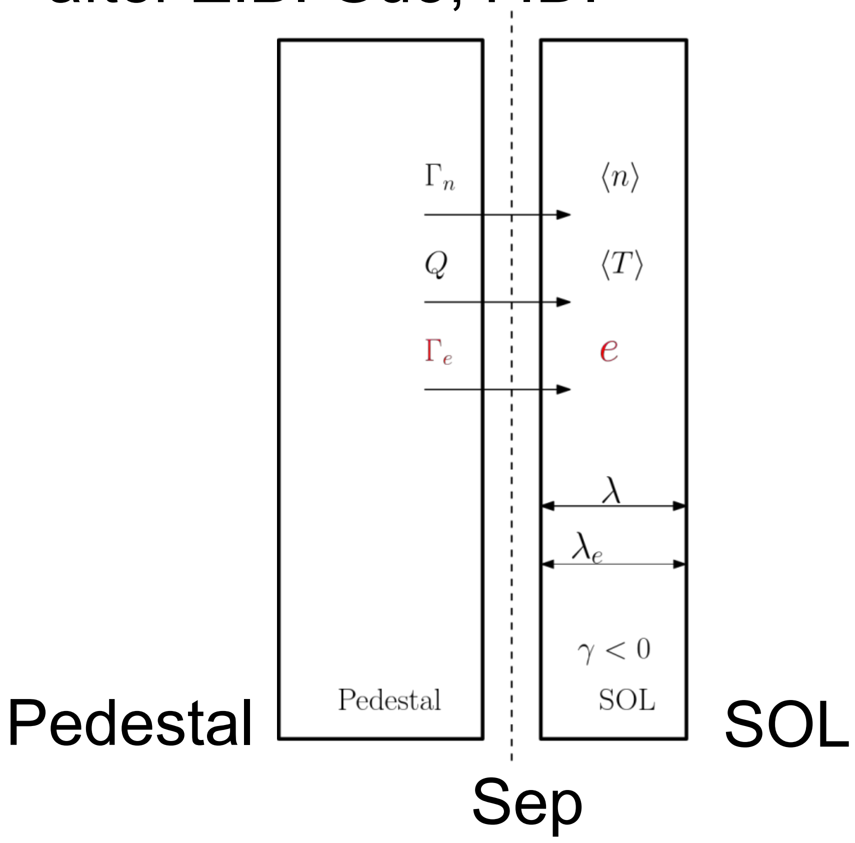


Illustration of Two Box Model: SOL driven by particle flux, heat flux and intensity flux (Γ_e) from the pedestal. The horizontal axis is the radial direction, and vertical axis is the poloidal direction.

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

➔ Problem in one of entrainment/penetration

Width of Stable SOL

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

  drift — fluctuating velocity

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

{ Dwell time $\tau_{\parallel}$ constrains excursion

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

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

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

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 i.e. drift + diffusion

- So $\lambda = \left[\lambda_{HD}^2 + \varepsilon \tau_{\parallel}^2\right]^{1/2}$ → SOL width [Effects add in quadrature]
- How compute ε ? → turbulence energy in SOL. Need relate to pedestal
- N.B. Can write: $\lambda = [\lambda_{HD}^2 + \lambda_e^2]^{1/2}$ λ_e is turbulent width

Calculating the SOL Turbulence Energy 1

- Need compute Γ_e effect on SOL levels
- $K - \epsilon$ type model, mean field approach (c.f. Gurcan, P.D. '05 et seq)
  - Can treat various NL processes via σ, κ
  - Exploit conservative form model
- $\partial_t \varepsilon = \gamma\varepsilon - \sigma\varepsilon^{1+\kappa} - \partial_x \Gamma_e$ → Spreading, turbulence energy flux

NL transfer $\gamma_{NL} \sim \sigma\varepsilon^{\kappa}$

* { Growth $\gamma < 0$
here contains shear + sheath }

→ • N.B.: No Fickian model of Γ_e employed, yet

- Readily extended to 2D, improved production model, etc.

Calculating the SOL Turbulence Energy 2

- Integrate ε equation $\int_0^\lambda$; "constant e" approximation
- Take quantities = layer average
- $\Gamma_{e,0} + \lambda_e \gamma \varepsilon = \lambda_e \, \sigma \, \varepsilon^{1+\kappa}$

Separatrix fluctuation energy flux → Single parameter characterizing spreading

So for $\gamma < 0$,

λ_e = layer width for ε

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

$\Gamma_{e,0}$ vs linear + nonlinear damping

- Ultimately leads to recursive calculation of Γ_e

Calculating the SOL Turbulence Energy 3

[Mean Field Theory]

- Full system:

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

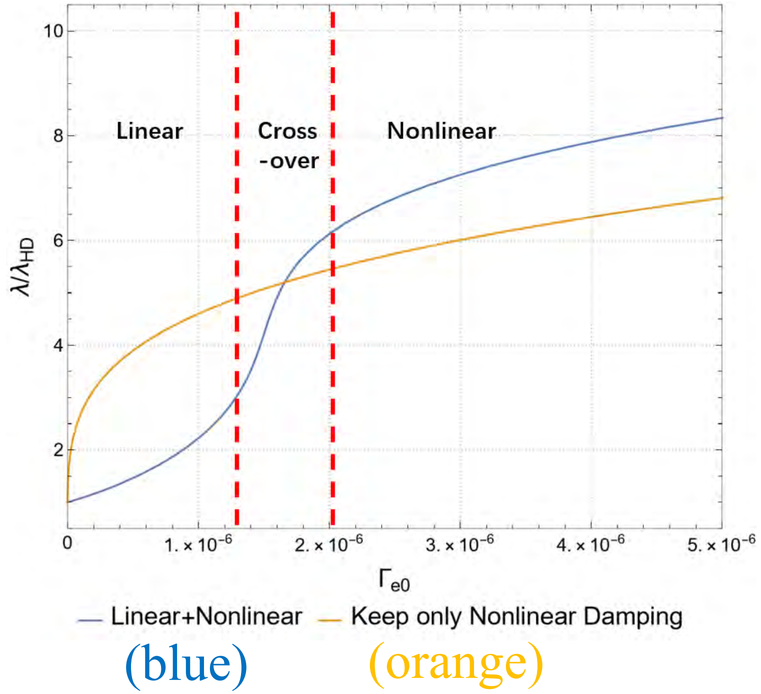
$$\lambda_e = \left[\lambda_{HD}^2 + \varepsilon \tau_{\parallel}^2\right]^{1/2}$$

Simple model of turbulent SOL broadening

- $\Gamma_{0,e}$ is single control parameter characterizing spreading
- $\tilde{\Gamma}_{0,e}$? Expect $\tilde{\Gamma}_e \sim \Gamma_0$

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

- SOL width broadens due spreading



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 dominated
  - Cross-over regime
  - Strong broadening regime

  ➔ NL damping vs spreading } relevant

- Cross-over for:

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

- Cross-over for $\tilde{V} \sim O(\epsilon) V_*$

SOL Width: Some Analysis

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

a) Damping dominated

$\Gamma_e \approx |\gamma|\, \lambda_e\, e$ $\qquad\qquad \lambda_q^2 = \lambda_e^2 + \lambda_{HD}^2$

$$\lambda_q = \left[\lambda_{HD}^2 + \left(\frac{\Gamma_e \tau_{\parallel}^2}{|\gamma|} \right)^{2/3} \right]^{1/2}$$

- Spreading enters only via Γ_e at sep.
- Shearing via $|\gamma|$
- τ scalings → $\tau_{\parallel}$ vs $\tau_{\parallel}^{2/3}$ → current scaling of λ_e weaker

SOL Width: Some Analysis, Cont'd

b) NL dominated

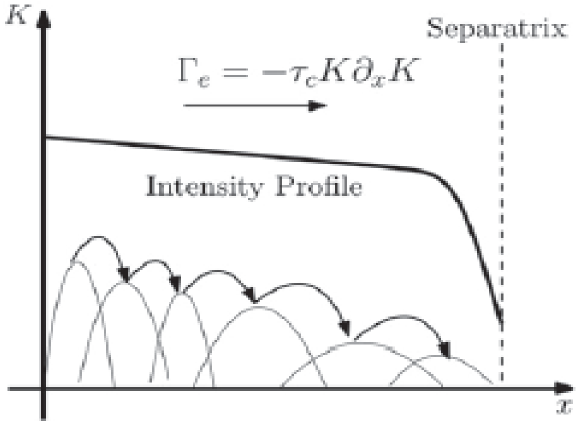
$\Gamma_e \approx \lambda_e \, \sigma \, e^{1+\kappa}$ $\qquad\qquad$ $\lambda_q^2 = \lambda_e^2 + \lambda_{HD}^2$

$$\lambda_q = \left[\lambda_{HD}^2 + \left(\frac{\Gamma_e}{\sigma}\right)^{2/(3+4\kappa)} \tau_\parallel^{[4(1+\kappa)/(3+2\kappa)]}\right]^{1/2}$$

– weaker Γ_e scaling, $\lambda_q \sim (\Gamma_e/\sigma)^{1/5}$; STT

– $\tau_\parallel^{3/4}$ vs $\tau_\parallel$ → weaker current scaling

Computing the Turbulence Energy Flux 1



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

Does another trade-off loom?

-- Pedestal Turbulence: Drift wave? Ballooning?

-- Effect of transport barrier ←→ ExB shear layer ➔ barrier permiability!?

- Key Point: shearing limits correlation in turbulent energy flux

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

ped turbulence intensity

correlation time → strongly sensitive to shearing

N.B. Caveat Emptor re: intensity flux closure !

Computing the Turbulence Energy Flux 2

- Familiar analysis for D → Kubo

$$D = \int_0^\infty d\tau \, \langle V(0)V(\tau) \rangle = \int_0^\infty d\tau \, \sum_k \left|\tilde{V}_k\right|^2 \exp\left[-k_y^2 \omega_s^2 D \tau^3 - k^2 D \tau\right]$$

- Strong shear (relevant) $\boxed{\tau_c = \tau_t^{1/2} \omega_s^{-1/2}}$

$\tau_t \sim 1 \, / \, k\tilde{V}, \quad \omega_s \sim V_E'$

Here, via RFB ➔ $\omega_s = \partial_r \frac{\nabla P_i}{n|e|} \sim \frac{\rho^2}{w_{ped}^2} \, \Omega_{ci}$

- $\tau_c + w_{ped}$ + turbulence intensity in pedestal gives $\Gamma_{e,0} \approx \tau_c I^2 / w_{ped}$
- Need $\Gamma_{e,0} \geq \Gamma_{e,\min} \approx |\gamma| \lambda_{HD}^3 \, \tau_{\parallel}^{-2}$

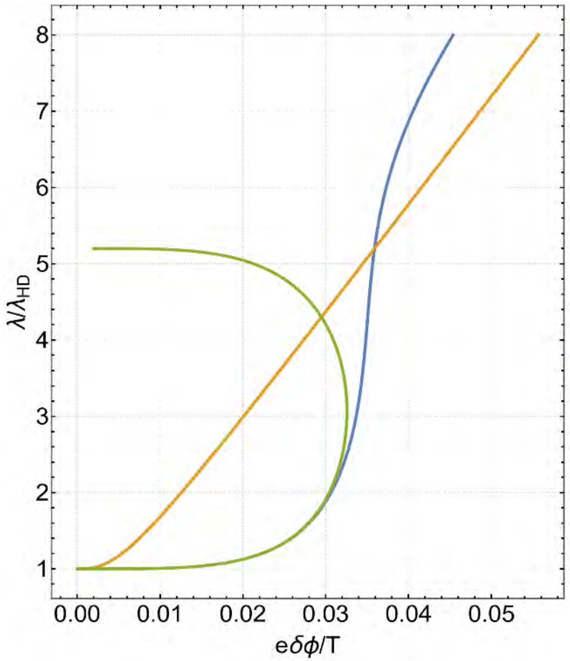
Computing the Turbulence Energy Flux 3

- Pedestal → Drift wave Turbulence
- Necessary turbulence level:
  - Weak Shear $\frac{\delta V}{c_s} \sim \left(\frac{\rho}{R}\right)^{1/2} q^{-1/4}$
  - Strong Shear $\frac{\delta V}{c_s} \sim \left(\frac{\rho}{R}\right)^{1/2} q^{-1/4} \left(\frac{w_{ped}}{\rho}\right)^{-1/8}$

blue – all damping

orange – nonlinear only

green – linear only



→ λ/λ_{HD} vs $|e|\hat{\phi}/T_e$ in pedestal

→ ρ/R is key parameter

→ Broadens layer at acceptable fluctuation level

Computing the Turbulence Energy Flux 4

- Pedestal → Ballooning modes ➔ Grassy ELMs
- Necessary relate turbulence to $L_{P,crit} \,/\, L_P \,-1$
- Strong shear:

$$\frac{L_{P_c}}{L_P} - 1 \sim \left(\frac{q\rho}{R}\right)^{\frac{10}{7}} \left(\frac{R}{w_{ped}}\right)^{\frac{16}{7}} \left(\frac{w_{ped}}{\Delta_r}\right)^{\frac{16}{7}} \beta$$

- Supercriticality scales with $\frac{\rho}{R},\ \beta_t$

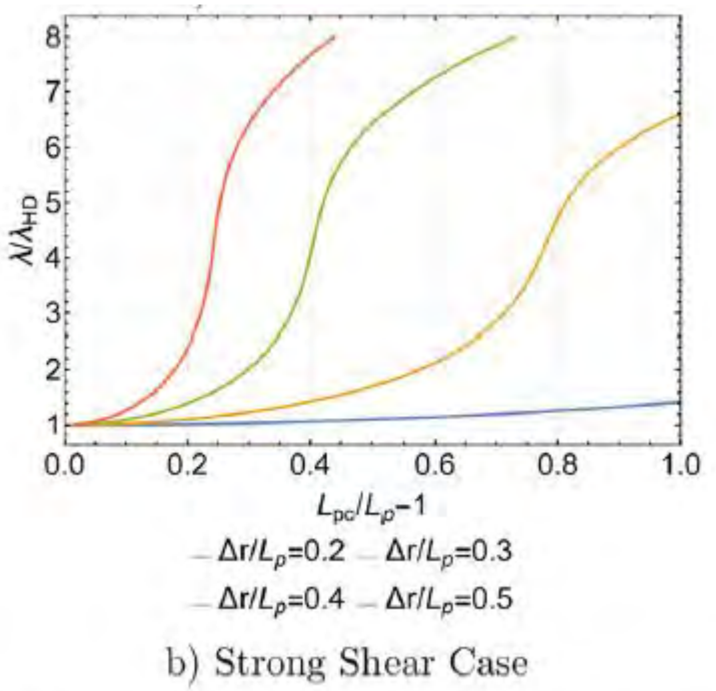


Figure 10. Typical cases for ballooning. The normalized pedestal width λ/λ_{HD} is plotted against supercriticality $L_{pc}/L_p - 1$ at different mode width Δ/L_p.

Computing the Turbulence Energy Flux 5 → Bottom Line

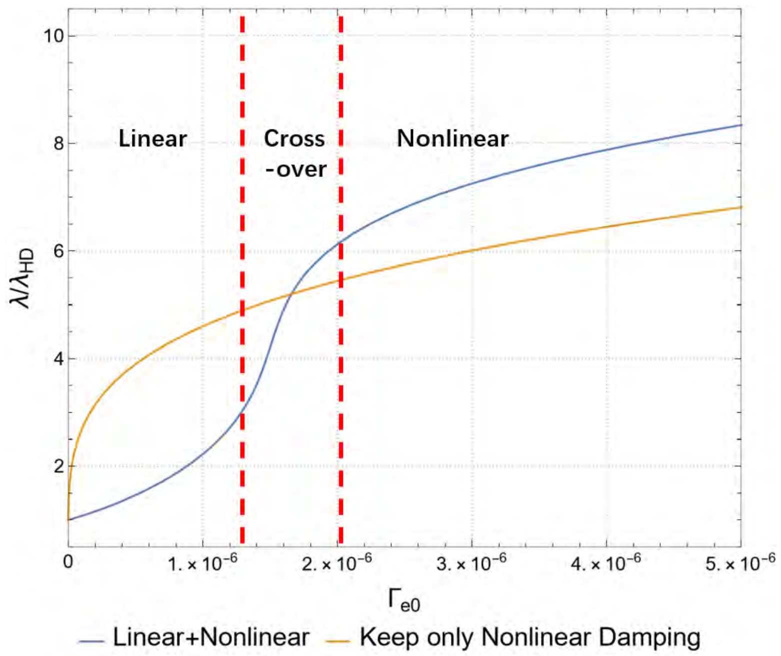
- SOL broadening to $\lambda > \lambda_{HD}$ achieveable at tolerable pedestal fluctuation levels
- DW levels scale ~ $\left(\frac{\rho}{R}\right)^{1/2}$
- Ballooning supercritical scale ~ $\left(\frac{\rho}{R}\right)^{10/7} \beta$
- 'Grassy ELM' state promising
- Sensitivity analysis → Cross over ε determined primarily by linear damping (shear). Conclusion ~ insensitive 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



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

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

Some Simulation Results

(cf. Nami Li, X.-Q. Xu, P.D.; N.F.(Lett) ‘23)

➔ BOUT++ → pedestal + SOL

➔ 6 field model (“Braginskii for 21st century”)

➔ Focus on weak peeling mode turbulence in pedestal

→ MHD turbulence state → small/grassy ELM, also WPQHM

3D Counterpart of Brunner (λ_q vs B_θ)

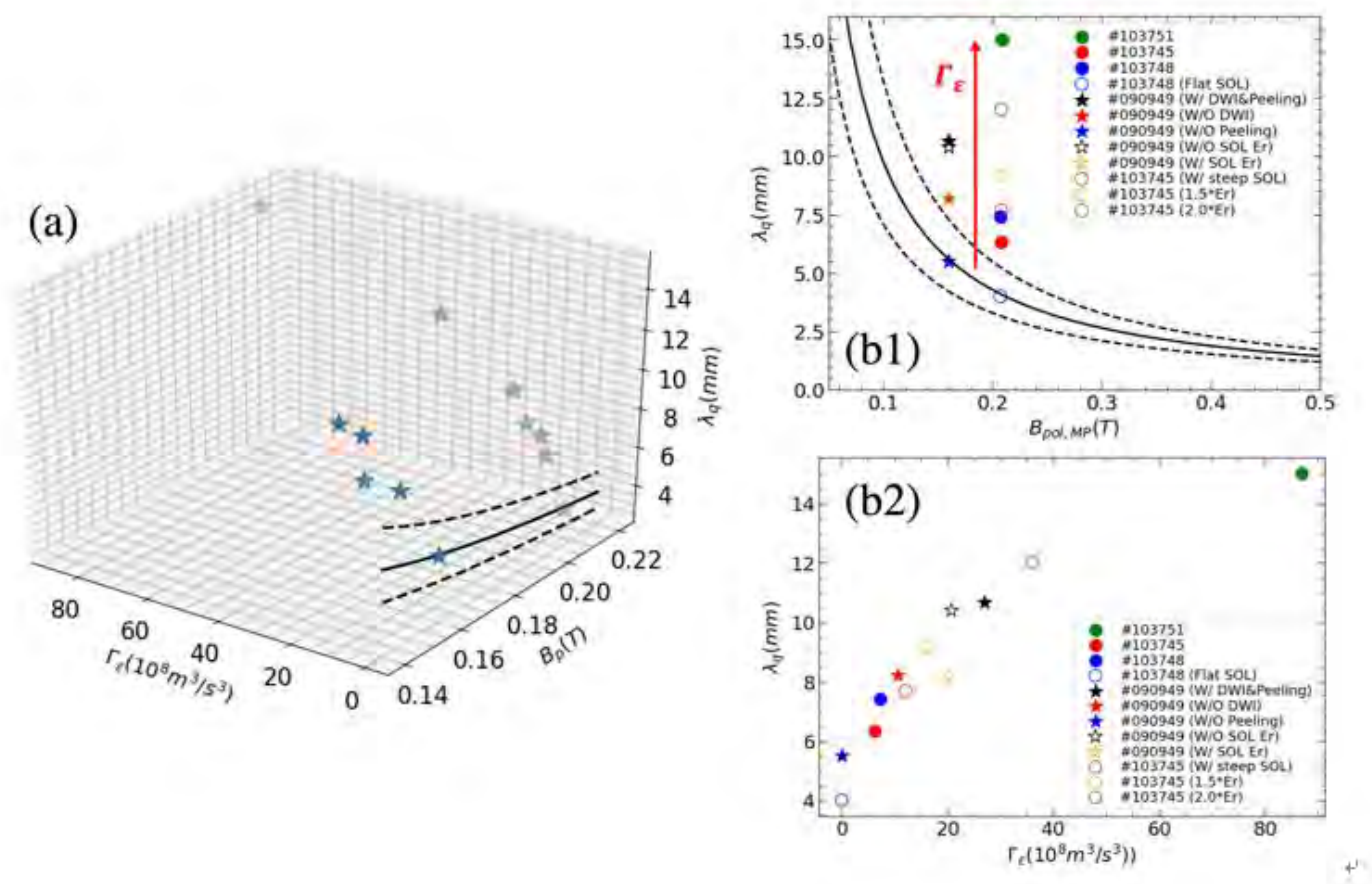


Fig. 3. (a) 3D plot of heat flux width λ_q vs poloidal magnetic field B_p and fluctuation energy density flux Γ_ε; (b) 2D plot of heat flux width λ_q vs poloidal magnetic field B_p (b1) and fluctuation energy density flux Γ_ε (b2).

3D Brunner Plot – Comments

- λ_q rises with Γ_e
- Low Γ_e , λ_q tracks hyperbola
- Large Γ_e , λ_q rises above Brunner/Goldston hyperbola
- λ_q grows with Γ_e

Spreading as Mixing Process ?

- Conjecture that λ_q should increase with pedestal mixing length ➔ Γ_e

- Note division into
  - drift dominated
  - cross-over (blue)
  - turbulent

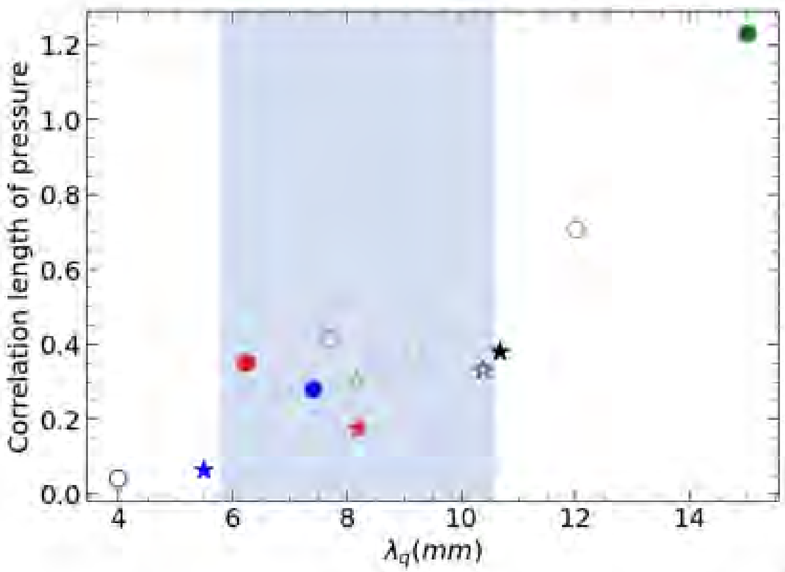


Fig 4. Radial correlation length of pressure near the separatrix vs. heat flux width λ_q.

Relate Spreading to Pedestal Conditions

N.B.

- Γ_e rises with pedestal ∇P_0 ←→ increased drive
- Collisionality dependence Γ_e:
  - high → no bootstrap current → ballooning → smaller l_{mix}
  - low → strong bootstrap → peeling → larger l_{mix}

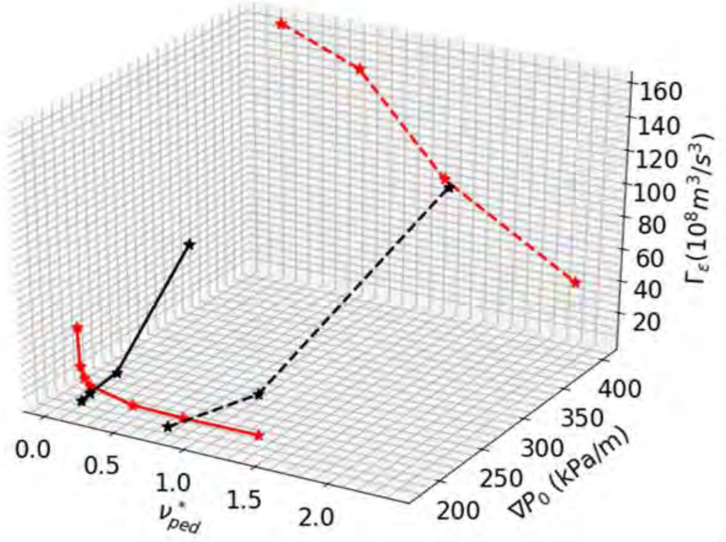


Fig. 7. 3D plot of fluctuation energy density flux Γ_ε vs pedestal peak pressure gradient ∇P_0 and υ^*_{ped}; black curves are ∇P_0 scan with low collisionality $\upsilon^*_{ped} = 0.108$ (solid curve) and high collisionality $\upsilon^*_{ped} = 1$ (dashed curve); red curves are υ^*_{ped} scan with small $\nabla P_0 \sim 200\ kPa/m$ (solid curve) and large $\nabla P_0 \sim 400\ kPa/m$ (dashed curve).

Fundamental Physics of Γ_e

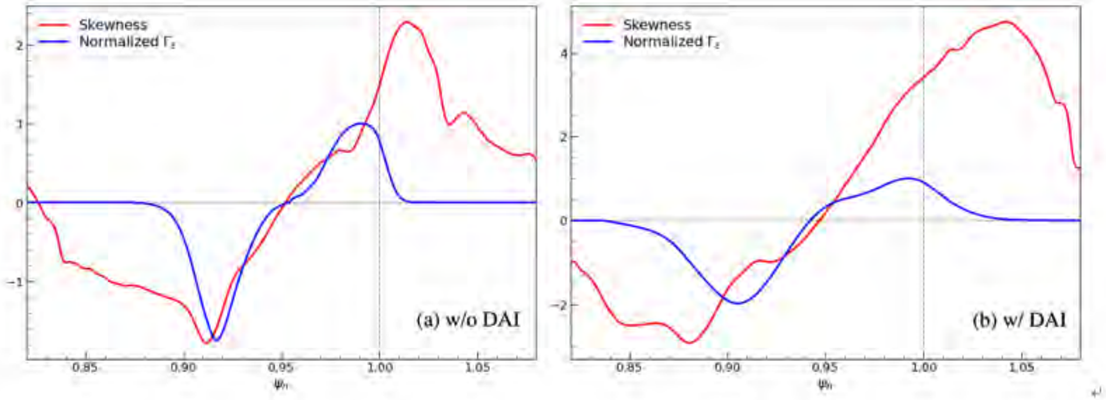


Fig. 6 Radial profiles of normalized fluctuation energy density flux Γ_ε (blue) and skewness (red) for without (a) and with (b) drift-Alfvén instability. Here fluctuation energy density flux is normalized to the max value for each case.

- Γ_e spreading tracks $\tilde{P}$ skewness
  - <u>Outward</u> for $s > 0$ → “blobs”
  - <u>Inward</u> for $s < 0$ → “voids”
- Zero-crossings Γ_e, s in excellent agreement

Fundamental Physics of Γ_e, cont'd

- Spreading appears likely linked to "coherent structures"
- Likely intermittent (skewness, kurtosis related)
- Related study (Z. Li); $Ku \sim 0.4$, so ➔ if Fokker-Planck analysis

$$\frac{\partial e}{\partial t} = -\frac{\partial}{\partial x}(Ve) + \frac{\partial^2}{\partial x^2}(De)$$

Convective !?

Relate V to pedestal gradient relaxation event (GRE) ?!

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, Turbulence 'Avalanches'
- Turbulent pedestal states attractive for head load management

Open Issues

- Quantify $\lambda = \lambda \left(\frac{|e|\hat{\phi}}{T} \Big|_{ped} \right)$ 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 ?

Concluding Philosophy

- MFE relevant questions within reach in near future. Great attention to λ_q problem (c.f. Samuel Johnson)
- Unreasonable for tokamak experiments to probe ~ critical dynamics so as to elucidate basic questions. Simulations???
- Well diagnosed, basic experiment with some relevant features are sorely needed – akin to ‘Tube’ studies of flows, ala’ CSDX
- How?

Thanks for Attention !

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