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TH/P2-9

Minimal Model Study for ELM Control by Supersonic Molecular Beam Injection and Pellet Injection

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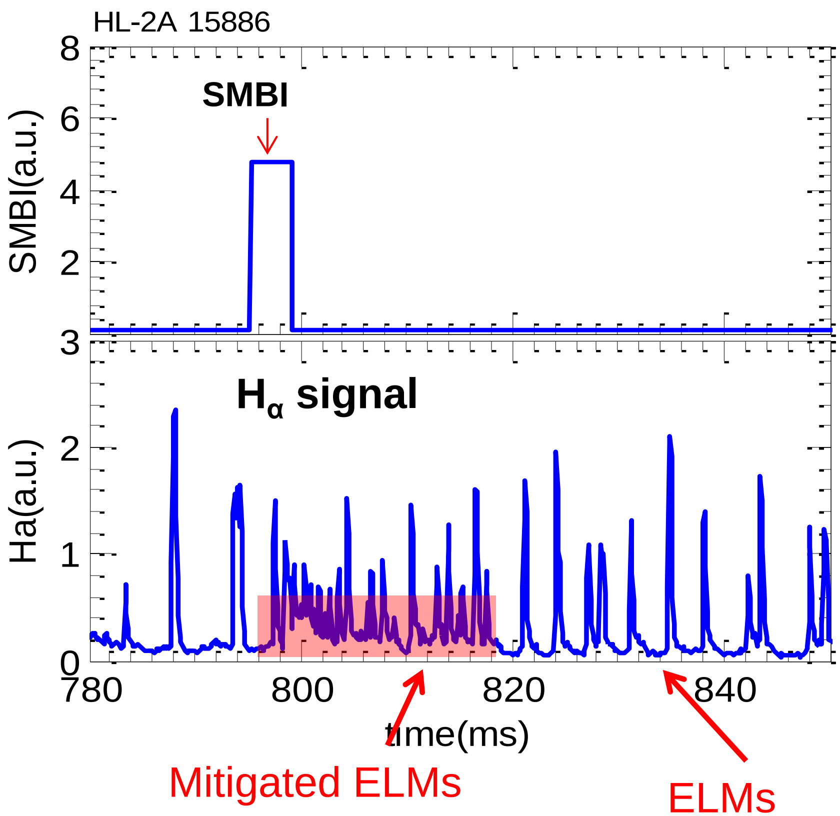
14 October
14:00 – 18:45

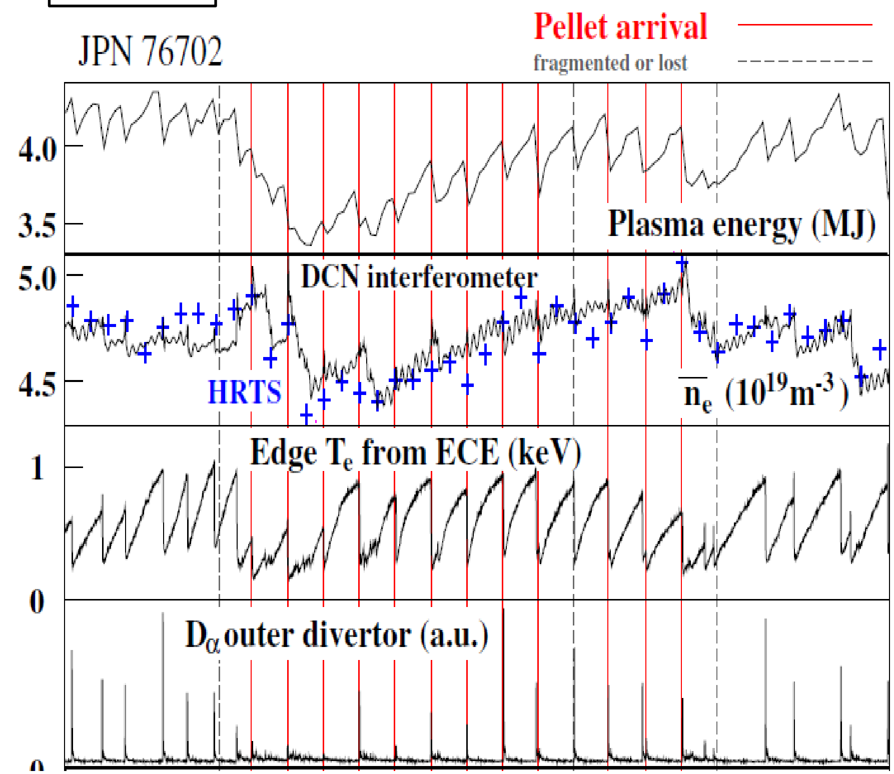
ELM control with SMBI and pellet injection

SMBI



- KSTAR (Type-I) and HL-2A(Type-III) (Xiao *et. al.* *2014*) experiments demonstrated that SMBI can mitigate ELM → reduction of H_α amplitude and increase of ELM frequency.

PI



- JET (type-I) (Lang *et. al. 2011*) experiments demonstrated that pellet injection can trigger ELM

Why sandpile model?

- ELM mitigation simulation is still beyond the scope of first principle code up to now.
- We need simplicity, so as to derive understanding.
- Sandpile is minimal model for ELM phenomena.

Analogies between the sandpile transport model and a turbulent transport model

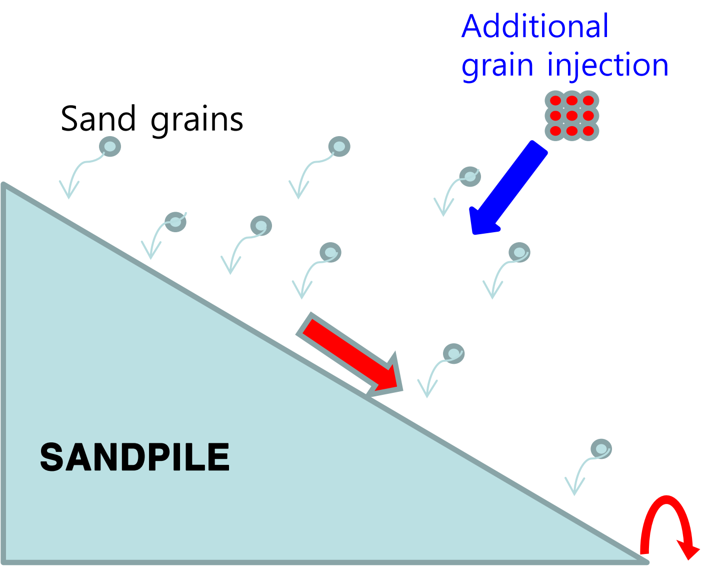
Turbulent transport in toroidal plasmas	Sandpile model
Localized fluctuation (eddy)	Grid site (cell)
Local turbulence mechanism:	***Automata rules:***
Critical gradient range for micro-turbulence	Unstable slope range
Moderate local eddy-induced transport	Fixed number of grains moved if unstable
Diamagnetic electric field shear suppression of turbulence	Steep slope stable range
Critical gradient for MHD event	Hard limit **(∇P : ballooning)**
Strong MHD-induced transport	Topple as many grains as needed to relax slope to stable state
Total energy/particle content	Total number of grains (total mass)
Heating noise/background fluctuations	Random input of grains/Fueling
Energy/particle flux	Sand flux
Mean temperature/density profiles	Average slope of sandpile
Transport event	Avalanche

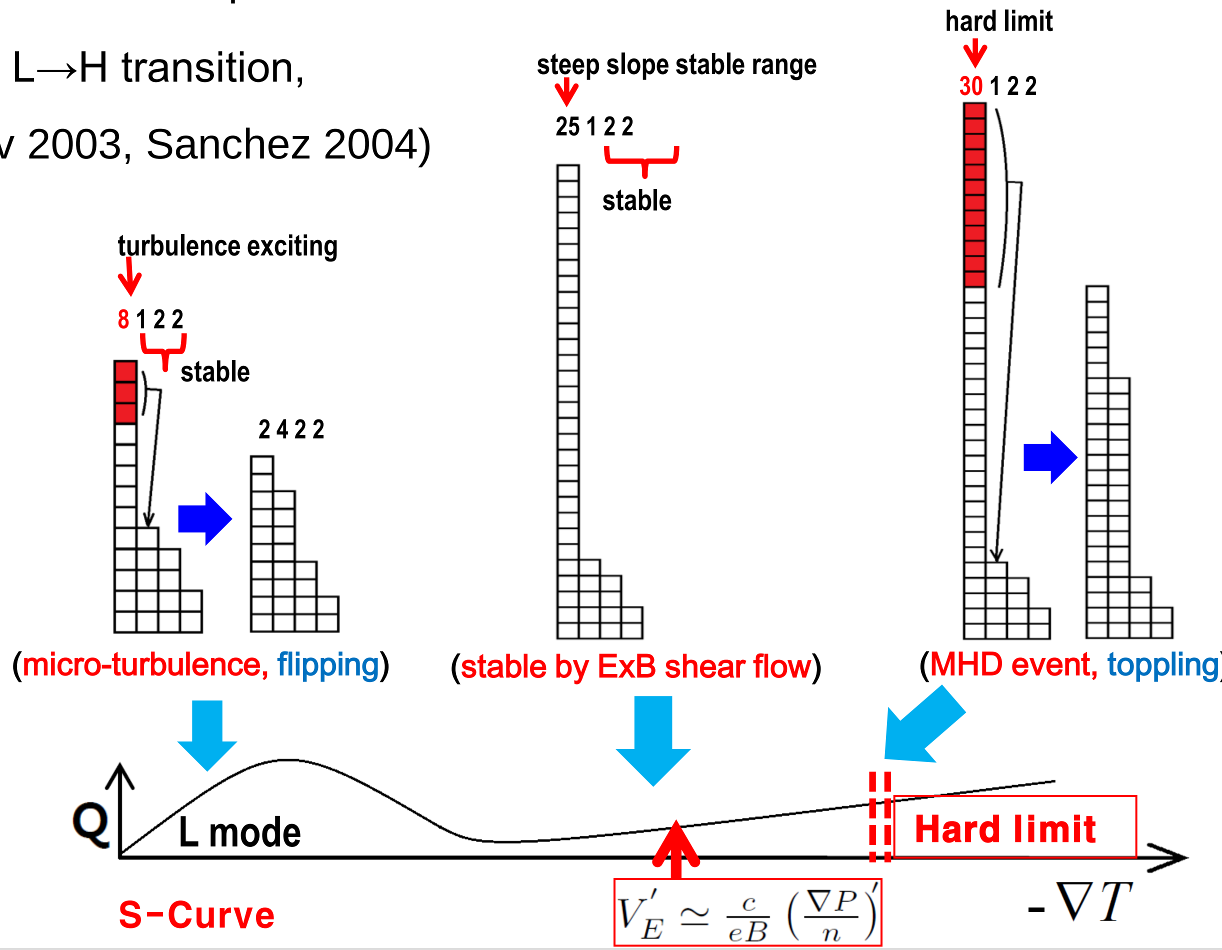
Ref. Newman et al. 1996, Gruzinov et al. 2003

Sandpile model

- **Sand Pile Model for ELMy H mode**
  - Bi-stable cellular automaton rule (Gruzinov 2002)
  - Simplest model for tokamak plasma transport
  - Yet retaining key physics e.g. L→H transition, hysteresis, ELM etc. (Gruzinov 2003, Sanchez 2004)

All that is necessary to capture essentials of L→H transition and ELM dynamics is diffusive bi-stable sand pile + hard upper limit on gradient.

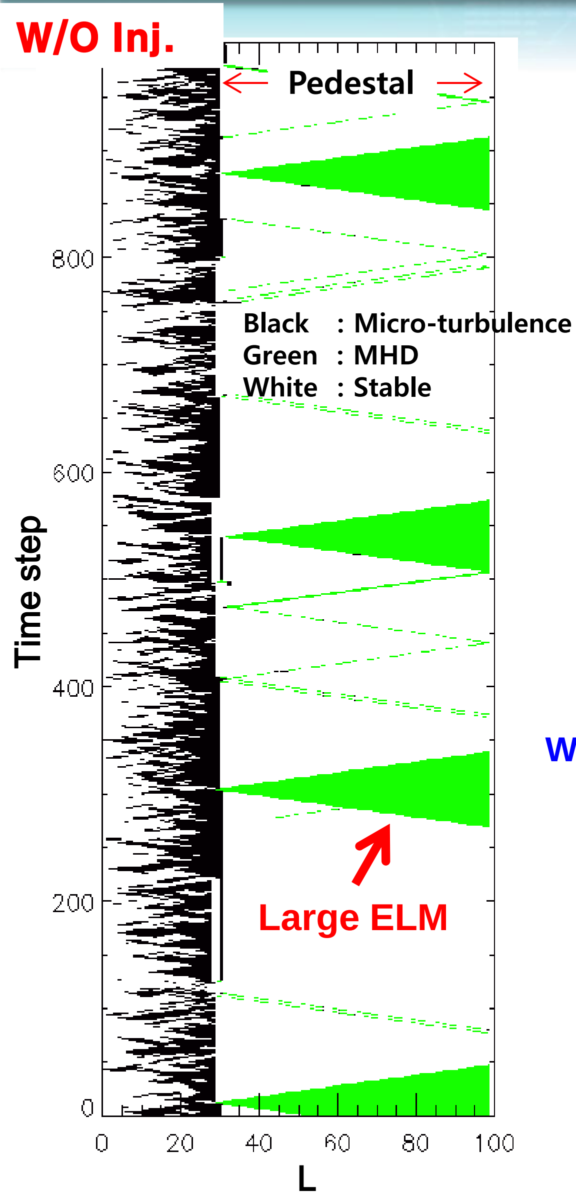


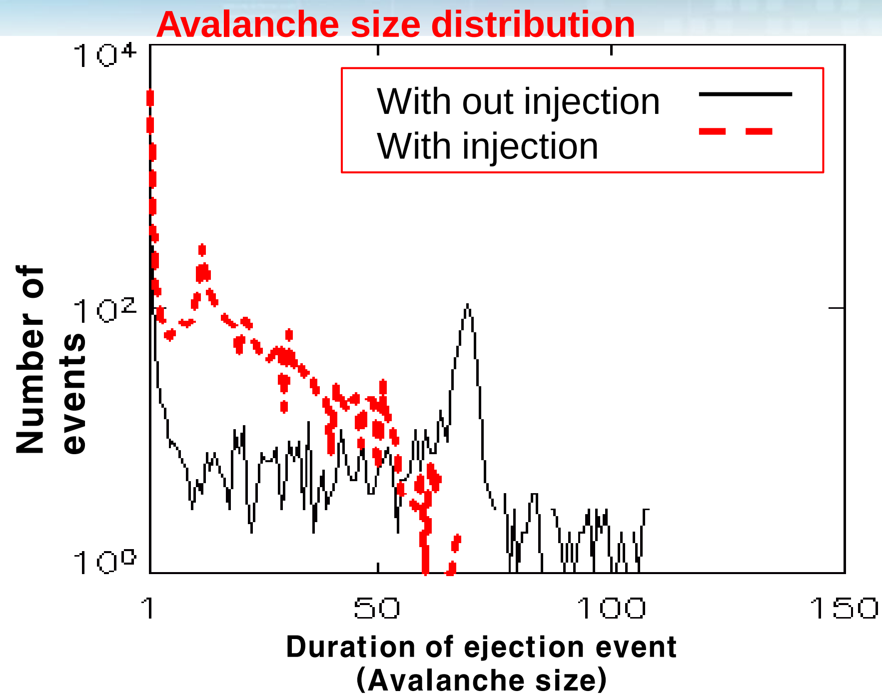


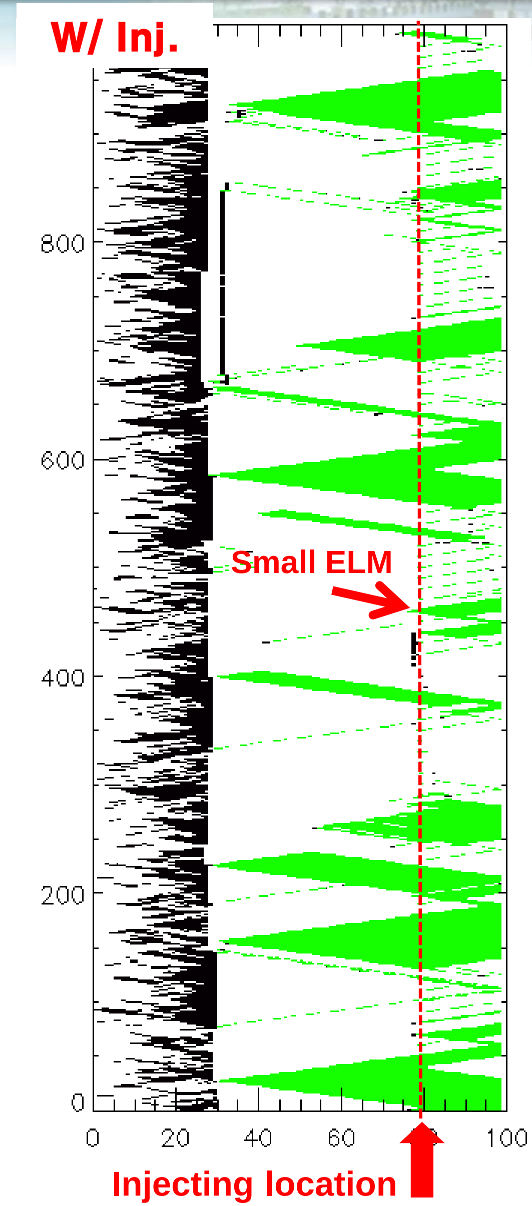
Detailed rules (Rhee et al. 2012)

- Two stable regimes
  - Stable slope ($Z_l < 8$)
  - Steep gradient stable slope ($20 < Z_l < 30$) ⇒ **"diamagnetic electric field shear suppression of turbulence"**
- Two unstable regimes (transport)
  - Unstable slope ($8 \le Z_l \le 20$): Flippling of D_z number of grains to downhill ⇒ **"micro-turbulence"**
  - Hard limit ($30 \le Z_l$): Toppling of $1+(Z_l-8)/2$ to downhill ⇒ **"Ballooning limit (∇P)"**
- Baseline diffusion
  - Diffusion flux: $D_0(Z_{l-1} - Z_l)$ ⇒ **"Neoclassical transport"**
- Grain injection
  - N_{Pl} number of grains are randomly scattered in the sand pile ⇒ **"Deposition"**
  - *Additional direct injection of grains into pedestal* ⇒ ***"SMBI"***

Physics of ELM mitigation by SMBI w/ ballooning (Review of Rhee et al. 2012)







What we learned from former work

- AGI simulating SMBI trigger frequent toppling events
- It prevents toppling avalanche, i.e. type-II ELMs.
- Induced density deformation fragments large sized toppling avalanche.
- AGI reduces the slope profile of pedestal and makes cavity at the injection position without pedestal top position change

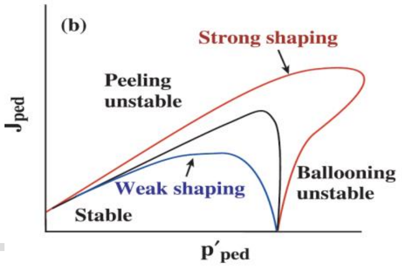
Additional transport rule for peeling instabilities

Why additional rule?

- The existing sandpile rule has the flipping to mimic ballooning instabilities driven by ∇P.
- Therefore, ELMs appearing in the sandpile model can be interpreted as type-II.
- However, we need to include the peeling instabilities for the study of broader H-mode experiments.

Requirement

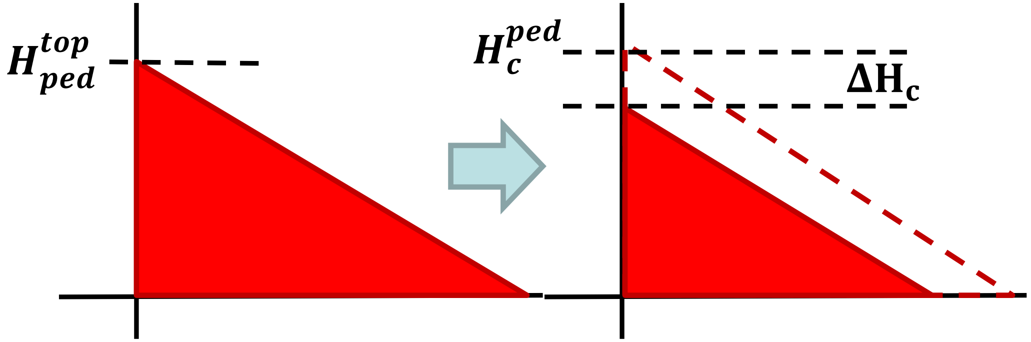
- The peeling instabilities are driven by the total current flowing in the pedestal and have global features. The total current mostly comes from the bootstrap fraction, which is proportional to the pressure gradient.
- Therefore, we can approximate the total current in the pedestal as the integral of the pressure gradient across the region. i.e. $j_{ped}^{top} \sim c\int_{r0}^{r1}\frac{dP}{dr}dr \sim cP_{ped}^{top}$.



Snyder et al., 2007 NF

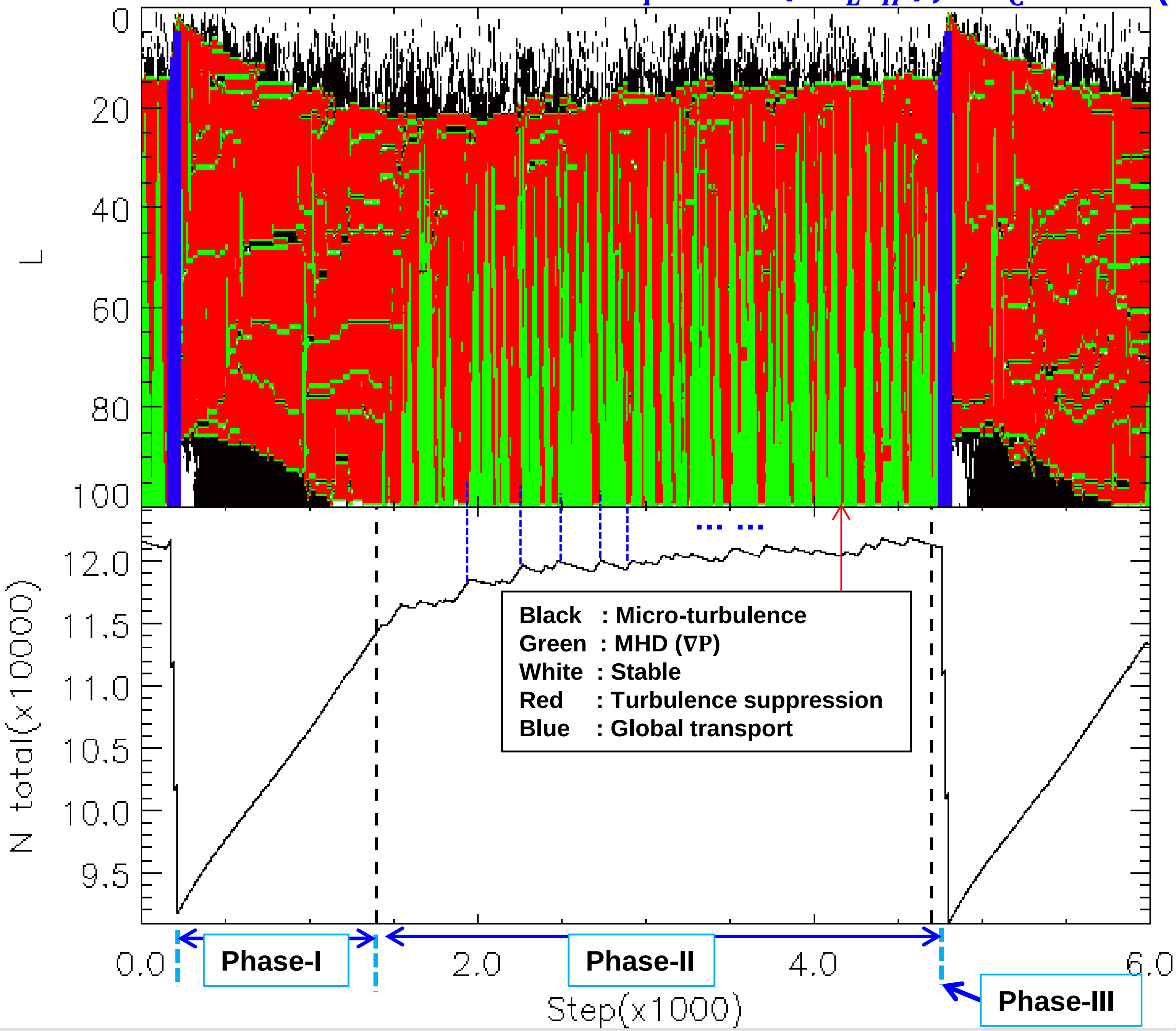
Transport rule for peeling

- Measure the averaged pedestal top height H_{ped}^{top} during assigned time ΔT.
- Time averaging is analogy of bootstrap current recovering time
- Check whether $H_{ped}^{top} > H_c^{ped}$. If so, **remove sands globally** (i.e. across the whole pedestal) to satisfy total grains $H_{top}^{ped} < H_c^{ped}$ while keeping the local gradients.
- We can calculate mean H_{top}^{ped} during inter-"ELM" periods.
- Then, we can tune ΔH_c to match the ratio $\int_{H_{ped}^{bot}}^{H_{ped}^{top}} dx\ \Delta H_c/H$ (i.e. stored energy in the pedestal) from the sand-pile modeling.
- We set $H_c^{ped} = 2100$, which is pedestal top height of $N_F = 15$ case



The role of global transport: Spatio-temporal evolution w/ peeling

$N_F = 12 \; (3N_{L-H})$, $\Delta H_C = 120$ (10% of pedestal grains)



Phase-I

- Ballooning free at the edge
- Total number of grains increase rapidly

Phase-II

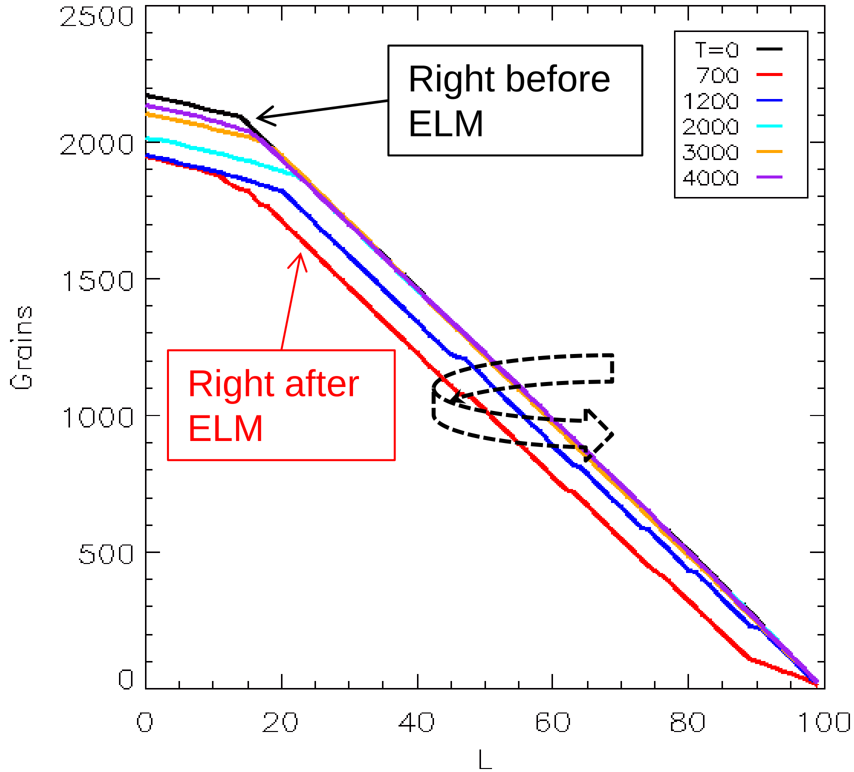
- Ballooning type MHD events are governing this phase.
- Local transport events form transport avalanches spanning whole pedestal
- Outward flux during avalanche is $\Gamma_N = 15$ w/ ballooning which is larger than fueling ➔ Total grains decrease.
- Total grains increase between ballooning events ➔ Time averaged total grain increase slowly.

Phase-III

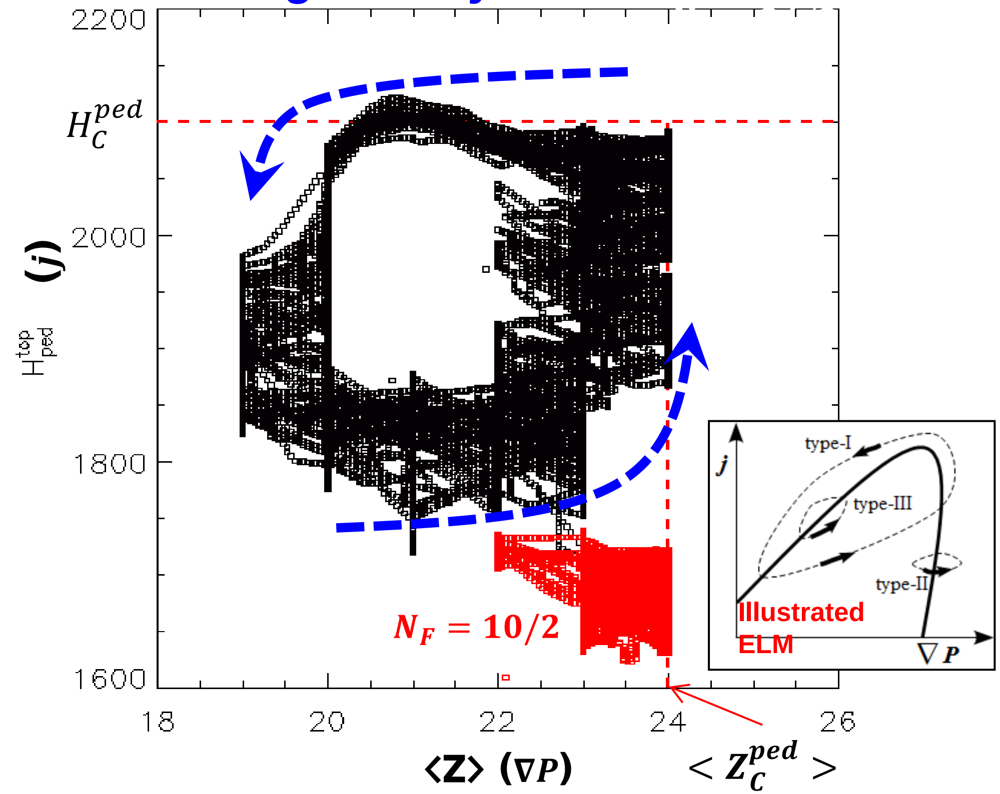
- Peeling type Global MHD events occur 2~3 times in a short time.
- Pedestal top move to inward.

Time evolution of ELM cycle

Profile change



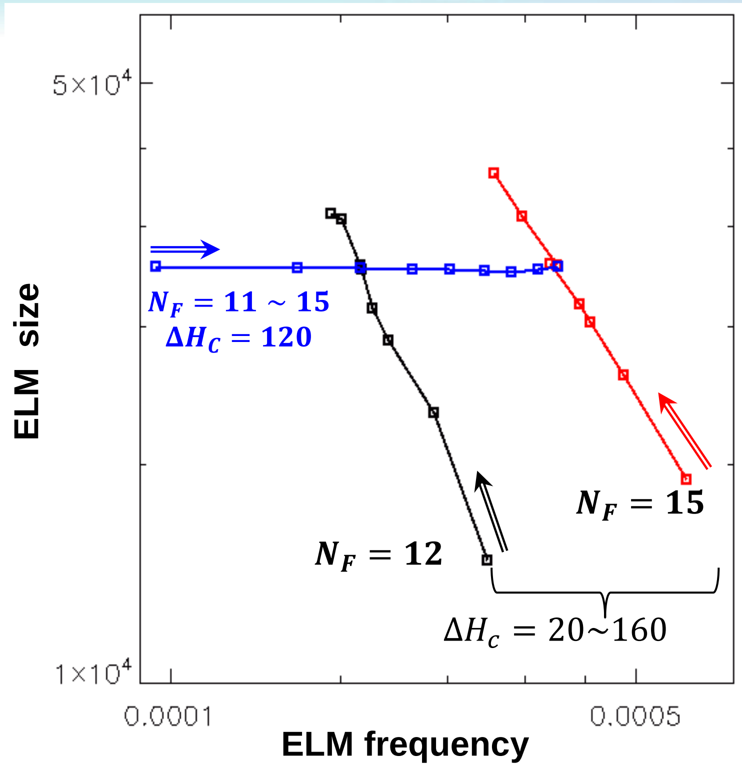
Gradient and Height Evolution during ELM cycles

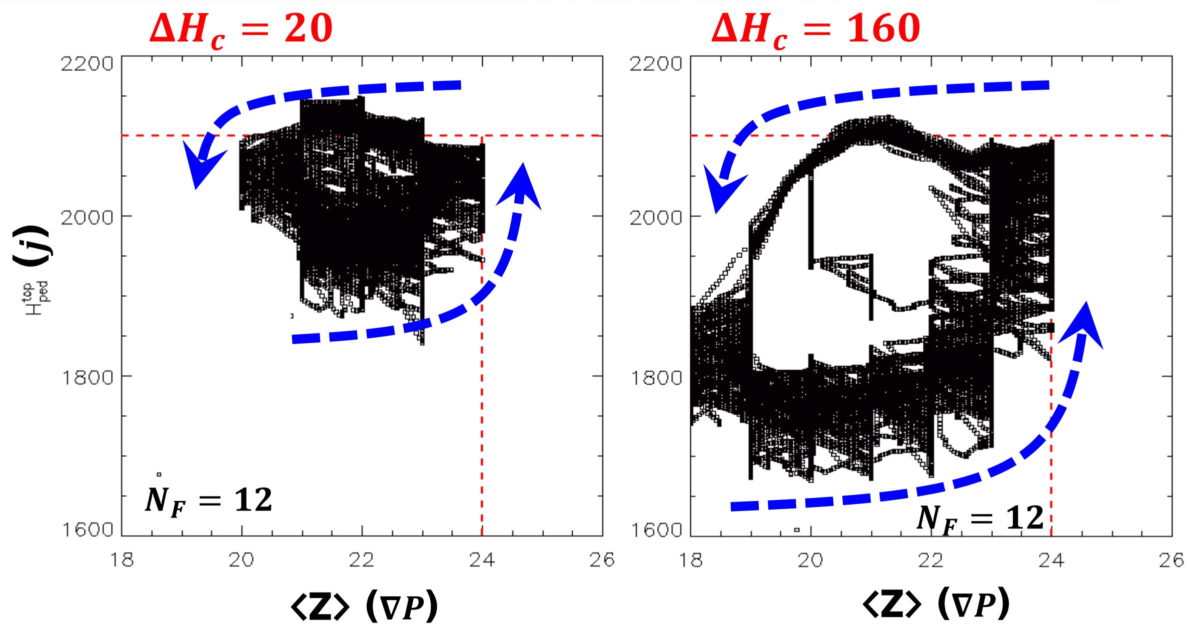


- Right before ELM, pedestal top approach to the ΔH_C^{top}.
- Global transport reduce pedestal top height w/ small reduction of pedestal slope.
- Recovering of pedestal bottom slope, pedestal extends to the core

- ELM cycle makes big circle bounded by H_C^{ped} and $< Z_C^{ped} >$.
- At first path meet $< Z_C^{ped} >$ limit and H_{ped}^{top} increases and hit the limit.
- Peeling-ballooning limit triggers large type-I ELMs

Parameter scan: Fueling rate and ΔH_c





- ELM frequency increases with increasing fueling rate (a characteristic feature of type–I ELM)
- ELM size is not related with the fueling rate
- ΔH_C increases ELM size but reduce the ELM frequency.
- ELM size is correlated with the size of circle in the phase diagram

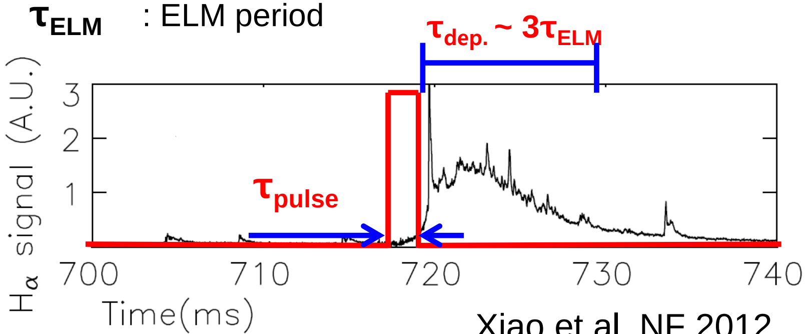
SMBI and PI modeling: Additional grain injection

HL-2A SMBI Experiment

τ_{pulse} : SMBI pulse duration (Xiao et al.)

$\tau_{dep.}$: Deposition duration to the plasma of neutral particle injected by SMBI pulse

τ_{ELM} : ELM period

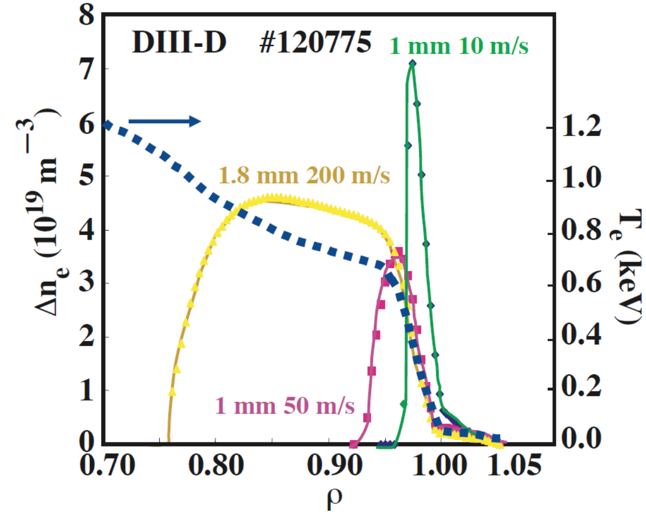


HL-2A #14052

Xiao et al, NF 2012

- H_α signal of SMBI indicates of deposition neutral density

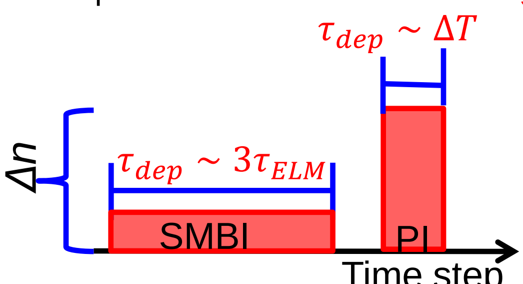
Pellet Injection



Baylor et al 2008 EPS

Additional Grain Injection

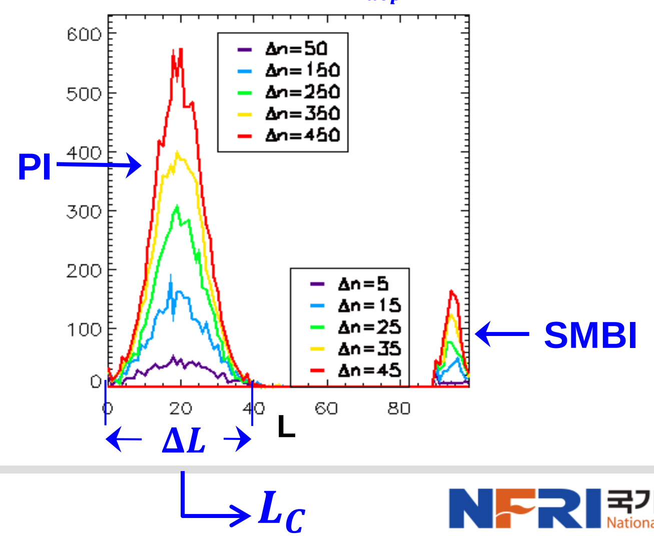
Neutral particle deposition duration=> additional grains injection duration



- Δn is the number of additionally injected grains during unit time step.

$\Delta t = 1 < \Delta T = 20 = \tau_{dep}^{PI} < \tau_{dep}^{SMBI} = 400 < \tau_{ELM}$

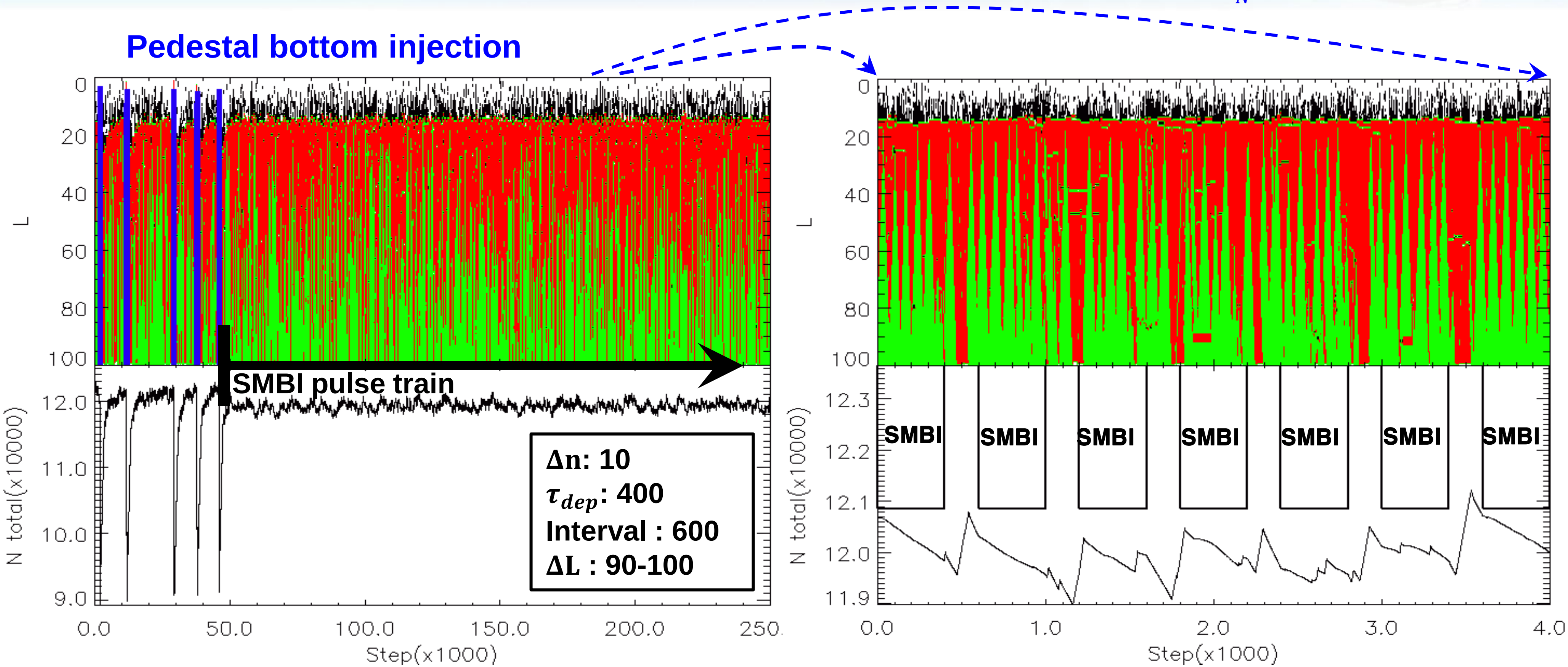
Deposition profile $\tau_{dep} = \Delta T$



SMBI to ELMy H-mode $\tau_{ELM} = 10764(\sim 1\tau_N)$ of type-I ELM

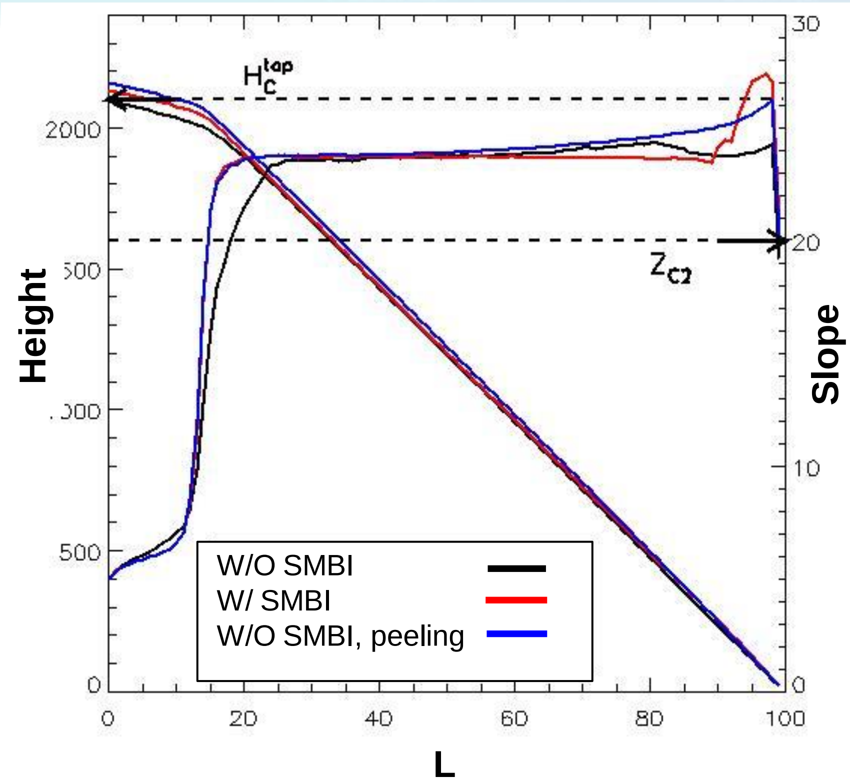
τ_N: Grain confinement time

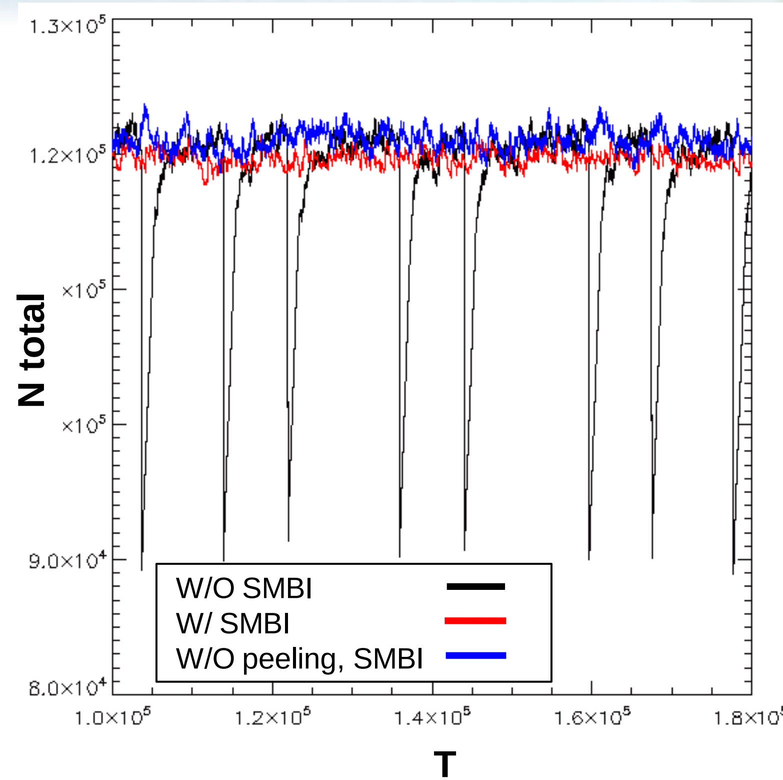
Pedestal bottom injection



- **Type-I ELMs are replaced by type-II or type-III (i.e. ballooning events) ELMs during SMBI**
- **SMBI trigger pressure limit event spanning whole pedestal → drive strong transport, which prevent pedestal from reaching global peeling limit**
- **This mechanism is the same with the ELM mitigation by SMBI in the cases w/o peeling (T.Rhee PoP2012)**

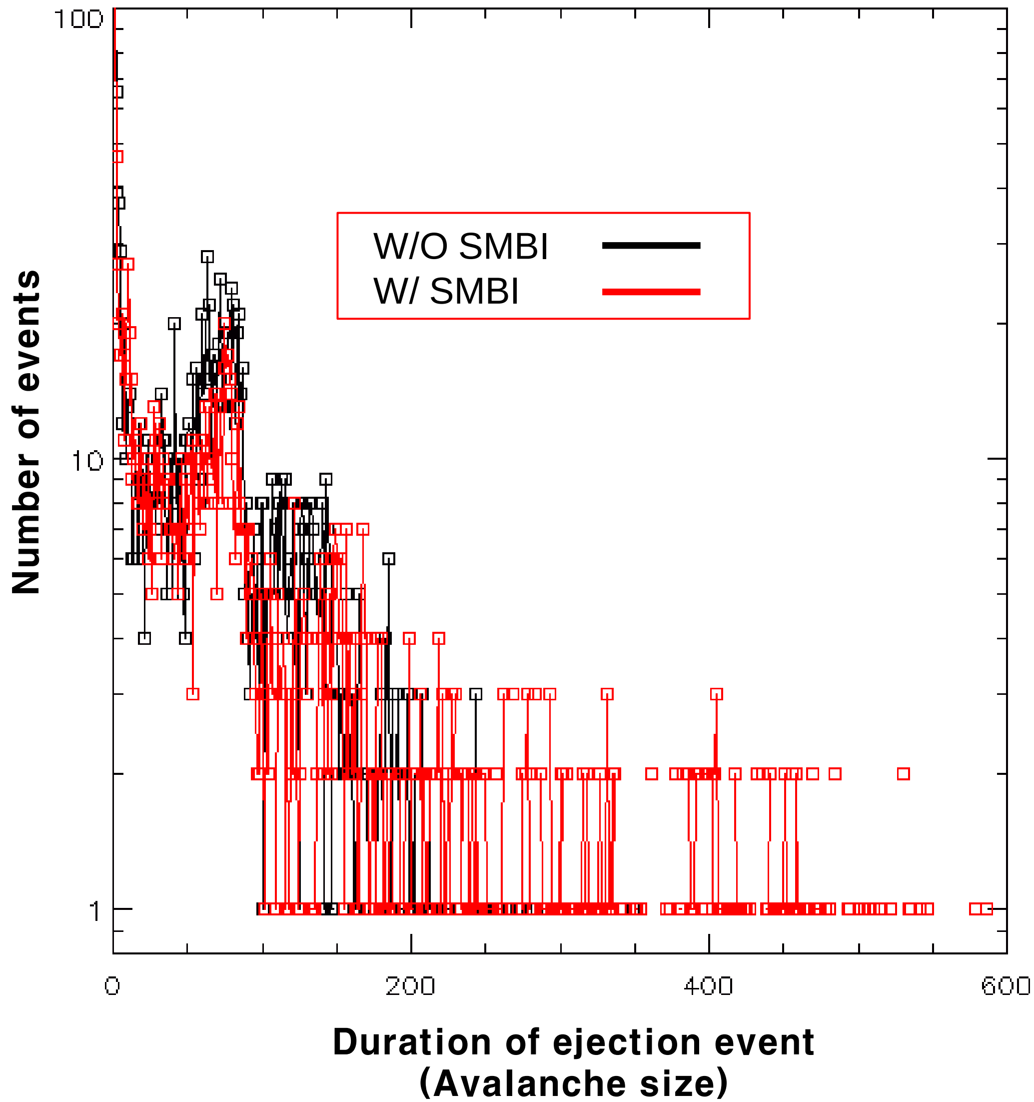
Change by AGI





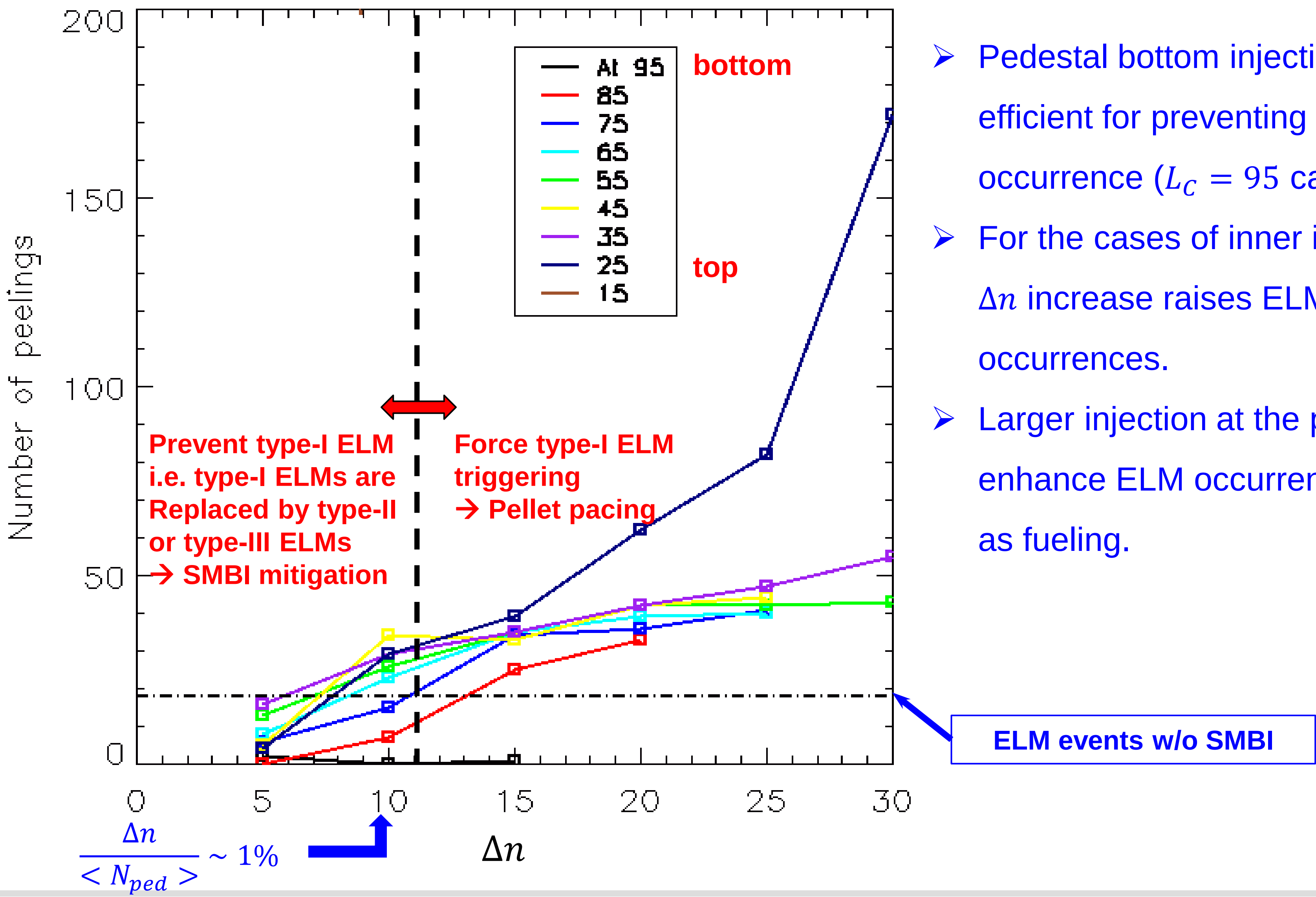
- Slope in SMBI deposition range, L=90~100, is increased by SMBI but inner range is reduced compared to w/o SMBI and peeling case.
- Pedestal top height slightly decrease compared to w/o peeling and SMBI ➔ SMBI prevents H_{ped}^{top} hitting H_C^{ped}
- But average pedestal top height increase compared to w/o SMBI and w/ peeling case

Avalanche size distribution change by SMBI



- Duration of ejection event by ballooning event represent the ballooning limit ELM size
- W/O SMBI, event size is quasi-regular 70~150.
- SMBI enhances occurrence of large sized avalanche ➔ Enhance transport of pedestal by ballooning limit event
- Enhanced transport prevents profile buildup for peeling-ballooning limit event

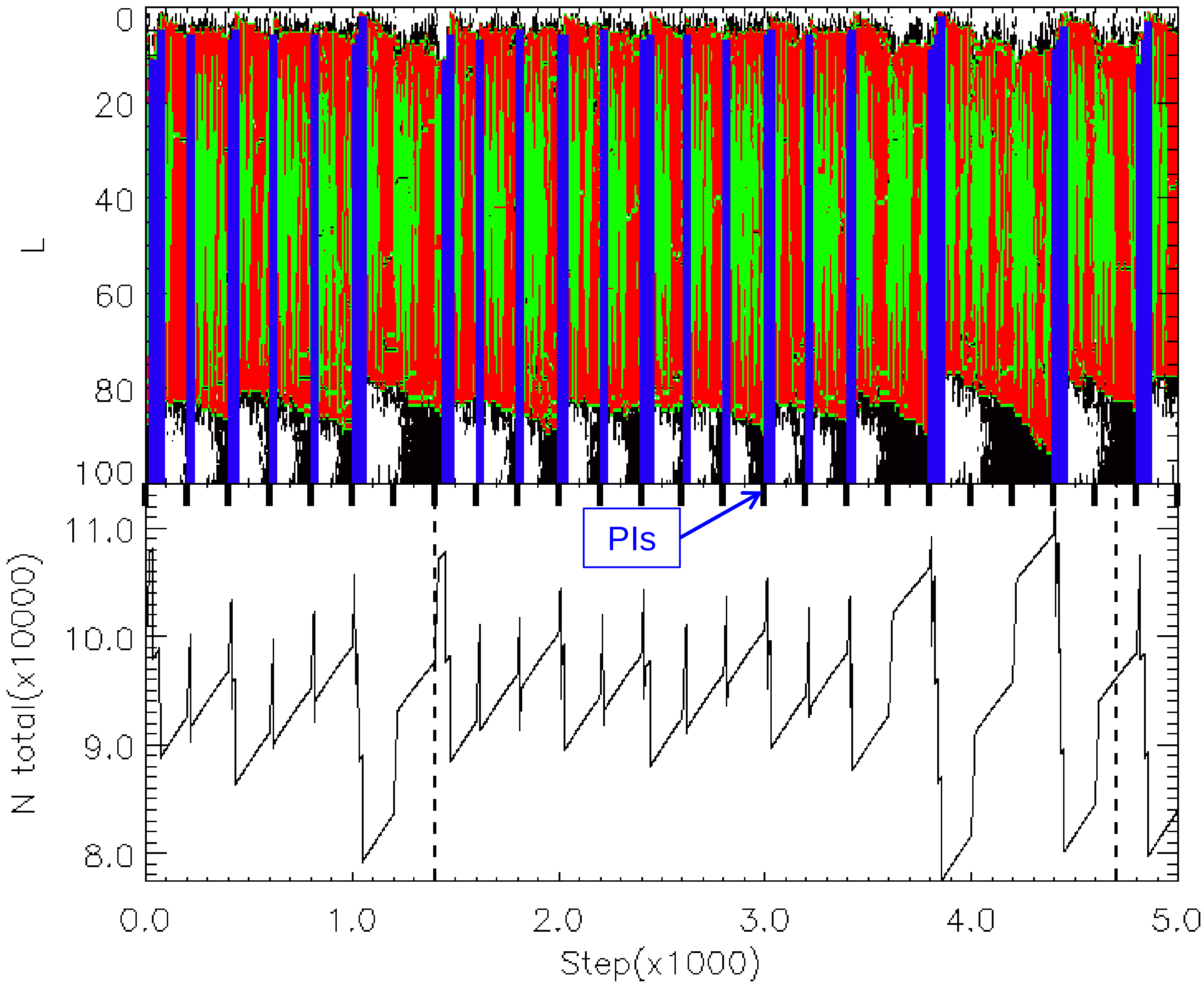
Effect of injection location and quantity of AGI



- Pedestal bottom injection is most efficient for preventing ELM occurrence ($L_C = 95$ case).
- For the cases of inner injections, Δn increase raises ELM occurrences.
- Larger injection at the pedestal top enhance ELM occurrence: it works as fueling.

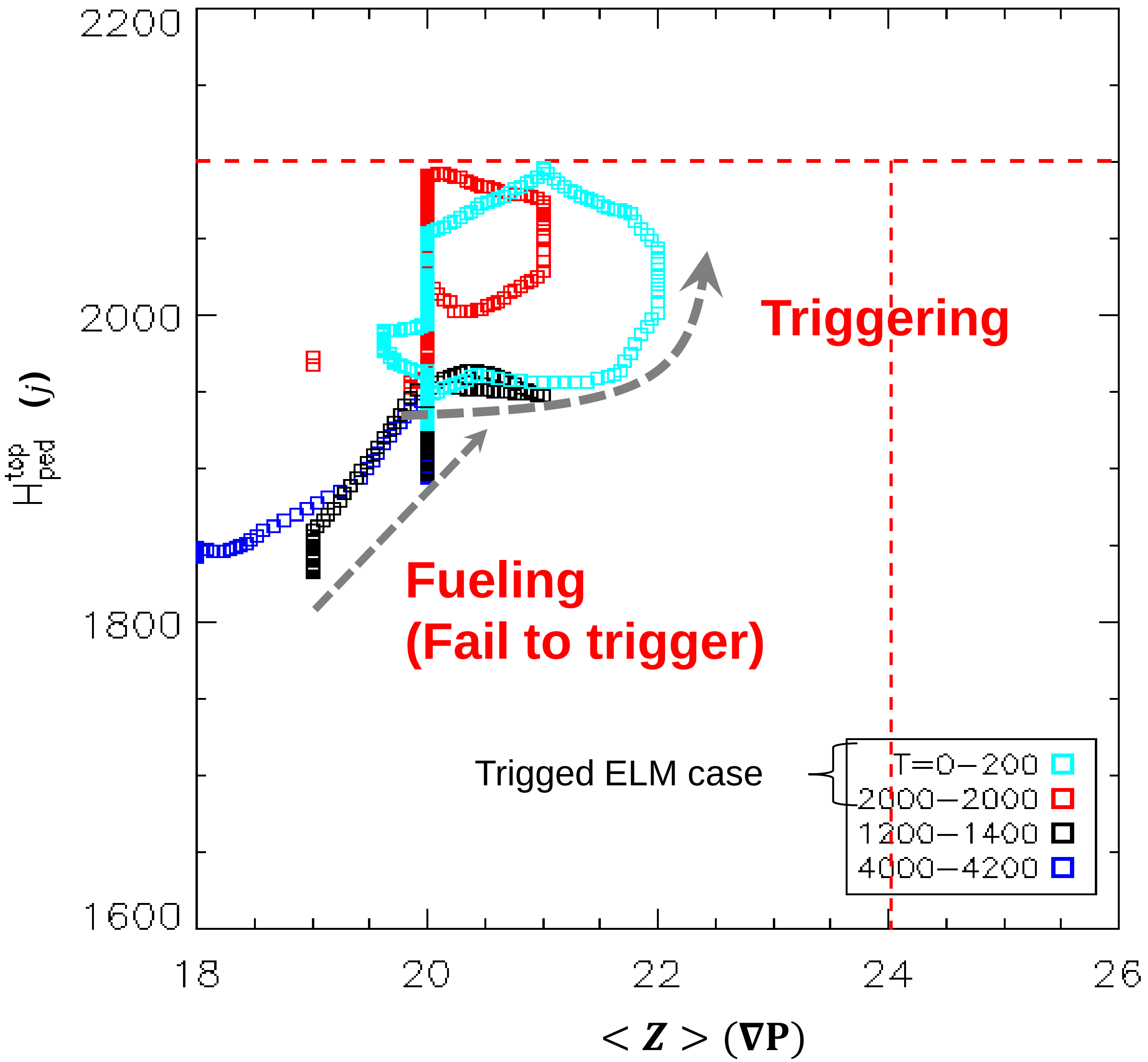
Pellet pacing of system with type-I ELM and $\tau_{ELM} = 2634(\sim 0.3\tau_N)$

AGI interval = 200



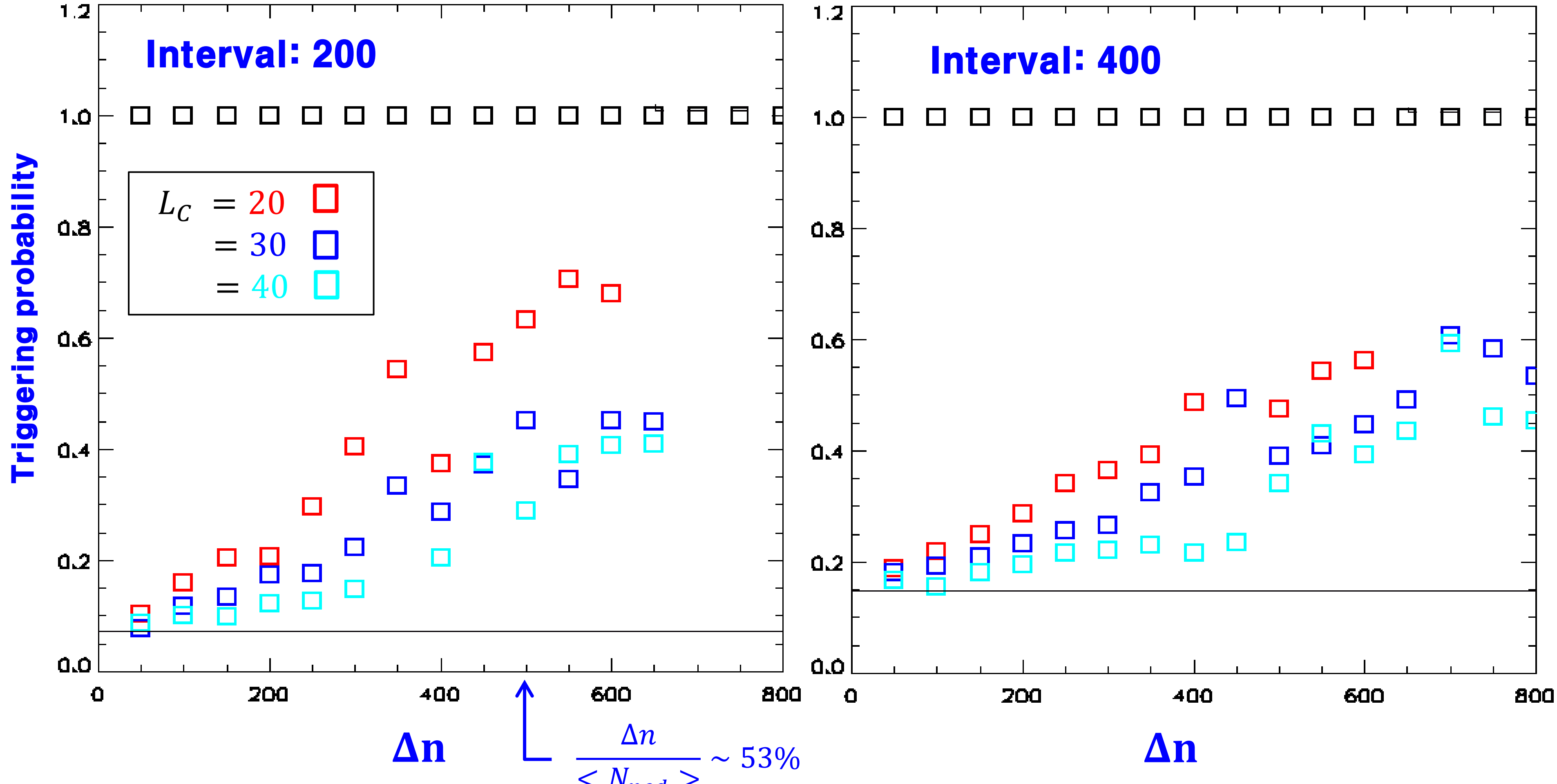
- PI of $\frac{\Delta n}{<N_{ped}>} \sim 53\%$ is injected to the pedestal top centered at 20
- with interval 200 ~ $0.07\tau_{ELM}$
- Most pellet injections trigger type-I ELMs.
- Most triggered ELMs have similar ejection flux
- Some PI's fail to trigger type-I ELM
- After large ELMs, PI's tend to increases pedestal pressure acting like fueling → they lead to even bigger type-I ELMs in later times.

Phase diagram of gradient and height for triggered and not-triggered



- Triggered ELM cases start from higher H_{ped}^{top} and $< Z >$ than fueling case.
- Its path on phase diagram hit H_C^{top} and makes smaller circle compared to general ELM..
- Fueling occurring after large sized triggered ELM does not make circle, it is increase of $< Z >$ and H_{ped}^{top}.

Parameter scan:
injection position, pellet size, injection interval



$\frac{\Delta n}{< N_{ped} >} \sim 53\%$

Optimal deposition position and quantity is pedestal top injection with larger than $\frac{\Delta n}{<N_{ped}>} \sim 53\%$.

Conclusion

1. Type-I ELM is reproduced in the sandpile model

- Transport (i.e. global transport) by current limit is added to sandpile model for type-II ELMy H mode.
- Type-I ELM evolution path of pedestal slope and height(current) makes a circle bounded by ballooning and peeling limit and triggered near its crossing point

2. SMBIs deposited shallow drive type-I ELM mitigation

- Large ELMs are replaced by frequent smaller ones of type-II (i.e. large toppling avalanches)
- SMBI reduce the H_{ped}^{top} height ➔ peeling-ballooning limit free.
- Optimized position is pedestal bottom and size is $\frac{\Delta n}{<N_{ped}>} \sim 1\%$ /step
- Large sized SMBI deposition distributed near pedestal forces peeling limit event → working like pellet pacing

3. Pellet injection near pedestal top trigger current limit event.

1. ELM dynamics triggered PI is resemble to that of type-I but smaller.
2. Effective PI parameter is pedestal top injection and size of $\frac{\Delta n}{<N_{ped}>} \sim 60\%$ /step

Clarification experiments

1. Pellet Injection control

- Broad, dense, and pedestal top deposition → pellet pacing
- Narrow, loose, and pedestal bottom deposition → work like SMBI

2. Synchronized pressure and current profile measurement to PI/SMBI

- ELM mitigation by SMBI hit pressure gradient limit not current limit.
- On the contrary, pellet pacing hit the current limit not pressure gradient limit.