Transport phenomena in Alcator C-Mod H-modes

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Abstract. Several interesting new results have come from studies of ICRF-heated, H-mode plasmas in Alcator C-Mod. Dimensionless scaling studies have found gyro-Bohm-like transport similar to that reported on other devices; however, the dependence on collisionality was surprisingly strong, with $B\tau_E \sim \nu^{*-1}$. Despite high edge temperatures and strong edge pressure gradients, type I edge-localized modes (ELMs) are not observed in C-Mod. Instead we obtain a regime that we have dubbed enhanced Dα (EDA) which is accompanied by high-frequency density fluctuations. For all H-modes, core gradients were found to increase linearly with edge temperature, suggesting the importance of critical gradient/marginal stability behaviour. Comparisons with the IFS-PPPL model have begun, showing quantitative agreement in some cases. Impurity particle transport was studied via the laser blow-off technique with impurity confinement found to be effectively infinite for ELM-free discharges but reduced into the range 0.1–0.2 s for the EDA plasmas.

1. Introduction

Previous work [1, 2] has reported on heating and confinement experiments on C-Mod H-modes. The C-Mod device is somewhat unique in several respects. First, as a compact high-field device, it typically runs at high densities where $T_i \sim T_e$ and where fast-ion content is minimal. Second, its only auxiliary heating scheme is ion-cyclotron resonance heating (ICRH), while most machines report results with neutral beam injection (NBI). Finally, all plasma facing components are made of the refractory metal molybdenum overcoated with boron. Energy confinement in the H-mode is typically about 2 times that of the L-mode and somewhat greater than that predicted by scaling laws derived using data from other devices [1]. Experiments described here were carried out with B_T from 2.6–8 T, I_P from 0.4–1.2 MA, n_e from 2–4 $\times 10^{20}$ m^{-3}, κ from 1.5–1.8, and input power from 1.7–3.5 MW.

We have observed a promising regime which evolves out of ELM-free discharges and is characterzied by high levels of Dα light, good energy confinement and moderate particle confinement [1, 2]. Because of the uncertainty over the relationship of this mode to ELM behaviour, we use the term enhanced Dα (EDA) to describe it. Edge temperature pedestals typically are slightly smaller than in ELM-free discharges, resulting in slightly reduced energy confinement. No type I ELMs have been observed so far on C-Mod, although the edge temperature can be high, 600–800 eV, and the edge β can reach 0.5% with pressure gradient lengths in the range 3–8 mm. The EDA is characterized by increased density fluctuations in the barrier region [3, 4]. These are broadband, extending to at least 400 kHz with a quasi-coherent feature which can appear anywhere from 60–130 kHz. Impurity particle confinement, τ_I, in ELMy/EDA plasmas is in the range 0.15–0.2 s, roughly

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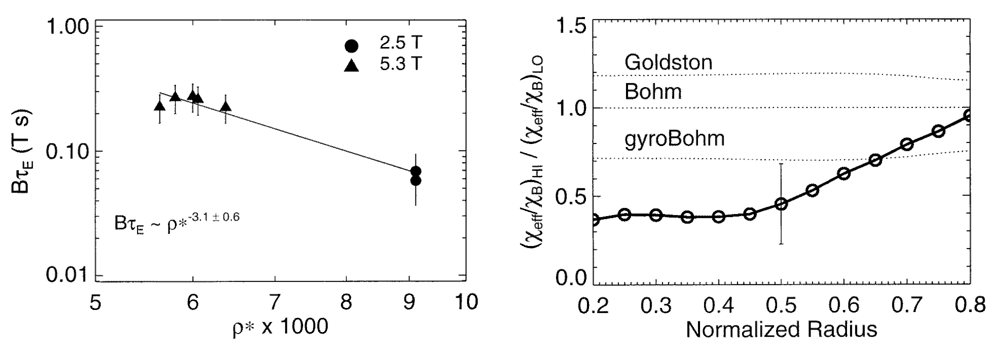
2–3 × τ_E, unlike ELM-free plasmas where $\tau_I > 0.5$ s. Analysis of impurity profile evolution following injection of trace amounts of scandium by the laser blow-off technique can yield estimates of the transport coefficients. Compared to L-mode plasmas, in the H-mode these are characterized by lower diffusivity in the core, and a transport barrier with very low diffusivity and a strong inward pinch in the plasma edge. Barrier diffusivity is higher and the pinch weaker for ELMy/EDA discharges than for ELM-free discharges. This difference may be the result of additional turbulence, which is observed as density fluctuations, seen during the EDA discharge as described above.

2. Dimensionless scaling

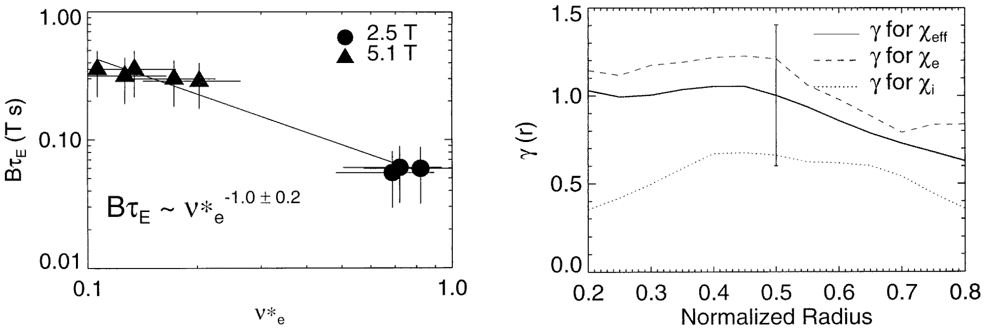
The difficulties encountered with traditional empirical scaling methods have encouraged several groups to begin systematic investigations into the dimensionless scaling of plasma transport [5, 6]. This approach offers the possibility of straightforward extrapolation to reactor regimes and at least a tenuous connection with the underlying physics [7]. On C-Mod, experiments were carried out to determine the scaling of the normalized confinement time, $B\tau_E$, and normalized thermal diffusivity, $\chi/\chi_{\mathrm{Bohm}}$, with ρ^* and ν^* [8]. With a fixed ICRH frequency of 80 MHz, these experiments compared deuterium discharges heated via the first harmonic hydrogen minority at 5.3 T to those heated at the second harmonic hydrogen minority at 2.6 T. In the first set of experiments, heating power, plasma current and density were adjusted to match the profiles for q, β, and ν^* while varying ρ^* by a factor of about 1.6. Further experiments matched β and ρ^* while varying ν^* by almost an order of magnitude.

The results of the ρ^* scans can be seen in figure 1. Global scaling was observed to be gyro-Bohm like; that is, $B\tau_E$ was found to be proportional to $\rho^{*-3.1}$ where Bohm scaling would imply $B\tau_E \sim \rho^{*-2}$. The error in the ρ^* coefficient was estimated conservatively to be ±0.6. Figure 1(b) shows the results of local analysis of a pair of shots from the same data set. In this case, the ratio of normalized thermal diffusivity between a high-field discharge and a low-field discharge are plotted. Again, the results are consistent with gyro-Bohm



(a) (b)

Figure 1. Results of normalized gyroradius, ρ^* scans with q_{95}, β (normalized plasma pressure), and ν^* (normalized collisionality) fixed. (a) Global scaling, showing the normalized energy confinement $B\tau$ against gyroradius, ρ^*; (b) local scaling showing the ratios of normalized diffusivity, $\chi/\chi_{\mathrm{Bohm}}$, between high-field (low-ρ^*) and low-field (high-ρ^*) plasmas. Expectations of different types of scaling are shown by the dotted curves [5]. Both local and global analysis show approximately gyro-Bohm-like scaling.



(a) (b)

Figure 2. Results of ν^* scans with q_{95}, β, and ρ^* fixed. (a) Global scaling, showing $B\tau$ against ν^*; (b) local scaling, showing the local exponent, γ, defined by $\chi \sim \chi_{\mathrm{Bohm}}\nu^{*\gamma}$. Approximately linear dependence is seen in both cases.

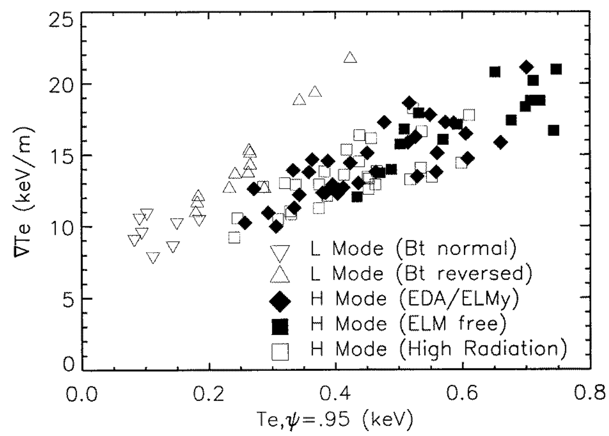


Figure 3. The average core T_e gradient is plotted against edge temperature (measured at the 95% flux surface). The core gradient is defined as the average gradient between the outer edge of the sawtooth region and the top of the H-mode pedestal.

scaling across most of the profile. Errors in this measurement are large and separation of the ion and electron channels is probably not statistically significant. These results are similar to those reported in [3, 4]. Surprisingly, even with all three experiments, C-Mod, DIII-D, and JET, showing gyro-Bohm scaling, scaling between these machines gives a result closer to Bohm [1]. The results of the collisionality scans, shown in figure 2, showed a surprisingly strong dependence. Both global and local analysis gave approximately a linear dependence on ν^*.

3. Critical gradient/marginal stability behaviour

Edge temperature and core confinement are tightly correlated [1] and L- and H-modes in C-Mod over a wide variety of regimes including ELM-free, and ELMy/EDA H-modes, ordinary L-modes, and 'enhanced' L-modes which are achieved by strong heating of reversed field plasmas. This result is summarized in figure 3 where the core electron temperature gradient is plotted against the pedestal temperature, demonstrating that the improved con-

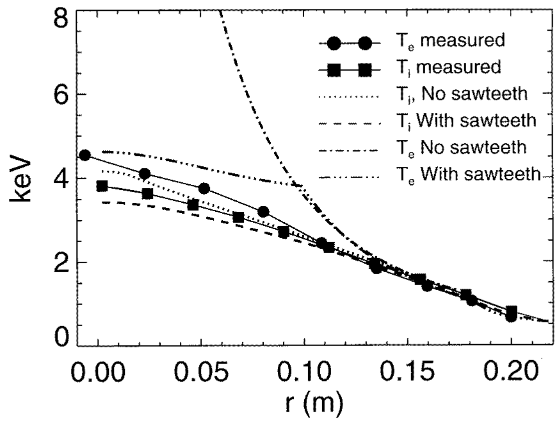


Figure 4. Comparison between experimental data and predictions of the IFS-PPPL model. Predictions both with and without an *ad hoc* sawtooth model are shown. Agreement is fairly good for H-modes in C-Mod.

finement is not merely the result of adding a temperature and density pedestal to an L-mode discharge. Here, the core gradient is defined as an average over the region outside the sawteeth and inside the edge transport barrier. This behaviour is qualitatively consistent with critical gradient transport models (for example, ion thermal gradient (ITG) turbulence).

Figure 4 shows the result of a simulation from a prominent implementation of ITG theory, the IFS-PPPL model [9], plotted against experimental data. The model gives fairly good agreement for ion temperatures in C-Mod H-modes (although it consistently under-predicts T_i in the L-mode) [8]. The electron temperature often overpredicted as shown in the figure. There are a number of possible reasons for this. First, the code, which is used for the simulations, does not have a sawtooth model and sawteeth are very strong in C-Mod discharges. The result of adding an *ad hoc* sawtooth mixing model to the simulation substantially reduces the discrepancy as shown in the figure. Second, the model only includes effects on the electrons from the ITG mode and additional mechanisms for electron transport may be present. Finally, it is worth noting that the C-Mod collisionality falls outside the range of validly assumed [9].

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