LOWER HYBRID WAVE HEATING

IN THE ALCATOR A TOKAMAK

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April 1979, PFC/JA-79-4

*Laboratory of Plasma Studies, Cornell University, Ithaca, New York
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Abstract

We report the results of injecting 90 kW of microwave power near
the lower hybrid frequency into the Alcator A tokamak through a two
waveguide array. The observed plasma heating is in disagreement with that
expected from linear waveguide-plasma coupling theory. From these
results and auxiliary rf probe measurements we infer the nonlinear for-
mation of a high $k_n$ wave power spectrum at the plasma edge.
There is currently extensive interest in raising plasma temperatures in tokamaks through auxiliary heating methods. Microwave heating of tokamaks near the lower hybrid frequency has been tried on ATC, \cite{1-2}, Wega, \cite{3}, Petula, \cite{4}, Doublet IIA, \cite{5}, and recently on JFT2. \cite{6} In these experiments, ion heating was obtained when the wave frequency was in the vicinity of the central lower hybrid frequency, and some electron heating was also observed at lower densities. This ion heating was accompanied by a density rise and some impurity influx. No contradiction with the Brambilla waveguide-plasma coupling theory \cite{7} was reported in these experiments.

Here we report the results of injecting 90 kW of microwave power at 2.45 GHz into the Alcator A tokamak through a split waveguide array. Ion heating occurs at well defined values of central plasma density; below these densities electron heating occurs. No density changes or impurity influx take place during the rf pulse. Contrary to previous experiments, the waveguide phasing has no effect on plasma heating. In addition, the densities at which heating occurs are significantly reduced from those expected from waveguide-plasma coupling theory. \cite{7} These results and the frequency spectra obtained from an rf probe suggest that the wave power spectrum formed near the plasma edge is shifted to higher \( k_\parallel = \vec{k} \cdot \vec{E} / |\vec{B}| \) than predicted by linear theory. \cite{7}

The waveguide array employed here consists of two adjacent, independently driven waveguides mounted flush with the vacuum vessel walls; each has inner dimensions of 1.275 cm by 8.13 cm and are separated by a 0.09 cm wide septum. Toroidally the array is located 180° away from the limiter, which extends out 2.5 cm from the wall and defines a plasma minor radius of 10.0 cm with a major radius of 54 cm. The vacuum windows in the waveguide were located outside the toroidal field magnets, so that the \( \omega_e = \omega_{ce} \) layer was within the evacuated section of waveguide; nevertheless, no breakdown in the waveguide was observed at power densities up to 4.5 kW/cm\(^2\), averaged over the waveguide mouth. With the exception of Petula \cite{4}, this power density is substantially higher than those reported in previous experiments. During this high power operation over 85% of the incident power was coupled into the vacuum vessel by the array.
The linear theory of lower hybrid waves is well developed.\(^8\)\(^-\)\(^10\) Warm plasma theory predicts that \(k = |k \times B|/|B|\) will become large near the warm plasma mode conversion layer, at a density

\[
\omega^2_{\text{pi}} = \frac{\omega^2}{1 - \omega^2/(\omega_{\text{ce}}\omega_{\text{ci}}) + 2n_z \left( M_{\text{i}} a/M_{\text{e}} \right)^{1/2}}
\]

where \(n_z = k c/\omega\), and \(a = 3 T_i/M_{\text{i}} c^2 + 0.75(\omega^2/\omega_{\text{ce}} \omega_{\text{ci}})^2 T_e/M_{\text{e}} c^2\). When \(k\) is large, ion absorption of the lower hybrid wave can occur. In addition if \(\omega/k_L < v_{Te}\), the wave will be absorbed by electron Landau damping.\(^12\) (This condition corresponds to \(n_z = 5\) for \(T_e = 1\) keV.) Waves with \(n_z < (1 - \omega^2/\omega_{\text{ce}} \omega_{\text{ci}})^{-1/2}\) will mode convert into whistler modes; for a given \(n_z\) this occurs at a density which satisfies the relation

\[
\frac{\omega_{\text{pi}}}{\omega} \approx \left( \frac{n_z \omega}{\omega_{\text{ce}} \omega_{\text{ci}}} \right)^{1/2} - \left[ n_z^2 \left( \frac{\omega^2}{\omega_{\text{ce}} \omega_{\text{ci}}} - 1 \right) + 1 \right]^{1/2}
\]

For \(n_z = 1.5\), \(B_T = 53\) kG (the value of \(B_T\) at the outside plasma edge when the central \(B_T = 62\) kG) and deuterium this corresponds to \(n_e = 7 \times 10^{13}\) cm\(^{-3}\), which occurs at \(r > 9\) cm. Waves that mode convert into whistlers do not penetrate and do not heat the plasma center.

Waveguide-plasma coupling theory is also well developed.\(^7\),\(^13\) For the double waveguide employed here the theory predicts a wave power spectrum that monotonically decreases as \(n_z\) increases past 1 for oppositely phased waveguides (\(\phi = 180^\circ\)); the part of the spectrum which penetrates to the plasma center is characterized by \(n_z \sim 3\), which for \(B_T = 62\) kG, \(T_e = 1.0\) keV, and \(T_i = 0.8\) keV would mode convert at \(n_e = 3.8 \times 10^{14}\) cm\(^{-3}\). Furthermore, only about 30% of the power spectrum has \(n_z < 1.5\) and thus over 70% of the power penetrates at least past the plasma edge. When the waveguides are in phase (\(\phi = 0^\circ\)) the power spectrum is compressed near \(n_z = 1\) with over 80% of the wave power having \(n_z < 1.5\) and being confined to the plasma exterior. We therefore would have expected a marked reduction in central plasma heating when \(\phi = 0^\circ\) over \(\phi = 180^\circ\).
Fig. 1a shows a typical plasma shot in the ion beating mode. The rf pulse produces no increase in density or loop voltage and no effect on the nitrogen, oxygen, carbon, or molybdenum impurity radiation; however, the fusion neutron flux increases by a factor of 15. Fig. 1b shows the results of many such shots; enhanced neutron rates are observed at $\bar{n}_e = 1.6 \times 10^{14} \text{ cm}^{-3}$ or central $n_{eo} = 2.4 \times 10^{14} \text{ cm}^{-3}$. The peak neutron rate obtained was $2 \times 10^{11} \text{ /sec}$. Sawteeth are clearly observable on the enhanced neutron rate, which indicates that its origin is within the $q = 1$ surface. During the rf pulse a high energy tail appears on the charge exchange energy spectrum which is well correlated to the occurrence of neutron enhancement. Any change in bulk ion temperature due to wave heating is less than the 100 eV resolution of the charge-exchange diagnostics; this is expected since the net rf power radiated by the array is 75 kW which is much less than the ohmic heating power of 270 kW. It should be noted that the observed charge-exchange particles originate from ions superbanana trapped in the magnetic well of the flange which rapidly VB drift out of the plasma. An up-down charge exchange scan exhibits an asymmetry due to this drift and indicates that the energetic ion production is localized near the plasma center.

The experimental ion heating density bands for both $D_2$ and $H_2$ discharges are plotted in Fig. 2 for different values of $B_T$. The density at which ion heating occurred in hydrogen was ascertained from increases in the 8 keV charge-exchange flux, while in deuterium the neutron enhancement was used. The curves are theoretical predictions of the densities at which the mode conversion layer will appear at the plasma center for typical Alcator A parameters. The curve for $n_z = 3$, which is the principal $n_z$ expected theoretically, results in a higher density for heating than experimentally observed in deuterium. At $n_z = 5$ the theoretical curve is in good agreement with the experimental points. A solution of the WKB wave equation incorporating perpendicular ion Landau damping shows that for Alcator A parameters and $n_z = 5$ ion heating will occur at a density 10% below that of Fig. 2 in deuterium, which is in even better agreement with the experiment.

When the density is lowered below the ion heating density band, electron heating is observed. At $B_T = 62 \text{kG}$ and $1.0 \times 10^{14} \text{ cm}^{-3} < \bar{n}_e < 1.2 \times 10^{14} \text{ cm}^{-3}$ a 10% increase in central $T_e$ is obtained from both
electron cyclotron emission at $\omega = 2\omega_{ce}$ and Thomson scattering measurements taken over consecutive identical shots. No energetic ion tail is measured by the charge-exchange diagnostics, indicating direct wave-electron heating. Electron Landau damping at $T_e = 1100$ eV would require

$$\frac{\omega}{k_{||} v_T} = 3 \text{ or } n \sim 5,$$

which is far above that predicted by waveguide plasma coupling theory, but consistent with the ion heating densities of Fig. 2. Thus both the electron and ion heating can be explained by an upshift in the wave power spectra to $n \sim 5$.

The experimental results strongly suggest that this high $n_z$ spectrum originates near the plasma edge. The neutron flux is found to change by less than $\pm 10\%$ when the waveguide phase is varied from $0^\circ$ to $180^\circ$ over identical plasma shots. From linear theory we would expect a factor of 4 change in the power that can penetrate past the plasma edge when $\phi$ is varied from $0^\circ$ to $180^\circ$. From this we postulate that the shift to higher $n_z$ occurs at $r > 9$ cm, and thereby allows unchanged accessibility even as $\phi$ varies from $0^\circ$ to $180^\circ$.

In Alcator A this upshift in $n_z$ from 3 to 5 would be more noticeable than in previous tokamak experiments. From Eq. (2) we can calculate the magnitude of the thermal correction to the lower hybrid density

$$C = 2 n_z m_i a / m_e^2 (1 - \omega^2 / \omega_{ce} \omega_{ci}),$$

which for $n = 3$ is about 0.5 for previous experiments, 1-6 but 2.1 for Alcator A. Thus due to the high $T_i \approx 800$ eV and $\omega < \omega_{ce} \omega_{ci}$ of Alcator A, a upshift in $n_z$ from 3 to 5 would lower $n_{LH}$ by 31%, while in previous experiments $n_{LH}$ could decrease only 18%.

Due to the high rf power densities present in Alcator A, the parametric decay of the pump wave into lower hybrid waves and ion acoustic waves could occur at the plasma surface and cause an upshift in $n_z$. As previously shown, this decay process can significantly deplete the pump since the lower hybrid decay wave then propagates along the pump wave resonance cone. 14 For our plasma edge parameters ($n_e < 5 \times 10^{13}$ cm$^{-3}$, $T_e < 10$ eV) 15 and $T_e > T_i$ the inhomogeneous plasma convective threshold conditions can be satisfied for total waveguide powers of the order or less than 1 kW, which we easily exceed; the finite pump extent and homogeneous plasma threshold powers are even lower. It should be noted that we have not measured the edge $T_i$; if $T_i \approx T_e$ and the acoustic wave is strongly damped, the inhomogeneous plasma threshold power might be considerably higher.
Fig. 3a shows the frequency spectrum obtained from the coaxial rf probe having a 1mm diameter by 3 mm long tip bent in the poloidal direction. This probe is located 90° toroidally away from the waveguides and 1.5 cm from the vacuum vessel wall in the limiter shadow; it can be shown that the ray originating from the waveguide mouth will not strike the probe due to the low density at the plasma edge (i.e., \( n_e < 5 \times 10^{13} \text{cm}^{-3} \)). The probe will therefore observe either surface waves or waves that cross the plasma column. The probe spectrum of Fig. 3a is asymmetrically downshifted and broadened in frequency. In addition, during the rf pulse a strong enhancement occurs in the amplitude of the low frequency fluctuations, as shown in Fig. 3b. (In the absence of rf the low frequency spectrum has a FWHM of 150 kHz.) The reflected waveguide power spectrum also exhibits an asymmetrically frequency downshifted sideband of 2 to 4 MHz FWHM, whose amplitude is 30 db down from the pump. Similarly frequency downshifted spectra are observed in the plasma interior by CO₂ laser scattering.

Fig. 3c shows the integrated intensity of the probe signal vs \( \bar{n}_e \). As the density rises, lower values of \( n_z \) are absorbed by the plasma column (as indicated by the arrows) and cannot reach the probe. The collected signal sharply drops an \( \bar{n}_e \) is raised above \( 1.5 \times 10^{14} \text{cm}^{-3} \), which indicates that a major part of the power spectrum traversing the plasma has \( n_z \sim 5 \). Furthermore, the low level of signal at high density suggests a small amplitude surface wave. From this probe data we infer that the pump wave may be significantly depleted while decaying into high \( n_z \) lower hybrid waves near the plasma surface, which results in the anomalous heating results obtained.

In conclusion, we have presented experimental plasma heating data and rf probe spectra from which we infer a nonlinear increase in \( n_z \) of the lower hybrid waves near the plasma surface. This \( n_z \) upshift could play an important role in future high power rf heating experiments on toroidal plasma devices.

We are happy to acknowledge the diagnostic work carried out by D. Cope, M. Greenwald, Y. Takase and J. West, and the engineering assistance of G. Chihoski and H. Israel. This work was supported by D.O.E. Contract No. ET-78-C-01-3019.
References

*Permanent address: School of Applied and Engineering Physics, Cornell University, Ithaca, N.Y.


6. JFT2 Group (to be published).


Figure Captions

Fig. 1  a) Typical plasma shot in ion heating mode: $B_{TO} = 62$ kG, $P_{rf} = 90$ kW, deuterium, and $\phi = 180^\circ$, b) neutron rates from several shots vs $\bar{n}_e$; $B_{TO} = 62$ kG, $I_p = 150$ kA, $P_{rf} = 90$ kW, and $\phi = 180^\circ$.

Fig. 2  Theoretically expected central densities at which mode conversion will occur for $n_z = 3.0$ and $n_z = 5.0$ in deuterium and hydrogen. $\bullet$ = experimental heating density in deuterium and $\square$ = in hydrogen.

Fig. 3  a) High frequency spectrum of rf probe (linear scale). $B_T = 62$ kG, deuterium plasma, $\bar{n}_e = 2.8 \times 10^{14}$ cm$^{-3}$, $I_p = 150$ kA and $P_{rf} = 80$ kW; the sudden drop in amplitude occurred at the end of the rf pulse. b) Low frequency spectrum of rf probe with and without rf power (10 db/div). $B_T = 62$ kG, deuterium plasma, $\bar{n}_e = 1.6 \times 10^{14}$ cm$^{-3}$, $I_p = 150$ kA and $P_{rf} = 80$ kW. (The peak at $OH_z$ is a reference marker.) In (a) and (b) the spectrum analyzer bandwidth was 300 kHz. c) Amplitude of high frequency integrated probe signal vs $\bar{n}_e$ for deuterium plasma, $I_p = 150$ kA, $B_T = 62$ kG and $P_{rf} = 75$ kW. The arrows indicate the values of $n_z$ that will mode convert at the plasma center.
(a)

RF On  RF Off
20 MSEC/DIV

V_R (1.07V/DIV)
I_p (52kA/DIV)
\bar{n}_e (1 \times 10^{14} \text{ cm}^{-3} / \text{FR})

NEUTRON RATE

(b)

NEUTRON RATE WITH RF-NEUTRON RATE WITHOUT RF
(ARB. UNITS)

\bar{n}_e (10^{14} \text{ cm}^{-3})