PFC/JA-94-29

Confinement of Ohmic and ICRF Heated Plasmas in Alcator C-Mod

M. Greenwald, R. Bovin, F. Bombarda[1], P. Bonoli,
C. Christensen, S. Fairfax, C. Fiore, J. Goetz, S. Golovato,
M. Graf, R. Granetz, S. Horne, T. Hsu, A. Hubbard,
I. Hutchinson, J. Irby, B. LaBombard, B. Lipschultz, T. Luke,
E. Marmar, M. May[2], G. McCracken, A. Niemczewski,
P. O'Shea, M. Porkolab, J. Rice, J. Schachter, J. Snipes,
P. Stek, Y. Takase, J. Terry, R. Watterson, B. Welch[3], S. Wolfe
Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

September 1994

[1]ENEA-Frascati, Frascati, Italy.
[2]Johns Hopkins University, Baltimore, Md., USA
[3]University of Maryland, College Park, Md., USA

This work was supported by the U. S. Department of Energy Contract No. DE-AC02-78ET51013. Reproduction, translation, publication, use and disposal, in whole or in part by or for the United States government is permitted.

INTERNATIONAL ATOMIC ENERGY AGENCY

FIFTEENTH INTERNATIONAL CONFERENCE ON PLASMA PHYSICS AND CONTROLLED NUCLEAR FUSION RESEARCH

Seville, Spain, 26 September – 1 October 1994

IAEA-CN-60/A2/4-P-2

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

M. Greenwald, R. Boivin, F. Bombarda[1], P. Bonoli, C. Christensen, S. Fairfax, C. Fiore, J. Goetz, S. Golovato, M. Graf, R. Granetz, S. Horne, T. Hsu, A. Hubbard, I. Hutchinson, J. Irby, B. Labombard, B. Lipschultz, T. Luke, E. Marmar, M. May[2], G. McCracken, A. Niemczewski, P. O'Shea, M. Porkolab, J. Rice, J. Schachter, J. Snipes, P. Stek, Y. Takase, J. Terry, R. Watterson, B. Welch[3], S. Wolfe

MIT - Plasma Fusion Center
Cambridge, MA.
United States of America

---

* *Supported by US DoE contract #DE-AC02-78ET51013*

[1] *ENEA-Frascati, Frascati, Italy*

[2] *Johns Hopkins University, Baltimore, Md., USA*

[3] *University of Maryland., College Park, Md., USA*

IAEA CN-60/A2/4-P-2

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 τ_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 $P_{tot}^{-1/2}$. 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 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 $.35 < I_p(MA) < 1.05$; $3.5 < B_T(T) < 5.4$; $.20 < a(m) < .24$; $.65 < R(m) < .70$; $.7 < n_e(10^{20}m^{-3}) < 2.4$; $1.1 < \kappa < 1.6$. The Z_{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 diamagetic 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 τ_E plotted against the calculated neo-Alcator τ_E[1]. Note that for most discharges, the measured τ_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 τ_E plotted against $\tau_{ITERP\text{-}89}$[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.

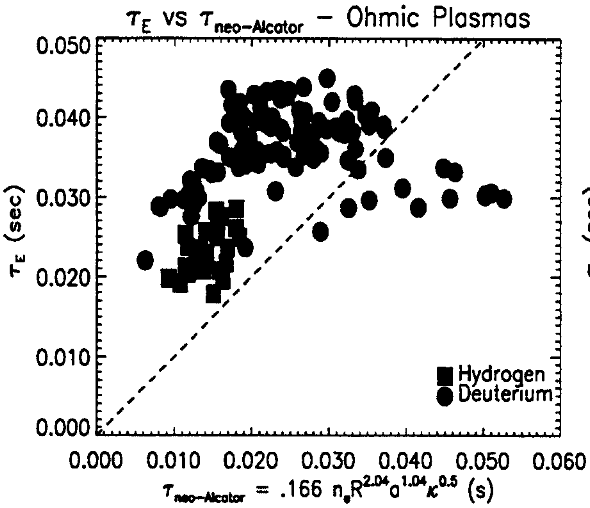

Fig.1) Measured τ_E vs $\tau_{E(neo\text{-}Alcator)}$ scaling for ohmic data. The data do not show agreement with the scaling.

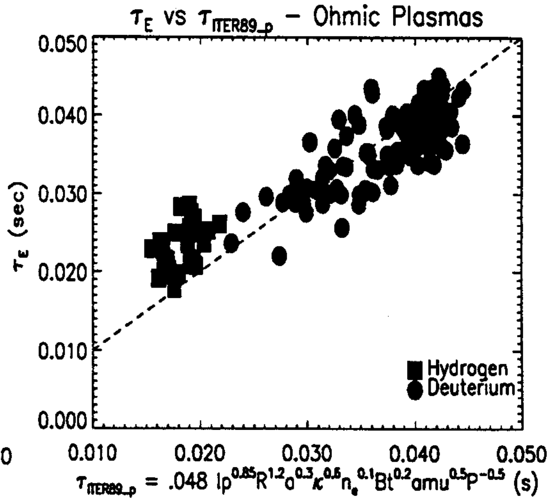

Fig.2) Measured τ_E vs $\tau_{E(ITER89\text{-}P)}$ for ohmic data.

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, κ, and amu (effective ion mass). It should be noted that there are significant covariances in the database. In particular I_p, n_e, κ, 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.

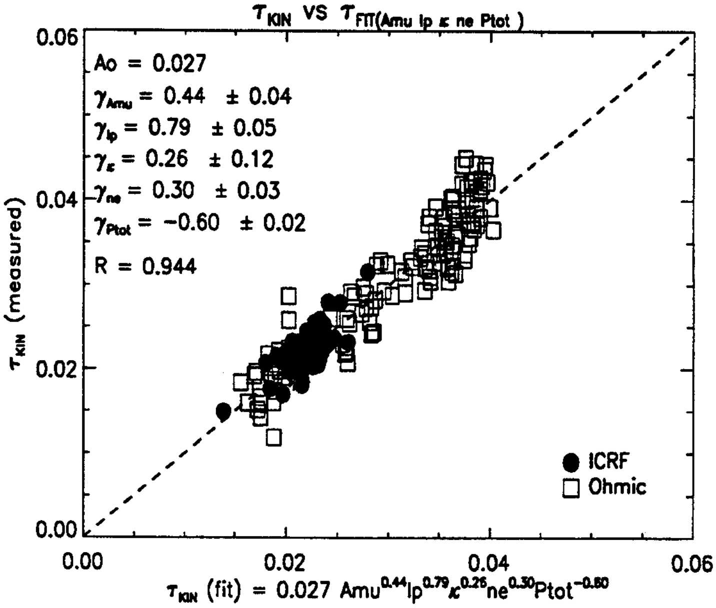

Fig.3) Measured τ_E vs power law regression, fitting to I_p, κ n_e, P_{tot}, and amu (effective mass). Both ohmic and ICRF data are included. The coefficients are essentially the same as for ITER89-P within the error bars.

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 Bt = 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.

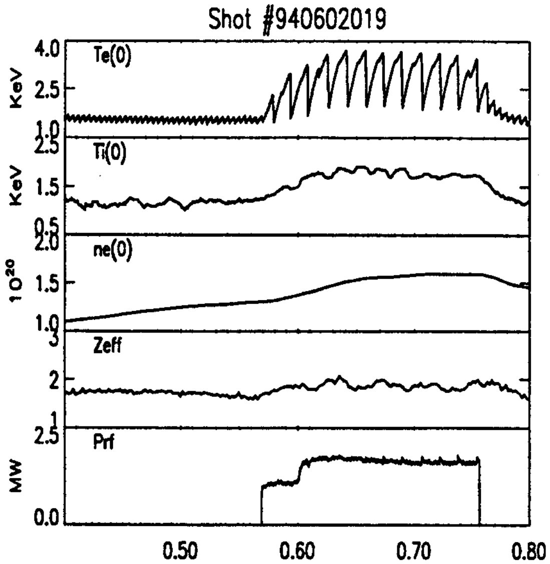

Fig.4) Time histories of Te(0), Ti(0), n_e, Z_{eff}, and P_{icrf} for shot 940602019

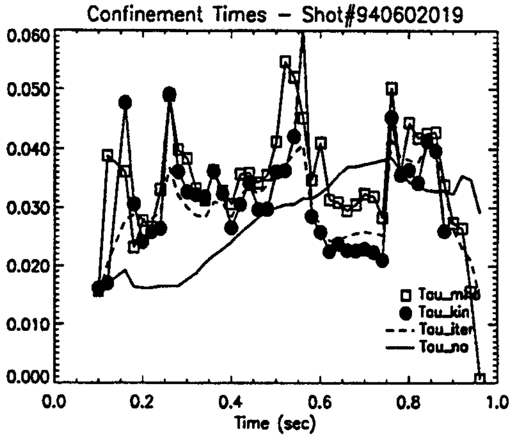

Fig.5) Measured τ_E vs time for the plasma shown in figure 4. τ_E neo-Alcator and τ_E ITER89-P are included for comparison. The transients seen at the time of RF turn-on and turn-off are artifacts of the long averaging period for the ECE data.

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 Z_{eff}, P_{rad}/P_{tot} is unchanged. Figure 5 shows traces of the calculated τ_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 τ_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, $n_e = 1\times10^{20}$, we have found $\chi_e(a/2) \sim 0.5$ m²/sec. At low densities, where electron and ion transport can be separated, $\chi_i \sim \chi_e$ and is mildly anomalous with χ_i/χ_{neo} = 1–3 with large uncertainties. For a typical ICRF plasma, with Prf = 1.8×10^6, Ip = .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 ΔW from kinetics, MHD, and diamagnetism. For the ICRF plasmas, χ_e rises to about 1.3 with little change in χ_i.

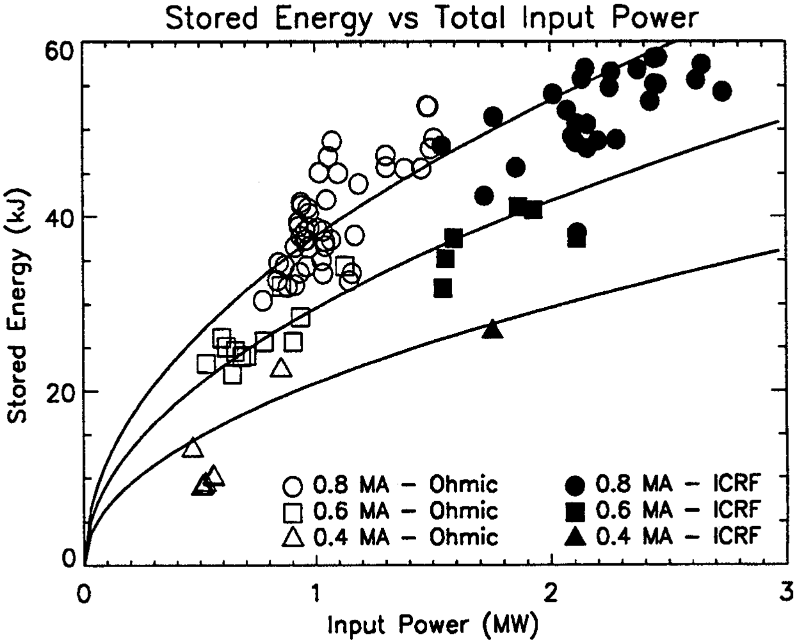

Fig.6) Plasma thermal energy vs total input power for various ranges in Ip. The solid lines shown are ITER89-P scaling.

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 Hα 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.

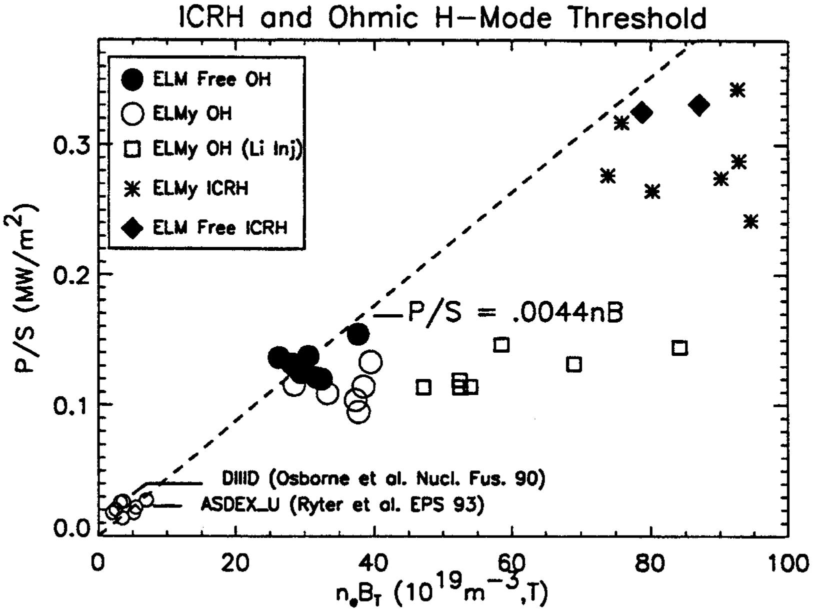

Fig.7) H-mode threshold data for ohmic and ICRF discharges. The dashed line is the ITER scaling P/S = .044nB and is a good fit to our elm-free data. Results from DIII-D[6] and ASDEX-UG[7] are shown for comparison.

The elm-free periods were short lived, lasting typically 50 msecs. 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. τ_E in the L phase of these plasmas was around 30 msec. After the L-H transition, τ_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 τ_E for these plasmas is around 55 msec [9]

References

[1] PARKER, R., GREENWALD, M., LUCKHARDT, S., et al., Nucl. Fus. 25, 9 (1985)

[2] YUSHMANOV, P.N., TAKIZUKA, T., RIEDEL, K.S., et al., Nucl. Fus. 30, 10 (1990)

[3] HAWRYLUK, R., Physics of Plasmas Close to Thermonuclear Conditions, Proceedings of the course held in Varenna, Italy, Vol.1, pg.19 (1979)

[4] SNIPES, J.A., GRANETZ R.S., GREENWALD, M. et al. to be published in Nuclear Fusion (also available as PFC/JA-94-02)

[5] RYTER, F., (for H-mode database working group), Cont. Fus. and Plasma Phys. Vol 17C, I-15

[6] OSBORNE, T.H., BROOKS, N.N., BURRELL, K.H., et al., Nucl. Fus. 30, 10 (1990)

[7] RYTER, F., GRUBER, O., BUCHL, K.. Cont. Fus. and Plasma Phys. Vol 17C, I-23

[8] SNIPES, J.A., GRANETZ R.S., GREENWALD, M. et al. to be published in Proc. 21st EPS, Montpelier, 1994 (also available as PFC/JA-94-20)

[9] KARDAUN, O., et al. (for H-mode database working group), Proceedings of 14th IAEA Conference on Plasma Physics and Controlled Nucl. Fusion Research.,. Wurzburg, Vol. 3, pg 251, 1992