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Spatio-temporal evolution of L→**I**→H transition

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- Motivating experimental observation
- Model description
- Simulation Results: L-I-H transition
- Analysis and Comparison to Experimental results
- Neutral CX scan
- Back Transition

- (Transport Noise effects)

- Summary

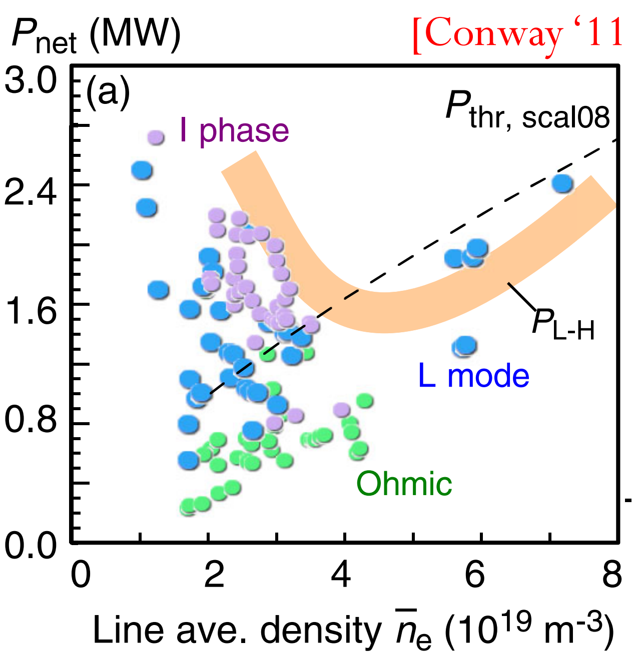
Motivating experimental observation:

-- L-H power threshold scaling deviates in low density region

-- New region related to I-mode, I-phase, and GAM

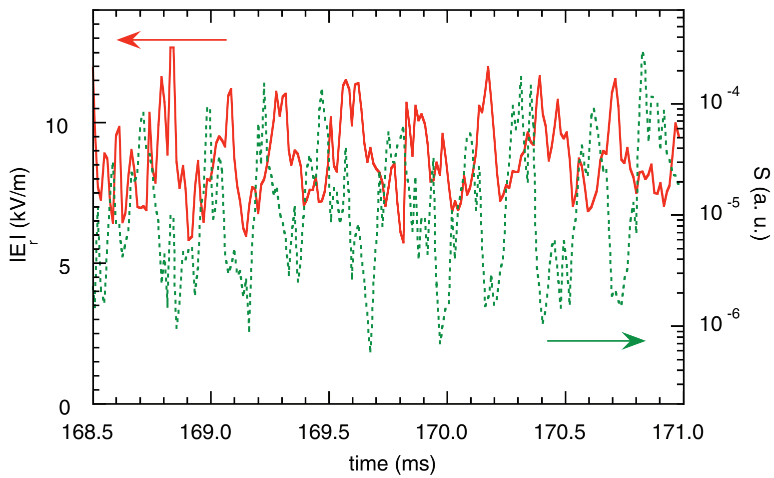
-- No theoretical model to quantitatively predict the threshold and to show spatio-temporal evolution

[Conway '11 PRL]

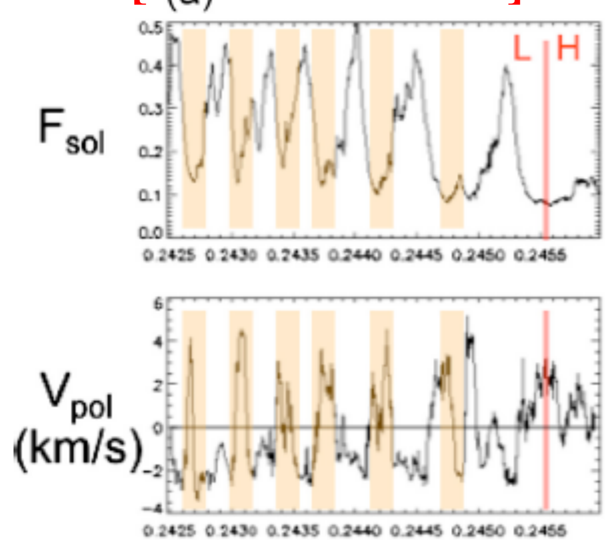


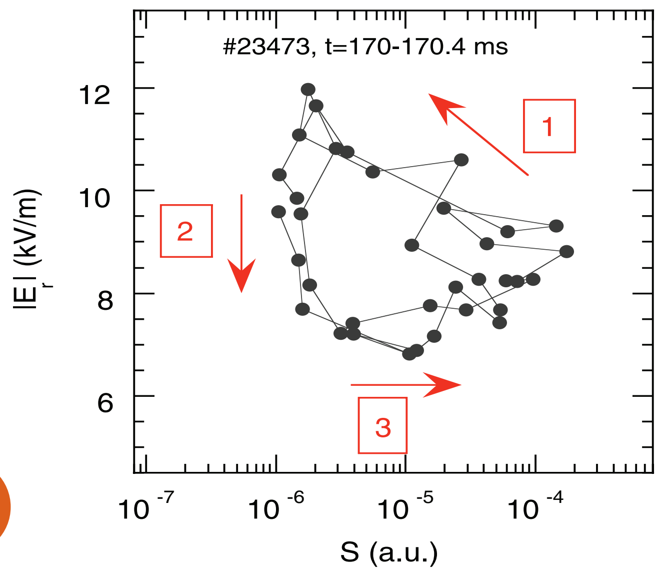
I-phase as a transient phase with limit-cycle oscillation(LCO), i.e. L⟶H transition can be replaced with L⟶I⟶H transition

TJ-II [Estrada '10 EPL]

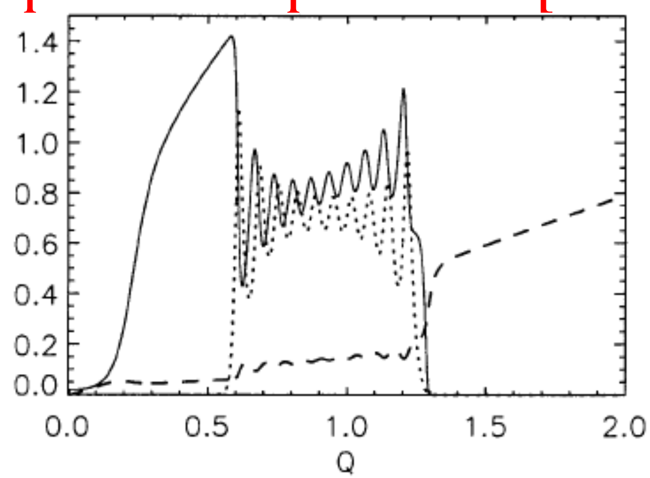


NSTX[Zweben, PoP 2010]



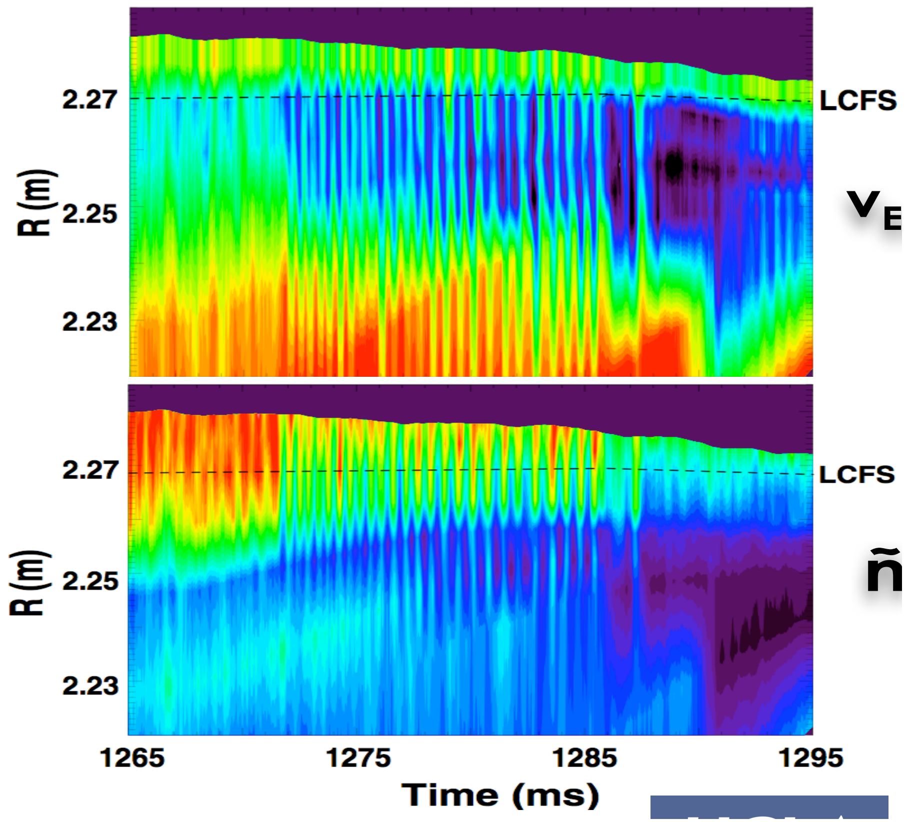


Can a simple model explain these? [E. Kim, PRL 2003]

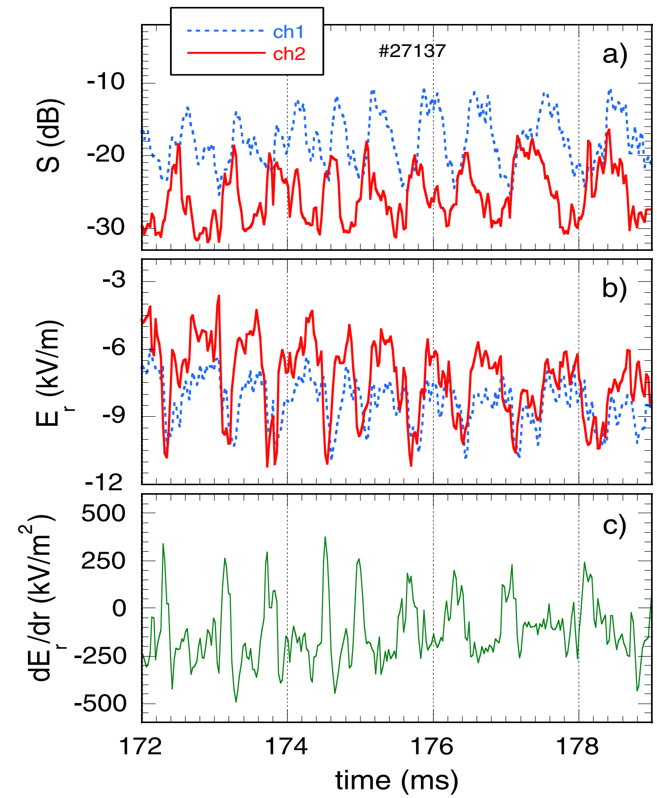


Radial structure of I-phase is identified in DIII-D and TJ-II

DIII-D [Schmitz, submitted to PRL]



TJ-II [Estrada, PRL '11]



→One-dimensional model to reproduce I-phase is necessary in that I-phase radial propagation and pedestal formation should be compared.

To address these issues, we have developed a 1D model.

- *Spatio-temporal* evolutions of 5-field (density, pressure, turbulence intensity, ZF, poloidal flow) equations
- Zonal flow / Mean flow competition , *a' la* 0D Kim-Diamond
  - ZF/MF as different players [E. Kim, PRL '03]
- NO MHD activities; NO ELMs
- **No 'first principle' simulations have ever reproduced or elucidated the L-H transition!**

Predator-prey model

Turbulence intensity: $\gamma_L \sim \gamma_{L0} \frac{c_s}{R} \sqrt{\frac{R}{L_T} - \left(\frac{R}{L_T}\right)_{crit}}$ ← from p,n profile

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

Driving term

Local dissipation

ZF shearing

MF shearing

Turbulence spreading

Zonal flow energy: $E_0 = V_{ZF}^2$

$\alpha_0 \sim \alpha_V \sim \tau_{ac0} \frac{\sqrt{a\rho_i}}{c_s}$ $(\tau_{ac} << 1)$

$\chi_N \sim \chi_{N0} \chi_{GB} \sim \chi_{N0} \frac{\rho_i^2 c_s}{a}$

$$\partial_t E_0 = A E_0 \alpha_0 (I / (1 + \zeta_0 E_V) - I_*)$$

Screening factor

Reynolds stress drive

MF/ZF competition

ZF collisional damping

$I_* = \gamma_{damp} / \alpha_0$

$\gamma_{damp} \sim (\nu_{ii} + \nu_{CX}) / R$

Mean flow shearing:

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

→ by radial force balance

Short time scale normalization $\omega_*(\sim c_s/a)t \rightarrow t$

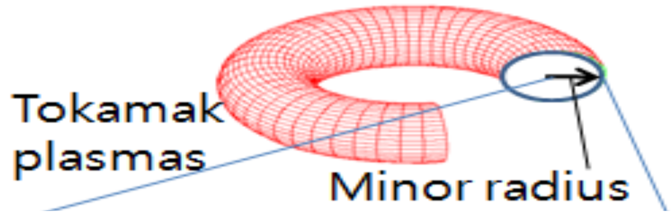
Long time scale τ_{ii} $(=1/\nu_{ii}) \sim 600(a/c_s)$

Small spatial scale $\rho_i \sim 0.01a$

Long spatial scale normalization $r/a \rightarrow r$

1D transport model

x: radial direction



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

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

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

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

Pinch term

TEP pinch

Thermoelectric pinch

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

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

$$n \sim \exp\left(-\frac{V}{D} r\right)$$

→density peaking

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***

a la' [Hinton '90 PFB], [Z.H. Wang, P.D, '11 NF]

Poloidal momentum spin-up

- Full-*f* gyrokinetic simulation predicts that poloidal flow driven by turbulence can be another mediator through L-H transition especially in low ρ_* plasmas. [Dif-Pradalier '08, PRL]
- Coupling radial and parallel momentum force balance equations, we obtain

Turbulence drive obtained from stress tensor **[McDevitt, PoP '10]**

Neoclassical effects

Eq. of poloidal rotation

$$-\frac{\partial u_\theta}{\partial t} = \frac{1}{nm}\left\langle \nabla \cdot (\hat{e}_y \overleftrightarrow{\Pi}_{turb}) \right\rangle + \mu_{ii}^{(neo)}(u_\theta - u_\theta^{(neo)})$$

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

Radial force balance equation:

from global profiles

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

Density gradient

Pressure curvature

Diamagnetic drift term

Toroidal flow (not considered here)

Poloidal flow driven by neoclassical and turbulent drives

$$= \rho_i c_s L_p^{-1}\left(-L_n^{-1} + L_{\frac{dp}{dx}}^{-1}\right) - u'_\theta$$

- Pressure curvature (ignored by Hinton *et. al.*, noted by Helander *et al.*, Malkov, P.D.) produces fine scale $<V_E>'$ structure
- Poloidal rotation from neoclassical, Reynolds drive
- Totally, time-evolving 5-fields (n, p, I, E_0, and u_θ) are solved numerically.

Numerical simulation results:
Slow Power Ramp Indicates L→I→H Evolution.

1D Model

c.f. DIII-D, [Schmitz et al.],

r/a

turbulence

ZF

MF

time

Cycle is propagating nonlinear wave in edge layer

ZF

Period of cycle increases approaching transition.

Turbulence intensity

Mean flow shear

- Turbulence intensity peaks just prior to transition.
- Mean shear (i.e. profiles) also oscillates in I-phase.

Mean shear location comparisons indicate inward propagation, and observed in experiments.

r/a=0.975

r/a=0.950

r/a=0.925

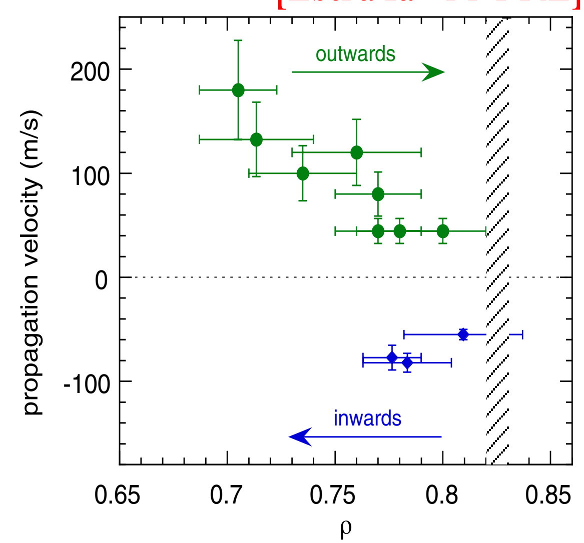
Turbulence

ZF shearing

MF shearing

- Inward propagation ~80 [m/s]
  - Similar to exp. [Estrada],[Schmitz]

[Estrada '11 PRL]



Phase delay between turbulence and zonal flow increases from $\pi/2$ to π during I-phase

$\sim\pi/2$
phase delay

1D model

$\sim\pi$
phase delay

DIII-D [Schmitz, '11 APS]

The phase lag relation is shown in DIII-D experiments!

Time evolution of diamagnetic shearing.

→Diamagnetic shear oscillates with growing amplitude in I-phase, then increases abruptly at L-H transition.

c.f. DIII-D [Schmitz]

Diamagnetic shearing $\omega_{E\times B,dia} = \frac{\partial}{\partial r}\left(\frac{1}{eBn}\right)\frac{\partial p}{\partial r}$

1D model:

Energy channel → Rate of coupling to ZF comparable to drive at the transition threshold.

1D Model:

- Peak of ZF shearing contribution increasing
  - Consistent with EAST results[Manz, Xu *et al.*, submitted]
- ZF triggers MF; ZF can be a heat 'reservoir' w/o increasing turbulence.
- Thus, ZF shearing dominant in prior to L→H transition.

Profile comparison in L, I, H

- Pressure and temperature profile

pressure

Density

$T(r)$

temperature

➔ Pedestal formation clearly recovered.

Fast ramp up indicates no LCO, but L⟶H transition occurs.

a) turbulence

b) ZF

c) log(MF)

Implications for Steady State Experiments (KSTAR, EAST, JT-60 SA, ITER)

$$\gamma_{ZF} \sim \nu_{ii} + \nu_{CX}$$

- neutral CX can damp zonal flows (c.f. Y. Xu, *et al.*, in preparation)
  - high edge n_{neutral} unfavorable to transition

  $\rightarrow$ long established experimental lore concerning Q_{thresh} , 'dirty machines,' re-cycling,...

- But:
  - in SST, with long pulse H-mode,

  can expect: $\rightarrow$ eventual wall saturation

  $\rightarrow$ subsequent increase in re-cycling

  $\rightarrow$ increase in CX damping of ZF

If/When discharge drops out of H-mode, will recovery be possible???

Increase γ_{ZF} and μ_{neo} increases L$\longrightarrow$H power threshold.

$\longrightarrow$ neutral CX increases power threshold!

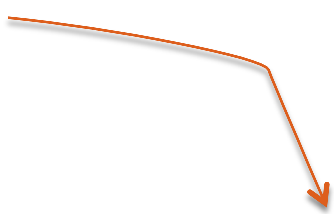
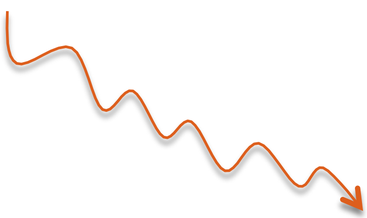
Back transitions --- More than hysteresis!

- Back transitions now both an interesting and a pragmatically critical topic for ITER
- Back transition issues: → hysteresis

→ rate of β_p decay (D. McDonald, '12)

→ observation of so-called 'small, Type III ELMs' during β_p decay at back transition

→ beneficial, as allows 'soft landing'

i.e.  vs 

→ hypothesize that 'small Type III ELMs' are really L.C.O. in back transition

→ Key Question: Does back-transition occur via H→I→L?

→ **YES! See [Schmitz '11 APS]**

Case with slow power ramp up and down

Slow power ramp up

S**low** power ramp down

L.C.O. nucleates at pedestal shoulder.

Case with slow ramp up and fast ramp down

Slow power ramp up

Fast power ramp down

← Little sign of I-phase

Hysteresis is here!

Scan of χ_{neo} indicate relation to 'strength of the hysteresis'

Area of hysteresis loop

Core pressure ~ <grad p>

$$A_{hyst} \sim Nu^{\alpha}$$

$$\alpha \sim 1$$

Heat power ramp

$$Nu \sim \frac{\chi_{turb,L \to H}}{\chi_{neo}}$$

[S.S. Kim and H. Jhang]

Summary of this study

- One dimensional extension of the Kim-Diamond model is introduced, including Pressure/Density profile, 0D K-D model components (turbulence, ZF, MF) , Radial force balance, i.e. mean flow equilibrium. Poloidal rotation spin-up
- L-I-H-transitions with power ramp up are shown. Observed properties are consistent with those observed in DIII-D, TJ-II, and EAST.
- Damping of ZF increases the L→H power threshold
  - ZF shearing contribution decreases the L→H power threshold.
  - Neutral CX hinders plasmas from H-mode transition, by shrinking ZF shearing contribution and increasing power threshold.
- I-phase on back transition possible but not certain.
  - Hysteresis: $A_{hyst} \sim \mathrm{Nu}^{\alpha}$

To-go message:

There are REAL clues, both from experiments and the model study, to indicate the connection between L→H transition and ZF.