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## CONFINEMENT OF OHMIC AND ICRF HEATED PLASMAS IN ALCATOR C-MOD

### Abstract

A series of confinement experiments has been carried out in Alcator C-Mod. We have found that data from both ohmic and ICRF heated plasmas can be fitted with an L-mode scaling law. The ohmic data show no scaling with density in any regime, the  $\tau_E$  of these discharges being as much as 2-3 times neo-Alcator. For the small size and relatively high current in this tokamak, L-mode confinement is often larger than neo-Alcator. With ICRF heating, confinement degrades with increasing power approximately as  $P_{\text{tot}}^{-1/2}$ . Overall, the confinement properties of the ohmic and ICRF plasmas are apparently distinguished only by the level of input power. Ohmic and ICRF H-modes are obtained over a wide range of discharge parameters, extending the range in the international database for surface power density, P/S, by almost a factor of 10. The power threshold for elm-free discharges was in rough agreement with the old ITER database scaling  $P/S = .044 \text{ nB}$ . Elmy H-modes were obtained at powers at least a factor of two lower than the elm-free ones. These results were obtained with all molybdenum plasma facing components and no special wall treatment or coating.

### 1. Introduction

The Alcator C-Mod tokamak is a compact high field device capable of producing shaped diverted plasmas. Confinement studies have been carried out in hydrogen and deuterium plasmas with  $.35 < I_p(\text{MA}) < 1.05$ ;  $3.5 < B_T(\text{T}) < 5.4$ ;  $.20 < a(\text{m}) < .24$ ;  $.65 < R(\text{m}) < .70$ ;  $.7 < n_e(10^{20} \text{m}^{-3}) < 2.4$ ;  $1.1 < K < 1.6$ . The  $Z_{\text{eff}}$  is low, typically  $< 1.5$  for  $n_e > 1.5 \times 10^{20}$ . All of the plasma facing components are made of molybdenum with no special wall treatment or coating. Plasma stored energy is calculated by integration of the density and temperature profiles and by analysis of the MHD equilibrium. These generally agree to within 20%,

however for ICRF plasmas,  $W_{mhd}$  is systematically higher than  $W_{kin}$ . This systematic difference is probably attributable to energy in the minority ion tail. When "no plasma" shots are available for subtraction of stray field effects, we can also obtain the stored energy by analysis of the diamagnetic loop signals. These are in good agreement with  $W_{mhd}$ . Shots for confinement analysis were chosen with "standard" criteria: quasi-steady state, sawtoothing, and non-disruptive.

## 2. Ohmic L-Mode Confinement

Early in our experimental campaign, clear differences between Alcator C-Mod and its predecessor Alcator C emerged. In the ohmic plasmas, stored energy increased with  $I_p$  but not with  $n_e$ . Figure 1 shows the measured  $\tau_E$  plotted against the calculated neo-Alcator  $\tau_E[1]$ . Note that for most discharges, the measured  $\tau_E$  is greater than the neo-Alcator value. The increase in stored energy with  $I_p$  suggested an L-mode behavior; figure 2 shows the measured  $\tau_E$  plotted against  $\tau_{ITERP-89}[2]$ . The agreement in this case is clearly much better. Our conclusion is that our ohmic confinement is following an L-mode like scaling which for low densities and high currents can exceed neo-Alcator by as much as a factor of 3.

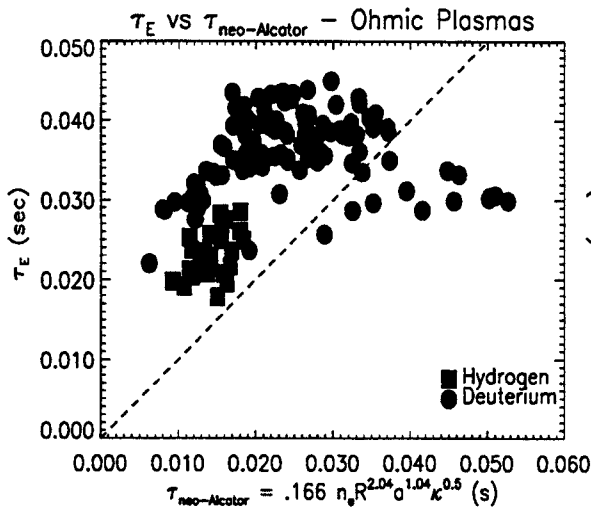


Fig.1) Measured  $\tau_E$  vs  $\tau_{E(neo-Alcator)}$  scaling for ohmic data. The data do not show agreement with the scaling.

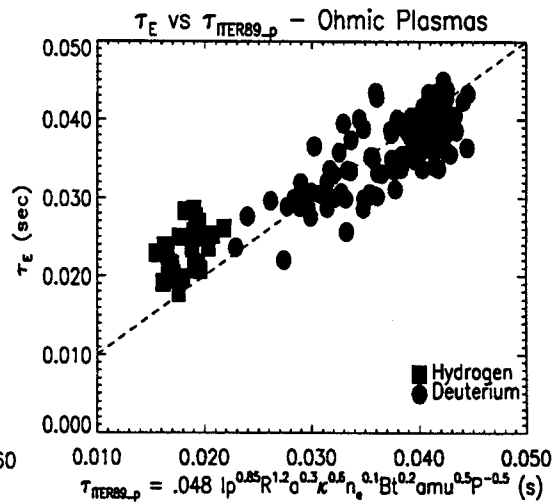
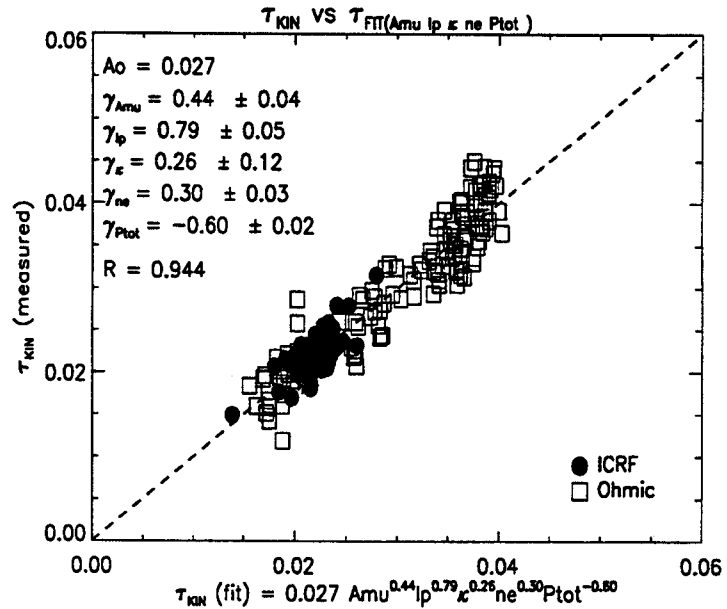


Fig.2) Measured  $\tau_E$  vs  $\tau_{E(ITER89-P)}$  for ohmic data.

A linear regression can be performed to calculate the best fit to a power law scaling for the C-Mod data alone. The range of some parameters ( $a$ ,  $R$ ,  $B_T$ ) in our data base is too limited to include in the regression, however significant results were obtained by fitting against  $I_p$ ,  $P_{tot}$ ,  $n_e$ ,  $\kappa$ , and  $amu$  (effective ion mass). It should be noted that there are significant covariances in the database. In particular  $I_p$ ,  $n_e$ ,  $\kappa$ , and  $amu$  are generally correlated. Of course for the ohmic data there is an additional correlation between  $I_p$  and  $P_{oh}$ . The results, which include data for ICRF plasmas, are shown in figure 3. The coefficients are not distinguishable from ITER89-P within the error bars of the two fits.

Fig.3) Measured  $\tau_E$  vs power law regression, fitting to  $I_p$ ,  $\kappa$ ,  $n_e$ ,  $P_{tot}$ , and  $amu$  (effective mass). Both ohmic and ICRF data are included. The coefficients are essentially the same as for ITER89-P within the error bars.



### 3. ICRF Heating and Confinement

ICRF heating was performed using a dipole antenna (two current straps spaced toroidally and driven out of phase) with up to 2 MW of power at 80 MHz. The heating scenario was hydrogen minority heating in deuterium at  $B_t = 5.3$  T. Efficient heating was observed, roughly doubling electron and ion temperatures at the higher RF powers. There were substantial variations in the relative temperature increase of the electrons and the ions. The minority concentration was typically around 10% but was not well controlled or characterized in these experiments. The energy of the ion minority tail should decrease at higher density and minority fraction, resulting in less slowing down on the electrons and more

(indirect) ion heating. Evidence so far suggests such a correlation but is not conclusive at this point.

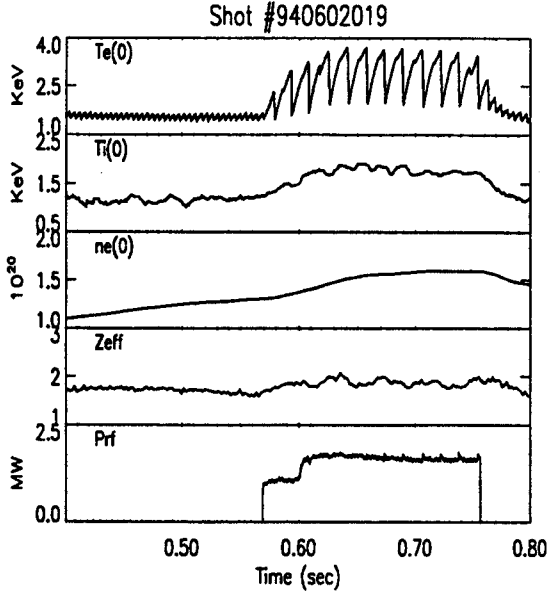


Fig.4) Time histories of Te(0), Ti(0), ne, Zeff, and Prf for shot 940602019

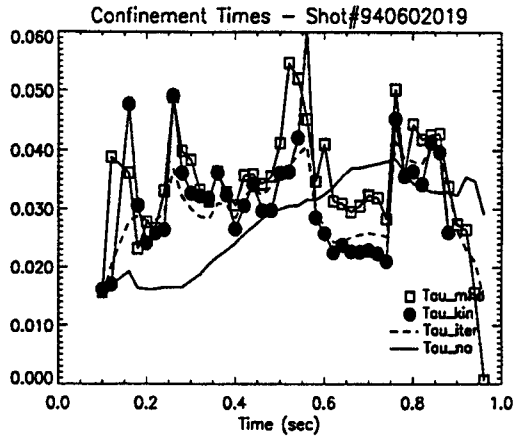


Fig.5) Measured  $\tau_E$  vs time for the plasma shown in figure 4.  $\tau_E$  neo-Alcator and  $\tau_E$  ITER89-P are included for comparison. The transients seen at the time of RF turn-on and turn-off are artifacts of the long averaging period for the ECE data.

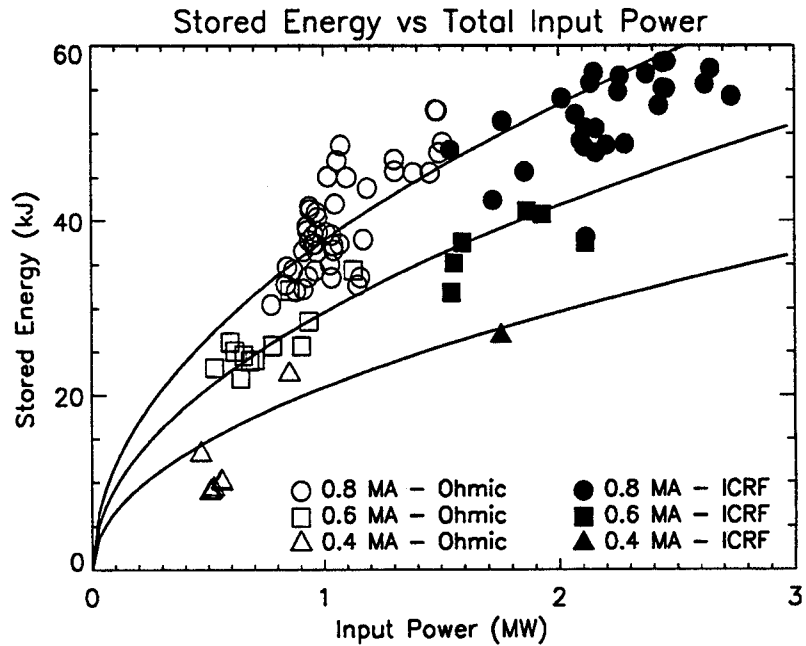
Traces of Te(0) and Ti(0) vs time are shown in figure 4. The electron and ion temperatures are strongly modulated by sawteeth activity. The sawteeth themselves are modified, their period increasing by factors of 2-4 over otherwise similar ohmic plasmas. Despite a small increase in density and Zeff, Prad/Ptot is unchanged. Figure 5 shows traces of the calculated  $\tau_E$  vs time - the data follow L-mode scaling right through the ohmic and ICRF phases. This point is reiterated in figure 6, where the stored energy is plotted vs total input power for several ranges of Ip. In figure 5, the larger value of  $\tau_E$  determined from the MHD equilibrium calculation is likely due the effect of the ion tail energy.

#### 4. Local Analysis

Initial runs of the TRANSP[3] code have been performed. For the ohmic shots at Ip = .8 MA, ne = 1x10<sup>20</sup>, we have found  $\chi_e(a/2) \sim 0.5$  m<sup>2</sup>/sec. At low densities, where electron and ion transport can be separated,  $\chi_i \sim \chi_e$  and is

mildly anomalous with  $\chi_i/\chi_{ne0} = 1-3$  with large uncertainties. For a typical ICRF plasma, with  $Prf = 1.8 \times 10^6$ ,  $I_p = .8$  MA, and  $n_e = 1 \times 10^{20}$ , the calculations show approximately 90% of the RF power is thermalized within  $r/a = .5$  and an ion tail with approximately 10-15 kJ out of a total stored energy of 60kJ. This is in good agreement with measurements of  $\Delta W$  from kinetics, MHD, and diamagnetism. For the ICRF plasmas,  $\chi_e$  rises to about 1.3 with little change in  $\chi_i$ .

Fig.6) Plasma thermal energy vs total input power for various ranges in  $I_p$ . The solid lines shown are ITER89-P scaling.



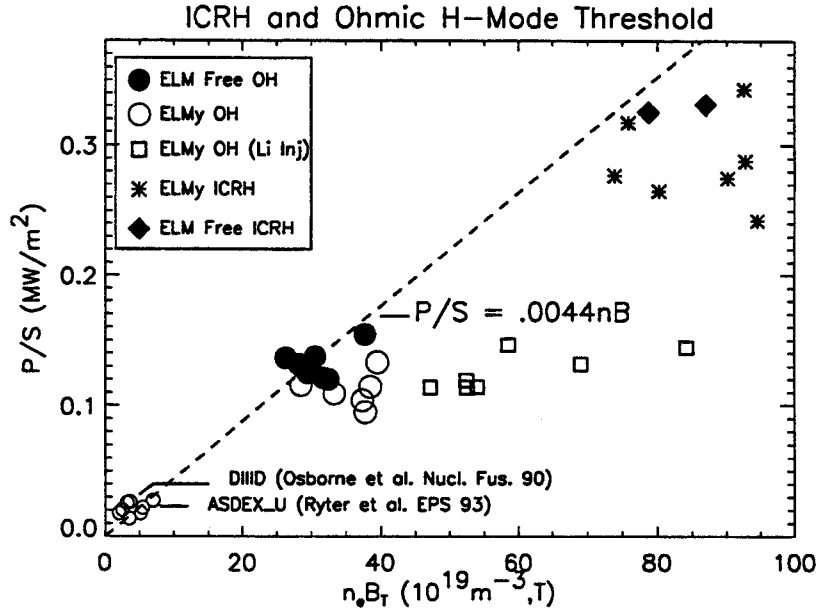
## 5. H-mode

A series of experiments was carried out to look for H-mode in ohmic plasmas. Because C-Mod operates at much higher toroidal field and density than other tokamaks, it offers the opportunity to significantly expand the international database.

With the ion grad-B drift toward the divertor, clear L-H transitions were observed. Further efforts to lower threshold power by ramping down  $B_T$  to 3T and lowering the density, resulted in the achievement of elm-free H-modes[4]. Accompanying the transition was a drop in  $H\alpha$  light, a strong rise in density and stored energy, a steepening of the edge profiles, and a decrease in edge turbulence. A plot of C-Mod data vs the "consensus" scaling  $P/S = .044 nB$ [5] is

shown in figure 7. While the elm-free data agree well with the empirical curve, elmy H-modes were obtained at substantially higher values of  $nB$ . No boronization or other coating on the all molybdenum first wall was necessary to obtain these results. There are some indications that lithium coating, the remnants of lithium injection experiments, may lower the power threshold further. H-Modes were also achieved with ICRF heating[8] with similar power thresholds as seen in the figure 7.

Fig.7) H-mode threshold data for ohmic and ICRF discharges. The dashed line is the ITER scaling  $P/S = .044nB$  and is a good fit to our elm-free data. Results from DIII-D[6] and ASDEX-UG[7] are shown for comparison.



The elm-free periods were short lived, lasting typically 50 msec. These were limited by an uncontrolled density rise and disruptions as  $q(a)$  dropped near 2 (due to the  $B_T$  ramp). While the energy confinement showed a large increase during the elm-free periods, it was not possible to make definitive measurements due to the strong transients.  $\tau_E$  in the L phase of these plasmas was around 30 msec. After the L-H transition,  $\tau_E$  rose to 50-100 msec. The latter figure comes from including the plasma  $dW/dt$  term which could be as large as 60% of the input power - thus the plasmas conditions were far from steady state. The ITER H-mode  $\tau_E$  for these plasmas is around 55 msec [9]

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