Progress in Performance and Understanding of Steady ELM-free I-modes on Alcator C-Mod

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Abstract. The I-mode has now been demonstrated on Alcator C-Mod to be a distinct, robust confinement regime over very wide parameter ranges. It is attractive in that it combines the high energy confinement and edge thermal barrier of H-mode with the low particle confinement of L-mode, avoiding impurity accumulation and the need for ELMs to expel particles. Divertor heat flux widths \( \lambda_{\text{SOL}} \) are also larger. Most I-mode discharges are ELM-free, and stability analysis confirms pedestals are below peeling-ballooning boundaries. Energy confinement in high power I-modes is close to the H98y2 scaling, but shows little power degradation. L-I power thresholds with unfavourable drift are above L-H mode scalings for favourable drift, and increase with current as well as density. The regime is most robust on C-Mod with upward \( B \times \nabla B \) and the X-point toward the closed lower divertor, and with moderate target density. In these conditions discharges stay in stationary I-mode for many \( \tau_E \), at up to the maximum available ICRH power and at least twice the threshold power. At the L-I transition, edge fluctuations in the 60-150 kHz frequency range decrease, correlated with the decrease in edge \( \chi_{\text{eff}} \). A higher frequency Weakly Coherent Mode is usually observed on density, magnetic and \( T_e \) diagnostics, which correlates with particle flux and appears to maintain particle transport, avoiding H-mode transitions. The regime and mode extend to low \( q_{95} \) and \( \nu^*_{\text{ped}} \). Initial assessments indicate that I-mode may be accessible on ITER with the planned heating power, at reduced density, and that \( Q=10 \) could be achievable at higher density. This exercise also highlights some of the key issues remaining to be addressed. Recent C-Mod experiments have succeeded in raising I-mode densities via fuelling, and further optimization and expansion of the discharge performance and operating space is planned in future campaigns. Multimachine experiments are needed to establish scalings with machine size and dimensionless parameters for a confident extrapolation.

1. Introduction

There is a significant need to find high confinement operational regimes in the tokamak which do not require intermittent edge instabilities to regulate particle and impurity transport across the edge transport barrier. In particular, the peak power loading from Edge Localized Modes (ELMs) [1], which usually are seen in the high performance H-mode regime [2], could be particularly problematic for next-step devices, including ITER [3], and for reactors, because of their potential to cause significant first-wall erosion in the divertor. Several promising approaches to ELM elimination or mitigation are being pursued, including suppression with externally applied 3D magnetic field perturbations [4], ELM pacing with small pellets [5], and ELM-free regimes including Quiescent H-mode (QH-mode) [6] and Enhanced D-Alpha H-mode (EDA H-mode) [7]. The I-mode regime [8,9] is another approach which combines several favorable characteristics: enhanced energy confinement with a strong thermal barrier near the last closed flux surface; little or no change in particle or impurity transport at the plasma edge, with L-mode like density profiles and global impurity confinement, hence no need for ELMs to regulate particle and impurity transport across the thermal barrier. There is no external momentum drive in these ICRF H-minority heated C-Mod plasmas. Easiest access to I-mode is found by operating in a single-null divertor configuration, with the ion \( B \times \nabla B \) drift in the so-called unfavorable direction for access to H-mode, away from the active X-point [10]. I-mode has also been accessed on C-Mod with
favorable drift, but the operational window in terms of input power between I- and H-mode is so far always observed to be small [11]. Global energy confinement is significantly enhanced over L-mode, and comparable to H-mode, with $\tau_E/\tau_{\text{ITER-H98,Y2}} \leq 1.2$.


An important issue for utilization of the I-mode regime to advance fusion energy is whether it can be reliably accessed and sustained for long time periods, in parameter ranges of interest. At the time of the 2010 Fusion Energy Conference, while I-modes were routinely accessed over a wide parameter space, their power range was relatively narrow; modest increases in power often resulted in a transition to H-mode, with resulting increases of density and radiated power (see e.g. Fig. 2 of [10]). ASDEX Upgrade has reported similar experience [12]. This would not be ideal in a burning plasma, where input power is dominantly self-generated and less readily controlled. The density range for which I-modes could be accessed and maintained was also relatively narrow.

In the 2011 and 2012 C-Mod campaigns, regions of configuration and parameter space have been identified in which I-mode is robustly accessed at moderate input power, and can be sustained at powers up to the maximum available (5 MW ICRF heating, a large power density for a device with 1.1 m$^3$ plasma volume). Stationary I-modes are now routinely sustained for the duration of the plasma discharge and heating power pulse, many energy and particle confinement times. The optimal configuration to date uses reversed field and current, with upward ion $\mathbf{B} \times \nabla \mathbf{B}$ drift and the X-point towards the closed lower divertor, and moderate L-mode target densities, typically in the range $\tilde{n}_e = 1.0-1.5 \times 10^{20} \text{m}^{-3}$. An example discharge with $q_{95}=3.4$ is shown in Figure 1. The global energy confinement is approximately equal to the ITER98y2 scaling for H-modes [13]; errors bars on

![Figure 1. Time evolution of C-Mod discharge 1120907028 (5.8 T, 1.1 MA). I-mode is maintained up to the maximum ICRF power of 4.8 MW, with $T_e(0)$ 8 keV, $T_{\text{ped}}$ 1 keV and confinement at the H98y2 level.](image1)

![Figure 2: Electron pedestal profiles in L-mode (black) and I-mode (red) for the discharge shown in Figure 1.](image2)
$H_{98}$ represent the uncertainty in estimating fast particle contributions to the stored energy. There is no increase in density or radiated power after transition to I-mode. Studies of impurity confinement using laser blowoff injection confirm $\tau_I$ remains at levels near L-mode [14]. Electron pedestal profiles for this discharge are shown in Figure 2. A substantial temperature gradient, up to 200 keV/m, and pedestal temperature ($>1$ keV) are sustained, while density profiles in the core, pedestal and SOL remain close to those in L-mode. This results in low pedestal collisionality, $\nu^*_95 =0.11$, within a small factor of that expected in ITER baseline scenarios.

Over 200 I-mode phases have now been identified on C-Mod and entered in a database. Analysis of many more discharges from the summer 2012 campaign is in progress. These represent a wide range of plasma parameters, $B_T=3.0-6.1$ T, $I_p=0.8-1.35$ MA, $q_{95}=2.5-5.3$, loss power $P_{\text{loss}}=P_{\text{ohmic}}+P_{\text{RF, obs}}-dW/dt =1.6-5.1$ MW and $\bar{n}_e=0.85-2.3 \times 10^{20}$ m$^{-3}$. The field, $q_{95}$ and density ranges span those of ITER and there is no apparent physics barrier to accessing the regime.

Studies of power threshold for the L-I transition in the unfavourable drift configuration show that it typically exceeds scalings developed for L-H transitions with favourable drift [15] and also has different parameter dependences [16]. Notably, the threshold increases with plasma current as well as with density. A regression analysis to a set of 46 transitions with $B_T=5-6$ T yields $P_{\text{thresh}}=2.11 I_p^{0.94 \pm 0.24} \bar{n}_e^{0.65 \pm 0.78}$. However, there is some covariance between density and current in the data set, making it difficult to unambiguously separate these dependences. Density scaling in a more restricted data set ($I_p=1-1.1$ MA, fixed lower null shape) yields a close to linear dependence (Figure 3). As can be seen, the power range for I-mode is much wider for the lower densities, with no I-H transitions occurring up to the maximum heating power available ($5$ MW ICRF). Higher powers are likely possible; transitions to H-mode are rare in these conditions. The scaling of the I-H threshold is much less clear; transitions have been observed at a range of powers for given density. As will be discussed further in

![Figure 3: Loss power vs $\bar{n}_e$ for a set of LSN discharges with $B_T$ 5-6 T and $I_p$ 1-1.1 MA. The time trajectory of an I-mode fuelled to high density (Fig 9) is indicated by the black arrows.](image)

![Figure 4. a,top)Volume average pressure as a function of $P_{\text{loss}}$ = $P_{\text{heat}}$ - $dW/dt$. The time derivative term is less than 10%.
b, bottom) The same data set, recast into a dimensionless fusion metric. The dashed line shows the expected value for ITER in the baseline H-mode at $Q=10$.](image)
Section 4, it appears that the operating window for I-mode is dependent on the discharge trajectory and can be expanded.

Confinement scaling studies on C-Mod show that there is at most weak confinement degradation with input power in I-mode [10]. Pedestal temperature profile measurements reveal that the width of the temperature barrier is relatively constant (~3-5% of the poloidal flux). The height of the temperature barrier scales approximately linearly with increasing heating power, unlike H-modes where it tends to saturate. One illustration of the global confinement effect is shown in Figure 4a, which shows the linear increase in plasma pressure, as inferred from equilibrium reconstructions of $\beta_p$, as a function of heating power. Figure 4b shows the same data, plotted in terms of the dimensionless fusion metric, $\beta_N H_{98}/q^2$. In spite of its much smaller size, C-Mod, operating at the ITER field, shape and $q_{95}$, reaches 85% of the value on ITER required for $Q=10$. In some discharges with $\beta_N=1.1-1.4$, neoclassical tearing modes have been triggered by the large sawteeth [17].

3. Advances in characterization of pedestal and SOL physics

Considerable progress has also been made since the 2010 FEC meeting in characterizing the edge and SOL turbulence, transport and profiles, and the relationships between them. A key signature of the L-I transition, accompanying the formation of $T_e$ and $T_i$ pedestals, is the reduction of edge broadband turbulence in intermediate frequencies, typically ~60-150 kHz. This contrasts with the usual increase in such turbulence with increased heating in L-mode. The reduction is seen most clearly in density, on reflectometry channels located in the outer 5-10% of the plasma, and is also visible in magnetic fluctuations [18]. A good correlation in time has been observed between the level of density fluctuations and the reduced thermal conductivity $\chi_{\text{eff}}$ inferred from power balance analysis in the outer 5% of the plasma, as shown in Fig. 5 [11]. This suggests that turbulence in this frequency range is an important contributor to thermal transport. The reduction may be related to the development of an $E_x$ well in I-mode, which is clearly visible from CXRS diagnostics though weaker than in H-modes [9]. Unlike H-mode, however, there is not a concomitant reduction in particle transport. Decreases in core turbulence have also been observed in I-mode, and comparison with turbulence codes is in progress.

Simultaneous with the formation of an edge temperature pedestal at the L-I transition, edge turbulence typically increases at frequencies > 150 kHz. This ‘weakly coherent mode’ (WCM) is evident at 240 kHz in the example of Figure 5 [11]. It is also detected in magnetic fluctuations measured on poloidal field pickup coils mounted outboard of the...
plasma on the low field side, and on Electron Cyclotron Emission (ECE) fluctuations [19]. The WCM density fluctuations are also observed by Gas Puff Imaging (GPI) [20]. The reflectometer, ECE and GPI measurements all show that the WCM is localized to the region of the strong edge temperature gradient. GPI measurements resolve the poloidal wavenumber, giving $k_{\parallel}r_s \sim 0.1$, $n_{\text{toroidal}} \sim 20$ and show that the mode propagates in the electron diamagnetic direction in the plasma frame [11,20]. Detailed analysis of the ECE data shows that this signal is dominated by temperature fluctuations, with $\delta T_e/T_e \sim 2\%$. This compares with a typical density fluctuation level, from GPI, of about 10%. This could be consistent with the WCM causing more particle than energy transport, perhaps being the main mechanism responsible for the edge particle transport (relative to that in H-mode) during I-mode operation.

As a test of this hypothesis, a series of experiments was performed to examine directly the relationship between density transport and the intensity of the WCM. The WCM amplitude was monitored using multiple frequencies of the reflectometry diagnostic and the deuterium particle source using an analysis of absolutely calibrated D$\alpha$ imaging near the outboard midplane. Correlations were found between the radial particle flux $\Gamma$ and the WCM amplitude, with an example shown in Figure 6 [21]. This supports the conjecture that there is a causal relationship between the WCM and particle transport, analogous to that established by a similar technique between the QC mode and particle transport in EDA H-modes [22].

The WCM is strongest and most coherent in high temperature and performance I-modes, particularly at low $q_{95}$. It is thus very compatible with low collisionality. In some I-modes, particularly those with $q_{95} > 4.5$ and/or input power which is marginal with respect to the L-I threshold, it is not distinguishable with available diagnostics. If the edge is cooled, by reduction in net power, the WCM amplitude and frequency reduce and a transition to either L-mode or H-mode can result. While the physical mechanism of the mode is not yet clear, these observations suggest it may be driven by the strong edge temperature gradient characteristic of I-mode. One candidate which has been proposed is the Heavy Particle Mode [23].

Peeling-ballooning instabilities are thought to be responsible for the ELM trigger in Type-I ELMing H-mode plasmas [24]. The reduced density and pressure gradients of the I-mode pedestal, relative to H-mode, are favourable for staying below their stability boundaries. Preliminary results using the ELITE code [25] show that the typical I-mode pedestal in C-Mod is below both the peeling (large pedestal current), and the ballooning (large pedestal pressure gradient) boundaries [26]. This contrasts with Type-I ELMing discharges from C-Mod, where, within error bars, the inter-ELM pedestal is at the ballooning boundary.

Given the challenge of handling divertor heat fluxes in future high performance plasmas, it is of interest to compare scrape-off-layer and heat flux profiles in I-mode and H-modes. The broad, L-mode-like density profiles seen in Figure 2 suggest that the SOL width may be greater than in H-mode. Recent comparisons have been made of I-modes in the reversed field, lower null configuration, employing the suite of thermocouple and infrared
thermography diagnostics in the C-Mod outer lower divertor [27]. The physics-based functional form proposed by Eich [28] is used to characterize the heat-flux footprint. Figure 7 shows that $\lambda_{\text{SOL}}$, a measure of the perpendicular transport in the common flux region, is indeed larger than in EDA H-modes with favourable drift, while $W_{\text{PFZ}}$, which reflects transport to the private flux zone, is slightly narrower. As is typical of ‘unfavourable drift’ configurations, power sharing is shifted such that more of the input power is deposited to the inner rather than outer leg. The lower particle confinement in I-mode results in lower intrinsic main chamber radiation than for typical H-modes, which is positive for global confinement but increases the heat flux to the divertor. However, it also means that impurity seeding can readily be used to reduce these fluxes, without accumulation in the core plasma. Indeed, Neon seeding has been routinely used in many of the highest power I-mode discharges, reducing PFC heating and resulting metallic impurity fluxes and also improving ICRF performance [29]. Unlike H-modes, boronization is not essential to achieve steady high performance plasmas.

4. Key issues for extrapolation to ITER.

As a first step in assessing possible applicability of I-mode to ITER, we have made a simple extrapolation based on observed scalings, and assumptions concerning size scaling for the I-mode threshold. Because of the significant size extrapolation from C-Mod to ITER, about a factor of 9 in linear dimension, it is clear that this has large uncertainty. Nevertheless, it is an instructive exercise, pointing the way for future multi-device investigations,

C-Mod matches ITER in aspect ratio (R/a=3), B (5.3 T), q95 (3) shape and divertor geometry. Presuming that ITER could operate with $B \times \nabla B$ away from the lower divertor, an extrapolation is made with the following assumptions:

1) $P_{\text{L}=1} = 1.8 \text{ MW} \times <n_{e,20}> \times (S_{\text{ITER}}/S_{\text{C-Mod}})$, where S is the area of the LCFS;
2) Match density profile shape to that seen on C-Mod ($n_0/<n> \sim 1.3$);
3) Scale the L-mode temperature profile to force $\tau_E = \tau_{\text{ITER}98}$, including alpha power in L-mode (typically 10 to 20 MW depending on density and auxiliary power);
4) Constrain $\tau_E < 1.2 \tau_{\text{ITER}98,2}$, $n < n_{\text{Greenwald}}$, $P_{\text{aux}} < 75 \text{ MW}$, $P_{\text{L}=1} < P_{\text{heat}} < 2 P_{\text{L}=1}$, pressure at $\Psi_{95}$ below that expected in ITER H-modes (i.e. no ELMs);
5) Scale core and pedestal temperature profiles from C-Mod data, using $\nabla T_{\text{core}} \propto (P_{\text{heat}}/S)^{1/2}$ (as in H-mode), and $\nabla T_{\text{pedestal}} \propto (P_{\text{heat}}/S)^{1/2}\nabla \Psi_{95}$.

Assumption 1) is an L-H threshold-like scaling, but cannot be confirmed from C-Mod data alone. The combination of core and pedestal temperature assumptions yields a global energy
confinement scaling with $P_{\text{heat}}$ consistent with the C-Mod results (Section 2, above). The results of this exercise are shown in Figure 8. The contour plot shows lines of constant fusion power. Under the assumptions, I-mode should be accessible from L-mode with available auxiliary power at line average density of about $5 \times 10^{19} \text{ m}^{-3}$ ($n_{e,95} = 4 \times 10^{19} \text{ m}^{-3}$), or with progressively less power as the target density is decreased. In I-mode, alpha heating takes over, and fusion power is controlled mainly through density control. The nominal $Q=10$ operation point is shown on the plot, at $n_{e,95} = 5.2 \times 10^{19} \text{ m}^{-3}$.

This exercise highlights key issues and uncertainties for extrapolation of I-mode to other devices, and is helping to focus the ongoing research program. Most obviously, multimachine experiments are urgently needed to establish the size scaling of thresholds and confinement, and the key dimensionless parameters, particularly regarding density (eg $v^* \text{ vs } n/n_0$). Comparisons with ASDEX-Upgrade and D3D tokamaks are beginning under the auspices of the ITPA, but much more work is needed.

Another key question is whether it is feasible to enter I-mode at low density, where access is easiest, and increase to high density for increased fusion power; the operational space of Figure 3 suggested that the power window narrows at higher target densities. Recent C-Mod experiments are quite encouraging in this regard. Gas fuelling was added to an I-mode phase similar to that of Figure 1, increasing $\bar{n}_e$ from 1.5 to $2 \times 10^{20} \text{ m}^{-3}$ (Fig. 9). Stored energy remained nearly constant, with $H_{98y2} \geq 1$, and I-mode turbulence features and transport barrier are clearly maintained. The trajectory of this discharge is shown on Fig. 3, and shows that I-mode is maintained for powers well above that which resulted in I-H transitions starting from higher target density. In a subsequent discharge, an I-H transition resulted from a decrease in heating power at comparable density (top right blue square). This again
suggests that maintaining an edge $T_e$ gradient is important in driving the higher frequency turbulence which appears to drive particle transport, and to avoid H-mode transitions. Thus, with further increases in power, from external sources or from alphas in a burning plasma, it could well be possible to extend the I-mode operating space to even higher densities and performance. Further optimization of I-mode discharge performance and expansion of the operating space for this attractive regime is planned in future C-Mod campaigns.

Acknowledgement:
This work has been supported by U.S. Department of Energy Office of Science, Fusion Energy Sciences grant DE-FC02-99ER54512-CMOD. The efforts of the entire C-Mod engineering, physics and technical team in these experiments are gratefully acknowledged.

References