When does turbulence spreading matter?

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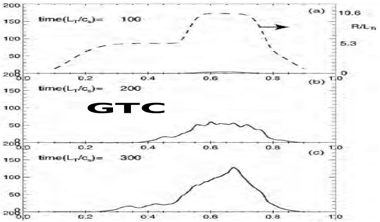
Outline

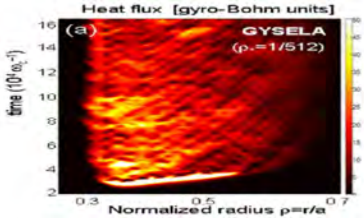
- Introduction & Motivation
- Take away message
- Spreading effect on L mode profiles
- Spreading effect on H mode profiles
- Conclusions
- Future directions

Introduction & Motivation

- Turbulence Spreading: spatial scattering from unstable →stable zone.



- Avalanches: space-time localized large transport events.



- Nonlocality, breakdown of gyroBohm transport scaling & breakdown of Ficks law.
- The "short fall problem": failure of G-K simulations to predict turbulence and transport in 'No Man's Land'
- Spreading into magnetic islands, impact on NTMs. [K. Ida 2018]
- **Most important: spreading effect on steady state profiles and confinement?**

Preview of the bottom line

- Spreading matters when profiles force strong intensity gradient.
- Particular interesting situations are :
    - L mode edge with edge localized source of intensity/ Turbulence invasion from SOL.
    - No Man's Land (NML) in H mode. [NML connects core to the pedestal]
- Spreading effect on most L mode profiles is weak.
- H mode profiles are strongly affected by turbulence spreading due strong intensity gradient in NML. Turbulence in NML is reduced, and so pedestal height and width increase in response to spreading.
- Spreading is actually good for H mode confinement.
- We argue that predictive models of pedestal structure must address NML turbulence spreading effects.

The Usual story

A simple nonlinear reaction diffusion model for turbulence intensity $I(x,t)$

$$\frac{\partial I}{\partial t} = f(I) + \boxed{\sigma \frac{\partial}{\partial x} I \frac{\partial I}{\partial x}} \leftarrow turb.\,spread.$$

- **Unistable**: Fisher Model
  $f(I) = \underbrace{\gamma I}_{L.\,growth} - \underbrace{\gamma_{NL} I^2}_{NL.\,damp.}$
  [TSH, PHD, ODG, XG, KI, SII, ...]
- <u>$\gamma(x)$ **is prescribed, i.e., frozen background profiles.**</u>
- **Gives space time evolution of an initial slug of turbulence. But more to the story than transient pulses.**
- **Ignored an important question: what is the effect of spreading on steady state plasma profiles?**

- **Bistable**: Subcritical turbulence spreading
  $f(I) = \gamma_1(x) I + \gamma_2 I^2 - \gamma_3(x) I^3$
- Inspired by hysteresis in I vs ∇T_e plot in LHD L-mode by Inagaki et al 2013.
- Threshold intensity $I > \alpha$, length scale $L > (I_0 - \alpha)^{-1/2}$
- Propagating solutions in stable zone. Stronger penetration than Fisher.(Invited talk by Robin Heinonen, this Friday)

Coupling spreading to profiles (New)

$$\frac{\partial I}{\partial t} = f(I) + \sigma \frac{\partial}{\partial x} I \frac{\partial I}{\partial x} + \underbrace{\delta(x-a)\frac{I_0}{\tau}}_{edge\ source}$$

$$\frac{\partial P}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\alpha_P I}{1+\epsilon V_E'^2} + D_{cP}\right)\frac{\partial P}{\partial x} + \phi_p$$

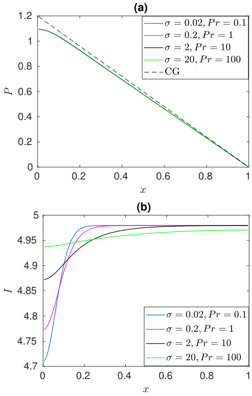
$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\alpha_n I}{1+\epsilon V_E'^2} + D_{cn}\right)\frac{\partial n}{\partial x} + \phi_n$$

- From radia force balance $V_E' = -\frac{1}{eBn^2}\frac{dp}{dx}\frac{dn}{dx}$
- Pressure source is core localized $\phi_p = \phi_{0p} e^{-w_p x^2}$
- Particle source is edge localized $\phi_n = \phi_{0n} e^{-w_n (x-x_0)^2}$
- Spreading effect is studied by varying σ

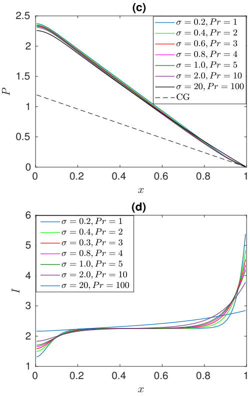
- L mode: $f(I) = \chi\left[\mu I + 2\beta I^2 - I^3\right]$; $\mu = \left(\frac{\partial P}{\partial x}\right)^2 - \mu_c^2$, w/o transport bifurcation→ 2-field (I & P) model
- H mode: $f(I) = \chi\left[\left(\left|\frac{\partial p}{\partial x}\right| - \mu_c\right)\Theta\left(\left|\frac{\partial p}{\partial x}\right| - \mu_c\right) - \lambda V_E'^2\right] I - \beta I^2$, w/ transport bifurcation→3-field (I,P & n) model

Spreading effects in L mode

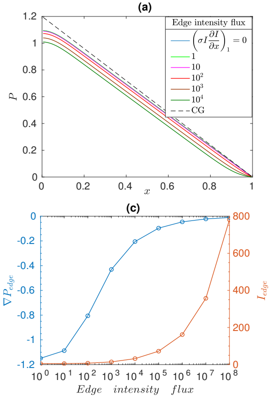
w/o edge source $I_0 = 0$



w/ edge source $I_0 \neq 0$

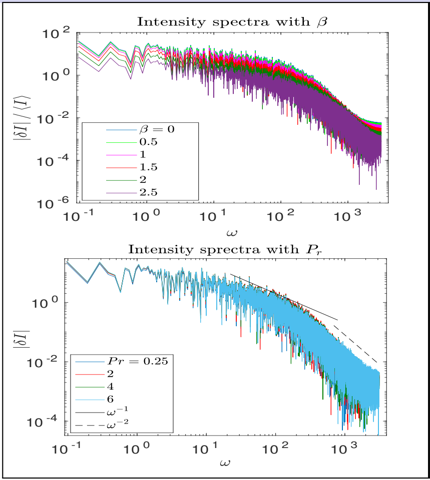


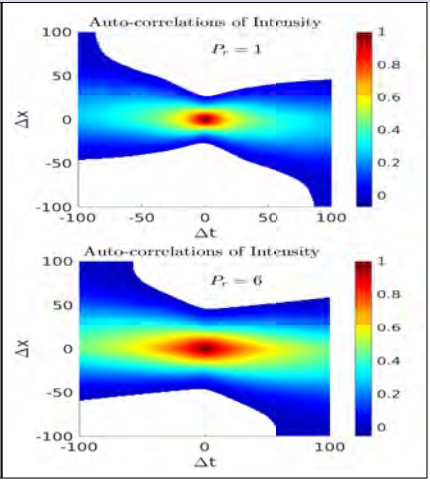
SOL invasion $I'|_1 \neq 0$



- Spreading effect is usually **weak** in L mode without edge sources/ SOL invasion.
- With edge sources: Both I_{edge} and ∇I_{edge} increases $\rightarrow \nabla P_{edge}$ softens.
- With σ : Both I_{edge} and ∇I_{edge} decreases $\rightarrow \nabla P_{edge}$ steepens

Interaction of spreading and avalanching



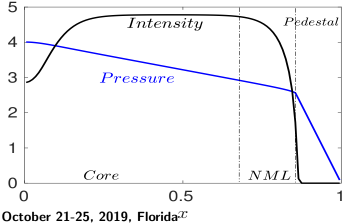


- Avalanche distributions are weakly affected by spreading.
- In-out velocity asymmetry increases with $P_r (= \frac{\sigma}{\alpha})$.
- Correlation length and time increases with P_r.

Profile issues in H mode

What are the effects of spreading on the H mode profile?

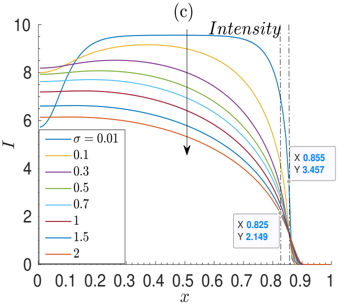
- Conventional wisdom: Pedestal height and width impact global confinement. The limiting stable height and width are believed to be set by P-B mode.
- At pedestal top: pressure gradient changes rapidly while flux continuous.
- Sharp variation in turbulence intensity across pedestal "corner" !
- Strong intensity gradient in NML needed to maintain flux continuity.
- Strong intensity near top of pedestal $\rightarrow$ pedestal performance?

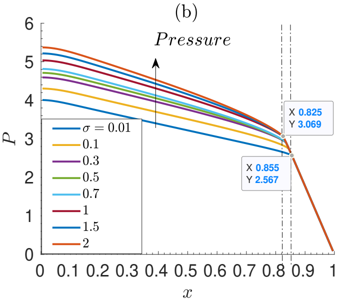


- Spreading affect profile and profile is related to P-B stability.
- How spreading affect onset of P-B?

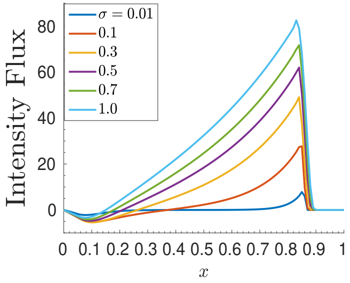
H mode results I

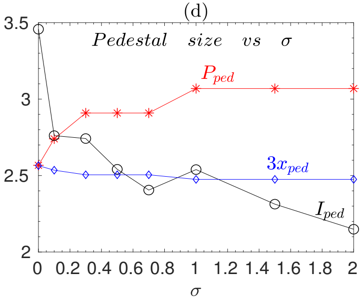
- Turbulence intensity is strongest in NML, when spreading is weakest.
- Intensity flux is radially outward in NML.
- Outward spreading from NML→Pedestal height increases and inward spreading in core decreases with σ.
- Spreading→Decrease of intensity in NML→ increase pedestal height and width.





- Turbulence spreads from NML$\rightarrow$ pedestal, where it is killed by strong $E \times B$ shear. Pedestal works as a sink of turbulence spreading from NML.
- Pedestal height grows with reduction of turbulence in NML.
- Width and height of pressure pedestal increase.





Effect of toroidal rotation shear (V'_ϕ) at NML

- Shear due to toroidal rotation added to diamagnetic shear at NML elevates the pedestal by reducing turbulence at NML !
- This appears consistent with wide pedestal QH mode transition during torque ramp down in DIII-D !

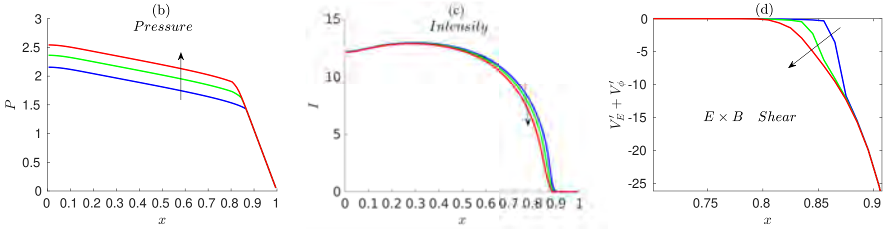


Figure: Radial profiles with $V'_\phi = V'_{\phi 0}\left[\Theta\left(x-0.8\right)-\Theta\left(x-0.86\right)\right]$ where $V'_{\phi 0} = 0, -1, -2$

Conclusions and Discussions

- Focus: Profiles.
- Spreading affect on profiles in L mode weak.
- Avalanche distributions are weakly affected.
- H mode profiles are strongly affected by turbulence spreading, due to naturally strong intensity gradient at interface connecting barrier and core. Turbulence in NML is reduced, and pedestal height and width increase in response to spreading.
- So spreading is good for H mode confinement.
- Hard to directly test results in G-K simulations and experiments, as there is no external knob to controll spreading.

  $$\boldsymbol{E \times B\, Non\, lin. \rightarrow Non\, lin.\, Saturation + Spread.}$$

  Scatterings in k-space and x-space are combined.
- Following transient response of pedestal after ITB collapse may elucidate spreading effect on pedestal height and width.
- These results suggest that predictive models of pedestal structure must address NML turbulence spreading effects.

Future work: CTRW model of spreading

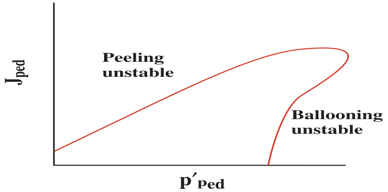
- Fokker Planck assumes finite drift and variance, time steps fixed. (Gaussian step size pdf p)
- Fluctuations pdf are often non-Gaussian with fat tails i.e., variance $\rightarrow \infty$.
- In CTRW times steps evolves as the walker position does. (waiting time pdf ψ)
- One can construct a **reaction-transport** equation for separable joint pdf $\xi(x-x', x'; t-t', t) = p(x-x', x'; t)\psi(x'; t-t')$

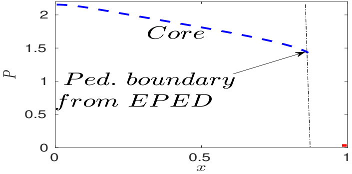
$$\begin{aligned}\frac{\partial I(x,t)}{\partial t} &= f(I) + \int_0^t dt' \int dx' \phi(x'; t-t') p(x-x', x'; t) I(x', t') \\ &\quad - \int_0^t dt' \phi(x; t-t') I(x, t')\end{aligned}$$

- Laplace transforms of the memory function ϕ the waiting time pdf ψ are related as $\phi(x; s) = s\psi(x,s)\left[1-\psi(x,s)\right]^{-1}$

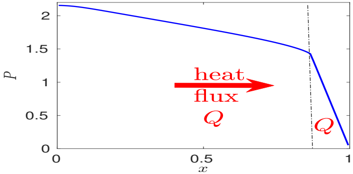
Back up slides

Boundary Condition vs **Flux matching**





- Pedestal parameters from EPED → BCs in GK codes for core turbulence simulation.
- But no spreading in EPED !



- Flux is continuous at pedestal top.
- Flux continuity takes care of turbulence spreading and vice-versa.
- Flux continuity is more accurate than fixing BC for core simulation with EPED.