I-mode: an H-mode energy confinement regime with L-mode particle transport in Alcator C-Mod

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Received 2 June 2010, accepted for publication 20 July 2010
Published 19 August 2010
Online at stacks.iop.org/NF/50/105005

Abstract
An improved energy confinement regime, I-mode, is studied in Alcator C-Mod, a compact high-field divertor tokamak using ion cyclotron range of frequencies (ICRFs) auxiliary heating. I-mode features an edge energy transport barrier without an accompanying particle barrier, leading to several performance benefits. H-mode energy confinement is obtained without core impurity accumulation, resulting in reduced impurity radiation with a high-Z metal wall and ICRF heating. I-mode has a stationary temperature pedestal with edge localized modes typically absent, while plasma density is controlled using divertor cryopumping. I-mode is a confinement regime that appears distinct from both L-mode and H-mode, combining the most favourable elements of both. The I-mode regime is investigated predominately with ion \( \nabla B \) drift away from the active X-point. The transition from L-mode to I-mode is primarily identified by the formation of a high temperature edge pedestal, while the edge density profile remains nearly identical to L-mode. Laser blowoff injection shows that I-mode core impurity confinement times are nearly identical with those in L-mode, despite the enhanced energy confinement. In addition, a weakly coherent edge MHD mode is apparent at high frequency \( \sim 100–300\,\text{kHz} \) which appears to increase particle transport in the edge.

The I-mode regime has been obtained over a wide parameter space (\( B_T = 3–6\,\text{T}, I_p = 0.7–1.3\,\text{MA}, q_{95} = 2.5–5 \)). In general, the I-mode exhibits the strongest edge temperature pedestal (\( T_{\text{ped}} \)) and normalized energy confinement (\( H_{98} > 1 \)) at low \( q_{95} \) (<3.5) and high heating power (\( P_{\text{heat}} > 4\,\text{MW} \)). I-mode significantly expands the operational space of edge localized mode (ELM)-free, stationary pedestals in C-Mod to \( T_{\text{ped}} \sim 1\,\text{keV} \) and low collisionality \( \nu^*_{\text{ped}} \sim 0.1 \), as compared with EDA H-mode with \( T_{\text{ped}} < 0.6\,\text{keV}, \nu^*_{\text{ped}} > 1 \). The I-mode global energy confinement has a relatively weak degradation with heating power; \( W_{\text{th}} \sim I_p P_{\text{heat}}^{0.7} \) leading to increasing \( H_{98} \) with heating power.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Optimized magnetic fusion energy (MFE) reactors face the seemingly contradictory requirements of high global energy confinement and low particle confinement. In order to produce net energy gain, a minimum level of confinement parametrized by \( n\tau_E \sim 10^{21}\,\text{m}^{-3}\,\text{s}^{-1} \) [1] is required. Primarily due to the degradation of energy confinement time (\( \tau_E \)) with heating power, it is generally acknowledged that the confinement quality factor, \( H \), must at least attain values equal to ‘H-mode’ high-energy confinement regimes in dominantly self-heated MFE reactors at reasonable size (see for example [2, 3]). However, high global particle confinement time (\( \tau_P \)) is not necessarily required since, unlike self-heating from alphas, the fuelling rate determining plasma density \( n \) is externally controlled. Simultaneously, overly high \( \tau_P \) is usually undesirable due to the deleterious effects on fusion gain from accumulation of helium ash and impurity particles generated from plasma–wall interaction. Also, these global confinement times are largely set by the edge pedestal [4, 5], where an additional constraint is the avoidance of peeling–ballooning instabilities which lead to MHD edge localized modes (ELMs [6]) and unacceptable transient heating of...
plasma-facing components [7]. In general, therefore, one desires independent understanding and control of the energy and particle transport channels in the core and pedestal regions in order to optimize MFE scenarios.

We describe an improved energy confinement regime, I-mode, on Alcator C-Mod [8]. I-mode simultaneously features the desired properties of high-energy confinement of H-mode and the relatively poor particle confinement of low-confinement L-mode. The improved energy confinement results from the formation of an edge temperature pedestal, while density edge profiles remain essentially identical to those in L-mode. I-mode is most readily observed on C-Mod with the ion $\nabla B$ drift pointed away from the primary X-point, i.e. in the ‘unfavourable’ configuration for obtaining H-mode from the power threshold standpoint. The pedestal is typically free in the ‘unfavourable’ configuration for obtaining H-mode from the power threshold standpoint. The pedestal is typically free, probably due to a high-frequency weakly coherent fluctuation contemporaneous with I-mode and observed in the pedestal region. I-mode demonstrates that the energy and particle transport channels in the pedestal can be separated and isolated.

Previously, an ‘improved L-mode’ regime was found and briefly described in ASDEX-Upgrade [9], which focused on the mode as an intermediate step in the transition to H-mode in the unfavourable $\nabla B$ configuration. Similar transient increases of edge electron temperature [10] and improved L-mode energy confinement [5] have been reported on C-Mod. Threshold studies on these tokamaks, as well as DIII-D, showed clearly that edge temperatures, $T$ gradients and required heating power are substantially higher at the L–H transition in the unfavourable versus favourable $\nabla B$ configuration [11–14]. More recently Alcator C-Mod [15] showed that the same enhanced confinement regime, labelled for the first time as ‘improved mode’ or I-mode, could be made stationary. Charge-exchange recombination spectroscopy was used to show that the I-mode pedestal had a radial electric field well structure similar to that of H-mode. (It should be noted that the I-mode described here and in [15] for diverted tokamaks should not be confused with the I-mode reported on the TEXTOR limiter tokamak [16] which does not feature an edge transport barrier.)

We significantly expand on these previous I-mode studies by reporting on an extensive experimental campaign on Alcator C-Mod (section 2). The study has the dual goals of (1) assessing the phenomenology of I-mode and (2) extending operational experience, particularly towards achieving stationary I-mode discharges. The experimental results are organized as follows: identification of the distinguishing features of I-mode (section 3.1), exploration of the parameter space which provides access to I-mode (section 3.2), characterization of the global energy and particle confinement of I-mode (section 3.3), and documentation of the edge pedestal and fluctuation characteristics of I-mode (sections 3.4 and 3.5). Section 4 discusses the C-Mod experimental results on I-mode and conclusions are presented in section 5.

2. Experimental setup

Experiments were carried out on the compact, high-field Alcator C-Mod divertor tokamak [8]: major radius $R \sim 0.67$ m, minor radius $a \sim 0.22$ m and toroidal magnetic field $B_T < 8$ T. C-Mod uses only high-Z bulk refractory metals of molybdenum and tungsten for plasma-facing components. Ion cyclotron range of frequencies (ICRFs) heating is the sole auxiliary heating method used in these experiments [17]. Fundamental hydrogen (H)-minority ICRF at 78–80.5 MHz up to 5.5 MW is used for central heating of deuterium (D) major plasmas at typical magnetic field $B_T \sim 5.4$ T. For the purposes of this study, a fixed 80% absorption efficiency is assumed for ICRF heating. This assumption is consistent with average H-minority ICRF absorption efficiencies measured on C-Mod with H-minority concentration $\sim 5\%$ [17]. In addition, the study includes a campaign at reduced $B_T$ field ($\sim 3–3.4$ T) which primarily uses central ICRF H-minority 50 MHz heating, and some additional 80 MHz 2nd harmonic H-minority heating (although the absorption efficiency of 2nd harmonic heating is more uncertain [17]). Experiments were also conducted at $B_T \sim 7.8$ T using D($^3$He) heating, which has reduced single-pass absorption, but neither I-mode nor H-mode were achieved with the available power at this field.

A typical C-Mod equilibrium shape for I-mode studies is shown in figure 1. The I-mode experiments mostly use an upper-single null divertor topology with ‘unfavourable’ ion $\nabla B$ drift, i.e. with $B \times \nabla B$ pointed away from the primary X-point, which is known to increase significantly the auxiliary heating threshold to access H-mode as well as the threshold edge temperature [10, 11, 18]. Upper-null shapes can exploit strong divertor pumping for density control using the axisymmetric cryopump located there [19]. In addition, neon impurity seeding was often used in conjunction with pumping since this was found operationally to reduce high-Z impurity injections and generally improve plasma performance at high ICRF power. At the cryopump major radius the upper divertor has toroidal gaps (50% toroidal coverage) for particle entry to the pump volume (figure 1). However, for $P_{\text{ICRF}} > 3$ MW we restrict the outer strikepoint to the inboard side of the entry gaps due to the reduced power handling of the entry gap tiles.

To date a small fraction (two cases, $< 5\%$ of discharges) of the I-mode results have been obtained in lower single null. In the first case, the magnetic field direction was simply reversed so that lower null has unfavourable ion $\nabla B$ direction. In the second more interesting case, I-mode was obtained with the standard $B$ direction, and thus $B \times \nabla B$ pointed towards the primary X-point. This I-mode was the unintentional result of using an atypical lower-null magnetic geometry for C-Mod (green dashed line, figure 1) with small upper triangularity, large lower triangularity and small X-point clearance to the inner divertor. Note that this general shaping is used on C-Mod to gain access to type-I ELMy H-mode [20]. However, the exact shaping shown in figure 1, which was the only case of I-mode with favourable $\nabla B$ direction, was used for only a single shot during another experiment studying ELMy H-modes. This was only identified as I-mode after the fact and further exploration of I-mode in this configuration has not yet been carried out. However, we include this singular case in our analysis since it will be shown that it exhibits a significantly different power threshold for I-mode (section 3.2).

As a result of the C-Mod experimental campaign we have identified and examined ~100 I-mode time slices. A wide variety of heating power, plasma parameters and topologies
has been explored: total heating power \( P_{\text{ICRF}} + P_{\text{ohmic}} \approx P_{\text{tot}} \approx 1.3 - 5.7 \text{ MW} \), \( B_T \approx 3 - 6 \text{ T} \), plasma current \( I_p \approx 0.7 - 1.3 \text{ MA} \), \( q_{95} \approx 2.5 - 5 \), plasma elongation \( \kappa \approx 1.5 - 1.78 \), primary divertor triangularity \( \delta \approx 0.3 - 0.85 \) and average \( \delta \approx 0.35 - 0.6 \). Although experiments were carried out through a campaign where boronization films were applied for plasma performance [21], none of the I-mode experimental days used boronization immediately preceding the experiment. Wall conditions were therefore variable and, in contrast to EDA H-modes [22], apparently not critical.

Several key C-Mod diagnostic [23] locations are shown in figure 1. Thomson scattering (TS) and electron cyclotron emission (ECE) are used to provide electron density and temperature profiles in the core and pedestal region. Magnetic fluctuations are measured with an array of edge poloidal magnetic field (\( B_{0y} \)) probes. Line-averaged density fluctuation spectra are measured with phase contrast imaging (PCI [24]). Edge density fluctuations are measured with a multi-frequency, outer midplane reflectometer system [25] and gas-puff imaging (GPI [26]). Edge and pedestal rotation and impurity analysis from \( B^+ \) charge-exchange recombination spectroscopy (CXRS) is presently limited to only a few cases at \( q_{95} \approx 4.8 \), \( I_p = 0.8 \text{ MA} \) [15, 27].

3. Experimental results

3.1. Identification of I-mode

In defining a confinement regime it is necessary to establish identifying features that make it distinct from standard L-mode confinement. For example, as auxiliary heating is increased an H-mode transition is experimentally identified by a sudden reduction in edge D-\( \alpha \) recycling light, a positive break in slope \( \alpha \), and confinement quality \( H_{98,y_2} \). (a) Plasma current and ICRF heating power, (b) D-\( \alpha \) recycling and core radiated power, (c) \( D_2 \) gas fuelling rate and line-averaged density \( n_e \), (d) \( T_{e,95} \) pedestal electron temperature at \( r/a \approx 0.95 \) from ECE, (e) \( T_{e,98} \) central electron temperature, (f) stored thermal energy \( W_{th} \) and confinement quality \( H_{98,y_2} \), (g) pedestal \( T_e \) gradient evaluated from edge TS, (h) local density at pedestal \( r/a \approx 0.95 \) and separatrix \( r/a \approx 1.0 \) from TS, (i) poloidal magnetic field fluctuation amplitude \( |B_\theta| \) averaged over the frequency range \( 100 - 150 \text{ kHz} \) (from \( B_{0y} \) coils, figure 1), (j) density fluctuation amplitude spectrum from outer midplane reflectometry at 88 GHz.

Figure 1. Example of upper single-null equilibrium used for I-mode studies (solid black separatrix) with \( B \times \nabla B \) pointed away from the X-point (upper null discharge of figure 2). Also shown is the separatrix (grey dashed line) for the I-mode case with \( B \times \nabla B \) pointed towards the X-point in lower single null. The upper divertor cryopump, pump entry gaps and key diagnostic locations are indicated.

Figure 2. Example of upper single-null \( B_T = 5.6 \text{ T} \), \( q_{95} \approx 3.2 \) I-mode discharge with divertor cryopumping (figure 1) with L-mode, I-mode and ELM-free H-mode phases indicated. (a) Plasma current and ICRF heating power, (b) D-\( \alpha \) recycling and core radiated power, (c) \( D_2 \) gas fuelling rate and line-averaged density \( n_e \), (d) \( T_{e,95} \) pedestal electron temperature at \( r/a \approx 0.95 \) from ECE, (e) \( T_{e,98} \) central electron temperature, (f) stored thermal energy \( W_{th} \) and confinement quality \( H_{98,y_2} \), (g) pedestal \( T_e \) gradient evaluated from edge TS, (h) local density at pedestal \( r/a \approx 0.95 \) and separatrix \( r/a \approx 1.0 \) from TS, (i) poloidal magnetic field fluctuation amplitude \( |B_\theta| \) averaged over the frequency range \( 100 - 150 \text{ kHz} \) (from \( B_{0y} \) coils, figure 1), (j) density fluctuation amplitude spectrum from outer midplane reflectometry at 88 GHz.
to H-mode, but featured neither a sudden D-α reduction nor a noticeable increase in density, making identification of the transition from L-mode to I-mode problematic based only on the standard L–H transition criteria. To avoid circular logic it is unacceptable to identify a transition in the confinement regime solely by its confinement quality factor (H).

Exploration of I-mode over a wider parameter space on C-Mod has shown that distinct transitions from L-mode to I-mode indeed exist and can be clearly identified in most cases. In particular, L–I transitions become very distinct on C-Mod in discharges with low \(q_{95} < 3.5\) and high heating power (P_{ICRF} ∼ 3 MW), an example of which is shown in figure 2, in a discharge that features small increasing steps in P_{ICRF}. Figure 2 also features a transition to ELM-free H-mode for comparison.

The L–I transition is most clearly identified by the rapid increase in pedestal temperature (\(T_{e,95}\)) from L-mode values, simultaneous with the power pulse from a sawtooth crash (figures 2(d)–(e)). In contrast to the edge temperature response to the sawtooth heat pulses in the preceding L-mode, \(T_{e,95}\) does not decay at the L–I transition but is instead maintained, and even increases further, following the barrier formation. Sawtooth crashes are always found to be the trigger for transitions to I-mode (and to H-mode) for the cases studied here. Where \(B^+\) ion temperature \(T_i\) edge measurements are available from CQRS, they have also been found to increase and are equal to \(T_e\) within the uncertainties [27]. Through stiff core temperature profiles [5] the core temperature and stored energy increase as a result of the higher edge \(T_e\). A confinement quality factor commensurate with H-mode [28], \(H_{98,y} \sim 1\) is obtained and maintained for more than 10 energy confinement times. However, there is no noticeable change in the core density. The external fuelling rate (figure 2(c), set by a feedback loop for density control with cryopumping) decreases gradually throughout the shot with its average value ∼30% lower in I-mode than L-mode, yet active density control is maintained. It is not clear if these gradual changes in fuelling requirements are an indication of a modest increase in global particle confinement (\(\tau_P \sim \text{density/fuelling rate}\) or a consequence of evolving fuel recycling from the inertially cooled metal walls. There is certainly no sudden change in \(\tau_P\) at the transition. Noticeable, but often weak, breaks in slope in D-α and \(P_{\text{grad}}\) also occur at the transition. The trend of the break in slope in \(P_{\text{rad}}\) is not consistent in all I-mode transitions, i.e. \(P_{\text{rad}}\) can sometimes increase or decrease at the L–I transition. The radiated power fraction (\(P_{\text{rad}}/P_{\text{tot}}\)) in I-mode tends to be relatively small and constant, varying between \(P_{\text{rad}}/P_{\text{tot}} \sim 0.25–0.4\).

The transition to a transient ELM-free H-mode (at \(t = 1.45\) s in figure 2) contrasts sharply with the L–I transition. At the H-mode transition the density and \(P_{\text{rad}}\) rise rapidly and uncontrollably. Although RF heating power is constant, the subsequent decrease in conducted power to the pedestal/edge region due to core radiation from high-Z impurities, together with the increase in \(n_e\), rapidly degrades the edge pedestal temperature and \(H_{98,y2}\) decreases to ∼0.5. These issues of transient ELM-free H-mode performance at low \(q_{95}\) and impurity accumulation with an uncoated high-Z wall have previously been documented on C-Mod [5, 21].

The evolution of the edge pedestal profiles is shown in figures 2(g)–(h) and 3. A large \(T_e\) pedestal gradient is established at the I-mode transition, and the \(T_e\) profile is comparable to that found in the H-mode. In contrast to H-mode, there is no significant change in the I-mode edge density or \(n_e\) gradient compared with L-mode. Only when a subsequent transition into the H-mode occurs, a clear density pedestal is formed. It is this formation of an edge thermal transport barrier in the absence of an edge particle transport barrier which is the key feature of I-mode.

There are also marked changes in edge fluctuations at the transitions as shown in figures 2(i)–(j). At the transition to I-mode there is a general decrease in low-frequency (∼25–150 kHz) broadband density/magnetic fluctuations (figure 2(i)), while simultaneously a weakly coherent density/magnetic fluctuation exists at higher frequencies (figure 2(j)). This is reminiscent of the quasi-coherent (QC) mode of EDA H-mode [22] but appears at higher frequency and is significantly broader in frequency. At the transition to H-mode the weakly coherent mode (WCM) promptly disappears, along with a general sharp reduction in broadband fluctuations. Based on multi-frequency reflectometry the WCM shown in figure 2 only exists between the 88 and 110 GHz cutoffs, i.e. the 110 GHz reflectometer channel (not shown) does not detect the WCM. This observation squarely places the WCM in the I-mode \(T_e\) pedestal region between \(0.9 < \rho/a < 1.0\) (figure 3(b) shows the densities associated with the cutoff frequencies). The fluctuation characteristics, including their behaviour at transitions, are examined in more detail in section 3.5.

In summary there are several means to identify I-mode. The C-Mod experience has been that the sudden I-mode transition based on increased \(T_{e,\text{ped}}\) is only observed at low \(q_{95}\).
(<4) and high plasma current (>1 MA), while at higher $q_{95}$ the transition from L-mode tends to be more gradual [10, 15]. On the other hand, the signature I-mode fluctuations described above are universally observed in both gradual and sudden I-mode transitions. Therefore the criteria for the identification of an I-mode are that it:

1. Must show the formation of an edge $T_e$ pedestal, either abruptly or gradually, without a significant change in the edge density profile as compared with L-mode,
2. Must show the appearance of a high-frequency (>100 kHz) weakly coherent magnetic/density mode (WCM) with an accompanying reduction in broadband fluctuations below the WCM frequency,
3. Must not show the signatures of an H-mode transition, namely an abrupt (<1 ms) and sharp decrease in $D$-$\alpha$ along with a positive break in slope of the core density.

In addition to these three criteria, it is often observed that I-mode transitions show a break in slope of the core density, either abrupt or gradual, without a significant change in the edge density profile as compared with L-mode.

These criteria have been used to identify ~100 time slices (from ~65 discharges) on C-Mod in the I-mode confinement regime. Furthermore, we have identified ~20 clear L-I transition cases, i.e. where the I-mode exhibited the abrupt formation of the T pedestal as shown in the example of figure 2. Time intervals just before (<$\tau_e$) the formation of an I-mode were selected for threshold analysis. Similarly, ~40 I-mode intervals just prior to H-mode (particle barrier) transitions were selected for I–H threshold analysis.

### 3.2. Access to I-mode and H-mode

The operational space of the discharges dedicated to I-mode studies is shown in figure 4. As expected, the density of I-mode is essentially identical to L-mode and ~1.5–2 × lower than H-mode. The I-mode density tends to organize to and increase with plasma current. It is also apparent that I-mode exists over a finite range of density at a given plasma current.

As density is lowered (using pumping) below some threshold value, at fixed $I_p$ and $P_{ICRF}$, the L-mode core radiated power fraction suddenly increases to near unity. This high core radiated fraction from high-Z impurities decreases the loss power to the edge and likely impedes the formation of the I-mode transport barrier (H-mode transitions are also absent at these lower densities). Conversely, as density is increased the subsequent increase in edge neutral pressure is problematic for ICRF antenna operations and heating often becomes too erratic to establish I-mode. In addition, at higher density, even if an I-mode transition occurs it can be as short lived as a single sawtooth period (~10–20 ms) before an H-mode transition occurs. It remains unclear if the I-mode density is constrained primarily by operational limits with the heating technique or by underlying transition physics.

Figure 5 shows that in general the required heating power ($P_{loss} = P_{tot} - dW_{th}/dt$) to sustain I-mode overlaps well with the range of heating power to sustain H-mode (except as noted, all discharges have unfavourable $\nabla B$). This observation is supported by examining the power requirements to trigger L–I and I–H transitions (figure 6(a)) established through small-range $B_t/I_p$ scans at fixed ICRF heating frequencies. It has been found that the threshold $P_{loss}$ for L and H mode transitions organizes well to $q_{95}$ (although the 50 MHz, low $B_t$ results of figures 5 and 6(a) show that there is a $B_t$ dependence as well). The ratio of measured L–I and I–H threshold power to the widely used H-mode threshold power scaling $P_{ LH, scaling}$ [29] is shown in figure 6(b). The ratio $P_{loss}/P_{ LH, scaling}$ is greater than unity as expected for the favourable $\nabla B$ drift direction. However, the approximately linear inverse $q_{95}$ ($I_p$) dependence we find for the threshold power does not appear in the standard H-mode threshold scaling prediction [29] and therefore appears to be a feature unique to unfavourable $\nabla B$ drift topology. This leads to a strong dependence on $q_{95}$ for the ‘normalized’ power to access L- or H-mode, with $P_{loss}/P_{ LH, scaling} \sim 1.5–2.5$ at $q_{95} \sim 3$ and $P_{loss}/P_{ LH, scaling} \sim 1.25$ at $q_{95} \sim 4.5–5$. A noteworthy exception to these trends is the one lower-null I-mode case with $B \times \nabla B$ towards the X-point (figures 1 and 6) which has a substantially lower I- and H-mode power threshold and closely follows the scaling prediction, i.e. $P_{loss}/P_{ LH, scaling} \sim 1$. Operational experience on C-Mod has suggested that higher triangularity also plays a role in easing access to...
I-mode. This trend is difficult to quantify precisely due to the requirement for continuous upper divertor sweeping (and hence sweeping in triangularity) in order to avoid heating limits in the upper divertor (figure 1). Nevertheless, there is a regular trend for the L–I transition to occur in otherwise stationary discharges as upper triangularity was increased. In addition, the single I-mode transition with favourable V×B topology in lower null was found as lower triangularity was increased (figure 1) from one discharge to the next. Section 3.3 will show that energy confinement of I-mode also depends on triangularity.

3.3. Global characterization of I-mode energy, particle and momentum transport

The I-mode has energy confinement properties that set it apart from L- and H-mode. Figure 7 shows the I-mode plasma stored energy \( W_{th} \) versus the product of total heating power \( P_{tot} \) and plasma current \( I_p \). Empirical scalings for energy confinement time, \( \tau_E \equiv W_{th}/P_{tot} \) are known to be \( \propto I_p \), (e.g. [28]). Therefore the observation that I-mode \( W_{th} \) increases nearly linearly (\( \alpha \approx 1 \) in figure 7) with \( P_{tot} \times I_p \) indicates that the I-mode features a weaker degradation of energy confinement (\( \tau_E \propto P^{\alpha-1} \)) with heating power than seen in L-mode (\( \alpha \approx 0.5 \)) or H-mode (\( \alpha \approx 0.3 \)). At this point it is not possible to provide a reliable regression analysis for the I-mode \( W_{th} \) due to the strong correlations between \( I_p, n_e \) and \( P_{tot} \). Nevertheless, the trend of weak power degradation in I-mode is confirmed by examining a subset of I-mode discharges (squares with diamond symbols overlaid in figure 7) featuring a significant scan in heating power (\( P_{tot} = 3.3 \text{ MW} \) to 5.1 MW) at fixed \( I_p \approx 1.2 \text{ MA} \) and density (\( n_e \approx 1.9 \pm 0.1 \)). In these cases, \( W_{th} \) appears to increase linearly with \( P_{tot} \) with no sign of rollover. A power law fit of these fixed \( I_p \approx 1.2 \text{ MA} \) cases yields \( \alpha \approx 0.7, \) consistent with the overall trend of \( W_{th} \) versus \( I_p \times P_{tot} \) in I-mode at \( B_T \approx 5.5 \text{T} \). The trend in \( W_{th} \) is less clear at lower \( B_T \approx 3–3.4 \text{T} \), although this is likely affected by the uncertain absorption of the additional 2nd harmonic H-minority heating needed to access \( P_{tot} > 3 \text{ MW} \). The favourable trend of \( W_{th} \propto P_{tot} \times I_p \), combined with the high heating power typical of low \( q_{95} \) I-modes, has allowed for stationary I-mode discharges with volume-average pressure \( \sim 1.5\text{ atm} \), which closely approaches the C-Mod absolute performance (1.8 atm) record set in H-mode using between-shot boronizations [21].

I-mode has an energy confinement quality roughly consistent with predictions of standard H-mode scaling over a wide range of parameter space. The confinement quality factor, \( H_{98,x,y} \) of I-mode lies in a narrow range near one as shown in figure 8 versus total heating power and \( q_{95} \). Note, however, that I-modes are not identified by \( H_{98,x,y} \). The general trend of increasing \( H_{98} \) with heating power is consistent with the weaker than expected power degradation shown in figure 7. The notable exceptions to this trend are I-modes with atypical shape for I-mode, i.e. favourable V×B drift or lower-single null shapes with reversed \( B_t \), both which obtain high \( H_{98} \) at \( P_{tot} \sim 2 \text{ MW} \). This suggests that further increases in performance may be achievable. Also, the lower field I-mode cases have consistently higher \( H_{98} \) than at nominal field \( B_T \sim 5.4 \text{T} \). Figure 8(b) shows that \( H_{98,x,y} \sim 0.9–1.1 \) can be obtained over a wide range of \( q_{95} \) with a greater tendency for consistently high \( H_{98} \sim 1 \) values at lower \( q_{95} < 3.5 \). This contrasts with EDA H-mode which is strongly favoured by \( q_{95} > 3.5 \) [30, 31]. The favourable V×B drift I-mode again stands apart from this trend with \( H_{98} \sim 1.1–1.2 \) at intermediate \( q_{95} \sim 3.8 \).

The \( H_{98} \) confinement quality is plotted versus upper triangularity in figure 9 for a subset of the I-mode cases with the following characteristics: upper null (figure 1), \( 5.3 < B_T < 5.9 \text{T} \), \( q_{95} < 3.5 \). With fixed lower triangularity, the \( H_{98} \) factor clearly increases with upper triangularity (the \( \tau_E \) resulting from the \( H_{98} \) scaling has no dependence on triangularity). Increasing lower triangularity at the smallest upper triangularity also appears to increase \( H_{98} \) (diamond
point in figure 9), but this has not been confirmed with systematic scans. These results again suggest means for further optimization of the I-mode shaping.

Figure 10 compares global impurity confinement time with \( H_{98,y} \) energy confinement quality for L-mode, I-mode and stationary EDA H-modes [32, 33]. Impurity confinement time \( (\tau_I) \) is obtained following laser ablation injection of calcium fluoride (CaF\(_2\)) and the measurement of the central plasma Ca emission decay time with x-ray spectroscopy [34]. Ca injections into ELM-free H-modes have confinement times significantly longer than the duration of the H-mode (i.e., \( >0.2-0.5 \) s) and so cannot be analysed for \( \tau_I \). I-mode has energy confinement consistent with H-mode, but with the weak impurity particle confinement of L-mode (\( \tau_I \approx 20-40 \) ms \( \tau_\text{AE} \)). I-mode impurity particle confinement time is considerably less than that found in stationary EDA H-modes. These observations are consistent with the fact that indicators of global particle confinement time are essentially unchanged between L- and I-mode: i.e. fuelling rate requirements (figure 2) and density profiles (figure 3) are not significantly modified when compared with the large changes in fuelling and density at H-mode transitions.

Consistent with the Ca transport, global impurity levels are found to change by small factors (\(<\text{factor of two}\)) when transitioning from L-mode to I-mode. At \( q_95 \approx 4.8 \) the I-mode boron (B) concentration is radially uniform and \( f_\text{B} \equiv n_\text{B}/n_e \approx 0.5\% \) [27], approximately double that found in the preceding L-mode (boron is usually the dominant low-Z impurity in C-Mod). However, visible bremsstrahlung and resistivity analyses indicate \( Z_{\text{eff}} \approx 1.4-1.6 \) in this case. Since \( f_\text{B} \approx 0.5\% \) leads to only \( \Delta Z_{\text{eff}} \approx 0.1 \), it is inferred that high-Z molybdenum (Mo), with \( f_\text{Mo} \equiv n_\text{Mo}/n_e \approx 0.03\% \), predominately sets the \( Z_{\text{eff}} \) increment. I-modes discharges at higher absolute confinement \( (q_{95} > 3) \) and heating power have increased \( Z_{\text{eff}} \approx 2-2.3 \). This is qualitatively consistent with a general increase in radiated power fraction from \( P_{\text{rad}}/P_{\text{tot}} \approx 0.25 \) at \( q_{95} > 4.5 \) to \( P_{\text{rad}}/P_{\text{tot}} \approx 0.4 \) at \( q_{95} < 3 \). In cases where neon seeding is used to improved ICRF performance \( Z_{\text{eff}} \) is found to be higher (\( \Delta Z_{\text{eff}} \approx 0.6 \)) than matched shots without seeding. However, absolute plasma performance (e.g. stored energy, neutron rate) is unaffected or improved by seeding.

I-mode plasmas also feature core intrinsic rotation behaviour similar to that found in EDA H-mode. Figure 11 shows the increment in core toroidal rotation velocity as a function of the increment of stored energy normalized to plasma current with the application of ICRF heating (which does not directly apply torque to the plasma). The I-mode results follow the same approximately linear relationship with \( \Delta W/\Delta I_p \) as found for a database of stationary EDA H-modes [35]. Since the I-mode increase in stored energy is solely from a temperature increase, rather than from density,
this result suggests that temperature, rather than density or pressure, may play the more important role in setting intrinsic rotation.

3.4. I-mode edge pedestal: profile characteristics

I-mode pedestal density and temperature profiles, including both core and edge TS and ECE, have been fitted (e.g. figure 3) to the modified hyperbolic tangent function conventionally used for H-mode pedestal analysis [36]. These fits include time slices from the I-mode campaign (figure 4), as well as example stationary EDA H-modes from earlier pedestal scaling studies [37] and recent ELMy H-modes, the latter two with favourable $\nabla B$ drift topology.

The I-mode discharges are on a lower collisionality $\nu$ versus $\nu^* \text{ ‘track’} \text{ than H-mode, i.e. the I-mode collisionality is lower for a given pedestal temperature. Figure 12 shows the pedestal electron temperature versus pedestal neoclassical collisionality, $\nu_v^*$ (see for example [38]). I-mode significantly expands the C-Mod operational space of stationary ELM-free regimes: from the collisional ($\nu_v^* > 1$) L-mode/EDA regimes with $T_{\text{ped}} < 0.6 \text{ keV}$ to the collisionless ($\nu_v^* \sim 0.1$) I-mode with $T_{\text{ped}}$ approaching $1 \text{ keV}$. For completeness, it should be noted that small, infrequent ELMs have occasionally been seen in I-mode. These ELMs are almost always triggered by a sawtooth pulse (similar to I--H transition triggers). The ELMs are quite small in size with $\Delta T / T_{\text{ped}} \sim 5\text{–}10\%$, i.e. smaller than edge perturbations caused by the sawteeth. Stored energy loss from the ELM is small enough in magnitude so as to make its measurement difficult in the presence of sawtooth crashes. For the infrequent case of an ELM not triggered by a sawtooth crash we roughly estimate from magnetic and kinetic profiles: $\Delta W_{\text{ELM}} / W_{\text{th}} \sim 0.5\text{–}1.5\%$ and $\Delta W_{\text{ELM}} / W_{\text{ped}} \sim 2\text{–}3\%$. Given the pedestal collisionality $\nu_{\text{ped}}^* \sim 0.2$ in this case, we make a preliminary assessment that these belong to a ‘small’ ELM category as compared with normalized ELM energy loss from other devices [38]. Whatever their characteristics, these ELMs play a minimal role in regulating core particle or impurity content during I-mode. To date we have not identified a particular operational condition(s) that causes these infrequent ELMs; more often the I-mode phases are completely free of ELMs (e.g. figure 2).

The $T_e$ gradient scale-length ($L_e$) and the $n_e$ gradient scale-length ($L_n$), both evaluated at the symmetry point of the $T_e$ pedestal. The L-, I- and ELM-free H-mode results are from the I-mode campaign with $B \times \nabla B$ away from the X-point while the EDA results [37] use standard $B \times \nabla B$ towards the X-point. The $T_e$ gradient scale-length ($L_e$) and the $n_e$ gradient scale-length ($L_n$), both evaluated at the symmetry point of the $T_e$ pedestal. The L-, I- and ELM-free H-mode results are from the I-mode campaign with $B \times \nabla B$ away from the X-point while the EDA results [37] use standard $B \times \nabla B$ towards the X-point.
Figure 14. The ratio of density to temperature gradient scale-lengths $n_e$ evaluated at the symmetry location of the $T_e$ pedestal versus edge safety factor $q_{95}$. I-mode cases at low and standard $B_1$ field are with $B \times \nabla B$ away from the X-point except as noted. In I-mode $n_e$ appears to have a minimum value which depends on $q_{95}$ (dashed line). In comparison, $n_e$ in EDA and ELMy H-modes with standard $B \times \nabla B$ towards the X-point does not vary with $q_{95}$.

$n_e \sim 2-4$ for ELMy H-modes with no strong dependence on $q_{95}$. This clustering of $n_e$ has also been reported on ASDEX-Upgrade [40]. In contrast, I-mode discharges have a much higher of $n_e$, up to $\sim 60$, and show a consistent trend that the minimum observed $n_e$ decreases with increasing $q_{95}$ regardless of $B_1$ field or $\nabla B$ drift direction. This is another clear delineation of I-mode from H-mode, particularly at lower $q_{95} < 3.5$, and may have implications for the dominant turbulence mechanisms in I-mode.

3.5. I-mode edge pedestal: fluctuations

An important identifying aspect of I-mode involves edge fluctuations (section 3.1), and in particular a WCM which is found to be concurrent with I-mode. Table 1 contains the results of spectral analysis of magnetic and density fluctuations for sample discharges in two ranges of $q_{95}/I_p$.

The WCM is an electromagnetic mode which exists in the outboard pedestal region of I-mode plasmas. Based on the cutoff density, multi-frequency reflectometry locates the WCM between $r/a \sim 0.9-1.0$ (e.g. figure 3). GPI at $q_{95} \sim 3$ has also shown that the mode persists at least into $r/a \sim 0.9$, but does not exist outside the separatrix. Like the QC mode found in EDA H-mode [30], the mode propagates poloidally in the electron diamagnetic direction in the lab frame. The WCM propagates toroidally in the counter-current direction, consistent with a field-aligned $(k \cdot B = 0)$ mode. The relative frequency broadening of the time-averaged spectrum is much larger for the WCM $(\Delta f/\Delta f_{max} \sim 0.5)$ than for the QC mode $(\Delta f/\Delta f_{max} < 0.2)$ [30]. Analysis of the WCM indicates that the frequency at which the peak spectral magnitude occurs swings rapidly throughout the frequency band of the mode. This may indicate a set of coupled modes existing over a wide frequency range.

Table 1. Characteristics of the weakly coherent MHD edge feature in I-mode $(B \times \nabla B$ away from the X-point, $B_T \sim 5.6$ T). Sign conventions for $k$ and phase velocity $V_{ph}$: positive toroidal = positive $\phi$ propagation (counter-current, figure 1), positive poloidal = electron diamagnetic drift direction (vertically upward at the outer midplane, figure 1).

| Case      | High $q_{95}$ | Low $q_{95}$ |
|-----------|--------------|-------------|
| $q_{95}$  | 4.5-4.8      | 3-3.3       |
| $I_p$ (MA)| $\sim 0.8$   | $\sim 1.25$ |
| Magnetic fluctuations, $B_T$ | | |
| Peak frequency (kHz) | $\sim 120-150$ | $\sim 200-300$ |
| Peak FWHM (kHz) | $\sim 60$ | $\sim 80-100$ |
| $\kappa_{toroidal}$ (m$^{-1}$)/n | $\sim 12-15/8-10$ | $\sim 30-37/20-25$ |
| $V_{ph,toroidal}$ (km s$^{-1}$) | $\sim 75-110$ | $\sim 42-62$ |
| Density fluctuations–reflectometry/GPI/PCI | | |
| Peak frequency (kHz) | $\sim 100$ | $\sim 200-240$ |
| Peak FWHM (kHz) | $\sim 50$ | $\sim 80$ |
| $\kappa_{poloidal}$ (m$^{-1}$) | N/A/N/A/210$^a$ | N/A/N/A/210$^b$ |
| $V_{ph,poloidal}$ (km s$^{-1}$) | $\sim 3$ | $\sim 6-10$ |

$^a$ PCI $k_{pol} \sim k_{\sin(\pi/4)}$ based on poloidal angle of flux surface at PCI chord (figure 1).

Note. Shots: 1080415017, 1080416021, 1080416028, 1100204019.

Table 1 shows how the WCM characteristics change as $q_{95}$ is decreased from $q_{95} \sim 4.8$ to $q_{95} \sim 3$: peak frequency and width are increased, toroidal mode number $n$ doubles from 10 to $\sim 20$, and the poloidal phase velocity increases from $\sim 3$ to $\sim 8$ km s$^{-1}$. GPI and PCI measurements indicate the poloidal wavenumber on the outboard midplane, $n_{pol} \sim 150-200$ m$^{-1}$, does not change appreciably with $q_{95}$ which provides a rough estimate of $m/n \sim 6$ at $q_{95} \sim 4.8$ decreasing to $m/n \sim 3$ at $q_{95} \sim 3$, self-consistent with an edge mode at $r/a > 0.9$. The wavenumber of the WCM is of similar magnitude to that found for the QC-mode in EDA H-mode ($k_{pol} \sim 250-300$ m$^{-1}$ from PCI [30]). The WCM toroidal phase velocity $\sim 50$ km s$^{-1}$ is opposite in sign to, and substantially larger in absolute magnitude than, the pedestal’s typical I-mode co-current plasma toroidal velocity $\sim 10$ km s$^{-1}$ as measured with B$^{+6}$ CXRS [27], indicating that the WCM also has a high frequency in the plasma frame. Simultaneous measurements of poloidal phase and fluid velocity are not yet available.

Figure 15 highlights a discharge with several confinement mode transitions (at constant ICRF heating) and the corresponding behaviour of the magnetic and density fluctuations. The heat pulse from a sawtooth crash triggers all transitions to I-mode or H-mode. In I-mode, the WCM at $\sim 200$ kHz is present on both magnetic and density fluctuations, and is accompanied by a reduction in broadband fluctuation amplitude at frequencies between $\sim 50$ kHz and $\sim 150$ kHz as compared with L-mode. The WCM is immediately terminated, along with fluctuations at other frequencies, by a transition to ELM-free H-mode. The broadband fluctuation amplitude increases at the back-transition to L-mode at 0.97 s. The WCM appears simultaneously with the formation of the I-mode T pedestal triggered by the sawtooth. In some instances there is a slight upsweep in WCM frequency after the L–I transition. This is in contrast with the QC-mode which sweeps down in frequency at its onset, presumably due to Doppler shifts as the plasma rotation evolves after the L–H transition [30].

The brief transition to H-mode at 0.83 s for $\sim 15$ ms ($\sim 1/3 \tau_e$) and transition back to I-mode is illustrative. With the
disappearance of the WCM the density starts to increase with a slope similar to the longer ELM-free H-mode at 0.9 s. But the sudden recurrence of the WCM clamps any further increase in density in ~ millisecond timescale. This strongly suggests that the WCM is directly responsible for regulation of the density (fuel or impurities) and the presence of the WCM is the cause of L-mode-like particle transport in the edge plasma. Yet, like the QC-mode, the WCM is compatible with an H-mode-like T pedestal and thermal transport barrier.

4. Discussion

The study of I-mode has two important motivations: (1) understanding transport and threshold physics and (2) developing optimized operational scenarios.

 Pertaining to the first motivation, I-mode is a self-organized plasma state like H-mode, but one in which the energy and particle transport channels are clearly separated. This feature makes I-mode a valuable tool in exploring the underlying transport, as well as the physics associated with the transition to high confinement modes. The I-mode edge stability parameter ($\eta_e$) can span a very large range of values (figure 14) unlike H-mode. The fact that the minimum accessible $\eta_e$ has a strong $q_{95}$ dependence suggests that magnetic shear plays an important role in I-mode pedestal regulation. In addition, plasma shaping/triangularity is seen to have a significant effect on I-mode normalized performance, as it does in H-mode. In H-mode these dependences are understood to be due to the important role of shaping on edge stability (e.g. peeling–ballooning for ELM onset [6], kinetic ballooning for transport [41]). Yet I-mode lacks a density pedestal, which obviously has important consequences for edge pressure profiles and the resulting self-consistent edge bootstrap currents important for stability. Along with the lack of ELMs, these observations suggest that I-mode is exploring a somewhat different (and interesting) part of the edge stability space than standard H-mode. Like the QCM of EDA H-mode, I-mode has a short wavelength, edge MHD mode (WCM) that appears to regulate particle transport. However, the QCM favours high $q_{95}$ and collisionality, while the WCM can manifest at low $q_{95}$ and low collisionality. Taken together the observations above argue that I-mode has a different set of feedback mechanisms between the underlying turbulence, the profile/gradient plasma fields and accompanying MHD stability. The cross-correlation among the fluctuation fields is also likely to be different in I-mode in order to permit significant cross-field turbulent particle transport, yet highly suppressed energy transport, in a collisionless edge plasma.

Furthermore, the prevalence of I-mode with $B \times \nabla B$ pointed away from the X-point would seem to provide clues as to the long-standing mystery of higher threshold powers with that configuration. The I-mode simultaneously features a definite, but relatively weak, $E_x$ well in the pedestal [15] and rotation profiles that evolve in a different way than H-modes [27]. Previous C-Mod studies of SOL flows and core rotation have shown that strong transport-driven flows in ohmic plasmas are in opposite directions in the favourable and unfavourable configurations, thus modifying the boundary conditions for rotations in the confined plasma [42, 43]. Yet the I-mode threshold in power is very similar to that found for H-mode, while no particle barrier is formed. It seems valuable to use both the similarities and differences of I-mode versus H-mode to uncover the underlying mechanisms controlling transitions to high-energy confinement regimes.

Pertaining to the second motivation, I-mode exhibits operational scenario advantages that make it highly attractive. I-mode features a high temperature, low collisionality pedestal without ELMs, a condition which will be required in ITER and other future large scale fusion devices. I-mode simultaneously provides impurity and density control in an ICRF-heated high-Z wall tokamak without the requirement of immediately preceding boronizations. In addition, power handling in the divertor should be largely aided by a broader L-mode SOL profile (figure 3). The I-mode stored thermal energy increases nearly linearly with heating power. I-mode certainly...
exhibits its best absolute and normalized performance at low $Q_{95}$ and high heating power, which makes it generally attractive for high fusion power density scenarios ($P_{\text{heating}}/P_{\text{plasma}} \sim 0.25$ MW m$^{-2}$ in ITER [2], $P/S \sim 0.7$–1 MW m$^{-2}$ in C-Mod and reactors [3]). A possible difficulty in exploiting I-mode in ITER is that the high power generally required to trigger the L-I transition (figure 6). However, it should be noted that in several individual cases, the threshold power is within <25% of the standard H-mode threshold scaling. It seems premature to assess if ITER can access I-mode at this time. But expanding access to I-mode at lower power densities, with a variety of fuelling techniques and with other magnetic topologies, would be valuable in determining its general applicability as an operational regime.

5. Conclusions

An improved energy confinement regime, I-mode has been studied in the Alcator C-Mod tokamak. I-mode features an edge energy transport barrier without a strong accompanying particle barrier. To date I-mode has primarily been accessed in C-Mod with the following experimental conditions: upper-null topology with high upper triangularity and $B \times \nabla B$ pointed away from the primary X-point, on axis H(D)-minority ICRH plasma heating and divertor cryopumping for density control.

H-mode energy confinement is obtained without core impurity accumulation. As a result, I-mode has stationary and reduced impurity radiation as compared with H-modes previously obtained with a high-Z metal wall and ICRF heating. I-mode also features a stationary edge pedestal, which usually is completely free of ELMs. I-mode is a confinement regime that appears distinct from both L-mode and H-mode, both in its global performance and in its local pedestal and fluctuation characteristics.

Acknowledgment

This work was supported by the US DOE Cooperative Agreement DE-FC02-99ER54512.

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