Theory of Cross-Phase Evolution and its Impact on ELM Dynamics

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2014 US-TTF

A <u>Different</u> Look at ELM Dynamics → Thoughts on Selected Issues

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Collaborators

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  on cross phase correlation, anomalous dissipation

- T. Rhee[3], J.M. Kwon[3], W.W. Xiao[3,4]

  on reduced models

- R. Singh[3]

  on anomalous dissipation

1) Peking University
2) LLNL
3) NFRI
4) UCSD

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- Utilized materials from APS Review by Tony Leonard

Caveat Emptor

- Not a professional ELM-ologist
- Perspective is theoretical, and focus is on issues in understanding dynamics
- Perspective is that of a transport theorist
- Aim is to distill elements critical to model building
- Unresolved issues are discussed
- Not a review!

N.B. : Many ideas discussed here are contrary to ‘conventional wisdom’ of ELM-ology

↔ Locale has a history of struggle against group think…

Outline

- The conventional wisdom of ELMs
  - Motivation
  - Mechanism
- Some issues in ELM dynamics
  - How do bursts occur?
  - Mechanism of anomalous dissipation?
  - Assembling the 'big picture' → sources and transport effects?

Outline, cont'd

- Recent progress on some issues:

  i) cross phase coherence and the origin of bursts

  ii) phase coherence as leverage for ELM mitigation

  iii) hyper-resistivity: single scale or multi-scale!?

  iv) a reduced model of the big picture → importance of flux-drive

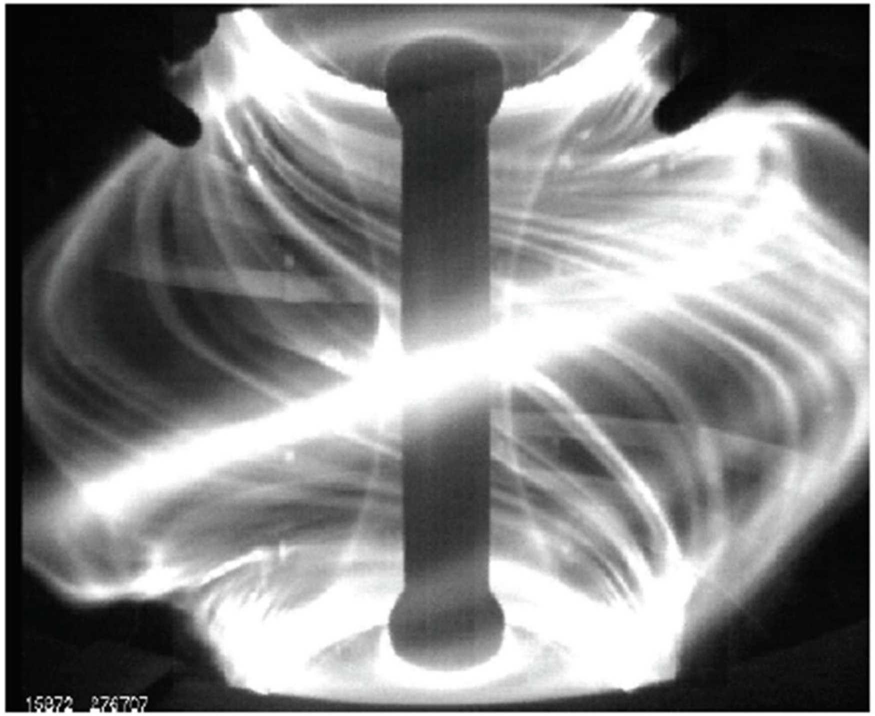
- Conclusions – at this point

- Discussion: where should we go next?

Terra Firma: Conventional Wisdom of ELMs

- ELMs are ~ quasi-periodic relaxation events occurring at edge pedestal in H-mode plasma
- ELMs
  - Limit edge pedestal –
  - Expel impurities +
  - Damage PFC –
- ELMs → a serious concern for ITER
  - $\Delta W_{ELM} \sim 20\% \, W_{ped} \sim 20$ MJ
  - $W_{ELM} / A \sim 10 \times$ limit for melting
  - $\tau_{rise} \sim 200 \, \mu sec$

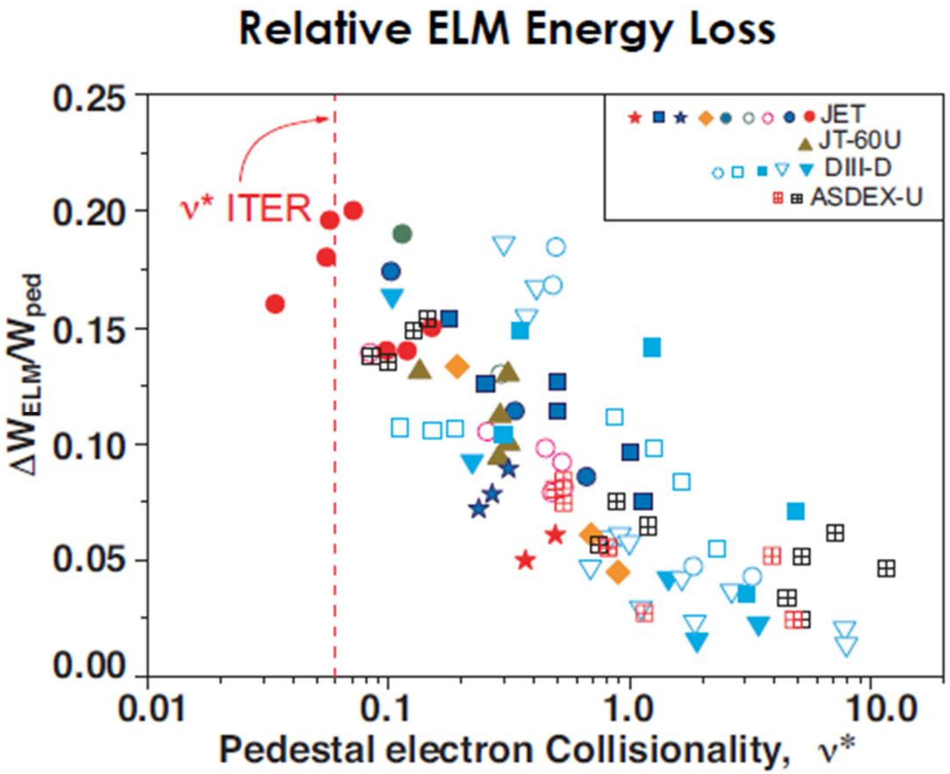
MAST



Terra Firma: Conventional Wisdom of ELMs

- ELM Types
  - I, II: ω_{ELM} ↑ as P ↑, greatest concern, related to ideal stability
  - III: ω_{ELM} ↓ as P ↑, closer to P_{Th}, unknown → resistive ??

- Physics
  - Type I, II ELM onset → ideal stability limit
  - i.e. peeling + ballooning



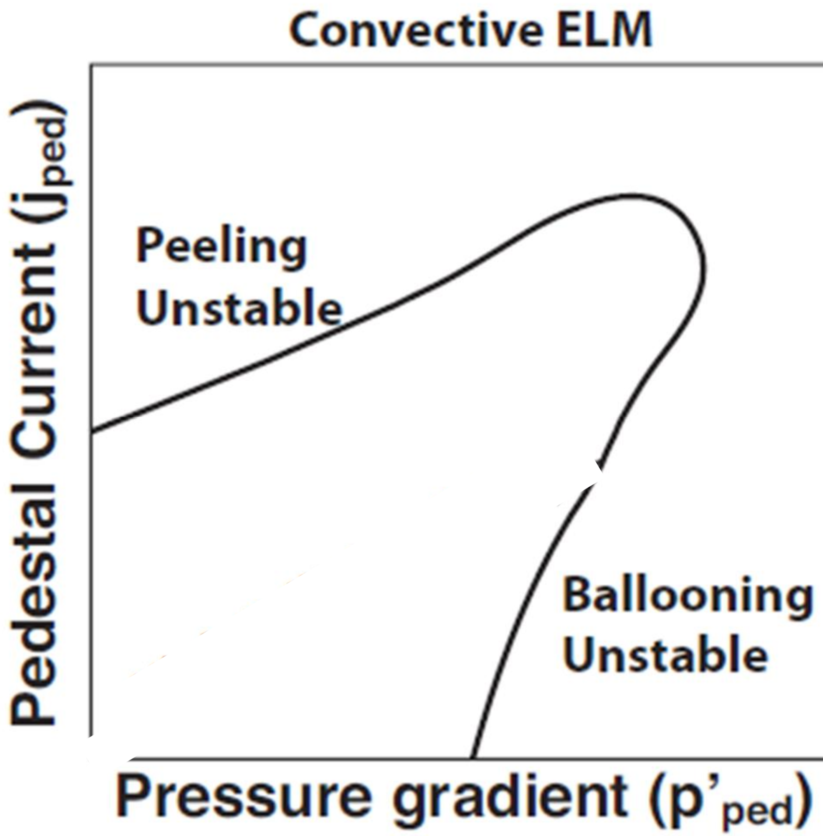
[A. Loarte, *Plasma Phys. Control. Fusion* 45 1549 (2003)]

Peeling + ballooning	mode	Edge kink / Curvature vs bending

δW + Pedestal, geometry

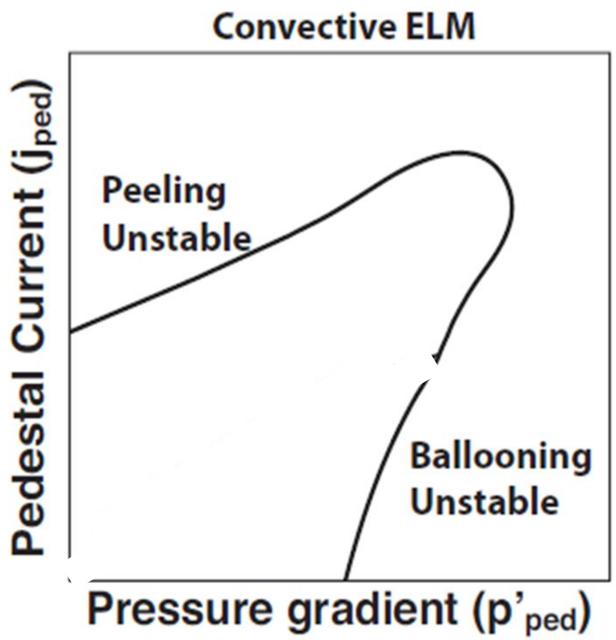
Terra Firma: Conventional Wisdom of ELMs

- Edge pressure gradient is ultimate energy source
  - $\delta W_P \sim \frac{1}{R_c}\frac{dP}{dr}\xi^2$ vs δW_{LB}
    $\leftrightarrow$ ballooning
  - $J_{bootstrap} \sim \frac{1}{B_\theta(1+0.9\sqrt{\nu_*})}\frac{dP}{dr}$
    $\leftrightarrow$ peeling



Terra Firma: Conventional Wisdom of ELMs

- Some relation of ELM drive character to collisionality is observed
  - Low collisionality → peeling ~ more conductive
  - High collisionality → ballooning ~ more convective
- Pedestal perturbation structure resembles P-B eigen-function structure
- Many basic features of ELMs consistent with ideal MHD peeling-ballooning theory



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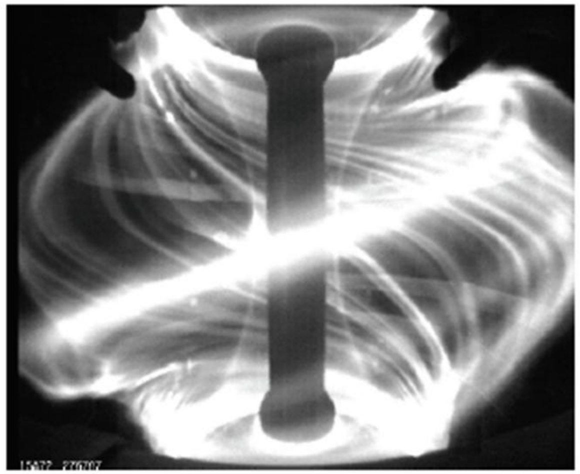


Some Physics Questions

- What IS the ELM?
  - ELMs single helicity or multi-helicity phenomena?

    Relaxation event ↔ pedestal avalanche?
  - How and why do actual bursts occur?

    Why doesn't turbulence force $\nabla P \sim \nabla P_{crt}$ oscillations?
  - Pedestal turbulence develops during ELM. Thus, how do P-B modes interact with turbulence? – either ambient or as part of MH interaction?
  - Does, or even should, the linear instability boundary define the actual ELM threshold?

Some Physics Questions

- Irreversibility?
  - Peeling-Ballooning are ideal modes. What is origin of irreversibility? How does fast reconnection occur?
  - If hyper-resistivity is the answer (Xu et al, 2010), what is its origin – ambient micro-turbulence or P-B's themselves? Can P-B modes drive the requisite hyper-resistivity?
  - What is the relation between hyper-resistivity, reconnection and heat transport, especially for 'conductive' ELMs?

Some Physics Questions

- How do the pieces fit together?
  - Do ELM events emerge from a model which evolves profiles with pedestal turbulence?
  - What profiles are actually achieved at the point of ELMs?
  - What is the minimal model in which ELMs emerge?
  - What are the necessary ingredients in a full model?
- How exploit dynamical insight for ELM mitigation?

I) Basic Notions of ELMs:

ELM Bursts and Thresholds as

Consequence of Stochastic Phase Dynamics

→ See P.W. Xi, X.-Q. Xu, P.D.; PRL 2014
P.W. Xi, X.-Q. Xu, P.D.; PoP 2014 in press

Simulation model and equilibrium in BOUT++

- **3-field model for nonlinear ELM simulations**
  - ✓ **Including essential physics for the onset of ELMs**

Peeling-ballooning instability
Resistivity
Hyper-resistivity
Ion diamagnetic effect

$$\frac{d\varpi}{dt} = B\nabla_{\|}J_{\|} + 2\mathbf{b}_0 \times \boldsymbol{\kappa} \cdot \nabla\widetilde{P} + \mu_{i,\|}\partial_{\|}^2\varpi$$

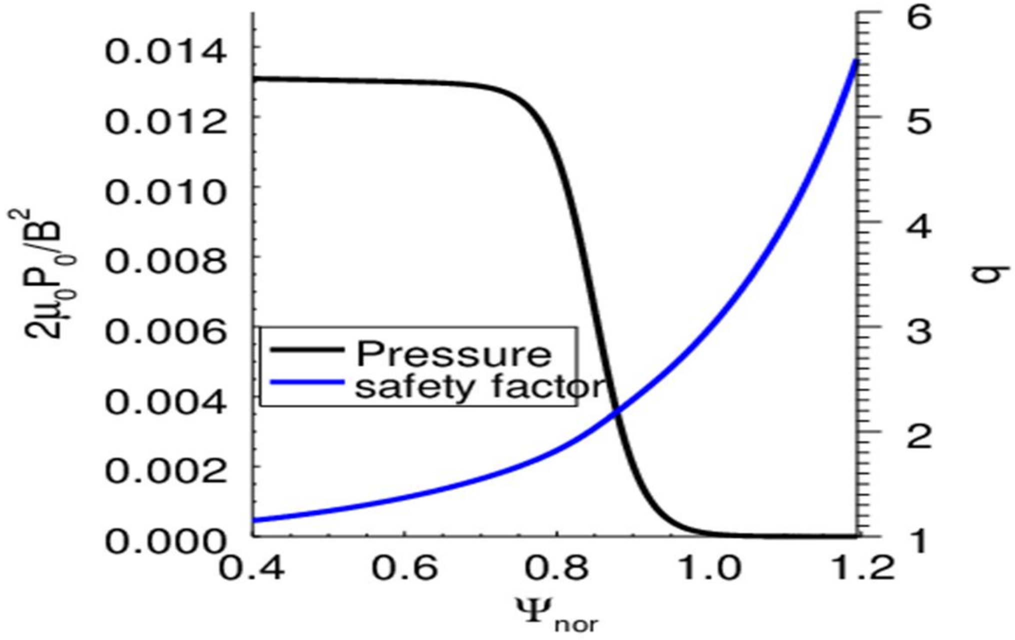
$$\frac{d\widetilde{P}}{dt} + \mathbf{V}_E \cdot \nabla P_0 = 0$$

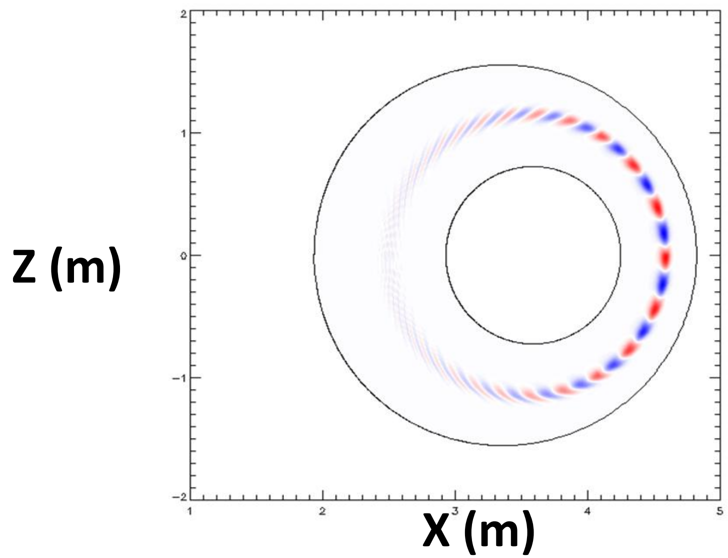
hyper resistivity

$$\frac{\partial A_{\|}}{\partial t} + \partial_{\|}\phi_T = \frac{\eta}{\mu_0}\nabla_{\perp}^2 A_{\|} - \frac{\eta_H}{\mu_0}\nabla_{\perp}^4 A_{\|}$$

$$\varpi = \frac{m_i n_0}{B}\left(\nabla_{\perp}^2\phi + \frac{1}{en_0}\nabla_{\perp}^2\widetilde{P}_i\right)$$

$$d/dt = \partial/\partial t + \mathbf{V}_{ET}\cdot\nabla,\ \mathbf{V}_{ET} = \frac{1}{B}\mathbf{b}_0 \times \nabla\phi_T,\ \phi_T = \phi_0 + \phi,\ \nabla_{\|}f = B\partial_{\|}\frac{f}{B},\ \partial_{\|} = \partial_{\|}^0 + \delta\mathbf{b}\cdot\nabla,\ \delta\mathbf{b} = \frac{1}{B}\nabla A_{\|} \times \mathbf{b}_0,\ J_{\|} = J_{\|0} + \widetilde{J}_{\|},\ \widetilde{J}_{\|} = -\nabla_{\perp}^2 A_{\|}/\mu_0$$



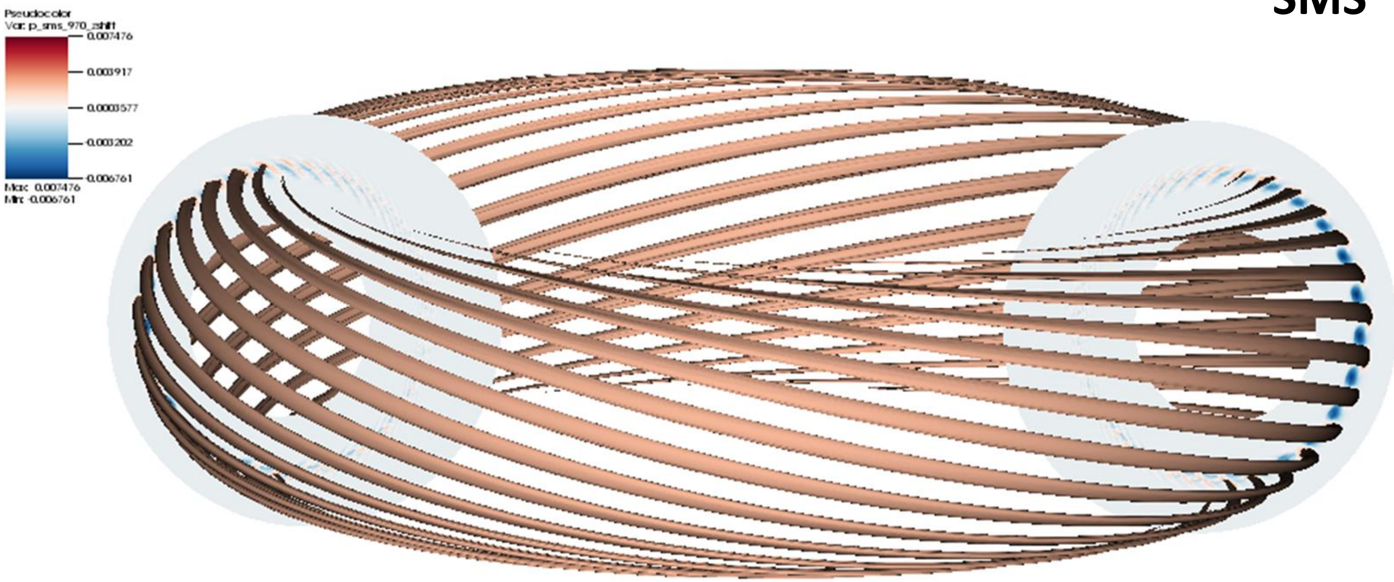


Comparison:

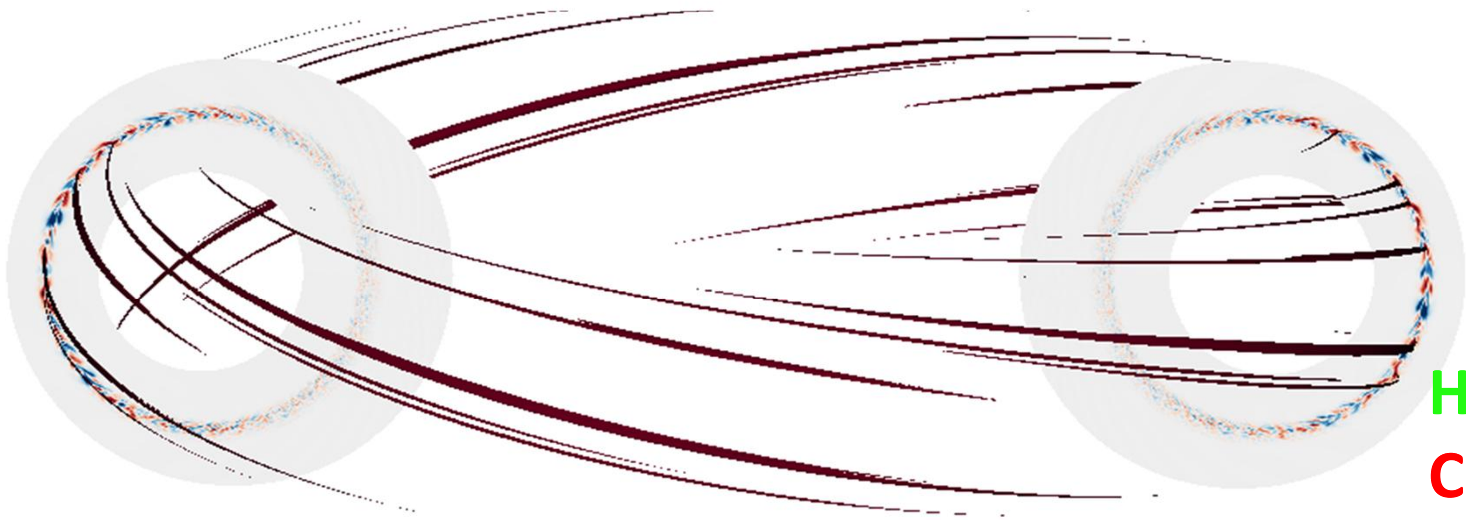
Single vs Multi-Mode Dynamics

3D structure of pressure perturbation: filaments– helical coherent perturbation with outward radial motion

SMS → Filaments



MMS → turbulence



Helical

Coherent

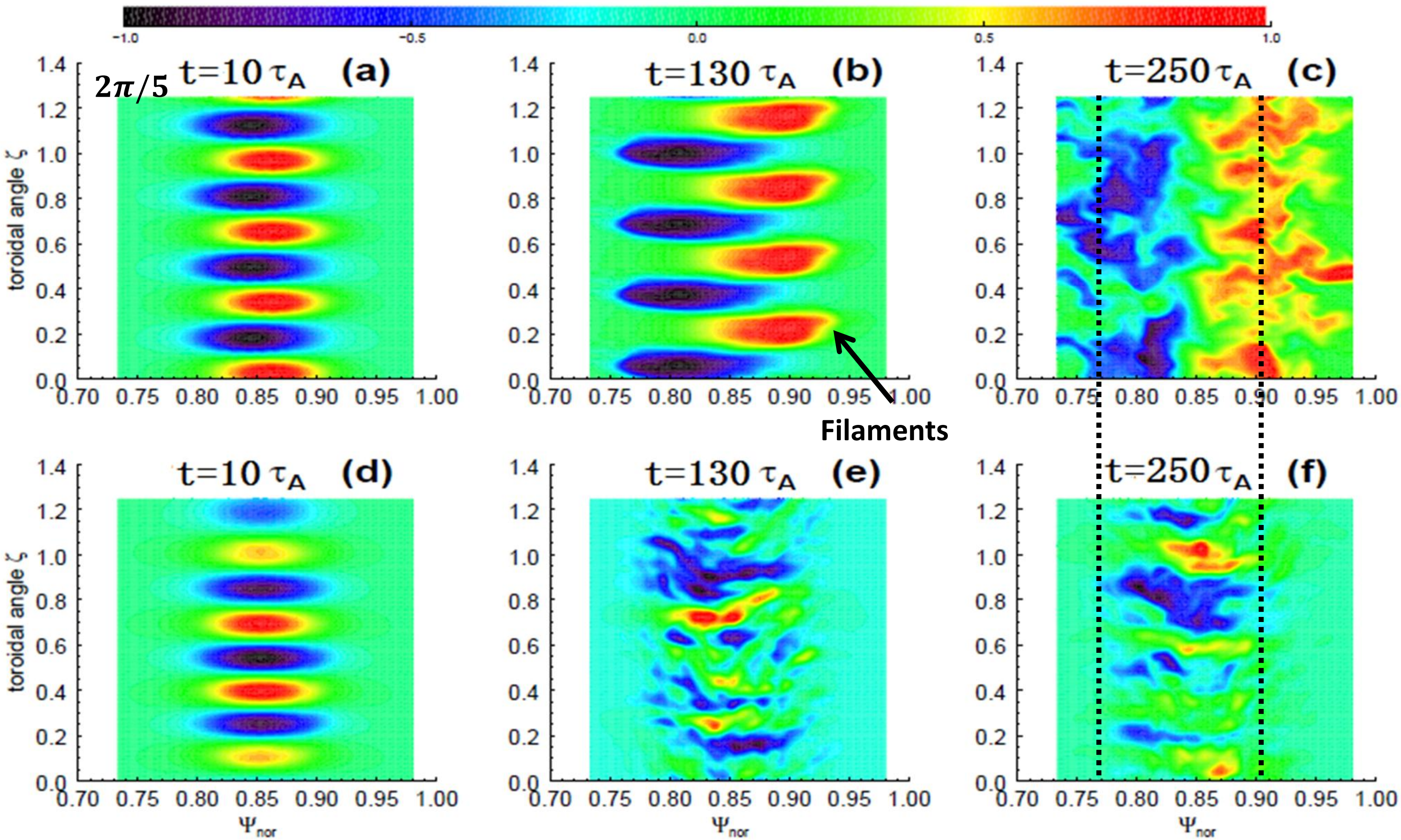
radial motion

Images generated with VisIt

Contrastive perturbation evolution (1/5 of the torus)

Single Mode

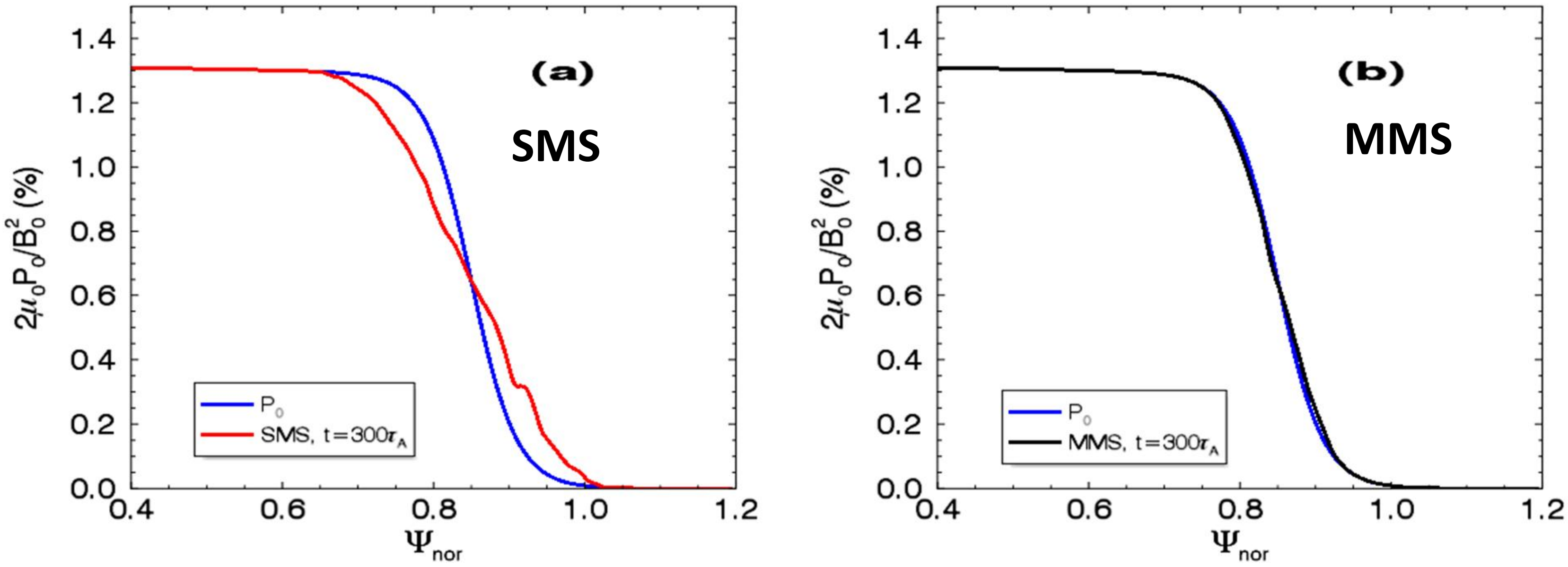
Multiple Mode

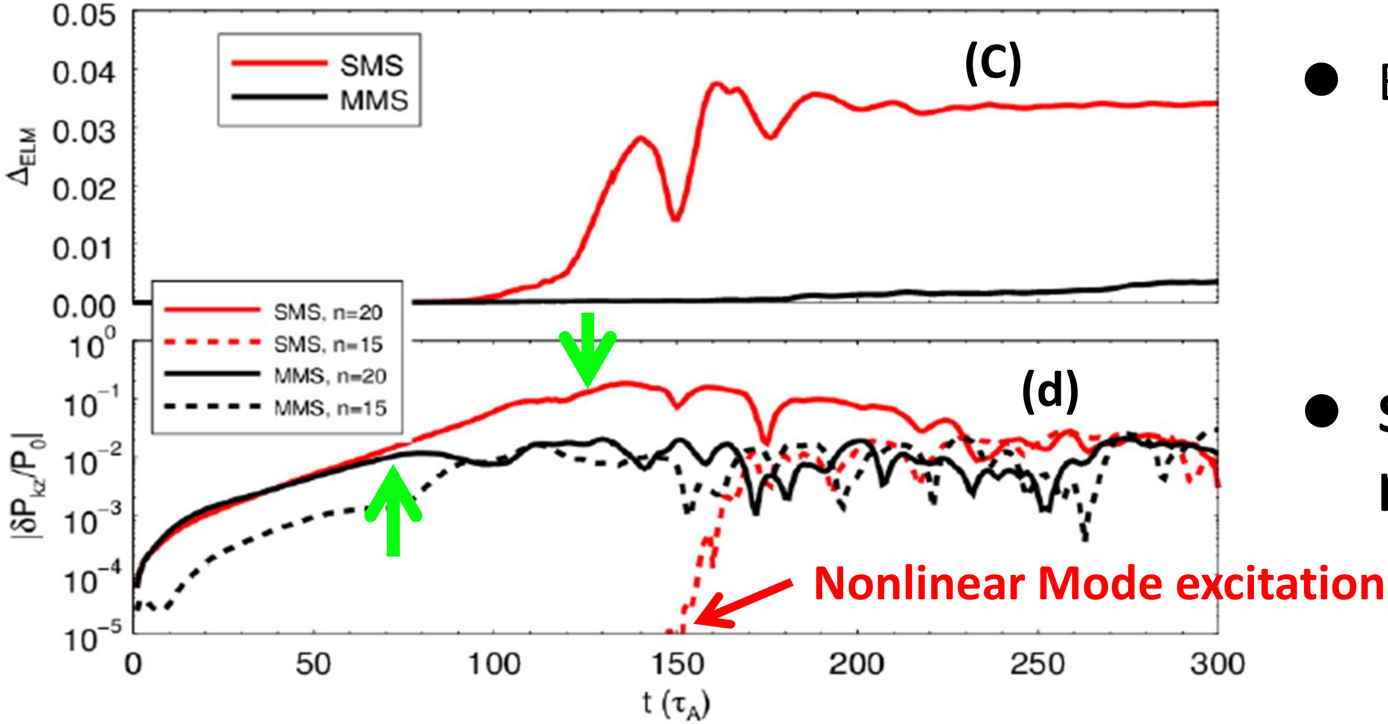


Linear phase **Early nonlinear phase** **Late nonlinear phase**

- **Single mode: Filamentary structure is generated by linear instability;**
- **Multiple modes: Linear mode structure is disrupted by nonlinear mode interaction and no filamentary structure appears**

Single mode: ELM crash || Multiple modes: P-B turbulence





- ELM size larger for SMS

$$\Delta_{ELM} = \frac{\Delta W_{ped}}{W_{ped}} = \frac{\int dx^3 (P_0 - \langle P \rangle_\zeta)}{\int dx^3 P_0}$$

- **SMS has longer duration linear phase than MMS**

Relative Phase (Cross Phase) Dynamics and Peeling-Ballooning Amplification

Peeling-Ballooning Perturbation Amplification is set by Coherence of Cross-Phase

i.e. schematic P.B. energy equation:

$$\frac{\partial}{\partial t}E_k = \langle\tilde{\phi}2\hat{b}_0\times\vec{k}\cdot\nabla\tilde{P}\rangle_{\vec{k}}$$

← $\sim\langle\tilde{v}_r\tilde{P}\rangle$ → energy release from $\nabla\langle P\rangle$ → quadratic

$$+\sum_{\vec{k}',\vec{k}''}\tau_{c\vec{k}}C(\vec{k}',\vec{k}'')E_{\vec{k}'}E_{\vec{k}''}-\sum_{\vec{k}'}\tau_{c\vec{k}+\vec{k}'}C(\vec{k}',\vec{k})E_{\vec{k}'}E_{\vec{k}}$$ - dissipation

↑ nonlinear mode-mode coupling ↑ → quartic

NL effects

- energy couplings to transfer energy (weak)
- response scattering to de-correlate $\tilde{\phi}$, $\tilde{P}$ → regulate drive

Growth Regulated by Phase Scattering

τ_c → phase coherence time

$\langle \tilde{v}_r \tilde{P} \rangle$ → net growth → intensity field → crash?

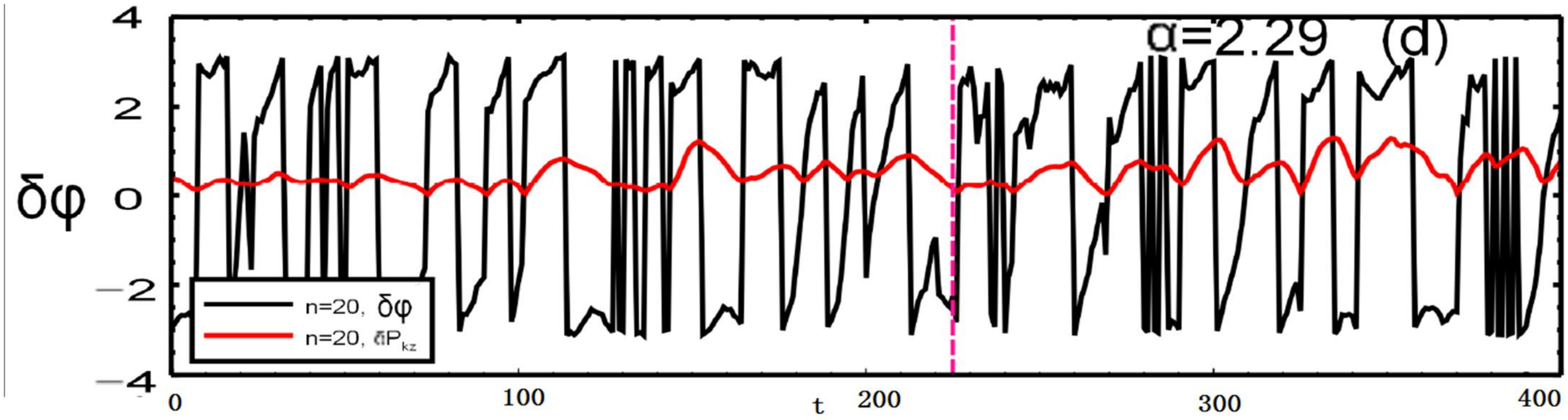
$\nabla P_o \xrightarrow{k} \tilde{P}$

↑ phase scattering

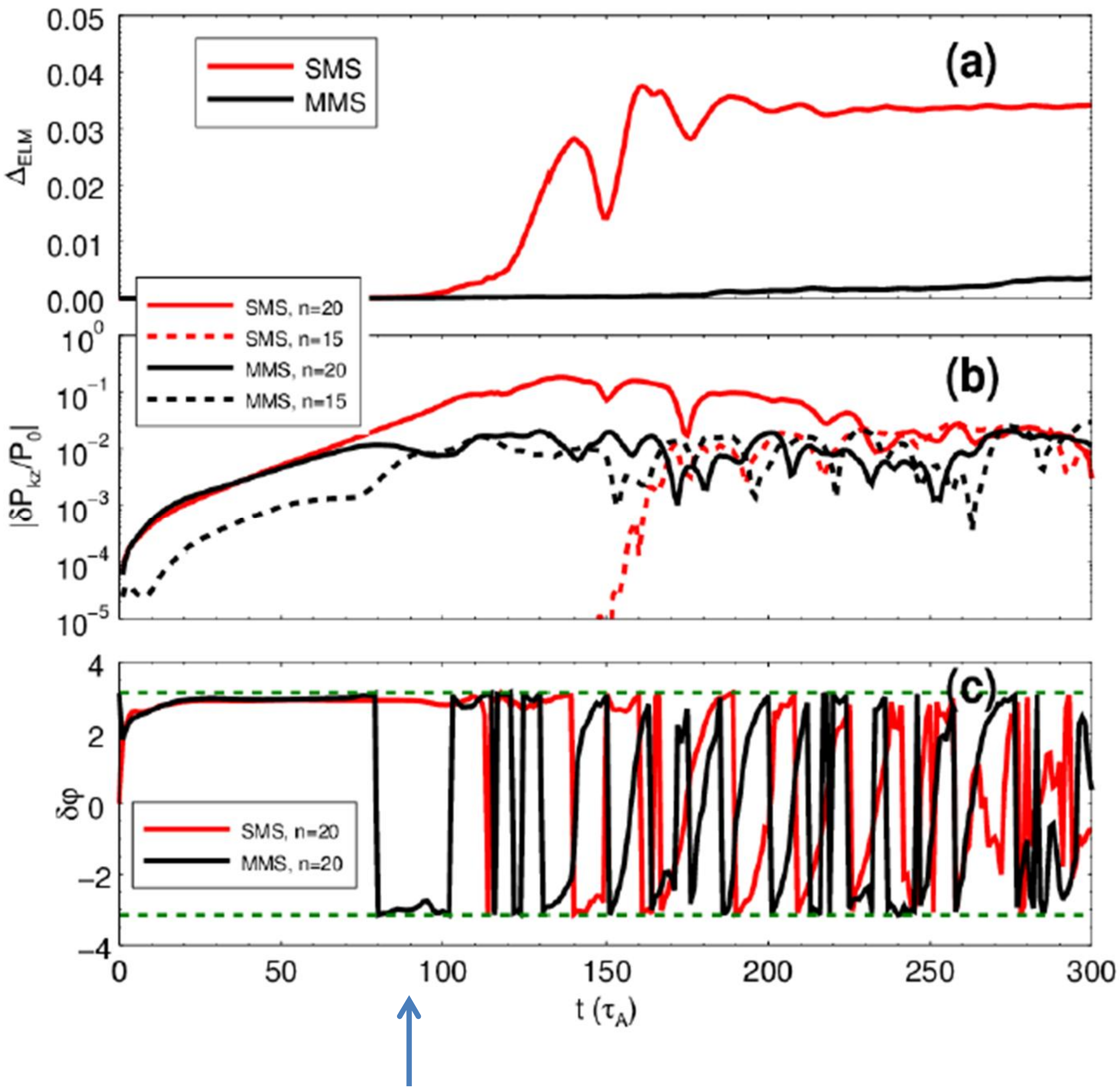
transfer → dissipation (weak)

Critical element: relative phase
$\delta\varphi = arg\ [\hat{p}_n\ /\ \hat{\phi}_n]$

Phase coherence time sets growth



Cross Phase Exhibits Rapid Variation in Multi-Mode Case



- Single mode case → coherent phase set by linear growth → rapid growth to 'burst'
- Multi-mode case → phase de-correlated by mode-mode scattering → slow growth to turbulent state

Key Quantity: Phase Correlation Time

- Ala' resonance broadening (Dupree '66):

$$\frac{\partial}{\partial t}\hat{P} + \tilde{v}\cdot\nabla\hat{P} + \langle v\rangle\cdot\nabla\hat{P} - D\nabla^2\hat{P} = -\tilde{v}_r\frac{d}{dr}\langle P\rangle$$

Nonlinear scattering — Linear streaming (i.e. shear flow) — Ambient diffusion

$$\hat{P} = Ae^{i\phi}$$

Relative phase ↔ cross-phase

Amplitude

$$\hat{v} = B$$

Velocity amplitude

➔ $$\partial_t\tilde{\phi} + \tilde{v}\cdot\nabla\tilde{\phi} + \langle v(r)\rangle\cdot\nabla\tilde{\phi} - D\nabla^2\tilde{\phi} - \frac{2D}{A}\nabla A\cdot\nabla\tilde{\phi} = 0$$

NL scattering — shearing

$$\partial_t A + \tilde{v}\cdot\nabla A + \langle v(r)\rangle\cdot\nabla A + D\left(\nabla\tilde{\phi}\right)^2 A - D\nabla^2 A = -B\frac{d}{dr}\langle P\rangle$$

Damping by phase fluctuations

Phase Correlation Time

- Stochastic advection:

$$\frac{1}{\tau_{ck}} = \vec{k} \cdot D_\phi \cdot \vec{k} + k^2 D$$

$$D_\phi = \sum_{k'} \tau_{ck'} |\tilde{v}'_{\perp k}|^2$$

- Stochastic advection + sheared flow:

$$\frac{1}{\tau_{ck}} \approx \left(k_\perp^2 (D_\phi + D) \langle v_\perp \rangle'^{\,2}\right)^{1/3}$$

➔ Coupling of radial scattering and Shearing shortens phase correlation

- Parallel conduction + diffusion:

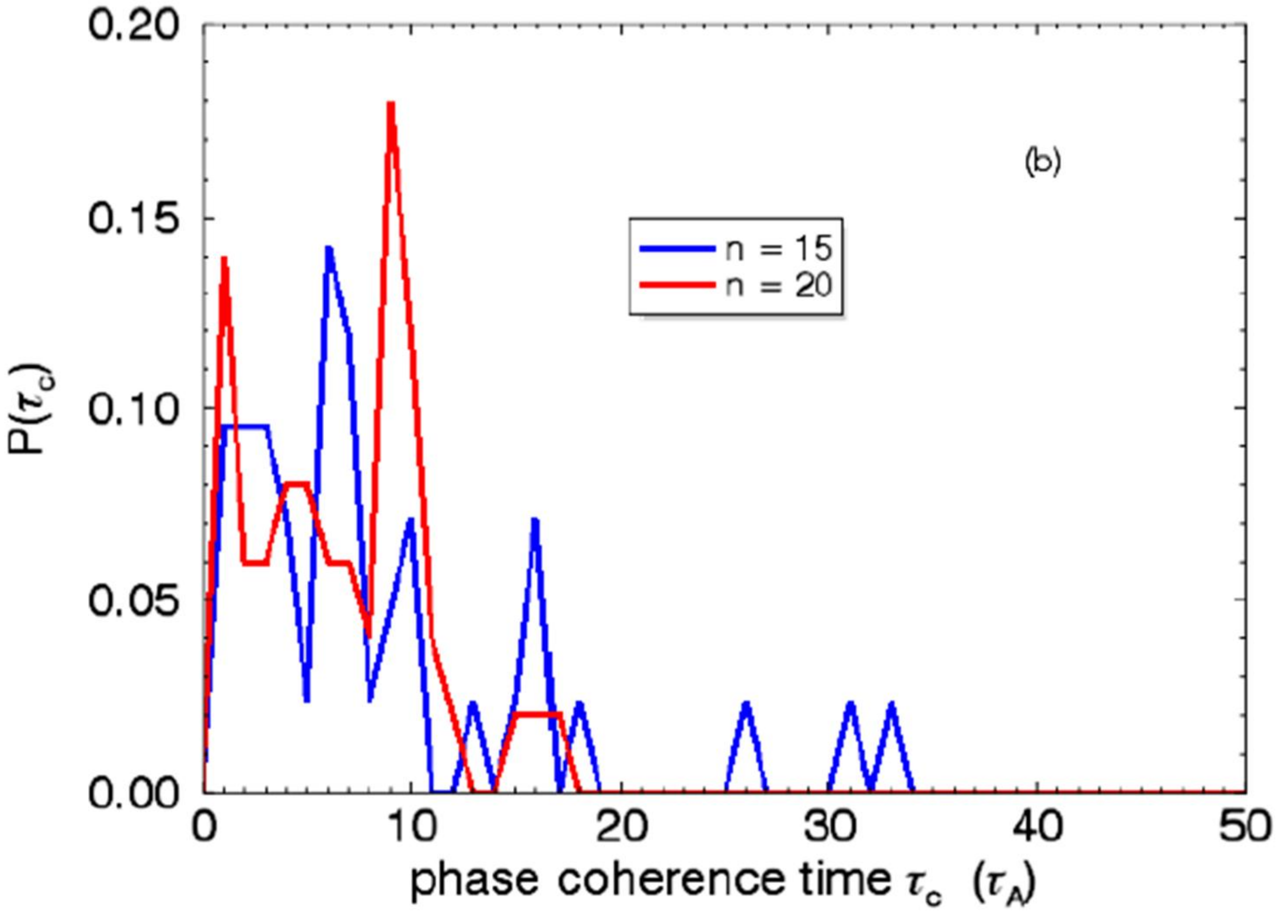
$$\frac{1}{\tau_{ck}} \approx \left[\frac{\hat{s}^2 k_\perp^2}{(Rq)^2}\, \chi_\parallel \left(D_\phi + D\right)\right]^{1/2}$$

➔ Coupling of radial diffusion and conduction shortens phase correlation

What is actually known about fluctuations in relative phase?

- For case of P.-B. turbulence, a broad PDF of phase correlation times is observed

pdf of τ_c



Implications for: i) Bursts vs Turbulence

ii) Threshold

Bursts, Thresholds

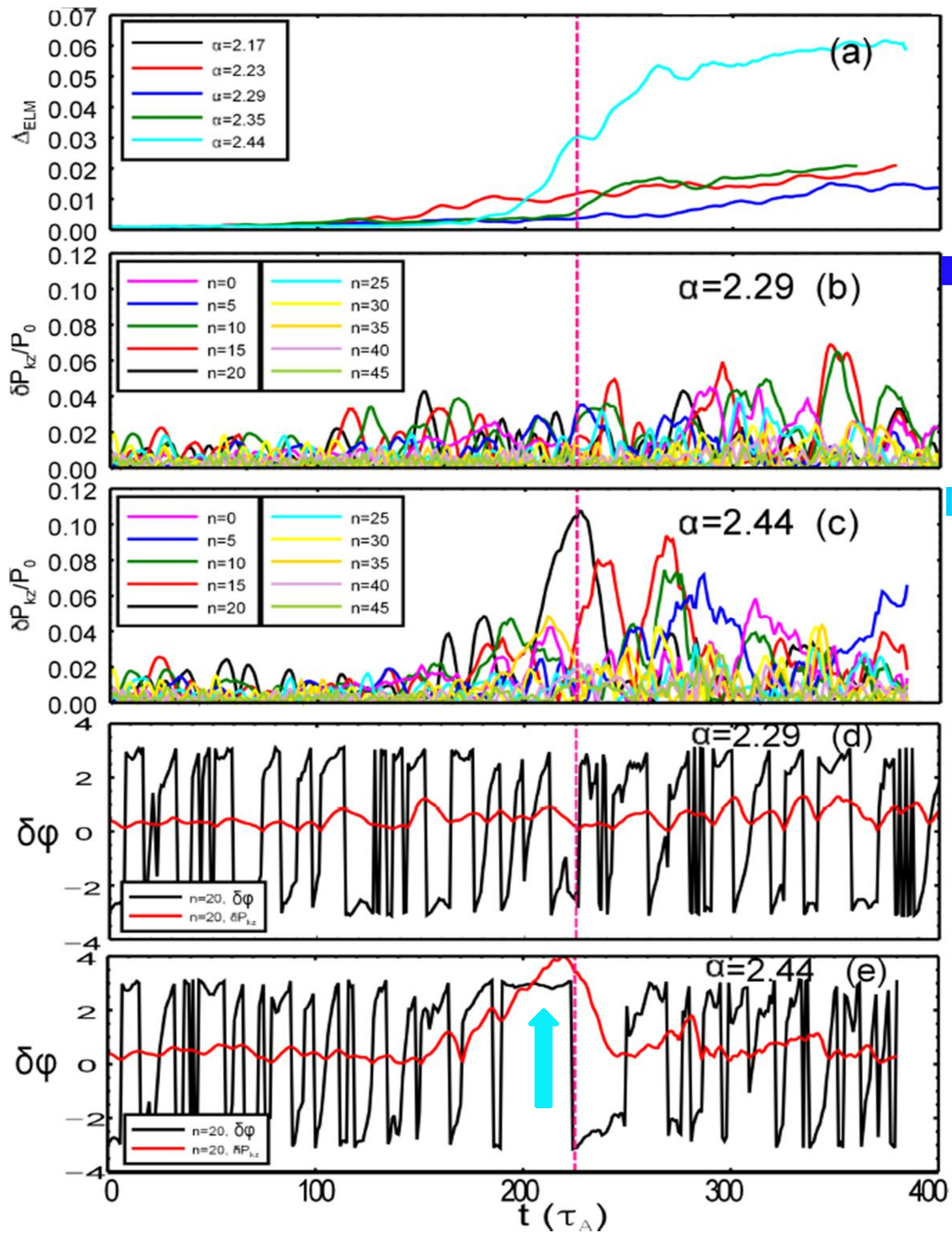
- P.-B. turbulence can scatter relative phase and so reduce/limit growth of P.-B. mode to large amplitude
- Relevant comparison is:

γ_k^L (linear growth) vs $\frac{1}{\tau_{ck}}$ (phase de-correlation rate)

- Key point: Phase scattering for mode $\vec{k}$ set by 'background modes $\vec{k}'$' i.e. other P.-B.'s or micro-turbulence

➔ is the background strong enough??

The shape of growth rate spectrum determines burst or turbulence

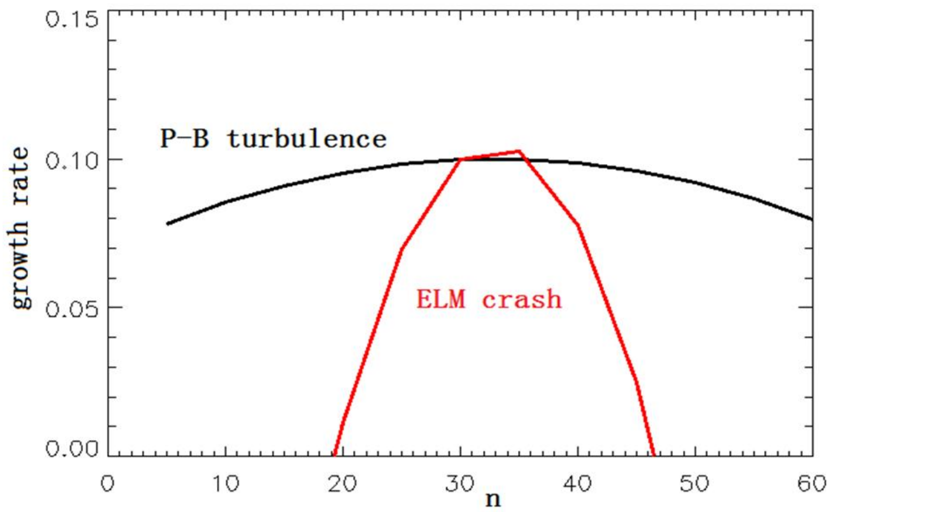


P-B turbulence

$$\gamma(n)\tau_c(n) < \ln 10$$

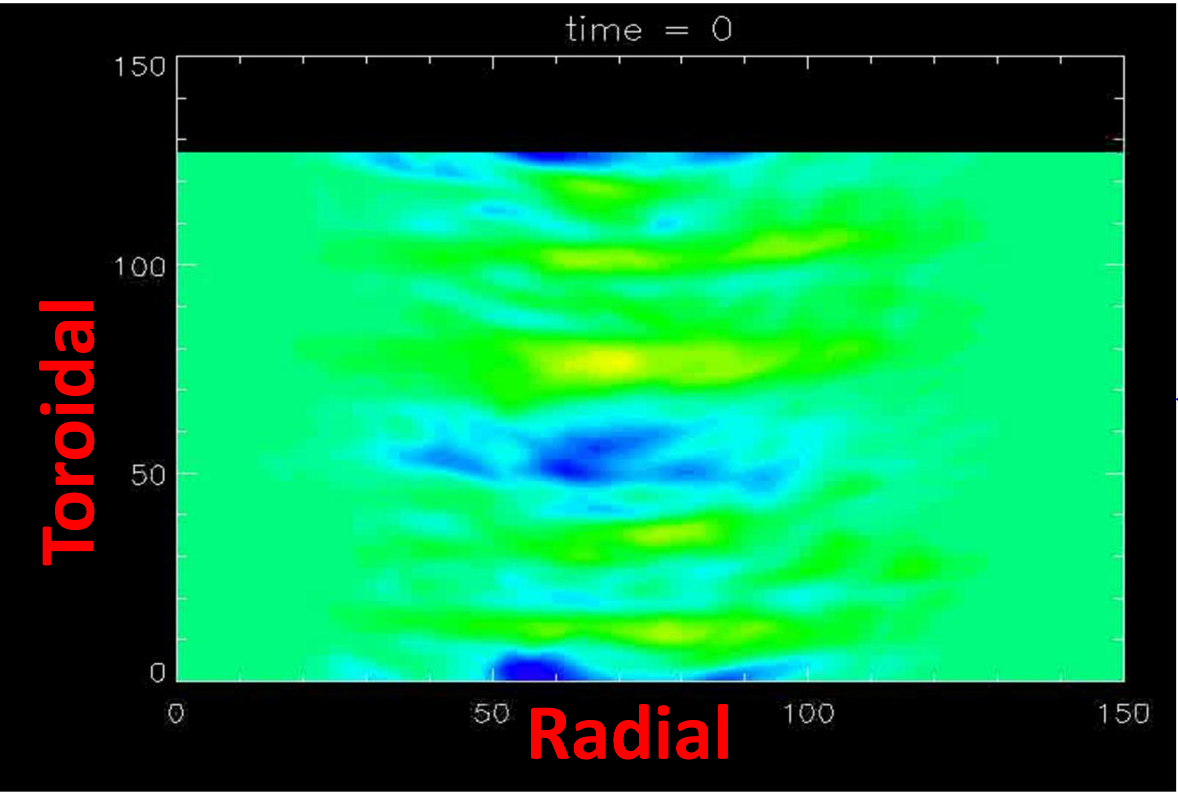
Isolated ELM crash

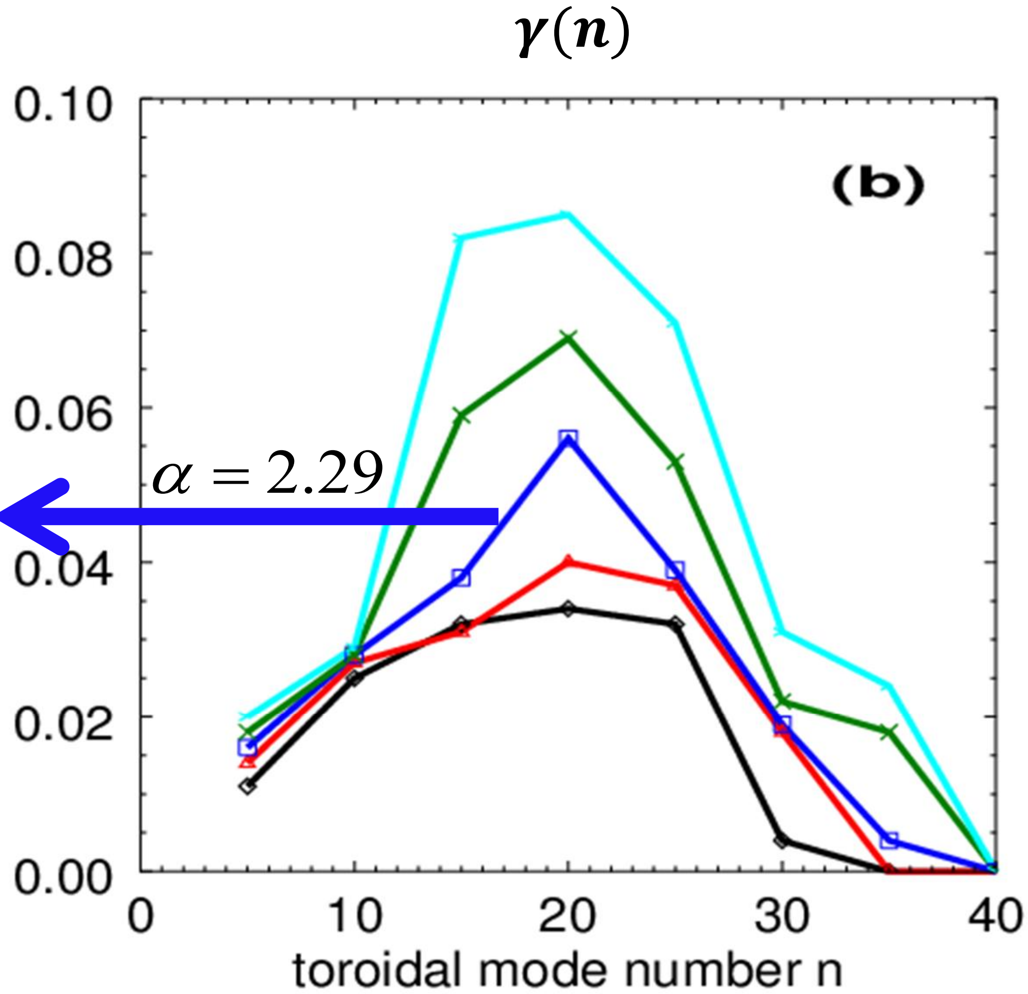
$$\begin{cases} \gamma(n)\tau_c(n) > \ln 10, n = n_{dom} \\ \gamma(n)\tau_c(n) < \ln 10, n \neq n_{dom} \end{cases}$$



So When Does it Crash?

Modest $\gamma(n)$ Peaking ➔ P.-B. turbulence

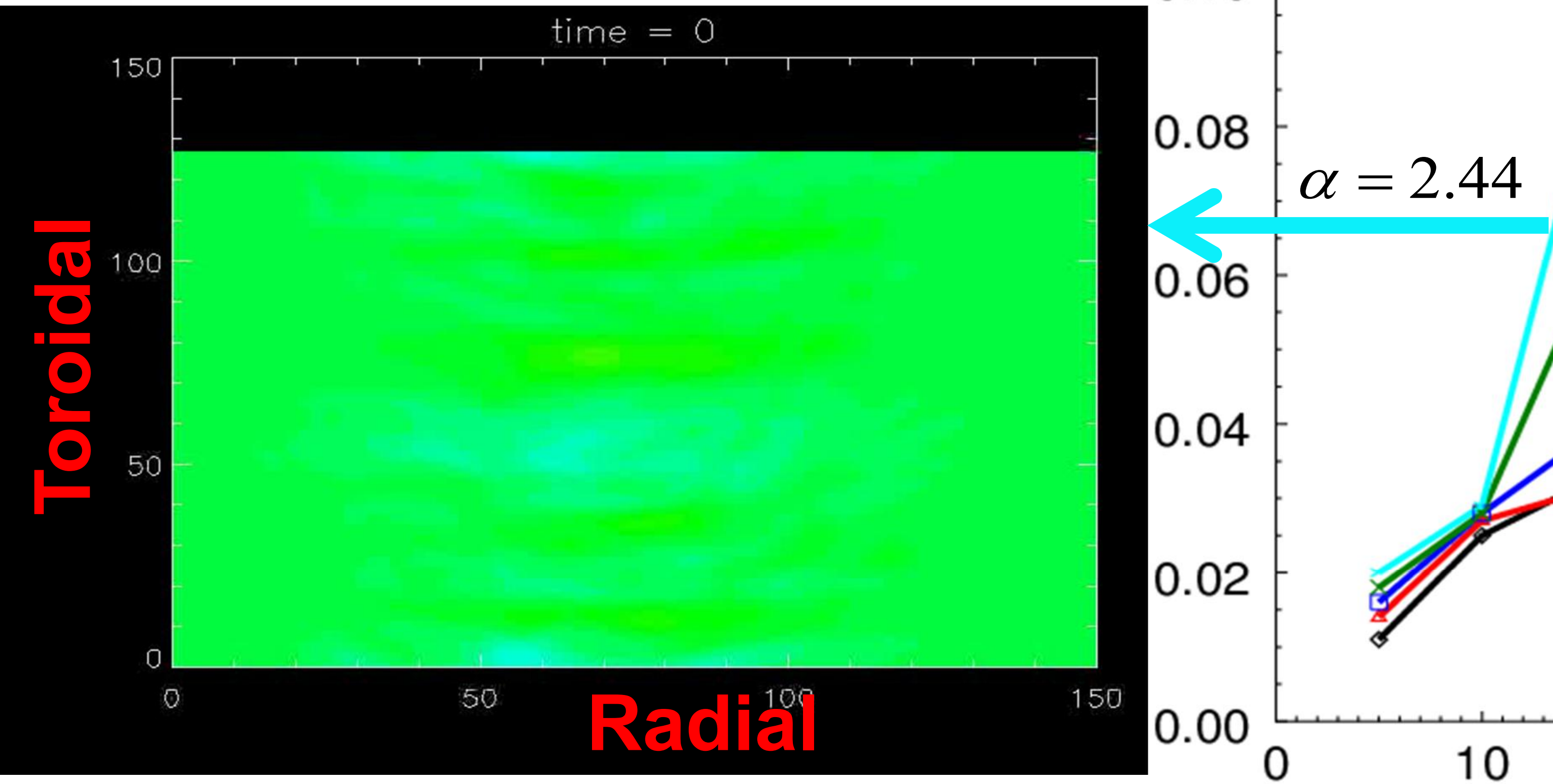


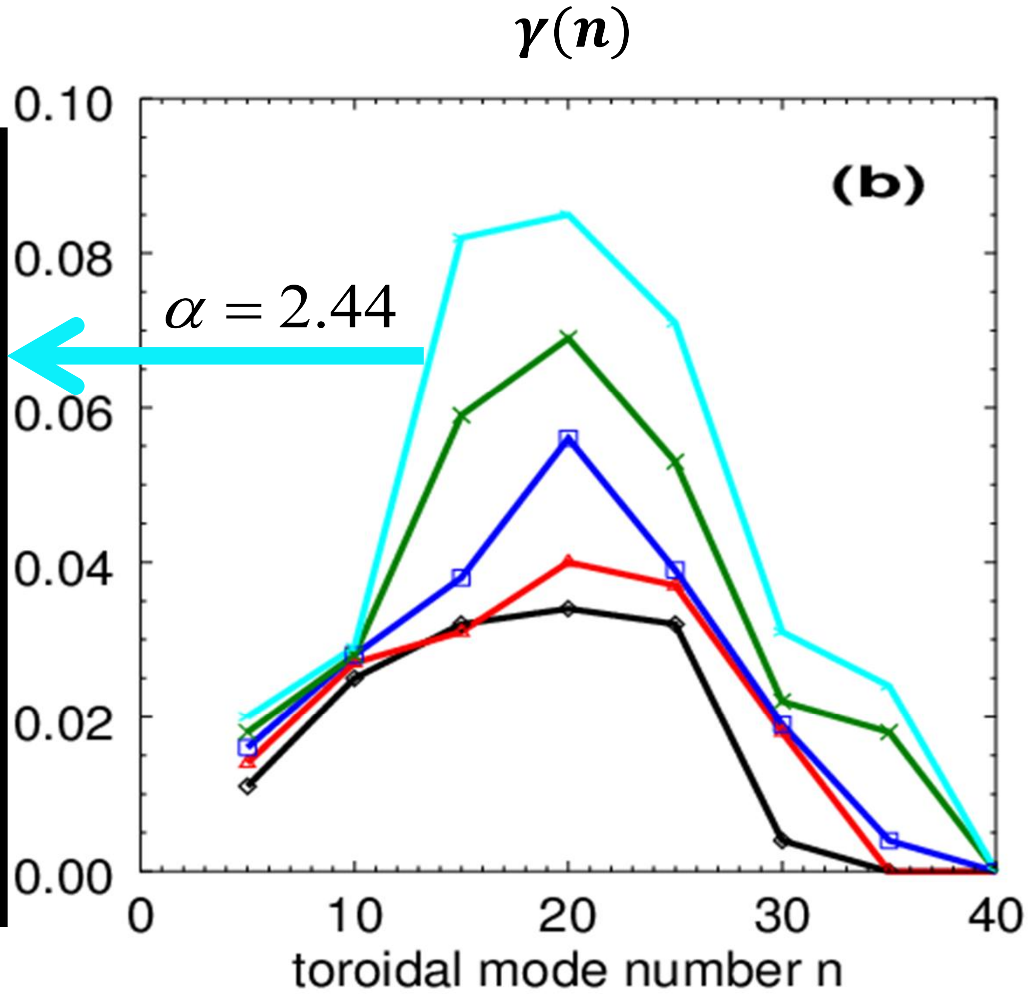


- Evolution of P-B turbulence
  - No filaments
  - Weak radial extent

$$\alpha = -2\mu_0 R P_0' q^2 / B^2$$

Stronger Peaking $\gamma(n)$ ➔ ELM Crash



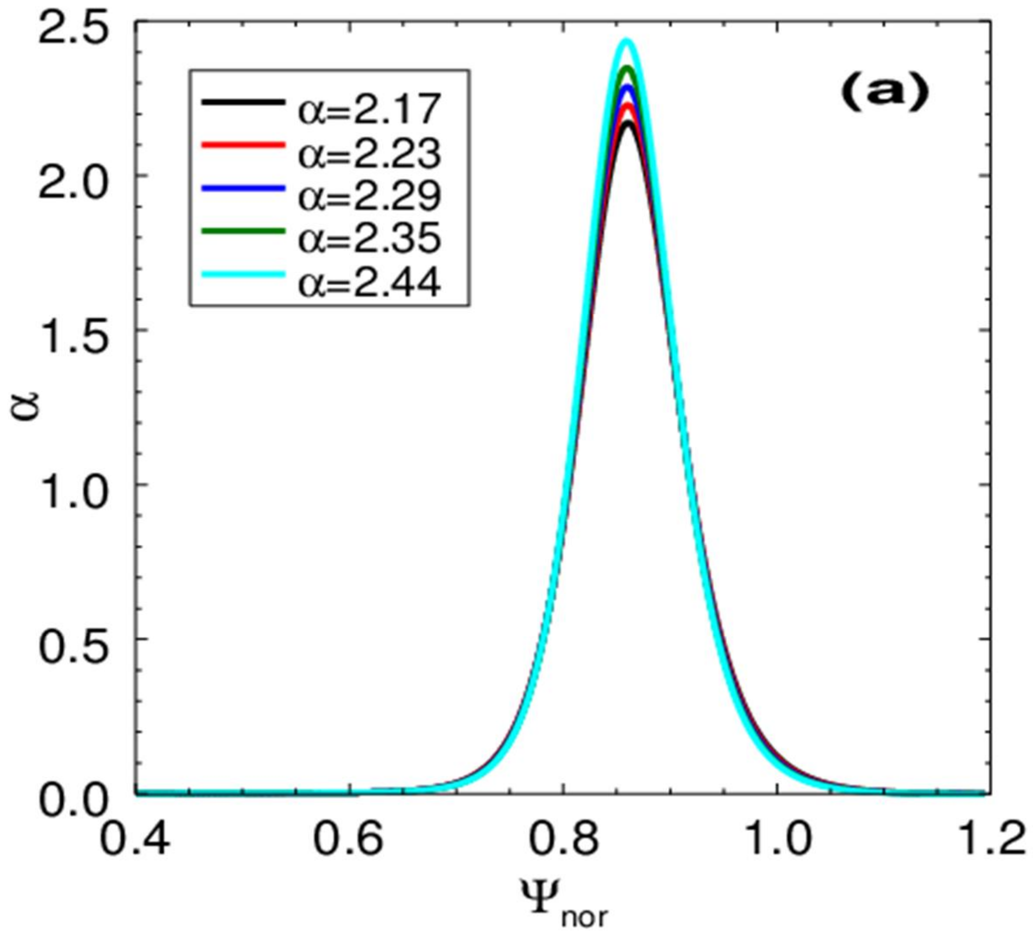


- ELM crash is triggered
- Wide radial extension

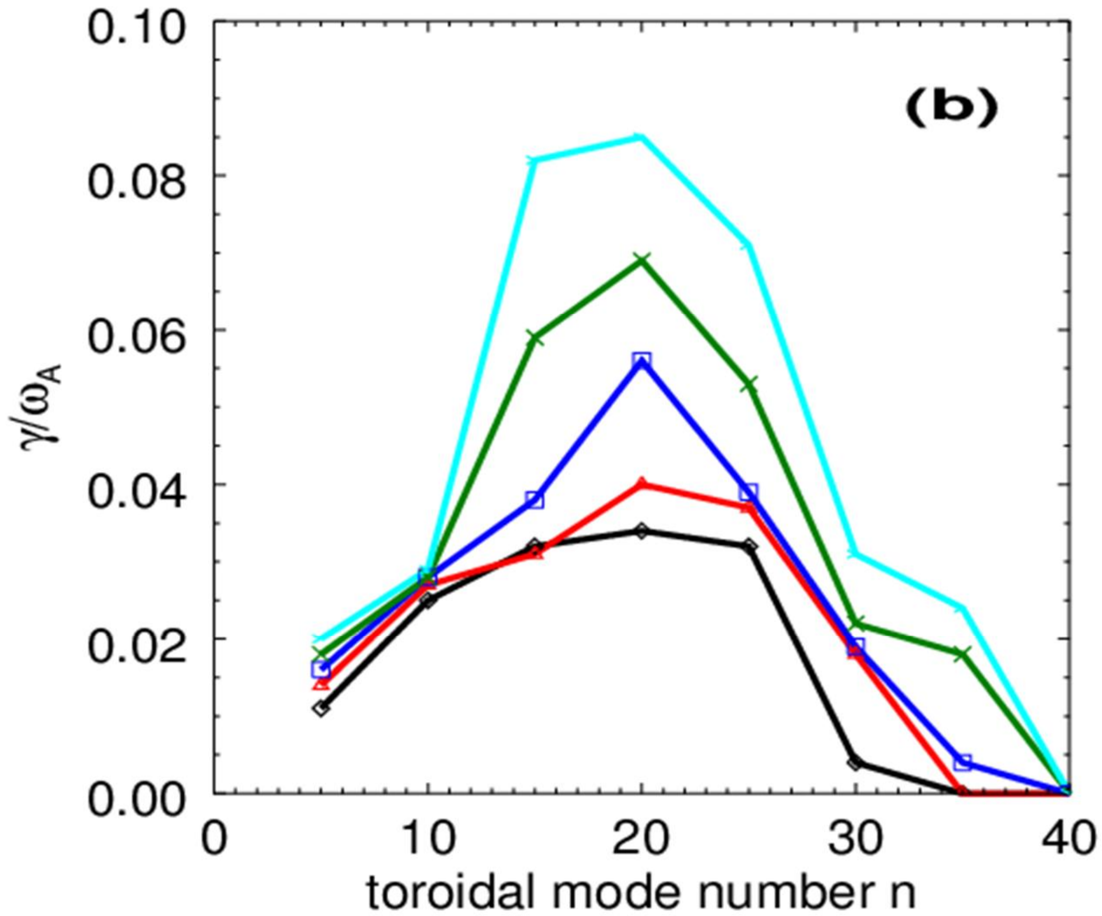
$$\alpha = -2\mu_0 R P_0' q^2 / B^2$$

$\gamma(n)$ Peaking VERY Sensitive to Pressure Gradient

Normalized pressure gradient



$\boldsymbol{\gamma(n)}$



$$\alpha = -2\mu_0 R P_0' q^2 / B^2$$

- ◆ **Higher pressure gradient**
  - ✓ Larger growth rate;
  - ✓ **Peaking of growth rate spectrum;**

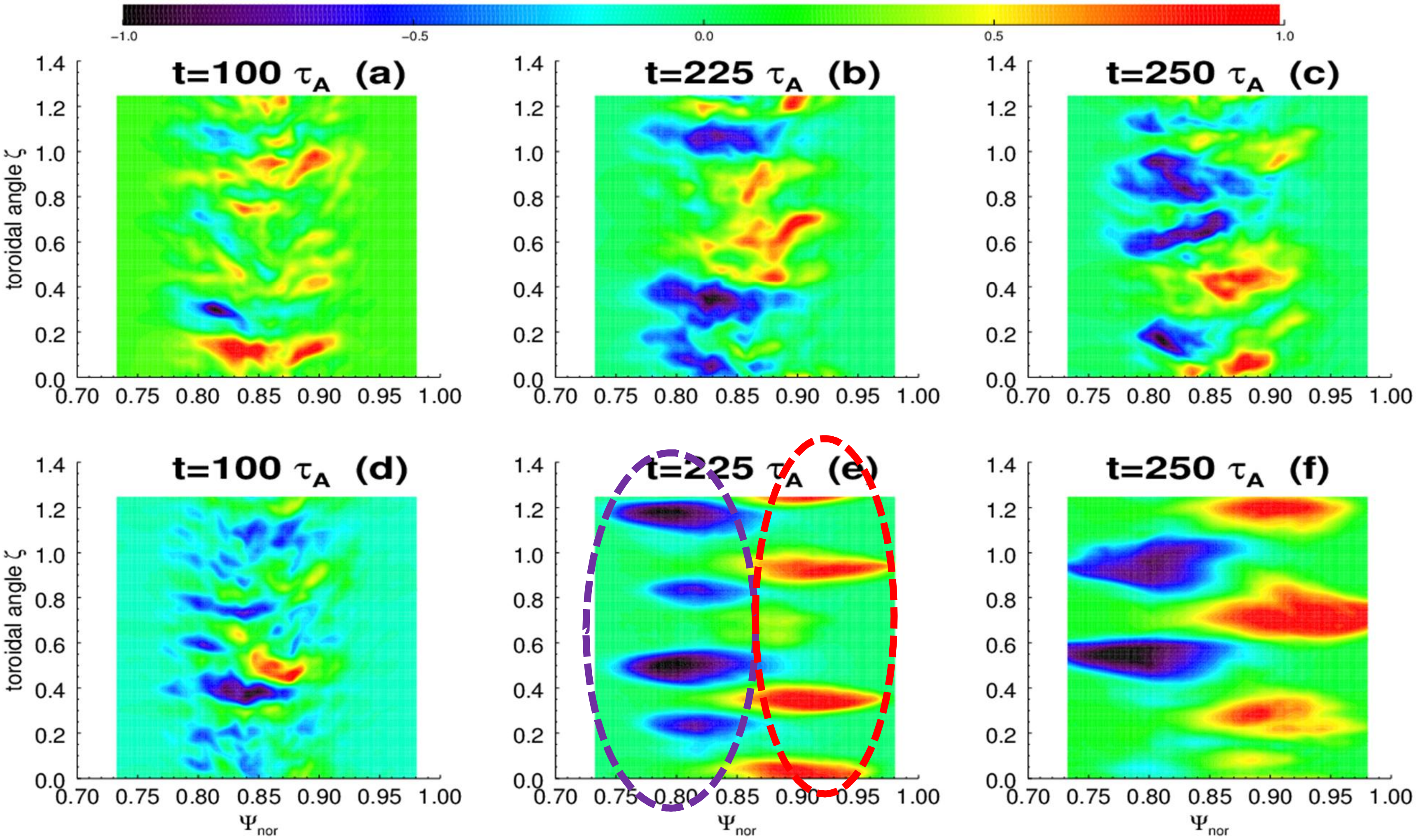
Filamentary structure may not correspond to that of the most unstable mode due to nonlinear interaction

$\alpha = 2.29$

P-B turbulence

$\alpha = 2.44$

ELM crash

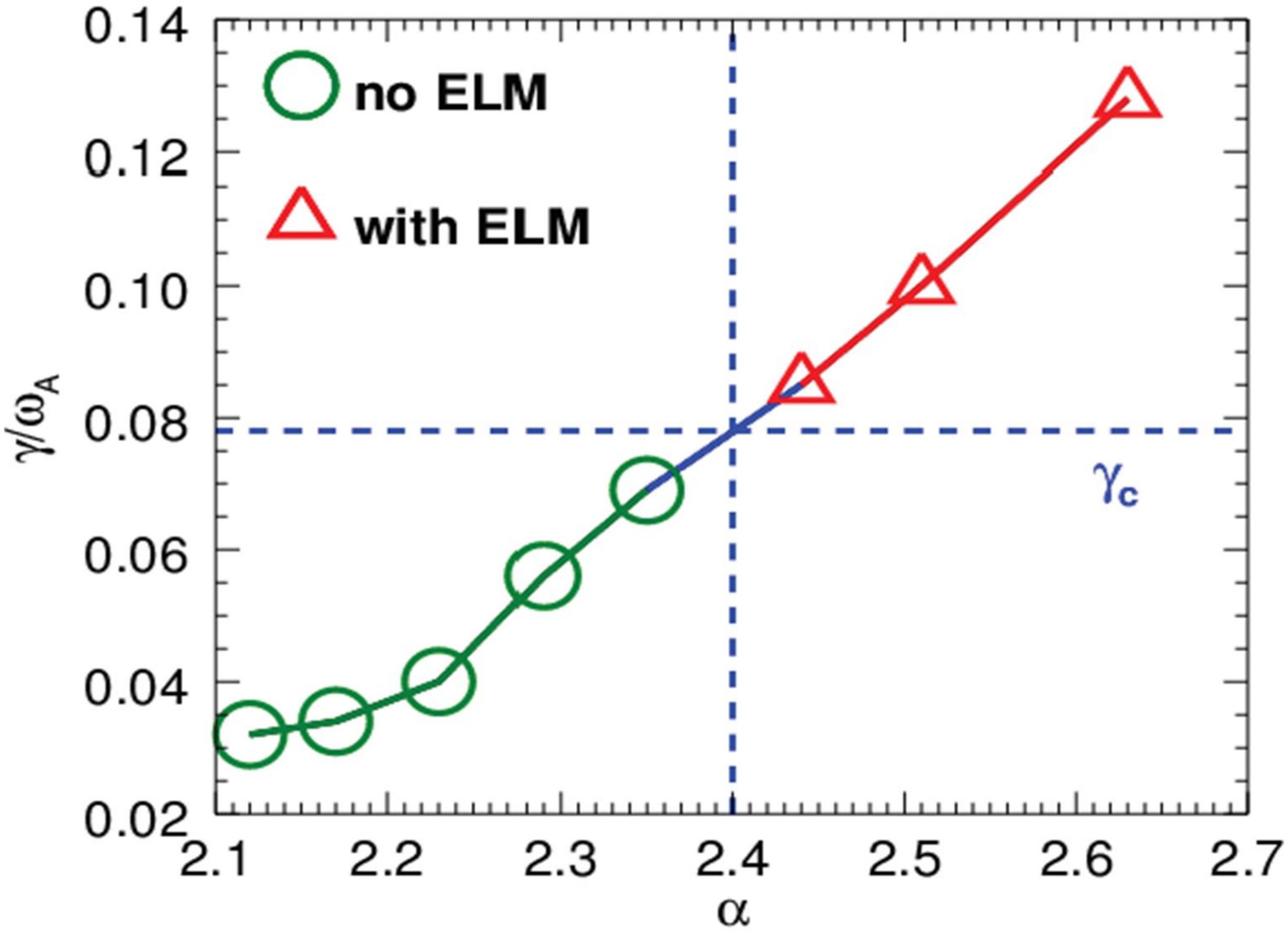


- **Triggering ELM and the generation of filamentary structure are different processes!**
  - ✓ **ELM is triggered by the most unstable mode;**
  - ✓ **Filamentary structure depends on both linear instability and nonlinear mode interaction.**

What is the Threshold for a Crash?

Linear criterion for the onset of ELMs $\gamma > 0$ is replaced by the nonlinear criterion

$$\gamma > \gamma_c \sim 1/\tau_c$$



- **Criterion for the onset of ELMs**

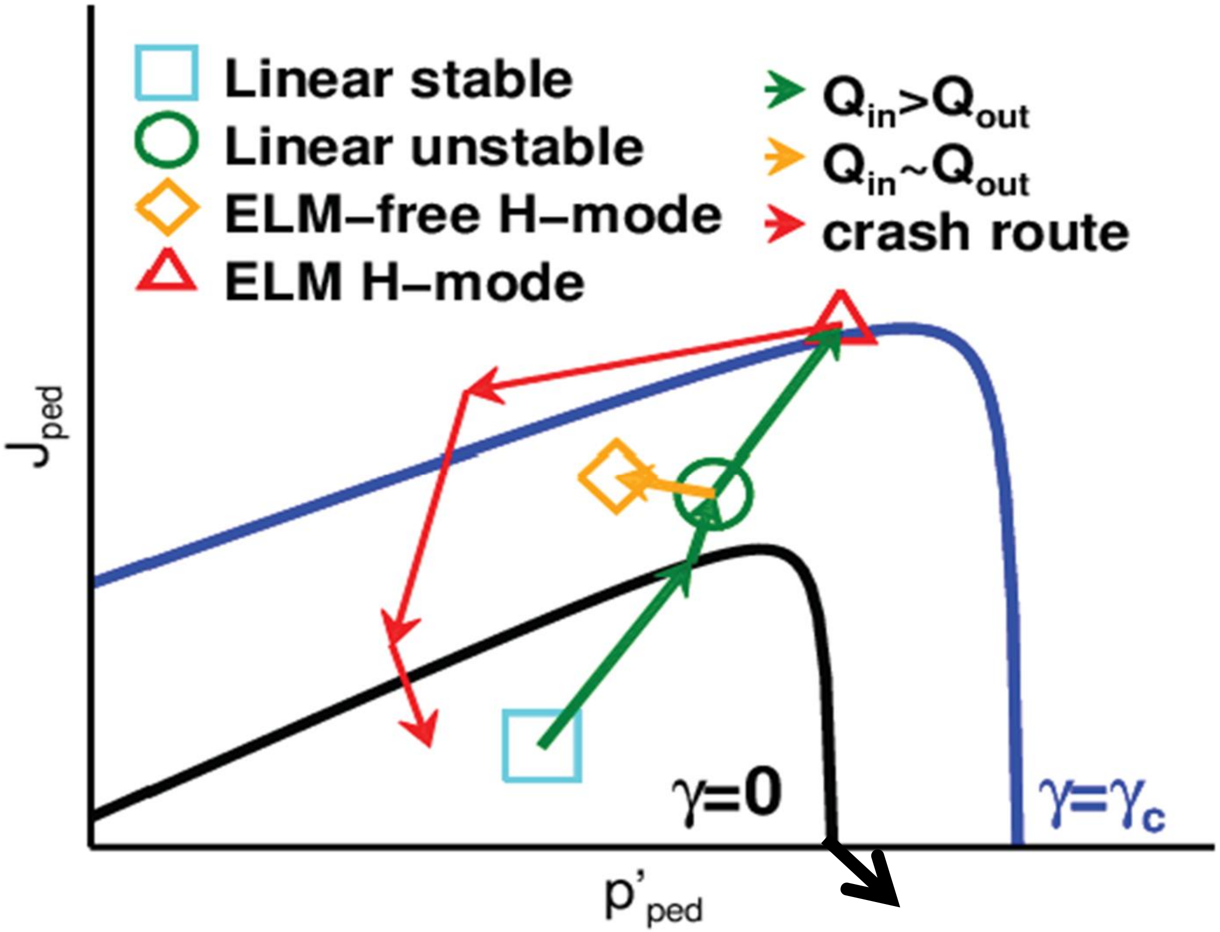
$$\gamma\tau_c > \ln 10 \Rightarrow \gamma > \frac{\ln 10}{\tau_c} \equiv \gamma_c$$

- **Linear limit**

$$\lim_{\tau_c \to \infty} \Rightarrow \gamma > 0$$

- **γ_c is the critical growth rate which is determined by nonlinear interaction in the background turbulence**
- **N.B. $1 / \tau_c$ - and thus γ_{crit} - are functionals of $\gamma_L(n)$ peakedness**

Nonlinear Peeling-ballooning model for ELM:



- $\gamma < 0$:
  Linear stable region
- $0 < \gamma < \gamma_c$: Turbulent region
  Possible ELM-free regime→
  Special state: EHO, QCM (?!)
- $\gamma > \gamma_c$:
  ELMy region

✓ Different regimes depend on both linear instability and the turbulence in the pedestal.

Including all relevant linear physics
(not only ideal P-B with ω_*)
Resistivity / Electron inertia /…

→ Turbulence can maintain ELM-free states

Partial Summary

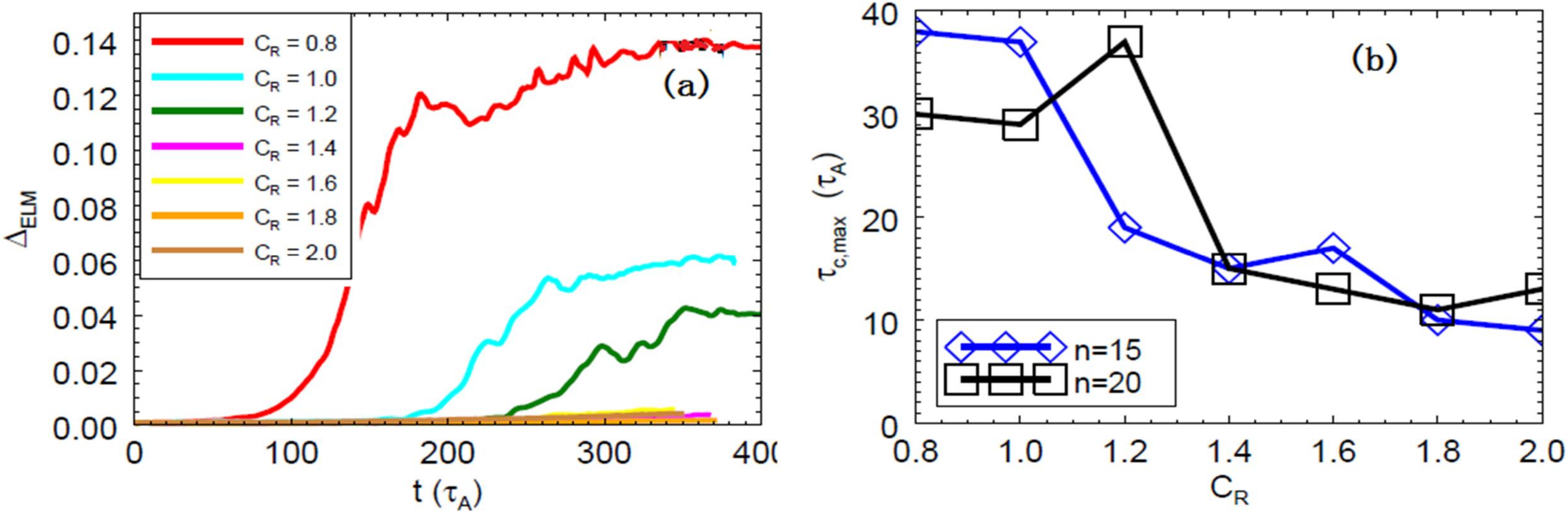
- Multi-mode P.-B. turbulence or ~ coherent filament formation can occur in pedestal
- Phase coherence time is key factor in determining final state and net P.-B. growth
- Phase coherence set by interplay of nonlinear scattering with 'differential streaming' in $\hat{P}$ response
- Key competition is γ_L vs $1 / \tau_c$ → defines effective threshold
- Peekedness of $\gamma(n)$ determines burst vs turbulence

How can these ideas be exploited for ELM mitigation and control?

ELMs can be controlled by reducing phase coherence time

$$\frac{\partial \varpi}{\partial t} + C_R \frac{\mathbf{b} \times \nabla \phi}{B} \cdot \nabla \varpi = RHS$$

i.e. scan C_R for fixed profiles



- ELMs are determined by the product $\gamma(n)\tau_c(n)$;
- Reducing the phase coherence time can limit the growth of instability;
- **Different turbulence states lead to different phase coherence times and, thus different ELM outcomes**

Keys to τ_c

- Scattering field
- 'differential rotation' in $\hat{P}$ response to $\hat{v}_r$

→ enhanced phase de-correlation

Knobs:

- ExB shear
- Shaping
- Ambient diffusion
- Collisionality

Mitigation States:

- QH mode, EHO
- RMP
- SMBI
- …

Scenarios

- QH-mode
  - enhanced ExB shear → $\frac{1}{\tau_c} \rightarrow (k_\perp^2 D \, \langle V_E \rangle'^2 \,)^{1/3}$
  - Triangularity strengthens shear via flux compression
  - Enhanced de-correlation restricts growth time

Also:

- Is EHO peeling/kink + reduced τ_c?
- $\langle V_E \rangle'$ works via γ_L and τ_c

N.B. See Bin Gui, Xu; this meeting for more on shearing effects

Scenarios

- RMP
  - $\frac{1}{\tau_c} = \left(\frac{k_\perp^2 \hat{s}^2}{(Rq)^2}\, \chi_\parallel D\right)^{1/2}$ $\qquad D = D_\phi + D_{am\ b}$
  - RMP → $D_{am\ b} \uparrow$ → enhanced de-correlation

  or

  - Enhanced flow damping → enhanced turbulence → increased D_ϕ
- SMBI
  - enhanced D_ϕ → reduced τ_c ?

  and/or

  - Disruption of pedestal avalanches?

II) Reconnection and Hyper-resistivity

Some Basics

- P.-B.'s are ideal modes ↔ frozen-in law… !?
- ELM phenomena requires irreversibility for:
  - field-fluid decoupling, reconnection
  - Transport, cross field
  - Magnetic stochastization
- What is mechanism of fast reconnection for ELM? Resistivity unlikely…
- $S \geq 10^8$ in pedestal → hyper-resistivity becomes natural candidate

- Hyper-resistivity!? – Electron momentum transport

  i.e. $E_{\parallel} = \eta J_{\parallel} + \nabla_{\perp} \mu_H \nabla_{\perp} \hat{J}_{\parallel}$ ←

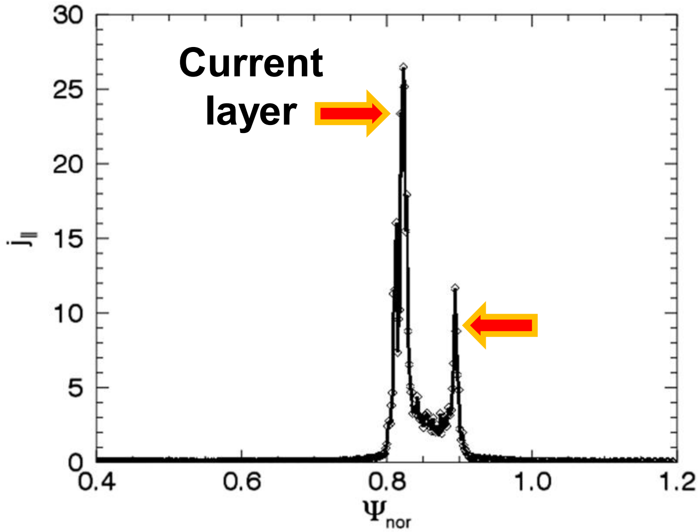
  ⊥ transport of parallel current - ambient micro-turbulence
  - P.-B. turbulence

- Xu et al 2010 → Hyper-resistivity $\sim \chi_e$ needed to dissipate current sheets, so as allow ELM crash

- Hyper-resistivity generally can trigger fast reconnection

  i.e. Sweet-Parker: - resistive: $\frac{V}{V_A} \sim \frac{1}{\sqrt{R_m}}$

  - hyper-resistive: $\frac{V}{V_A} \sim \frac{1}{(R_{m,H})^{1/4}}$



- Origin?

- Simplest Approach: Electron inertia + MHD

  i.e. Ohm's law becomes:

$$\frac{m_e}{e}\frac{d}{dt}\tilde{v}_{\parallel e} + \tilde{E}_{\parallel} = \eta \tilde{J}_{\parallel}$$

Electron inertial effect → electron momentum

- Scale : $\frac{c}{\omega_{pe}}$

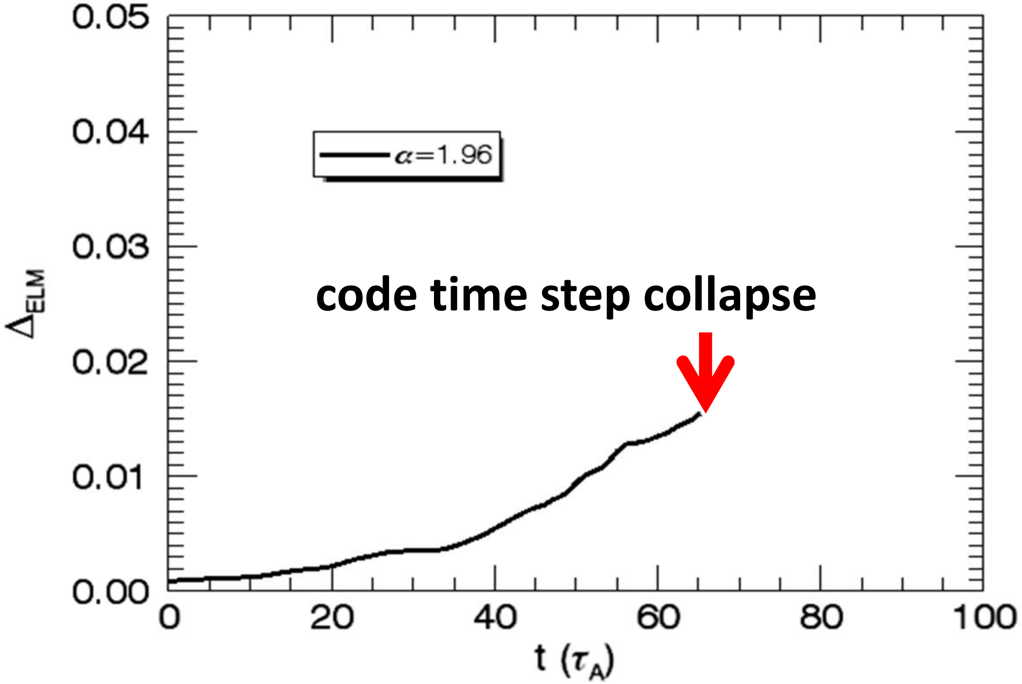
Low n → $\rho_i \sim c/\omega_{pe}$

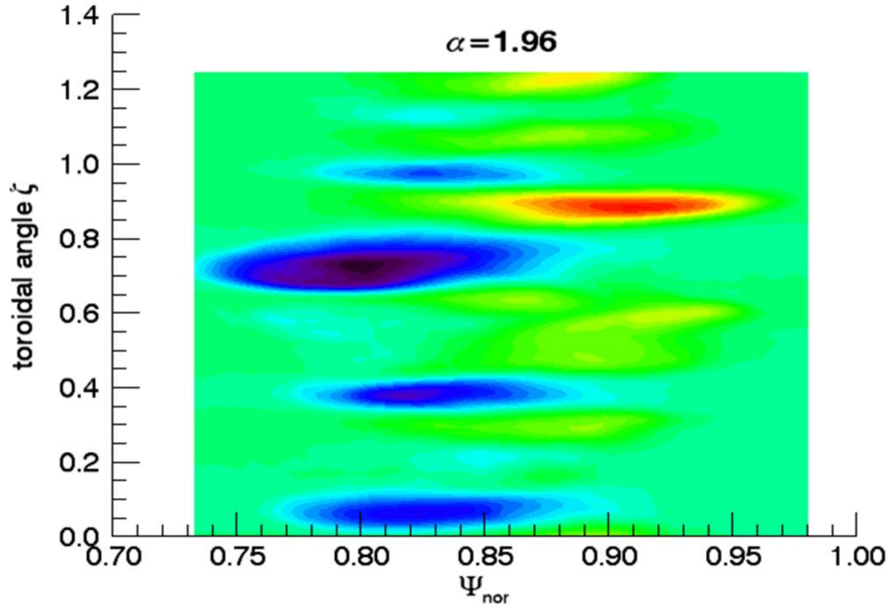
→ significant effect on linear growth for $k_{\perp}\left(\frac{c}{\omega_{pe}}\right) \sim O(1)$

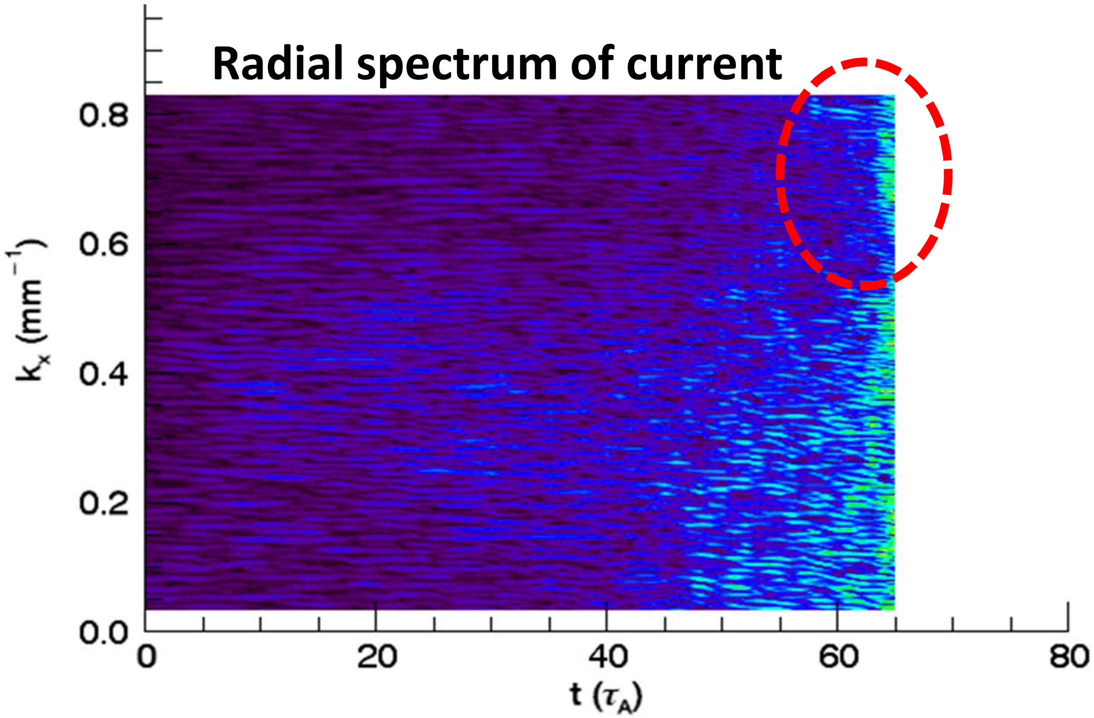
  P.-B. → 'hyper-resistivity' ballooning mode…

- Examine impact on nonlinear evolution… → self-consistent crash?

Electron inertia and P-B turbulence cannot generate enough current relaxation for ELM crash







- ✓ Micro-turbulence is needed to generate enough current relaxation
- ✓ The self-consistent nonlinear ELM simulation is a multiple scale issue.

- Interesting candidate for hyper-resistivity

  ➔ ETG turbulence in pedestal?!

- ETG indicated by pedestal micro-stability studies → survive $\langle V_E \rangle'$

- Mechanism is advection of electron momentum

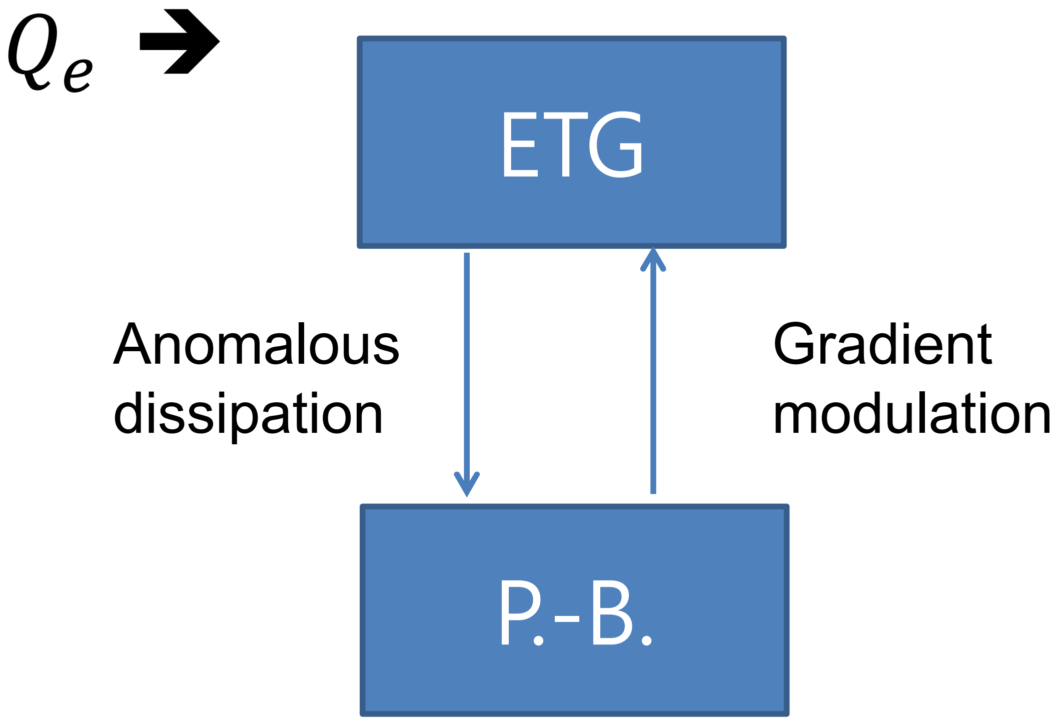
ITG	⟺	ETG	→ hyper-resistivity linked to pedestal electron heat transport
$\chi_\phi \sim \chi_i$		$\mu_H \sim \chi_e$	

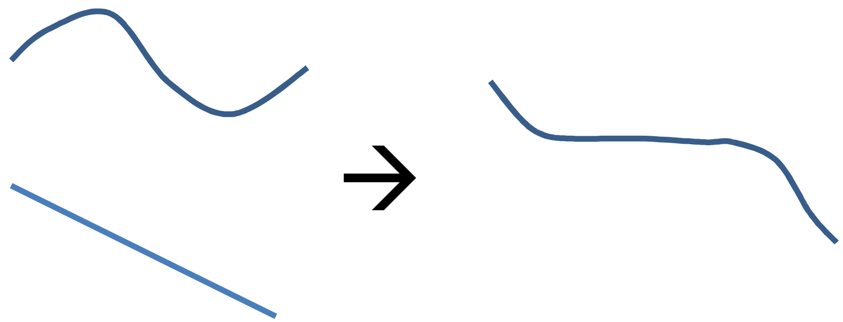
- $\mu_H \approx \left(\frac{c}{\omega_{pe}}\right)^2 C \, D_{GBe}$ $\qquad D_{GBe} \leftrightarrow L_{Te}^{-1}$

  (C: anisotropy factor)

- Modulation of driving ∇T_e by P.-B.'s crucial effect

Feedback Structure





Approach as disparate – scale modulation problem via gradient evolution due P.-B.

Partial Summary

- Hyper-resistivity required for dissipation of P.-B. current sheets, and crash
- P.B. + electron inertia insufficient to trigger fast reconnection
- Multi-scale approach to current dissipation is required
- ETG is interesting candidate for origin of μ_H
- Considerable further work required

III) Towards a 'Big Picture'

- Is there a 'minimal' model of ELMs?
- What are the key ingredients?
- Might this help us understand ELM-related phenomena better?

→ See: W. Xiao, et al; NF 2013
T. Rhee, et al; PoP 2012

Needed: Simple Model…

N.B. full ELM phenomena far beyond "First Principle" Simulations!

- Minimal Model of Pedestal Dynamics
- Necessary Ingredients:
  - Bi-stable flux → capture turbulence, transport, L→H transition
  - Fixed ambient diffusion → capture (neoclassical) transport in H-mode pedestal

    N.B. key: how does system actually organize profiles for MHD activity??
  - Hard stability limit → capture MHD constraint on local profile. Can be local. (i.e. ballooning ←→ ∇P) or integrated (i.e. peeling ←→ $J_{BS} \sim \int dr \nabla P \sim P_{ped,top}$

N.B. Transport vs 'hard stability'?

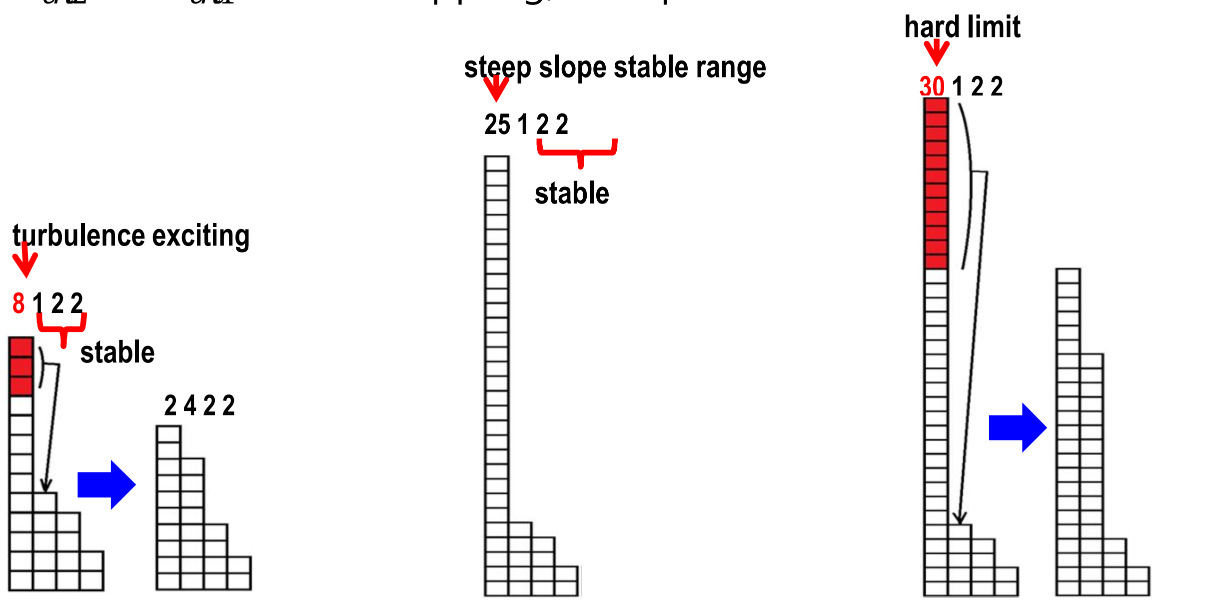
➔ $Q \sim C\left(\frac{L_{P_{crit}}}{L_P} - 1\right)^{\alpha}$ $\therefore$ c, α large for 'hard stability limit'

Sandpile (Cellular Automata) Model

- Toppling rule: $Z_i - Z_{i+1} > Z_{crit}$ topple Y_i cells → move adjacent
- Bi-stable toppling:

$Z_i - Z_{i+1} > Z_{crit1}$ ➔ toppling, threshold, transport

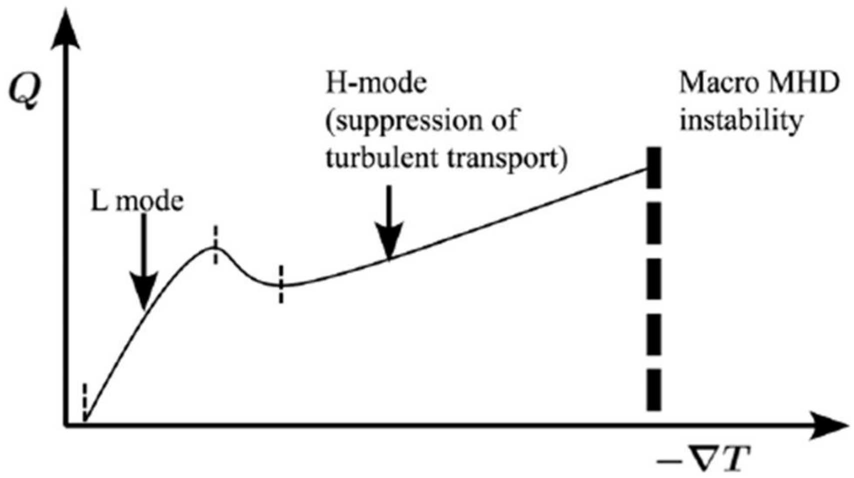
$Z_i - Z_{i+1} > Z_{crit2}$, $Z_{crit2} > Z_{crit1}$ ➔ no toppling, transport bifurcation



(micro-turbulence, flipping) (stable by ExB shear flow) (MHD event, toppling)

Sandpile Model, cont'd:

- Constant diffusion ➔ neoclassical transport (discretized)
- N.B. Bi-stable toppling + diffusion ➔ S-curve model of flux



- Hard Limit ➔ $Z_i - Z_{i+1} > Z_{hard}$ ➔ topple excess Z_i according to rule
- Drive:
  - Random grain deposition, throughout
  - Additional "active grain injection" in pedestal, to model SMBI

L→H Transition

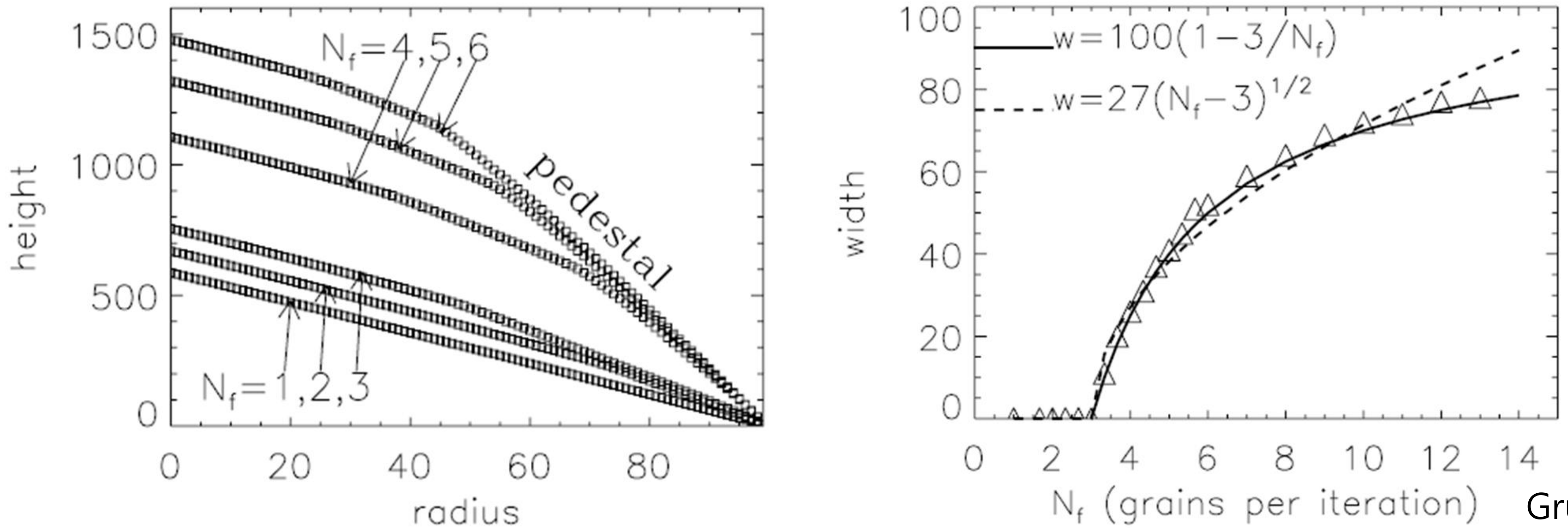
- Now try bi-stable toppling rule, i.e. if $Z_i - Z_{i+1}$ large enough

  ➔ reduced or no toppling

- Obvious motivation is $Q = -\frac{\chi \nabla P}{1+\alpha {V'}_E^2}$ and $V_E \approx \frac{c}{eB}\frac{\nabla P}{n}$

- Hard gradient limit imposed

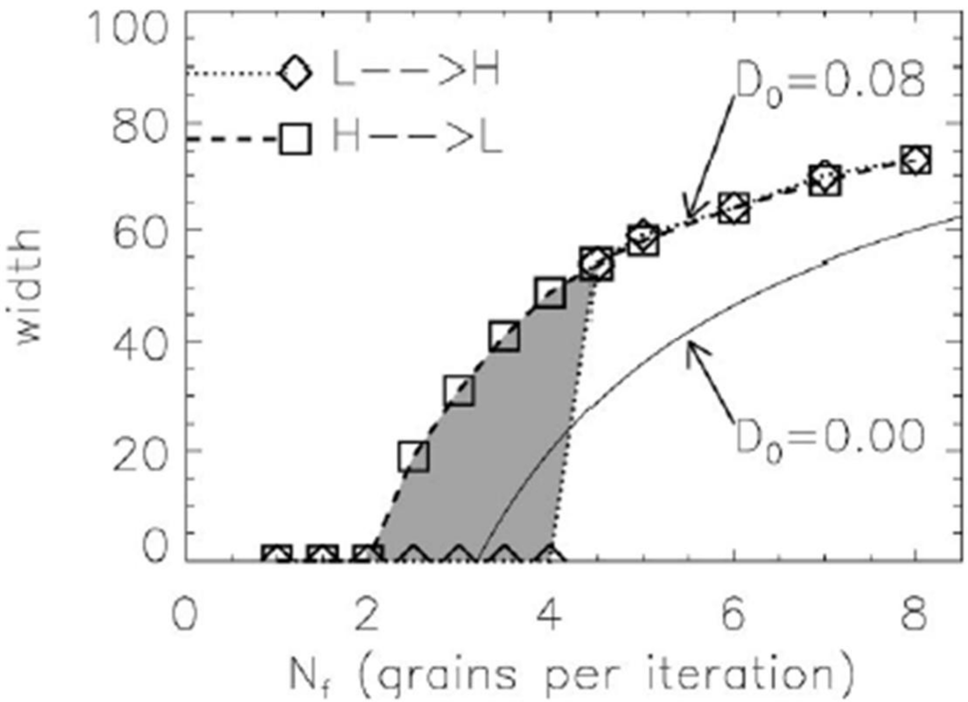
- Transitions happen, pedestal forms!



Gruzinov PRL2002

Note

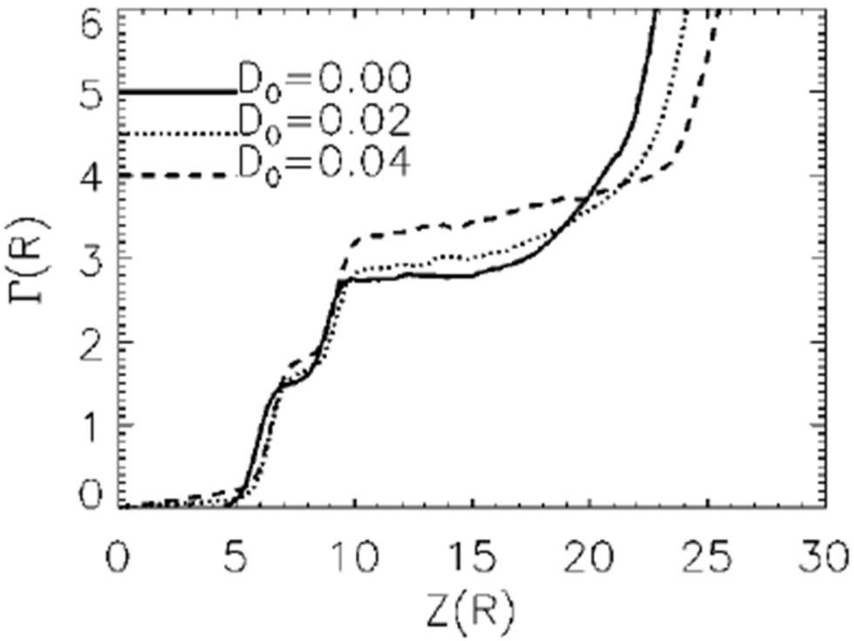
- Critical deposition level required to form pedestal ("power threshold")
- Pedestal expands inward with increasing input after transition triggered
- Now, including ambient diffusion (i.e. neoclassical)
  - N_F threshold evident
  - Asymmetry in L→H and H→L depositions

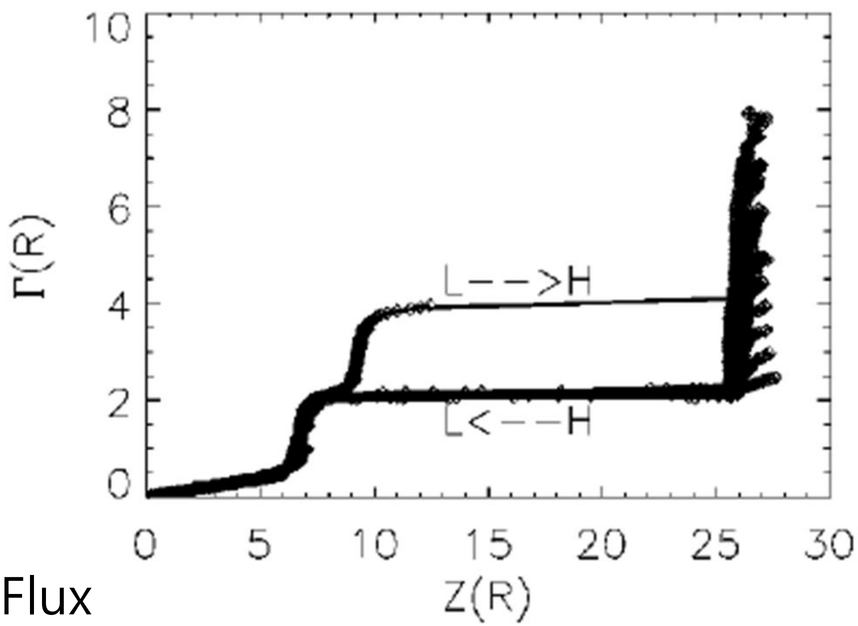


Gruzinov PoP2003

Hysteresis Happens!

- Hysteresis loop in mean flux-gradient relation appears for $D_0 \neq 0$
- Hysteresis is consequence of different transport mechanisms at work in “L” and “H” phases
- Diffusion ‘smoothes’ pedestal profiles, allowing filling limited ultimately by large events



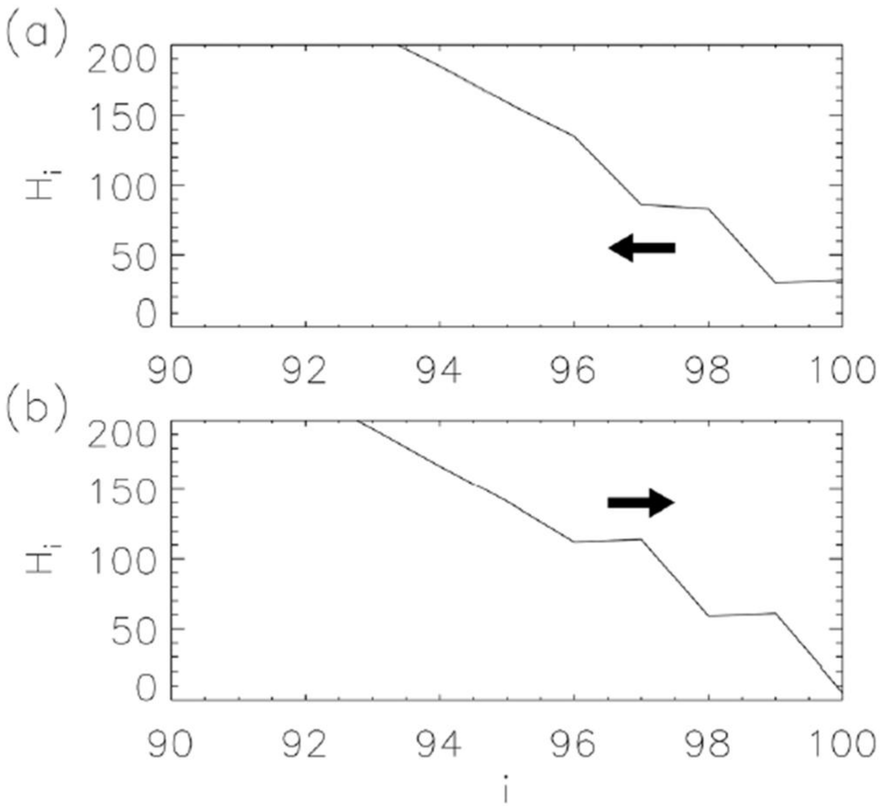


$\Gamma(R)$=Flux
$Z(R)$=Mean Slope

Gruzinov PoP2003

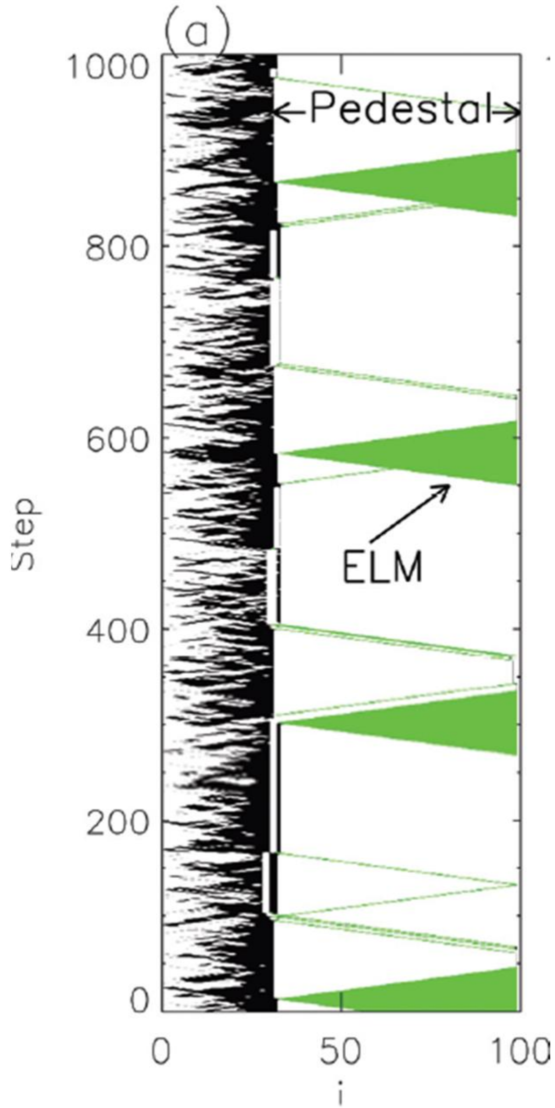
ELMs and ELM Mitigation

- ELMs happen!
- Quasi-periodic Edge Relaxation Phenomena (ELM) self-organize. Hard limit on ∇Z (∇P) is only MHD 'ingredient' here
- ELM occurs as out → in and in → out toppling cascade



Voids → inward

bump → outward



ELM Properties

- Periodic with period $\sim 10^{-2}\tau_p$. τ_p = grain confinement time
- ELM flux ~ 500 diffusive-flux
- ELMs span pedestal
- Period ←→ pedestal re-fill (approximate)

The What and How of ELMs?

What?

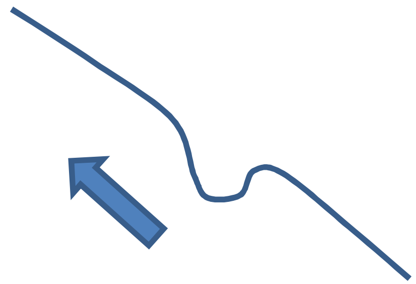
- ELMs are a burst sequence of avalanches, triggered by toppling of ‘full pedestal’
- ELMs are not global (coherent) eigen-modes of pedestal

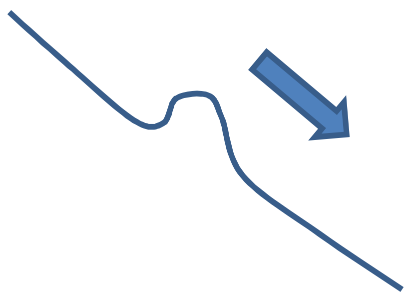
The What and How of ELMs?

How?

- Toppling cascade:
  - Void forms at boundary, at hard limit
  - Propagates inward, to top of pedestal, triggering avalanche
  - Reflects from top of pedestal, becomes a bump

    (N.B. core is subcritical → void cannot penetrate)
  - Bump propagates out, causing further avalanching
  - Bump expelled, pedestal refills

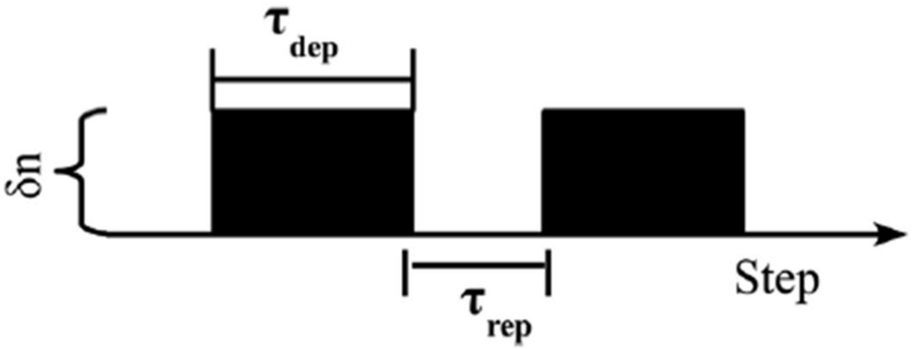




N.B. ELM phenomena appear as synergy of H-phase, diffusion, hard limit

With Active Grain Injection (AGI):

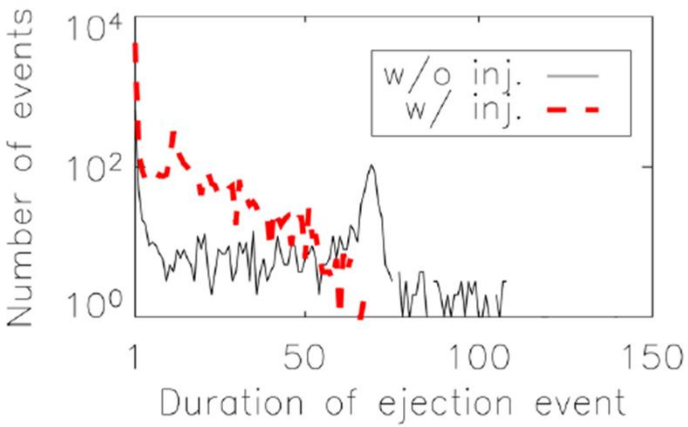
- AGI works by adding a group of grains over a period τ_{dep}
- Can repeat at τ_{rep}



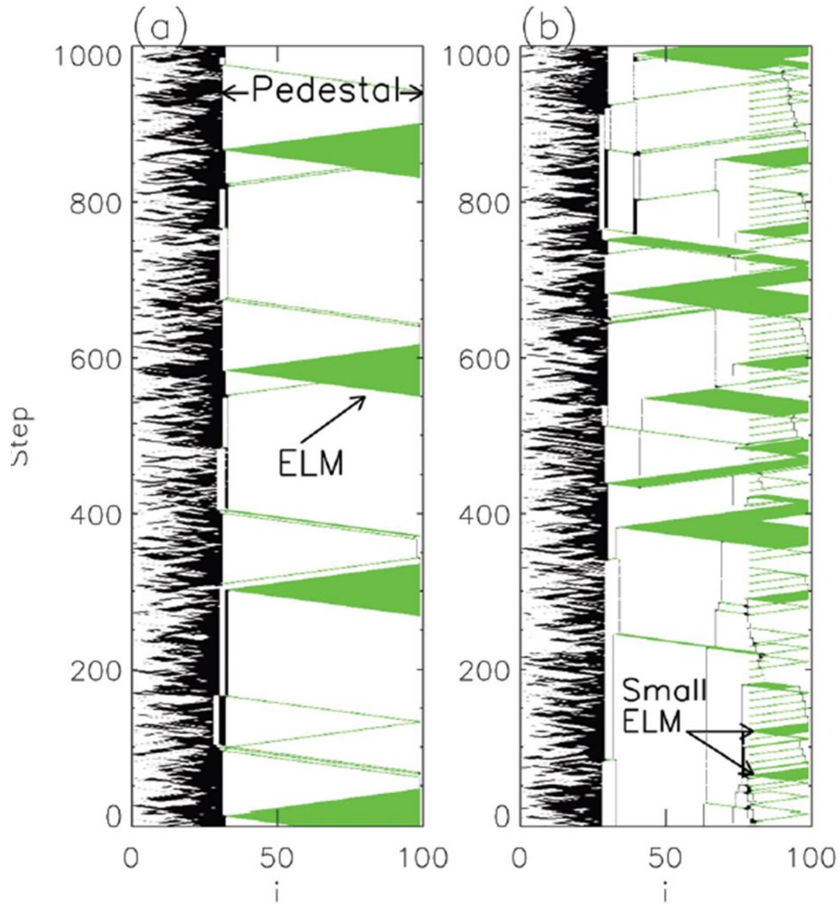
- Obviously, model cannot capture dynamics of actual SMBI, time delay between injection and mitigation. See Z. H. Wang for injection model
- Model can vary strength, duration, location

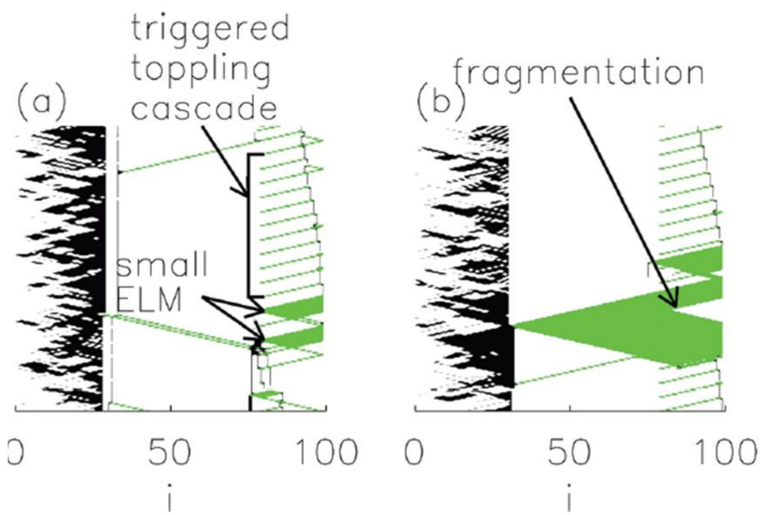
Results with AGI

- AGI clearly changes avalanche distribution, and thus ELM ejection distribution



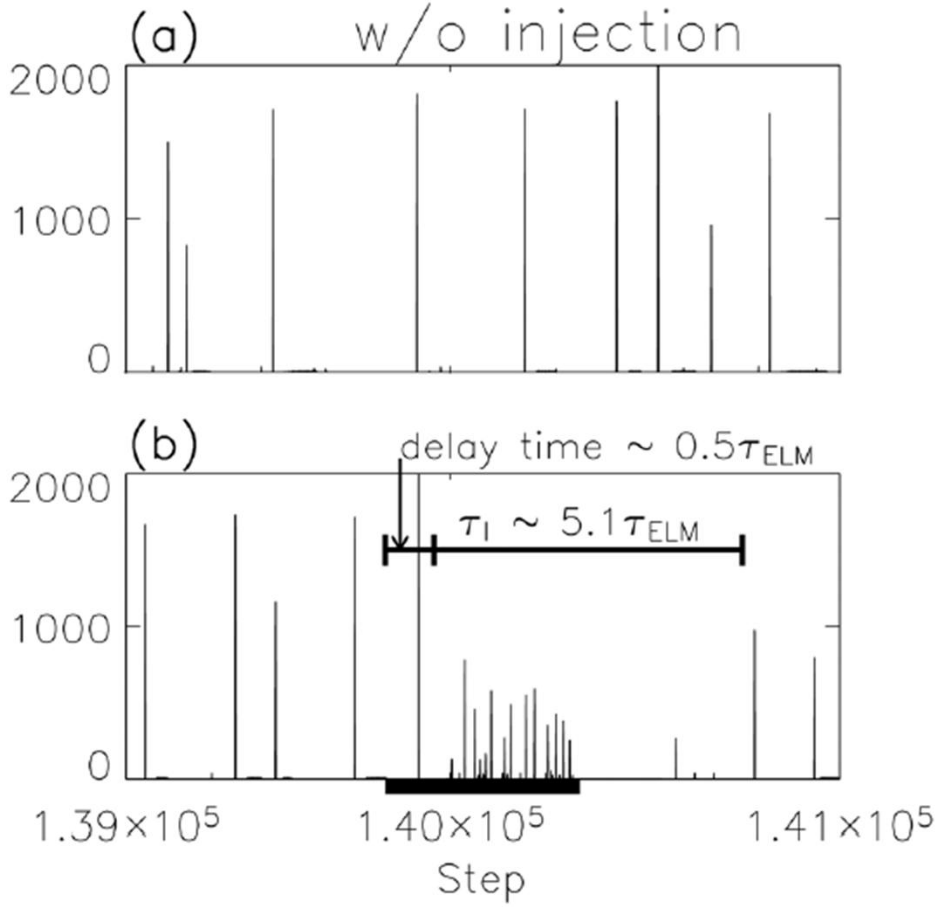
- Mitigation due fragmentation of large avalanches into several smaller ones
- Injection destroys coherency of large avalanches by triggering more numerous small ones
- Consistent with intuition





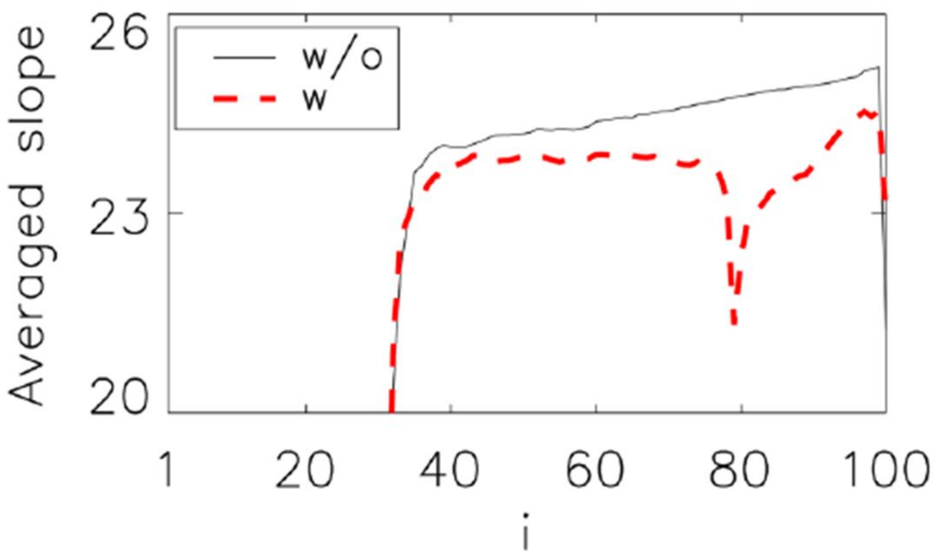
Edge Flux Evolution (in lieu D_α)

- A/A_0 drops, f/f_0 increases
- An “influence time” τ_I is evident ➔ duration time of mitigated ELM state
- $\tau_I \sim 5\,\tau_{ELM}$



AGI tends to reduce gradient at deposition region

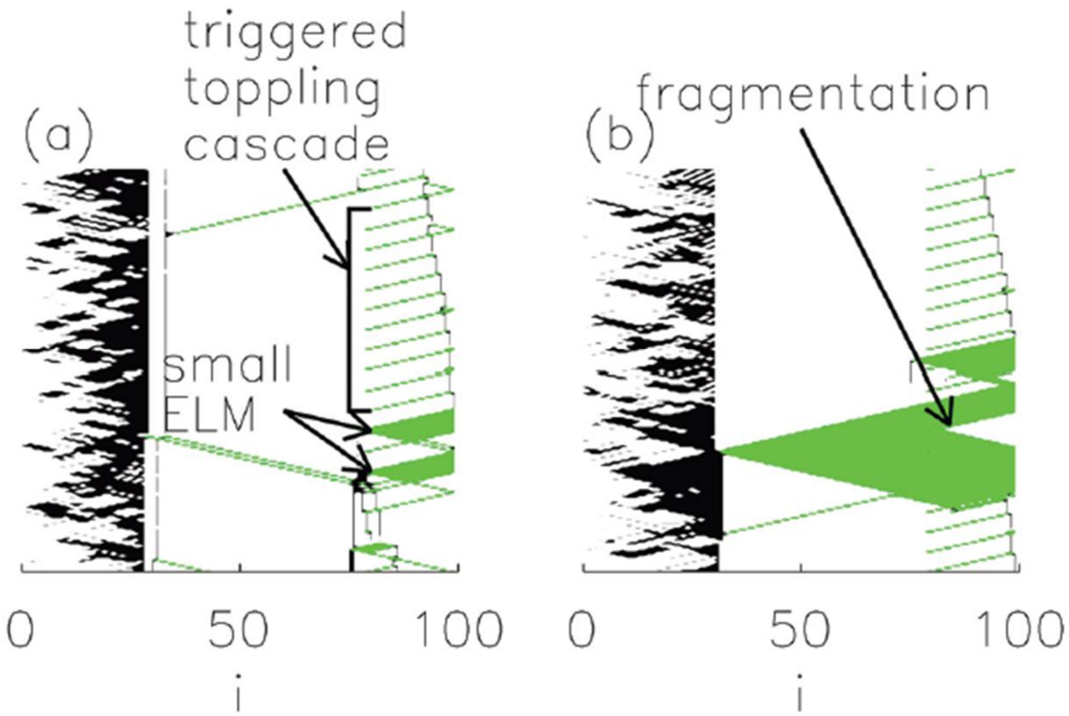
- Drive triggers local toppling → prevents recovery of local gradient
- 'flat spot' is effective beach, upon which avalanches break
- τ_I is recovery time of deformed local gradient
- Related to question of optimal deposition location



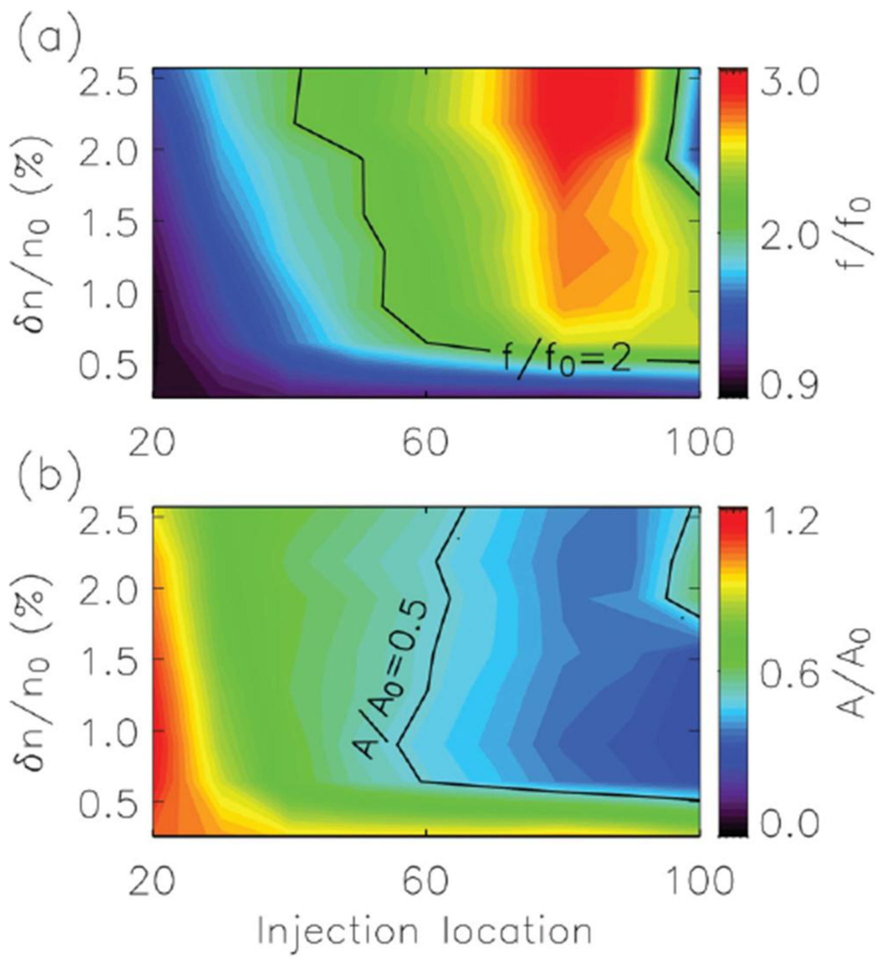
Which deposition location is optimal?

- Clue: deep deposition, at top of pedestal, allows avalanches to re-establish coherence ‘behind’ deposition zone
- Clearly desirable to prevent large avalanches from hitting the boundary

➔ points toward deposition at base of pedestal as optimal



Results of Study on Deposition



X → location
Y → injection intensity

Color: Red high
Purple low

Results of model study point toward optimal deposition near pedestal base

- Study suggests optimal location slightly inside pedestal base
- Here $20 \leq i \leq 100$ → pedestal domain

Here → optimal location ~ 80

Summary of Reduced Model Results

- ELM phenomena emerge from synergy of bi-stable turbulence, ambient diffusion and hard gradient limit. ELM appears as result of avalanche in pedestal
- N.B. Multi-mode interaction necessarily triggers avalanching
- SMBI mitigation may be understood as a consequence of fracturing of pedestal-spanning avalanches

Conclusions – Coarse Grained

Conclusions

- ELM phenomena are intrinsically multi-mode and involve turbulence
- P.-B. growth regulated by phase correlation

  → determines crash + filament vs turbulence
- Phase coherence can be exploited for ELM mitigation
- Hyper-resistivity dissipation is likely a multi-scale phenomena
- ELMs appear as pedestal avalanching in reduced model

Where to Next?

- Simulations MUST move away from IVP – even if motivated by experiment – and to dynamic profile evolution, with:
  - sources, sinks i.e. flux drive essential
  - pedestal transport model
  - anomalous electron dissipation

  i.e. → - what profiles are actually achieved?

  - how evolve near P.-B. marginality?

- Should characterize:
  - pdf of phase fluctuations, correlation time
  - Dependence on τ_c control parameters
  - Threshold for burst
- Need understand feedback of P.-B. growth on turbulent hyper-resistivity
- Continue to develop and extend reduced models.