Pedestals and transitions in I-mode and comparison to H-mode

Amanda Hubbard,

*MIT Plasma Science and Fusion Center*

*With thanks for input from*


I. Cziegler, P. Diamond, N. Fedorczak, G. Tynan, *UCSD*

Z. Liu, *ASIPP*, X. Xu, *LLNL*,

L. Schmitz, T. Rhodes, UCLA, A. Diallo, *PPPL*

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Pedestals and transitions in I-mode and comparison to H-mode

Scope and aim
Overview of current, rapidly evolving results in I-mode, compare and contrast with the more familiar H-mode regime.

– What is the same?
– What are key differences?
– What may this tell us about the physics?
– Key open questions for TTF.
Will not be a comprehensive review.

Outline
1. Global characteristics (brief reminder).
2. Pedestal structure and stability.
3. Thresholds, transitions and turbulence.
I-mode and H-mode are each stationary, high energy confinement regimes.

**H-mode** has both density and temperature transport barrier/ pedestals.

_defining feature of **I-mode**\(^*\) is a temperature pedestal, without a density pedestal._

\(^*\) Obligatory clarification: This is NOT the same as the Limit Cycle Oscillation phase between L and H-mode, sometimes known as “I-phase”. 

A. Hubbard, MIT, TTF 2015
I-mode is now established on Alcator C-Mod, ASDEX Upgrade and DIII-D,

- Multi-device study through ITPA, presented at IAEA 2014 (Hubbard, Ryter, Osborne et al).
- I-mode is usually formed with unfavorable ion $B_x\nabla B$ drift direction in all devices (all results in this talk).
- Wide ranges of dimensional and dimensionless parameters: including $T_{\text{ped}}\ 0.2-1\ \text{keV}$, $v_*$ $0.17-4$, $q_{95}\ 2.4-5.3$, $n/n_G\ 0.1-0.6$. 

A. Hubbard, MIT, TTF 2015
AUG and DIII-D I-modes tend to be less stationary, have smaller power range

**DIII-D**
- NBI heating
- 0.98 MA, 2.05 T, \( q_{95} = 5.1 \)
- Note \( T_i > T_e \) in DIII-D pedestals with NBI.

**ASDEX Upgrade**
- NBI + ECH heating.
- 1 MA, 2.45 T, \( q_{95} = 4 \).

Hubbard, Ryter, Osborne et al, IAEA 2104
**I-mode:** Stored energy does not saturate with input power as in H-mode

- Stored energy (and pedestal pressure) increase near linearly with power for fixed $I_p$.
  - Contrasts with $W \sim P^{0.3}$ in H-mode ($\tau_{\text{ITER98p}} \sim P^{-0.7}$).
  - Consistent with stable pedestals.

Details of I-mode confinement scaling in talk by John Walk this afternoon.

- This confinement trend is very favorable. The more power one can add, the higher $H_{98}$.
- Power may be limited either by transitions to H-mode or (in the C-Mod case shown) by available heating power.
Key difference between regimes is in particle transport channel

- H-mode has a particle as well as thermal barrier. I-mode does not – density and impurities behave as L-mode.
  - Even lower than quiescent H-mode regimes (EDA, QH mode).
- Low $\tau_p$ has many advantages as a fusion regime. Avoids accumulation of impurities (from PFCs, seeding, ‘ash’).
  => Compatible with high Z PFCs.
- Other key difference (and advantage) is that the regime is naturally ELM-free while remaining stationary.

- These differences challenge our understanding of transport barrier physics.
  - Why are transport channels separated?
  - Why is the pedestal stable to ELMs? What keeps it stationary?
Pedestal structure and stability
Compared to H-mode, I-mode pressure pedestals are wider. Much weaker $\nabla n_e$, hence lower $\nabla p$.

- Pedestal width exceeds $\beta_p^{0.5}$ scaling in EPED based on KBM limit.

![Graphs showing pedestal width vs. $\beta_p^{0.5}$ scaling](image)

A. Hubbard, MIT, TTF 2015
I-modes are well below pedestal linear MHD limits, explaining lack of ELMs

- Pedestals in ELMy H-modes generally lie at boundary set by peeling-balloononing (ELITE) and expected KBM thresholds (Wilson talk).
- I-mode pedestals lie well away from these limits – explaining lack of ELMs, and consistent with pedestals not predicted by EPED.
- I-mode pedestal height must be limited by turbulence and heating power, which in turn are related to thresholds – room to increase.

A. Hubbard, MIT, TTF 2015
Thresholds and transitions
L-I and L-H transitions are qualitatively different

- At L-H transition (in all devices) get a sharp (sub-ms) drop in turbulence, in all freq ranges.
- Clear break-in-slope in $n_e$, stored energy.

- At L-I transition, get decreases in some freq ranges, increase in others. May be sharp or gradual.
- No break-in-slope in $n_e$. Change in energy, $T_e$ may be distinct or gradual.
- If there is later an I-H transition, it is sudden, much like L-H.
L-I power threshold increases with density, current

- **Density dependence of** \( P(L-I) \) **at least linear**, with an offset on AUG.
  - Similar trend to ITPA L-H scaling. (though values \( \sim 1.5\text{-}3x \) higher)
  - C-Mod observes a minimum threshold power at \( n_e \sim 10^{20}\text{m}^{-3} \), analogous to ‘low \( n_e \) limit’ for L-H transitions.
  - Positive \( n_e \) scaling not seen on DIII-D, perhaps below low \( n_e \) limit?

- **Increase in** \( P(L-I) \) **with plasma current** \( \sim I_p^{1.2} \) **has also been observed on C-Mod.**
  
  - *Not* present in L-H scalings, eg \( P_{L-H,ITPA08} = 0.0488 \ n_e^{0.717} B_T^{0.8} S^{0.941} \).

[Hubbard NF 2012]

A. Hubbard, MIT, TTF 2015
I-H transitions are complex, depend on both power and \( n_e \)

- I-H transition does not have a clear power threshold or even \( T_e \) scaling – quite variable; must be different physics than L-H scaling.
- I-H transitions do not always occur at the maximum loss power of I-modes.
- On C-Mod, maximum density for sustaining I-mode depends on discharge trajectory and power, can be increased by fueling into hot, high power I-mode.
  - Often an I-H transition occurs when \( P_{RF} \) decreases.
- More meaningful to look at maximum power for sustained I-mode: “power range”.

A. Hubbard, MIT, TTF 2015
Power range while remaining in I-mode increases strongly with field

Compared C-Mod discharges in same LSN configuration, same run day, $B_T=2.8$ T (second harmonic D(H)) and 5.4 T (typical D(H) ICRH).
Wider dataset also shows expanded power range for I-mode at high magnetic field.

- Normalize loss power by density, as measured in L-I scalings.

- **Weak (no?)** scaling of L-I threshold $P/n$ with $B_T$.
  - Contrasts with L-H scaling $\Rightarrow$ different physics.

- **Strong ($\sim$linear)** scaling of upper range for I-mode with $B_T$.
  - Similar to Martin ITPA scaling, $P(L-H) \sim B^{0.78}$
Wider dataset also shows expanded power range for I-mode at high magnetic field.

- Normalize loss power by density, as measured in L-I scalings.
- **Weak (no?)** scaling of L-I threshold $P/n$ with $B_T$.
  - Contrasts with L-H scaling => different physics.
- Strong (~linear) scaling of upper range for I-mode with $B_T$.
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- AUG and DIII-D thresholds, normalized to surface area $S$, are also consistent; lower I-mode power range than at high $B$. Hubbard IAEA 2014, NF in prep.
- I-mode thus seems particularly well suited to high field tokamaks, such as most planned burning plasma experiments/reactors. Whyte talk Tues am.
  - Some examples of 8 T I-modes, plan to explore this year on C-Mod.
L-H transition dynamics, mechanism has been identified in recent years

Consistent results have been found in recent years on several tokamaks (eg HL2A, DIII-D, EAST...)

See talk by L. Schmitz Tues pm, HMW14 review by Tynan.
Modeling is in progress using XGC1

Typical sequence at L-H transition:
1. Turbulence transiently increases (in this case due to sawtooth pulse)
2. Loss of turbulence power exceeds effective growth rate ($R_T > 1$)
3. Turbulence transfers energy to ExB flow
4. Full pedestal evolves
5. $\nabla P$ locks in the H-mode
(from Cziegler poster Wed pm, PoP 13 paper)
I-mode

- In I-mode on C-Mod, in addition to the "Weakly coherent mode", ~200 kHz, GPI has observed a GAM in fluctuating poloidal flow, which is ONLY seen in I-mode.
L-I transition contrasts with L-H, seems related to this GAM

The drive term is compared to the collisional damping rate predicted from neoclassical theory:

\[ \gamma = \frac{4}{7} \left( \frac{\nu_{ii}}{q} \right) \]

\[ \gamma_{NL}^{GAM} = \sum_{f} T_{v} \left( f_{1}^{GAM}, f \right) \frac{1}{|v_{\perp}|^2(f)} \]

At the L-I transition, the GAM drive overcomes damping due both to decreasing collisionality and enhanced drive.

At the I-H transition the drive becomes substantially smaller, and the GAM disappears.

Cziegler, EU-TTF 2014, PoP 2013

A. Hubbard, MIT, TTF 2015
L-I transition – first few ms

no significant Dα drop
(mass transport L-mode-like)

beginning of heat pulse

total turbulence power
does not seem affected

onset of GAM
(due to $T_e$ rise, $\nu_\parallel$ drop)

GAM drive rate
normalized to GAM power

Cziegler, EU-TTF 2014, PoP 2013
New L-I transition and turbulence details are very helpful, but leave several open questions

1. Why are transitions in heat and particle channels so different with drift away from X-point?
   – Separated in time, very different dynamics.
   – Suggests there is not a strong feedback loop/hard bifurcation for thermal transport.

2. Why does an L-H transition NOT occur, despite a significant $E_r$ well in I-mode?

3. GAMs are common in many other tokamaks in favorable drift, even in L-mode (eg DIII-D, AUG). Why is I-mode occurring in the C-Mod case?

4. What is the physical instability underlying the Weakly Coherent Mode? What is its role in I-mode? Is it an essential feature?
**Er well in I-mode is significant, between L-mode and H-mode**

- On both AUG and C-Mod, an $E_r$ well builds up with $T_i$ pedestal. Intermediate between L and H-mode, correlated with H-factor.

- Are $E_r$ well depth and mean $E_r$ shear in best I-modes greater than “threshold” values at L-H transition, in favorable drift? *(Wolfrum 2012)*

  Seems quite possible, but careful comparison of the same quantities needs to be done.

- *If so, then why is H-mode not occurring?*

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A. Hubbard, MIT, TTF 2015
Possible explanation for the grad B-Drift asymmetry in H-mode power threshold proposed by Diamond and Fedorczak

Diamond, IAEA 2012

Heuristics: Interplay of magnetic shear \( \hat{s} \) and ExB shear induced eddy tilting

\[
k_r(\theta) = k_r(\theta_0) + \left[ (\theta - \theta_0) \hat{s} - V_E' \tau_c \right] k_\theta
\]

Thus, residual Reynolds stress:

\[
\langle \tilde{v}_r \tilde{v}_\theta \rangle = \langle \tilde{v}_r^2 (0) \rangle F^2(\theta) \left[ -\theta \hat{s} + V_E' \tau_c \right]
\]

Vanishes upon flux surface average, but for X-point-induced asymmetry between \( \pm \theta \).
→ An up-down asymmetry effect appears!
Possible explanation for the grad B-Drift asymmetry in H-mode power threshold (2)

To determine self-consistent ExB shear induced by the magnetic shear $\hat{s}$ stress, poloidal momentum balance is used.

$$\partial_t v_\theta + \partial_r (\prod^{R}_{\hat{s}} + \prod^{R}_{V_E}) = -(\gamma C \chi - \partial_r \chi \partial_r) [V_E + V_{*i}].$$

$\hat{s}$ induced residual stress  \hspace{0.5cm} \hspace{0.5cm} \hspace{0.5cm} $E_r$ driven residual stress  \hspace{0.5cm} \hspace{0.5cm} \hspace{0.5cm} Frictional damping  \hspace{0.5cm} \hspace{0.5cm} \hspace{0.5cm} Turbulent viscosity

$\rightarrow$ Favorable (LSN) configuration yields a stronger edge $V'_E$ than does unfavorable (USN) configuration, other parameters comparable

How can we quantitatively test this explanation?

• Requires calculations for geometry and parameters of tokamaks which have L, I and H-modes.
• What quantities, where, do we need to measure?

Would this theory explain why, in unfavorable configuration below L-H, we get thermal but not particle barrier (I-mode), with a gradual transition?
Another difference with configuration is direction of flows in HFS SOL

- Flows are consistent with ballooning transport on LFS + parallel flow to X-point.
- **Net toroidal component is**
  - Co-current for LSN (favorable)
  - Counter current for USN.
- Correlated to ohmic core $V_\phi$, and to L-H threshold.
  - presumably affects mean $E_r$ shear.

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C-Mod
LaBombard
NF 2004
Rice
NF 2005
Pedestal turbulence and transport
**H-mode pedestals** often have continuous fluctuations in addition to ELMs.

Typically a very quiescent period right after L-H transition, as the pedestal builds. But then:

**ELMy H-mode**
- **Inter-ELM fluctuations** appear near pressure limit. Many features of predicted KBM turbulence.

**QH-Mode**
- **Edge Harmonic Oscillation**, thought to be a saturated peeling mode.

**EDA H-Mode**
- **Quasicoherent** mode. Recent mirror probe measurements reveal as an electron drift-wave with interchange drive and EM contributions LaBombard PoP2014 (Challenges prior simulations.)

**What about I-mode?**
Feature common to all I-modes in all devices is a decrease in the pedestal broadband turbulence.

Can be a distinct change or a very gradual decrease.

- On C-Mod, this correlates well with the decrease in edge thermal conductivity, increase in $T_{\text{ped}}$, global stored energy.
  - Qualitatively true also on AUG, DIII-D. Talks by Happel, Manz
- Consistent with this turbulence being a main contributor to $\chi$.
- $E_r$ wells also develop on a similar time scale. *Are they responsible for the decrease?*
- Prompt decreases in *core* turbulence are also seen on C-Mod. White NF 2014
- Studying changes in core transient $\chi$ (HPP), and stiffness. Talk by A. Creely Wed pm.
C-Mod and AUG observe a Weakly Coherent Mode, coupled to GAM

Analysis of C-Mod GPI shows GAM is responsible for broadening of WCM spectrum, transferring energy from its peak.

New AUG results seem consistent.

Does GAM also contribute to the mid-freq turbulence reduction in I-mode?

I. Cziegler, PoP 2013
Poster Wed pm
On DIII-D, not a clear WCM, but turbulence spectra evolve towards H-mode.

- PCI shows evolution, upshift between L-mode and H-mode spectra.  
  Marinoni, submitted to NF.
  - Is WCM present but masked by other broadband turbulence?

- DBS shows turbulence decrease, localized near pedestal top.
- BES did not change from L-I mode – but resolution was not optimal.
- GAM exists from start of heating, in both L and I-mode.
I-modes can often include ‘Bursty’ events.

- On **AUG**, a substantial difference between L-mode and I-mode density turbulence behavior.
- While low-amplitude fluctuations are reduced, the I-mode PDF develops a heavy tail at large amplitudes; Bursts are correlated with other diagnostics.
- In some **DIII-D** I-modes, small discrete events (few kHz, with precursors) are seen on BES and ECE, $D_\alpha$. (Not Type I ELMs).
- On **C-Mod**, some bursty ELM- or LCO-like events seen on divertor probes, $D_\alpha$. D. Brunner, Poster 2, 4pm.

A. Hubbard, MIT, TTF 2015
Recent BOUT++ simulations of I-mode show promising agreement with WCM

- Find a broad feature which is consistent with Drift Alfvén Wave.
- The frequency spectrum of the mode at n=20 is similar to reflectometry measurements at the same location (midplane, outer pedestal).
- Radial and poloidal locations of peaks vary with mode number, and linear vs non-linear simulations.

Work by Zixi Liu, X. Xu et al (ASIPP/LLNL), simulating a high performance, high \( n_e \) C-Mod I-mode. Details in talk Fri. am.

Recent BOUT++ simulations of I-mode show promising agreement with WCM.
Particle diffusivity is larger than thermal; Both values are roughly consistent with C-Mod expt.

- Larger particle diffusivity is consistent with the key feature of I-mode. Particle diffusivity from ExB convection dominates.
- Predicted $\chi_e$ and $\chi_i$ (dashed lines) are close to experimental $\chi_{eff}$ (from power balance over 0.95 < $\psi$ < 1).
- Particle flux $\Gamma$ is ~4x larger than determined in Dominguez Ph.D. (in a lower $n_e$ I-mode, so value is reasonable).

$$\Gamma_{ir} = \langle n_i \nu_r \rangle = \left\langle n_i \left( \frac{b_0 \times \nabla \Phi}{B_0} \right)_r \right\rangle + \left\langle n_i \left( V_{th,i} + V_{||i} \right) \cdot \left( \frac{b_0 \times \nabla A_{||}}{B_0} \right)_r \right\rangle.$$

A. Hubbard, MIT, TTF 2015
Ongoing advances in measurement, theory and simulation are important to resolve open issues.

**L-I and I-H transitions and thresholds.**

- Understand separation of particle and energy transport, transitions.
  - Why a ‘hard’ bifurcation in particles, slower change in heat? New ideas by D. Newman Wed pm, based on phase of n, T, ϕ fluctns
  - What is happening at a turbulence/flows level?

- What is the key difference with favorable vs unfavorable configuration? E_r? Magnetic shear? SOL flows? Combination of effects, or something else?
  - Comparison of mean E_r profiles at favorable L-H transition vs I-mode/unfavorable I-H transition would help, seems feasible now.
  - How can we test Diamond/Fedorczak model? Other ideas?

- What determines I-H transitions and thresholds? Why so variable? 

- Can we predict power ranges for each regime in future experiments?

- Will take continued experiments on multiple tokamaks, and must be part of a quantitative L-H transition model and simulation, still lacking after 30 years! Glad to see and hear of active L-H model work, at this meeting.
Open issues (2).

**Pedestals and turbulence in I-mode.**

- What are instabilities regulating pedestal? Drift Alfven, others (eg ETG, ITG, microtearing)?
- Can we optimize for even higher pressure pedestals?
- Connection to microinstabilities in H-mode pedestals; note parameter ranges are quite similar.
- Coordinated pedestal modeling effort including both H-mode and I-mode cases would be valuable.
I-mode transitions and pedestal turbulence may well be related.

E.g., a potential scenario might be (speculating):

1. Some effect raises H-mode (particle barrier) threshold with unfavorable drift configuration.
2. Opens a parameter window for temperature pedestals to form. Reduction in thermal transport.
3. $\nabla T$ or $\nabla P$ drive instabilities (eg GAM+WCM) which increase particle transport, further increasing H-mode threshold.

Could explain some experimental observations:

- I-H threshold depends on discharge trajectory (higher if we first drive strong GAM+WCM, then increase power and density)
- I-H transition can occur when the input power (turbulence drive) drops.
- Power window is lower on DIII-D which does not see WCM. (instabilities likely depend on parameters, shape...)

Therefore, more than for H-mode, modeling needs to consider both transitions and the developed I-mode pedestal.
Summary of key recent I-mode results

- I-mode is a stationary, high energy confinement regime, without a particle transport barrier.
  - Now observed in many C-Mod, AUG, DIII-D discharges, experiments planned in other devices. Results are generally consistent.
  - Favorable scaling of $\tau_E$ with power.
- Naturally ELM-free, pedestal stable to peeling-ballooning and KBMs.
- L-I power threshold is higher than L-H scalings, increases with density, current, but not $B_T$.
- Upper range of I-mode power *does* increase with $B_T$, opening up a greater window at high B, and leading to more robust I-modes.
- L-I transition seems related to GAM onset, triggered by heat pulse.
- Turbulence in I-modes is complex, features GAM, weakly coherent mode, and intermittent events.
  - Modeling of this regime is beginning.