Power requirements for high performance H-modes in Alcator C-Mod

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The power requirements for access to the H-mode regime and the dependence of these requirements on global plasma parameters such as plasma density and toroidal field have been the subject of extensive experimental studies on multiple tokamaks, due to the requirement for H-mode operation in ITER. On the other hand, the power required to maintain suitably high confinement (*i.e.*, normalized energy confinement time $H_{98(y,2)} \geq 1$) in the resulting H-mode and its relation to the H-mode threshold power P_{th} have been studied sparsely, and mainly on one device [1]. This question is of critical importance to ITER, since present estimates [2] of the edge power flow required to access H-mode indicate it is only marginally lower than that expected for H-mode plasmas in ITER. This is the case both for alpha-dominated plasmas during Q_{DT}=10 operation and for the earlier, non-activated phase, in which experimental strategies for controlling Type I edge localized modes (ELMs) must be developed. In order to better characterize power requirements for high performance, recent experiments on the Alcator C-Mod tokamak have investigated H-mode properties, including the edge pedestal, edge relaxation mechanisms and global confinement, at power levels both marginal to H-mode access and well in excess of the threshold. We have examined the compatibility of impurity seeding with high performance operation, and the influence of plasma radiation and its spatial distribution on performance. This addresses the potential for mitigating high divertor heat fluxes in H-mode, another crucial issue for ITER operation [3]. Initial results of these experiments are described below and in [4].

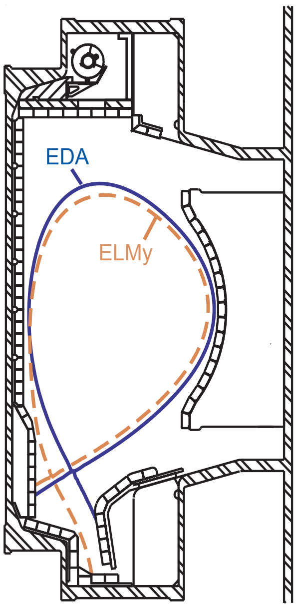

Figure 1: Examples of equilibria used to obtain EDA (blue solid) and ELMy (orange dashed) H-modes

Alcator C-Mod typically operates at or near the ITER magnetic field and at ITER relevant densities, employs bulk metal plasma facing surfaces (Mo), and chiefly uses ion cyclotron range of frequencies (ICRF) waves for auxiliary heating [5]. Two classes of ICRF-heated H-modes at B_T=5.4T with $3.9<q_{95}<4.1$ were used in these experiments. The first consisted of stationary enhanced D_α (EDA) H-modes with no large ELMs, with line-averaged density $\bar{n}_e$ in the range of 2.5—3.0x10^{20} m^{-3}. These were run in a conventionally shaped equilibrium for C-Mod, shown in Fig. 1. The second class comprised ELMy H-modes with $\bar{n}_e$ of 1.7—2.4x10^{20} m^{-3} and run using an atypical equilibrium with high lower triangularity (see Fig. 1), which is known to promote access to ELMy H-mode [6]. Scans of loss power $P_{in}=P_{oh}+P_{ICRF}–dW_P/dt$ were made in each case in order to correlate core power with pedestal and confinement qualities. Using bolometric measurements of core and total radiated power, as well as inferences of outer divertor heat flux from IR measurements, correlations are also possible with (1) power flowing into the scrape-off layer $P_{net}=P_{loss}-P_{rad,core}$ and (2) power to the outer divertor $P_{o\text{-}div}$.

Figure 2 shows that in both EDA and ELMy H-mode, energy confinement can be very good, with $H_{98(y,2)}$ generally near or above unity, provided sufficient heating power is available and core radiated power is sufficiently low, *i.e.* when $P_{rad}/P_{loss}<0.4$. If the scaling law used to project L-H threshold power, P_{th}, to ITER [2] is here used to normalize power, then $H_{98}>1$ is favored by $P_{loss}/P_{th}>1.5$ or $P_{net}/P_{th}>1.0$. As seen in the panels in Fig. 2, the H_{98} in each H-mode regime (EDA or ELMy) is well correlated to P_{net}, rather than P_{loss}, indicating that power flow into the SOL is indeed the correct physical metric for setting global confinement, as is assumed for ITER. Furthermore, Fig. 2(d) shows that dividing P_{net} by the concurrent L-H threshold scaling law value, P_{th}, provides a useful organization of all the H-mode data. This does not imply that the L-H threshold physics is important to determining the H-mode confinement; it is likely that the normalization is effectively accounting for the systematic difference in

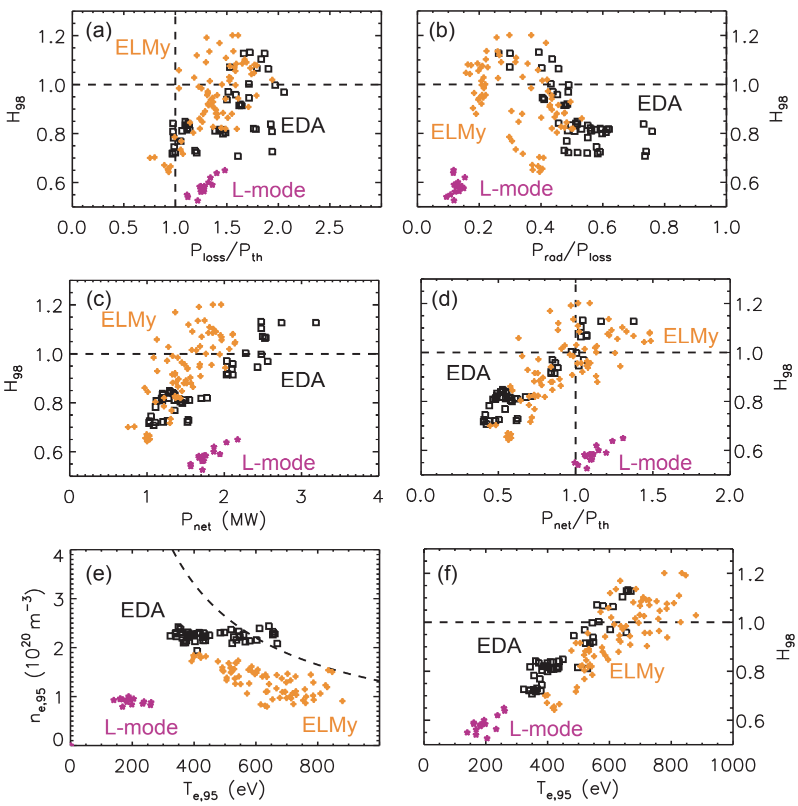

Figure 2: Confinement in L-mode and EDA, ELMy H-modes with intrinsic impurity content only, as a function of (a) P_{loss}/P_{th}, (b) P_{rad}/P_{loss}, (c) P_{net}, (d) P_{net}/P_{th} and (f) pedestal T_e. Pedestal n_e and T_e are shown in (e).

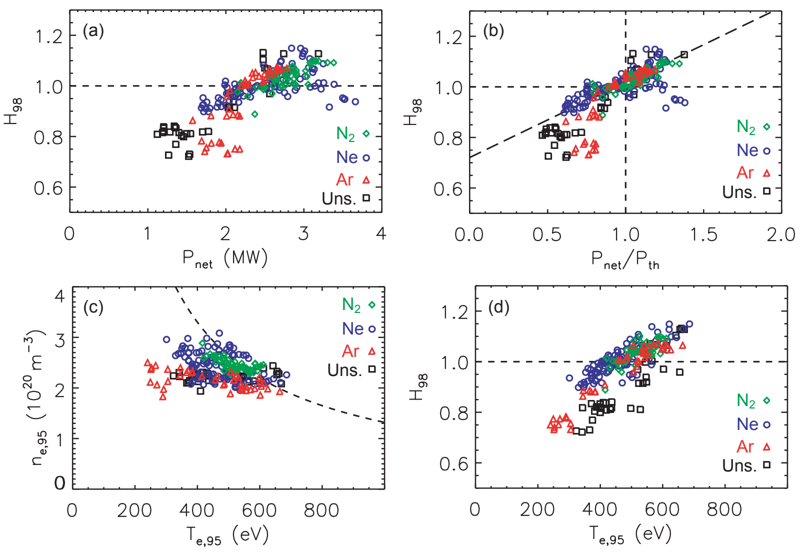

Figure 3. Confinement in EDA H-modes with intrinsic impurity content only (black) and seeded with Ar (red), Ne (blue) and N_2 (green), as a function of (a) P_{net}, (b) P_{net}/P_{th} and (d) pedestal T_e. Pedestal n_e and T_e are shown in (c). All cases shown have $n_{e,sep}$<1.7×10^{20}m^{-3}.

density observed between EDA and ELMy H-modes at otherwise similar plasma parameters [Fig. 2(e)]. Also noteworthy in these results are the tendency of the P_{th} scaling law to underpredict the L-H power in this experiment [Figs. 2(a,d)] and the significant power hysteresis [7] evident in the L-H-L cycle. As P_{net} is reduced to levels approaching that in L-mode, pedestal temperature diminishes significantly and normalized confinement time drops. These changes appear to happen continuously, and, while Type III ELMs and dithering can be observed in the most weakly powered H-modes, this is observed in a relatively narrow window in P_{loss}/P_{th}, in both EDA and ELMy H-modes.

The above trends remain generally valid in cases in which EDA H-modes underwent controlled impurity seeding, with Ar, Ne and N_2 [4]. A pleasing result is that with seeding, core intrinsic Mo concentration is mostly unaffected despite the expected increase in sputtering of plasma facing components. The data in Fig. 3 show that, provided sufficient P_{net} is available, H_{98} can be maintained at or above unity, just as in the unseeded cases. Much as in the comparison between EDA and ELMy H-mode above, systematic differences in H_{98} at a given P_{net} can be somewhat resolved by normalizing to the P_{th} scaling law [Fig. 3(b)]. The clear trends of confinement with edge temperature shown in Figs. 2(f) and 3(d) suggest that in all cases, the edge pedestal is the most significant lever on global confinement, consistent with the common expectation of

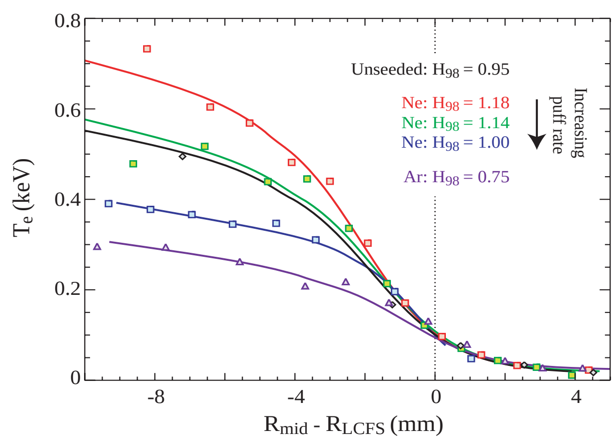

Figure 4. Examples of temperature pedestals with and without impurity seeding from Ne and Ar.

stiff core temperature profiles [8]. Examples of edge T_e profiles in both unseeded and seeded H-modes are shown in Fig. 4.

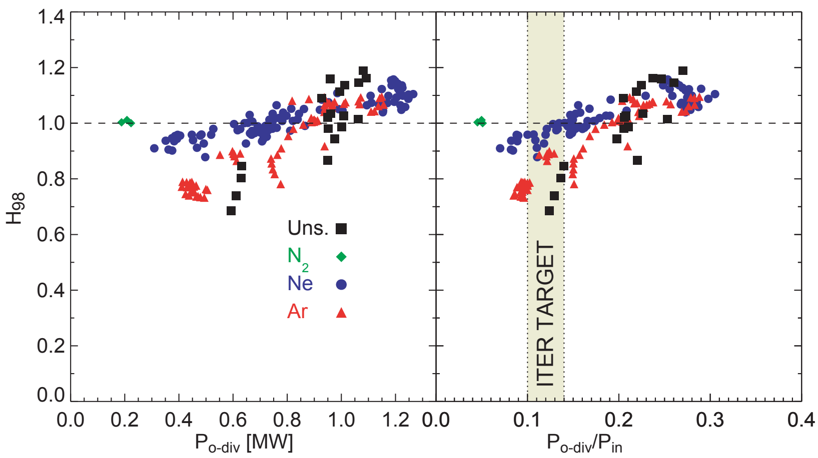

Figure 5: Low-Z impurity seeding of EDA H-modes demonstrates the capability to reduce power to the outer divertor by a substantial factor, while maintaining H_{98}~1

When using low-Z impurities, a substantial reduction in divertor heat flux is possible without a significant degradation in energy confinement. This is most easily realized in EDA H-modes, as described above, with 4—5MW of ICRF heating. When seeding these H-modes with Ne or N_2 via a main-chamber gas puff, the total radiative power loss can be increased by a factor of two, with reduction of power to the outer divertor by a similar factor, all while maintaining H_{98} ~ 1.0—1.1. By contrast, when Ar is used to increase the total radiation to comparable levels, confinement degrades to H_{98} ~ 0.75. Measured radiation profiles show variation with impurity species in P_{rad} contributions from the core, edge and divertor regions. Approximately 25% more power is lost inside the LCFS for Ar seeded plasmas compared to Ne and N_2, and the Ne and N_2 emissivity profiles are hollow relative to those employing Ar seeding [4].

This research provides increased confidence that the power flow across the separatrix is the correct physics basis for ITER extrapolation. Furthermore, it provides a demonstration that substantial fractions of input power can be radiated effectively in the SOL/divertor with no degradation of core confinement, as desired for ITER. Especially striking is the fact that many of the H-modes with highest performance on C-Mod (H_{98} up to ~1.2) are those that take advantage of impurity seeding.

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