Physics of the Power Threshold Minimum for L-H Transition

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Outline

1. Motivation
   - $P_{\rm thr}$ - the LH transition Power Threshold
   - -Micro - Macro connection → How does physics set P_{thr}?
2. Key Questions
3. Reduced Model
   - Basic Structure
   - T_e and T_i equations
   - Anomalous Coupling
4. Model Studies
   - Recovering the Minimum
   - Towards the Anomalous Regime (Preliminary, if time allows)
5. Conclusions

Motivation and brief history of LH studies

- L→H transition is a 33 (!) year-old story *(Wagner, et al 1982)*
- revolutionized confinement physics
- central to ITER ignition

Underlying ideas

- dimensional analysis *(e.g. Connor and Taylor, 1977)* and simple scalings
  - in general $P_{\mathrm{thr}} \propto nBS$
  - early phenomenology (fit) $P_{thr} \propto n^{0.7}$ - inconsistent with the minimum in $P_{thr}(n)$
- connection of the power threshold to the edge parameters *(Fukuda et al 1988)*: evolving story
- Mechanism: shear suppression paradigm *(Biglari, Diamond and Terry, 1990 ++)*

Emerging Scenario

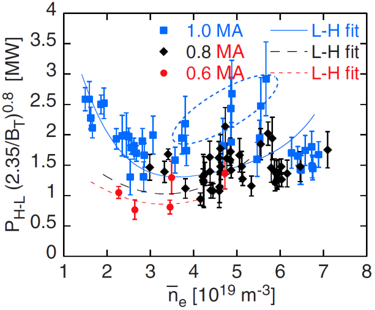
LH-triggering sequence of events

$Q \uparrow \implies \tilde{n},\ \tilde{v}\ \uparrow \implies\ < \tilde{v}_r \tilde{v}_\vartheta >;\ \ < \tilde{v}_r \tilde{v}_\vartheta > d < v > /\mathrm{dr} \uparrow\ \implies\ |\tilde{n}|^2\ \downarrow,$ etc.

$\implies \nabla P_i|\ \uparrow \implies$ lock in transition (*Tynan et al. 2013*)

- ∇T etc. drives turbulence that generates low frequency shear flow via Reynolds stress
- Reynolds work coupling collapses the turbulence thus reducing particle and heat transport
- Transport weakens $\rightarrow \nabla \langle P_i \rangle$ builds up at the edge, accompanied by electric field shear $\nabla \langle P_i \rangle \rightarrow \langle V_E \rangle'$
- locks in $L \rightarrow H$ transition: (*see Hinton ,Staebler 1991, 93*)
- Complex sequence of Transition Evolution and Alternative End States (I-mode) possible (*D. Whyte et al. 2011*)

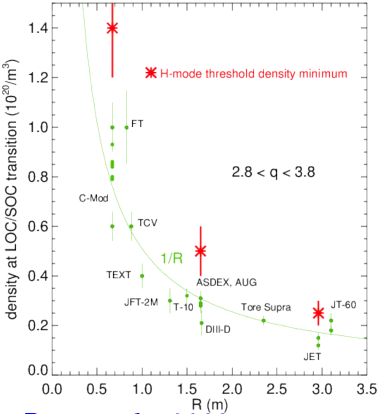
Some Questions:



Ryter et al 2013

- How does the scenario relate to the Power Threshold?
  - Is $P_{\text{thr}}(n)$ minimum recoverable?
- Micro-Macro connection in threshold, if any?
- How does micro-physics determine threshold scalings?
- What is the physics/origin of $P_{thr}(n)$? Energy coupling?
- Will P_{min} persist in collisionless, electron-heated regimes (ITER)?

Further Questions and important Clue:

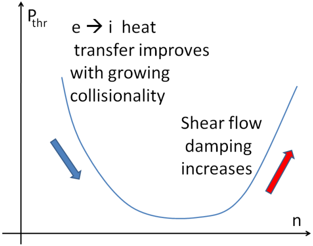


Rice et al., 2009

J. Hughes, Y. Ma, J. Rice, 2011,12

- Is P_{thr} set only by local properties at the edge? (Common wisdom)
- Is P_{thr} minimum related to collisional energy transfer? i.e. $\nu n (T_e - T_i)$. Low n branch couples to ions, enables ∇P_i?
- $P_{\mathrm{thr}}(n)$ minimum correlates with n 'LOC-SOC' transition $\Rightarrow$ i.e. min power related to collisional inter-species transfer
- Threshold is controlled by *global* transport processes!?

Scenario (inspired partly by *F. Ryter, 2013-14*)



- $\nabla P_i|_{\mathrm{edge}}$ essential to 'lock in' transition
- to form ∇P_i at low n, etc. need (collisional) energy transfer from electrons to ions

$$\frac{\partial T_e}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_e = -\frac{2m}{M\tau}(T_e - T_i) + Q_e$$

$$\frac{\partial T_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_i = +\frac{2m}{M\tau}(T_e - T_i) + Q_i$$

- suggests that the minimum is due to:
  - P_{thr} decreases due to increasing heat transfer from electrons to ions
  - P_{thr} increases (stronger edge∇P_i driver needed) due to increase in shear flow damping
  - Power and edge heat flux are not the only crit. variables: also need the ratio of electron energy conf. time to exceed that of $e-i$ temp. equilibration $T_r = \tau_{Ee}/\tau_{ei}$- most important in pure e-heating regimes
    - $T_r \gg 1$ somewhat equivalent to direct ion heating
    - $T_r \ll 1$ ions remain cold → no LH transition (or else, it's anomalous!)

Predator-Prey Model Equations

- Based on 1-D numerical 5-field model (*Miki & Diamond++ 2012,13+*)
- Currently operates on 6 fields ($+P_e$) with self-consistenly evolved transport coefficients, anomalous heat exchange and NL flow dissipation (*MM, PD, K. Miki, J. Rice and G. Tynan, PoP 2015*)
- Heat transport, + Two species, with coupling, i,e (*anomalous heat exchange* in color):

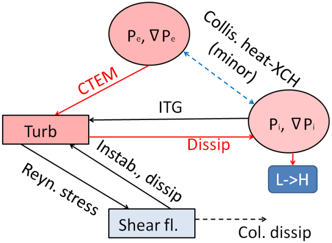
$$\frac{\partial P_e}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_e = -\frac{2m}{M\tau}(P_e - P_i) + Q_e - \gamma_{CTEM} \cdot I$$

$$\frac{\partial P_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_i = \frac{2m}{M\tau}(P_e - P_i) + Q_i + \gamma_{CTEM} \cdot I + \gamma_{ZFdiss} \cdot I$$

$$\Gamma = -(\chi_{neo} + \chi_t)\frac{\partial P}{\partial r}, \quad \gamma_{ZFdiss} = \gamma_{visc}\left(\frac{\partial \sqrt{E_0}}{\partial r}\right)^2 + \gamma_{Hvisc}\left(\frac{\partial^2 \sqrt{E_0}}{\partial r^2}\right)^2$$

- I and E_0 - DW and ZF energy (next VG), plasma density and the mean flow, as before

Equations cont'd; Anomalous Heat Exchange



- in high T_e low n regimes (pure e-heating) the thermal coupling is anomalous (through turbulence)
- ZF dissip. (KH?) supplies energy to ions, and returns energy to turbulence
- DW turbulence:

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

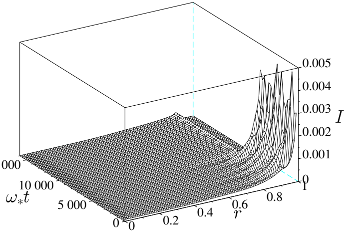
Driver : $\gamma = \gamma_{ITG} + \gamma_{CTEM} + NL\ ZF\ Dissip\ less\ P_i\ Heat\ (currently\ balanced)$

- ZF energy:

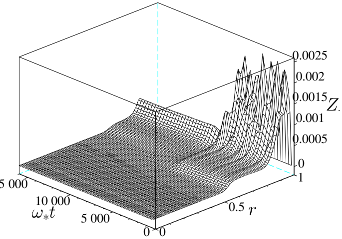
$$\frac{\partial E_0}{\partial t} = \left(\frac{\alpha_0 I}{1 + \zeta_0 \langle V_E \rangle'^2} - \gamma_{damp}\right) E_0, \quad \gamma_{damp} = \gamma_{col} + \gamma_{ZFdiss} \cdot I / E_0$$

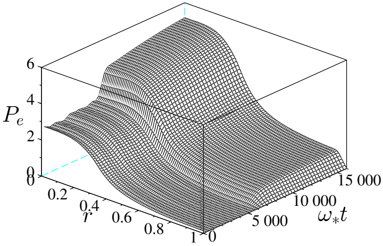
$\gamma_{ZFdiss} = \gamma_{visc} \left(\frac{\partial \sqrt{E_0}}{\partial r}\right)^2 + \gamma_{Hvisc} \left(\frac{\partial^2 \sqrt{E_0}}{\partial r^2}\right)^2$ - toy model form (work in progress)

Model studies: Transition (Collisional Coupling)



- ion heat dominated transition $H_{i/(i+e)} = 0.7$
- strong pre-transition fluctuations of all quantities
- well organized post-transition flow
- strong P_e edge barrier





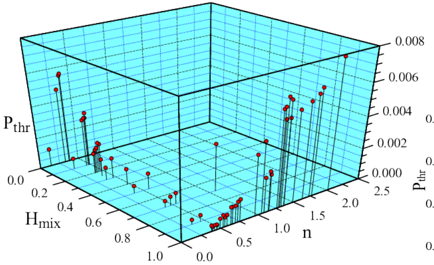
Model Studies: Control Parameters

- Heating mix

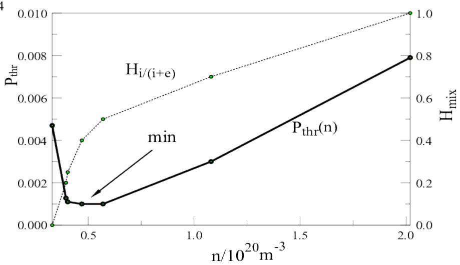
$$H_{i/(i+e)} \equiv \frac{Q_i}{Q_i + Q_e} \quad (\text{aka } H_{\text{mix}})$$

- Density (center-line averaged) is NOT a control parameter. It is measured at each transition point
- Related control parameter is the reference density given through BC and fueling rate
- There is a complicated relation between density and ref. density
- Other control parameters:
  - fueling depth
  - heat deposition depth and width, etc.
    $\rightarrow$they appear less critical than $H_{i/(i+e)}$

$P_{th}\left(n, H_{i/(i+e)}\right)$ scans: Recovering the Minimum



- Relate $H_{i/(i+e)}$ and n by a monotonic $H_{i/(i+e)}(n)$



$P_{\mathrm{thr}}\left(H_{i/(i+e)}, n\right)$-

- electron heating at lower densities
- ion heating at higher densities

- $P_{\mathrm{thr}}(n)$ min recovered!

Summary of collisional coupling results

- $P_{\mathrm{thr}}(n)$ grows monotonically in both pure ion $H_{i/(i+e)} = 1$ and pure electron $H_{i/(i+e)} = 0$ heating regimes with collisional coupling
- The descending (low-density) branch, followed by a distinct minimum, results from a combination of:
  1. increase in electron-to-ion collisional heat transfer and
  2. growing fraction of heat $H_{i/(i+e)} \uparrow$ deposited to ions (relative to total heat)
- The later upturn of $P_{\mathrm{thr}}(n)$ is due to increase of the shear flow damping
- The heating mix ratio $H_{i/(i+e)} \neq 0$ is essential for the heat transport from the core to build up the ion pressure gradient at the edge, ∇P_i, which is the primary driver of the LH transition
- There are many possibilities to render $H_{i/(i+e)} \neq 0$

Anomalous Regime (Preliminary)

- Anomalous Regime: $\nu_{ei} n (T_e - T_i) < \gamma_{\mathrm{anom-ei} coupl} \cdot I$ *(Manheimer, '78; Zhao, PD, 2012; Garbet, 2013)*
  - Anomalous regime, strong electron heating (ITER)
  - n scaling coupling $\Longrightarrow$ Anomalous coupling

$$\frac{\partial T_e}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_e = -\frac{2m}{M\tau}(T_e - T_i) + Q_e$$

$$\frac{\partial T_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_i = +\frac{2m}{M\tau}(T_e - T_i) + Q_i$$

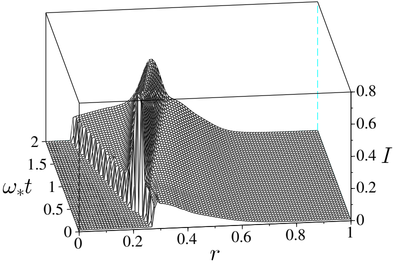
  - Anomalous coupling dominates
    - scaling + intensity dependence $\Longrightarrow$coupling

$$\frac{\partial T_e}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_e = Q_e + \langle E \cdot \mathbf{J_e} \rangle \rightarrow (< 0)$$

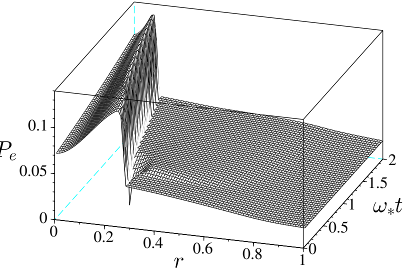
$$\frac{\partial T_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r} r\Gamma_i = Q_e + \langle \mathbf{E} \cdot \mathbf{J_i} \rangle \rightarrow (> 0)$$

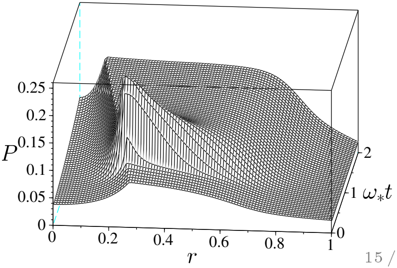
LH transition: Anomalous Transfer Dominates

Extreme limit to illustrate temperature relaxation: Pure electron heating, $\nu_{ei} \to 0$



- CTEM →Heat Exch ↗ turbulence ↘ ions
  - Is $P_{\rm thr}$ set only by local properties at the edge?
- $e - i$ *-temperature equilibration front*
- P_i ↑ globally→strong ∇P_i at the edge → LH transition





Anomalous Regime: Issues

- An Issue:
  - Predator-Prey $\Rightarrow$ Shear Flow Damping
  - $\Rightarrow$Anomalous regime: collisional drag problematic
  - Low collisionality $\rightarrow$ what controls heat exchange?
  - NL damping $\Leftrightarrow$ mediated by ZF instability (i.e. KH, tertiary; *Rogers et al 2000; Kim, PD, 2003*)
    $\Rightarrow$ hyperviscosity, intensity dependent
  - Returns ZF energy to turbulence $\rightarrow P_i$

Results so far

- transition with anomalous heat exchange happens!
- requirements for LH transition in high T_e regimes when the collisional heat exchange is weak:
  - efficient ion heating by CTEM turbulence
  - energy return to turbulence by ZF damping (caused by KH instability?!)
  - may be related to *Ryter 2014*. Subcritical $\nabla T_e \uparrow$ states at ultra-low density

Conclusions

1. density minimum in $P_{thr}(n)$ is recovered in the extended model
   - P_{thr} decrease: due to $e \to i$ heat transfer and ion heating increase
   - P_{thr} increase: due to increase in flow damping
2. ion heat channel (direct or indirect $\Leftrightarrow$ through electrons) is ultimately responsible for LH transitions
3. The role of $T_r = \tau_{Ee}/\tau_{equil}$ (global quantity!) in LH is crucial:
   - $a^2/D_{GB}\tau_{equil} \ll 1$ - no electron-heated LH transition
   - $a^2/D_{GB}\tau_{equil} \gg 1$ - LH trans. originated by electron heat. is possible
4. Threshold physics requires, but is not limited, to edge physics
5. anomalous heat exchange important in low collisionality, anomalous coupling regimes (collisional $e - i$ heat coupling negligible)
   - Anomalous exchange $\Leftrightarrow$ Fluctuation intensity dependent
   - CTEM driven turbulence dissipation $\to$ ion heating
   - ITG driven turbulence dissipation $\to$ ion heating
   - ZF dissipation $\to$ ion heating
6. Density minimum is TBD

Future (ongoing) work

- complete exploration of anomalous regime
- explore effects of ZF spreading
- back transitions: quantify hysteresis
- fate of minimum in anomalous regime
- what are relevant global parameters?
- toroidal rotation
- geometry/configuration (builds on *Fedorczak, PD, et al. 2012*)
    - ∇B-drift asymmetry
- Collisionless saturation/damping of CTEM-driven ZF is fundamental issue

Short Conclusions

- $P_{th}(n)$ minimum recovered with collisional coupling
- Threshold physics not limited to edge
  $a^2/\chi\tau_{eq} > 1$ required for electron heated transitions
  $\Longrightarrow$some global dependence

Predictions:

- Anomalous heat exchange and shear flow damping initiated in collisionless, electron heated regimes (ITER).
- Transition manifested as propagating thermal equilibration front; triggers ∇P_i increase at edge.