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BY

G. R. ALLEN, D. K. OWENS,

S. W. SEILER, M. YAMADA,

H. IKEZI, M. PORKOLAB

PLASMA PHYSICS LABORATORY

MASTER

PRINCETON UNIVERSITY PRINCETON, NEW JERSEY

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PARAMETRIC LOWER-HYBRID INSTABILITY DRIVEN BY

MODULATED ELECTRON BEAM INJECTION

G. R. Allen, D. K. Owens, S. W. Seiler, and M. Yamada
Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08540

H. Ikezi
Bell Laboratories
Murray Hill, New Jersey 07974

and

M. Porkolab
Department of Physics and Plasma Fusion Center
M.I.T., Cambridge, Mass. 02139

A modulated electron beam is injected into a low β plasma parallel to the confining field to investigate the energy-transfer-rate from the electron beam to the plasma. Parametric excitation of electrostatic lower-hybrid waves and ion cyclotron quasimodes is experimentally identified. The temperature of both ions and electrons is observed to increase significantly concomitant with the growth of the instability.

Plasma heating by high energy particle beam injection is considered to be one of the most promising methods of obtaining the ion temperatures necessary for a thermonuclear plasma. Relativistic electron beam (REB) injection has the advantages of high energy density, easy beam production, and efficient beam-target energy transfer.[1] The mechanism by which the beam transfers its energy to the target plasma has been a subject of intensive research.[1-5]

In this paper we investigate a method for increasing the coupling of the energy of an electron beam to the target ions by modulating the beam density at or above the lower-hybrid frequency of the target plasma.[3,4] We observe that such a modulation can parametrically excite a lower hybrid wave and either an ion quasi-mode or an ion cyclotron mode.[6-11]

In the present experiment a density-modulated electron beam is injected parallel to the confining magnetic field of a low β, isothermal ($T_e \simeq T_i$) plasma. The significant contributions of this work are the detailed measurements of the subsequent parametric instability, including the frequency and wavenumber matching of the decay process ($\omega_o = \omega_1 + \omega_2$, $\vec{k}_o = \vec{k}_1 + \vec{k}_2$), the dispersion relations and the time dependent ion and electron heating caused by the instability.

The experiments were performed in the thermally ionized potassium plasma of the Princeton Q-1 device converted into a double-plasma machine, as shown in Fig. 1. A negatively biased mesh ($V_{mesh} \sim -18$ V, grid spacing

< Debye length) divides the plasma column (3.2 cm diam.) into a beam extraction plasma and an 87 cm long target plasma ($n_e \simeq 10^9 cm^{-3}$, $T_e \simeq .3$ eV, $T_i \simeq .4$ eV, confining magnetic field, B = 2 - 6 kG). With the target end-plate grounded and the beam end - plate at a slightly less negative voltage than the mesh, a suprathermal electron beam is driven into the target plasma. The beam is defined by a mechanical aperture (6 mm diam.) and has a velocity $v_b \simeq (-2e\, V_{bias}/m_e)^{1/2}$ and density $n_b \propto n_e(-eV_{bias}/T_e)^{1/2} \exp [e\, \Delta V_{mesh}/T_e]$. The sharp radial drop in plasma potential at the edge of the electron beam results in a strong radial electric field, and with an unmodulated high-density beam, the cross-field electron current ($c\, \vec{E}_r \times \vec{B}/B^2$) drives a modified two-stream instability with a peak amplitude at the lower-hybrid frequency and localized near the beam edge.[5] In the present experiment, V_{bias} is sufficiently small that this wave is not excited.

Superimposing a modulated voltage ($V_{mod} \sim 1$ V peak to peak on the mesh bias at a frequency $\omega_o \gtrsim \omega_{LH} \simeq (\omega_{pi}^2 + \omega_{ci}^2)^{1/2}$ (where $\omega_{pe}/\omega_{ce} << 1$ and $\omega_{pi}/\omega_{ci} \sim 7$) causes the beam density, and therefore the radial electric field, to oscillate at ω_o . This pump wave decays into a lower-hybrid wave ($\omega_2 = \omega_o - \omega_1$) and a low frequency decay wave ($\omega_1 \sim \omega_{ci}$) where the subscripts 0, 1, 2 denote the pump and the low and high frequency decay waves. The minimum threshold pump electric field is typically $c\tilde{E}_{ro}/BC_s \lesssim 0.15$ where $C_s^2 = T_e/m_i$, $\tilde{E}_{ro} = k_{ro}\, \tilde{\phi}_o$ is the fluctuating pump potential which is measured with a calibrated Langmuir probe.[12] The most unstable regime corresponds to pump frequencies $1 < \omega_o/\omega_{LH} < 1.4$. The amplitudes of both decay waves are peaked at nearly twice the beam radius, in contrast to the $\vec{E} \times \vec{B}$ driven instability.[5] Parametric decay occurs in discrete intervals of ω_o, typically $1 < \omega_o/\omega_{LH} < 2$, $4.5 < \omega_o/\omega_{LH} < 6.5$, and others up to $\omega_o/\omega_{LH} = 27$ (upper limit of wave generator). A typical frequency spectrum is shown in Fig. 2(a). The frequency matching rule ($\omega_o = \omega_1 + \omega_2$) is strictly satisfied for all ω_o.

The perpendicular wavenumbers were determined by measuring the phase shift between the signals detected by two probes as one probe was moved radially (k_r) or rotated azimuthally (k_θ) with respect to the other. Figure 2(b) demonstrates azimuthal wavenumber matching: $k_{\theta 1} = - k_{\theta 2}$, $k_{\theta 0} = 0$. The decay waves have standing wave structures in the radial direction where $|k_{r0}| < |k_{r1}| \simeq |k_{r2}| < |k_{\theta 2}|$, confirming radial wavenumber matching. The pump and decay waves are mixtures of traveling and standing waves in the axial direction. From the phase shift between two probes separated axially by L/3 (L = length of target plasma) and aligned to B, we find that $k_{z(0,1,2)} = 2\pi/NL$ with N = 1, 2, or 4 for each wave. The standing wave structures, determined from calibrated wave amplitude measurements at three probe positions separated by L/3, indicate k_z matching where $|k_{z1}| = |k_{z2}| = \pi/2L = 1/2|k_{z0}|$.

By comparing the experimental and theoretical dispersion relations (ω_2 vs. $k_{\perp 2}$), the high frequency decay wave has been identified as a lower hybrid wave (LHW) as shown in Fig. 3. The theoretical results are obtained from a numerical solution of the warm, fully magnetized plasma dispersion relation in a slab geometry.[12]

As candidates for the low frequency decay wave ($\omega_1 \sim \omega_{ci}$) one can consider the ion Bernstein wave (IBW, $\omega_1/k_{z1} v_e >> 1$,

$1.25 < \omega_1/\omega_{ci} < 2$), the ion cyclotron wave (ICW, $\omega_1/k_{z1}v_e << 1$, $1 < \omega_1/\omega_{ci} < 1.15$) and the ion quasi-mode (IQM) which has maximum growth rate[10] for $\omega_1/k_{z1} v_e \simeq 1$. where $v_e^2 = 2 T_e/m_e$. Experimentally, we find that $1/3 < \omega_1/k_{z1} v_e < 3$ and $0.4 < \omega_1/\omega_{ci} < 1.25$ for all ω_o, and the IQM requirements are always satisfied. The ICW requirements are occasionally met for $\omega_o > 1.2 \omega_{LH}$, but the ICW dispersion relation is not satisfied. The IBW is not found.

In the theory of parametric decay into a lower-hybrid wave (LHW) and an IQM, the LHW is a normal mode $[\varepsilon(\omega_2,\vec{k}_2) = 0]$ satisfying the dispersion relation as shown in Fig. 3(a). For a given ω_o , the IQM is a forced oscillation with ω_1 and k_1 determined by $\omega_1 = \omega_o - \omega_2$ and $k_{\perp 1} = -k_{\perp 2}$ (since $k_{\perp o} \simeq 0$). A typical IQM curve for $\omega_o/\omega_{LH} = 1.48$ is shown in Fig. 3(a). Each different ω_o results in a similar curve, but shifted in frequency, which intersects its corresponding IQM data point since ω and $\vec{k}_\perp$ matching and the LHW dispersion are satisfied. A numerical solution of the IQM dispersion theory predicts maximum growth rates for $k_\perp \rho_i \sim 2$, as observed.

Assuming an electrostatic pump wave of the form $E = E_o \cos (\omega_o t - \bar{k}_o \cdot \bar{x})$ where $k_{z0} << k_{\theta 0} < k_{r0}$ and $k_{z0}k_{z1}/k_{r0}k_{\theta 1} < \omega_o/\omega_{ce} << 1$, the dominant term in the parametric coupling coefficient is $\mu \equiv c \tilde{E}_{ro} k_{\theta 1}/B\omega_o$, corresponding to the azimuthal $\bar{E} \times \bar{B}$ drift of the electrons.[7]
For $\mu << 1$, $|\chi_{i,e}(\omega_2)| << |\chi_{i,e}(\omega_1)|$, and ignoring the decay wave at the upper sideband of the pump, the dispersion relation for

the parametric decay of the pump wave is[7,10]

$$\varepsilon(\omega)\varepsilon(\omega_0-\omega) + \frac{1}{4}\mu^2\chi_i(\omega)\chi_e(\omega) = 0 \quad , \qquad (1)$$

where $\varepsilon(\omega)$ and $\varepsilon(\omega_0-\omega)$ are the dielectric constants of the low- and high-frequency decay waves, and $\chi_{i,e}(\omega)$ are the ion and electron susceptibilities of the low-frequency decay wave.

In Fig. 3(b) the measured threshold values for the pump amplitude $[U/C_s = c(E_0/BC_s)]$ are compared with the calculated threshold $(\nu_e/\omega_{ci} = 0.3)$[7]: the agreement between experiment and theory is quite satisfactory considering that we have neglected the fine structure of χ_i.[10]

An important consequence of this instability is the strong perpendicular ion heating found experimentally and its possible implications for lower-hybrid or electron beam heating in fusion plasmas.[13] To investigate the dependences of the instability amplitude and the ion heating on the pump power, the modulated mesh voltage (pump) was pulsed on (rise time < 1 μsec) for 400 μsec. As seen in Fig. 4(a) the amplitudes of both decay waves grow, saturate, and fluctuate together as expected. Parallel and perpendicular ion temperatures were measured using a small (2 mm diameter) gridded Faraday cup positioned where the decay waves have maximum amplitude. The collector current signal is sampled with a resolution of 5 μsec. In Fig. 4(a), one sees a pronounced increase of $T_{i\perp}$ as the decay waves grow, without much change in $T_{i\parallel}$. Although this ion heating can be partly due to ion cyclotron damping of the IQM, the perpendicular interaction of the lower-side-band wave[5] with the ions is likely to cause most of the $T_{i\perp}$ increase with ion tail formation

We have plotted the probe-detected amplitudes of the pump, the LHW and the IQM as a function of V_{mod} in Fig. 4(b), and the associated increase in T_e is plotted in Fig. 4(c). With the onset of the instability one observes an enhanced absorption of the pump wave as shown in Fig. 4(b). For the IQM wave $\omega_1/k_{z1}v_e \simeq 1-2$, which indicates that the strong electron heating is due to electron Landau damping of the low frequency wave $[\tau_h = T_{eo}/(\partial T_e/\partial t) = 5\ \mu sec]$. The increase in T_e is limited by the heat conduction loss to the end-plate ($\tau_E = 5 \sim 10\ \mu sec$). Furthermore, for pump frequencies without parametric decay, the increase of $T_{i\perp}$ and T_e was small when compared with the heating when parametric instabilities were excited.

In summary, we have demonstrated that by modulating the density of an electron beam at or above the lower-hybrid frequency, the heating efficiency of both electrons and ions in a target plasma can be greatly increased. This increase is associated with the parametric excitation of lower-hybrid waves and ion cyclotron quasi-modes. Similar effects may be expected during heating of tokamaks with rf near the lower-hybrid frequency. Furthermore, similar heating techniques can be applied by modulating a beam at other eigenmode frequencies of the plasma.

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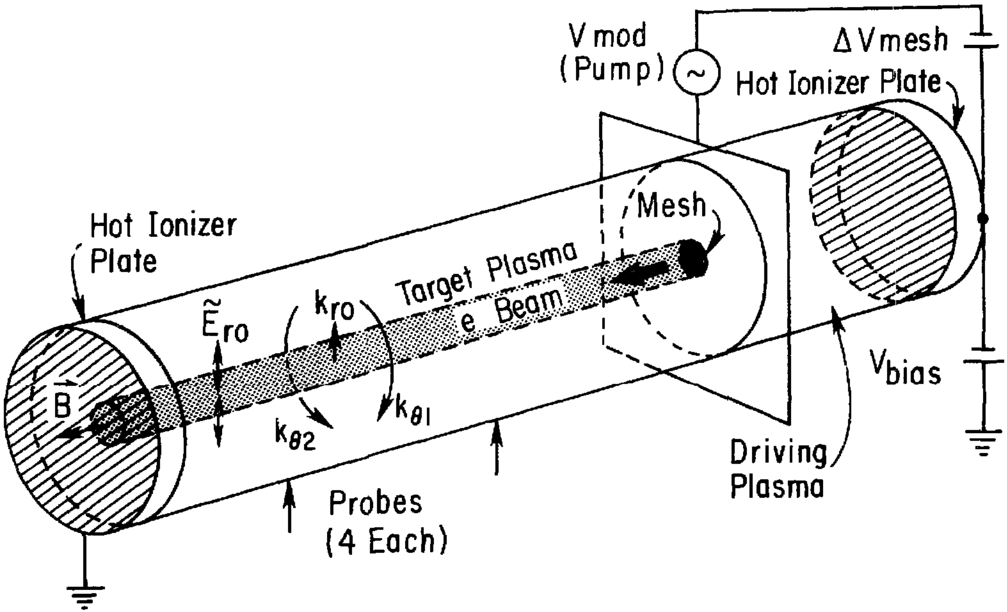
FIGURE CAPTIONS

Fig. 1. Schematic of beam-plasma system.

Fig. 2. (a) Typical frequency spectrum ($\omega_{ci}/2\pi$ = 156 kHz, $\omega_{LH}/2\pi \simeq$ 1.1 MHz). (b) k_θ matching (solid line is $k_{\theta 1} = - k_{\theta 2}$). Data points correspond to various ω_o with all other parameters constant (1.40 MHz $\leq \omega_o/2\pi \leq$ 1.53 MHz).

Fig. 3. (a) Dispersion relations of LHW and IQM. Solid curves are from warm fully magnetized plasma theory.[12] The 10 LHW and 10 IQM data points result from 10 different ω_o ($1.40 < \omega_o/\omega_{LH} < 1.53$). The X data points are for $\omega_o/\omega_{LH} = 1.48$. (b) Threshold pump power vs. ω_o, data and theory.[7] $\zeta = \omega_{ci}/k_{z1} v_e = 1,2$.

Fig. 4. (a) Decay wave amplitudes and $T_{i\perp}$ vs. time. V_{mod} (pump) is applied for $0 \leq t \leq 400$ μsec. Decay wave signals at $t < 20$ μsec are due to ringing from V_{mod} pulse. (b) Pump and decay wave amplitudes vs. V_{mod}. (c) T_e vs. V_{mod}. Closed circles are with the parametric instability present. Open circles are for a pump frequency without decay.



V mod
(Pump)
ΔV mesh
Hot Ionizer Plate
Mesh
Hot Ionizer
Plate
Target Plasma
e Beam
$\tilde{E}_{ro}$
k_{ro}
$k_{\theta 1}$
$k_{\theta 2}$
$\vec{B}$
Probes
(4 Each)
Driving
Plasma
V_{bias}

Fig. 1. 783221

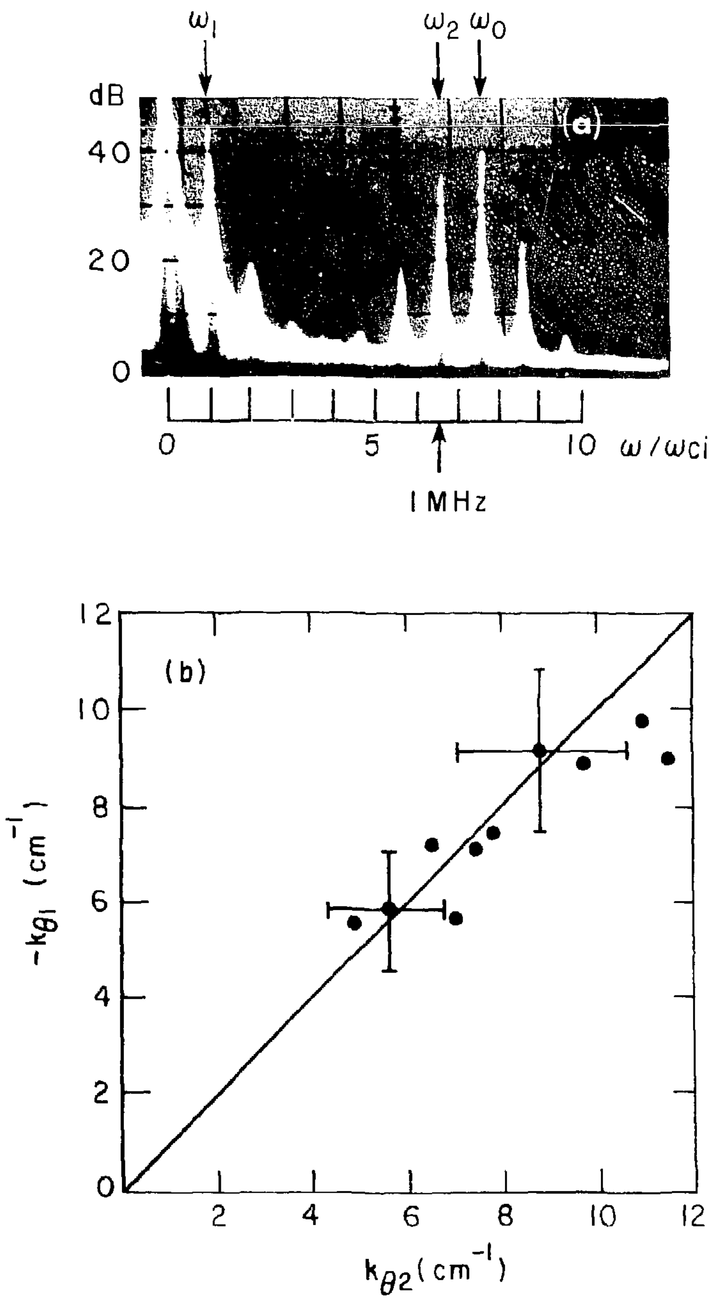

ω1
ω2 ω0
dB
40
20
0
(a)
0
5
10 ω/ωci
1MHz
12
(b)
10
8
6
4
2
0
2
4
6
8
10
12
-kθ1 (cm⁻¹)
kθ2(cm⁻¹)

Fig. 2. 783777

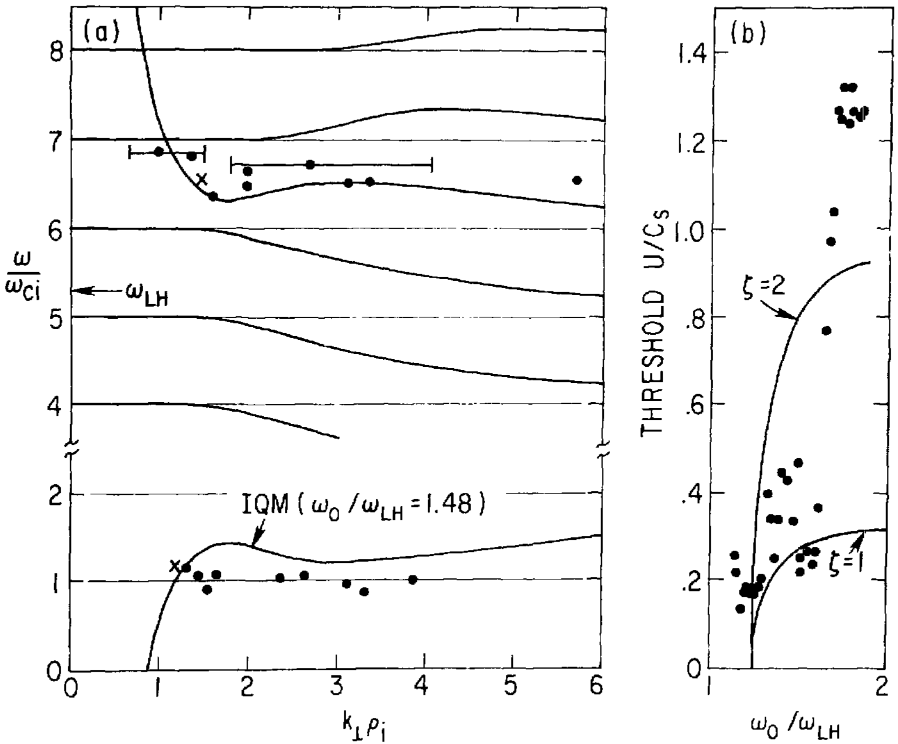


Fig. 3. 783786

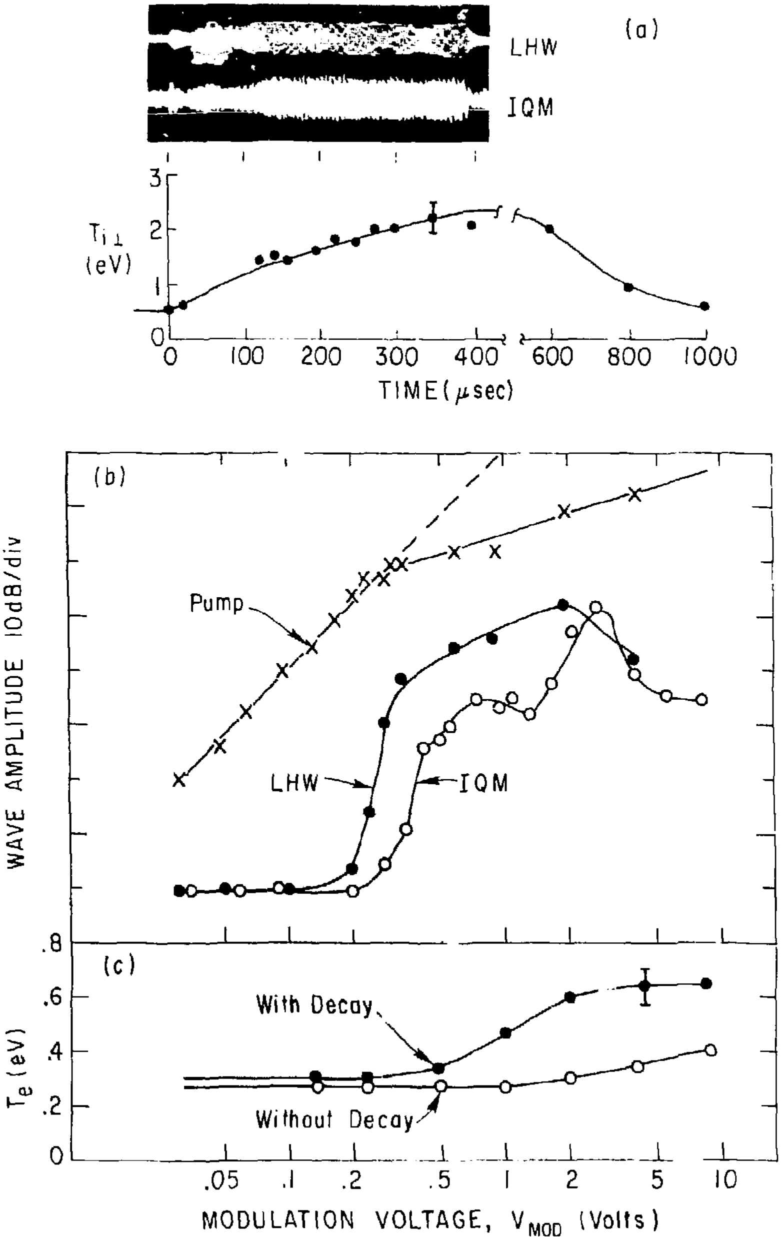

(a)
LHW
IQM
3
2
1
0
$T_{i\perp}$ (eV)
0
100
200
300
400
600
800
1000
TIME (μsec)
(b)
WAVE AMPLITUDE 10dB/div
Pump
LHW
IQM
.8
(c)
.6
.4
.2
0
T_e (eV)
With Decay
Without Decay
.05
.1
.2
.5
1
2
5
10
MODULATION VOLTAGE, V_{MOD} (Volts)

Fig. 4. 783787