PFC/JA-96-39

ICRF Heating Scenarios on Alcator C-Mod

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October 1996

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To be published in the Proceedings of the 16th IAEA Fusion Energy Conference.

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.

ICRF HEATING SCENARIOS IN ALCATOR C-MOD

ABSTRACT

Successful high power ICRF heating of L-mode and H-mode plasmas has been performed in the Alcator C-Mod tokamak with up to 3.5 MW of RF power at 80 MHz. Efficient absorption (90–100%) of the RF power was observed for D(H) heating at 5.3 T (here the minority ion species is indicated parenthetically). Lower single-pass absorption experiments were also performed in D(^{3}He) at 7.9 T, D($2\Omega_{^3He}$) at 4.0 T, and D($2\Omega_H$) at 2.6 T. Boronization has been found to improve the heating efficiency of these lower single pass absorption schemes through a reduction in the radiated power. Direct on-axis electron heating via mode converted ion Bernstein waves (IBW) has been observed in H(^{3}He) plasmas at 6.5 T and off-axis electron heating has been observed in D(^{3}He) at 7.9 T. The electron heating power density profiles were inferred in these experiments using an RF power modulation technique. The implications of these heating results for steady state advanced tokamak operation in C-Mod are discussed.

1. INTRODUCTION

Alcator C-Mod is a compact high field tokamak [1] ($a = 0.21$ m, $R_0 = 0.67$ m, $\kappa \lesssim 1.8$) with present operating range of $0.5 \lesssim I_p(\mathrm{MA}) \lesssim 1.5$, $2.5 \lesssim B_T$ (T) $\lesssim 8.0$, and $0.5 \times 10^{20} \lesssim \bar{n}_e(\mathrm{m}^{-3}) \lesssim 1 \times 10^{21}$. Up to 3.5 MW of RF power at 80 MHz has been coupled into the tokamak through two dipole antennas. Each antenna consists of two straps (0.1 m in width) driven out of phase and separated toroidally by 0.17 m (on-center) [2]. Extremely high power densities are obtained during ICRF injection (5 MW/m^3 volume averaged and 0.6 MW/m^2 surface averaged). The large range in magnetic field makes possible a variety of minority ion heating scenarios, including D(H) at 5.3 T, D(^{3}He) at 7.9 T, D($2\Omega_{^3He}$) at 4.0 T, and D($2\Omega_H$) at 2.6 T. The highest RF absorption rates were observed in the D(H) minority heating scheme as expected theoretically. The RF absorption rates were found to be lower in D(^{3}He) plasmas. This result is expected since the left circularly polarized component of the fast wave electric field is significantly reduced in D(^{3}He) minority heating relative to D(H). Even so, H-mode plasmas were achieved in all of the minority heating schemes.

Efficient on-axis electron heating via mode converted IBW has been observed in $H(^3He)$ plasmas at 6.5 T and $n_{^3He}/n_e \simeq 0.2-0.3$. In this scenario, the ion-ion hybrid layer is located near the plasma center, the hydrogen cyclotron resonance layer is located on the low field side at about $r/a \simeq 0.75$, and the ^3He cyclotron layer is on the high field side at $r/a \simeq 0.56$. The location of the electron heating could be controlled by varying the magnetic field or changing the ^3He concentration. The location and shape of the electron heating profiles were found to be in agreement with the predictions of a 1-D full-wave ICRF model (FELICE) [3] which solves explicitly for the IBW electric fields. Off-axis ($r/a \simeq 0.6$) electron heating via mode converted IBW has also been demonstrated in $D(^3He)$ discharges at 7.9 T and $n_{^3He}/n_e \simeq 0.2-0.3$. Again the experimentally inferred power deposition profiles agree with the predictions of 1-D full-wave ICRF calculations.

It is noteworthy that C-Mod can operate for pulse lengths of $t_{pulse} \simeq (5-7)$ s at intermediate fields of (4–5) T. For $T_e(0) \gtrsim 5$ keV the current skin time is $t_{skin} \simeq 1$ s , $\tau_{L/R} \simeq 3$ s, and hence $t_{pulse}/\tau_{L/R} \lesssim 2$. Furthermore, the direct electron heating via mode converted IBW could be used for off-axis current profile control by employing directional wave excitation. Thus C-Mod offers the unique opportunity to study both noninductive current drive and fully relaxed reversed shear current profiles in advanced tokamak configurations near the β-limit. The possibility of achieving such operating modes in C-Mod is discussed in the final section.

2. MINORITY ION HEATING RESULTS IN C-MOD

During the Dec. 1995 to March 1996 experimental campaign, high quality H-mode plasmas were obtained routinely after boronization of the tokamak [4]. The D(H) minority heating scheme was used at $B_T = 5.3$ T and $I_p \simeq 1.0$ MA. An RF power absorption rate of 90–100% was inferred for this type of heating based on a break in slope analysis of the stored energy at the time of RF turn-off. A confinement time enhancement factor defined as $H_{ITER89-P} = \tau_E/\tau_{ITER89-P}$ of up to 2.5 was observed in ELM-free H-modes, where $\tau_{ITER89-P}$ is the empirical L-mode confinement time [5]. The corresponding normalized $\beta \equiv \beta_N$ was about 1.5, where $\beta_N = \beta_t/(I_p/aB_T)$ $(\% - m - T/MA)$, $\beta_t = < p > /(B_T^2/2\mu_0)$, and $<>$ denotes a volume average. At $\bar{n}_e \simeq 3.0 \times 10^{20}$ m^{-3} and $P_{RF} = 2.4$ MW, the maximum electron and ion temperatures achieved were $T_e(0) \simeq 5.7$ keV (sawtooth peak) and $T_i(0) \simeq 3.9$ keV (sawtooth averaged). The relative concentration of hydrogen was estimated to be $n_H/n_e \lesssim 6 - 8\%$, from charge exchange analyzer measurements. The FPPRF Fokker Planck / ICRF package [6] has been used to determine the minority tail power balance. At these concentrations and electron density, $\frac{1}{2} - \frac{2}{3}$ of the power absorbed by the minority ions should dissipate collisionally via electron drag and the remainder of the tail power should be dissipated collisionally into background deuterons.

ELM-free H-mode plasmas have also been obtained in D(^{3}He) minority heating at 7.9 T. An example of this is shown in Fig. 1, where $P_{RF} = 2.4$ MW, $I_p = 1.2$ MA, and $\bar{n}_e \simeq 3.4 \times 10^{20}$ m^{-3}. After a period of dithering (from 0.73–0.86 s), a transition into ELM-free H-mode is observed, as is evident on the edge T_e and D_α signals. The stored energy increases from an ohmic value of 0.056 MJ to a near–maximum value of 0.200 MJ. Assuming 100% of the RF power is absorbed, the confinement time at this point is 0.061 s, which yields a confinement enhancement factor $H_{ITER89-p}$ of 1.5. Again, using a break in slope analysis of the stored energy at the RF turn-off point, an RF absorption rate of about 75% is inferred. Assuming this absorption rate for the RF, the confinement time is 0.073 s and $H_{ITER89-P} \simeq 1.7$. The maximum electron and ion temperatures were $T_e(0) \simeq 3.3$ keV and $T_d(0) \simeq 2.9$ keV. Thus H-modes have been achieved in C-Mod with $T_e \simeq T_i$. The relative concentration of ^{3}He in this discharge is estimated to be $\simeq 5$ %. At this density and concentration, FPPRF calculations indicate more than $\frac{2}{3}$ of the power absorbed by the ^{3}He ions is dissipated collisionally into background deuterons. The increased tail power flow to the deuterons, relative to D(H) is largely a consequence of the double charge state of the (^{3}He) minority component.

Second harmonic minority heating experiments have also been performed at $\simeq 4$ T in D($2\Omega_{^3He}$). This heating scheme was unsuccessful [7] prior to boronization. The reason was thought to be the presence of an H fundamental resonance layer on the high field side edge of the tokamak at $r/a \simeq 0.75$, which resulted in parasitic absorption at that location. After boronization, the H resonance appears to result in edge heating which helps to attain H-mode. The best heating results were found at $B_T \simeq 4.2$ T where the H resonance had moved in on the high field side to r/a $\simeq$ 0.63. The field was also reduced to 3.4 T to remove the fundamental H layer from the plasma. However, the overall heating was reduced and the impurity production increased, presumably because the $2\Omega_H$ resonance then appeared on the low field side edge of the tokamak at r/a $\simeq$ 0.91. Typical discharge parameters for this heating scheme were $I_p \simeq 0.6$ MA, $\bar{n}_e \simeq 0.8-1.0\times10^{20}\ m^{-3}$ (before H-mode), $T_e(0)$, $T_d(0) \simeq 1.5$ keV during ICRF injection, and $P_{RF} \simeq 2.2$ MW, with stored energy increases from 0.025 MJ to about 0.045 MJ. The confinement enhancement factors for these H-modes were $H_{ITER89-P} \simeq 1.0$, assuming an RF absorption rate of 100%. However, break in slope analysis of the diamagnetic stored energy indicates an RF absorption rate of only 30% in which case $H_{ITER89-P} \simeq 1.3$. The relative concentration of ^{3}He was typically low in these shots (2–3%). We expect better heating with $D(2\Omega_{^3He})$ at 80 MHz when combined with fundamental D(^{3}He) heating at 40 MHz.

Second harmonic heating at 2.6 T in $D(2\Omega_H)$ plasmas also resulted in achievement of H-mode. These experiments were performed at $I_p \simeq 0.55$ MA, $\bar{n}_e \simeq (0.5-1.2)\times10^{20}\ m^{-3}$, and $P_{RF} \simeq 1.3-1.4$ MW. The stored energy typically doubled in these H-mode plasmas (increasing from about 0.02 MJ to 0.035-0.043 MJ), and the confinement enhancement factors were $H_{ITER89-P} \simeq 1.4$, assuming 100% of the ICRF power was absorbed. Again, taking into account the RF absorption rate estimated from diamagnetic stored energy rate change at the RF turn-off, an absorption rate of about 80% with $H_{ITER89-P} \simeq 1.6$ is inferred. Both ohmic and ICRF heated H-modes were obtained at low density, only ICRF heated H-modes were observed at intermediate density, and no H-modes were observed at high densities ($\bar{n}_e \gtrsim 1.1-1.2\times10^{20}\ m^{-3}$). The relative concentration of H injected into the plasma was varied from 0-100% and similar heating results were obtained at all concentrations. However, H_α/D_α measurements indicated the concentration of H only varied from $\simeq 5-40\%$.

3. MODE CONVERSION ELECTRON HEATING EXPERIMENTS IN C-MOD

Direct on-axis electron heating via mode converted ion Bernstein waves (IBW) has been observed [7] in H(^{3}He) plasmas at $B_T \simeq 6.0-6.5$ T, $\bar{n}_e \simeq 1.4\times10^{20}\ m^{-3}$, $I_p = 0.8$ MA, $P_{RF} \simeq 1.2$ MW, and $n_{^3He}/n_e \simeq 0.2-0.3$. These experiments were carried out in 1995 prior to boronization and the plasmas remained in L-mode during ICRF injection. The central T_e was observed to increase from 2.1 keV to 4.7 keV (sawtooth peak) and the stored energy increased from 0.043 MJ to 0.050 MJ. In these experiments the ICRF power was modulated to obtain the electron RF power density from a break in slope analysis of the electron temperature versus time (as given by grating polychromator measurements). The result of such an analysis is shown in Fig. 2. The on-axis value of the RF power density ($\simeq 25$ MW/m^3) is about a factor of 10 higher than the local ohmic power density. The RF power density profile in Fig. 2 corresponds to an electron absorption rate of about 66%. The location and shape of the electron heating power density profile in Fig. 2 is in qualitative agreement with the predictions of the 1-D slab geometry code FELICE. However, the electron power densities predicted by FELICE are about a factor of 2-3 less than what is observed experimentally, presumably due to the absence of wave focussing effects in the 1-D slab model.

Direct off-axis heating of electrons was also measured in D(^{3}He) L-mode plasmas after boronization, at $B_T = 7.9$ T, $I_p = 1.0$ MA, $\bar{n}_e \simeq 1.5 - 2.0 \times 10^{20}$ m^{-3}, and $n_{^3He}/n_e \gtrsim 0.15 - 0.20$. In this heating scheme the ^{3}He minority resonance is at the plasma center and the IBW mode conversion layer is located on the tokamak high field side at $r/a \gtrsim 0.5$. In these experiments the RF power was stepped from about 1 to 2.5 MW and the electron heating rate at the RF power transition was inferred using a break in slope analysis of the electron temperature channels. An example of off-axis electron heating determined from this method is shown in Fig. 3. The absorbed RF power fraction to electrons in Fig. 3 is $\simeq 0.4 - 0.45$. The electron power density profile shown in Fig. 3 is also in qualitative agreement with 1-D full-wave results from FELICE.

4. DISCUSSION

Significant heating has been achieved during minority heating experiments in C-Mod and direct electron heating via mode converted ion Bernstein waves has been clearly demonstrated. This plasma heating and direct electron interaction are two key elements necessary for the access of steady state advanced tokamak modes of operation in C-Mod. A current drive simulation code (ACCOME) and MHD equilibrium and stability package (JSOLVER/PEST II) have been used to study the stability properties of non-inductively driven, reversed shear type current profiles that may be achieved for C-Mod parameters [$I_p \simeq 0.8\,\mathrm{MA}$, $R_0/a = 3$, $T_e(0) \simeq T_D(0) \simeq 5\,\mathrm{keV}$, and $< n_e > \gtrsim 1.2\times10^{20}\,\mathrm{m}^{-3}$] [8]. It is found that highly shaped C-Mod equilibria ($\kappa_x \simeq 1.8$, $\delta_x \simeq 0.7$) are stable up to $\beta_N \simeq 3.7$, without a conducting shell, to the $n = \infty$ ideal ballooning mode and the n=1,2,3 external kink modes. These equilibria have relatively broad pressure profiles ($p_0/p_{avg} \simeq 3$), $q_{min} \gtrsim 2.2$, $q_0 \gtrsim 3$, and high bootstrap current fractions ($f_{BS} \simeq 0.75$). The off-axis current profile control used in these studies could be provided by mode converted ion Bernstein waves in D(^{3}He) plasmas at $B_T \simeq 4$ T, 40 MHz, and $n_{^3He}/n_e \simeq 0.2 - 0.3$.

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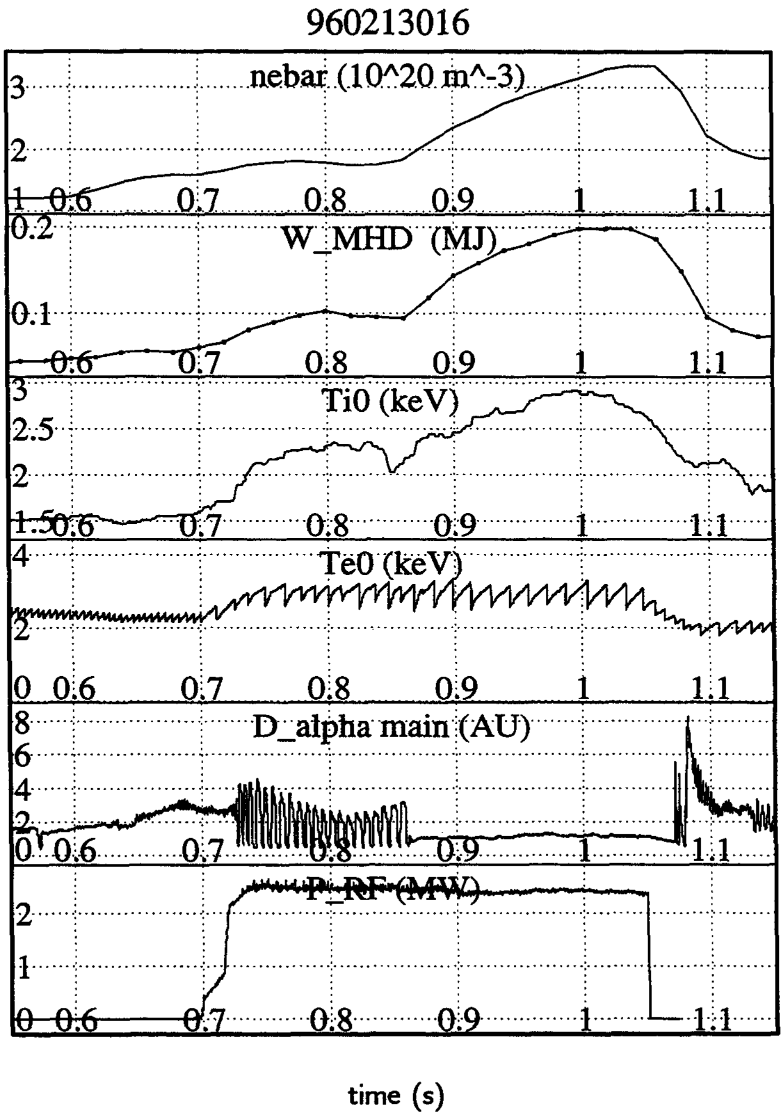

Fig. 1 D(^{3}He) ICRF heated H-mode (B_T = 7.9 T, I_p = 1.2 MA).

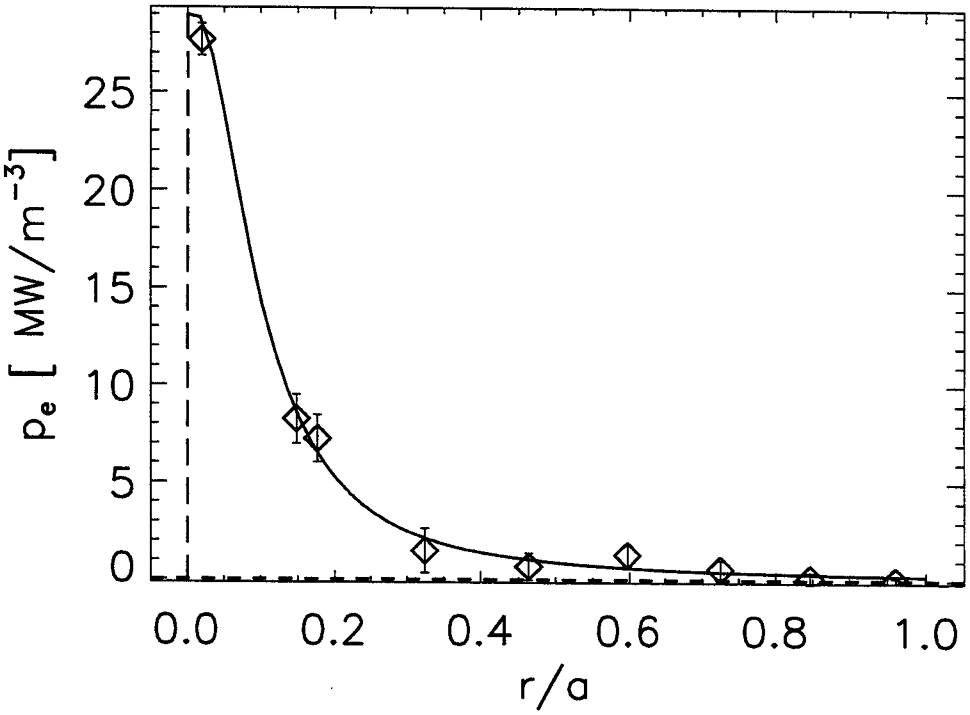

Fig. 2 On-axis H-^{3}He mode conversion heating at 6.5 T.

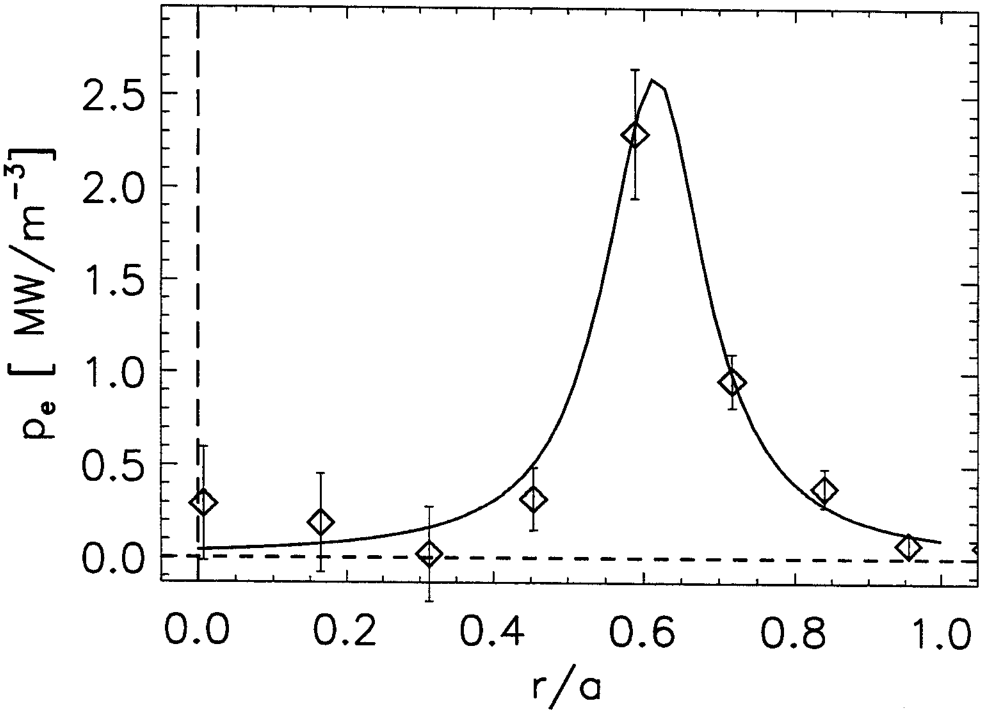

Fig. 3 Off-axis D-^{3}He mode conversion heating at 7.9 T.