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Plasma Current and Toroidal Field Dependence of the H-mode Threshold Low Density Limit on Alcator C-Mod

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Introduction A number of devices have observed that the power required to access the H-mode increases sharply, up to several times the global H-mode threshold scaling predicted by the ITPA H-mode threshold database group [1,2], when the density is reduced below a certain minimum density. On DIII-D, ASDEX-Upgrade, JET, and JT-60U, this minimum density occurs around $\bar{n}_e \sim 0.25 \times 10^{20}$ m^{-3}, but on Alcator C-Mod, operating at approximately the ITER toroidal field, the minimum density occurs between 0.8 – 1.0 × 10^{20} m^{-3}[3]. Since ITER intends to operate with an L-mode target density of 0.5 × 10^{20} m^{-3}, it is imperative to understand how this low density limit will scale to ITER. If the low density limit in ITER is like that of C-Mod, ITER will need much more input power to achieve H-mode at the prescribed density than is currently planned to be installed. This is a high priority joint ITPA experiment. Three such experiments with a standard C-Mod plasma shape ($\kappa \sim 1.6$, $\langle\delta\rangle \sim 0.4$) and lower single null with the ion ∇B drift toward the X-point were performed during the last campaign on C-Mod.

Plasma Current Dependence The first set of experiments to determine the dependence of the low density limit of the H-mode threshold on plasma parameters was a plasma current scan at B_T = 5.4 T with hydrogen minority ICRF heating of deuterium plasmas at 78 and 80 MHz. The plasma current was scanned from 0.6 MA to 0.9 MA to 1.2 MA. At each current, the density was scanned from shot-to-shot over a range from $0.7 < \bar{n}_e < 1.5 \times 10^{20}$ m^{-3} and the ICRF power was ramped from typically 0.5 MW up to 2.5 MW to look for the H-mode threshold power. The idea of the experiment was to determine if the low density limit to the H-mode threshold scaled with a fraction of the Greenwald density limit. If the low density limit were a fraction of the Greenwald limit, then that could provide a normalization across machines and the extrapolation to ITER would imply that the low density limit would be well below the L-mode target density.

Figure 1 shows the results of the plasma current scan where the total input power minus the time rate of change of the plasma stored energy (P_{in} – dW/dt) normalized to the latest ITPA H-mode threshold scaling expression ($P_{th} = 0.049 n_e^{0.72} B_T^{0.80} S^{0.94}$) [4] is

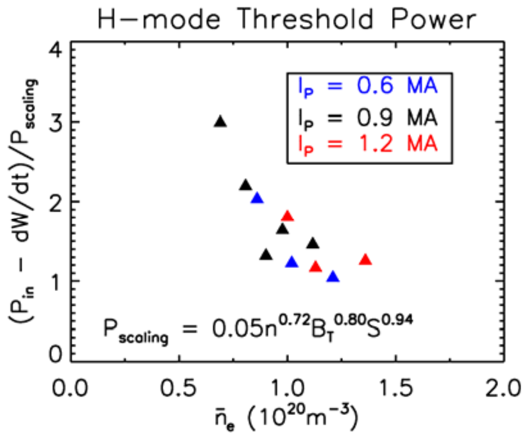

Fig. 1. Normalized H-mode threshold power vs line averaged density for a plasma current scan showing that the low density limit does not change.

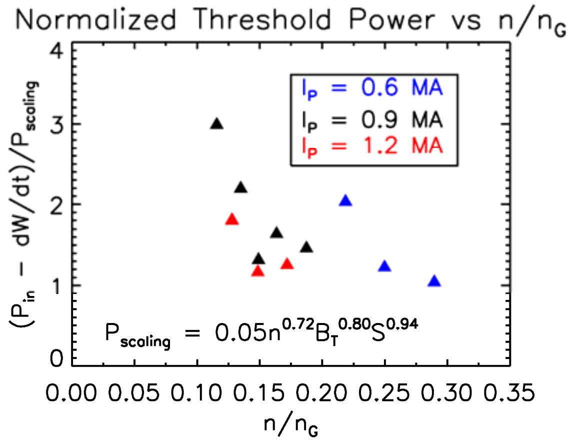

Fig. 2. Normalized H-mode threshold power vs the line averaged density normalized to the Greenwald limit showing that the low density limit does not scale with n/n_G .

plotted versus the line averaged density taken just before the first L-H transition. The data from the three different plasma currents overlay indicating that the density at the minimum threshold power at B_T = 5.4 T is about $\bar{n}_e \sim 1 \times 10^{20}$ m^{-3} independent of the plasma current. If the total radiated power from the main plasma is subtracted from the input power, the points drop somewhat but the trend remains the same.

Figure 2 shows the same data as in Fig. 1 plotted versus the line averaged density normalized to the Greenwald density limit ($n_G = I_p / (\pi a^2)$). The separation of the data with different plasma currents clearly shows that the density at the minimum threshold power does not scale with the Greenwald limit.

Toroidal Field Dependence To assess the toroidal field dependence of the density at the minimum threshold power, data were compared with only Ohmic heating at 5.3 T, 3.0 T, and 2.2 T and with ICRF hydrogen minority heating at 50 MHz and 3.3 T and 80 MHz at 5.4 T. The Ohmic data includes $2.8 < q_{95} < 4$ and the ICRF data includes $3 < q_{95} < 6.2$. The density was scanned from shot-to-shot from intermediate densities down to as low as H-mode was achievable with the power available.

Figure 3 shows the normalized threshold power versus the line averaged density for all of these toroidal field scans. Ohmic H-modes at 5.3 T (cyan) were not achieved below $\bar{n}_e < 0.9 \times 10^{20}$ m^{-3} and the density for the minimum threshold is ~ 1×10^{20} m^{-3}. At 3.0 T (green), Ohmic H-modes were achieved down to $\bar{n}_e = 0.5 \times 10^{20}$ m^{-3} with a density for the minimum threshold of about 0.6×10^{20} m^{-3}. At 2.2 T (black), the density for the minimum

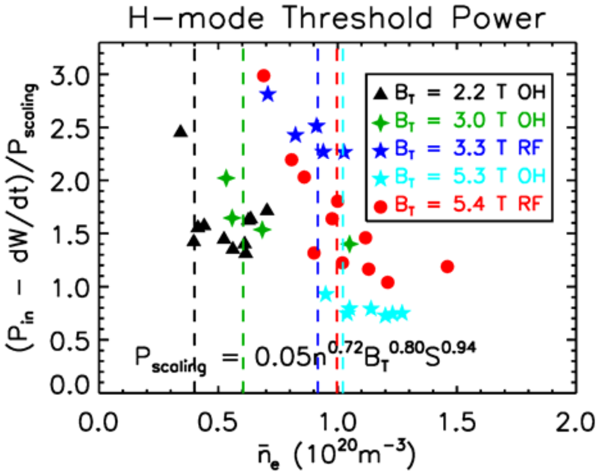

Fig. 3. Normalized threshold power vs line averaged density for Ohmic and RF heated heated plasmas at various toroidal fields. The density at minimum threshold is indicated by a dashed line for each field.

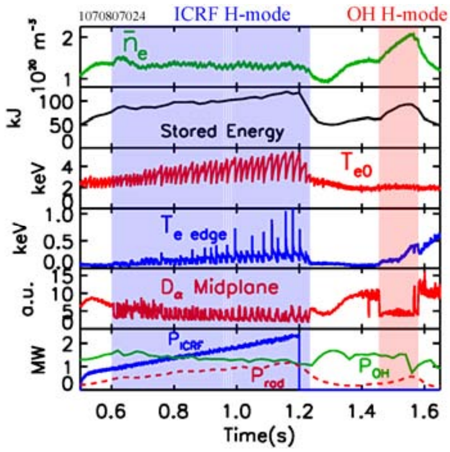

Fig. 4. Direct comparison of RF and Ohmic H-mode thresholds in the same discharge showing that a clear H-mode is achieved with much less Ohmic power than can be achieved with RF heating.

threshold dropped to about 0.4×10^{20} m^{-3} and H-modes were achieved down to $\bar{n}_e = 0.34 \times 10^{20}$ m^{-3}. These Ohmic data clearly show that the density for the minimum threshold power decreases approximately linearly with decreasing toroidal field. The density for minimum threshold at 2.2 T is close to that observed in ASDEX Upgrade, DIII-D, JET, and JT-60U. Attempts to run at still lower density led to runaway discharges that remained in L-mode. Sawteeth were maintained even at these low densities and there was no evidence of locked modes in these low current discharges down to $I_p = 0.45$ MA. Low toroidal field and low plasma current operation is unlikely to drive locked modes since the error fields decrease with decreasing toroidal field and current. Note that the minimum Ohmic thresholds are about 20% below the scaling at 5.3 T but are 40 - 50% higher than the scaling at 3 T and at 2.2 T. Only part of this discrepancy is due to increased radiated power at low density and the remainder is probably due to a weaker density dependence than this scaling on C-Mod.

Looking instead at the ICRF data in Fig. 3, the data at 5.4 T (red) and 3.3 T (blue) indicate that the density for minimum threshold power is about $\bar{n}_e \sim 0.9 - 1 \times 10^{20}$ m^{-3}, decreasing only slightly with toroidal field. ICRF heated H-modes can only be achieved below this density by greatly exceeding the H-mode threshold scaling and could not be achieved below $\bar{n}_e = 0.7 \times 10^{20}$ m^{-3} with the ICRF power available (up to 2.5 MW). Note that the ICRF power for hydrogen minority heating at both 3.3 T and 5.4 T has been multiplied by 0.9 assuming 90% of the input power is absorbed in the plasma. The uncertainty in heating efficiency for different ICRF heating scenarios does, however, make direct comparison of the absorbed RF power at different toroidal fields difficult.

Figure 4 shows a direct comparison of the difference between the H-mode threshold with Ohmic and ICRF heating in the same discharge. A weak dithering H-mode is obtained from about 0.6 s to just after 1.2 s (blue shading) with over 1 MW of Ohmic heating plus RF heating ramping from about 1 to 2.5 MW. A clear ELM-free H-mode is obtained from about 1.45 s to 1.57 s (red shading) with only 1.5 MW of Ohmic heating. Even when the radiated power from the main plasma (red dashed line) is subtracted, the Ohmic threshold is lower than the RF threshold. Note that the toroidal field and plasma current were constant until 1.5 s at 5.25 T and 1.2 MA, respectively, corresponding to $q_{95} = 3.3$.

Conclusions The density for which the H-mode threshold is minimum decreases linearly with toroidal field for Ohmic H-modes reaching $\overline{n}_e = 0.4 \times 10^{20}$ m^{-3} at 2.2 T, nearly the same low density limit observed on other tokamaks. Locked modes do not appear to play a role in this low density limit, but runaway electrons do prevent C-Mod from operating in H-mode at still lower densities. A comparison of ICRF heated H-modes at both 5.4 T and 3.3 T exhibits a density of $\overline{n}_e \sim 1 \times 10^{20}$ m^{-3} for which the H-mode threshold is minimum, indicating a dependence on the heating scheme. The comparison between Ohmic and ICRF heated H-mode thresholds in both Figs. 3 and 4 indicates that lower thresholds are obtained with Ohmic heating than with ICRF heating across the density range. This seems surprising in that a number of theories of the L-H transition imply that the transition should favor ion heating to electron heating [5]. The inability to obtain ICRF H-mode below about $\overline{n}_e \sim 0.7 \times 10^{20}$ m^{-3} may be due to increased plasma wall interactions at low density with high power RF, but subtracting the main radiated power does not change the overall trend. Another possible explanation for reduced RF heating efficiency could be enhanced fast ion losses at low density if the fast ion energies exceed about 500 keV.

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