Access to and Performance of I-Mode Plasmas on Alcator C-Mod

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Abstract

The I-mode regime of operation features an edge thermal transport barrier, without a particle barrier. Stationary conditions are thus achieved without impurity accumulation, and usually without ELMs. In contrast to the EDA H-mode regime on Alcator C-Mod, it is readily accessed at low $q_{95}$ and low collisionality, both relevant for ITER. Analysis of a dataset of 400 discharges at $q_{95} \sim 3$ shows normalized energy confinement in I-modes reaches or exceeds that in most H-modes, up to $H_{98}=1.2$. Confinement and pedestal temperature increase with input power. In some cases I-mode is maintained up to the maximum available power (5 MW ICRF) while in others a transition to H-mode limits the performance. Understanding and extending the conditions for entering and staying in I-mode is thus critical for extrapolation of the regime. Experiments have extended the regime both to lower densities and to higher densities and powers through gas puffing into established I-modes. Results from an expanded database of C-Mod discharges will be presented, along with details of I-mode profiles and fluctuations, including GAMs and a weakly coherent mode, which are providing insights into the physics of the regime.

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Key features of the I-mode regime
Why I-mode?
H-mode regime has some big issues

- H-mode features **simultaneous formation of edge density and temperature barriers** or “pedestal”.
- **Energy confinement** roughly doubles over L-mode, a major advance which has made it the standard operating regime for present tokamaks. **GOOD**

- **BUT**, increased **particle confinement** leads to some serious issues:
  1. **Impurities can accumulate.** (esp with metal walls)

  2. **Pedestals rise to stability limit, triggering ELMs.**
     **Edge instabilities are needed to expel particles.**
     ELM heat pulses are unacceptable in ITER!
     **ELM mitigation or avoidance is needed, and a serious challenge, for ITER and even more for fusion reactors.**

- An energy transport barrier without a particle barrier (but with controllable density) would be ideal.
I-mode regime has $T_e$ and $T_i$ pedestal, without density barrier.

- Steep $T_e$ pedestal – up to 1 keV, $\nabla T > 100$ keV/m.
  - $T_i$ pedestals are similar.
  
  Pedestal details in J. Walk invited talk this afternoon! UI2:3
  
  This leads to higher $T_e$, $T_i$ and pressures across profile.

- L-mode density profile, with broad SOL.

I-mode has also been observed on ASDEX Upgrade (Ryter EPS 2011) and recently on D3D (Marinoni poster UI2:3, Thurs pm).
**I-mode is a stationary, high energy confinement, ELM-free regime**

- **Steady I-modes can be maintained for many** $\tau_E$, **often limited only by plasma and heating pulse duration.**
- Energy confinement comparable to, can even exceed, H-mode scalings. Whyte, Nucl. Fusion 2010
- **I-modes are usually ELM-free.**
- **L-mode particle confinement,** compatible with high Z PFCs, and with impurity seeding.

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**Graph:**

- $\tau_I$ vs. $H_{98}$
- L-mode vs. I-mode
- EDA H-mode
- $P_{ICRF}$ (MW)
- $n_e (10^{20} \text{m}^{-3})$
- $T_e(0)$ (keV)
- $T_{e,ped}$ (keV)
- $<P>$ (atm)
- $H_{\text{ITER98/2}}$
- $D_\alpha$
- ELM-free
- High confinement

**Data Points:**

- $I_{\text{mode}} = 1.1 \text{ MA, } 5.8T$
- $q_{95} = 3.4$
Characteristic changes in edge fluctuations at L-I transitions

- As the T pedestal forms, see
  - A DECREASE in edge broadband turbulence (n and B) in mid-f range (~60-150 kHz)
  - Usually a PEAK in turbulence at higher f “Weakly Coherent Mode” (~ 200-400 kHz).

- At the H-mode (particle barrier) transition, remaining turbulence drops suddenly, density rises.

1.3MA, 5.8T
$q_{95}=3.1$
Access to I-mode
I-mode is generally achieved with $B \times \nabla B$ drift away from X-pt.

- For C-Mod, can use either ‘normal’ $B_T$ and $I_p$, USN, or ‘reversed’ $B_T$ and $I_p$, LSN.
  - Some I-modes have been seen with “favorable” drift towards X-pt, but limited to an atypical shape, and low power.
Thresholds for L-I transitions increase with both current and density

- Thresholds for L-I transition, in unfavorable drift are, not surprisingly, above the ITPA L-H scaling for “favorable” (for H-mode) drift. Typically 1.5-3 times.

Loss power defined as

\[ P_{\text{loss}} = P_{\text{ohmic}} + P_{RF, \text{abs}} - \frac{dW}{dt} \]

\( P_{\text{loss}} \) (L-I) increases with current as well as density. Regression fit to 2011 dataset gave

\[ P_{\text{L-I}} (\text{MW}) = 2.1 I_p^{0.94} n_e^{0.65} \]

Hubbard
Nucl. Fusion
October 2012
Threshold studies extended to higher and lower densities

- For 1.1 MA, 5.8 T LSN discharges, L-H transitions were observed for target nebar between $0.9$ and $1.8 \times 10^{20} \text{ m}^{-3}$.
- Minimum L-I threshold at $\sim 1.4 \times 10^{20} \text{ m}^{-3}$.
- Below $0.8 \times 10^{20}$, just get poor L-mode. Impurity issue?
- Above $1.8 \times 10^{20}$, get transitions from L-mode directly to H-mode.

- BUT, higher density and power I-modes could be achieved by fueling into I-mode. (arrows show shot below)
Gas fuelling into I-modes on C-Mod enables higher densities

- Gas fuelling into hot I-mode raised $n_e$ by 30%, to $2\times10^{20}$ m$^{-3}$, with nearly constant stored energy, and $H_{98}>1$.
  - This is above the density for which transitions to I-mode typically occur.

→ Implies I-mode can exist as long as power is sufficient to maintain $T_e$ pedestal, drive WCM

- Only tried fueling in a few I-mode discharges late in 2012 campaign – there is room to increase density range!

- Important for potential extrapolation to ITER scenarios.
I-mode confinement and performance
Parameter space for C-Mod I-modes is very wide

- Robust regime, obtained over a wide range of parameters:
  
  \[
  \begin{align*}
  I_p & = 0.8 - 1.3 \text{ MA} \\
  B_T & = 3.0 - 6.1 \text{ T} \\
  q_{95} & = 2.5 - 5.3 \\
  \langle n_e \rangle & = 0.85 - 2.3 \times 10^{20} \text{ m}^{-3} \\
  \text{ICRF power} & = 1 - 5.5 \text{ MW} \\
  \nu^* & = 0.1 - 5.4
  \end{align*}
  \]

  Note that \(B_T\), \(n_e\) and \(q_{95}\) span ITER ranges.

  Collisionality is close, no lower limit observed.

All C-Mod experiments use molybdenum PFCs, RF heating, no momentum or core particle input.
3 databases established for different studies

- **I-Mode scalar database.**
  - Contains many global parameters, some pedestal parameters, but not from most accurate profiles.
  - Hand-selected slices, 262 I-modes, 58 L-I transitions, 56 I-H transitions.

- **I-mode pedestal database.**
  - Carefully calibrated and fit edge TS profiles, suitable for pedestal scalings and stability analysis.
  - 72 I-mode slices.

- **Low q\textsubscript{95} global database**, set up by request of IOS ITPA to guide ITER projections.
  - Contains ALL suitable discharges since 2007 with $2.7 < q_{95} < 3.3$.
  - 682 shots, including 252 H-modes (mostly EDA, ELM-free), 157 I-modes, 202 L-modes, remainder transitions.
Power and density ranges for I-mode are increased in Lower Null configuration

- Configuration with LSN, reversing $B_T$ and $I_p$, enables I-mode at lower density, and over much higher power range (> 2x) than USN. *Due to shape, or closed divertor?*

- Power range can be up to max available power (5 MW ICRF), at least a factor of two above L-I threshold

- This in turn has led to more robust, longer duration I-modes, in most cases without transitions to L or H-mode as long as heating is maintained.
  - Do not know limits in P, beta.
I-mode has H-mode-like energy confinement, but with little power degradation

- \( H_{98y2} = 0.7-1.2 \), comparable to H-modes. But, scatter indicates differences in \( \tau_E \) scaling.

- A key difference to ELMy H-mode is much less (no?) confinement degradation with power!

Note: \( H_{98} \) is computed using \( W_{\text{MHD}} \). Some of the highest \( T_e \) discharges can have significant fast ion contributions to \( W \).
At $q_{95} \sim 3$, typical confinement of C-Mod I-modes exceeds H-modes.

- Includes all RF-heated discharges with $2.7 \leq q_{95} \leq 3.3$, the expected range of ITER baseline, meeting a few other criteria.
Used automated analysis to assess typical duration of highest performance phase

- For each discharge, the “data interval” is taken where \( W > 0.85 \) maximum \( W \); averages are near but not at peak performance.
- Also must meet other ITPA criteria:
  - \( 2.7 < q_{95} < 3.3 \)
  - \( P_{\text{rf}} > 1 \text{MW} \)
- “Heating interval” taken where \( P_{\text{rf}} > 1 \text{MW} \); may not be constant (or reach I-mode or H-mode thresholds) for entire interval.
- Relative duration of intervals (following page) thus gives a sense of typical discharge evolution, but can be affected by operational as well as physics issues.

Example: Discharge with 2 H-modes, radiation increasing.
At $q_{95} \sim 3$ typical duration of high confinement phase in I-modes exceeds H-modes.

- Plots show selected data interval duration/ heating interval duration.
- **Low $q_{95}$ H-modes** are often transient (ELM-free or marginal EDA). Impurity accumulation leads to radiative cooling.
- **I-modes** are generally more steady (ie high $H_{98}$ phase lasts most of heating pulse).
- Difference is greatest at high power; note C-Mod has ICRH, Mo PFCs.
H$_{98}$ at q$_{95} \sim 3$ increases with $\beta_N$

- H-mode data shows “saturation” around $H_{98} \approx 1$ at high $\beta_N$ (all low B)
- I-mode data appears more linear, but
  - Range of $\beta_N$ is limited (due to power; no low-field cases)
  - All I-mode data is at low $f_{GW}$
- Extending the I-mode data to higher $\beta_N$ in C-Mod requires operation at lower field, or even higher power.
- Extending to higher $f_{GW}$ will require fueling into I-modes, at high power.
- NEED MORE C-Mod EXPERIMENTS TO EXPLORE LIMITS!!
  (pumped, baked and ready to run, on ~2 weeks notice)
Pedestal physics
**Edge T barrier** and **decrease in mid-f turbulence** are key signatures of L-I transitions

- At transition from L to I-mode, **edge $\nabla T$ steepens**, at near-constant $P_{\text{net}}$ and edge $n_e$
  
  $\Rightarrow$ **Edge $\chi_{\text{eff}}$ is decreasing.**
  
  Quantified by edge power balance calculations over outer 5%.

- **Edge $\chi_{\text{eff}}$ correlates well to the drop in mid-f turbulence** ($\sim$60-150 kHz) from reflectometry
  - Sharpest drop at low $q_{95}$.

- **CORE transport and turbulence (both $\delta n_e$ and $\delta T_e$)** also promptly decrease.
  
  Anne White talk CO4:3
Weakly Coherent Mode seen in density, magnetics, ECE, localized to barrier region

- In most I-modes, a higher frequency turbulence feature appears, simultaneous with mid-freq reduction. $f_0 \sim 200-400$ kHz, $\Delta f/f \sim 0.3-1$, increasing with $q_{95}$.

- Fluctuations seen in $B$ (magnetics), Density (Reflectometry, Gas Puff Imaging, PCI, and Electron Temperature (ECE). $\delta T_e/T_e < 1.6\% < \delta n_e/n_e < 6-13\%$.

- Refl, ECE and GPI all localize the mode to within 1-2 cm of the separatrix, ie region of $T$ pedestal. ($0.9 < r/a < 1.0$).
  - Can be very narrow in some cases (few mm radial extent)

A. White, Nucl. Fusion 2011
Amplitude of WCM correlates with edge particle flux

- Analysed power steps within I-mode discharges.
- Relative amplitude of WCM from edge reflectometer.
- Edge particle flux $\Gamma_{\text{LCFS}}$ derived from absolutely calibrated $D_\alpha$ imaging near the outboard midplane.
- Correlation with $\Gamma_{\text{LCFS}}$ is consistent with the WCM playing a key role in driving particle transport, perhaps helping avoid transition to H-mode.
  - Analogous to role of QC mode in EDA H-mode.

A. Dominguez, MIT Ph.D. 2012
Some discharges show a T pedestal, without WCM measured on reflectometer

- WCM is strongest and most coherent at low \( q_{95} \), high \( T_{\text{ped}} \) (both favorable trends for burning plasmas).

- Database analysis reveals cases without evident WCM on reflectometer are at higher \( q_{95} \), lower \( T_e \).
  - In at least this example, WCM is present on GPI but radially localized to only few mm. Perhaps between reflectometer channels?
  - Study of more such cases is ongoing.
Gas Puff Imaging also shows GAMs in I-mode

- **2-D Gas Puff Imaging** in addition to WCM shows a $k=0$ feature in $v_\theta$ at $\sim 20$ kHz, which interacts with WCM.
  - From Time Delay Estimation

- Modes co-exist in same radial region, in $E_r$ well.

- Frequency agrees well with GAM scalings.

I Cziegler, PoP 2013
GAM on C-Mod is unique to I-Mode, persists throughout regime.

- Both GAM and WCM disappear at I-H transition.
- Around this time, the estimated non-linear GAM drive (black curve, top panel) drops below $4v_{ii}/7q$, related to the collisional damping rate (red curve); [Cziegler PoP 2013].

Details of GPI diagnostic and analysis, and L-H transition physics, in I. Cziegler Poster U13:03, (this session).
Typical I-mode pedestal calculated to be stable to peeling-balloonning and KBM modes (ELITE)

- Peeling-baloonning instability thought responsible for ELM trigger in Type-I ELMing H-mode, with KBM also limiting gradient. C-Mod ELMy H-modes confirm this picture.
- I-modes, due to reduced density & pressure gradients, stay below p-b stability boundary, and also infinite-n ballooning stable, suggesting KBMs are stable.
  - I-mode has wider pedestal, lower pedestal $j_{\text{boot}}$
I-mode pedestals are wider than EPED scaling for H-mode, also consistent with WCM stability.

Details of this and many other pedestal scalings in John Walk’s invited talk this afternoon.
Key Issues for I-mode
Initial extrapolation from C-Mod indicates I-mode may be an attractive ITER scenario.

- Extrapolating from C-Mod threshold scalings access to I-mode appears possible at nebar $\approx 5 \times 10^{19}$ m$^{-3}$.
- Confinement trends indicate ITER could achieve $Q=10$ by raising $n_e$, staying within stability limits.
- BUT, these trends have large uncertainties.

Whyte
APS 2011
Key uncertainty and power limit is set by transitions to H-mode

- Confinement in I-modes increases with power. Upper limit to pressure is thus set by how much can be injected.
- In the best C-Mod examples, all of the available power can be coupled while remaining in I-mode; have not yet reached $\beta$ limit.
- However, in many cases, increasing power results in a transition to H-mode. The power window can be quite narrow, with $P_{\text{loss}} (I-H)$ close to $P_{\text{loss}} (L-I)$.
  - Typical so far on AUG and DIII-D, and at higher target densities on C-Mod.

- I-H power threshold is highly variable – not a good scaling yet.
- Experiments where I-mode window was extended by fueling while heating offer a potential route to expanding operating space.

- Need a better understanding of thresholds and transitions with unfavorable drift!
Multi-device experiments are needed (and underway) for size and parameter scaling

Cannot extrapolate to ITER (or present devices) from C-Mod alone.

**Key open questions:**

- What is size scaling of L-I threshold? I-H threshold?

- Which dimensionless parameters are most important?

- What is the ultimate limit on beta in I-mode? (set by MHD or I-H?)

- How does I-mode confinement scale with size, \( I_p, B_T \) etc?

I-mode has been clearly demonstrated on AUG for several years (eg Ryter EPS 2011).

Recently produced on DIII-D, as part of US Joint Research Target experiments. Several ITPA Joint Experiments: PEP-31, TC-18, TC-19

Experiments are planned on EAST in 2014, being considered elsewhere.
Summary

• I-mode regime features thermal transport barrier, but with L-mode density profiles and impurity confinement, and without a need for ELMs. VERY ATTRACTIVE FOR FUSION!
  o Energy confinement \( \sim \tau_{98y2} \), but with little power degradation.

• C-Mod LSN, unfavorable Bx\(\times\)B drift configuration enables stationary I-modes without transitions, over a wide range of power and plasma parameters, many spanning ITER’s.

• At \( q_{95} \sim 3 \), relevant to ITER, ITPA database shows:
  o I-modes have higher average confinement than H-mode.
  o I-modes have longer duration, especially at high ICRH power.

• Measurements of edge turbulence, profiles and transport show
  o Decrease in mid-freq fluctuations correlates with pedestal \( \chi_{\text{eff}} \).
  o Core turbulence and transport are also reduced in I-mode.
  o Weakly Coherent Mode in \( n_e, B, T_e \) correlates with particle flux.
  o GAM seen throughout I-mode, interacts with WCM.
  o Pedestals stable to peeling-ballooning and KBM, hence ELM free.

• Initial extrapolations of C-Mod results to ITER are encouraging. Further experiments, on both C-Mod and other tokamaks, are needed!!