# L-H Transitions Triggered by SMBI: Experiment and Theory

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# Motivation

- Control of transitions to an H-mode becomes more important for modern tokamak operations
  - Standard ITER scenario requires access to H-mode
- Tokamaks equipped with full superconducting magnets, like KSTAR or ITER, have limitations on controlling the wall conditions by conventional methods
  - Mainly due to huge time costs for any conventional glow actions
    - About 60 minutes for discharging/re-energizing of big toroidal field magnets in KSTAR case
  - Limitations lead to gradual increase recycling, hence increase of the required external power for given threshold even in adjacent shots
- Given external heat resources, **a need arises for methods of controlling/enhancing hysteresis for L-H transition**
  - Rapid fuelling is historically known methods for reduction of the L-H threshold [1,2]
  - Attempts for explaining the phenomena from view of modern L-H theory only started recently [3,4]


[1] L. G. Askinazi et al., Phys. Fluids B Plasma Phys. 5, 2420 (1993).
[2] P. Gohil et al., Phys. Rev. Lett. 86, 644 (2001).
[3] K. Miki, P.H. Diamond, S.-H. Hahn, et. al, PRL 110 (2013) 195002
[4] K. Miki et al., PoP 20 (2013) 062304

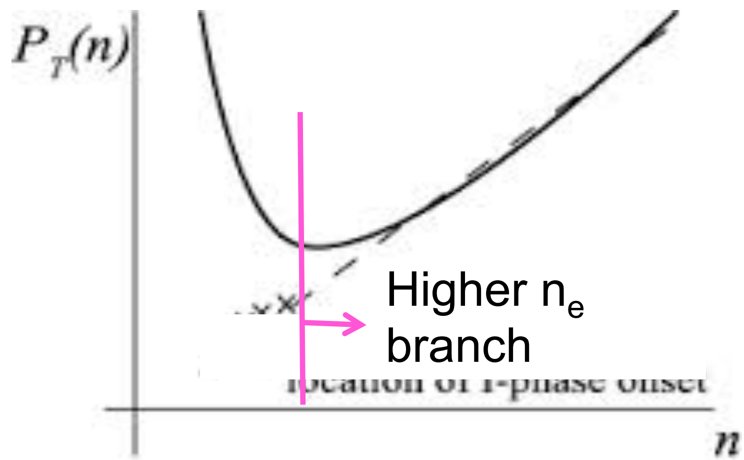
# Highlights

- **Supersonic molecular beam injection (SMBI)** into LFS @ L-mode discharge with subcritical heating @ KSTAR, including a "Stimulated ETB state" at higher $n_e$ branch for $P_{thr}$ vs $n_e$ curve:
  - Similar to previous gas-induced transitions seen at TUMAN-3[1] and D3D 2.7mm pellets[2]
  - Experimental evidence of direct edge profile change

- Theoretical model [3,4] demonstrates optimal injection depth, principal means and possibility of sustainment of the Stimulated ETB by repetitive injections

Could be useful as another control knob for controlling access to H-mode, **especially for superconducting tokamaks like ITER**

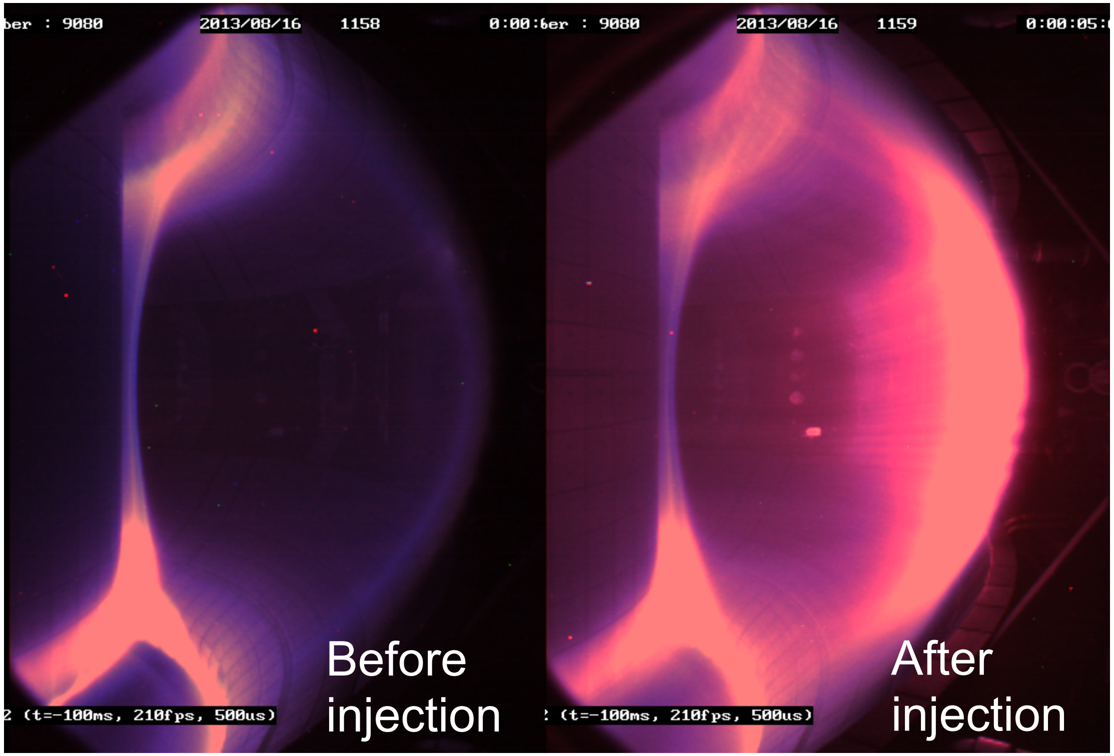
Power threshold ($P_{thr}$) vs $n_e$



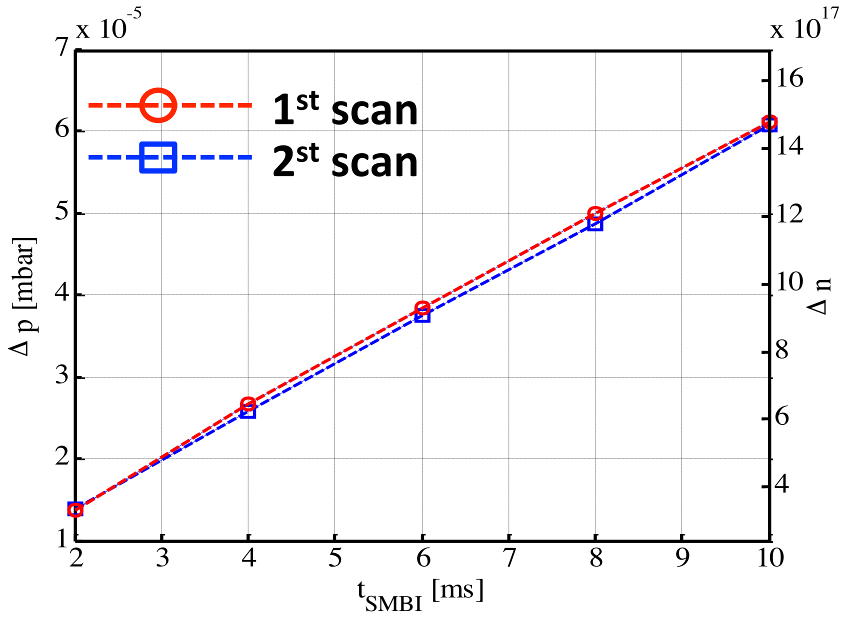
# Supersonic Molecular Beam Injections (SMBI) @ KSTAR

- R=1.8 m, a = 0.5 m, BT = 2.0 ~ 2.5 T, Ip = 0.5 MA, k~ 1.8 diverted plasma
- D2 SMBI / cooled down to 105 K / injection pressure at 1 MPa

An SMBI injection on outer midplane (200 frames/s CCD camera)

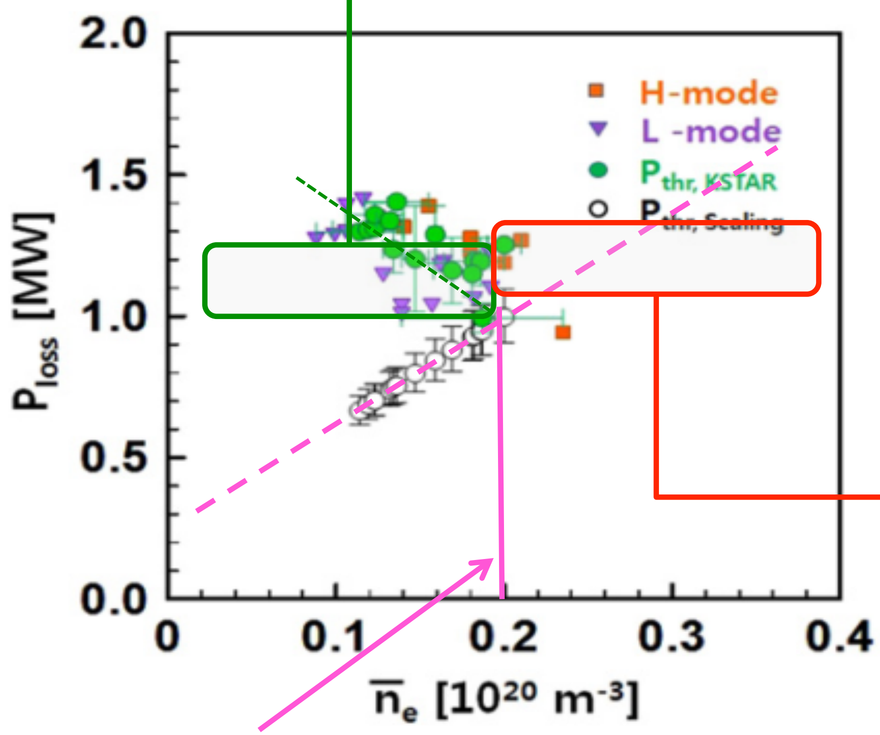



# of particle vs SMBI duration[ms] at reservoir pressure =1 MPa



# Summary of various dynamics induced by SMBI injections

$P_{loss}$ vs $n_e$:
Measurement & Scaling for yr2011 KSTAR [5]




Known density turnover:
$n_{crit} = 2.0e^{19}\ m^{-3}$

lower $n_e$ branch (ne < $n_{crit}$ = 2.0e19 [3])
+ small SMBI (4 ms):
various dynamics are triggered as

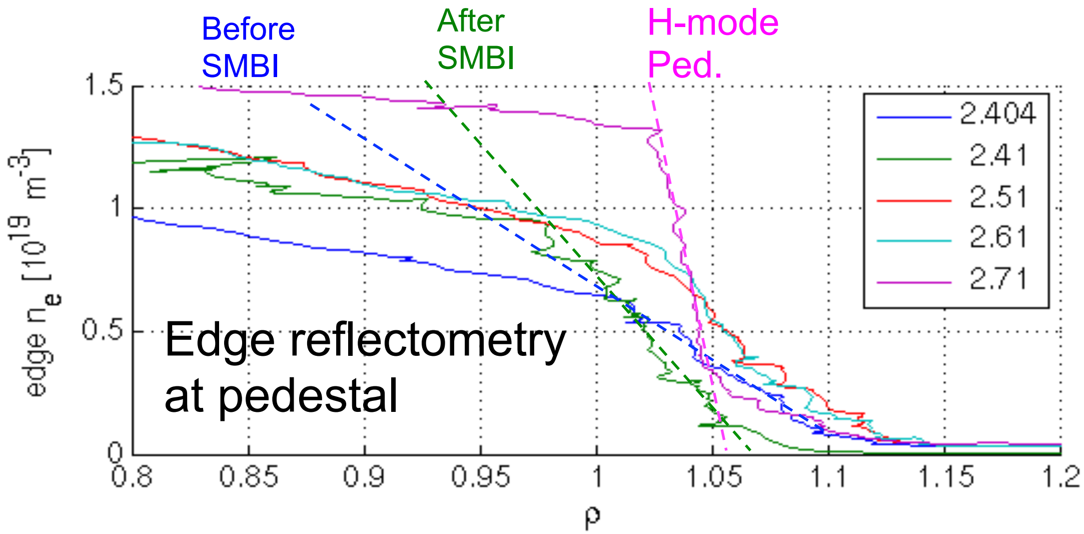
- Extension of LCO
- Enhancement of density pedestal
- Transition is often delayed in time

At higher $n_e$ branch, + stronger SMBI (8 ms):

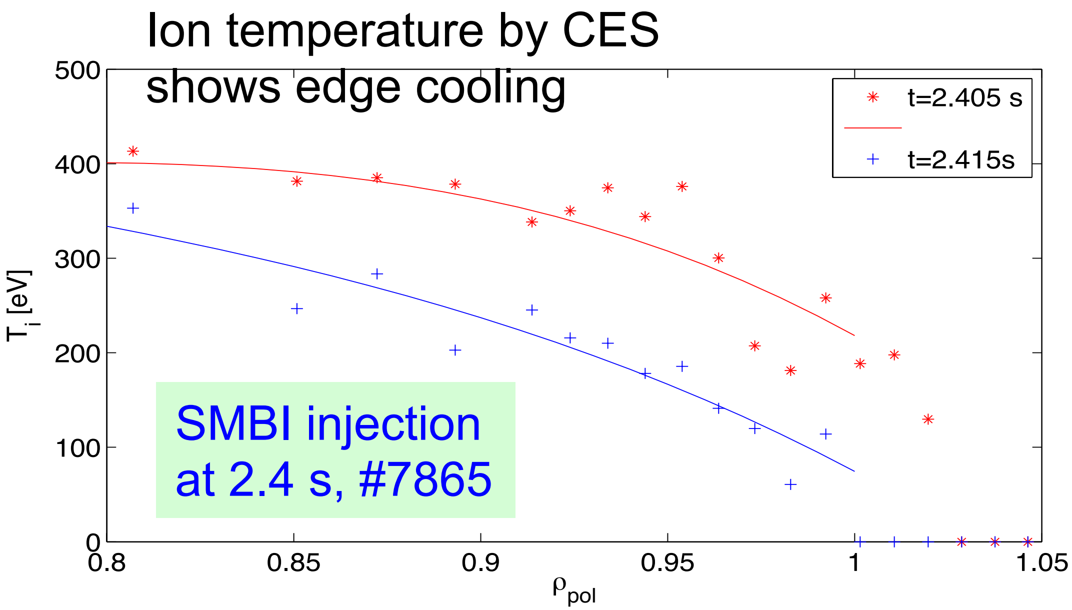
- **Stimulated L-H occurs with increase of density toward which the transition is more unlikely to occur**
- Reduction of required absorbed power = $P_{inj}$ – dW/dt – $P_{rad}$ has been reported, up to 30% less than baseline
- The profile change seems to be localized in space, according to spatial BES profile

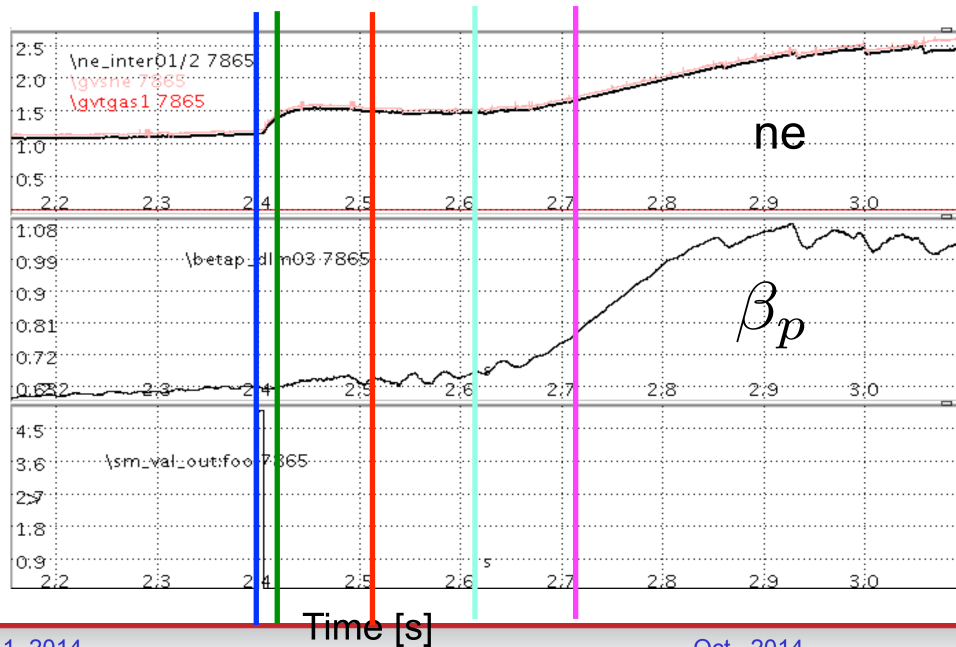

[5] S. W. Yoon et al., Nucl. Fusion 51, 113009 (2011).

# Edge ne, Ti profile changes are accompanied for the stimulated dynamics

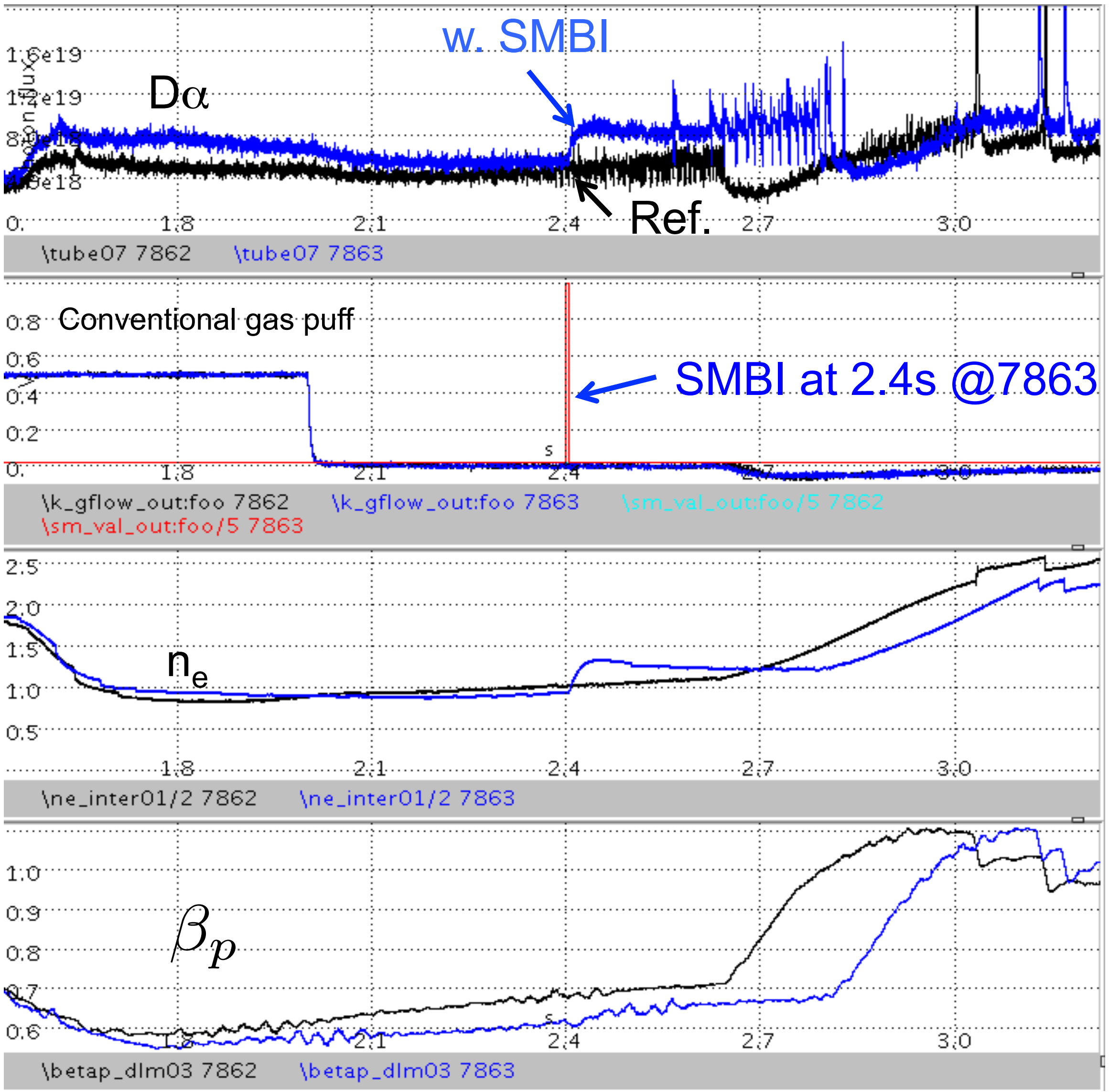



- SMBI makes a **direct, localized density gradient enhancement**, which leads to enhanced edge $E_r$ shear
- **The induced edge density profile steepening is maintained** until the H-mode onset at 2.65s
  - Longer than particle confinement time



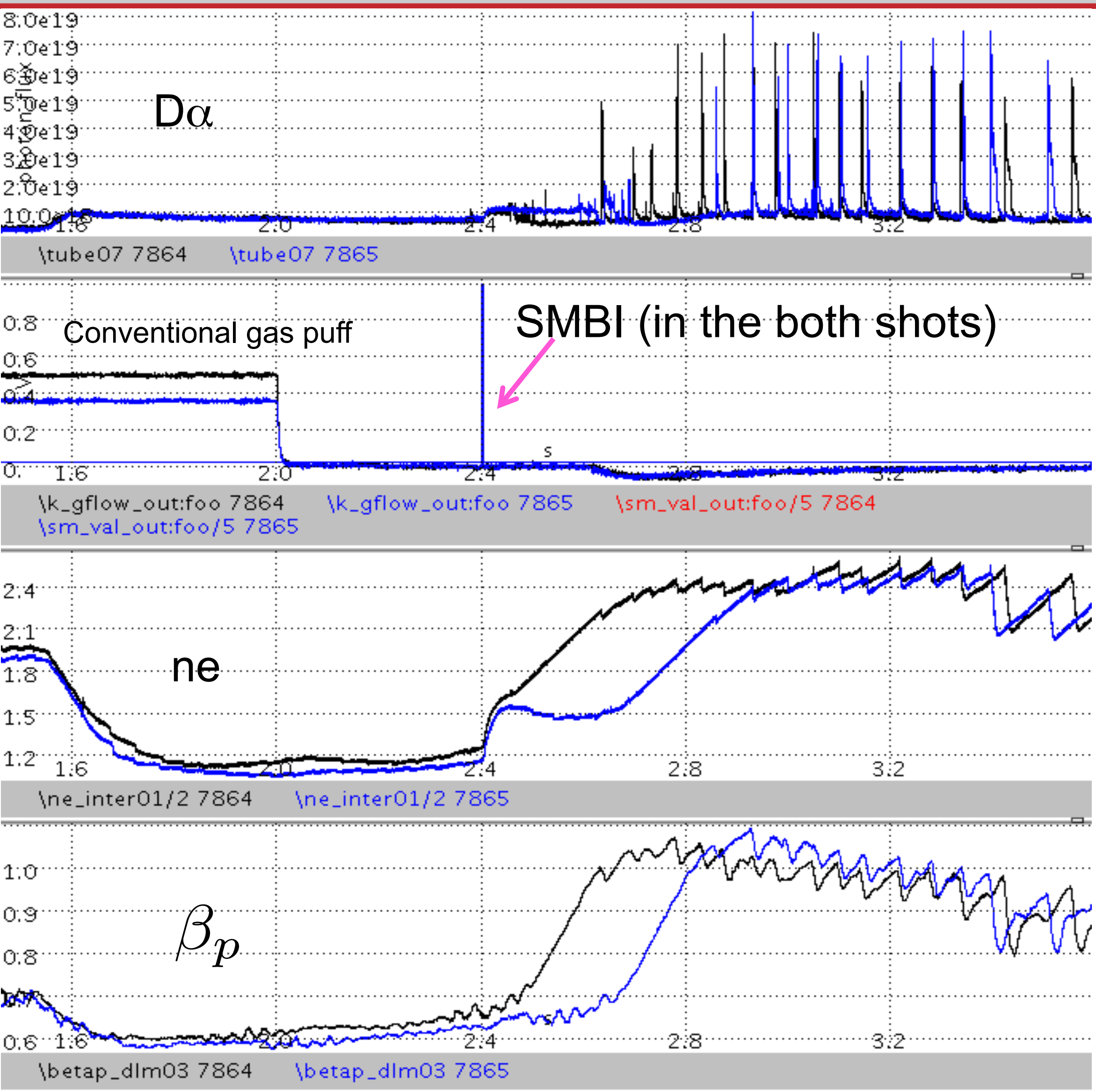



# Lower $n_e$ branch : D$\alpha$ oscillation extends by conventional puff / SMBI




- $B_T$ = 1.96 T, Ip = 500 kA, with ~1.4 MW NBI
- Shot 7862 shows oscillations similar to "limit cycle oscillations (LCO)" at D$\alpha$ line, before going to an H-mode
  - A hint of marginal $P_{th}$, generally
- #7863: Injection of 4 ms SMBI at 2.4s **makes larger oscillations at D$\alpha$, extends the I-phase before the L-H at 2.8s**

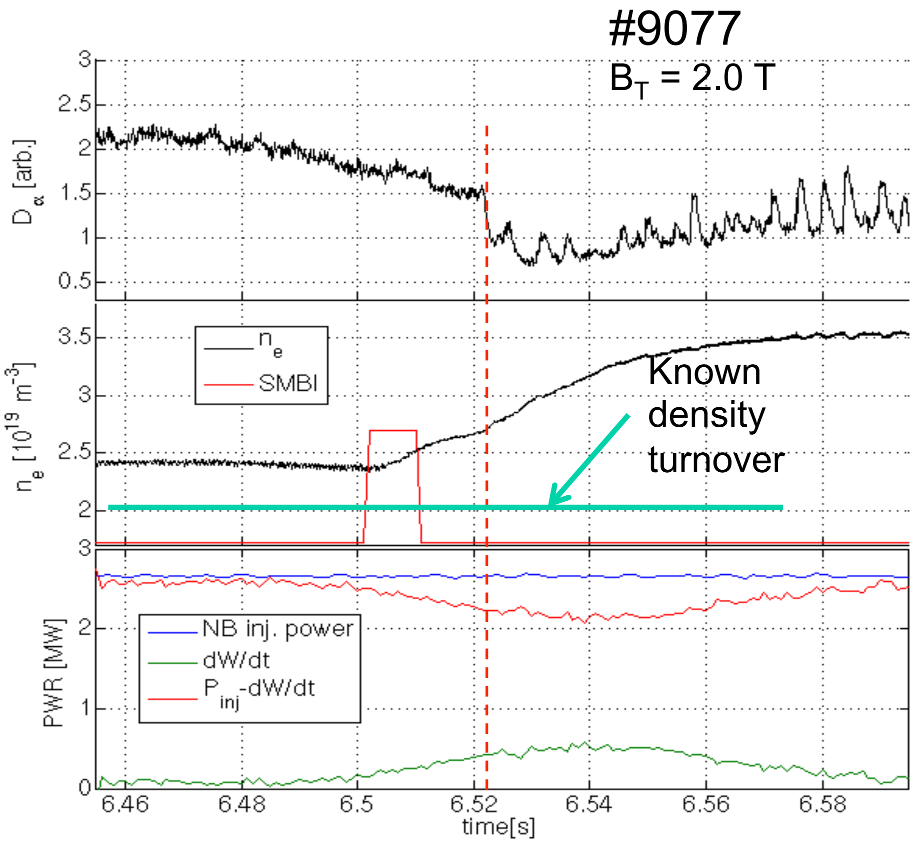
# Lower $n_e$ branch : Bifurcation on path to L-H found for identical parameters



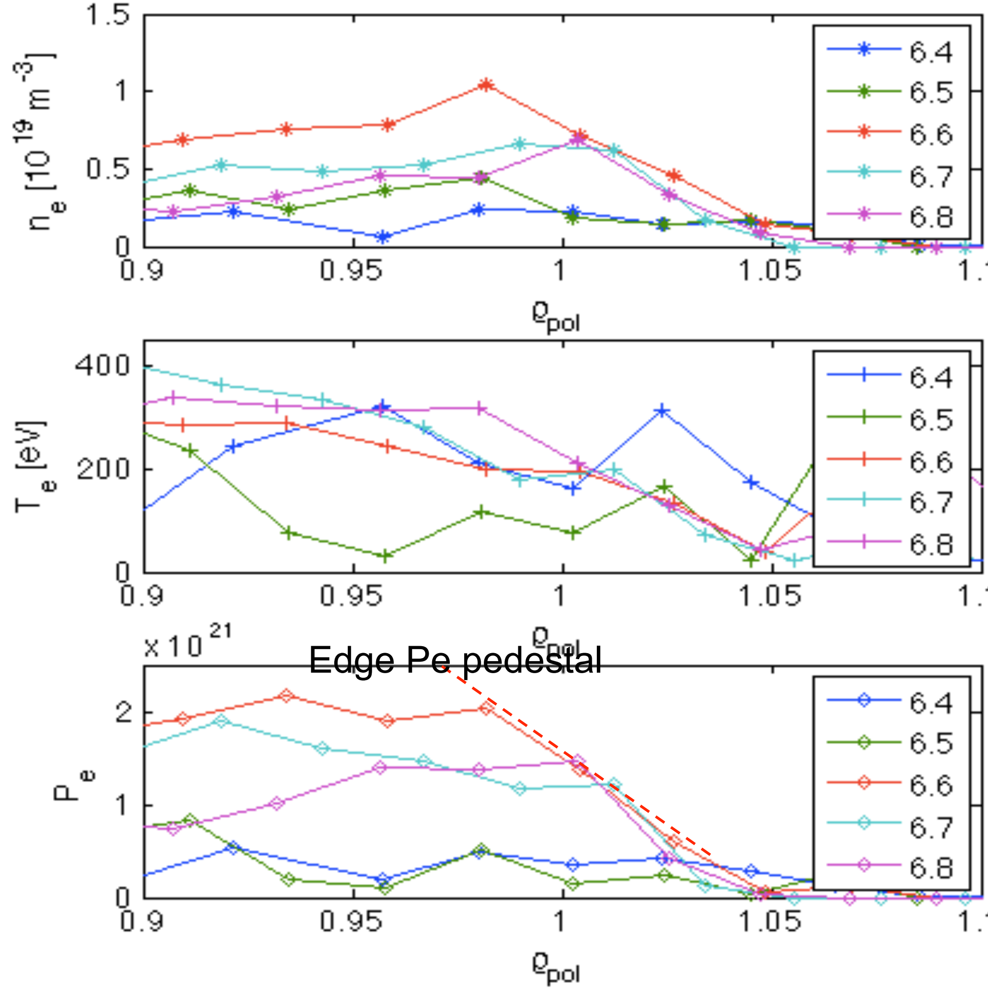

- **Black (#7864) :** Immediate transitions triggered by an SMBI injection at 2.4s
- **Blue** (#7865) has a time delay on onset of the LCO and the transitions
  - For the same level of the SMBI pulse / electron density / temperature / heating power in comparison with in the previous shot (#7864)

# higher $n_e$ branch : Stimulated ETB is transient, but pressure pedestal is maintained during the state

**A non-trivial Dα drop** occurs above the known density turnover (i.e. ne > $n_{crit}$ = 2.0e$^{19}$ m$^{-3}$ ) by a deuterium SMBI injection at t=6.5s :




$n_e$, $T_e$, electron pressure evolution by KSTAR Thomson during the stimulated ETB period (6.5-6.8s)



# higher $n_e$ branch : transient Stimulated ETB transitions found with reduced absorbed power

**Triggering of L-H & small ELM is observed by 8 ms of SMBI**

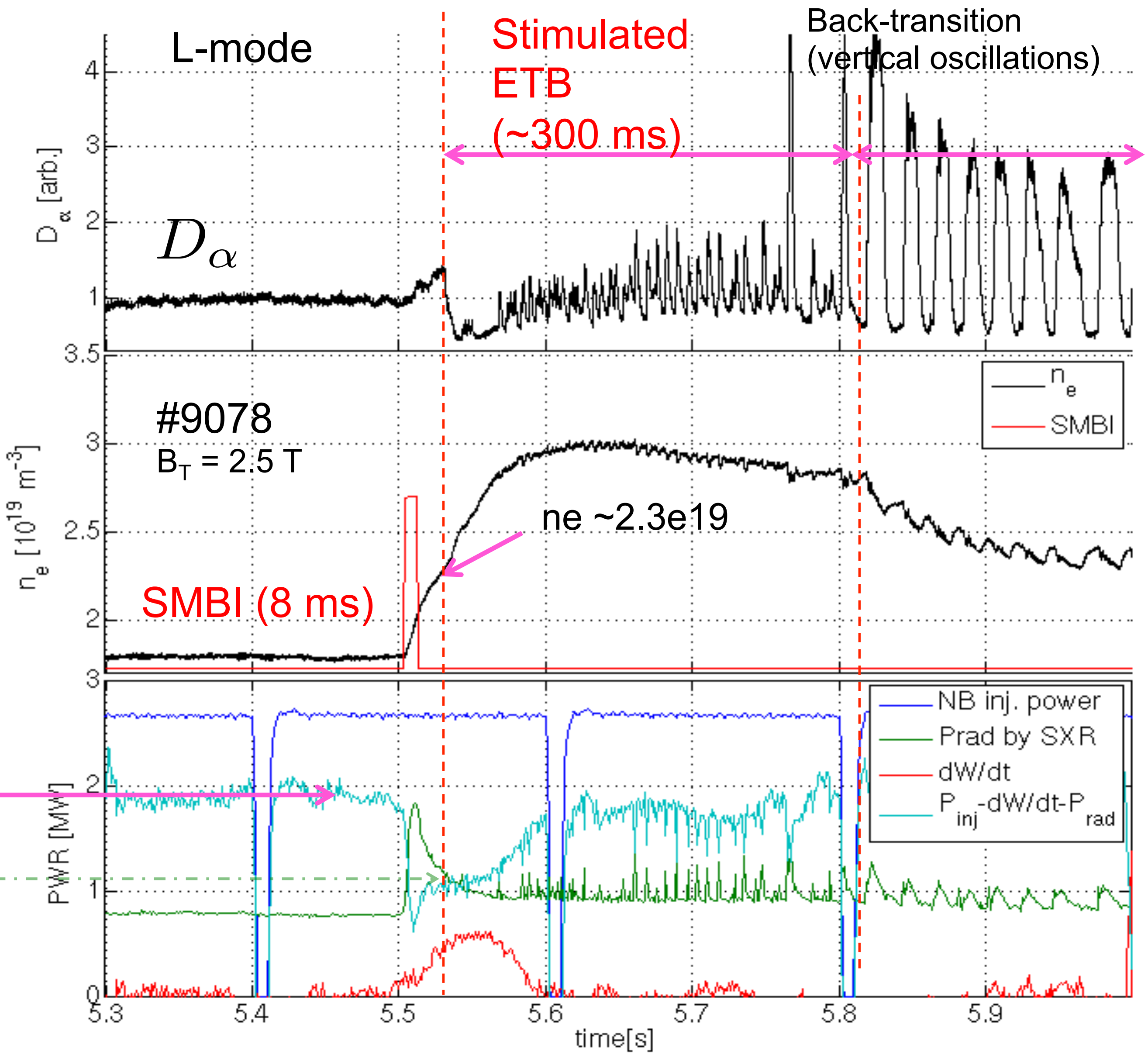
- Transition occurred for less absorbed power than "baseline"

  $P_{abs} = P_{inj} - dW/dt - P_{rad}$ (cyan line)

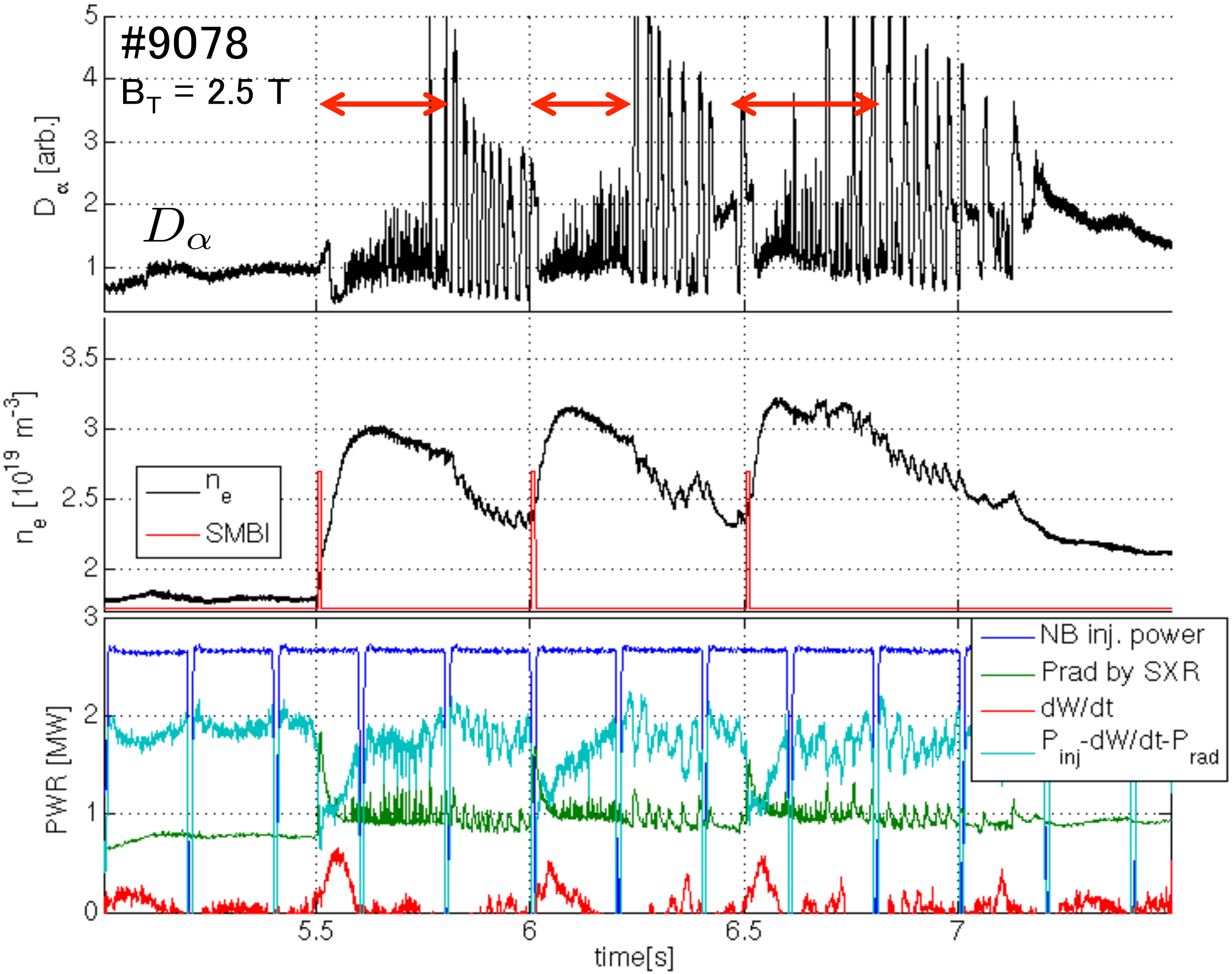
- Time delay (~23ms) observed until Dα drop, likely due to $P_{rad}$ (green) increase by SMBI ablation

$P_{abs}$ "baseline":
No L-H occurs until 5.5s
$P_{abs}$ ~1.9 MW

Dα drop occurs at $P_{abs}$ ~1.1 MW



# higher $n_e$ branch : Sustainable stimulated transitions found by repetitive SMBI injections




The Dα drop is able to reproduce by repetitive SMBI injections

: suggests that this "driven H-mode" could be sustainable

# Model is used for predictions on important parameters for Stimulated L-H physics

A reduced **five-field** (turbulence intensity, mean square ZF shear, ion pressure, density, and mean poloidal mass flow), **two-predators-one-prey model** of the L-H transition [3,4] is used for pre-experiment model study to figure out important parameters:

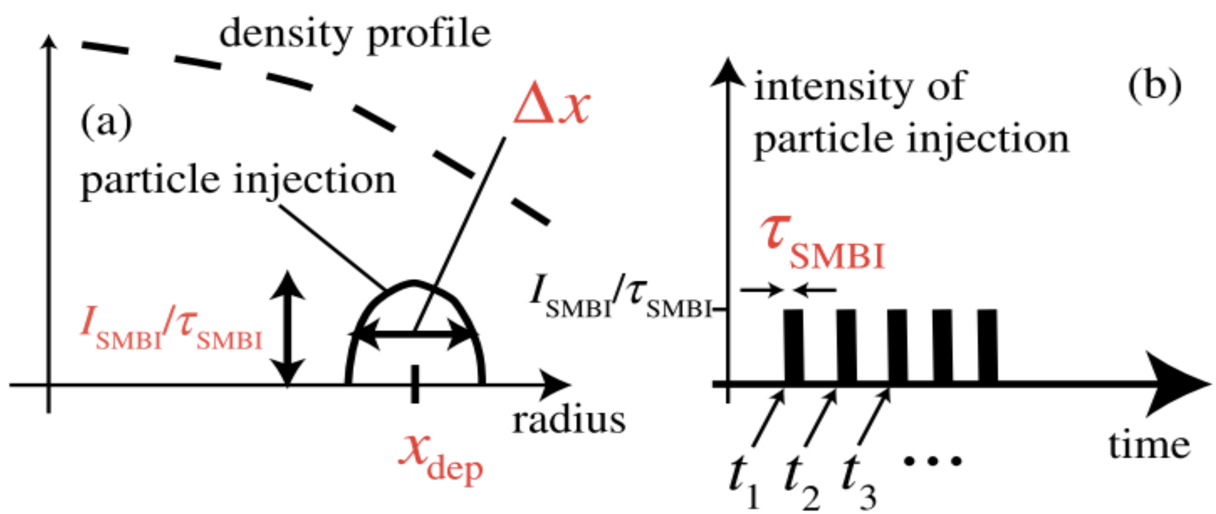
→ Additional fueling (pellets, SMBI, etc…) is modeled as a density equation change

$$\delta\Gamma_{n,\mathrm{SMBI}} = \frac{I_{\mathrm{SMBI}}(n_{\mathrm{ref}})}{\tau_{\mathrm{SMBI}}} \sum_i \frac{1}{2}\left[H(t - t_i) - H(t - t_i - \tau_{\mathrm{SMBI}})\right] \exp\left(-\frac{(a - x_{\mathrm{dep}})^2}{2\Delta x^2}\right).$$

Gas intensity

Pulse duration

Deposition depth



# Model study demonstrates conditions, principal means and possibility of driven H-mode sustainment

Model results demonstrate[3]:

1) shallow deposition is optimal, and superior to strong puffing

2) transient improved confinement states can be maintained by repetitive injections

3) the principal means of accessing enhanced confinement is via stronger edge ExB shear

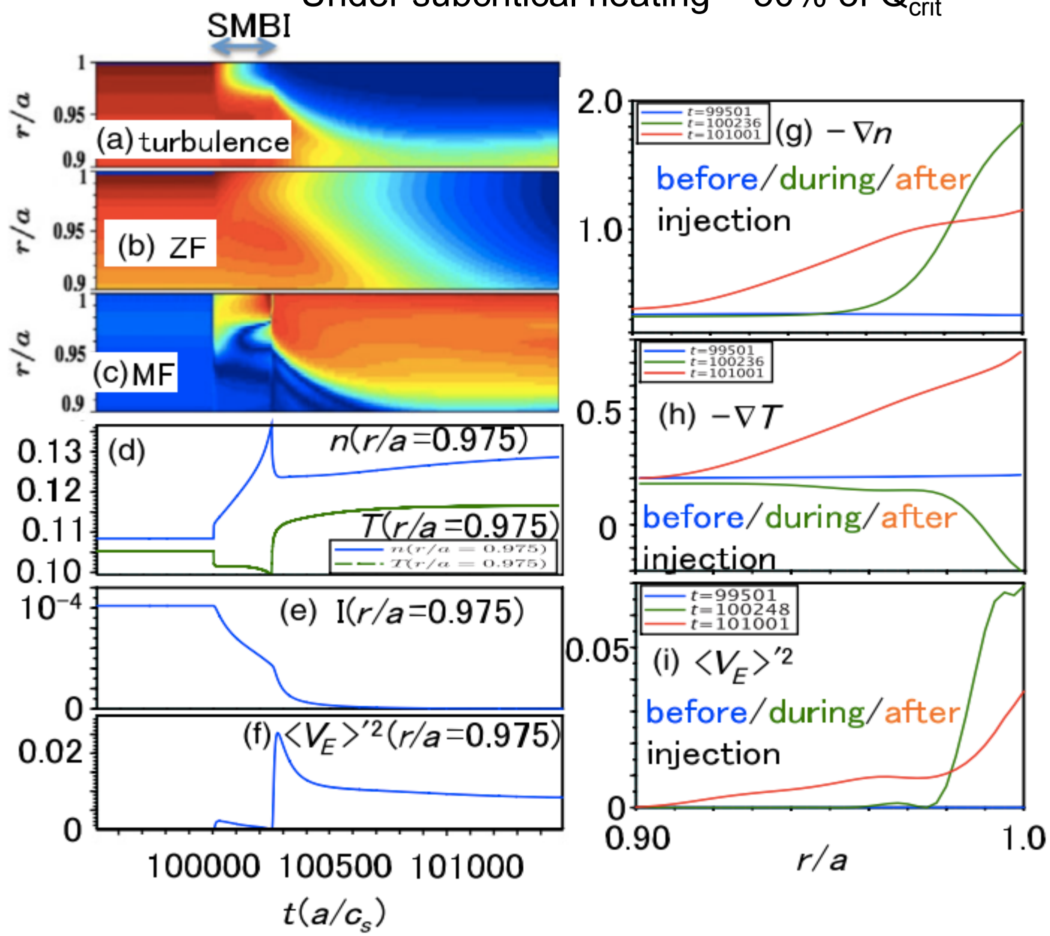
4) in contrast to standard (i.e. spontaneous) transitions, a burst of zonal flow growth does <u>not</u> lead stimulated transition events

Turbulence suppression induced by

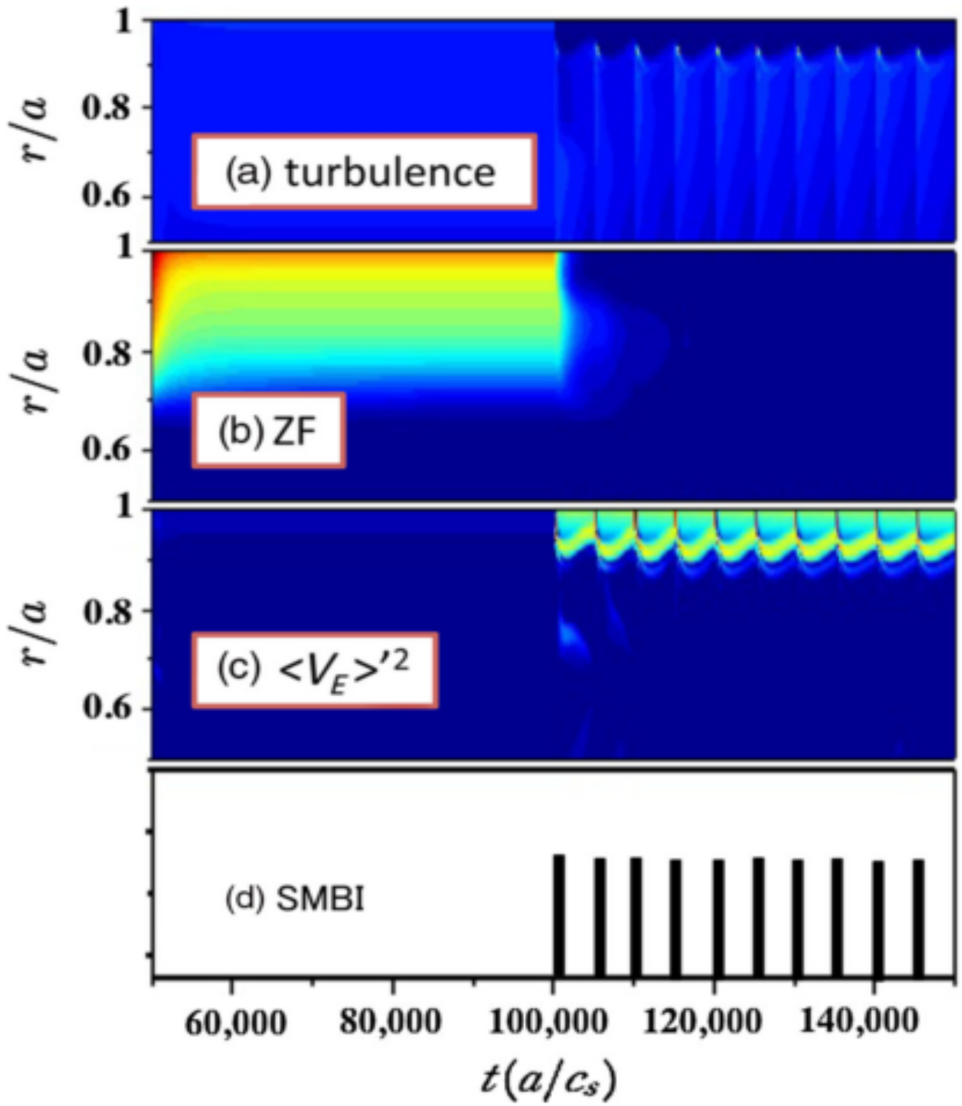
$I_{SMBI}$ = 30,

$\tau_{\mathrm{SMBI}}, x_{\mathrm{dep}}/a, \Delta x/a,$ = $250(a/c_s)$, 0.975, 0.02

Under subcritical heating = 50% of $Q_{crit}$



# Model study shows that repetitive SMBI injections allow sustainment of the “Stimulated ETB State”




Model demonstration of sustained transient improved confinement states :

the SMBI pulses per 5,000 steps of characteristic timescale ($a/c_s$), deposition site = 0.975, under the given ambient heating power $dQ = (Q_{crit} - Q)/Q_{crit} = 0.7$.

Sequential injections of the particles maintains the enhanced edge $\langle V_E \rangle'$ (MF shear) and this “driven H-mode”

→ Role of zonal flow for Stimulated ETB?

# Spontaneous vs Stimulated L-H:
# Role of ZF is NOT critical for stimulated transitions

**Spontaneous transition :**

Preceding ZF growth leads to steepening of pressure gradient, and MF shear occurs as a consequence

**Simulated transition:**

**ZF growth occurs, but does <u>not</u> have any direct relations with MF shear**

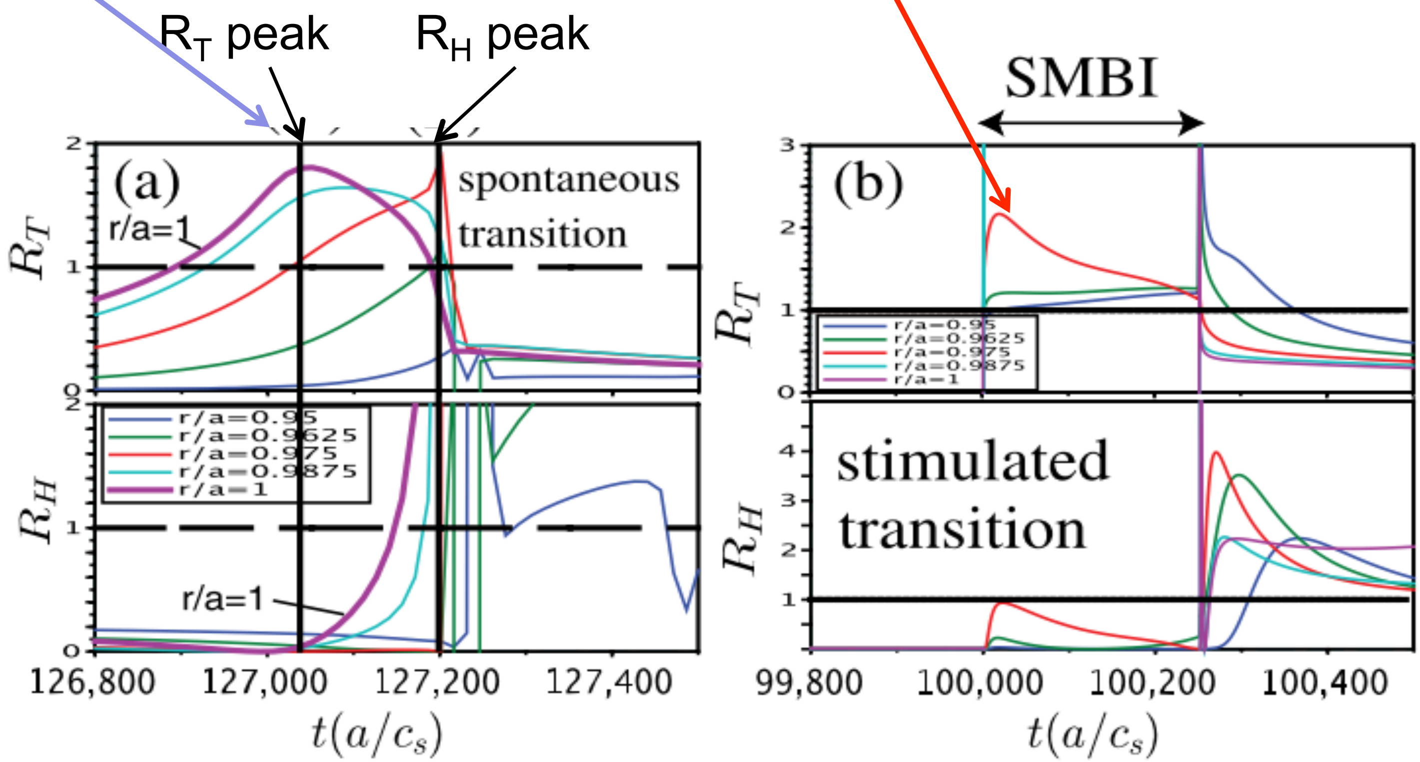
$$R_T = \frac{\alpha_0 E_0}{(\gamma_L - \Delta\omega I)}$$

: ratio of Energy transfer from turbulence to ZF

*vs*

$$R_H = \frac{\alpha_V E_V}{(\gamma_L - \Delta\omega I)}$$

: ratio of Energy transfer from turbulence to MF



# Summary and Future Work

- Various phenomena regarding L-H transition are observed by injection of SMBI in KSTAR, including a "Stimulated ETB state" and corresponding transient L-H transition
  - The stimulated ETB state has a finite lifetime but sustainable by repetitive injections -> **useful for early ITER with marginal heating**
  - Power balance analysis showed reductions on the required total absorbed power, based on available radiation estimates

- A five-field, 1D-reduced mesoscale model study (aka 2-predators-1-prey model) indicates that Stimulated L-H takes fundamentally different route from the Spontaneous

- Still, model results should be demonstrated by corresponding experiment:
  - Profile change on density cannot fully account for the accompanied time delay until D$\alpha$ drop – Fluctuation study is essential for direct comparison on the model
  - Criteria for deposition depth, intensity, and injection frequency for optimal duration of Stimulated ETB
    - What is most responsible for sustaining Stimulated ETB states?