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The SOL as an Intensity and Heat Flux Driven Boundary Layer: Implication for Heat Load Scalings

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- A work in progress...

Outline

- Motivation: LaBombard-Eich-Goldston Scaling and its implications
- Many Questions...
- Constraints on Turbulence Production in SOL
- Turbulence Spreading: Core→SOL
- The Key Questions
- Some Equations
- Scalings
- Discussion and Conclusions

Motivation

- SOL heat load width is a critical issue for ITER, and M.F.E. in general
- LaBombard-Eich-Goldston scaling is a classic "3S's" case:
  - Successful – works well for present day experiments
  - Simple (Goldston) - $\lambda \approx V\tau$ with $V \approx V_D$, $\tau \sim (V_{thi}/Rq)^{-1}$

    drifts !

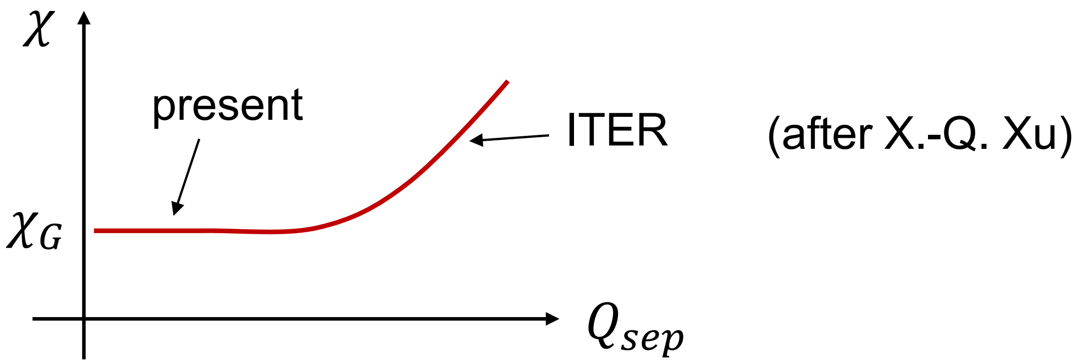
    So $\lambda \sim 1/B_\theta$

    $$\text{“}\chi\text{”} \approx V_D \lambda$$

  - Scary → extrapolation to future is pessimistic

Many Questions

- Will the L-E-G trend continue? Why not?



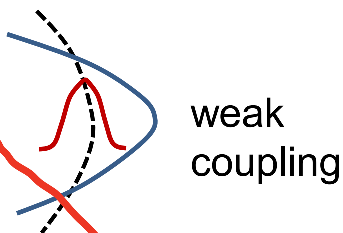
- SOL is turbulent ! (infinity of measurements)
  - Why turbulence, yet transport seemingly described by drifts?
  - As transport ←→ relaxation linked, what is origin of SOL turbulence?
  - Under what conditions might turbulent transport control SOL width? Cross-over?

Many Limitations on SOL Relaxation

- Long history of instability studies for SOL

  (cf: Garbet et al, Myra and Krash '02)

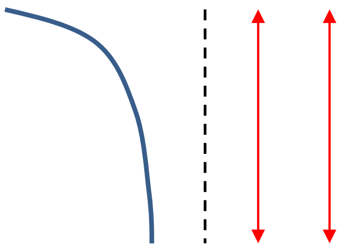
- Despite unfavorable average curvature, a remarkable number of restrictions on instability!
  - $k_\perp \rho_i$
  - $k_r \rho_b$ ←→ drifts → radial excursion, akin banana width
  - line tying ←→ sheath boundary condition → vorticity damping
  - ExB shear, PV gradient → crucial to distinguish from mass flows, etc
  - parallel flows to PFC's depletes drive → turbulence not really "flux driven"



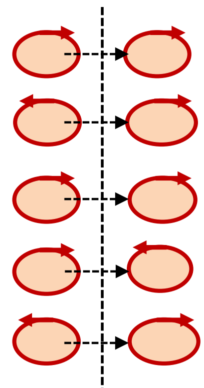
Origin of SOL Turbulence?
→ "Turbulence Spreading"

(Garbet, Hahm, P.D.)
(See Hahm, P.D.;
J. Kor. Phys. Soc. '18)

- SOL adjacent to pedestal/edge



pedestal
turbulence
entrains SOL



- Simple model: $\Gamma_\varepsilon = -D_0 \varepsilon \partial_r \varepsilon$
- Point: SOL fluctuations excited in edge, scattered to SOL
- Pedestal Turbulence:
  - usual suspects: KBM, ETG, ...
  - 'MHD' turbulence: marginal PB + 'noise'
  - "Blobs", etc.
  - Spreading from no man's land (R. Singh, P.D., '19)

The Key Questions:

- Given the SOL 'stability', is the origin of SOL turbulence in the pedestal? SOL turbulence not locally driven ?!

- Model the SOL as a boundary layer driven by:
  - heat flux { drift driven / turbulent driven → classic (see L+L)
  - * turbulent intensity input/flux

    i.e. $\Gamma_I = \Gamma_I$(Q, pedestal gradients, parameters)
  - $\lambda = \lambda(\Gamma_I, V_D, Q)$?! → transitions ?!

Some Equations → Toward a Reduced Model

Heat

$$\begin{cases} \partial_t T + \nabla \cdot \vec{Q} = 0 \\ \nabla \cdot \vec{Q} = \nabla_r Q_r + \nabla_\parallel Q_\parallel \\ \nabla_r Q_r = \partial_r Q_D + \partial_r Q_T \end{cases}$$

drift turbulent

B.C. $Q \equiv Q_0 \hat{r}|_{sep}$

$$Q_T(r) = Q_0 - \int_0^r \nabla_\parallel Q_\parallel - Q_D$$

turbulent flux, parallel losses, drift flux

Fluctuations — $\langle (\nabla_\perp^2 \phi)^2 \rangle$ → Enstrophy

— Γ_q = Enstrophy Flux

$$\partial_t \varepsilon + \partial_r \Gamma_\varepsilon = g_{eff} \langle \nabla_y T \nabla_\perp^2 \phi \rangle - \frac{\tilde{V}}{l} \varepsilon - \langle \tilde{V}_r \nabla_\perp^2 \phi \rangle \partial_r \langle \nabla^2 \phi \rangle + \langle \nabla_\perp^2 \tilde{\phi} \nabla_\parallel \tilde{J}_\parallel \rangle$$

Enstrophy Flux
→ spreading

NL damping

$\partial_r \langle \tilde{V}_{rE} \tilde{V}_{\theta E} \rangle$

ExB Reynolds Force

sheath

+ Temperature Equation

$\langle \phi \rangle \leftrightarrow \nabla \cdot \vec{J} = 0$

B.C. $\Gamma_\varepsilon = \Gamma_{\varepsilon 0}|_{sep}$

Comments

- In spirit of flux-driven B.L. (see Landau & Lifshitz)
- <u>Two</u> flux drives: Q_0 → heat flux, from separatrix; Γ_{ε_0} → intensity flux, from pedestal

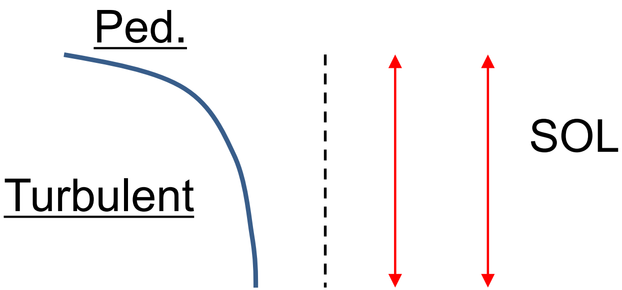
  $\Gamma_{\varepsilon_0} = \Gamma_\varepsilon(\nabla P_{ped}, \ldots)$ → Induces SOL "non-locality"; Drives SOL turbulence; Noisy ?!
- SOL production → ala' interchange
- ExB flow → production/<u>destruction</u> by $\underline{\partial_r \langle \nabla_r^2 \phi \rangle}$

  vs interchange → $\underline{R_{ieff}}$

  → sheat B.C. - scale indep. damping
- $\tilde{V} / l$ → Nonlinear damping rate. Compare with ω_{Ti}?!

Scalings

- Even reduced model is daunting ... so explore scalings



Pedestal as turbulence reservoir for SOL...

- Taking SOL damped, spreading from SOL ...

$\partial_t I = \gamma I - \partial_x (D_0 I \partial_x I)$ (Hahm, P.D. '04)

→ $\delta_I \approx (D_0 I_0 / |\gamma|)^{1/2}$ → SOL penetration depth for turbulence

I_0 → intensity at LCFS ?!

How characterize?

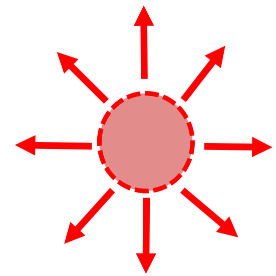
Utility ??

- Also estimate δ_I by

(Prop. Speed) / Width $\approx$ Damping rate

$u \equiv D_0 \epsilon / w^2$ → speed

$\epsilon = \int_{-w}^{0} I \, dx$ → pedestal turbulence energy



expanding slug of turbulence

$$\boxed{\delta_I \approx \frac{D_0 \epsilon}{w^2 |\gamma|}}$$ → <u>width</u>

- <u>Equating</u>: $\boxed{I_0 \approx D_0 \epsilon^2 / w^4 |\gamma|}$ { separatrix intensity in terms of pedestal turbulence energy

- then Γ_I , the intensity flux into SOL:

$$\boxed{\Gamma_I \sim I_0 \delta_I |\gamma| \sim \epsilon I_0 D_0 / w^2}$$, so...

- Turbulence Intensity Penetration Depth into SOL

$$\boxed{\delta_I \approx \Gamma_I^{1/3} D_0^{1/3} |\gamma|^{-2/3}}$$

- If $D_0 \sim D_B$, $|\gamma| \sim V_{thi}/Rq$

$$\delta_I \approx \Gamma_I^{1/3} \left(\frac{m_i q^2 R^2}{|e|B_0}\right)^{1/3} \approx \Gamma_I^{1/3} B_\theta^{-2/3} m_i^{1/3}$$

- For $\delta_I > w_{Goldston}$; $\boxed{\Gamma_I > V_D^3 / D_0|\gamma|^{1/3}}$, $|\gamma| \sim \omega_{Ti}$
  - Defines the critical intensity flux required to broaden the SOL
  - Gives cross-over criterion

Comments

- $\Gamma_I > V_D^3 / D_0|\gamma|^{1/3}$ → critical intensity flux to exceed $\lambda_{Goldston}$

  $|\gamma| \sim \omega_{Ti}$ → can translate into "blobs" formulation

- Weak B_θ dependence !

- Large R favorable → weakens V_D

- If turbulence sufficient s/t ← damping rate

  $\tilde{V} / l > \omega_{Ti}$, can eliminate unfavorable B_θ scaling

- Turbulent pedestal states obviously of great interest;

  Experiment to measure and visualize spreading ?!

Conclusions

- Turbulence spreading from pedestal as likely origin of SOL turbulence

- Model: SOL as dual-flux-driven turbulent boundary layer:

  Q_0, Γ_{I0} ← Intensity flux

- Turbulence penetration depth δ_I

  Critical Γ_I s/t $\delta_I > w_{Goldston}$

  } estimated

  Reln. to pedestal ?
  → Coupled domains.

- Begs for studies of pedestal and SOL turbulence spreading dynamics, especially in "turbulent pedestal" states

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