ELM Mitigation by Particle Injection - Towards a Model

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Collaborators

- Recent Work: Tongnyeol Rhee, J.M. Kwon, W.W. Xiao

  See: Phys. Plasmas 19, 022505 (2012)

  and motivating experimental results

- Fundamentals:

  Irina Gruzinov, M.N. Rosenbluth

  See: Phys. Rev. Lett. 89, 255001 (2002)

  Phys. Plasmas (lett) 10, 569 (2003)

  and earlier work with Hahm, Newman, Carreras

- Ackn: X.-L. Zou, P.T. Lang, H. Zohm

Outline

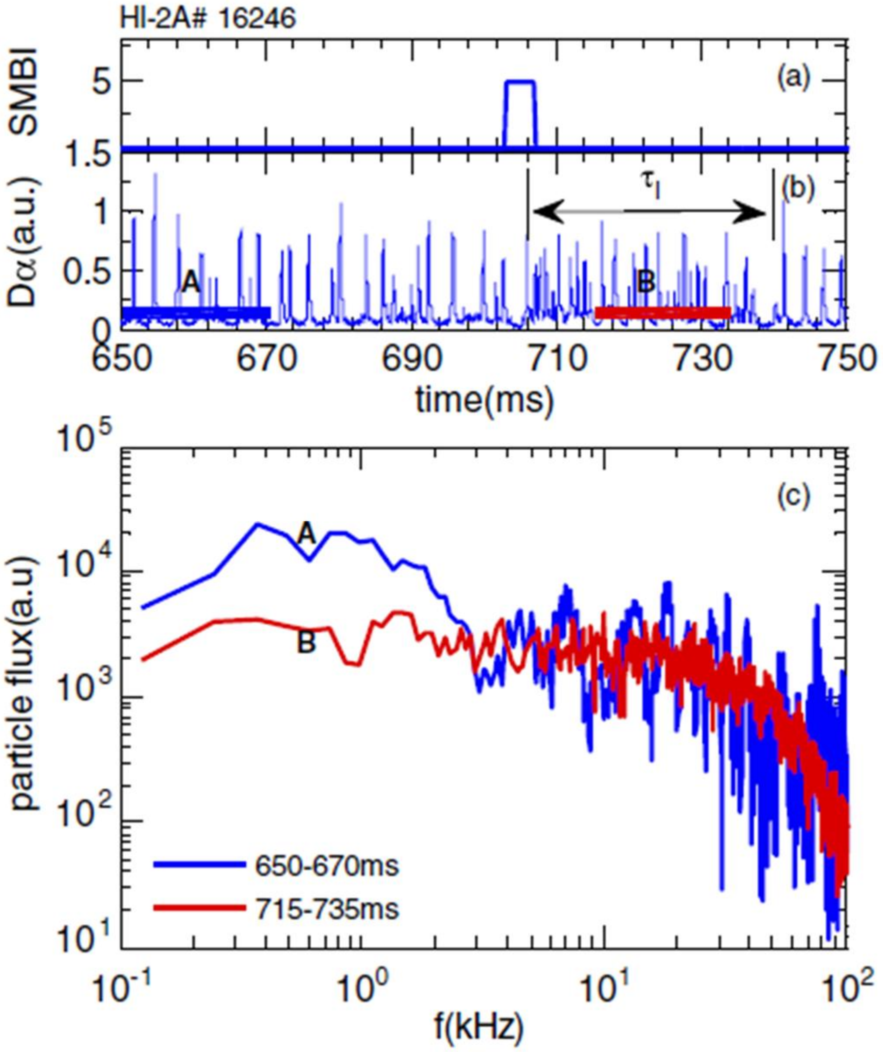
- Motivation
  - SMBI and pellet ELM mitigation
  - Mechanism? Deeper question?
- Towards a Minimal Model – the CA/Sandpile
- Basic Concepts of Avalanches and SOC Profiles
- Bi-stable transport, ambient diffusion and pedestal formation
- Modeling ELMs and ELM mitigation
- Discussion and Conclusions

Motivation

- ELM control is the ‘crisis du jour’ of ITER
- Now well established that particle injection into pedestal mitigates ELMs i.e.
  - mitigation by SMBI and pellet injection (HL-2A, KSTAR, AUG, DIII-D, EAST, …)
  - increases of f/f_0, decreases $\Delta W/W_0$ (as much as OOM)
  - minimal (or no?!) degradation of confinement
  - minimal (or no?!) net fueling
  - shallow injection seems optimal

Key Question:

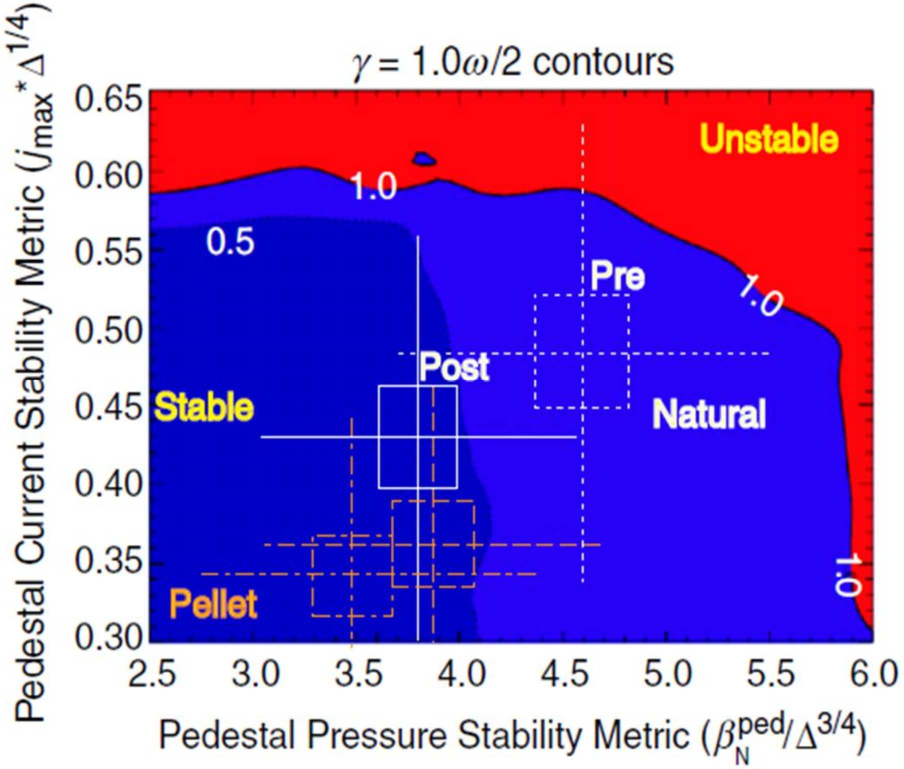
- Why?
- Intuitive Suggestions:
  - ‘decrease in population of large pedestal transport events/avalanches with increase in small event population
  - HL-2A, SMBI
  - Likely type-III ELMs
  - Measured outside separatrix
  - Theory motivated



W.W. Xiao, NF 2012

Key Question:

- "These results have suggested that very shallow pellets penetrating from LFS may be sufficient to trigger rapid ELMs. The trigger mechanism is hypothesized to be the destabilization of high-n localized ballooning mode by the local pressure perturbation … and triggers a large-n ELM crash."
  - DIII-D small pellet
  - Type-I ELMs
  - Deduced from profiles+analysis
  - Implicit: "large-n" = small?



Baylor, PRL 2013

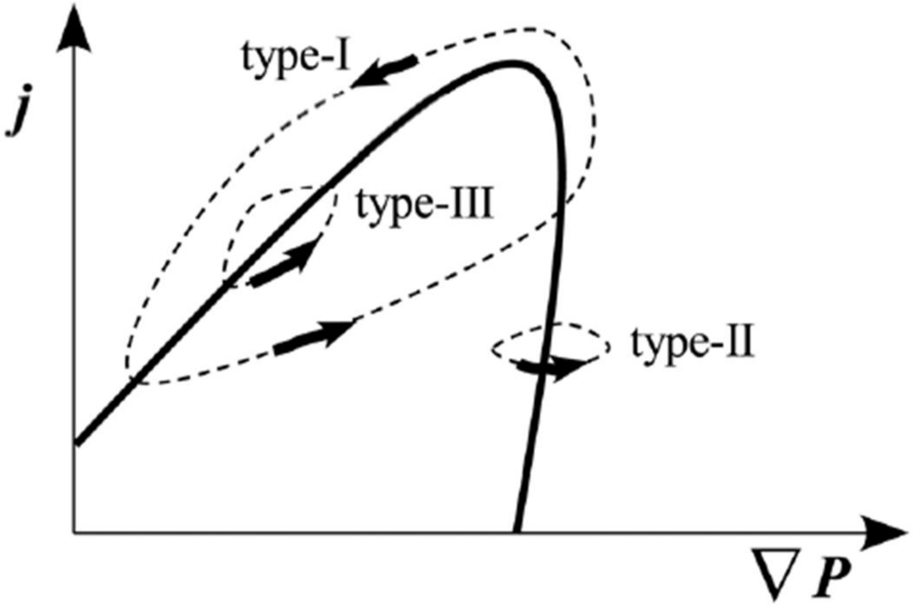
N.B. Explanations appear fundamentally similar

Underlying Question: What really is an ELM?

- Ever increasing zoology of ELMs….
- Type-I → associated with ideal MHD peeling-ballooning, due some correlation with stability limits
- Type-III → resistive ballooning ???

BUT

- Connection to dynamics not established
- Profiles should be constrained near marginality → interplay of MHD, transport, …



∴ a bit philosophically:

- is an ELM really a “mode”?
- is an ELM better thought of as an Edge Relaxation Phenomena (ERP)?

Needed: Simple Model…

N.B. 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’?

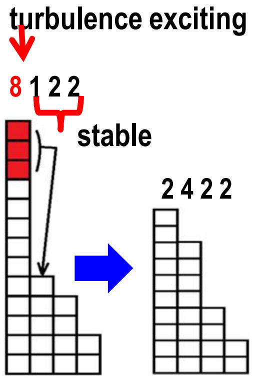
➔ $Q \sim C\left(\frac{L_{P\,crit}}{L_P} - 1\right)^{\alpha}$ $\therefore c, \alpha$ large for ‘hard stability limit’

Sandpile (Cellular Automata) Model

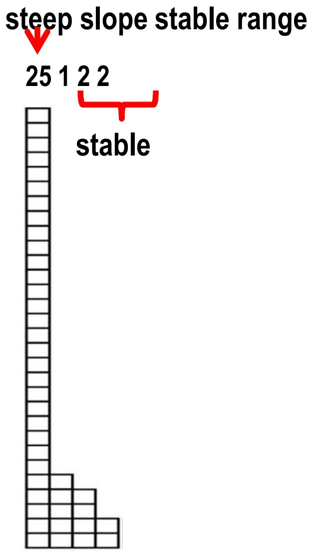
- Toppling rule: $Z_i - Z_{i+1} > Z_{crit}$ topple Y_i cells → move adjacent
- Bi-stable toppling:

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

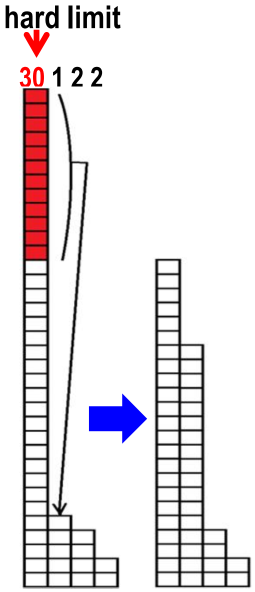
  $Z_i - Z_{i+1} > Z_{crit2}$, $Z_{crit2} > Z_{crit1}$ ➔ no toppling, transport bifurcation



(micro-turbulence, flipping)



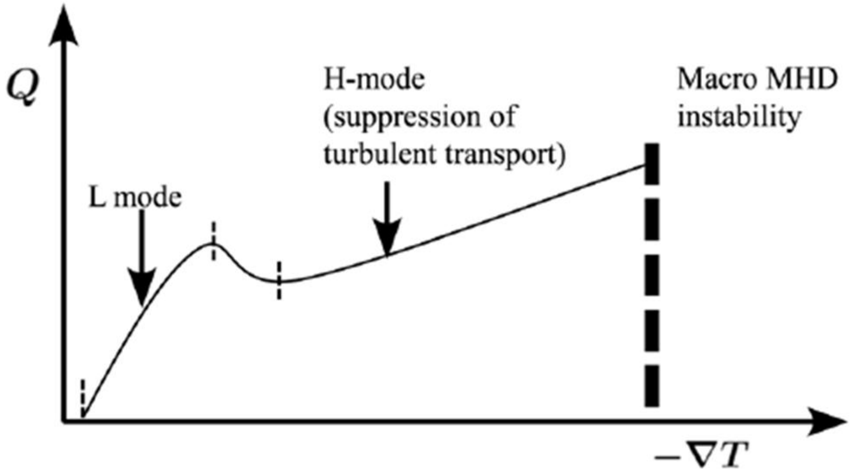
(stable by ExB shear flow)



(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

Sandpile Model, cont'd:

- Comparison: Turbulent Transport vs Cellular-Automata Model (sandpile)

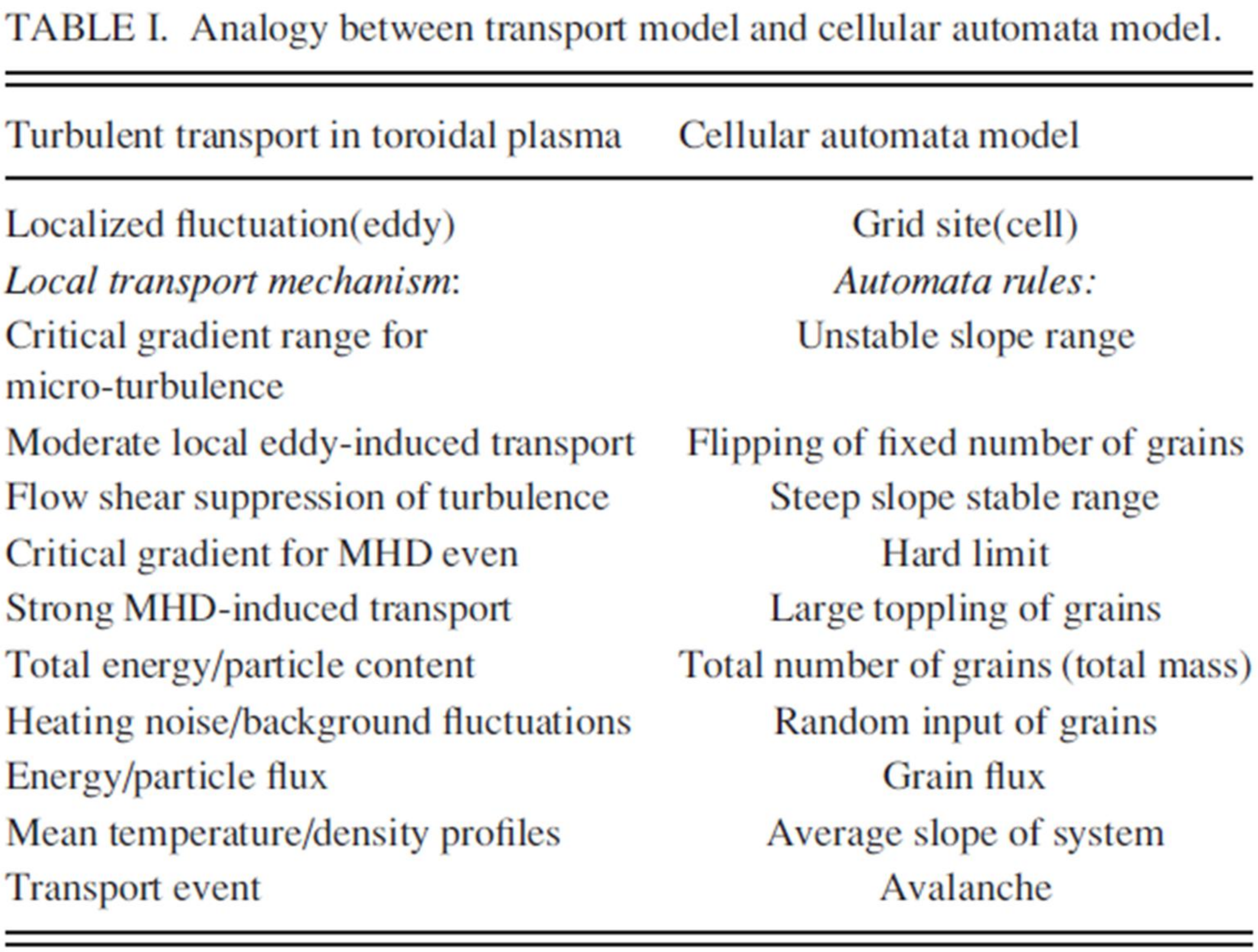
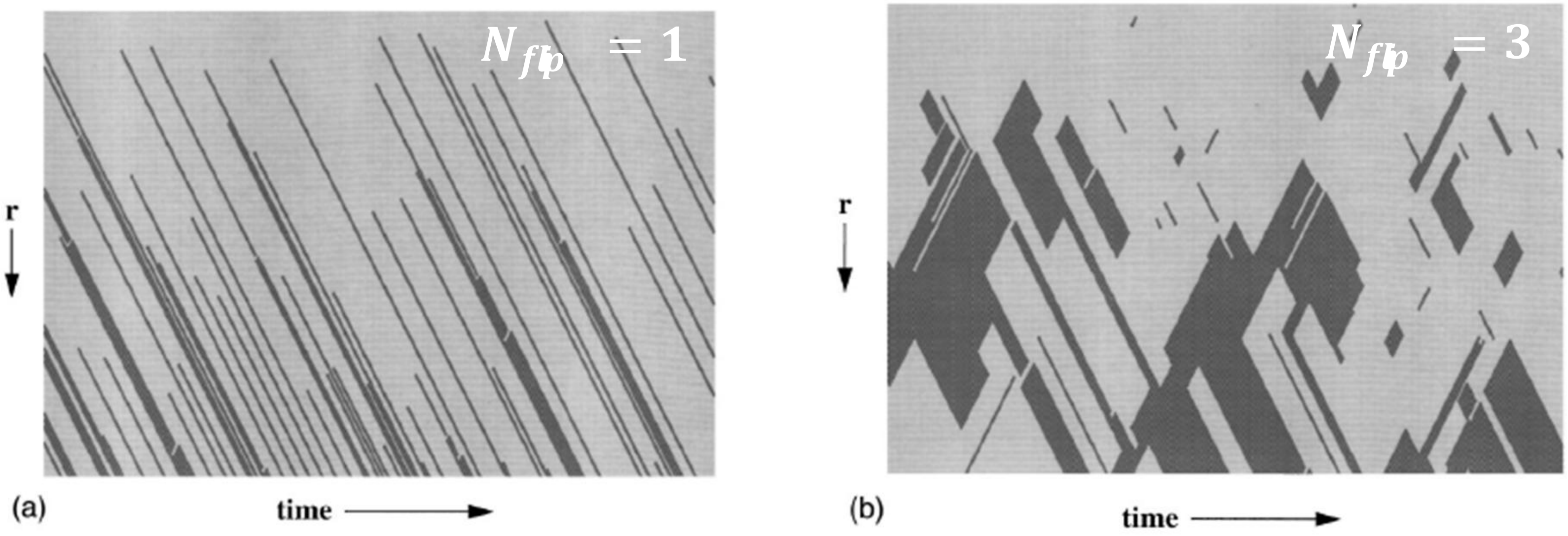


TABLE I. Analogy between transport model and cellular automata model.

Turbulent transport in toroidal plasma	Cellular automata model
Localized fluctuation(eddy)	Grid site(cell)
Local transport mechanism:	*Automata rules:*
Critical gradient range for micro-turbulence	Unstable slope range
Moderate local eddy-induced transport	Flipping of fixed number of grains
Flow shear suppression of turbulence	Steep slope stable range
Critical gradient for MHD even	Hard limit
Strong MHD-induced transport	Large toppling of grains
Total energy/particle content	Total number of grains (total mass)
Heating noise/background fluctuations	Random input of grains
Energy/particle flux	Grain flux
Mean temperature/density profiles	Average slope of system
Transport event	Avalanche

Basic Phenomenology of CA Models – and Transport

- See: P.D. and Hahm, PoP’95; Newman, et al. PoP’96
- Avalanches happen:

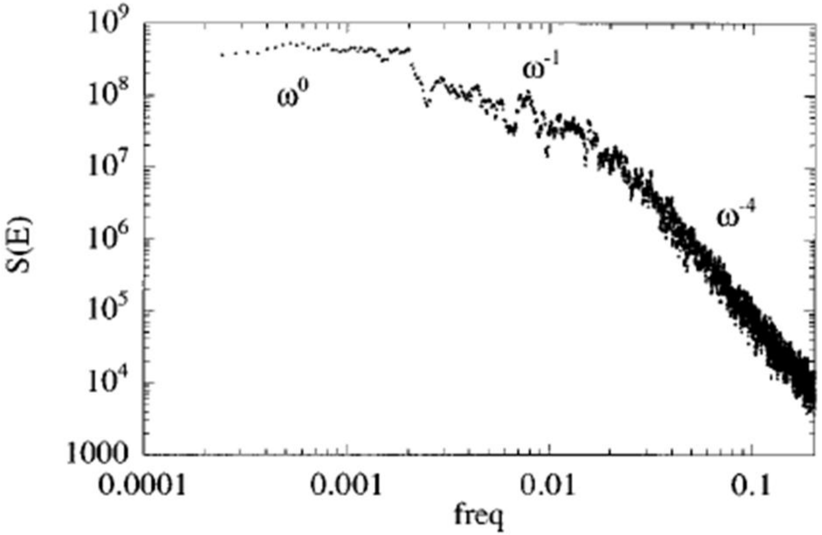


➔ broad spectrum of inward, outward propagating avalanches evident

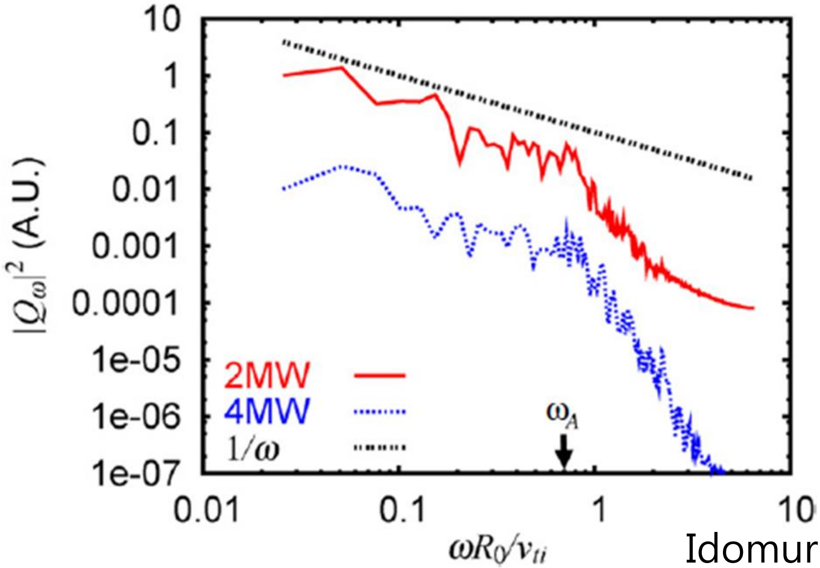
- What is an avalanche?
  - sequence of correlated toppling or eddy over-turning events
  - akin to fall of dominos
  - typically: $\Delta_c < l_{aval} < L_p$ → meso-scale

Are avalanches a consequence of the toy CA model? NO!

- Avalanches observed, studied in flux driven simulations
  - First: Carreras , et. al. PoP'96 → resistive interchanges
  - GK: GYSELA, GT5D, XGC1p …



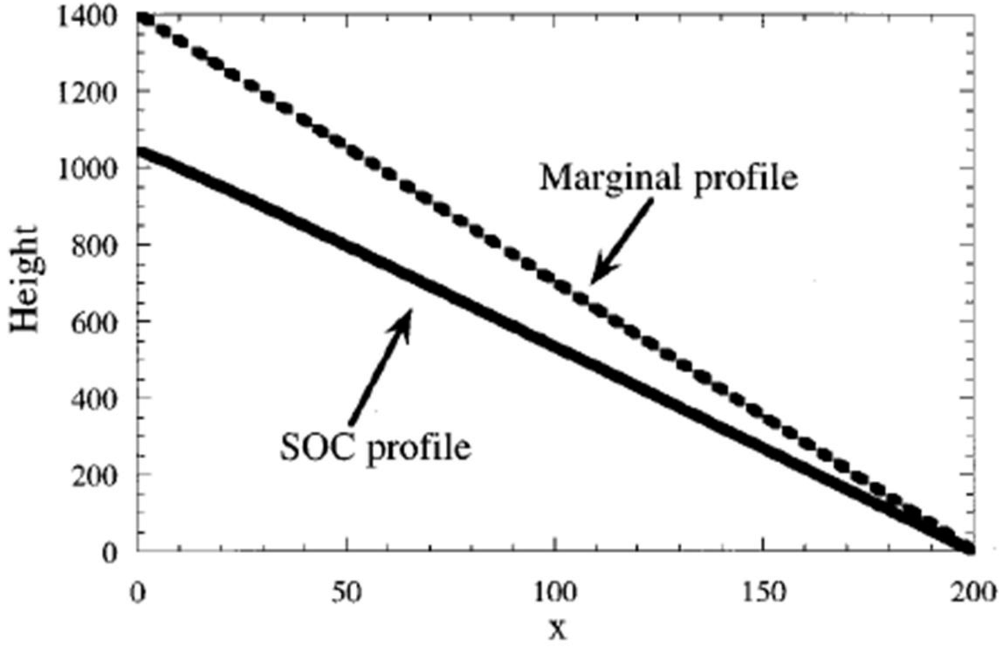
Newman PoP96



Idomura NF09

- Comment:
  - flux tube and δf simulations and those which artificially constrain ∇P, will not capture (full) avalanche dynamics
  - avalanching not captured in quasi-linear models

What Do Profiles Look Like?



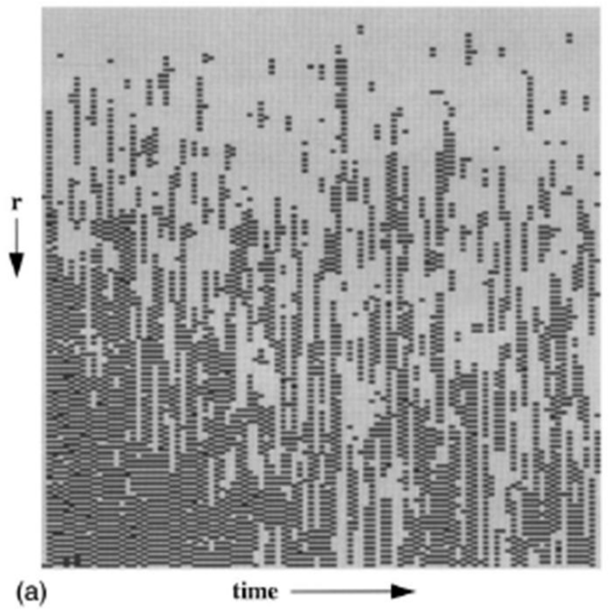
Newman PoP96

- SOC profile ≠ linearly marginal profile
- For moderate drive, SOC occupation profile < marginal profile
- N.B. Important
  - Observe SOC profile approaches marginal profile near boundary
  - Flip intensity largest near boundary → losses
  - As deposition increases, edge gradient steepens

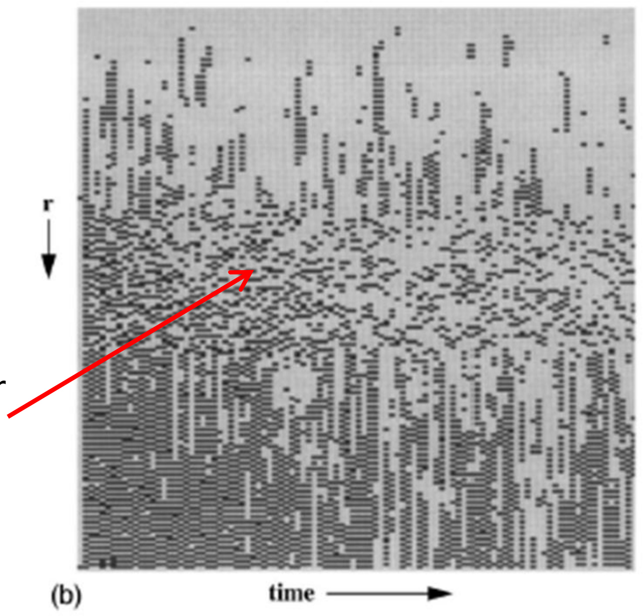
➔ with bi-stable flux, transport bifurcation naturally initiated first, at boundary

External shear decorrelates and destroys avalanches → mean gradient steepens

- Not surprising…
- But, stability rule unchanged!
- Not a ‘linear’ mechanism!
- Three fundamental lessons:
  - Avalanche is basic transport event; broad spectrum over meso-scales.
  - Seemingly ‘non-local’, intermittent phenomena arise from local rules
  - Gradient steepening strongest at boundary ➔ transport bifurcation starts at the edge



(a)



(b)

Shear Zone

Newman PoP96

L→H Transition

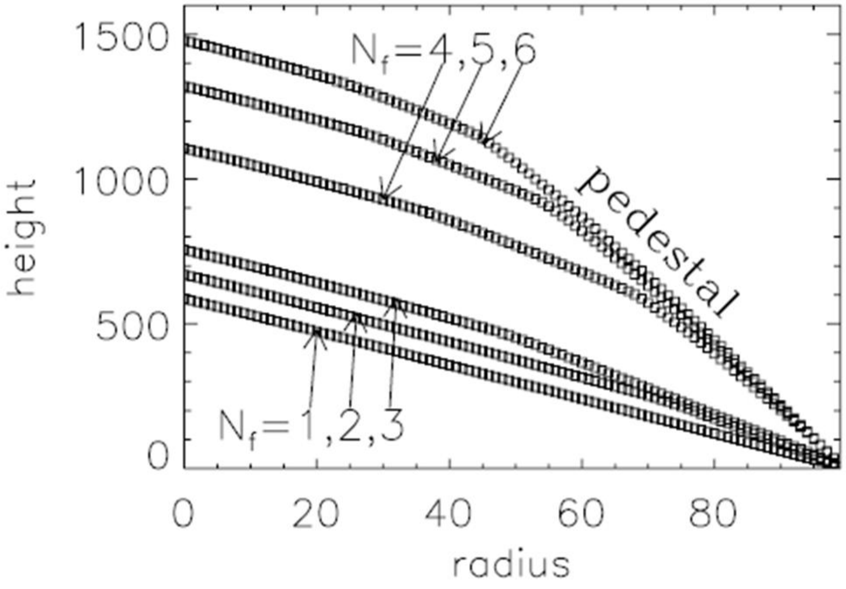
- Now try bi-stable toppling rule, i.e. if $Z_i - Z_{i+1}$ large enough

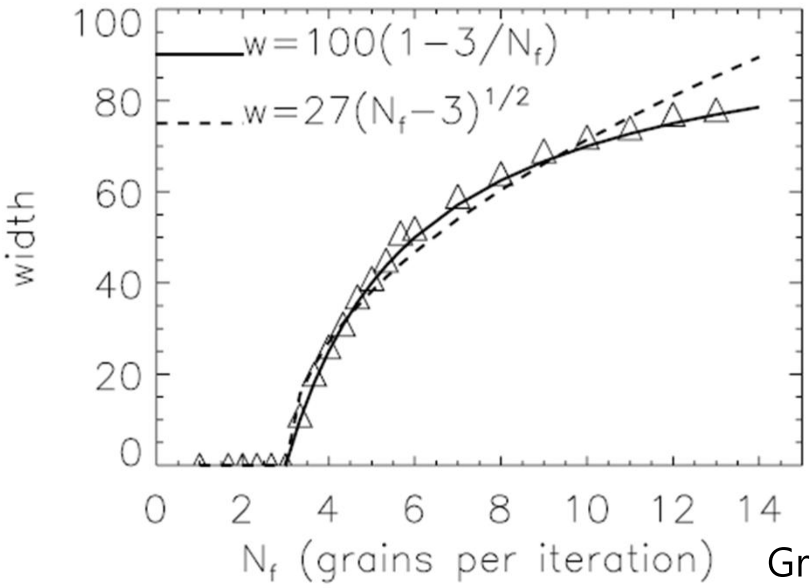
  ➔ reduced or no toppling

- 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!

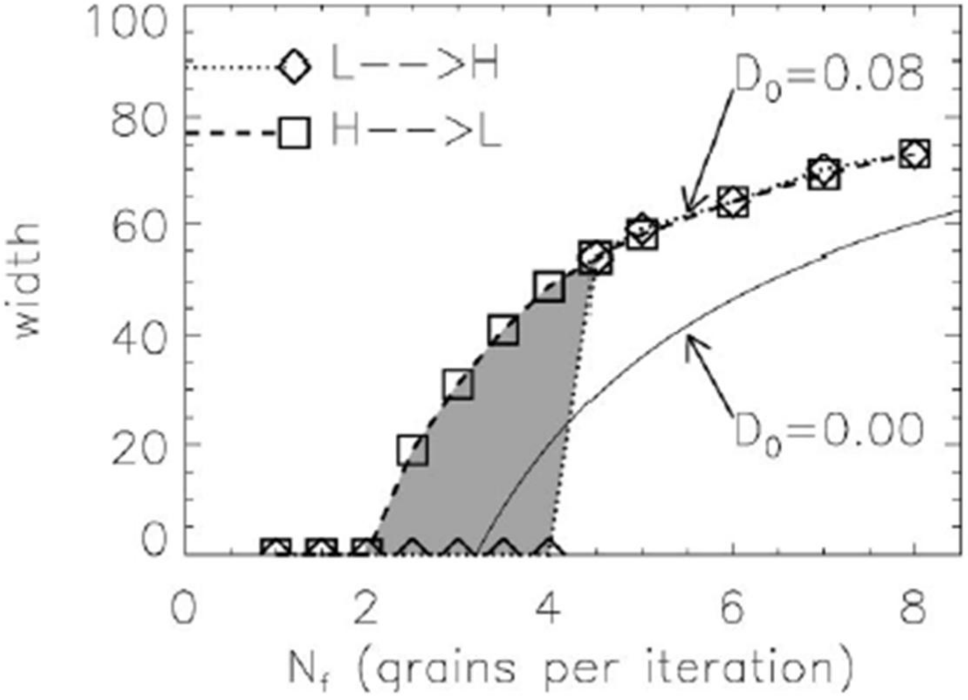




Gruzinov PRL2002

Note

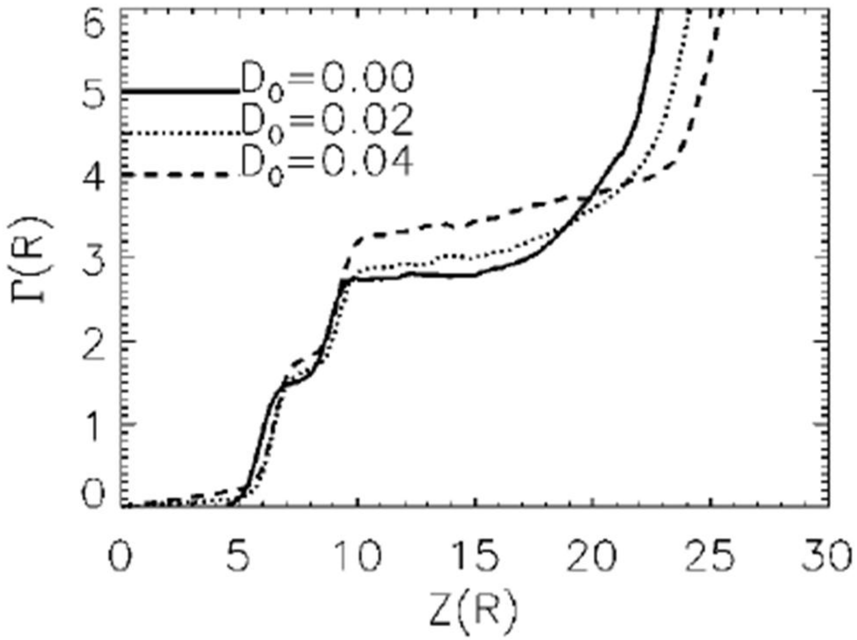
- Critical deposition level required to form pedestal (“power threshold”)
- Pedestal expands inward with increasing input after transition triggered
- Now, including ambient diffusion (i.e. neoclassical)
  - N_F threshold evident
  - Asymmetry in L→H and H→L depositions

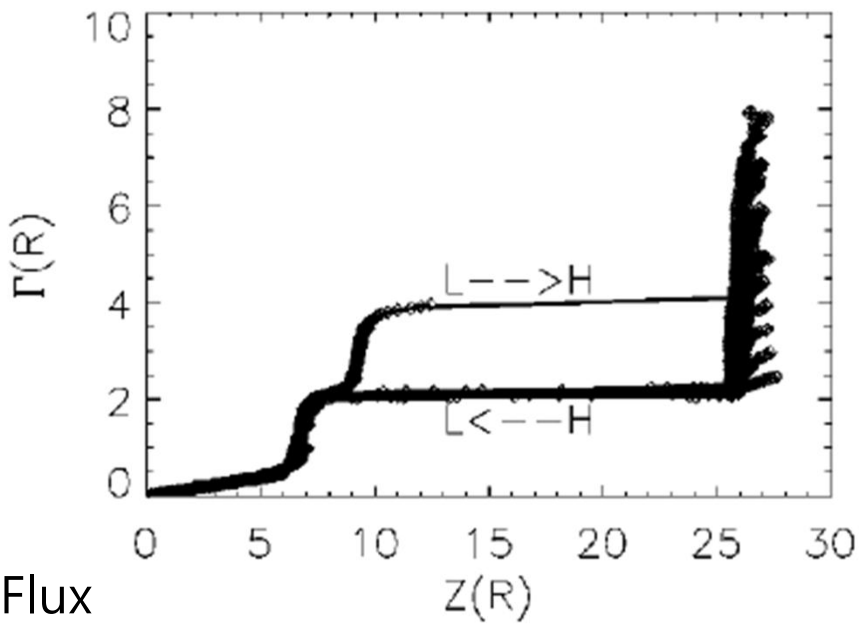


Gruzinov PoP2003

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



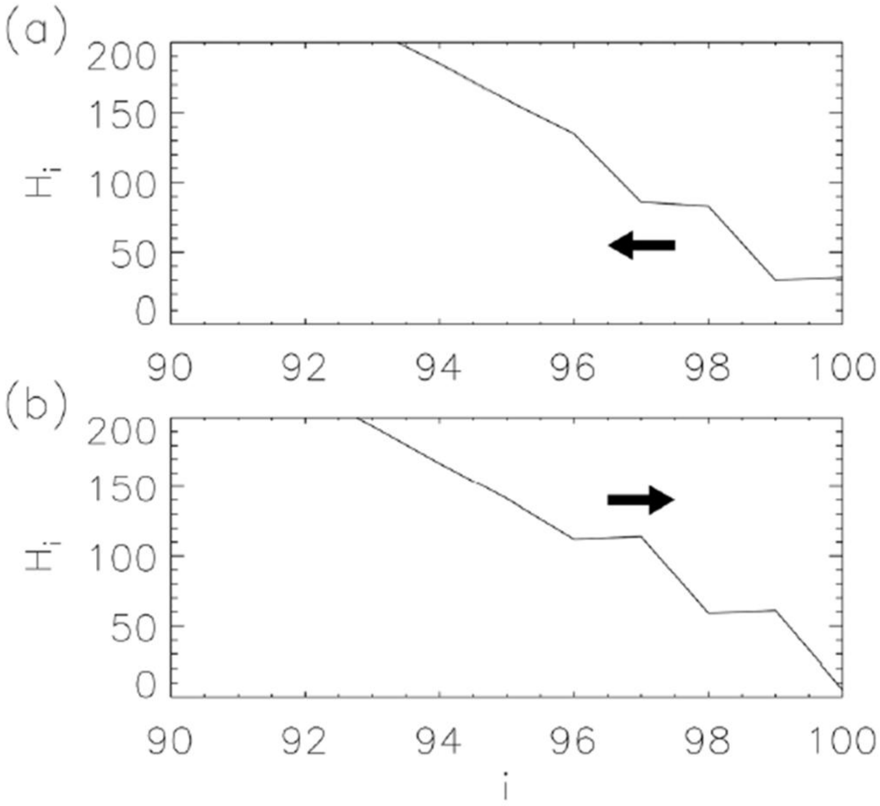


$\Gamma(R)$=Flux
$Z(R)$=Mean Slope

Gruzinov PoP2003

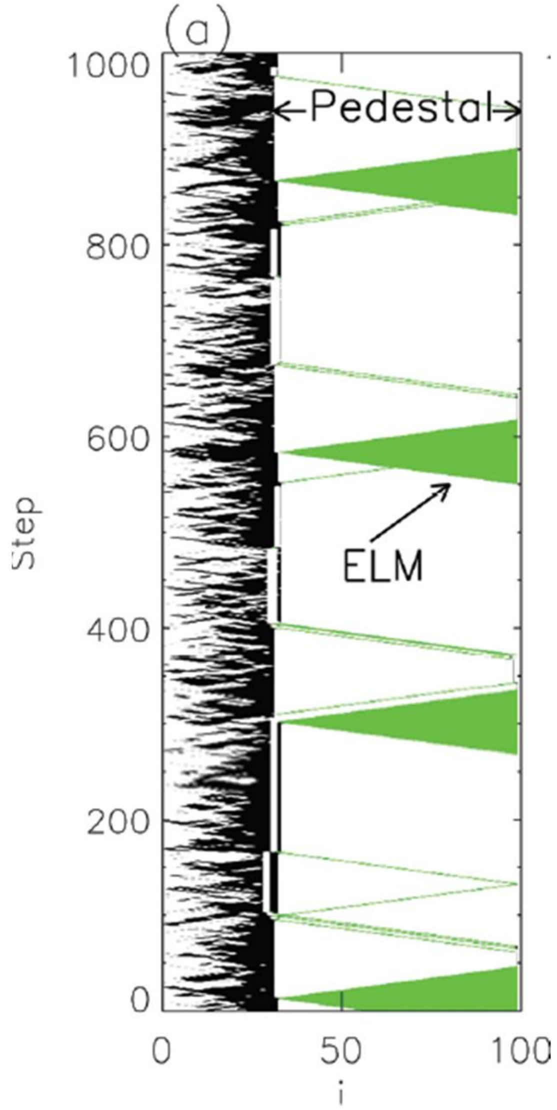
ELMs and ELM Mitigation

- 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?

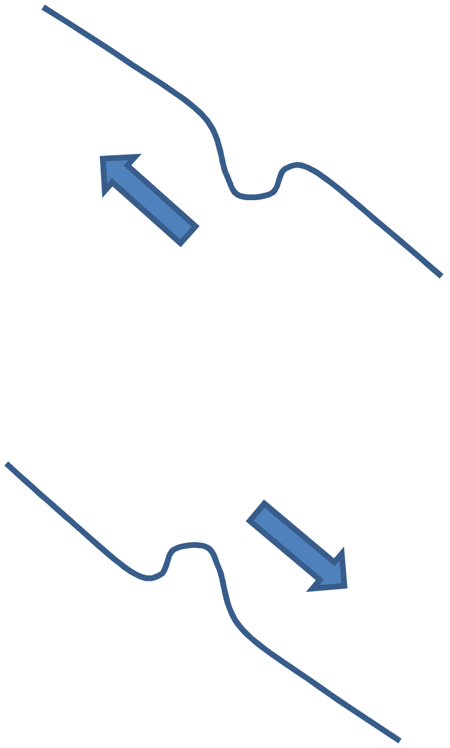
What?

- 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?

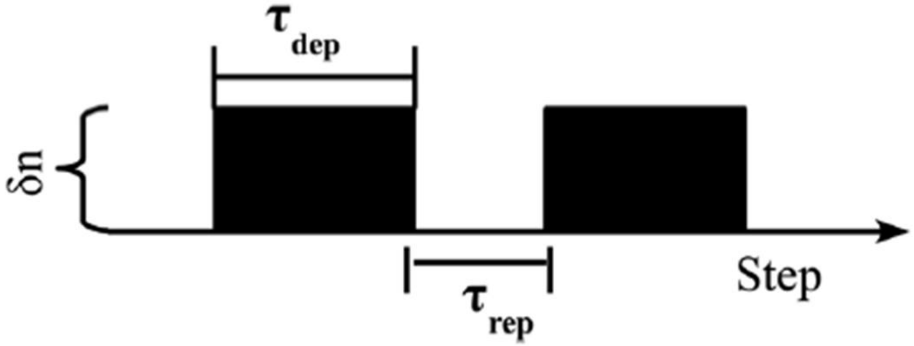
- Toppling cascade:
  - Void forms at boundary, at hard limit
  - Propagates inward, to top of pedestal, triggering avalanche
  - Reflects from top of pedestal, becomes a bump
  - (N.B. core is subcritical → pulse cannot penetrate)
  - Bump propagates out, causing further avalanching
  - Bump expelled, pedestal refills



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

With Active Grain Injection (AGI):

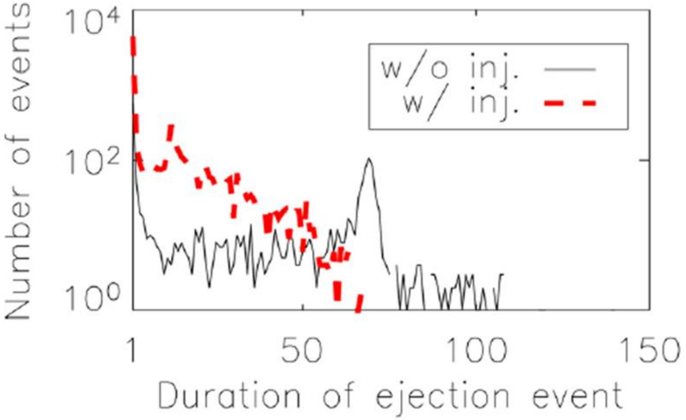
- AGI works by adding a group of grains over a period τ_{dep}
- Can repeat at τ_{rep}



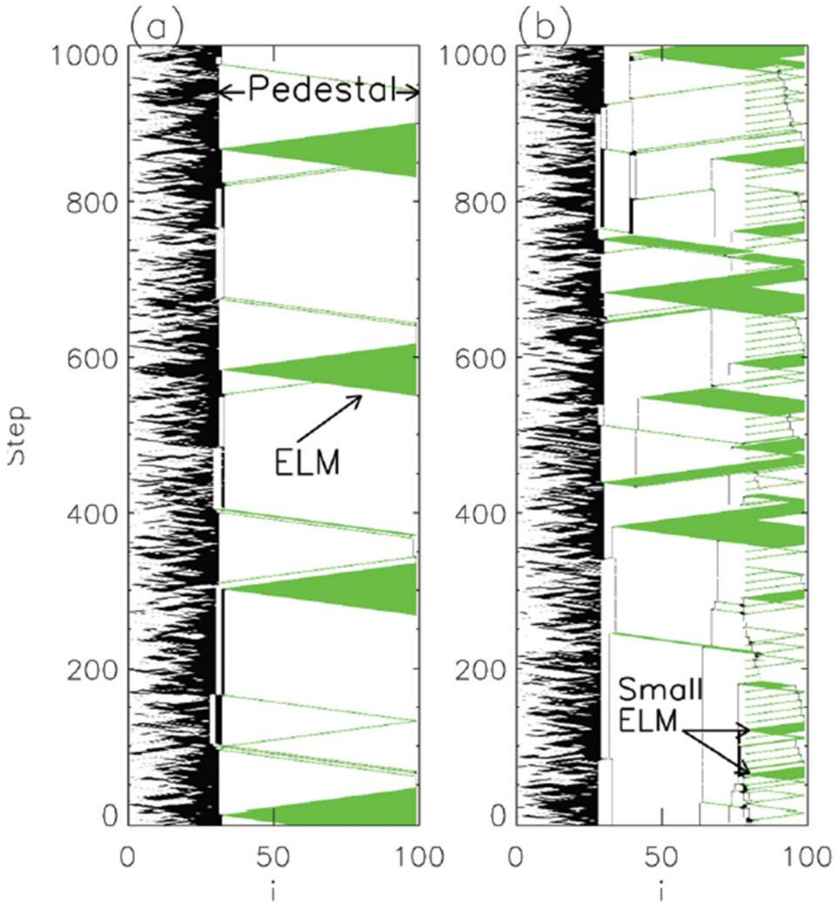
- Obviously, model cannot capture dynamics of actual SMBI, time delay between injection and mitigation. See Z. H. Wang for injection model
- Model can vary strength, duration, location

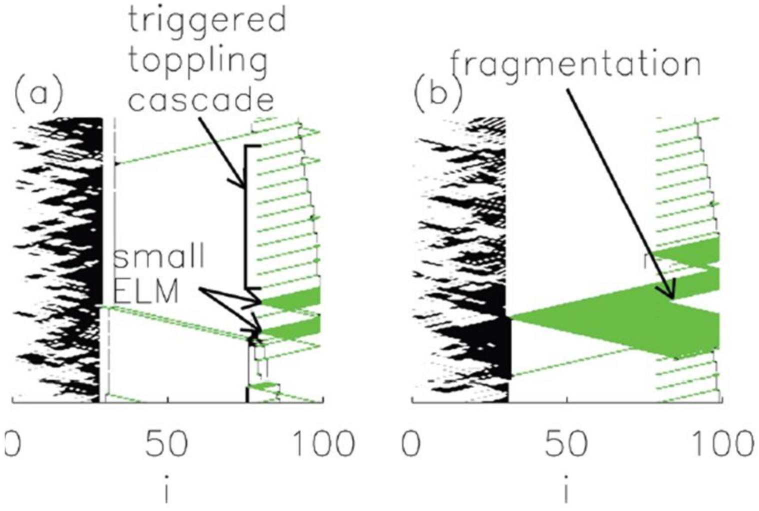
Results with AGI

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



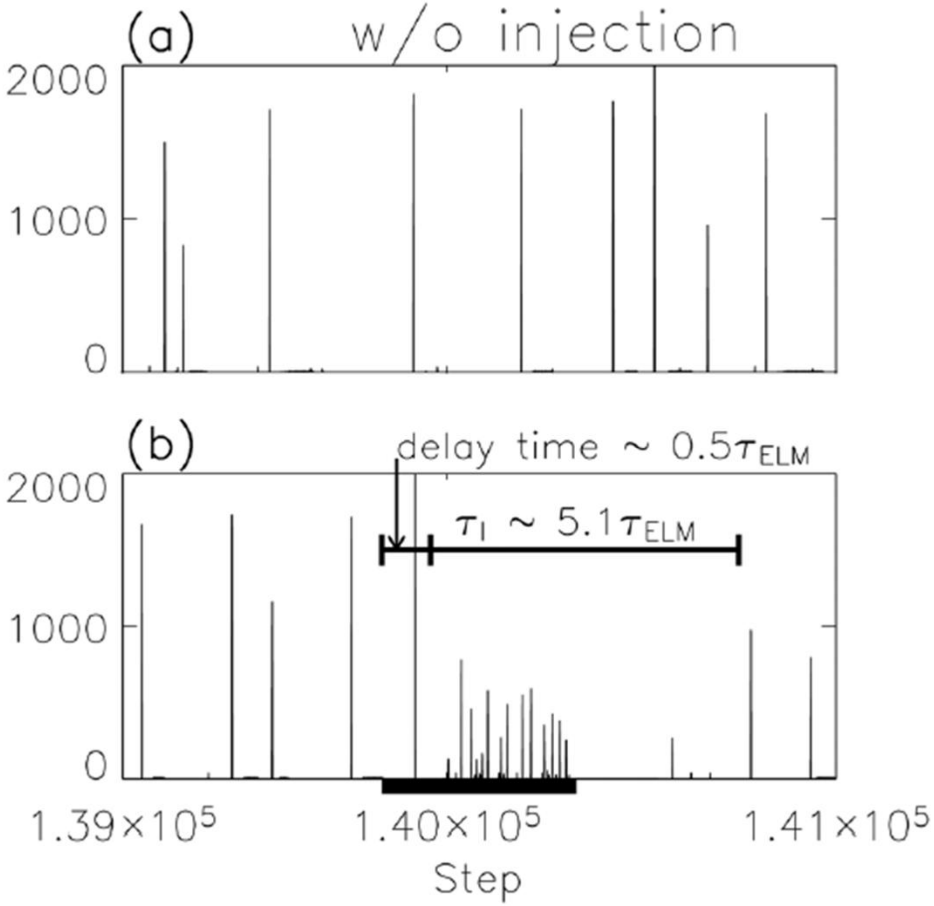
- Mechanism is fragmentation of large avalanches into several smaller ones
- Injection destroys coherency of large avalanches by triggering more numerous small ones
- Consistent with intuition





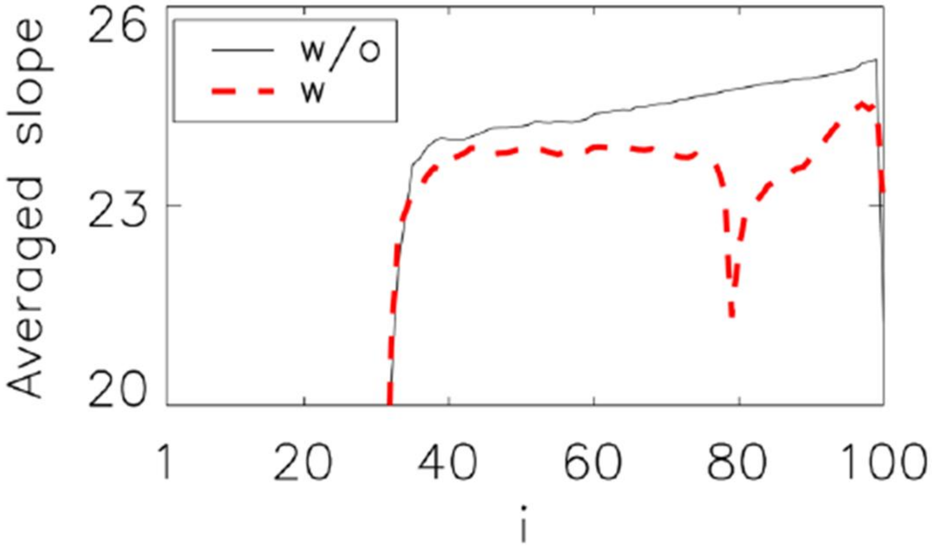
Edge Flux Evolution (in lieu D_α)

- 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

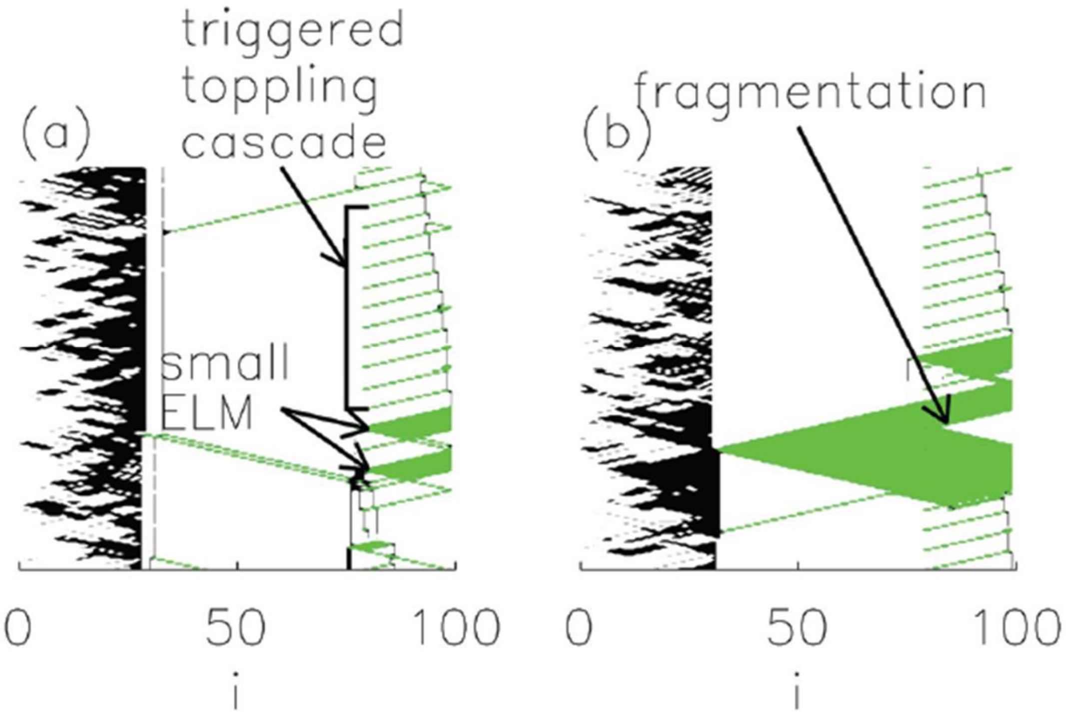
- Drive triggers local toppling → prevents recovery of local gradient
- ‘flat spot’ is effective beach, upon which avalanches break
- τ_I is recovery time of deformed local gradient
- Related to question of optimal deposition location



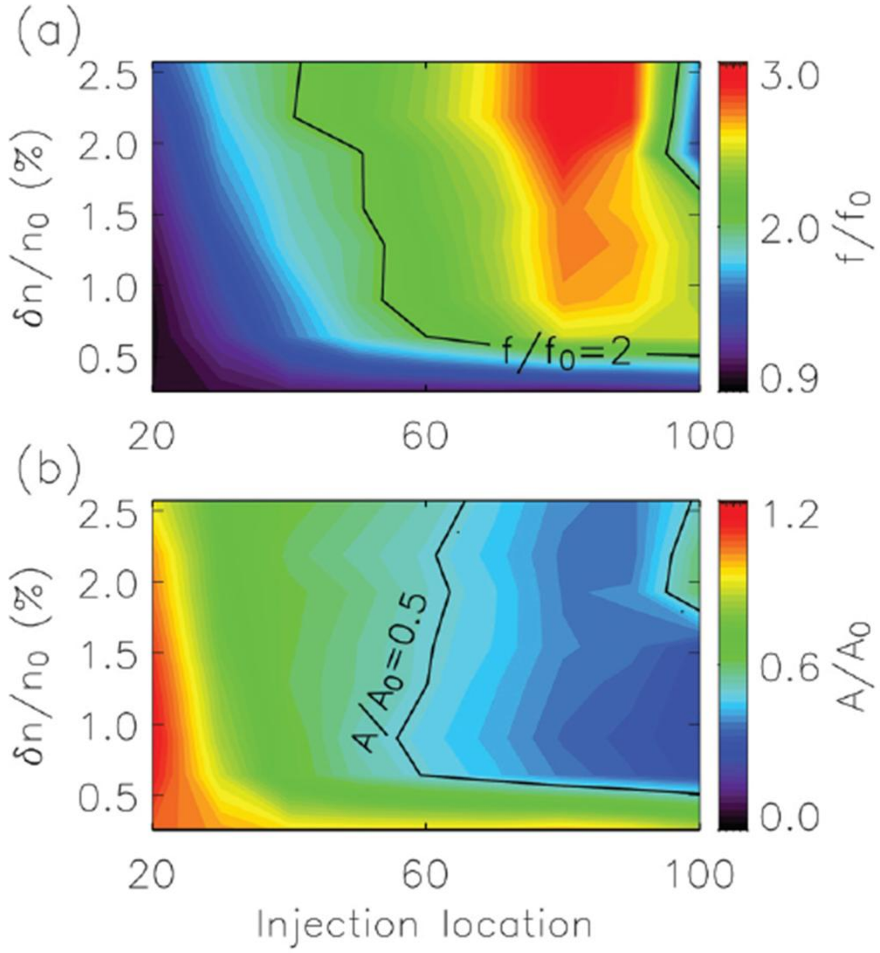
Which deposition location is optimal?

- 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

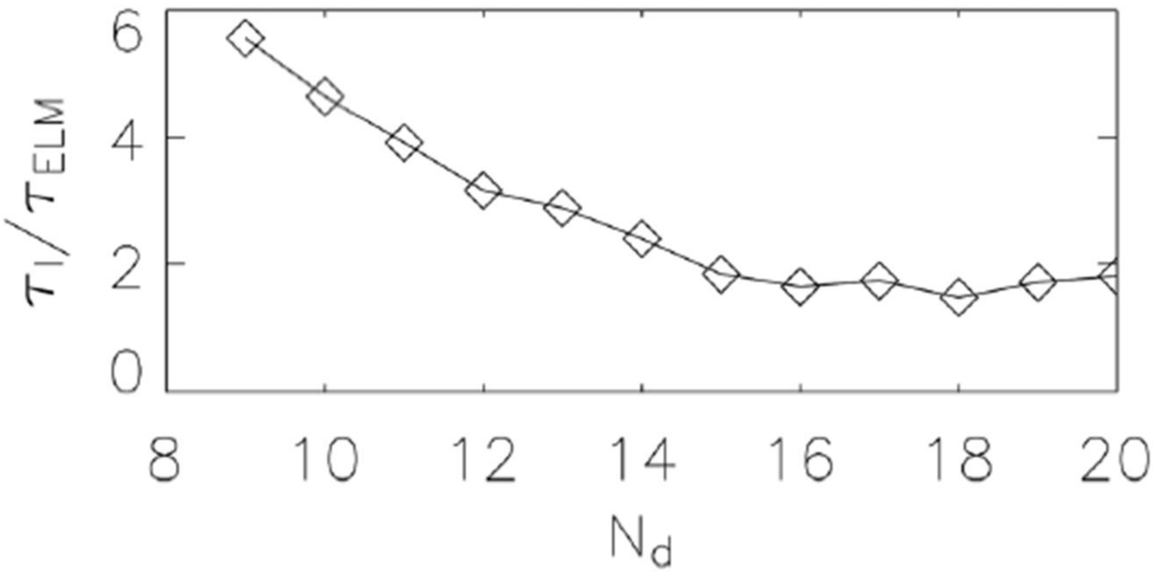
Results of model study point toward optimal deposition near pedestal base

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

Here → optimal location ~ 80

Injection Pulse Duration

- Can adjust τ_{dep} so $\frac{\tau_{dep}}{\tau_{ELM}} \sim \frac{\tau_{dep}^{exp}}{\tau_{ELM}^{exp}}$ ('exp' ➔ Xiao, et. al.; HL-2A)
- τ_I emerges as $\tau_I \sim 5\tau_{ELM}$ for parameters chosen
- τ_I is recovery time of injection-modified profile. This is related to, but, not quite same, as pedestal 're-fill time'.
- τ_I (normalized to fixed baseline) drops with increasing deposition



Rough comparison of dimensionless results:

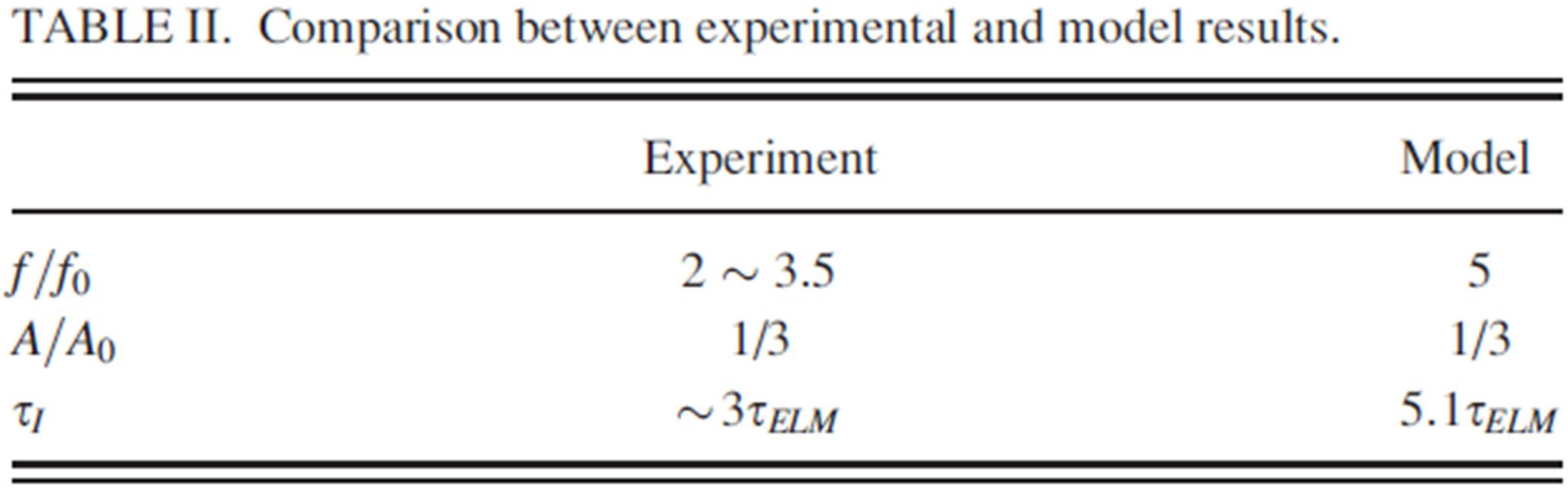


TABLE II. Comparison between experimental and model results.

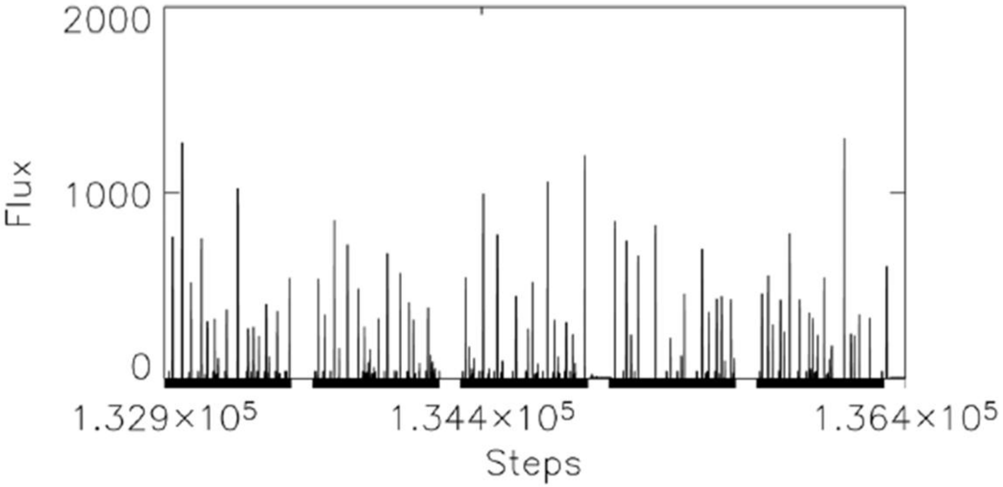
	Experiment	Model
f/f_0	$2 \sim 3.5$	5
A/A_0	1/3	1/3
τ_I	$\sim 3\tau_{ELM}$	$5.1\tau_{ELM}$

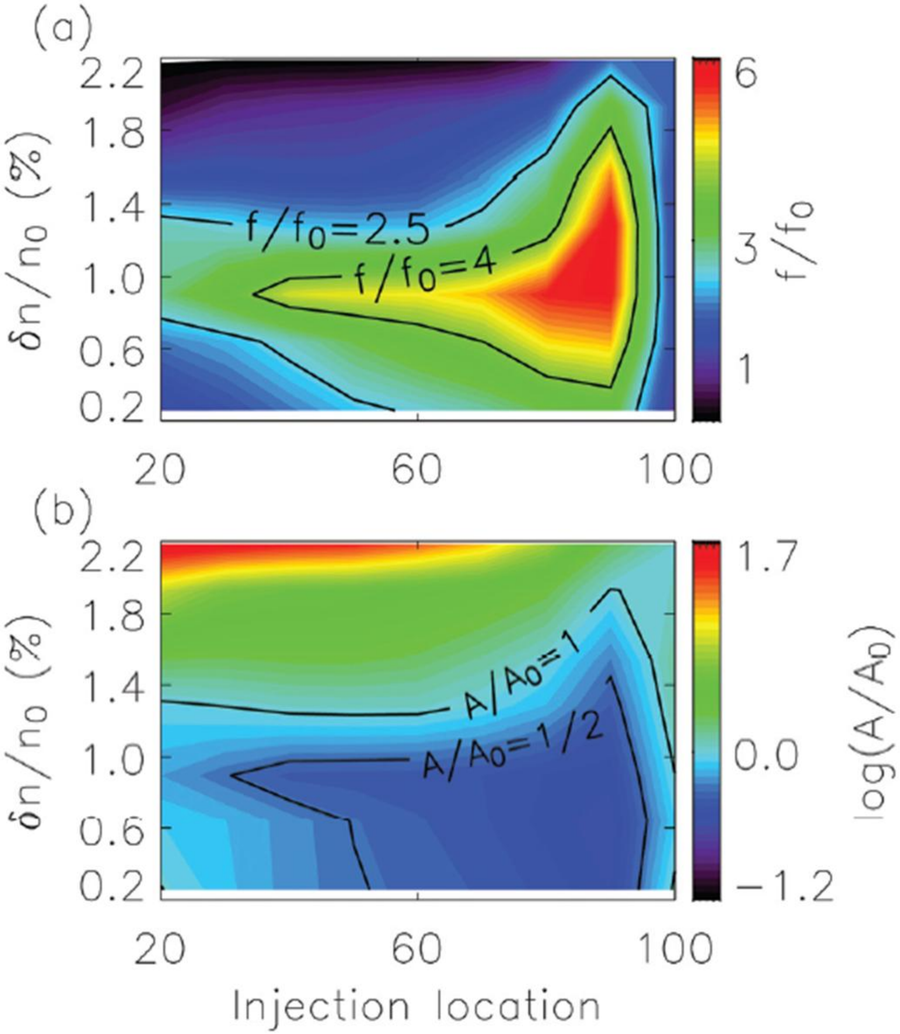
What of Repetitive Injection?

- Take: $\tau_{rep} \sim \tau_{ELM} < \tau_I$

  Bold = AGI

- Injection near base optimal
- Stronger injection reduces effectiveness





Summary of CA Model Results

- Shallow AGI can mitigate ELMs by altering avalanche distribution

  ➔ reduce # larger, increase # smaller

- Mechanism is decorrelation of pedestal-spanning avalanches by inducing localized flattening of gradient. inhomogeneities in pedestal gradient hinder large events.

- Optimal deposition characteristics are:
  - Shallow → near base of pedestal
  - Strong enough to hit hard gradient boundary

Summary of CA Model Results, cont'd

- τ_I set by duration of gradient inhomogeneities
- Can sustain mitigation with $\tau_{rep} < \tau_I$
- Shaped pulse injection correlates with (some) HL-2A results
- More generally, ELM-like phenomena emerge from synergy of bi-stable turbulence, ambient diffusion and hard gradient limit w/o detailed MHD dynamics

Some Open Questions

- Peeling effect?
    - Set toppling rule to $\mathrm{c}\int dr\,\frac{dP}{dr} \sim P_{ped}$ ongoing
    - Nonlinear peeling evolution?
- Nature of 'hard limit' ?
    - Turbulence vs burst?
    - See Xi, Xu, P.D. submitted
- Ambient edge fueling? (c.f. Lang, Zohm; FEC 2012) i.e. what is "gain" from injection? ←→ avalanche decorrelation due beach effect?
- SMBI vs pellet ?

Concluding Thoughts

- What, really, is an ELM?

  Is it better though of as an ERP?

- “What’s in a name? that which we call a rose,

  By any other name would smell as sweet?”

  - from “Romeo and Juliet” by William Shakespeare