Theoretical Analysis of Mode Conversion Electron Heating Experiments in Alcator C-Mod

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Abstract

Experimental measurments of highly localized (FWHM $\lesssim 0.2$ a) electron heating via mode converted ion Bernstein waves (IBW) have been made in the Alcator C-Mod tokamak. Mode conversion electron heating (MCEH) at or near the plasma center ($r/a \lesssim 0.3$) was observed in H(^{3}He) plasmas at $B_0 = 6.2-6.5$ T, $f_0 = 80$ MHz, $\bar{n}_e \simeq 1.5 \times 10^{20}$ m^{-3} and $n_{^3He}/n_e \simeq 0.2-0.3$. Off-axis heating ($r/a \gtrsim 0.5$) was observed in D(^{3}He) plasmas at $B_0 = 7.9$ T and $n_{^3He}/n_e \simeq 0.2-0.3$. An improved toroidal ICRF code (TORIC) has been used to successfully simulate these experiments. On-axis and off-axis MCEH and current drive experiments are planned for C-mod at $f_0 = 40$ MHz and $B_0 \simeq 3.5 - 4.7$ T. The TORIC code has been used to simulate the MCEH in these proposed experiments and simple estimates of the current driven by mode converted IBW have also been made.

Introduction and Background

Experimental measurments[1] of highly localized (FWHM $\lesssim 0.2$ a) electron heating via mode converted ion Bernstein waves (IBW) have been made in the Alcator C-Mod tokamak [$a = 0.22$ m, $R_0 = 0.665$ m, $\kappa_x \simeq 1.7$, $\delta_x \simeq 0.4$][2]. The rf power dissipation to electrons was measured at rf power transitions using a break in slope analysis of the electron temperature versus time, as measured by a nine channel grating polychromator (GPC)[1]. Mode conversion electron heating (MCEH) at or near the plasma center ($r/a \lesssim 0.3$) was observed in H(^{3}He) plasmas at $B_0 = 6.2 - 6.5$ T, $f_0 = 80$ MHz, $\bar{n}_e \simeq 1.5 \times 10^{20}$ m^{-3} and $n_{^3He}/n_e \simeq 0.2 - 0.3$. Off-axis heating ($r/a \gtrsim 0.5$) was observed in D(^{3}He) plasmas at $B_0 = 7.9$ T and $n_{^3He}/n_e \simeq 0.2 - 0.3$.

Recently, an improved toroidal ICRF code (TORIC) has become available[3] which solves explicitly for the mode converted IBW. A fourth order wave equation for $\vec{E} = (\vec{E}_\perp, \vec{E}_\parallel)$ is solved using a semi-spectral representation of the electric field. The ion-ion hybrid layer ($n_\parallel^2 \simeq S$) is numerically broadened in this model in order to ensure a well-behaved solution for the electric field near mode conversion. This technique was found to work well when the ion-ion hybrid layer is well-separated from the $n_\parallel^2 = L$ cut off[3,4]. The TORIC simulations shown in this paper were all done with 240 radial elements and 32 poloidal modes ($-16 \leq m \leq 16$).

On-axis and off-axis MCEH and current drive experiments are planned for C-mod at $f_0 = 40$ MHz and $B_0 \simeq 3.5 - 4.7$ T. The lower frequency and toroidal field will allow current profile control and transport barrier formation experiments to be carried out with the goal of achieving enhanced reversed shear mode (ERS) in C-Mod. The TORIC code has been used to simulate the MCEH in these proposed experiments and simple estimates of the current driven by mode converted IBW have also been made using the

Ehst-Karney parameterization of the current drive efficiency[5].

Mode Conversion Electron Heating at 80 MHz

The experimental and predicted rf power deposition profiles to electrons for on-axis MCEH in an H(^{3}He) C-Mod plasma are shown in Fig. 1(a). The plasma parameters were $B_T = 6.2$ T, $n_e(0) = 1.8 \times 10^{20}$ m^{-3}, and $I_p = 0.8$ MA. The relative ion concentrations used in the TORIC simulation were $n_{^3He}/n_e = 0.25$, $n_H/n_e = 0.45$, and $n_D/n_e = 0.05$. A single toroidal mode number characteristic of the C-Mod antenna was used ($n_\phi = 10$). The measured and predicted rf deposition profiles agree quite well in shape and magnitude. The integrated rf power fraction to electrons for the predicted profile is $\eta_e^{RF} = 0.91$, while the measured rf power fraction to electrons is $\eta_e^{RF} = 0.79$. The remaining rf power in the simulation is absorbed at the ^{3}He cyclotron resonance ($\eta_{^3He}^{RF} = 0.09$). Calculations carried out with a 1-D full-wave ICRF code (FELICE)[6] for this same case indicate similar absorbed rf power fractions but much lower central rf power densities (by a factor of 10). The lower peak power densities arise from the absence of wave focussing and volumetric effects in the 1-D analysis. The spatial effect of wave focusing on the wave electric field can be seen in Fig. 1(b). The nearly vertical contours in $Re(E_+)$ at the plasma center correspond to the mode converted IBW. The peakedness of the rf power deposition profile was found to be a strong function of the level of background deuterium in the experiment[1]. Theoretical and numerical analysis[1,4] of this effect indicates that as the level of D increases to $n_D/n_e \gtrsim 0.1$, the wave dispersion changes and the perpendicular damping lengths of the IBW increase because of an increase in the perpendicular group velocity.

The experimental and predicted rf electron heating profiles for off-axis MCEH in a D(^{3}He) C-Mod plasma are shown in Fig. 2(a). The plasma

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parameters were $B_T = 7.9$ T, $I_p = 1.2$ MA, and $n_e(0) = 2.5 \times 10^{20}$ m^{-3}. The relative ion concentrations used in the TORIC simulation were $n_{^3He}/n_e = 0.27$, $n_D/n_e = 0.41$, and $n_H/n_e = 0.05$. The location of the peak in the predicted power deposition ($r/a \simeq 0.55$) is in reasonably good agreement with experiment. The absorbed rf power fraction to electrons predicted by TORIC is $\eta_e^{RF} = 0.59$, with $\eta_{^3He}^{RF} = 0.41$. This electron absorption is close to the experimentally deduced value of $\eta_e^{RF} \simeq 0.50$. The electric field contours corresponding to the IBW are evident in Fig. 2(b) as the plane wavefront on the high field side of the plasma at $X \simeq -10$ cm.

Mode Conversion Electron Heating at 40 MHz

Localized mode conversion electron heating and current drive will be tested on C-Mod at $f_0 = 40$ MHz and $P_{RF} \simeq 4.0$ MW. The phased ICRF excitation will be produced by a four strap antenna with characteristic $n_\phi \simeq 5$. The ICRF power and antenna are being installed on C-Mod through a collaboration with PPPL. An example of the on-axis MCEH predicted by TORIC for a D(^{3}He) plasma at 40 MHz and $B_0 = 4.7$ T is shown in Fig. 3(a). Other parameters used in this simulation were $n_e = 1.5 \times 10^{20}$ m^{-3}, $T_e(0) = 3.0$ keV, $n_{^3He}/n_e = 0.25$, $n_D/n_e = 0.45$, and $n_H/n_e = 0.05$. The predicted deposition profile is highly localized with $\eta_e^{rf} \simeq 0.61$ and $\eta_{^3He}^{rf} = 0.39$. The driven current from the damped IBW is estimated to be $I_{RF} \simeq 130$ kA, using $n_e \simeq 1.5 \times 10^{20}$ m^{-3}, $T_e \simeq 3.0$ keV, $v_\parallel/v_{te} \simeq 1.0$, and the Ehst-Karney parameterization for the current drive efficiency[5]. This current drive estimate assumes 2 MW of incident rf power is damped on electrons by mode converted IBW. Note that on-axis MCCD has the advantage that electron trapping effects are negligible since $r/R \simeq 0$. Counter phasing could be used with this MCCD scheme to drive reverse current at the plasma center and thus invert the q-profile.

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An example of the off-axis MCEH predicted by TORIC for a D(^{3}He) plasma at 40 MHz and $B_0 = 3.9$ T is shown in Fig. 3(b). Other plasma parameters in this simulation were identical to those used in the on-axis heating case. Again the deposition profile is highly localized with $\eta_e^{\mathrm{rf}} \simeq 0.64$ and $\eta_{^3\mathrm{He}}^{\mathrm{rf}} = 0.36$. The driven current from the damped IBW is estimated to be $I_{\mathrm{RF}} \simeq 70$ kA, using $r_{\mathrm{mc}}/a \simeq 0.5$, $n_e \simeq 1.3 \times 10^{20}$ m^{-3}, $T_e \simeq 2.4$ keV, and $v_\parallel/v_{\mathrm{te}} \simeq 0.97$. Typical ohmic currents in C-Mod at $B_0 \simeq 4.0$ T are in the range of 600 kA so that significant modification of the local current density profile should be obtained with application of this localized MCCD.

Acknowledgements

References

[1] P.J. O'Shea et al., Bull. Am. Phys. Soc. **41**, 1548 (1996).

[2] I.H. Hutchinson et al., Phys. Plasmas **1**, 1511 (1994).

[3] M. Brambilla, paper presented at this conference.

[4] P.T. Bonoli et al., Phys. Plasmas, to be published in May (1997).

[5] D.A. Ehst and C.F.F. Karney Nucl. Fusion **31**, 1933 (1991).

[6] M. Brambilla, Nucl. Fusion **28**, 549 (1988).

Figure Captions

Figure 1: On-axis MCEH in an H(^{3}He) C-Mod plasma. (a) RF electron heating from break in slope analysis compared with predictions of TORIC code. Power densities normalized to 1 MW injected power. (b) Electric field contours for $Re(E_+)$.

Figure 2: Off-axis MCEH in a D(^{3}He) C-Mod plasma. (a) RF electron heating from break in slope analysis compared with predictions of TORIC code. Power densities normalized to 1 MW absorbed power. (b) Electric field contours for $Re(E_+)$.

Figure 3: TORIC predictions for MCEH in D(^{3}He) C-Mod plasmas at $f_0 = 40$ MHz. (a) On-axis MCEH at $B_0 = 4.7$ T. (b) Off-axis MCEH at $B_0 = 3.9$ T. Power densities normalized to 1 MW absorbed power.

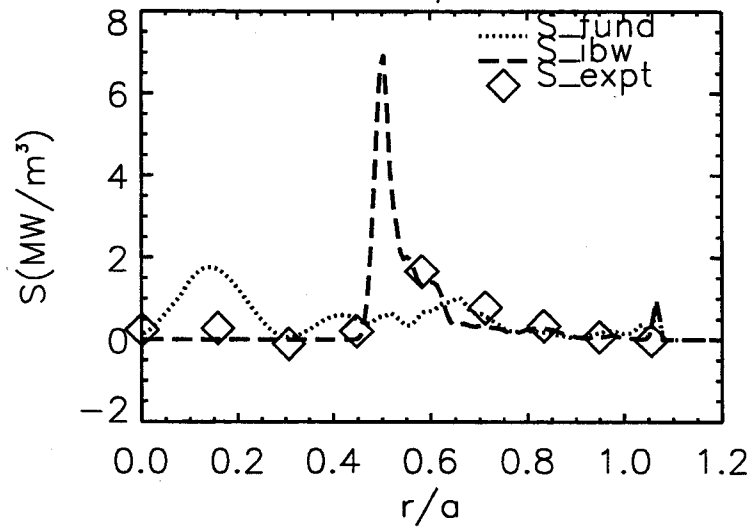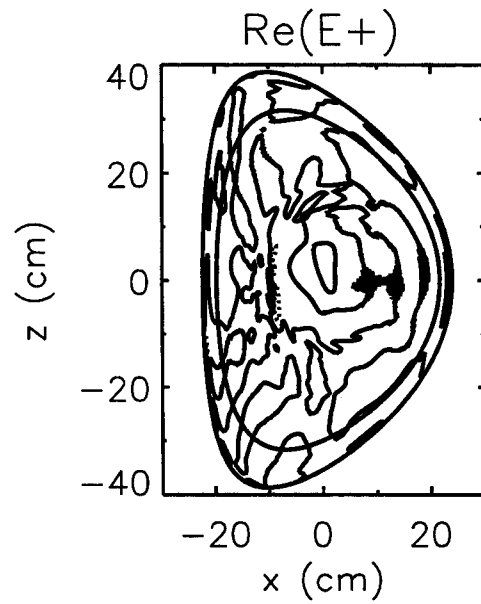## Radial Power Deposition Profiles
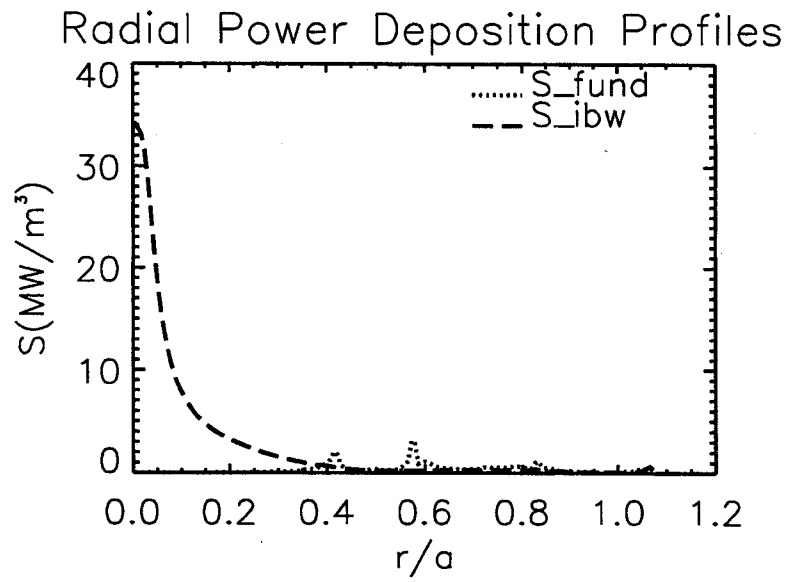

(a)

Re(E+)
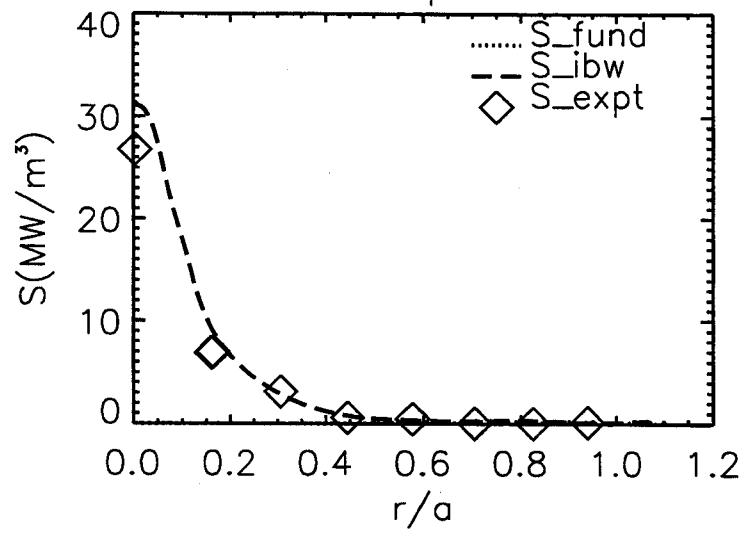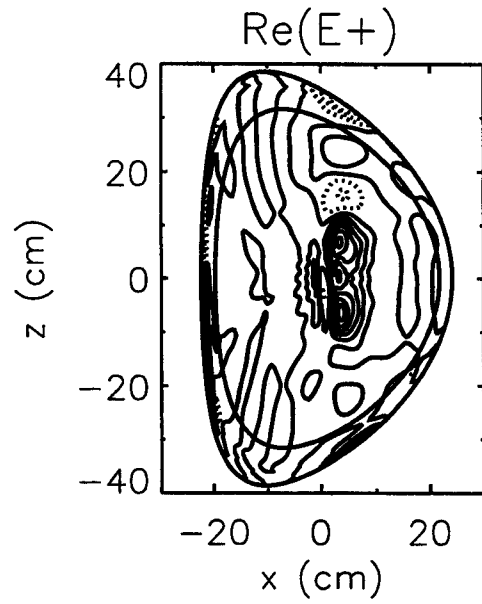
(b)

Figure 1

Radial Power Deposition Profiles
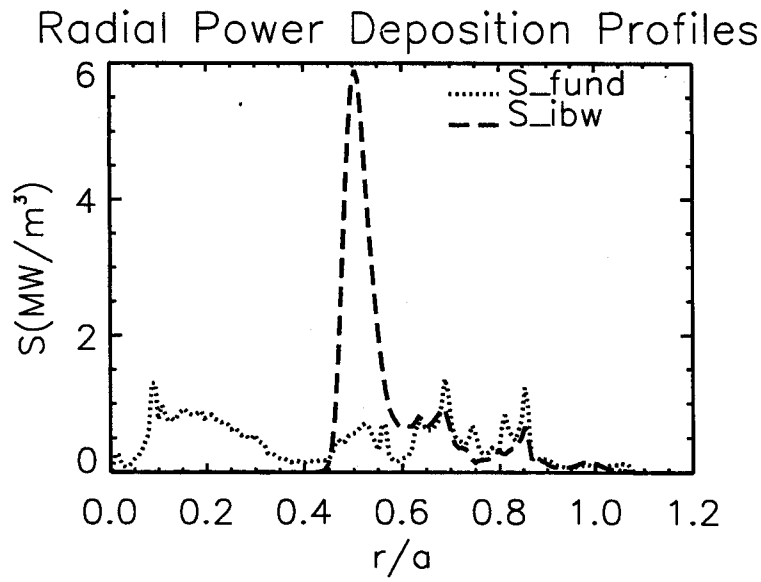

(a)

Re(E+)

(b)

Figure 2

Radial Power Deposition Profiles

(a)

Radial Power Deposition Profiles

(b)

Figure 3