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ION HEATING DUE TO MODULATED PARAMETRIC DECAY

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Under circumstances where parametric decay occurs in a plasma, a lower hybrid pump wave modulated near ion cyclotron harmonics is found to increase ion temperatures up to a factor of two over CW pump wave application.

1. Introduction. Lower hybrid waves may be used simultaneously for current drive and heating in tokamaks. The availability of microwave power and wave guide structures make it an attractive candidate for heating reactor-grade plasmas. The high powers necessary for current drive in this environment can produce ion heating via nonlinear interactions. Heating via parametric decay of lower hybrid waves could be an auxiliary heating method for tokamaks. In previous experiments ion heating has been observed along with parametric decay of lower hybrid waves (LHW) in ACT-1 [1], ATC [2], JFT [3], Doublet-IIA [4], WEGA [5], PETUAL [6], ALCATOR A [7], H—1 [8,9], and the Irvine Q-machine [10].

In this letter we present data showing enhanced ion heating due to modulation of a parametrically decaying lower hybrid pump wave. The launched lower hybrid wave decayed into a daughter LHW and an electrostatic ion cyclotron wave (EICW). Ion heating consistent with heating due to parametric decay was measured when the pump wave amplitude was constant in time. By modulating the LHW pump at frequencies near the ion cyclotron frequency the ion heating was increased up to a factor of 2 over the CW application.

2. Theory. In the regime $\omega_{ci}, \omega_{pi} \ll \omega \ll \omega_{pe} \ll \omega_{ce}$, where $\omega = \omega_{pump}$ the pump frequency or $\omega = \omega_d$ the daughter LHW frequency; the LHW dispersion relation simplifies to $\omega \approx \omega_{pe} k_\parallel / k_\perp$ where $k_\parallel$ ($k_\perp$) is the wave number parallel (perpendicular) to the confining magnetic field [11]. For $\omega = \omega_{icw}$, the EICW frequency, the dispersion relation is $\omega = \omega_c + (T_e/T_i)\Gamma_1(\rho_i^2 k_\perp^2)$ for $V_e \gg \omega/k_\parallel \gg V_i$, where V_e (V is the electron (ion) thermal speed $(2T_e/m_e)^{1/2}$ and $\Gamma_1(x) = e^{-x}I_1(x)$. The theory of parametric decay has been applied to the LHW by several authors [12–14].

In parametric decay the EICW (daughter LHW) is driven by the beat between the pump LHW and the daughter LHW (EICW). This requires plasma conditions which give the proper frequency and wavelength matching ($\omega_{pump} = \omega_{icw} + \omega_d$ and $k_{pump} = k_{icw} + k_d$). When the pump LHW is modulated near ω_{icw} its lower sideband coincides with ω_d and will pump the daughter LHW. The increased amplitude of the pump and the daughter LHW when coupled to the EICW will increase the amplitude of the EICW.

From kinetic theory [10] the heating rate for parametric decay of a CW pump LHW is

$$\frac{\partial T_\perp}{\partial(\omega_{ci}t)} = \left[4\pi^2 \frac{T_\perp}{T_e} \left(\frac{\omega_{pi}}{\omega_{ci}}\right)^4 \sum_{L=1}^{9} \left(\frac{\delta n}{n}\right)_L^2 J_L \right] T_\perp ,$$

where J_L is essentially a maxwellian integrated over weakly Landau damped resonant particles and L represents each of the ion cyclotron harmonics above which a decay wave was observed. An increase in the amplitude of the EICW, $\delta n/n$, will increase the heating rate.

Enhanced heating also arises from the higher peak

values of the modulated signal over the CW signal. This
was found to descrease the threshold average power
level for parametric decay [15]. Thus for a given power
above the threshold the amplitude of the EICW decay
wave would be larger and thus the heating due to the
parametric decay would be increased.

3. Experimental set up.

This experiment was per-
formed in a single ended Q-machine [16] which pro-
vided a low density ($5 \times 10^9 < n_e < 2 \times 10^{10}$
cm^{-3}), low temperature ($T_i = T_e \approx 0.2$ eV) nearly
completely ionized barium and cesium plasma 1.0 m
long and 5 cm in diameter (fig. 1). The confining mag-
netic field was 2–6 kG. The LHW were launched from
a slow wave antenna consisting of eight coaxial loops
[17]. The radial wavelength and resonance cone width
were measured and found to be consistent with the
dispersion relation. The modulated signal was created
by mixing a 30 MHz CW signal with a low frequency,
ω_{mod} (kHz), modulating signal in a mixing circuit.
Electron temperature was estimated with a Langmuir
probe.

Ion temperatures were determined from velocity
distributions measured with a laser induced fluores-
cence (LIF) diagnostic [18,19] which uses a tunable
dye laser to induce transitions to an excited state in
target plasma ions. Measuring the Doppler shifts of
the decay transitions in the direction perpendicular to
the magnetic field gave $f(V \perp B)$ (fig. 1). The spatial
resolution was limited only by the laser beam width
(collimated to 1 mm diameter). The velocity resolu-
tion was limited only by the natural linewidth of the
absorption line, corresponding to an uncertainty of
1000 cm/s or 0.03 V_{th} for cold ions ($T_i = 0.2$ eV).

4. Results.
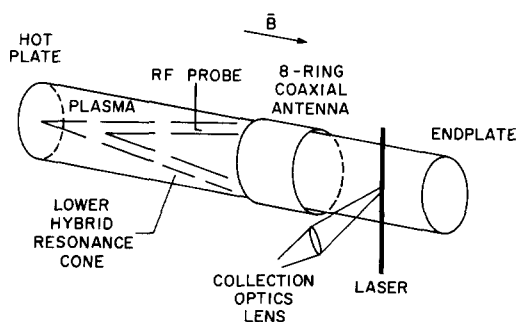
The conditions for the CW parametric
decay of LHW into EICW [20] were created. The de-
cay was characterized by the appearance of several
sidebands below the CW pump frequency, and the ap-
pearance of several low frequency waves. The low fre-
quency waves were identified as EICW by their B-field
dependence. Each low frequency wave and sideband
pair satisfied the frequency matching conditions sep-
erately. The low frequency waves followed $\omega_L = L(1$
$+ \delta_L)\omega_{ci}$, $\delta_L \neq \delta_{L+1}$, where L indicated the Lth har-
monic. Nine waves above the harmonics were seen.

The modulated RF signal consisted of the main
center frequency and several sidebands. When this sig-
nal was coupled into the plasma through the coaxial
antenna at an average power level 6 dB above thresh-
old not only were the LHW pump wave and its side-
band waves driven but several low frequency waves
were observed. It was found that these low frequency
waves were driven even at average power levels 2 dB
below the threshold level for the parametric decay of
the CW pump wave. The low frequency waves and side
band pairs satisfied the frequency matching conditions
These low frequency waves were all harmonics of the
frequency of modulation of the pump waves and fol-
lowed, $\omega_L = L\omega_{mod}$ where L is the Lth harmonic.

Fig. 2 shows increased heating due to the modu-
lated LHW with peaks near 70 kHz and 140 kHz.
From the EICW dispersion relation $\omega_{icw} \approx \omega_{ci}(1$
$+ 0.22 T_e/T_i)$, we expect frequencies around 68 kHz
for the EICW decay wave. The parametric decay of

Fig. 1. Schematic of experiment showing laser beam geometry.
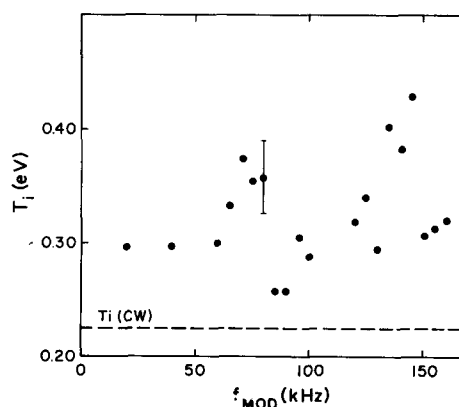Antenna launches waves toward hot plate.

Fig. 2. Ion heating versus frequency of modulation showing
enhanced ion heating at modulation frequencies near the ion
cyclotron frequency, 55 kHz. Dashed line: ion temperature
with unmodulated pump wave.

the CW LHW showed EICW waves at 65 kHz and 125 kHz. The peaks in heating (about a factor of 2 over the CW heating levels) suggest a resonant interaction between the low frequency harmonics of the modulated wave and the EICW of the parametric decay. This resonant interaction is consistent with the observation that these heating resonances disappeared at power levels below the parametric decay threshold.

The frequencies of modulation which showed heating peaks may not match the parametric decay waves, because of frequency mismatching. Since the set of EICW waves of the parametric decay are not exactly multiples of each other they will not match the set of low frequency harmonics of the modulated wave. Any resonant heating of the ions will be the sum of the heating over all harmonics. Only some of the modulated waves harmonics will be able to interact with the EICW for a given modulation frequency.

5. Conclusions. Ion heating enhanced by the modulation of a parametrically decaying LHW was examined. Peaks in heating at modulation frequencies near the ion cyclotron harmonics suggested resonant interactions between the EICW of the parametric decay and the low frequency wave generated by the modulated LHW. Modulation of LHW increased the ion temperatures up to a factor of 2 over that of the CW LHW.

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