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Physics of stimulated L-H transition

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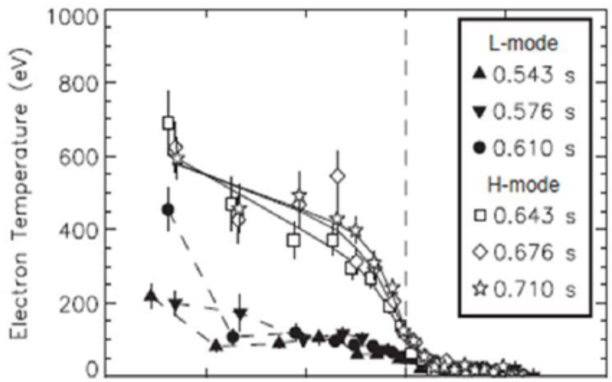
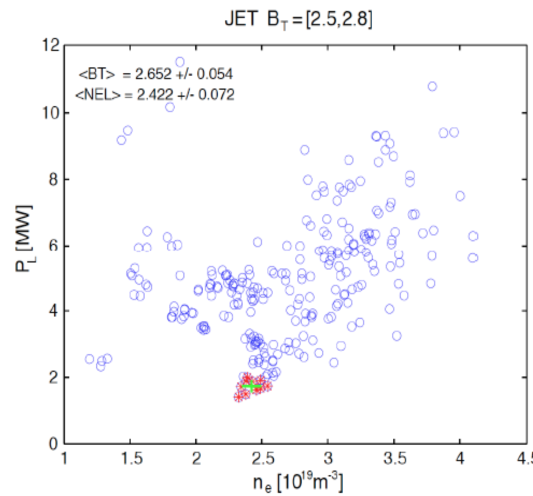
L-H Transition



J.W. Huges et al., PSFC/JA-05-35



[Martin '08 JoCP]

- H-mode is first initiated by ASDEX [Wagner '82 PRL]
  - Improvement of confinement at edge plasmas
  - Likely related to V_{ExB} shear suppression of turbulent transport
- Standard scenario for ITER
- Many anecdotes of transitions with variation of power threshold

Dynamics of stimulated transition

I.) Motivation

[K. Miki, P.H. Diamond *et al.*, PRL '13],
[K. Miki, P.H. Diamond *et al.*, PoP '13]

OV: Particle injection to probe and Control the L→H and H→L transitions.

Pragmatic:

→Small pellets and/or SMBI to lower P_{Th}, *enhance hysteresis* and control plasma transport.

Physics:

→Use particle injection as profile perturbation technique to explore interplay of mean flow shear, zonal flows and turbulence. This interplay is thought to be critical to the L→H transition.

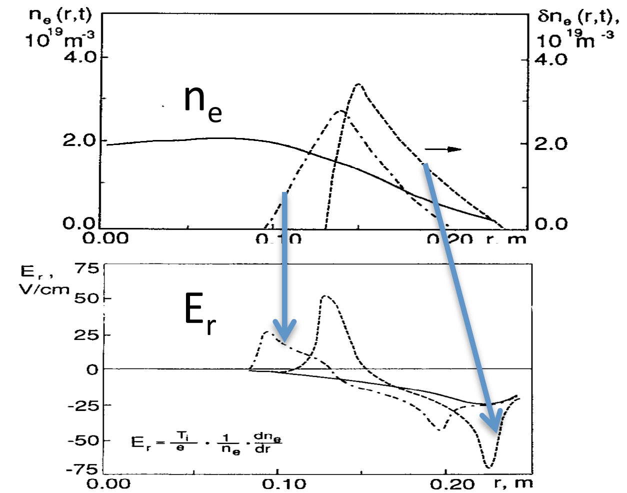
→Explore and understand physics of 'stimulated' transitions in addition to usual, spontaneous transitions.

Previous Work on particle-injection-induced L-H transition

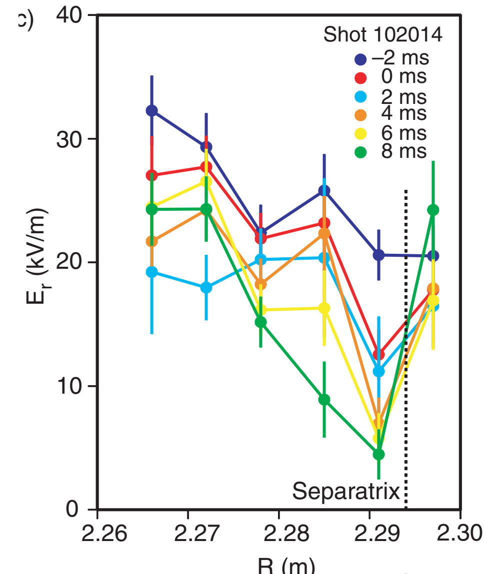
- Askinazi, *et al*., (1993) – Tuman-3
  - → Transitions triggered by strong, rapid gas puffing
  - → LiD pellet induced H-mode ("PCH") of short duration
  - → Some evidence that PCH mode triggered by <V_E>' increase near edge.

- Gohil, Baylor, *et al*., (2001, 2003) – DIII-D
  - → Transitions triggered by pellet injection
  - → Reduction of P_{Th} by ~30%
  - → Limited evidence that <V_E>' steepened near edge.

[Askinazi, '93]



[Gohil, '03]



Model: One-dimensional reduced mesoscale transport modeling

[K. Miki, and P.H. Diamond *et al*., Phys. Plasmas, 2012]

- 5 field reduced mesoscale model(p, n, I, E_0, v_θ), motivated by
  - 1D transport model ([Hinton '91 PoF] etc.) + Local predator-prey model [E.J. Kim and Diamond '03, PRL]
- Simplified boundary condition on p and n at LCFS; no SOL-edge interaction, fixed boundary.
- NO MHD activity, no ion-orbit-loss (or E_r bifurcation)
- **N.B.: No 'first principle' simulations have reproduced or elucidated the L-H transition**

Description of the 1D model (1): Predator-Prey model (a‘ la Kim-Diamond)

Turbulence intensity:

Assuming ITG turbulence

$$\partial_t I = (\gamma_L - \Delta\omega I - \alpha_0 E_o - \alpha_V E_V)I + \chi_N \partial_x (I \partial_x I)$$

Driving term

Local dissipation

ZF shearing

MF shearing

Turbulence spreading [Hahm, Lin]

Zonal flow(ZF) energy: $E_0 = V'^2_{ZF}$

$$\partial_t E_0 = \alpha_0 I E_0 / (1 + \zeta_0 E_V) - \gamma_{damp}$$

Reynolds stress drive

ZF collisional damping

MF inhibition in Reynolds cross-phase [E. Kim '03 PRL]

Mean flow(MF) shearing:

$$\mathrm{E}_V = (\partial_x V_{E\times B})^2$$

by radial force balance

Description of the 1D model (2):1D transport model

pressure

$$\partial_t p(x) + \partial_x \Gamma_p = H$$

density

$$\partial_t n(x) + \partial_x \Gamma_n = S$$

$$\Gamma_p = -(\chi_{neo} + \chi_o)\partial_x p$$

$$\Gamma_n = -(D_{neo} + D_o)\partial_x n - Vn$$

Neoclassical transport term

Banana regime

$$\chi_{neo} \sim \chi_{Ti} \sim \varepsilon_T^{-3/2} q^2 \rho_i^2 \nu_{ii}$$

$$D_{neo} \sim (m_e / m_i)^{1/2} \chi_{Ti}$$

Turbulent transport term

$$D_0 \sim \chi_0 \sim \frac{\tau_c c_s^2 I}{(1 + \alpha_t V_E'^2)}$$

→**_Predator-prey model_**

Pinch term

TEP pinch Thermoelectric pinch

$$V = (v_{0,TEP} + v_{0,TE})$$ Inward

$$\cong \left(\frac{D}{R} - \frac{D}{L_T} \right) \quad (\propto I,\ L_T < 0)$$

Poloidal flow Evolution:

$$-\frac{\partial u_\theta}{\partial t} \cong \alpha_5 \frac{\gamma_L}{\omega_*} c_s^2 \partial_x I + (\nu_{ii} + \nu_{CX}) q^2 R^2 \mu_{00} (u_\theta + 1.17 c_s \frac{\rho_i}{L_T})$$

Radial Force Balance:

$$V'_{E\times B} = \frac{1}{eB}\left[-\frac{1}{n^2} n'p' + \frac{1}{n} p'' \right] + \left(\left[\frac{r}{qR} u_\parallel \right]' - u'_\theta \right)$$

Poloidal flow

Density gradient

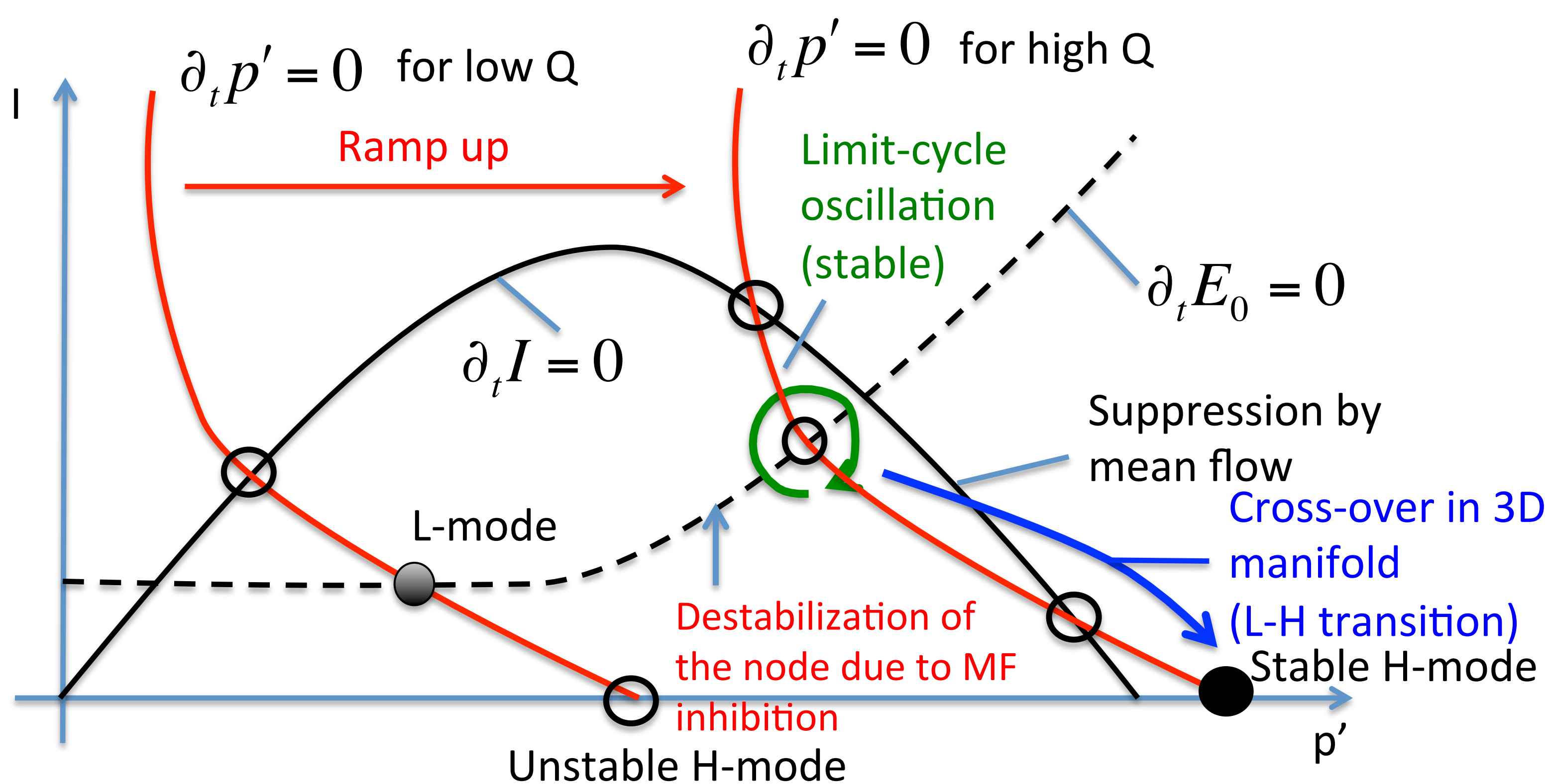
Pressure curvature

Diamagnetic drift

Toroidal flow (not considered here)

Bifurcation in the dynamical systems

- In the local limit, this model is reduced to the local predator-prey (Kim-Diamond) model.
- Phase-portrait on the projection of E_0=0

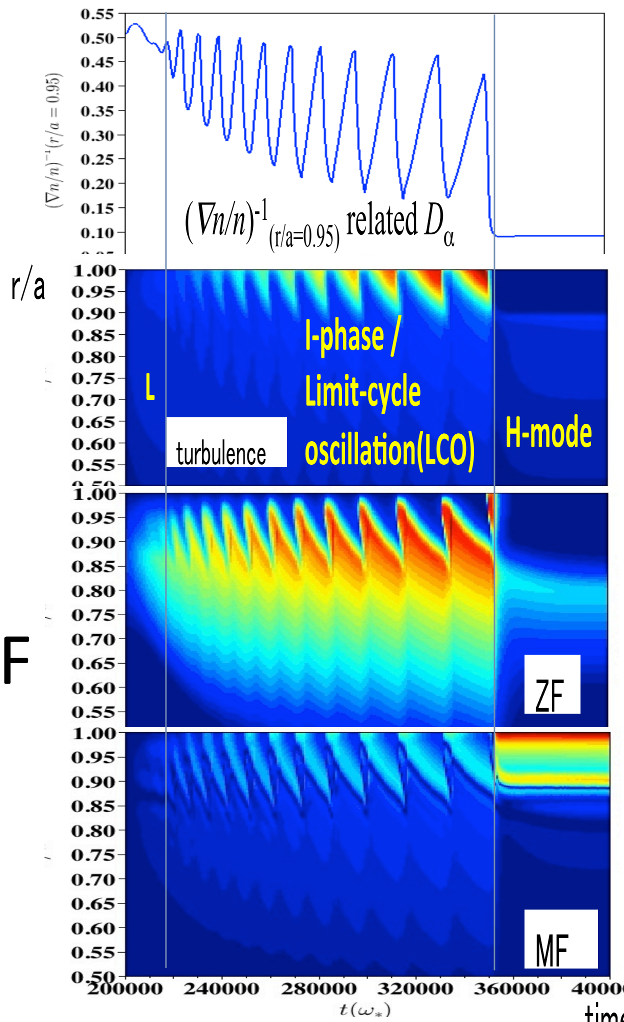


A case of standard L-H transition

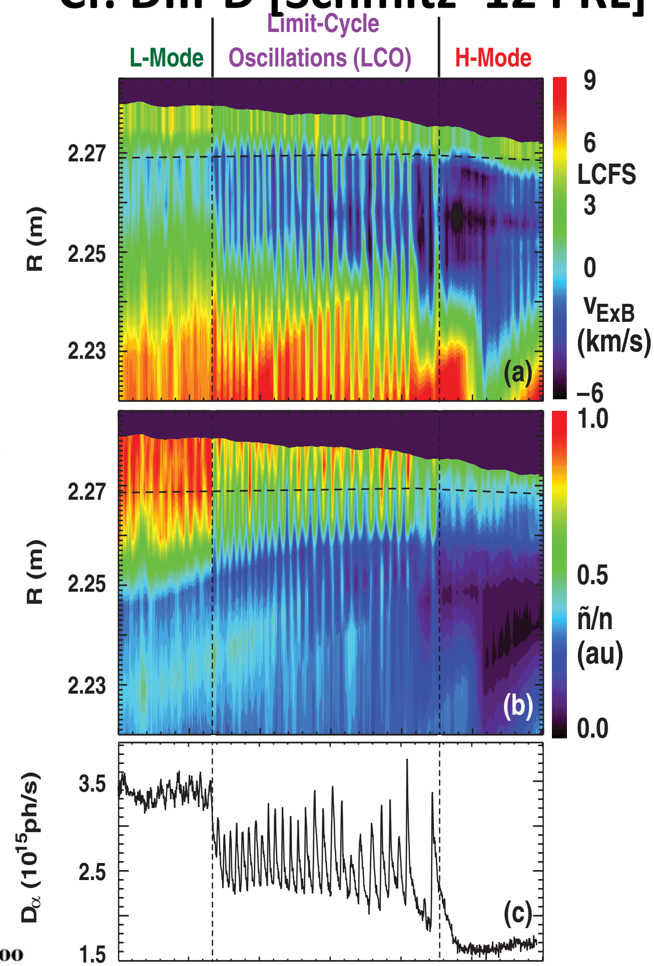
Model studies recover the spatio-temporal evolution of the spontaneous L-I-H transition.

→ At L-I transition
- Limit-cycle oscillation(LCO) begins.

→ At I-H transition
- MF increases.
- Turbulence and ZF drop in the pedestal



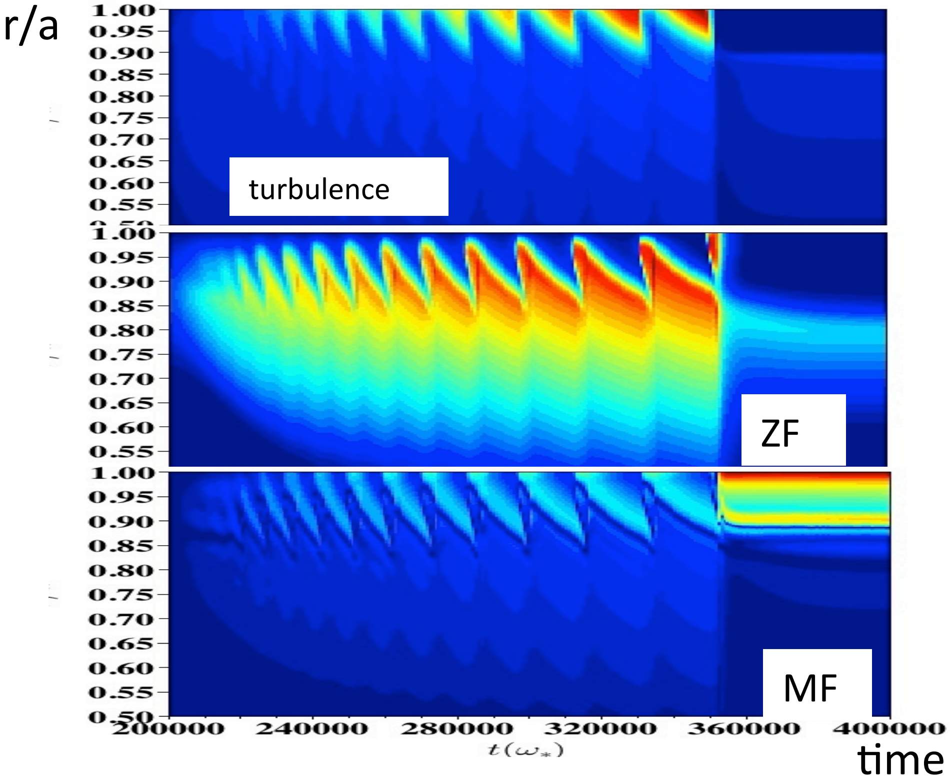
Cf. DIII-D [Schmitz '12 PRL]

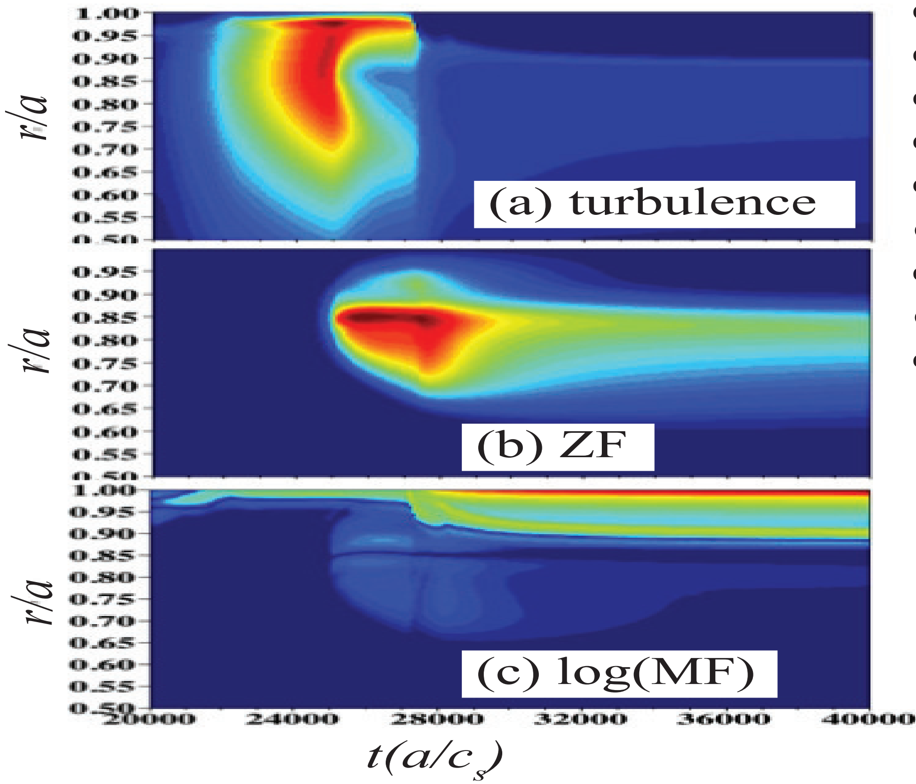


→Note: Extended LCO I-phase is conceptually and diagnostically useful but NOT intrinsic to transition

→Stress driven flow can be excited in burst

i.e. cycle → 1 Period





Slow ramp up

Fast ramp up

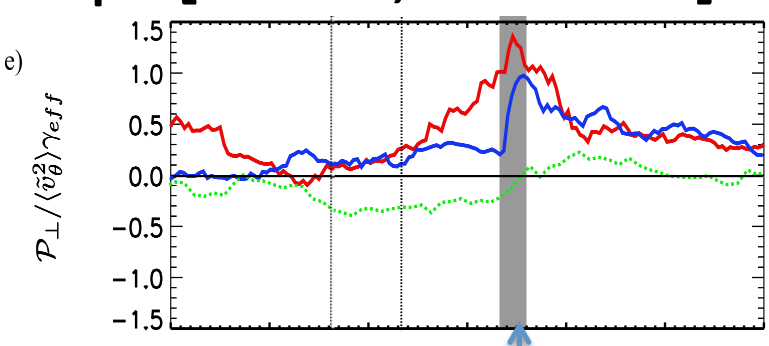
→ Emerging Scenario for L→H Transition

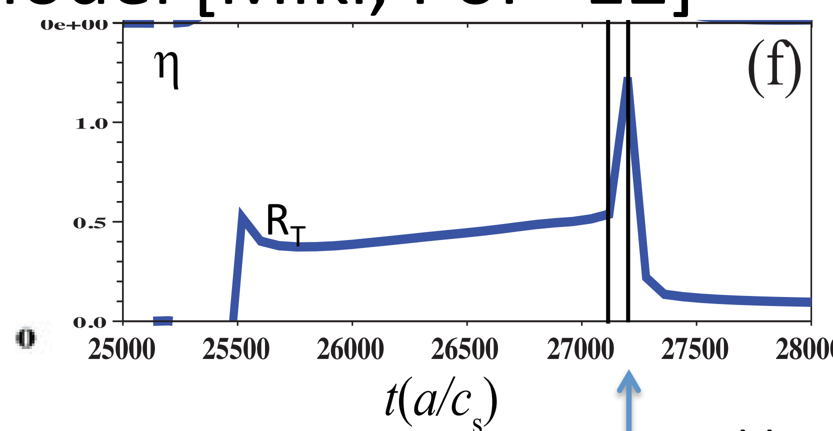
- Increased Q_{edge} → increased turbulence drive → increased Reynolds work on flow → turbulence collapse → ∇p_i growth → transition
- Useful parameter:

$$R_T \equiv \left\langle \tilde{v}_{r_E} \tilde{v}_{\theta_E} \right\rangle \partial \left\langle V_\perp \right\rangle / \partial r \Big/ \gamma_{eff} \mathcal{E}_T$$

$R_T \geq 1 \Rightarrow$ turbulence collapse and transition

- Exp. [Manz, PoP '12]   Model [Miki, PoP '12]





See also TEXTOR [Shesterikov PRL '13]

Extension: Representing particle injection

<u>Important parameters:</u>

I_{SMBI}: particle injection intensity

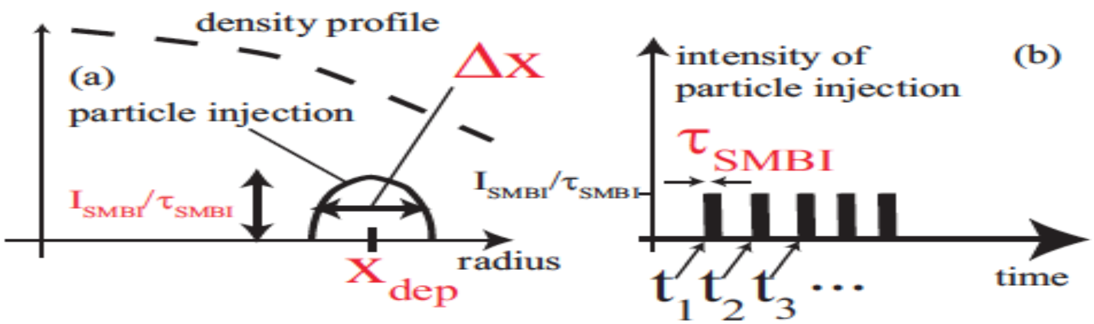
x_{dep}: deposition point of injection

τ_{SMBI}: duration of particle injection

Δx: particle deposition layer width

$$\frac{\partial n(x,t)}{\partial t} = \text{(original terms)} + \frac{I_{SMBI}}{\tau_{SMBI}} \sum_i \left[H(t-t_i) - H(t-t_i-\tau_{SMBI}) \right] f\left(\frac{a - x_{dep}}{\Delta x} \right)$$

Injection Fueling



Since *p=nT:*

$$\frac{\partial T(x,t)}{\partial t} = \text{(original terms)} - \frac{\Delta T}{\tau_{SMBI}} \sum_i \left[H(t-t_i) - H(t-t_i-\tau_{SMBI}) \right] f\left(\frac{a - x_{dep}}{\Delta x} \right)$$

$$\frac{I_{SMBI}}{n_{ref}} = \frac{\Delta T}{T_{ref}}$$

Cooling due to particle injection

→Limitations of Model

Specific to injection:

- No ablation, ionization, etc. Injection is instantaneous ⇒ time delay related to ionization, etc. *not* accurately represented. Model *can* capture time delay related to plasma transport dynamics.
- Source asymmetry ⇒ toroidal and poloidal
- V_ϕ not evolved ⇒ model does not include possible benefit from reduction in rotation.

General:

- Need separately evolve T_e, T_i and ion, electron heating ⇒ low $P_T(n)$ behavior
- Generalize turbulence model: ITG+TEM
- Relation between $T_e(\rho=1)$ and SOL heat transport (Fundamenski)
- LSN vs USN asymmetry (Fedorczak, et al.,)

III.) Model Studies

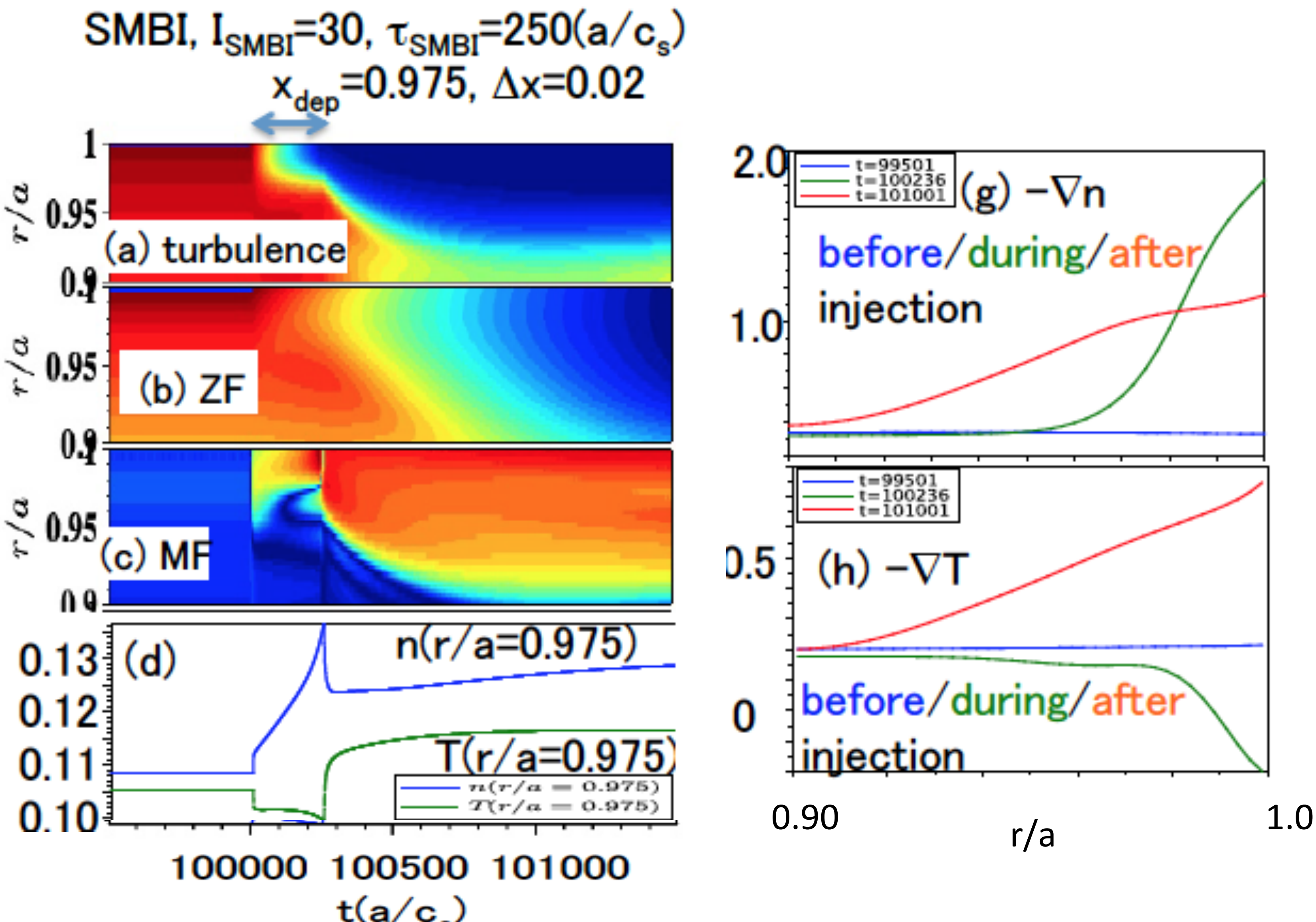
A.) Comparison/ Contrast (A.)

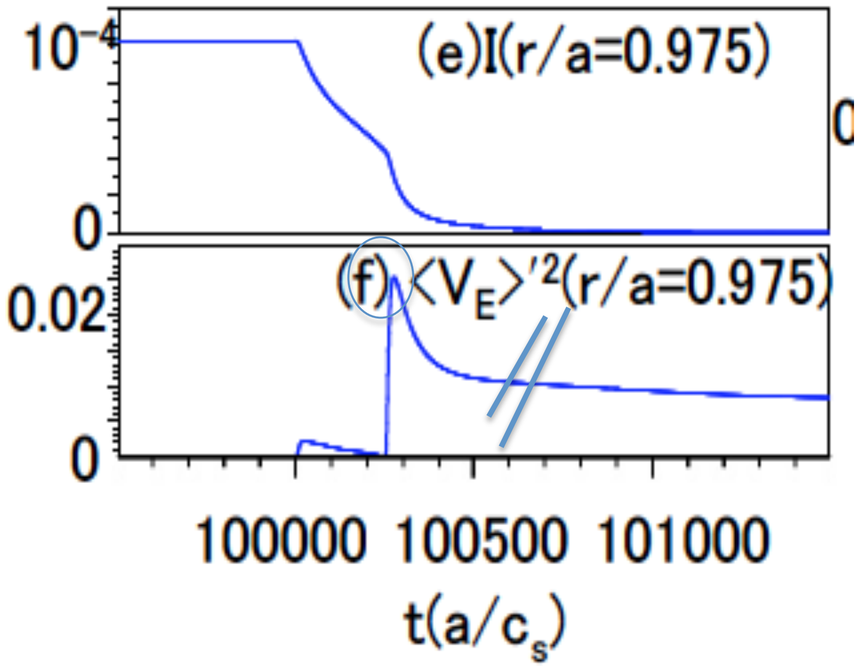
- Case 1: Injection Triggers L→H
- Case 2: Deeper injection triggers damped LCO

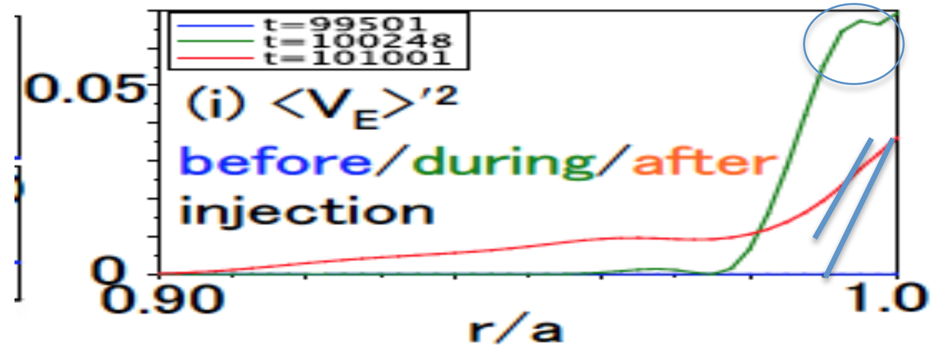
B.) Comparison/ Contrast (B.)

- Case 3: Injection to subcritical state triggers turbulence collapse
- Case 4: Sequential Injection into Subcritical state maintains turbulence collapse.

A.) Case 1: Injection Triggers L→H Transition

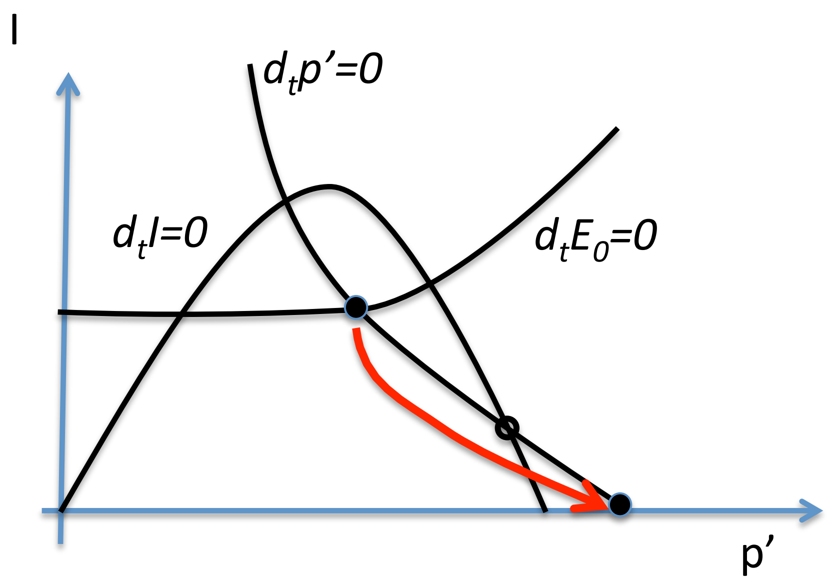






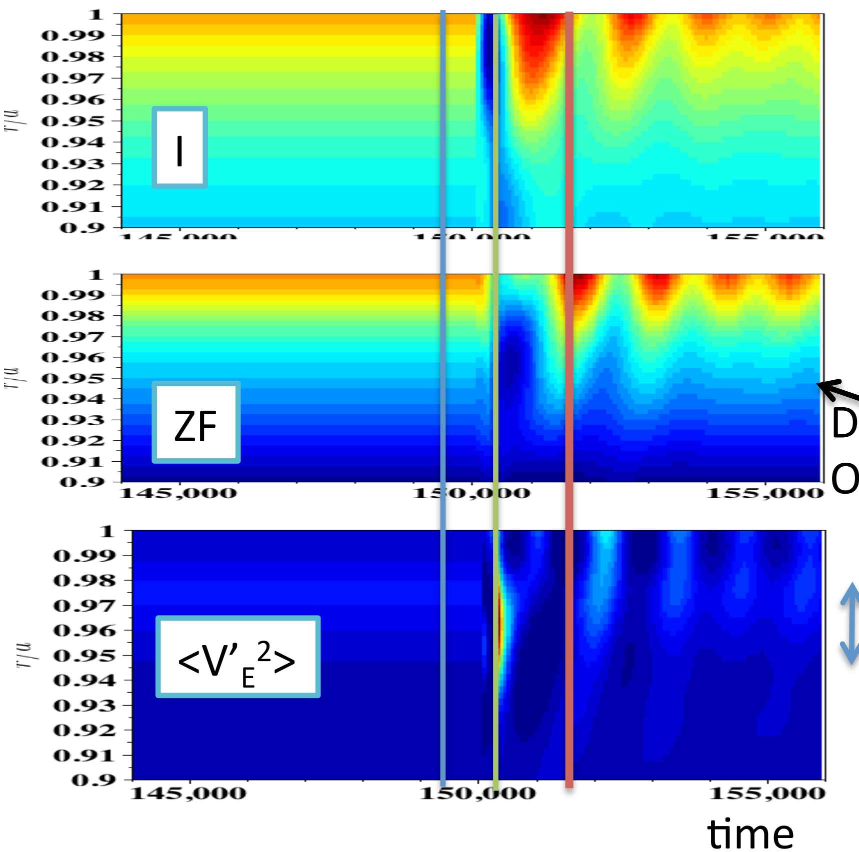
→Turbulence quenched quickly following injection

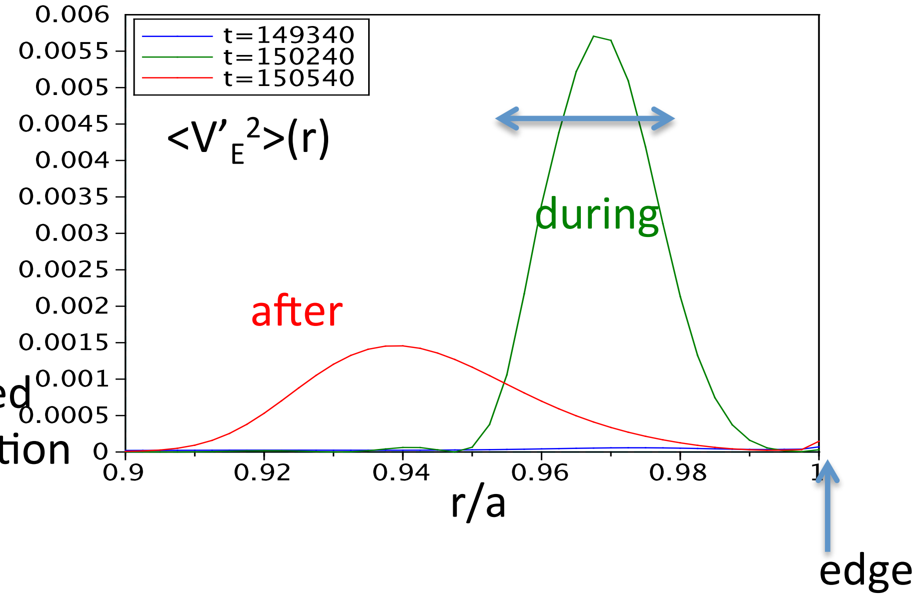
→Single rapid burst in $\langle V_E \rangle'^2$ followed by relaxation to H-phase value with enhanced $\langle V_E \rangle'^2$ edge.



A.) cont'd Case 2:Deeper Injection Triggers damped oscillation

- Same deposition, but for x_{dep}=.95 instead x_{dep}=.975





⇒Injection triggers damped oscillation

⇒Key difference with case 1 is that edge $\langle V_E \rangle'$ not enhanced.

A.) The Lesson

- Edge $\langle V_E \rangle'$ seems critical to turbulence collapse and L→H transition

→ Despite comparable $\langle V_E \rangle'$ magnitudes,

  → case with stronger $\langle V_E \rangle'$ at edge ⇔ transition,

  → while case with weak $\langle V_E \rangle'$ at edge ⇒ no transition.

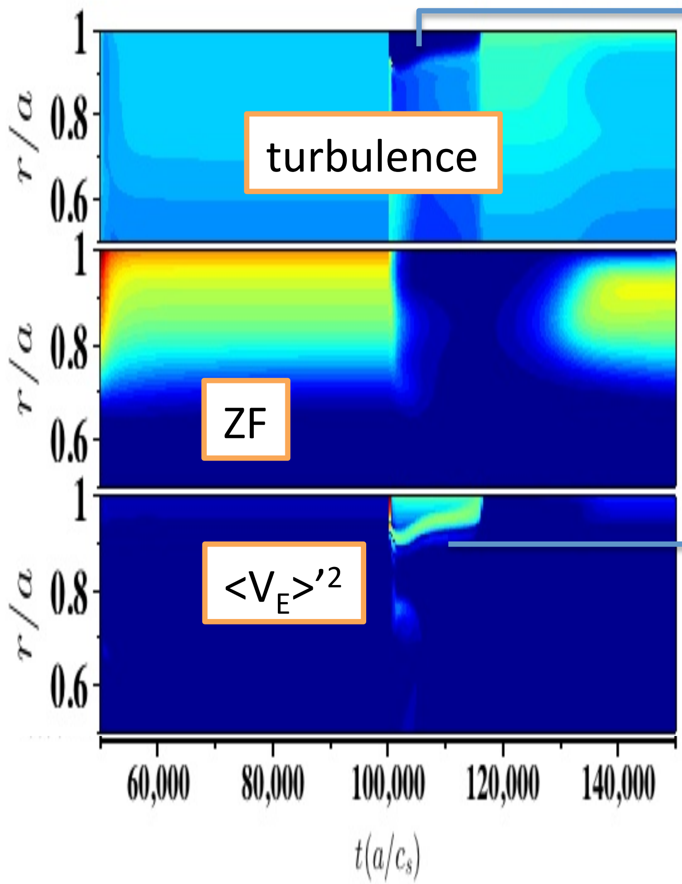
→ No transition case exhibits damped oscillation

→ No apparent evidence for ZF role in transition (!?)

B.) Effective Hysteresis

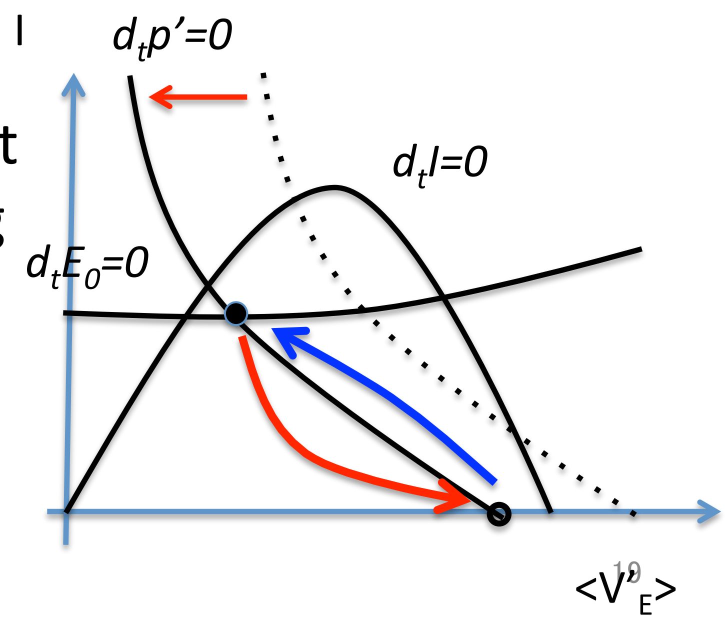
1.) Case 3: dQ=.7, I_{SMBI}=100 (Δ_{dep}=0.01)

Strong single injection into *subcritical state* can trigger a *transient* turbulence collapse.



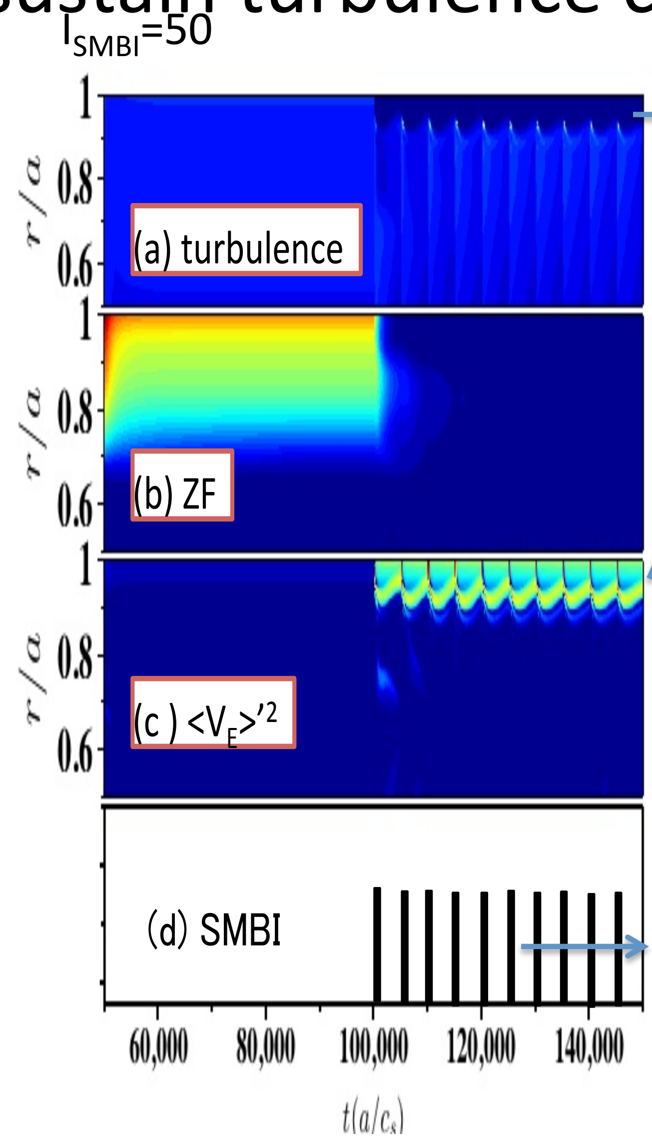
Transient collapse of turbulence, followed by return to L-mode

Transient burst in $\langle V_E \rangle'$ during collapse.

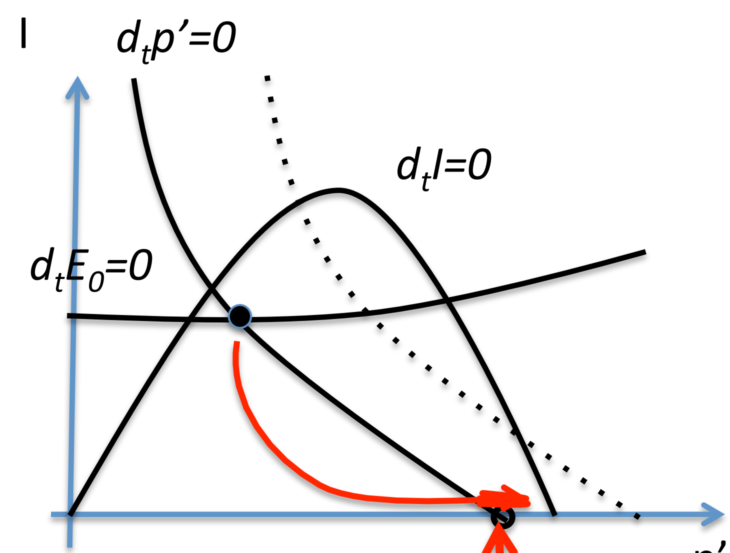


2.) Case 4

Sequential, repetitive injection into subcritical state can sustain turbulence collapse. ⇒ ‘ stimulated H-mode’



Sustained state of turbulence collapse (‘H-mode’?)



Repetitive, sequential injection

Repetitive injection

Lesson:

→Strong injection can trigger *transient* turbulence collapse in subcritical regime.

→Repetitive, sequential injection can *sustain* subcritical turbulence collapse

⇒driven, or 'stimulated' H-mode

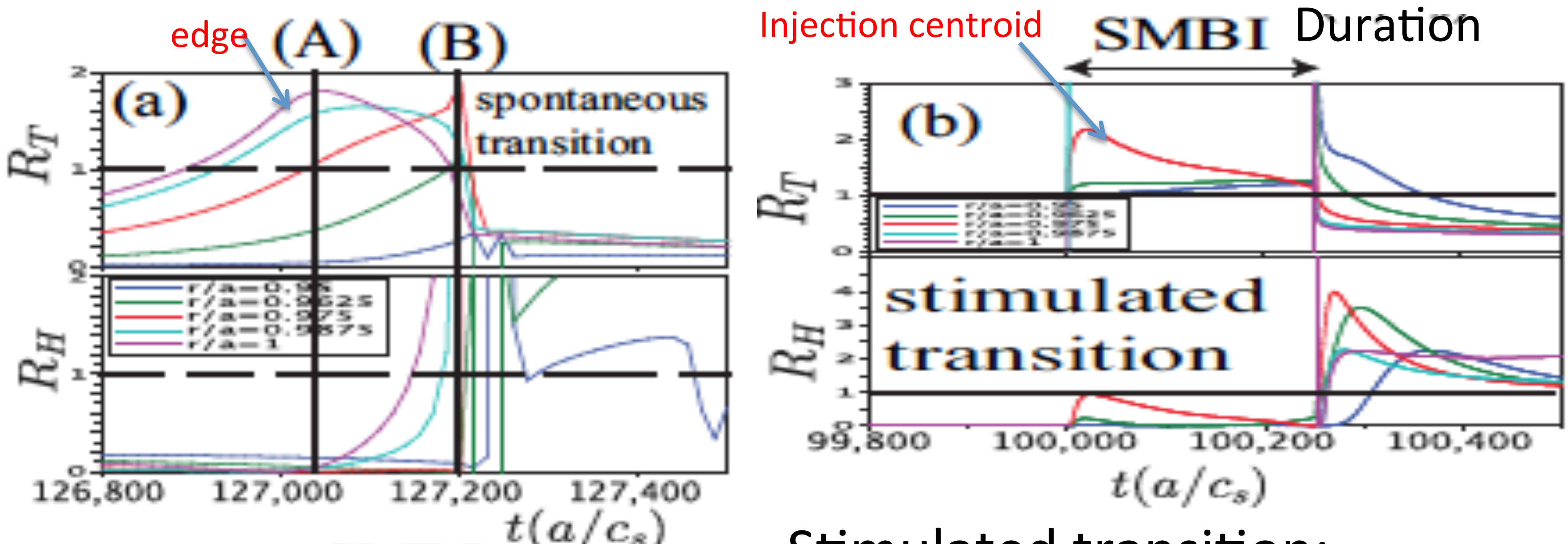
∴

→Speculation: Sequential injection can enhance effective hysteresis, facilitating control of H→L back transition.

→Quantitative Test: Compare Time Evolution

$R_T \equiv \left\langle \tilde{v}_{r_E} \tilde{v}_{\theta_E} \right\rangle \partial \left\langle V_\perp \right\rangle / \partial r \Big/ \gamma_{eff} \mathcal{E}_T = \alpha_0 E_0 / (\gamma_L - I\Delta\omega)$ → Normalized Reynolds Work

$R_H \equiv \left\langle V_E \right\rangle' / \gamma_{eff} = \alpha_V E_V / (\gamma_L - I\Delta\omega)$ → Normalized Shearing Rate



Spontaneous transition: R_T(edge) leads R_H prior to transition

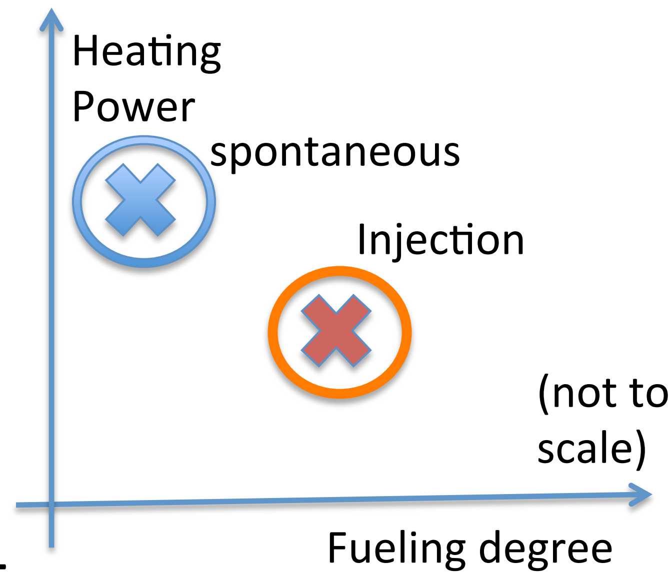
Stimulated transition: R_T(edge) and R_H peak simultaneously, at transition.

How Reconcile?

→Spontaneous and Stimulated Transition take fundamentally different routes to transport and profile bifurcation:

i) Spontaneous transition steepens $\nabla \langle p_i \rangle$ to achieve transition via Reynolds stress driven flow excitation and shearing to reduce turbulence and transport.

ii) injection-induced transition steepens $\nabla \langle p_i \rangle$ and $\langle V_E \rangle'$ via direct injection effects on edge gradients



∴ While evolutions differ, no real contradiction!

Key Test: Compare

a.) moderate → weak injection for $r_{dep} \to 1$

b.) no injection but particle source increment (static and pulsed) i.e. $S_0 \to S_0 + \delta S$

Is there a significant difference in number of injected particles required to trigger a transition?

a.)

$$\Delta N_{SMBI} = \iint dt\,dr\,\delta n_{SMBI}$$

$$= \int_0^a dr \int dt \frac{I_{SMBI}(n_{ref})}{\tau_{SMBI}} \frac{1}{2}\left[H(t-t_i) - H(t-t_i-\tau_{SMBI})\right] \exp\left(-\frac{(x-x_{dep})^2}{2\Delta x^2}\right)$$

$$= \sqrt{2\pi}\, f_{x_{dep}} \Delta x \frac{I_{SMBI}(n_{ref})}{\tau_{SMBI}} \tau_{SMBI} \sim 0.083$$

b.)

$$\Delta N_{gaspuff} = \iint dt\,dr\,\delta n_{gaspuff}$$

$$= \tau_{gaspuff}\left(\frac{S}{S_0}\right)\int dr\,\partial_r S \sim \left(\frac{S}{S_0}\right)\tau_{gaspuff}\Gamma_a \sim 1.08$$

Conclusion

- Subcritical transitions can indeed occur.
  - Zonal flow do *not* play a key role in such fueling-induced transitions, in contrast to their contribution to spontaneous transitions.
- The crucial element for a subcritical transition appears to be how the injection influences the edge $\langle V'_E \rangle$.
- Below a certain power, subcritical injection can induce a *transient* turbulence collapse which later relaxes back to L-mode.
  - However, repetitive injection can sustain subcritical improved H-mode states.