L-H Transition Dynamics and Power Threshold Minimum

M.A. Malkov[1], P.H. Diamond[1,2], K. Miki[2,3] and G.R. Tynan[1]

[1]University of California, San Diego, USA; *e-mail*: mmalkov@ucsd.edu [2]WCI, NFRI Daejeon, Korea,[3]JAEA, Kashiwa, Japan

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Abstract

A physical model to explain the minimum in the power threshold of the L→H transition is suggested. Its crucial new elements, compared to the prototype due to (Miki & Diamond 2012), are the separately evolved electron and ion heat transfers and the independent power supply in each chanel.

The power threshold minimum may be explained as follows. The low-density branch, where the heat initially goes to the electrons, is associated with growing efficiency of $e - i$ heat transfer and the flow generation. This suppresses the transport and lowers the threshold $P_{th.}$. The high-density branch is associated with increased collisional damping of the flow. Model studies also reveal: (a) an increase in threshold power for off-axis electron heat deposition and (b) the absence of a clear $P_{\mathrm{thr}}(n)$ minimum for pure ion heating.

Outline

1. Basic physics of LH transition
2. Recent Experiments and Shortcomings of Available Models
3. Predecessor Model and its Extension to Studies of P_{th} Minimum
4. Model Equations
5. Results and analysis
6. Conclusions

Mechanism and occurrence of LH transition

- originates via coupling of turbulence to low frequency shear flows by Reynolds work
- Reynolds work causes collapse of turbulence and then turbulent transport
- diamagnetic electric field grows, associated with ∇P
- $\rightarrow$LH transition
- can occur via a protracted I-phase or in a single burst of shear flow

Objectives of this work (ongoing)

- establish link between microscopics and macroscopics in power threshold scaling
- reproduce and understand observed threshold $P_{th}(n)$ minimum
- explore P_{th} in terms of other parameters, such as e-i thermal coupling efficiency, noise...
- investigate the role of heating profile in LH transition
- e-i heating branching ratio
- role of mean shear in locking-in of the transition

Observations of power threshold minimum

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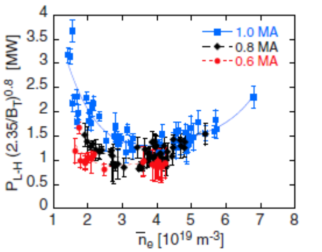


Figure 3. Power threshold versus density for the L–H transition normalized to $|B_T| = 2.35$ T by the $B_T^{0.8}$ dependence. The fits to the P_{L-H} data indicated here are also shown in figure 4. The error bars include all the contributions to P_{loss}. The larger error bars are due to the dW/dt term for discharges with a rather strong change of heating power before the occurrence of the L–H transition.

Ryter et al 2013 [1]

- ion heat flux plays a dominant role in LH transition $\rightarrow \nabla P$
- electron channel thought to be ignorable
- But: in low-density regimes with dominant EC heating electrons must transfer energy to ions to steepen ∇P
- electron description must be separated from that of ions
- temperature and density dependence of collision rate need to be included (average values do not suffice)

1-D Numerical Model

- Based on 1-D numerical 5-field model (Miki & Diamond 2012,13+) [2] significantly extends Kim & Diamond 2003 [3] 0D model
- MD 2012 captures transition layer evolution but *does not separate species*
- **modify** MD 2012 by adding **separate** electron heat transport equation
- **include e-i thermal coupling** depending on locally evolved temperatures and density
- include these parameters in ZF damping description
- include trapped electron growth

Predator-Prey Model Equations

- Heat transport i,e:

$$\frac{\partial P_{i,e}}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_{i,e}^{(p)} = \pm\frac{2m}{M\tau}\left(P_e - P_i\right) + Q\exp\left[\frac{(r-a)^2}{2\Delta r^2}\right]$$

$$\Gamma = -\left(\chi_{neo} + \chi_t\right)\frac{\partial P}{\partial r}$$

- Density

$$\frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma^{(n)} = \Gamma_a \frac{a-r}{L_{dep}^2}\exp\left[\frac{(a-r)^2}{2L_{dep}^2}\right]$$

$$\Gamma^{(n)} = -\left(D_{neo} + D_t\right)\frac{\partial n}{\partial r}$$

$$\chi, D_t = \frac{\tau_c C_s^2 I}{1 + \alpha_t \langle V_E\rangle'^2}, \quad \langle V_E\rangle' = \rho_i C_s L_p^{-1}\left(L_p^{-1} - L_n^{-1}\right) - \langle V_\vartheta\rangle'$$

Equations cont'd

- DW turbulence with ITG and TEM instabilities

$$\frac{\partial I}{\partial t} = \left(\gamma_L - \Delta\omega I - \alpha_0 E_0 - \alpha_V \langle V_E \rangle'^2\right) I + \chi_N \frac{\partial}{\partial r} I \frac{\partial I}{\partial r}, \quad \chi_N \sim \omega_* C_s^2$$

$$\gamma_L = \gamma_{0i} \frac{C_s}{R} \sqrt{\frac{R}{L_p} - \frac{R}{L_n} - \left(\frac{L}{R}\right)_{crit}} + \gamma_{0e} C_s \left(L_{T_e}^{-1} + L_n^{-1}\right)$$

- ZF energy

$$\frac{\partial E_0}{\partial t} = \frac{\alpha_0 E_0 I}{1 + \zeta_0 \langle V_\vartheta \rangle^2} - \gamma_{damp} E_0$$

- mean flow shear

$$\frac{\partial \langle V_\vartheta \rangle}{\partial t} = -\alpha_5 \gamma_{0i} C_s^2 \frac{a}{R} \sqrt{\frac{R}{L_p} - \frac{R}{L_n} - \left(\frac{L}{R}\right)_{crit}} \frac{\partial I}{\partial r}$$

$$-\mu^{neo} \nu_{ii} q^2 R^2 \left(V_\vartheta - 1.17 C_s \rho_i L_T^{-1}\right)$$

Control parameters for transition

- plasma density
  - n_{ref} -reference (fixed) density
  - n -center line averaged (current) density
- Heat mix parameter

$$H_{mix} = \frac{Q_i}{Q_i + Q_e} \equiv \frac{Q_i}{Q}$$

  i.e., $Q_i = H_{\text{mix}} Q$, $Q_e = (1 - H_{\text{mix}}) Q$, where Q denotes the total power deposited into the plasma.
- widths of the heat sources
  $\Delta r_e = \Delta r_i = 0.15a$,
- heat deposition radii $a_{e,i} = 0.3a$

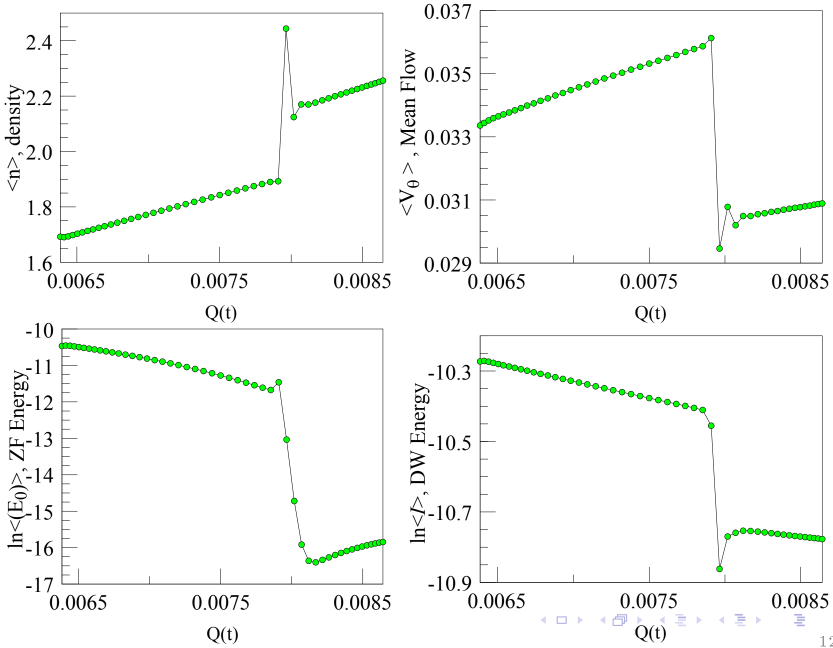
Transition morphology

L→H transition event shown in four characteristic variables center line averaged:

- density,
- ZF energy,
- MF $E \times B$ velocity,
- DW energy.

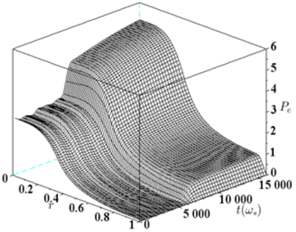
shown as functions of heating rate $Q(t)$. Data points are taken at equal time intervals so their density indicates both the rate at which Q is changing and how quickly the changes in the variables occur.

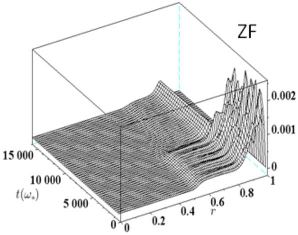
Transition morphology

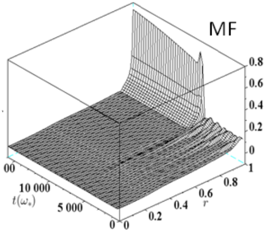


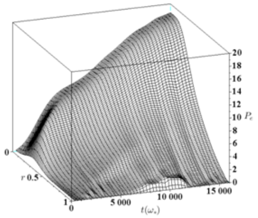
Transition morphology

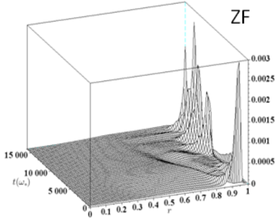
- Top row:
  - an example of LH transition with an extended pre-transition I-phase shown for the electron pressure P_e, ZF energy and the MF velocity
  - strong, edge-localized MF is a marker of the H-mode.
- Bottom row:
  - an example of a failed transition with inward propagation
  - the edge MF jet starts to form but then merge with the large scale MF

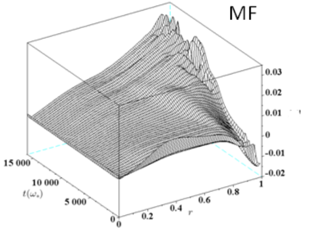



ZF

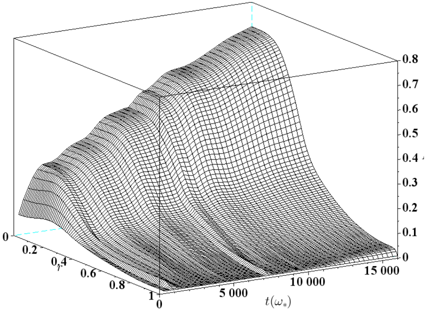

MF



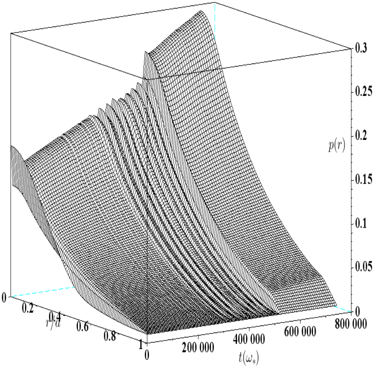

ZF


MF

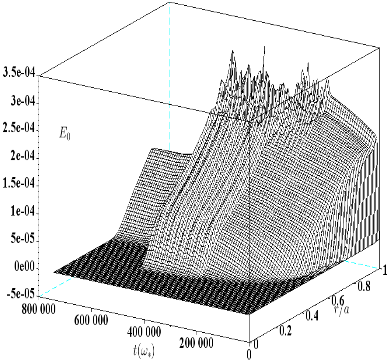
Identifying transitions



- take half-way to clean pedestal
- cross-check with DW,ZF,MF channels

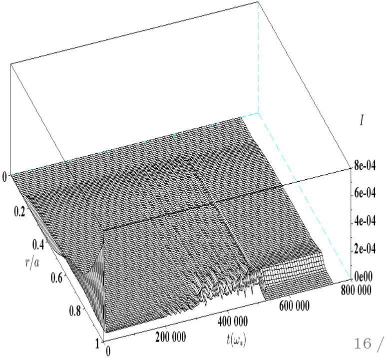


$\rightarrow$need transition criterion to scan $P_{th}\left(n, H_{e,i}, L_{dep}, \ldots\right)$
- very weak transitions occur and are hard to detect

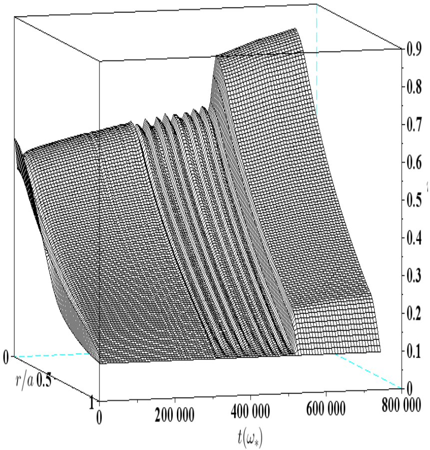


- I-phase persists before transition
- clearly spatio-temporal behavior beyond 0-D model (similar to MD 2012)

ZF significantly advances into the core before transition

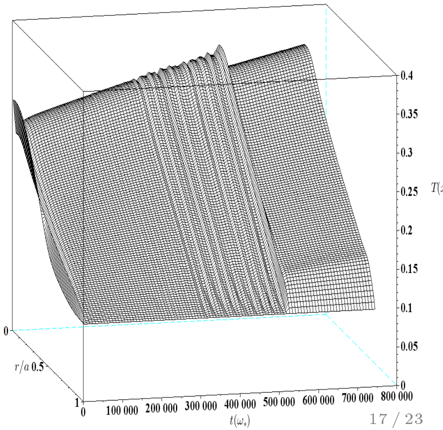


Spatio-temporal dynamics of transition

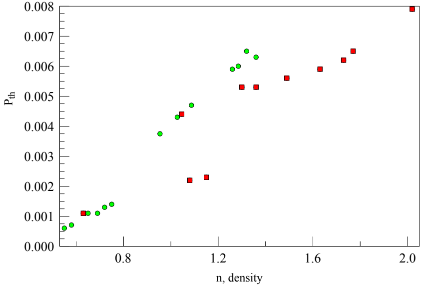


I-phase in density

- slight temperature flattening in the core due to enhanced turbulent transport



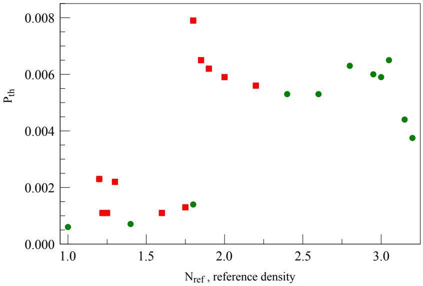
$P_{th}(n)$ scans



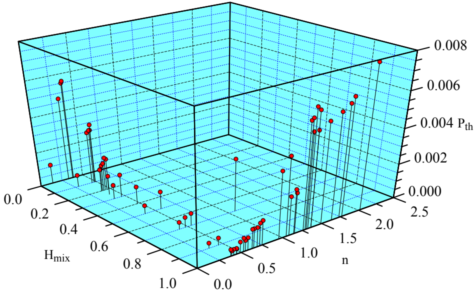
- P_{thr}, shown against the center-line averaged n

Squares indicate strong transitions with the density jumps $\gtrsim 0.1$
Circles indicate weaker transitions.

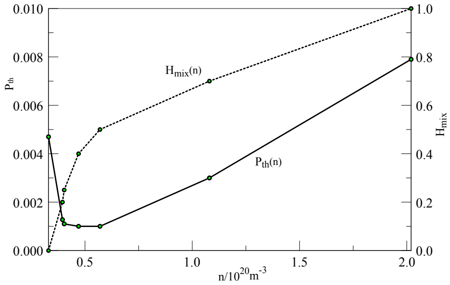
- as a function of reference density



$P_{th}\left(n, H_{mix}\right)$ scans



Monotonic dependence of $H_{mix}(n)$, arbitrarily chosen from the sample shown in the previous Figure and the resulting $P_{\mathrm{thr}}(n)$ constrained by the above relation.



P_{thr} in heating mix -density variables, H_{mix} and n.

n, H_{mix}choice: electron/ion biased heating at lower/higher densities extended sub-sample at $H_{mix} = 1$ is also included

Model Findings

- no clear threshold minimum for pure ion heat deposition
- minimum consistend with observations [1, 4] found for mixed $e - i$ heating
- on low-density branch of $P_{\mathrm{thr}}(n)$ electrons absorb most of the heat initially and as they transfer it to ions more efficiently with growing density, $P_{\mathrm{thr}}(n)$ decreases
- on high-density branch ions are heated and as ZF damping is growing with n, P_{thr} must also grow

Model Findings

- the overall picture is consistent with the following two premises:
  - L-H transition is locked in by $V_E' \sim (\nabla P_i/n)'$
  - DW turbulence coupling to flow is a key trigger
- P_{th} increases for off-axis electron heat deposition (reduced electron-ion coupling)
- shallow minimum power is predicted for heating mix scan as well as for density scan
- from above findings a *global minimum in multi-parameter space is predicted*

Ongoing work: quantifying strength of hysteresis in terms of multiple macroscopic parameters;
relating this to observed back-transition shear flow and turbulence dynamics

Conclusions

- an extended 6-field 1-D PDE model is developed (P_e, P_i, n, DW, ZF, Mean Flow)
- link between microscopics (e-i collisional heat exchange, turbulence) and macroscopics (transport barrier, P-n profiles) in power threshold scaling is established
- threshold $P_{th}(n)$ minimum is reproduced and understood using a simple model of e-i heat transfer
- $P_{th}(n, L_{dep}, \ldots)$ is explored in terms of its dependence on other parameters, such as e-i thermal coupling efficiency
- the role of heating profile in LH transition is investigated
- the role of e-i heating split ratio is studied, minimum of P_{th} predicted
- role of mean shear in locking-in of transition is significant

References

[1] F. Ryter *et al.*, Nucl. Fusion **53**, 113003 (2013).

[2] K. Miki *et al.*, Phys. Plasmas **19**, 092306 (2012).

[3] E.-J. Kim and P. H. Diamond, Physical Review Letters **90**, 185006 (2003).

[4] C. F. Maggi *et al.*, Nuclear Fusion **54**, 023007 (2014).