Advances in physics and performance of the I-mode regime over an expanded operating space on Alcator C-Mod


Abstract. New results on the I-mode regime of operation on the Alcator C-Mod tokamak are reported. This ELM-free regime features high energy confinement and a steep temperature pedestal, while particle confinement remains at L-mode levels, giving stationary density and avoiding impurity accumulation. I-mode has now been obtained over nearly all of the magnetic fields and currents possible in this high field tokamak ($I_p 0.55-1.7$ MA, $BT 2.7-8$ T) using a configuration with $B \times \nabla B$ drift away from the X-point. Results at 8 T confirm that the L-I power threshold varies only weakly with $B_T$, and that the power range for I-mode increases with $B_T$; no 8 T discharges transitioned to H-mode. Core transport simulations are giving insight into the turbulence reduction and confinement improvement, while pedestal models explain the observed stability to ELMs, and are simulating the observed weakly coherent mode. I-modes have now been maintained in near-DN configurations, leading to improved divertor power flux sharing. Prospects for I-mode on future fusion devices such as ITER and ARC are encouraging. Further experiments on other tokamaks are needed to improve confidence in extrapolation.

1. Introduction

The I-mode confinement regime features an edge barrier in thermal confinement, similar to that in the H-mode (high confinement) regime, but without the particle transport barrier also present in H-mode discharges [1]. This combination leads to high energy confinement but low particle confinement, which is beneficial for fusion in several respects; accumulation of impurities and He ‘ash’ is avoided, and density can be more readily controlled. Importantly, I-modes are generally stable to Edge Localized Modes (ELMs), avoiding the transient heat pulses which it is now known would damage the divertor of ITER or other fusion devices, while maintaining steady density.

I-mode has been observed since the late 1990’s on Alcator C-Mod [2] and ASDEX Upgrade [3], and was initially termed ‘improved L-mode’, often a transient phase. It is most commonly and robustly accessed when the ion $B \times \nabla B$ drift is away from the active X-point, the so-called ‘unfavorable’ drift direction for H-mode. Its development as a stationary regime and recognition of its potential attractiveness for fusion scenarios have led to increasing interest and exploration in recent years. A multidevice study coordinated by ITPA has compared results on C-Mod, AUG and DIII-D, based on a joint data set assembled in 2014 and detailed measurements on each of the three tokamaks [4,5]. This shows that I-mode can be accessed over a very wide range of global and dimensionless parameters, including low $q_{95}$ and low collisionality. Features which are common to all three devices include the formation of an edge $T_e$ and $T_i$ pedestal, with L-mode density profiles, and changes in edge turbulence including a decrease in fluctuations across a mid-frequency range.
Both C-Mod and AUG have reported a Weakly Coherent Mode (WCM), at typically 150-250 and 120 kHz respectively, and a fluctuating flow at the frequency of Geodesic Acoustic Modes during I-mode [6,7,8,9].

We report at this conference on several new I-mode experiments which were conducted on C-Mod during the 2015 and 2016 campaigns, since the ITPA dataset was assembled. These aim to better understand the conditions to access and maintain the regime, and its performance, for improved confidence in its extrapolation. We have also begun to investigate the boundary heat flux in I-mode, a critical issue for any regime, and explore means of reducing it. Section 2 summarizes the expanded range of C-Mod parameters over which I-mode has now been accessed and discusses L-I and I-H threshold conditions. Notably, magnetic field $B_T$ has been varied from 2.8 to 8.0 T, revealing surprising dependences which lead to a wider operating window at higher $B_T$. Section 3 presents studies of core particle and energy confinement in the I-mode regime. New results on the physics of fluctuations and flows at I-mode transitions and in the pedestal, enabled by improved diagnostics and simulations, are summarized in Section 4. Divertor heat flux and its control, including first experiments with a near double null configuration are discussed in Section 5. In Section 6, we use these results to examine the prospects for extrapolation of I-mode to future burning plasma experiments, focusing on ITER and the high field demonstration fusion reactor Pilot plant design ARC [10]. Key issues and uncertainties are identified. Results are summarized, and future research on a range of devices to address these issues proposed, in Section 7.

2. Expanded parameter space for I-mode regime

Plasma discharges in the I-mode regime have now been produced on C-Mod over essentially all the magnetic fields and currents achievable on this high field, compact tokamak, $B_T$=2.7-7.8 T and $I_p$=0.55-1.7 MA, as shown in Figure 1; not all discharges from the most recent campaigns have yet been included in the dataset. In many cases, I-mode has been maintained, without transitions to H-mode, at the highest heating powers available, up to 5 MW ICRH with frequency 50-80 MHz. These results demonstrate the robust nature of the regime under appropriate conditions. This includes operating in a configuration with the $\mathbf{B} \cdot \nabla \mathbf{B}$ drift away from the active X-point; while there are a few examples with drift towards the X-point, all of the I-modes in this paper were accessed in this configuration, which is ‘unfavourable’ for H-mode.

An unexpected result, first presented at FEC 2014 [4], was that in contrast to the L-H threshold, the power required to access I-mode scales at most weakly with toroidal field; $P_{L-I}$ was essentially the same at 2.8 T as the more typical C-Mod operating range of 5-6 T. The upper limit of power for I-mode, set in many cases by I-H transitions, does increase with $B_T$, leading to a much wider power range in I-mode at higher field. Motivated by these results, and a few observations of transient I-modes in earlier 8 T experiments,
exploration of the I-mode regime in the 7.8-8T range was carried out in the 2015 and 2016 campaigns. At this field the D(He\(^3\)) ICRH scenario is used to heat the discharges. This has lower single pass absorption than the D(H) scenario most often used at lower fields, leading to overall heating efficiency which is reduced and more difficult to quantify accurately; analysis of threshold power and energy confinement is uncertain and results from these very recent experiments are preliminary. An example of an I-mode at 7.8 T, 1.35 MA, with 4.8 MW ICRH is shown in Figure 2. This shows the same characteristic features of lower field I-modes, namely increases in temperature and stored energy and the development of a strong T pedestal, with near constant density. The slow density rise is due to external fueling. Reduction of pedestal turbulence is seen in the range 50-200 kHz or higher, and an edge Weakly Coherent Mode appears. Typical WCM frequencies are higher at the increased field and current, 350 kHz in this example and up to 450 kHz at higher \(I_p\). Importantly, no transitions to H-mode were observed in any 7.8-8 T discharges, up to the maximum available RF power of 5 MW. This indicates that the power range for I-mode does further increase at higher field, and that performance could have been further improved with more input power.

\[P(n_e S) \approx B^{0.25}\]

An initial assessment of the power range is shown in Figure 3. In order to compare powers at different densities, based on earlier results of increasing P(L-I) with density [11], power is normalized to \(n_e\) and surface area \(S\); multidevice studies found at most a linear dependence on \(S\) [5]. \(P(L-I)\) has at most a weak dependence on magnetic field, \(\sim B^{0.25}\). As noted, different ICRH scenarios lead to significant uncertainties. We note that the scaling of I-H power with density is more complicated, and not yet well understood. Expected ranges of power for ITER and the high field reactor concept ARC [10] are shown for comparison, as discussed further in Section 6.
3. Particle and energy confinement in the I-mode regime

Perhaps the biggest advantage of the I-mode regime vs H-mode, in addition to the lack of ELMs, is the much lower particle confinement. Main species confinement appears essentially the same as L-mode, based on unchanged density profiles and little or no change in $D_{\alpha}$. More quantitative assessments have been made of impurity confinement time, using injected impurities from a Laser Blowoff Injection system and time resolved spectroscopic measurements of the decay time [12]. Figure 4 shows that $\tau_P$ (for Ca) is indeed at the levels of L-mode, and well below that of even EDA H-mode which is a relatively low particle confinement H-mode regime. $\tau_P$ for Mo is very similar. This is important since accumulation of high Z impurities, a known serious issue for H-modes with metal PFCs [13], is avoided. Frequent boronization, essential for high confinement H-modes on C-Mod, is not needed or used for I-mode experiments.

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**FIG. 4.** Particle confinement time of injected Ca, vs normalized energy confinement time $H_{98,y,2}$ for a subset of C-Mod L, I and EDA H-mode discharges.

Fig 4 also shows that the normalized energy confinement $\tau_E$ is significantly higher than L-mode and comparable to EDA H-mode; $H_{98,y,2}$ often exceeds 1.0. The range of values indicates however that the $\tau_E$ scaling is somewhat different than $\tau_{98,y,2}$. One important difference is that degradation with input power is much weaker; stored energy continues to increase near linearly with input power as shown in Figure 5. $\tau_{98,y,2}$, in contrast, scales as $P^{-0.7}$, so that $H_{98}$ values in I-mode increase with input power. Given that I-mode is a distinct confinement regime, it is likely that other dependences (eg on density, current, field) are also somewhat different. An initial regression on a large I-mode dataset gave $\tau_{E,\text{mode}} = I_p^{0.66} B_r^{0.77} n_e^{0.02} P_L^{-0.29}$ [14]. However, given the variations in power to access the I-mode, it is possible that correlations between these parameters (eg, power and field) bias these results. Very recent experiments have been conducted to separately scan each parameter, as well as key dimensionless parameters, and determine the $\tau_E$ dependence. Preliminary analysis indicates some differences from the regression fit; further analysis is in progress. Data from tokamaks of different sizes and parameters are required to determine scaling with R and a and enable a robust scaling which can be extrapolated to other and future devices; such a database activity is planned through the ITPA.
We are also investigating core turbulence and transport in I-mode, comparing to L-mode and H-mode and to simulations. Linear gyrokinetic simulations find that ITG is dominant in both L-mode and I-mode, across the bulk of the core plasma, with little to no change in the growth rate across the transition (Figure 6). The observations of 30-70% reductions of long-wavelength core turbulence fluctuation levels in I-mode compared to L-mode [15] and the reduction of core electron thermal diffusivity, by about a factor of two, are at odds with these calculations that indicate no change in linear ITG stability. Recent results from nonlinear GYRO simulations and new measurements of the incremental electron thermal diffusivity [16,17] suggest that high-k electron-scale ETG turbulence is important in the core of I-mode plasmas. In addition, the nonlinear gyrokinetic simulations suggest that the effects of ExB shear of suppression of the ITG mode are more pronounced in the I-mode than in L-mode. These results can help to unify the observed changes in core turbulence and transport, but more detailed core transport validation studies are needed to better understand the changes in transport, including the particle transport, which is currently under active investigation using turbulence transport models.

4. Pedestal and transition physics

Given the core profile stiffness, the pedestal in I-mode, as in H-mode, is critical to determining the improved core confinement. Steep temperature pedestals form at the L-I transition in both T_e and T_i. Consistent with, and likely causing, the stored energy increase, T_{ped} also increases near linearly with input power and can be over 1 keV at high current and power, which is higher than typical for steady H-modes on C-Mod. Pedestal widths, however, are somewhat larger than in H-modes [6]. This, combined with the lack of an increased density pedestal, gives lower pressure gradients for given T_{ped}. Stability analysis using ELITE shows the pedestal to be well below the peeling-ballooning stability boundary, even considering transient steepening due to sawtooth heat pulses. This is consistent with the lack of saturation in pedestal and global pressure, and with the absence of ELMs which is one of the key benefits of the I-mode vs ELMy regime. With sufficient power, it is possible to further increase pedestal pressure. Pedestals are also away from expected Kinetic Ballooning Mode (KBH) thresholds.

Good progress is also being made on understanding the pedestal physics of the I-mode regime, through detailed measurements of fluctuations and flows and using simulations. Gas Puff Imaging (GPI) measurements show that both a GAM and a broad high frequency fluctuation termed the Weakly Coherent mode are present [6]. The two modes interact strongly, with the GAM apparently helping to broaden the WCM spectrum. Recent observations on AUG are consistent [9]. Simulations with BOUT++ show I-mode pedestals are unstable to Drift Alfven waves and resistive ballooning modes. Nonlinear BOUT++ predictions are in agreement with many observed features of the WCM [18,19]. GPI has
also shown that transfer of energy from turbulence to zonal flows is a key component in transitions to H-mode [20]. A key new result is that the transfer rate varies with ion \( \mathbf{B} \times \nabla \mathbf{B} \) drift direction, which may help explain the window for I-mode [21].

5. Divertor heat flux and power handling

Perhaps the greatest challenge for future fusion devices, in any transport regime, is integration with divertor solutions. While elimination of transients due to ELMs and lack of impurity accumulation with I-mode are major advantages, stationary SOL heat flux can still be high. When operating in configurations with ion \( \mathbf{B} \times \nabla \mathbf{B} \) drift away from the active X-point, heat flux tends to be largest on the inner divertor leg [22]. Recent experiments have explored the response to changing \( \Delta R_{sep} \), the difference between upper and lower X-points when mapped to the outer midplane. For operation with reversed \( B_T \) and \( I_p \), negative \( \Delta R_{sep} \) corresponds to drifts away from the X-point. It was found that \( \Delta R_{sep} \leq -3 \text{ mm} \) was required to reliably produce L-I (instead of L-H) transitions. However once I-mode is accessed, it is possible to maintain the regime in near-DN configurations, with \( \Delta R_{sep} \) as small as -1 mm; higher values resulted in or I-L transitions I-H. H-modes following such transitions tend to have exceptionally high confinement, with \( H_{98} \) often > 2, but are ELM-free and transient, accumulating impurities. An example of a steady I-mode with \( \Delta R_{sep} = -2.5 \text{ mm} \) is shown in Figure 7.

In these near-DN configurations, the in-out balance of integrated thermal flux shifts predominantly to the outer legs. As \( \Delta R_{sep} \) approaches zero, the up-down balance becomes more evenly shared; at \( \Delta R_{sep} = -1 \text{ mm} \) approximately 60% of the power flux is on the lower outer leg and 30% on the upper, with the remaining 10% on the inner strike points. This more even sharing, compared to larger \( \Delta R_{sep} \), would reduce the peak heat flux. The challenge is, however, likely to remain great. While low Z impurity seeding (N\(_2\) or Ne) has been demonstrated to reduce heat flux and divertor temperatures, experiments have not yet succeeded in obtaining divertor detachment without an I-L transition. Advanced divertor concepts which can attain a stable X-point detached divertor condition while not affecting pedestal conditions are likely to be required in any fusion reactor. In this regard, recent analysis of the performance of long leg divertor concepts, in particular an ‘x-point target’ configuration, compared to conventional divertors is very promising and may provide a viable path forward for a reactor [23].

6. Extrapolation to future fusion devices

In many respects I-mode, with its low particle confinement, high energy confinement and lack of ELMs, is the ideal regime for a fusion reactor, if it can be obtained robustly in the needed conditions, and sustained without transitions to H-mode or L-mode. The C-Mod team has thus been exploring prospects for extrapolation to larger fusion devices, including ITER.
Scaling C-Mod values of $P_{\text{loss}}/n$, which are also consistent with thresholds on AUG and DIII-D at ~2 T [5], we predict ITER would need about 70 MW to enter I-mode at low density. If I-mode is accessed, it should be possible to remain in I-mode without transition to H-mode and to produce high fusion power, provided that density can be sufficiently increased; fueling during I-modes has been demonstrated on C-Mod. Accessibility for compact, high B fusion reactors such as ARC [10] is even more favorable. The expected parameter ranges for ITER and ARC are indicated on Figure 3 and lie within the operating window for I-mode on C-Mod. Further experiments on other devices are required to confirm the size and parameter scalings for I-mode, as discussed below.

7. Conclusions and needs for future research

The I-mode regime of confinement has now been established on Alcator C-Mod as extremely robust and reliable. In recent campaigns a significant fraction of our operation has been in this regime, with I-modes established over nearly all of the magnetic fields and currents possible in C-Mod ($I_p$ 0.55-1.7 MA, $B_T$ 2.7-8 T) using a configuration with $B \times \nabla B$ drift away from the X-point. The power range for maintaining I-mode increases with magnetic field. While at 2.8 T small increases in power lead to I-H transitions, many discharges at 5-6 T remain in I-mode at our maximum heating of 5 MW ICRF, and at 8 T no transitions to H-mode have been observed in this configuration. Particle confinement is at L-mode levels, leading to steady conditions without impurity accumulation in this metal walled device. In contrast to H-mode, frequent boronization is not required to obtain steady conditions and $q_{95}$ can be as low as 2.4. These features make I-mode an attractive regime for future devices. Energy confinement is generally high, and can exceed H-mode scalings. Importantly, $\tau_E$ does not degrade strongly with input power. Parameter scans have recently been conducted which should enable a new I-mode confinement scaling to be established for extrapolation to future devices. It will be important to include results from other tokamaks to confirm parameter scalings and to establish a size scaling; I-modes on large devices such as JET will be particularly valuable. An I-mode database is planned as an ITPA activity, following up on recent multidevice studies [5]. Similarly, multi-device studies of L-I and I-H threshold conditions are needed to confirm conditions for access; the I-H transition is complex and has interrelated dependencies on both power and density.

Good progress has also been made in documenting and understanding pedestal and core transport physics at the transitions between regimes, and in the I-mode, using detailed profile, turbulence and flow diagnostics. Pedestals are found to be robustly stable to peeling-ballooning modes, consistent with the observed lack of ELMs which is another highly attractive feature of the regime. Both a broad, high frequency ‘weakly coherent mode’ and a GAM fluctuation coexist in the pedestal and exchange energy [7]. Nonlinear simulations of an I-Mode pedestal with BOUT++ reproduce many features of the WCM [19]. Very consistent results are observed on ASDEX-Upgrade [9], and it will be important to study this complex physics, on other tokamaks and using multiple simulation codes; collaborative efforts in both regards are planned. The I-mode regime provides an interesting test of core transport models, with observed and modelled stiffness similar to the H-mode regime and a reduction in core turbulence. More work is needed for a complete picture of particle transport; simulations for other tokamaks with different parameters would again be valuable.

Another important challenge is understanding and ameliorating the divertor heat flux in the I-mode regime. Here the lack of ELMs, which eliminates transient heat pulses, is an advantage over H-mode, and the recent demonstration of I-modes in near-balanced
configuration enables better sharing of power fluxes. Further work is needed on seeding and detachment. Simulations of integration of I-mode with advanced divertors are promising.

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