JULY 1976 MATT-1268

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Price: Printed Copy $ _*__; Microfiche $1.45

*Pages	NTIS Selling Price
1-50	$ 4.00
51-150	5.45
151-325	7.60
326-500	10.60
501-1000	13.60

LOWER HYBRID INSTABILITY DRIVEN
BY A SPIRALING ION BEAM

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ABSTRACT

A lower hybrid instability with ion cyclotron harmonics is observed to be resonantly driven by an ion beam injected obliquely to the confining magnetic field, in agreement with a linear, warm plasma theory. Quasilinear velocity space diffusion of the beam is observed.

The interaction between an ion beam and a magnetized plasma is a topic of growing interest.[1] Injection of neutral beams into fusion plasmas is predicted to create unstable ion velocity distributions, especially for nontangential injection,[2] which may cause rapid velocity-space diffusion of the beam.[3] Recently many groups have reported ion-beam excited ion cyclotron modes.[4,5] A perpendicular ion-beam-driven lower hybrid mode has been observed[6] with unmagnetized beam and target ions ($k_y \rho_i >> 1$, $\omega_{pi}/\omega_{ci} \approx 10^2$-$10^3$) in a nonisothermal rf discharge plasma ($T_e >> T_i$), unlike a fusion plasma, and the observed instability was nonresonant.

The significant properties of the instability reported here are that it: (1) occurs in a magnetized isothermal target plasma ($k_\perp \rho_i \approx 1$, ω_{pi}/ω_{ci} = 2-30, $T_i \simeq T_e$); (2) occurs at the lower hybrid frequency (ω_{LH}) and, or nearby ion cyclotron harmonics; (3) is resonantly driven by the perpendicular velocity of the ion beam ($\omega/k \approx u_{b_\perp}$, $k_z \approx 0$); (4) is destabilized by low density beam ($n_b/n_t \lesssim 0.01$). These results are well explained by a linear electrostatic theory including a numerical analysis of a warm beam-plasma dispersion relation. Furthermore, instability induced anomalous velocity space diffusion of the ion beam is observed.

The experiment was performed in the thermally ionized potassium plasma of the Princeton Q-1 device ($T_e \lesssim T_i \simeq .35$ eV). To create an ion beam, the double-ended plasma is divided by a negatively biased mesh used to prevent electron flow[7,4] and the beam ions are accelerated from the positively biased source side into the grounded target plasma along the normal to the mesh surface (see Fig. 1). The angle with respect to the uniform magnetic field (1-7 kG in $\hat{z}$ direction), and the energy (0-100 eV) of the beam determine the spiral radius, ρ_b, and pitch length, L_{pitch}, of the resultant helical beam. A ring of meshes, each at a 45° angle, was used to create a cylindrical beam spiraling around the center of the target plasma, and Langmuir and energy analyzer probes were used to confirm the helical path.

The identification of the instability as a lower hybrid mode begins with the frequency measurements shown in Fig. 2 where the spectrum shifts with target density in agreement with the relation $\omega \simeq (\omega_{pi}^2 + \omega_{ci}^2)^{1/2}$ while the beam parameters are held constant. The instability occurs at just above the cyclotron harmonics near ω_{LH}, $\omega = n\omega_{ci} + \delta$, while the number of the harmonics present depends on the beam-target density ratio.

In the simple, cold, unmagnetized electron beam-plasma interaction, the most unstable mode is near ω_{pe}.[8] For a wave propagating perpendicular to B, strongly magnetized electrons do not contribute to the wave dynamics ($\omega/k_z >> v_e$, $k_y\rho_e << 1$, $\omega_{pe}/\omega_{ce} << 1$), so that an ion beam perpendicular to a magnetically confined target plasma can easily excite perpendicularly propagating ion Bernstein waves[9] at $\omega \approx n\omega_{ci}$ and, the most unstable mode is near ω_{pi}.[10]

The linear, electrostatic theory presented here uses a

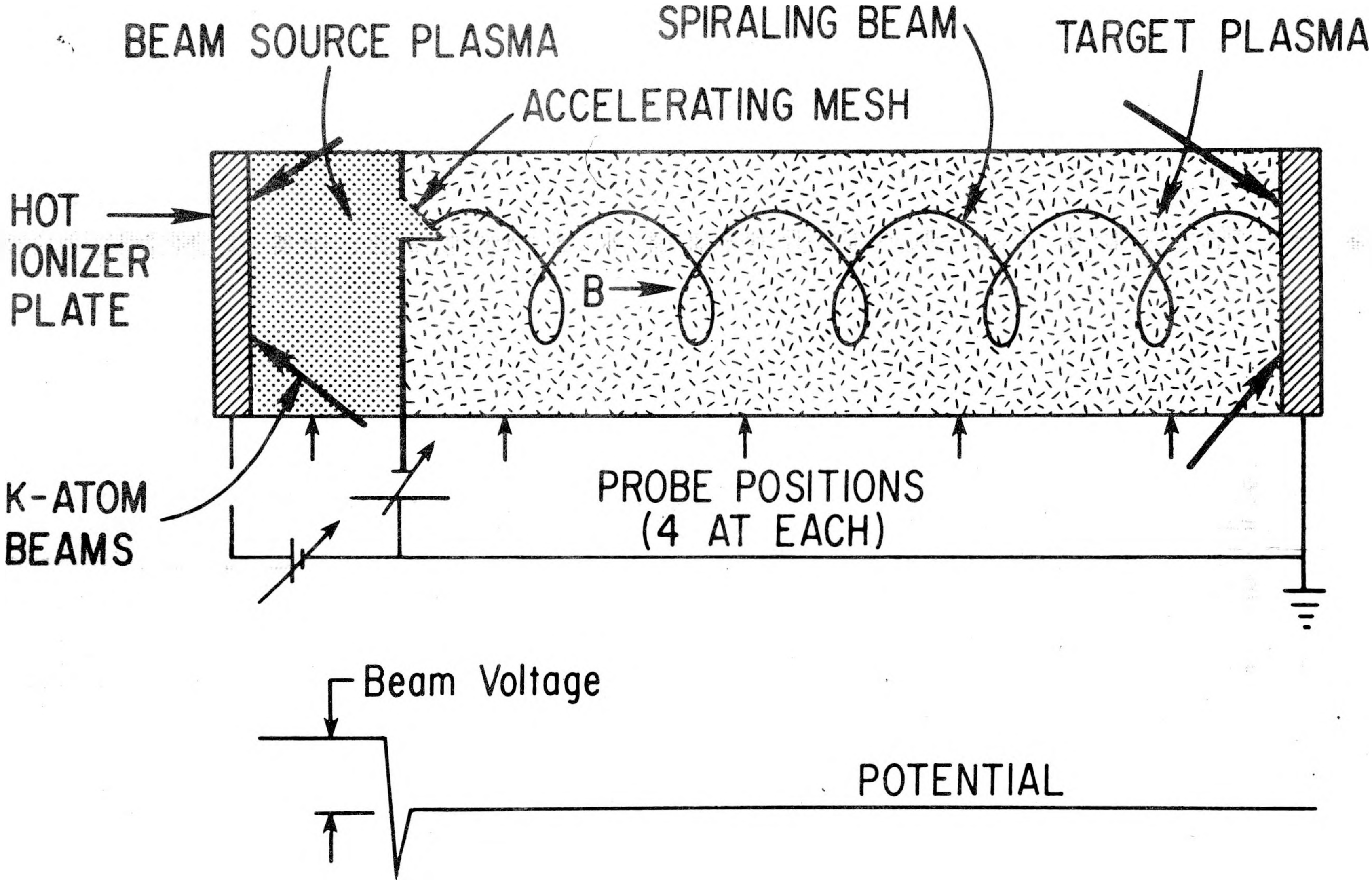

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Fig. 1. Schematic of machine layout.

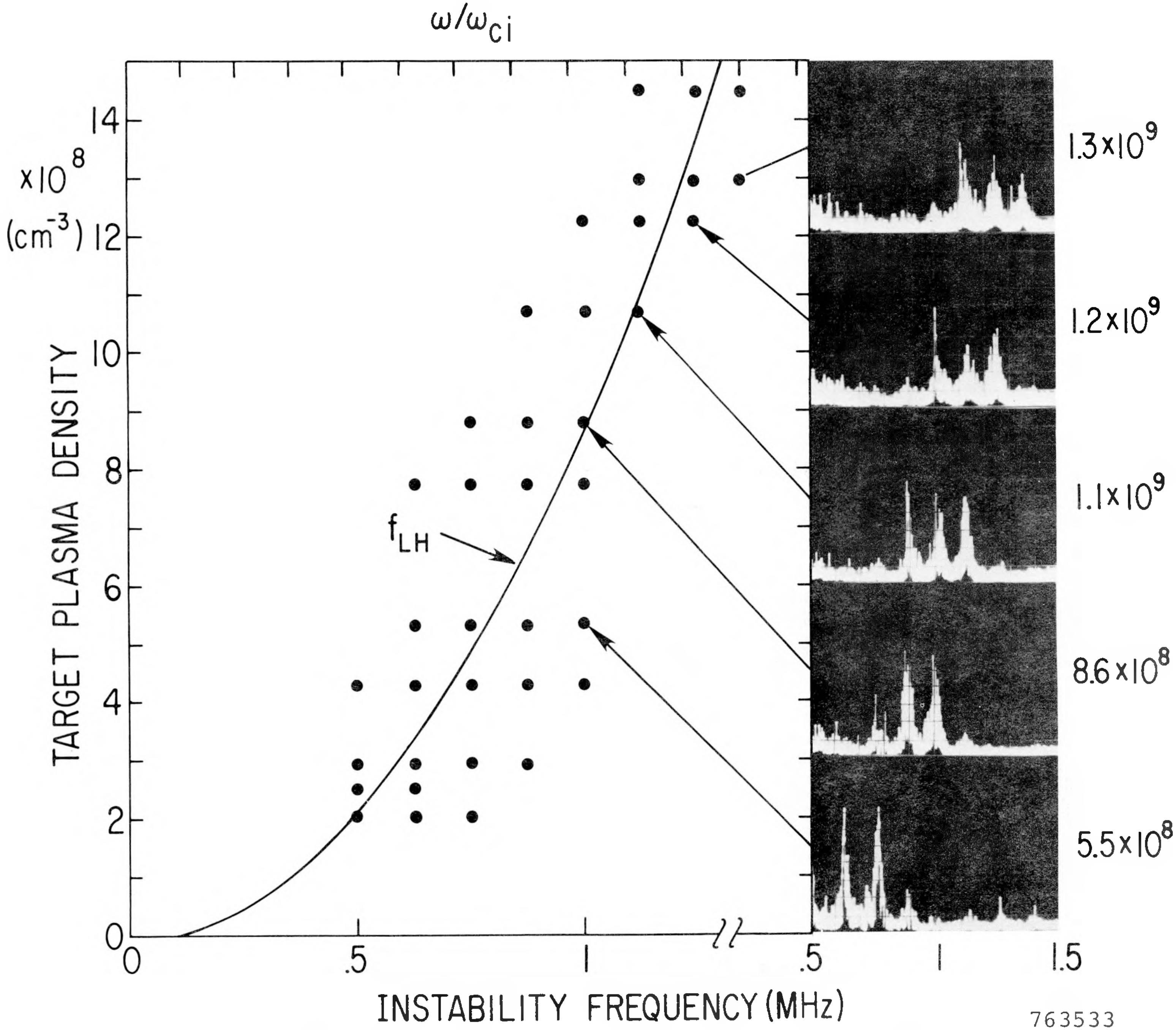

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Fig. 2. Frequency shift vs. target density for constant beam energy and density. Data points are the peak frequencies of the harmonics present at each density. Solid line is $f_{LH} = (\omega_{pi}^2 + \omega_{ci}^2)^{1/2}/2\pi$. Frequency spectra are shown at selected densities.

slab model with warm, Maxwellian beam and target ions and includes the kinetic coupling. The target ions are magnetized with $k_y \rho_i \approx 1$ and temperature T_t, but the perpenducularly injected beam ions are treated as unmagnetized, with velocity $u_{b_\perp}$ and thermal velocity spread $v_b \ll u_{b_\perp}$. Collisions are negligible since for the plasma conditions used $\lambda_{mfp} \gg L_{machine}$. The dispersion relation for $k_z \approx 0$, $\omega_{pe}/\omega_{ce} \ll 1$ is:

$$0 = 1 - \frac{k_{Di}^2}{k^2} \left[2e^{-\lambda} \sum_{n=1}^{\infty} \frac{(n\omega_{ci})^2}{\omega^2 - (n\omega_{ci})^2} I_n(\lambda) + \frac{1}{2} \frac{n_b}{n_t} \frac{T_t}{T_b} Z' \left(\frac{\omega - ku_{b_\perp}}{kv_b} \right) \right], \qquad (1)$$

where,

$\lambda = k_y^2 \rho_{it}^2/2$, $\rho_{it} = (2T_t/M\omega_{ci}^2)^{1/2}$,

$k_{Di}^2 = 4\pi n_t e^2/T_t$, $v_{i(b)} = (2T_{i(b)}/M)^{1/2}$,

$u_{b_\perp}$ = beam $\perp$ velocity, $n_{t(b)}$ = target (beam) density ,

I_n = modified Bessel function of n^{th} order ,

Z' = derivative of plasma dispersion function .

This equation is mathematically similar to the one used for electron Bernstein waves driven by a perpendicular ion beam,[11] and was solved numerically using experimentally measured parameter values. Without the beam term it is the ion Bernstein dispersion relation.[9] Figure 3(a) shows the calculated dispersion curve for the beam-plasma system when the spectrum 3(b) was taken. The coupling between the beam acoustic mode and the target ion Bernstein waves is clearly seen and the maximum growth is near the lower hybrid frequency in agreement with the experiment. In Fig. 3(b), the peak below ω_{ci} is a mode driven by the beam's parallel velocity component.[4]

This instability is resonant with the beam's perpendicular velocity and propagates azimuthally with the spiral beam. The resonance is confirmed in Fig. 4, where 4(a) shows the variation of the phase velocity ω/k of a single mode with $u_{b_\perp}$ and 4(b) the phase velocities of many cyclotron modes occurring for a single beam velocity. Some spread in the angle of injection is caused by the finite ratio of Debye length to mesh spacing[12] and may explain the spread of phase velocities in Fig. 4(a). Mode selection due to the closed azimuthal propagation ($m\lambda_y = 2\pi\rho_b$, where m is the azimuthal mode number) was observed and used to measure the group velocity, $d\omega/dk \simeq \Delta\omega\rho_b/(M_1 - M_2)$ around the most unstable harmonic; the results were in agreement with theory.

Phase shift measurements indicate that the instability is a standing wave both in the parallel direction[13] with $\lambda_z \gtrsim 2\,L_{machine} >> L_{pitch}$ and in the radial direction with $k_x \sim \pi/\rho_b < k_y$. Since perpendicularly propagating waves are not subject to either electron Landau or ion cyclotron damping, instability onset in this experiment is determined by the requirement that

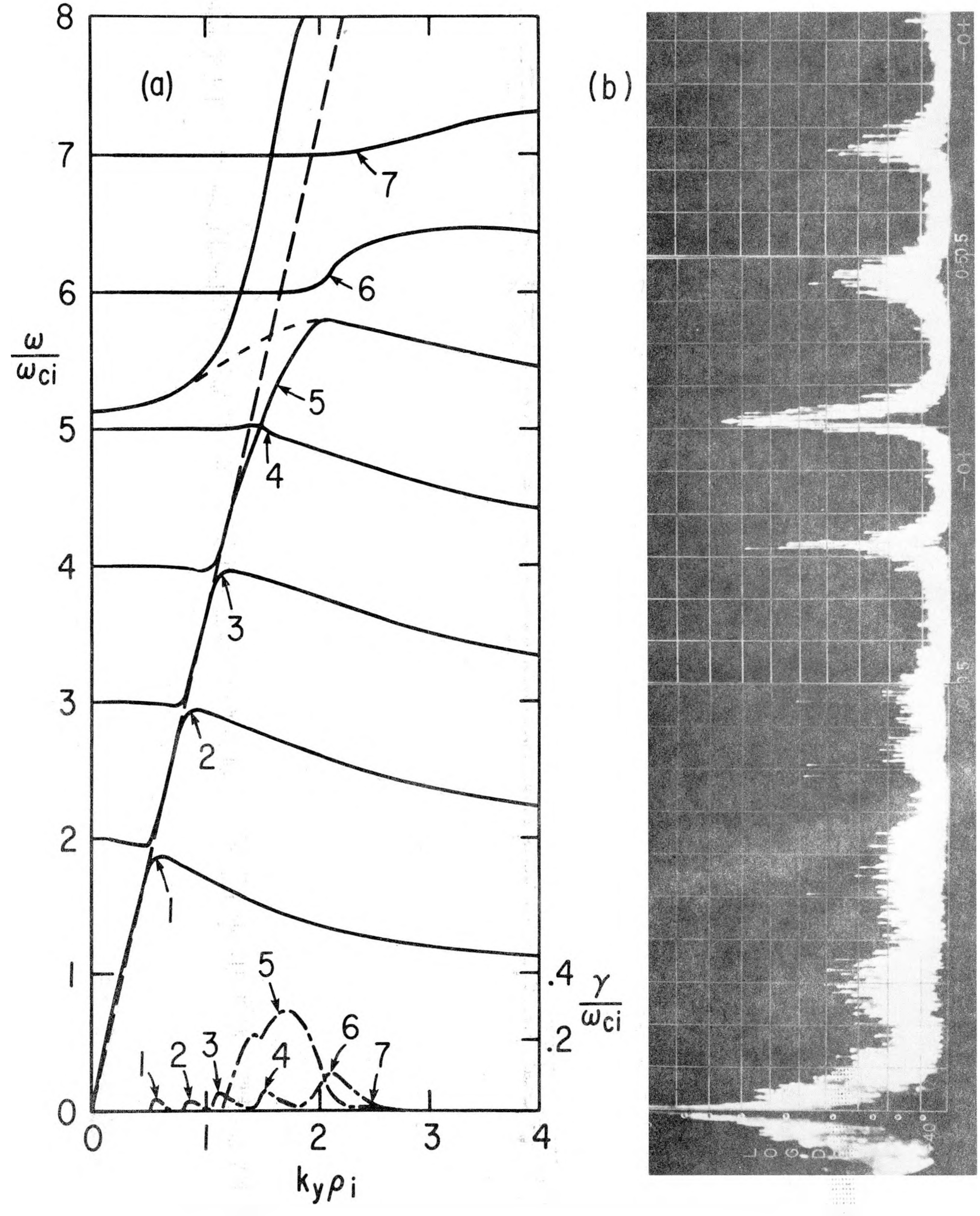

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Fig. 3. Dispersion relation and spectrum. (a) Computed dispersion for $n_t = 5.5 \times 10^8 cm^{-3}$, $n_b = 4 \times 10^6 cm^{-3}$, $T_t = .35$ eV, $B = 4$ kG, $u_{b\perp} = 3.6\ v_i$, $f_{LH} = 5.1\ f_{ci}$. Dashed line indicates beam velocity ($u_{b\perp} = \omega/k_y$); dot-dash the growth rates corresponding to the different cyclotron harmonics. (b) Observed frequency spectrum with the same parameters.

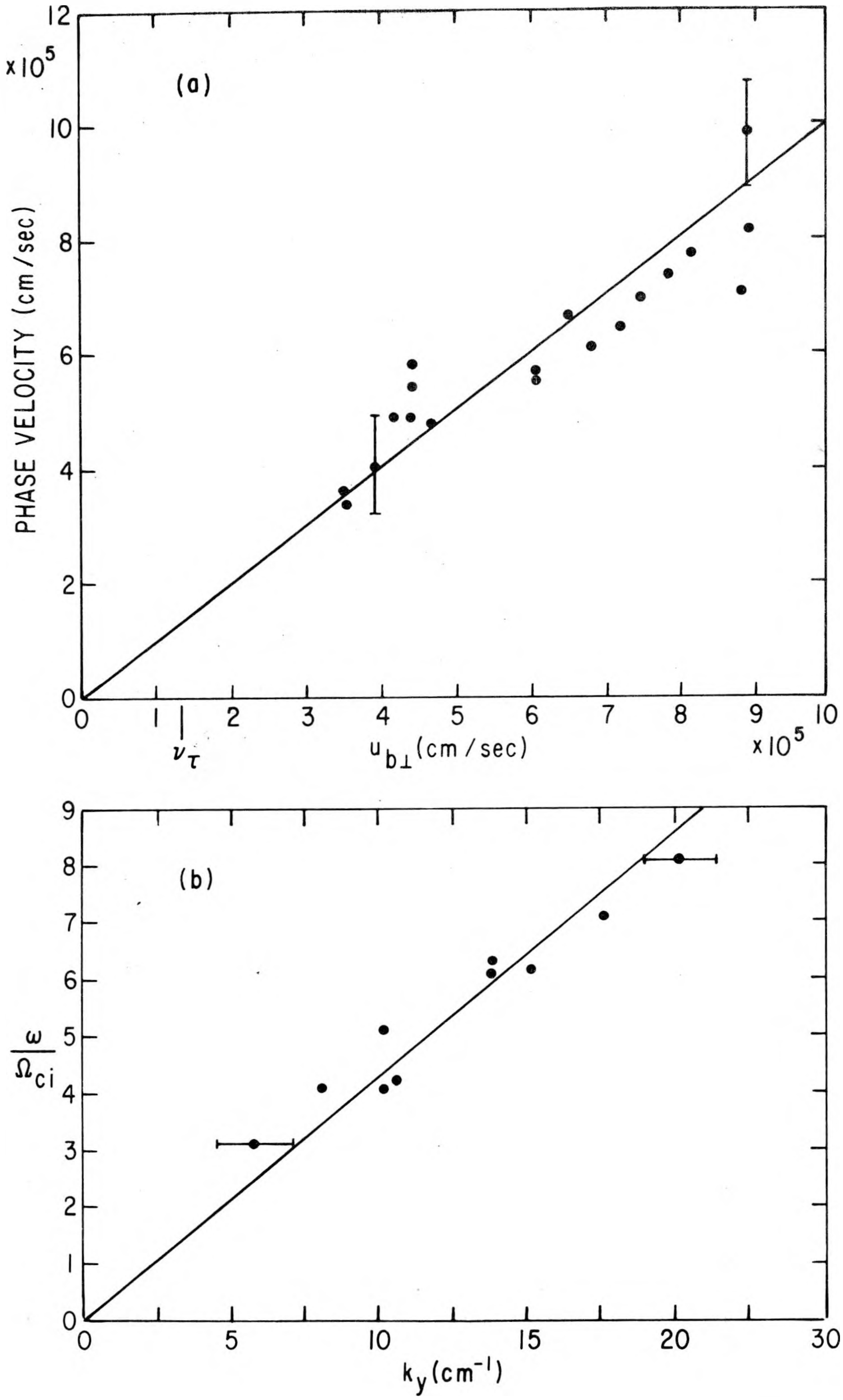

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Fig. 4. Beam-wave resonance. (a) Perpendicular phase velocity of a single mode vs. perpendicular beam velocity. (b) Dispersion for harmonics for a single beam energy. Solid line indicates constant phase velocity.

$\tau_{conf} \cdot \text{Im}\,\omega > 1$, where τ_{conf} is the beam lifetime[13] ($\approx 100/\omega_{ci}$). Because of its closed azimuthal propagation and standing wave parallel nature, the instability has no spatial growth. Temporal growth rates exceeding ω_{ci} are predicted by Eq. (1) for $n_b \gtrsim .05\, n_t$ and $u_{b_\perp}/v_i \gtrsim 3.5$, but since the beam transit time in the linear machine is much longer than the growth time and the parallel wavelength is longer than the machine, no reliable growth rate measurements could be obtained with pulsed beams. It is noteworthy, however, that the spectra observed in the nonlinear, saturated state exhibited maxima at the most unstable frequencies of the linear calculations, indicating the absence of strong mode-mode coupling or cascading phenomena.[14] The saturated amplitudes observed were roughly proportional to the linearly calculated growth rates. The measured dependences of wave onset (at $u_{b_\perp} \gtrsim v_i$) and amplitude on the beam and target parameters were in qualitative agreement with the theory.

Both the beam and target plasma were observed with an energy analyzer which measured both the parallel and perpendicular energy distributions. The positive slope of the beam's perpendicular velocity distribution was observed to be flattened by nonlinear wave-particle interactions when a strong instability was present. An estimate of the time necessary for perpendicular velocity space diffusion can be made from quasilinear theory;[3] using the experimental parameters it is $\tau_o \approx 7/\omega_{ci} << \tau_{conf}$ and the identification of the flattening as quasilinear velocity space diffusion is therefore justified. Anomalous heating of the target plasma could not be detected and was not expected because of the absence of electron Landau and ion cyclotron damping.

We have observed a lower hybrid instability driven by a perpendicular ion beam and instability induced nonlinear beam slowing. Good agreement was found with a warm-plasma theory. Similar ion distributions to the one in the present experiment can occur in both tokamaks and mirror machines during perpendicular neutral beam injection and anomalous velocity space diffusion is expected to play a major role in beam slowing,[2] and in plasma confinement in mirror machines.[15]

ACKNOWLEDGEMENT

It is a pleasure to thank Drs. F. W. Perkins, T. H. Stix, H. Eubank, and R. Kulsrud for their valuable discussions and comments.

This work was supported the U. S. Energy Research and Development Administration, Contract E(11-1)-3073, and H. Ikezi's work by Bell Laboratories.

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