Turbulence Spreading and Entrainment: Dynamics of SOL Broadening

P.H. Diamond

U.C. San Diego

APS-DPP 2022

This research was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Number DEFG02-04ER54738.

Collaborators:

Ting Long[(1)], **Xu Chu**[(2)], **Ting Wu**[(1)], R. Hong[(3)],

Z.B. Guo[(4)], R. Ke[(1)], and HL-2A and J-TEXT Teams

(1) SWIP; (2) Princeton; (3) UCLA; (4) PKU;

Acknowledge:

Nami Li, Jose Boedo, Zheng Yan, G. Tynan, Z. Li, X.-Q. Xu

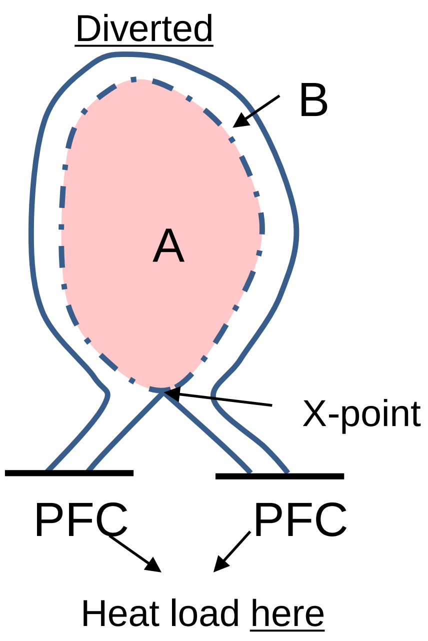
Background: The SOL Width Problem

- Long history, Key: Open field lines
- H-mode → HD Model (Goldston +)

  $\lambda_q \sim \varepsilon\, \rho_{\theta i}$ - pathetically small, unfavorable B_θ scaling

- Why? → ExB shear quenches SOL modes
- Calculate SOL width for turbulent pedestal but locally stable SOL
  – Penetration depth of turbulence spreading ?!
  – See Chu, PD, Guo ‘22 NF
- N.B.: Many visualizations from simulation available

  See Nami Li +, this meeing, for analysis



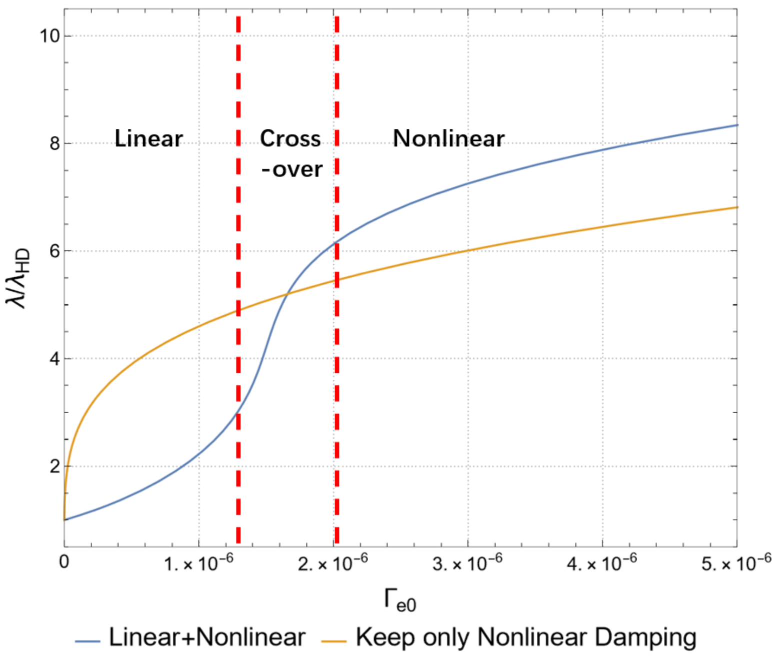
A – confined plasma
B – SOL
Dashed – separatrix

Summary: Chu, P.D., Guo '22 NF

- Turbulent scattering broadens stable SOL

$$\lambda = \left(\lambda_{HD}^2 + \varepsilon\tau_{\parallel}^2\right)^{1/2} \qquad \varepsilon \approx \text{Turbulence energy intensity}$$

- Separatrix turbulence energy flux specifies SOL turbulence drive



Spreading Calculation for ε :

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

Broadening increases with $\Gamma_{0,e}$

Non-trivial dependence

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

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

Fundamental Physics of Turbulence Spreading

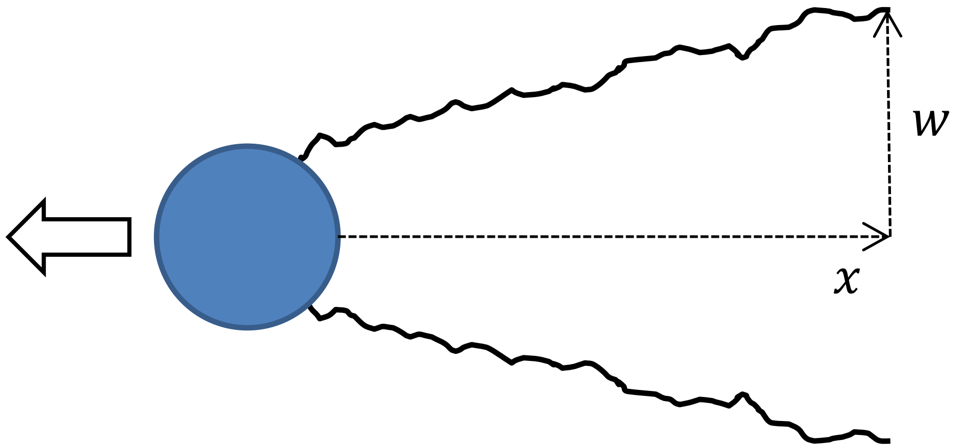
- **Structure of the intensity flux-gradient relation ?**

- **Experiments: Ancient and Modern**

- **Pulsation Model of Spreading (New)**

On Spreading: A Familiar Phenomenon

- Turbulence spreading underpins turbulent wake → central example in high Re fluids



Mixing length model
Similarity theory
$\Rightarrow w \sim (F_d/\rho U^2)^{1/3} x^{1/3}$

$F_d \sim \rho U^2 S C_D$;

C_D → indep ν

- Spreading fundamental to $k - \varepsilon$ type models, as ε evolved as unresolved energy field → subgrid models

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \left(\tilde{V}\varepsilon\right) + \cdots = 0$$

How render tractable ?

On Spreading: cont'd

- What you get (usually):

$$\partial_t \varepsilon + \vec{V}_D \cdot \nabla\varepsilon + \langle \vec{V}_E(r) \rangle \cdot \nabla\varepsilon \; - \partial_r \, D(\varepsilon)\partial_r \varepsilon = P(\varepsilon) - P_{\text{damp}}(\varepsilon) \; \to \gamma(\vec{x})\varepsilon$$

drift shear turbulent mixing via closure

$\gamma = \gamma$(gradients, etc)

$\boxed{D(\varepsilon) \approx D_0 \varepsilon \text{ , et. seq.} \rightarrow \text{nonlinear diffusion}}$

→ ε evolution as nonlinear Reaction-Diffusion Problem!

(P.D., Garbet, Hahm, Gurcan, Sarazin, Singh, Naulin…)

- Used also in:
  - Multi-scale style layering models (Ashourvan +)
  - 1D L→H models (Miki +)

On Spreading: cont'd

- Spreading as Front ➔ Fast Propagation

  i.e. $V_f \sim (\gamma D)^{1/2}$, etc   i.e. Fisher

- Key component:

  $\nabla \cdot \langle \vec{V} \varepsilon \rangle \;\rightarrow\; -\nabla \cdot D(\varepsilon) \cdot \nabla \varepsilon$ [Fickian Model]

  Expectation: $D(\varepsilon) \sim \chi$, D_n etc. for electrostatic turbulence

- Copious simulations: Z. Lin, W.X. Wang, S. Yi, Jae-Min Kwon, Y. Sarazin, …

➔ Observations of front tracking but critical analysis of model absent

No test of Fickian flux-gradient model

Experiments: Ancient

- Not exactly a new idea … See Townsend '49 and book

Momentum and energy diffusion in the turbulent wake of a cylinder

By A. A. Townsend, *Emmanuel College, University of Cambridge*

(*Communicated by Sir Geoffrey Taylor, F.R.S.—Received 6 October* 1948)

A detailed experimental investigation of the turbulent motion in the wake of a circular cylinder, 0·953 cm. diameter placed in an air-stream of velocity 1280 cm.sec.$^{-1}$, has been carried out with particular reference to those quantities determining the transport of turbulent energy and mean stream momentum. At distances of 80, 120 and 160 diameters down-stream from the cylinder, direct measurements have been made of mean flow velocity, turbulent intensity, viscous dissipation, energy diffusion, scale, and form factors of the velocity components and their spatial derivatives. These observations show that, except close to the wake centre, the flow at a point fixed with respect to the cylinder is only intermittently turbulent, due to the passage of the point of observation through jets or billows of turbulent fluid emitted from the inner wholly turbulent core of the wake. Further consideration of the results indicates that the turbulent motion within the jets is solely responsible for the turbulent transfer of momentum, while diffusion of turbulent energy and of heat is carried out by the bulk movement of the jets. Most probably, the jets are initiated by local fluctuations of pressure inside the turbulent core, and in the later stages of their development that are slowed down by adverse pressure gradients. The existence of pressure-velocity correlations of sufficient magnitude is demonstrated by using the equation for the conservation of kinetic energy in the wake, all terms of which are known excepting the one involving the pressure-velocity correlation, which is then obtained by difference. While the conception of jets of turbulent fluid is more convenient for following the physical processes in the wake, the alternative but equivalent description that the turbulent motion consists of a motion of scale small compared with the mean flow superimposed on a slower turbulent motion whose scale is large compared with the mean flow may be used. A formal explanation of this two-stage turbulent structure in terms of the Fourier representation of the velocity field is suggested, which relates the structure to the presence of a quasi-constant source of energy of nearly fixed wave-number, and to the free boundary which allows an unlimited range of wave-numbers. It is expected that this type of motion will occur in all systems of turbulent shear flow with a free boundary, such as wakes, jets and boundary layers.

➔ Wake flow intermittently turbulent

➔ Compare transport of momentum and energy (spreading)

Experiments: Ancient, cont'd

The product uv may be regarded as the rate of transport of momentum (per unit mass), and similarly the rate of transport of turbulent energy is

$$\tfrac{1}{2}(\overline{u^2v}+\overline{v^3}+\overline{vw^2}),$$

and, in principle, it is possible to calculate an energy diffusion coefficient δ, analogous with ϵ, by use of the defining equation

$$\overline{u^2v}+\overline{v^3}+\overline{vw^2} = -\delta\frac{\partial}{\partial y}(\overline{u^2}+\overline{v^2}+\overline{w^2}).$$

When this is attempted (figure 5), no simple behaviour is found either for δ, or for the corresponding mixing length. Negative values occur near the wake centre, and, even where the turbulence gradient is fairly uniform, δ remains large compared with ϵ,

and decreases rapidly with distance from the wake centre. It must be concluded that the use of a diffusion coefficient to describe the transport of turbulent energy is not justified, and that energy diffusion is a process independent of momentum diffusion.

To remove this difficulty, it is not sufficient to consider the effects of intermittency. If the intermittency factor is known, then the mean intensity in the turbulent regions is

$$I_j = \frac{\overline{u^2}+\overline{v^2}+\overline{w^2}}{\gamma},$$

and I_j is found to vary only slightly over the greater part of the wake (figure 6). So a considerable transport of energy is found in the almost complete absence of a real intensity gradient, and it is difficult to see how energy flow can take place by turbulent

movements inside the jets. For the transport mechanism, there is only left the bulk movement of the jets, which is naturally outwards and away from the wake centre. The compensating inflow will consist of non-turbulent fluid transporting no turbulent energy. Consequently, the flow of energy is not dependent on the local intensity gradient (if any), but only on the mean jet velocity and the jet turbulent intensity, which in turn are determined by conditions in the turbulent core.

➔ Fickian model for turbulent energy transport

➔ "It must be concluded that the use of a diffusion coefficient to describe the transport of turbulent energy is not justified and that energy diffusion is a process independent of momentum diffusion"

Experiments: Modern (c.f. Ting Long) 1

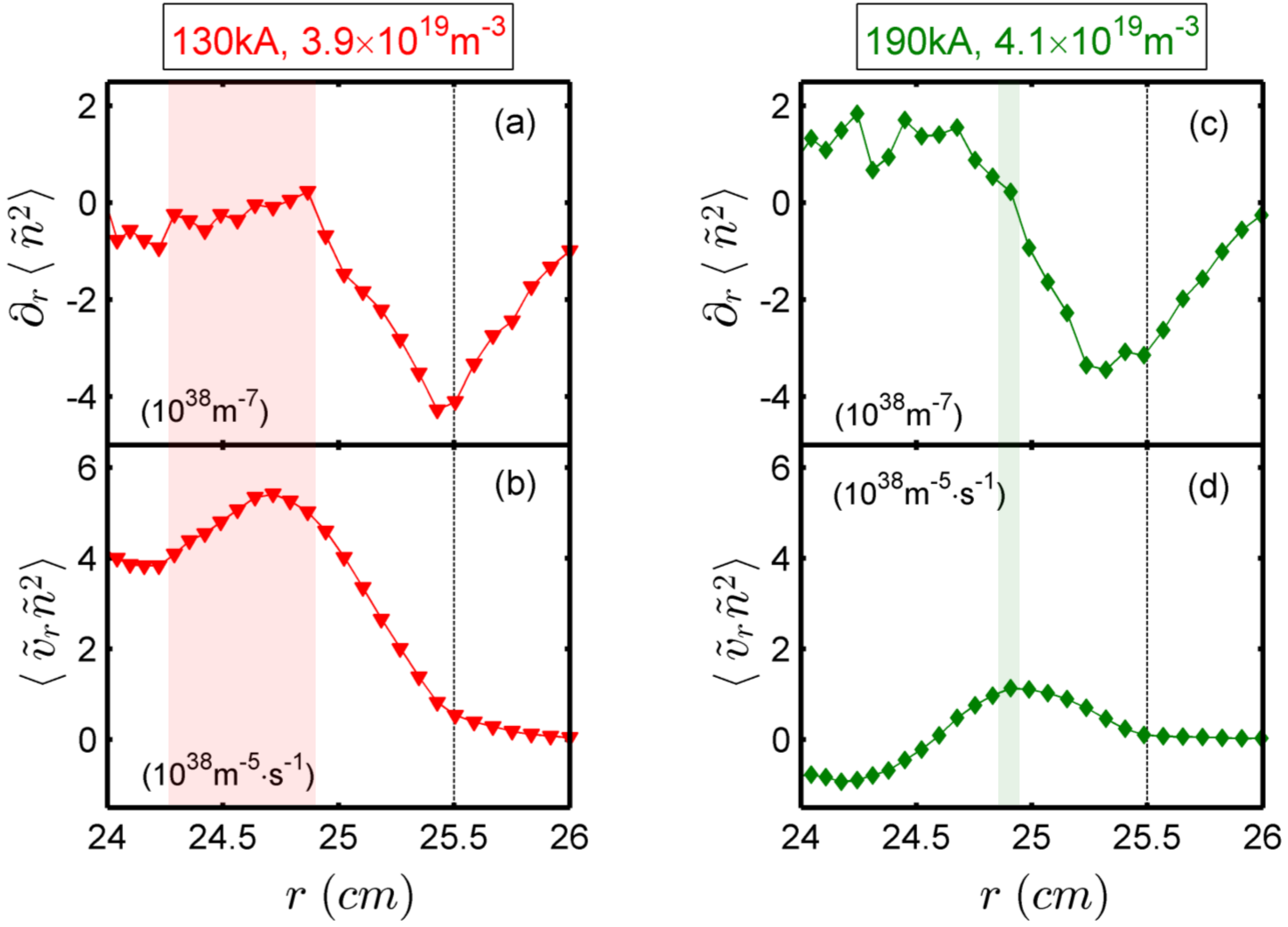
- HL-2A
- Aims:
  - Exploration of intensity flux – intensity gradient relation in edge turbulence (exploits spreading, shear layer collapse and density limit studies Long + NF'21)
  - Physics of "Jet Velocity" profile

$$V_I = \langle \tilde{V}_r \tilde{n}^2 \rangle / \langle \tilde{n}^2 \rangle$$

N.B. Identified by Townsend

Experiments: Modern 2

- There exits a region in plasma edge, where the turbulence spreading flux $\langle \tilde{v}_r \tilde{n}^2 \rangle / 2$ **is large**, but the turbulence intensity gradient $\partial_r \langle \tilde{n}^2 \rangle$ **is near zero**



For close $\bar{n}_e$

- Lower current,
  width of region is $\sim 5\ mm$
  ($l_{cr} \sim 4.5\ mm$)

*

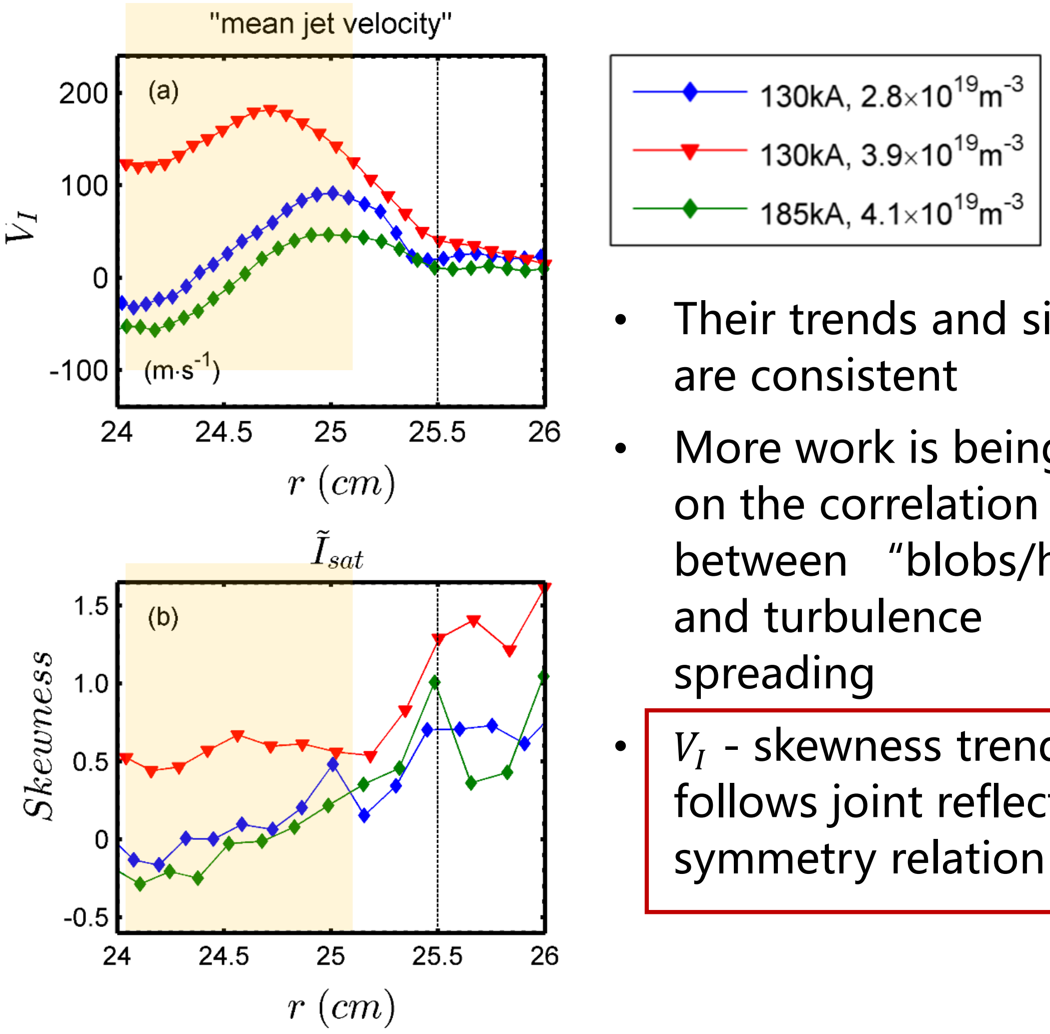
- Higher current,
  width of region is $< 1\ mm$
  ($\rho_i \sim 0.25\ mm$)

- Notice: spreading diffusivity

$$\chi_I = -\frac{\langle \tilde{v}_r \tilde{n}^2 \rangle}{\partial_r \langle \tilde{n}^2 \rangle}$$

Experiments: Modern 3

- The "mean jet velocity" of turbulence spreading $V_I = \frac{\langle \tilde{v}_r \tilde{n}^2 \rangle}{\langle \tilde{n}^2 \rangle}$ and skewness of density fluctuations show strong correlation



- Their trends and signs are consistent
- More work is being done on the correlation between "blobs/holes" and turbulence spreading
- V_I - skewness trend follows joint reflection symmetry relation

Spreading Pulses

- Avalanches, pulses are natural description

  $\delta P \equiv$ deviation of profile from criticality

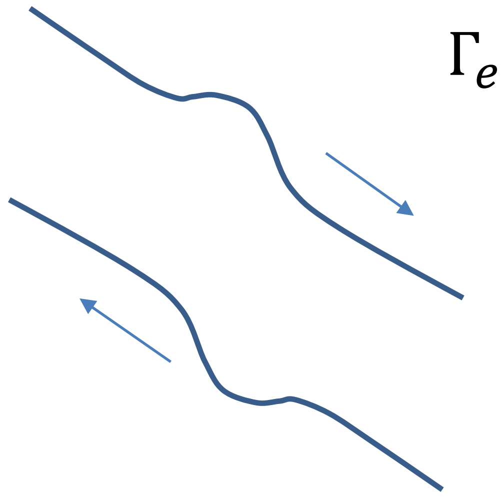
  $\delta P \quad \leftrightarrow \quad (\nabla P - \nabla P_{crit})/P$

  $\delta P \ \sim \ \delta\varepsilon$

 → Spreading as intensity pulses dynamics

  (after PD, Hahm '95)

$$\Gamma_e = \langle \Gamma_e \rangle + \tilde{\Gamma}_e$$



Pulsation, void symmetry argument

- New:
  - Order parameter not conserved → finite SOL dwell time
  - V_D - mean curvature drift
  - $\Gamma_{0,e}\big|_{sep}$ drives system

Fluctuation Energy Pulses, cont'd

- Pulse model:

1 drift

2 dwell time decay

3 spreading

$$\underset{1}{}\ \partial_t\tilde{\varepsilon} + V_D\partial_x\tilde{\varepsilon} + \alpha\tilde{\varepsilon}\partial_x\tilde{\varepsilon} - D_0\partial_x^2\tilde{\varepsilon} + \frac{\tilde{\varepsilon}}{\tau} = 0$$

$\tau \equiv$ SOL dwell time

regularization

$$\tilde{\varepsilon}(0,t) \leftrightarrow \tilde{\Gamma}_{sep}(t)$$

- Some limits:

  – $\varepsilon \to 0$, $V_D\partial_x\tilde{\varepsilon} \sim \frac{\tilde{\varepsilon}}{\tau} \to \lambda \sim \lambda_{HD}$ scale (1 vs 2)

  – For ε to "matter" – i.e. broadening significant:

  $\alpha\tilde{\varepsilon} > V_D$ → amplitude vs neo drift comparison (1 vs 3)

- Structure is Burgers + Krook → 'Crooked Burgers'

Fluctuation Energy Pulses, cont'd

- Predictions ? → Goal Pdf(l | $\tilde{\Gamma}_{0,e}$)

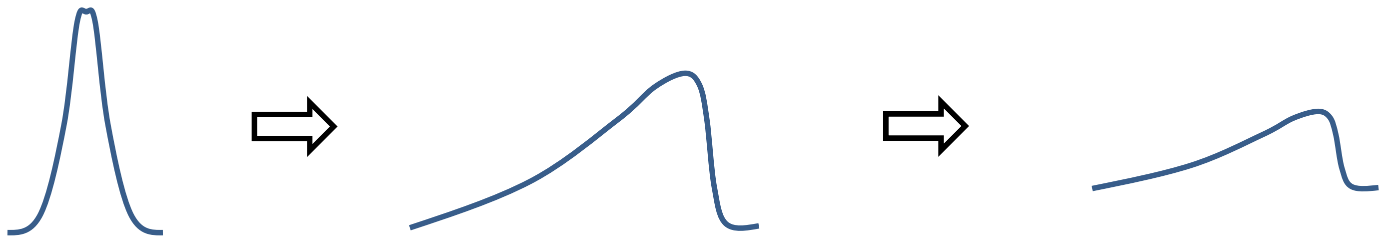
→ Pulse equation characteristics: $\frac{dx}{dt} = \alpha\varepsilon, \quad \frac{d\varepsilon}{dt} \approx -\frac{\varepsilon}{\tau}$

Solution: Shock for $f'(z) < -1/\tau$

Initial slope steep enough to shock before damping by $1/\tau$

→ $\alpha \frac{\partial\varepsilon}{\partial x} < -\frac{1}{\tau}$ → separatrix intensity gradient defines pulse formation criterion

→ pulse evolution → penetration depth



Broader Messages

- Turbulence spreading is important – even dominant – process in setting SOL width
- Spreading dynamics best treated statistically. Pdf(l_{pene}) is goal. Traditional mean field approach problematic.
- Simulation should stress calculation of spreading flux Pdf over visualizations
- Turbulent pedestal states attractive for heat load management