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ELECTROSTATIC ION CYCLOTRON
INSTABILITIES DRIVEN BY
PARALLEL ION BEAM INJECTION

BY

M. YAMADA, S. SEILER, H. W. HENDEL
AND H. IKEZI

PLASMA PHYSICS
LABORATORY

MASTER

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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Electrostatic Ion Cyclotron Instabilities

Driven by Parallel Ion Beam Injection

M. Yamada, S. Seiler, H. W. Hendel*

Plasma Physics Laboratory, Princeton University

Princeton, New Jersey 08540

and

H. Ikezi

Bell Laboratories

Murray Hill, New Jersey 07974

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ABSTRACT

We report the detailed identification of two instabilities driven by an ion beam injected parallel to the confining magnetic field; a resonant ion cyclotron instability and a nonresonant ion cyclotron drift wave driven by the beam's density gradient. Experimental results are in good agreement with numerical calculations based on the kinetic Vlasov equations. Quasi-linear velocity space diffusion of the beam ions by wave-particle interaction is observed, demonstrating enhanced energy transfer. The relevance of these results to Tokamak neutral beam injection heating is discussed.

* Consultant from RCA Laboratories, Princeton, N. J.

1. INTRODUCTION

Ion beams streaming with supersonic velocity through a plasma may give rise to a number of different instabilities. Free energy stored in velocity anisotropies and density gradients may be tapped, driving eigenmode oscillations which relax the system into a new equilibrium. In isothermal ($T_e \approx T_i$), magnetized plasmas, such as those of fusion devices and Q-machines, ion acoustic waves are ion Landau damped and not expected to play an important role. However, ion cyclotron waves with higher phase velocity parallel to the confining magnetic field may be destabilized more easily by an ion beam with velocity above the ion thermal velocity of the plasma.

Thus, with the rapidly increasing use of neutral beam injection as the main auxiliary-heating method for fusion devices, strong interest in the possible destabilization of both microscopic¹⁻⁴ and macroscopic⁵ ion-beam-driven instabilities has been generated. Such instabilities may in turn lead to anomalous beam and plasma behavior and reduce the effectiveness of neutral beam injection. Beam ion distributions resulting from parallel beam injection were generally predicted to be unstable for electrostatic¹⁻⁴ and possible for electromagnetic⁴ ion cyclotron instabilities during the initial stage, but stable after slowing down of the beam ions. However, conclusive identification of such instabilities was impeded by experimental limitations.⁶

Recently, we reported briefly the identification of a resonant ($\omega/k_z \approx u_b$) ion cyclotron instability driven by a parallel ion beam, and explained the results by a kinetic theory which includes the beam acoustic term.⁷ Since then, two other ion cyclotron instability observations have been reported for beam-driven plasmas.^{8,9} In both cases, however, interpretation was complicated by the fact that the beam also had a large perpendicular component, and neither work attempted a complete numerical comparison of kinetic theory and experiment. An ion cyclotron instability destabilized by perpendicular ion injection has been observed.¹⁰

Ion beam injection in linear machines is easy to set up and can contribute to the understanding of neutral beam injection and instability effects, but differs from neutral injection in certain aspects. In the present experiment collisional slowing-down of the injected beam ions is negligible, whereas for neutral beam injection into fusion devices collisional relaxation of the beam velocity distribution plays an important role due to the longer particle confinement time.

In this work, we report the detailed identification of two instabilities driven by a parallel ion beam, the resonant ($v_{\text{phase}} = u_b$) ion cyclotron instability briefly described in a Letter earlier, and the nonresonant, beam-density-gradient driven ion cyclotron drift wave, and discuss the nonlinear wave-particle interactions leading to velocity-space diffusion of the beam ions. Section 2 describes the theory for the relevant instabilities excited by parallel ion beam injection. Section 3 contains the experimental results. Section 4 presents conclusions together with the discussion of the relevancy of these results to Tokamak neutral beam injection.

2. THEORY

Consider the injection of an ion beam into a uniform, low β (m_e/m_i), Maxwellian target plasma slab confined by a constant magnetic field in the $\hat{z}$ direction; m_e and m_i denote masses of electrons and ions. The target plasma is at equilibrium with $T_{e\perp} = T_{e\parallel} = T_{i\perp} = T_{i\parallel} = T_0$, but is drifting with velocity $-u_t \hat{z}$. The ion beam is injected on axis parallel to B , with $T_{b\perp} = T_0$, velocity u_b , and parallel velocity spread characterized by $v_{b\parallel} = (2T_{b\parallel}/M)^{1/2}$. The beam density profile is not uniform ($\partial n_b/\partial x \neq 0$ in the slab model). All species are singly charged so that $n_e = n_{it} + n_{ib}$, where n_e , n_{it} , n_{ib} are the electron, target ion, and beam ion densities. Collisions are neglected since the experiments were performed in the low density regime ($n_e < 10^9 \text{ cm}^{-3}$).

The dispersion relation from the Vlasov and Poisson equations for electrostatic waves with $k_{\perp} \rho_e \ll 1$, $\omega_{ce}/\omega_{pe} \gg 1$ is:

$$\begin{aligned}
 1 + \frac{k_{De}^2}{k^2} \left[1 + \frac{\omega - \omega_e^*}{k_z v_e} Z\left(\frac{\omega}{k_z v_e}\right) \right] \\
 + \frac{k_{Di}^2}{k^2} \left[1 + \frac{\omega + k_z u_t}{k_z v_i} \sum_{n=-\infty}^{\infty} I_n(\lambda) e^{-\lambda} Z\left(\frac{\omega + k_z u_t - n\omega_{ci}}{k_z v_i}\right) \right] \\
 + \frac{n_{ib}}{n_{it}} \frac{k_{di}^2}{k^2} \left[\frac{T_0}{T_{b\parallel}} + \sum_{n=-\infty}^{\infty} I_n(\lambda) e^{-\lambda} \right. \\
 \left. \times \frac{(\omega - k_z u_b - n\omega_{ci})T_0 + (n\omega_{ci} - \omega_{bi}^*)T_{b\parallel}}{T_{b\parallel} \cdot k_z v_{b\parallel}} Z\left(\frac{\omega - k_z u_b - n\omega_{ci}}{k_z v_{b\parallel}}\right) \right], \quad (1)
 \end{aligned}$$

where,

$$\begin{aligned}
 k_{De(i)}^2 &= \frac{4\pi n_{e(i)} e^2}{T_o} , & v_{e(i)} &= \left(\frac{2T_o}{m_{e(i)}} \right)^{1/2} , \\
 v_{b\parallel} &= \left(\frac{2T_{b\parallel}}{m_i} \right)^{1/2} , & \lambda &= \frac{k_{\perp}^2 T_o}{m_i \omega_{ci}^2} , & k_{\perp}^2 &= k_y^2 + k_x^2 , \\
 \omega_e^* &= - \frac{k_y T_o}{m_e \omega_{ce}} \frac{1}{n_e} \frac{dn_e}{dx} , & \omega_{bi}^* &= \frac{k_y T_o}{m_i \omega_{ci}} \frac{1}{n_{ib}} \frac{dn_{ib}}{dx} .
 \end{aligned}$$

The radial density gradient of the beam (but $n_{it} = \text{const}$) introduces diamagnetic drift frequencies. For drift waves, we thus use the conventional assumption $k_y > k_x$ in the slab model. $Z(\zeta)$ is the plasma dispersion function¹¹ and $I_n(\lambda)$ the modified Bessel function of order n . No static electric field was observed in the experiment and $\vec{E} \times \vec{B}$ drift has been neglected. The small parallel drift of the electrons ($v_d/v_e \leq m_e/m_i$) does not affect the results and has been excluded.

2.1 Resonant Ion Cyclotron Instability (Homogeneous Beam)

To consider the instabilities occurring in the uniform region of the beam we set $\omega_e^* = \omega_{ib}^* = 0$. The dispersion relation for $\omega/k_z < v_e$ becomes

$$\begin{aligned}
 & 1 + \frac{k_{De}^2}{k^2} (1 + i \sqrt{\pi} \omega / k_z v_e) \\
 & + \frac{k_{Di}^2}{k^2} \left[1 + \sum_{n=-\infty}^{\infty} I_n(\lambda) e^{-\lambda} \times \frac{\omega + k_z u_t}{k_z v_i} Z \left(\frac{\omega + k_z u_t - n \omega_{ci}}{k_z v_i} \right) \right] \\
 & + \frac{n_{ib}}{n_{it}} \frac{k_{Di}^2}{k^2} \frac{T_o}{T_{b\parallel}} \left[1 + \sum_{n=-\infty}^{\infty} I_n(\lambda) e^{-\lambda} \right. \\
 & \left. \frac{\omega - k_z u_b - n \omega_{ci} (1 - T_{b\parallel} / T_o)}{k_z v_{b\parallel}} Z \left(\frac{\omega - k_z u_b - n \omega_{ci}}{k_z v_{b\parallel}} \right) \right] . \quad (2)
 \end{aligned}$$

This equation is the same as Eq. (1) of Ref. 7 except for the addition of a small electron Landau damping term. Although this term is negligible for the present experiment, it may effectively stabilize a fusion plasma in which m_i/m_e is much smaller and $u_b \leq v_e$. Without the last term, representing the contribution of the ion beam, the dispersion equation would result in electrostatic ion cyclotron waves (neutralized ion Bernstein modes) with frequencies^{12, 13}

$$\omega \approx p \omega_{ci} [1 + I_p(\lambda) e^{-\lambda}] ,$$

in the target-ion frame ($u_t = 0$). These modes, which are stable in equilibrium plasmas, can be excited by an electron current^{12,14} or ion beam¹⁻³, when the drift or beam velocity falls into the region $v_i \ll u_b \ll v_e$. In both cases anisotropy in the parallel velocity distribution is the cause of instability. Equation (2) implies

that unstable roots are obtained when arguments of the two Z functions are small at the same time, i.e. when both

$$\omega + k_z u_t - p\omega_{ci} \approx 0, \quad (3a)$$

and
$$\omega - k_z u_b - q\omega_{ci} \approx 0, \quad (3b)$$

are satisfied, where p, q are integers.

Weibel,¹⁵ in the earliest contribution to ion beam-driven ion cyclotron waves, predicted instabilities driven by reactive coupling of beam and target ion cyclotron modes $p, q \geq 1$. With the approximation $|(\omega - k_z u)/k_z v_{ti}| > 3$, valid for the hydrodynamic limit, he omitted instabilities generated by the kinetic beam-target interaction. However, Eq. (2) invokes instabilities not only by reactive coupling of cyclotron or acoustic mode oscillations of target and beam ions, but also by kinetic interaction between modes and particles. Instability can occur when inverse Landau damping of the beam ions is greater than the target's ion cyclotron and electron Landau damping, allowing the wave to grow.

Perkins⁴ pointed out that the mode driven by kinetic, i.e. resonant, coupling of beam acoustic and target cyclotron terms has the lowest threshold beam velocity for destabilization. We call this mode a resonant ion cyclotron wave. Other modes with harmonic frequencies ($p\omega_{ci}$, $p = 0, \pm 1, \pm 2, \dots$, for $u_t \approx 0$) may also be expected from Eq. (3a) and (3b). These modes have different phase velocities in the target frame depending on the value of p and q . For the resonant cyclotron mode $p = 1$, $q = 0$, the phase velocity is almost equal to the beam velocity (Eq. (3b)). Kinetic effects become dominant when

$$\left| \frac{\omega - k_z u_{t,b} \pm n\omega_{ci}}{k_z \bar{v}_{b\parallel}} \right| \approx 1$$

and numerical computations were necessary to solve Eq. (2).

In Fig. 1 the numerically calculated growth rates versus frequency for the resonant ion cyclotron wave are shown for various beam velocities. This calculation includes the fact that accelerating the ions by a potential drop maintains the same spread in parallel energy but decreases parallel velocity spread ($T_{b\parallel}/T_o \approx T_o/2E_b$).¹⁶

From Eq. (3a) and (3b)

$$\omega \approx \omega_{ci} \frac{pu_b + qu_t}{u_b + u_t}, \text{ and } k_z \approx \frac{(p-q)\omega_{ci}}{u_b + u_t}, \quad (4)$$

are the frequencies and wave numbers with positive growth rate. The terms containing $p=1$ and $q=0$ result in oscillation frequencies below ω_{ci} and the mode between ω_{ci} and $2\omega_{ci}$ is due to $p=2$ and $q=0$. The frequencies increase when u_b becomes large, approaching ω_{ci} or $2\omega_{ci}$. We show in Fig. 2 the growth rate of the cyclotron-cyclotron mode which is mainly due to the terms of $p=1$ and $q=-1$. Although this mode can have a larger growth rate, it always has a higher threshold beam velocity than the resonant ion cyclotron instability. Also, in the experiment, the diamagnetic drift current of the beam effectively reduces the cyclotron damping and enhances the growth rate of the resonant ion cyclotron mode but not that of the cyclotron-cyclotron mode. These instabilities are convective in the parallel direction and absolute in the perpendicular direction, and there is no transport of wave energy across the magnetic field

$$\left(\frac{\partial \omega}{\partial k_{\perp}} = 0 \right).$$

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Fig. 1. Growth rate of resonant ($\omega/k_z \leq u_b$) wave vs. frequency. Numbers in circles refer to various beam velocities with optimum $k_{\perp \rho i}$. ① $u_b/v_i = 2.7$; ($k_{\perp \rho i} = 0.73$); ② 2.29, (0.80); ③ 3.2, (0.85); ④ 3.4, (0.85); ⑤ 3.6, (0.88); ⑥ 3.8, (0.94); ⑦ 4.1, (1.0); ⑧ 5.4, (1.05); ⑨ 7.0, (1.13). $u_t/v_i = 1.4$ (const.).

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 Fig. 2. Growth rate of cyclotron-cyclotron mode ($\omega/k_z \leq \frac{u_b}{2}$) vs. frequency. Numbers in circles refer to various beam velocities with optimum $k_{\perp} p_i \approx 1.45$;
 ① $u_b/v_i = 3.5$; ② 4.0; ③ 5.0; ④ 6.0; ⑤ 7.0; ⑥ 10.0.

2.2 Ion Cyclotron Drift Instability (Inhomogeneous Beam)

If the density gradient of the beam is included in the theory, another mode may become unstable, the ion cyclotron (diamagnetic) drift wave. In the experiment, the ion beam has a strong radial density gradient so that Mikhailovskii and Timofeev's criterion¹⁷ for destabilization of the ion cyclotron drift instability in a plasma without ion beam or current is satisfied. This instability is driven by the free energy associated with the beam's pressure gradient perpendicular to the magnetic field.

A flute type mode with $k_z \approx 0$ is most easily destabilized since neither electron Landau nor ion cyclotron damping of the wave occurs. In this limit Eq. (1) becomes:

$$1 + \frac{k_{De}^2}{k^2} \frac{\omega_e^*}{\omega} + \frac{k_{Di}^2}{k^2} \left[1 - \sum_{n=-\infty}^{\infty} \frac{\omega}{\omega - n\omega_{ci}} I_n(\lambda) e^{-\lambda} \right] \\ + \frac{n_{ib}}{n_{it}} \frac{T_o}{T_{b\parallel}} \frac{k_{Di}^2}{k^2} \left[1 - \sum_{n=-\infty}^{\infty} I_n(\lambda) e^{-\lambda} \right. \\ \left. \frac{\omega - n\omega_{ci} (1 - T_{b\parallel}/T_o) - \omega_{bi}^* T_{b\parallel}/T_o}{\omega - n\omega_{ci}} \right] = 0 \quad (5)$$

The stability criteria for the fundamental ion cyclotron mode ($\omega \approx \omega_{ci}$) can easily be found in the limit $k_{\perp}^2 \rho_i^2 \gg 1$ for the two cases (i) $T_{b\parallel} = T_o$ and (ii) $T_{b\parallel} \ll T_o$.

(i) For $T_{b\parallel} = T_o$

$$1 + \frac{k_{De}^2}{k^2} \frac{\omega_e^*}{\omega} + \frac{k_{Di}^2}{k^2} \left[1 - \frac{\omega}{\omega - n\omega_{ci}} I_1(\lambda) e^{-\lambda} + \frac{n_{ib}}{n_{it}} \left(1 - \frac{\omega - \omega_{bi}^*}{\omega - \omega_{ci}} I_1(\lambda) e^{-\lambda} \right) \right] = 0 \quad (6)$$

By a calculation similar to that of Ref. 17, the condition for overstability can be simplified using the fact that $n_e = n_{it} + n_{ib}$:

$$\kappa \rho_i \geq 2 \frac{\omega_{ci}}{\omega'_{pi}}, \quad (7)$$

$$\text{where } \kappa = \frac{1}{n_{ib} + n_{it}} \frac{dn_{ib}}{dx} = \frac{1}{n_e} \frac{dn_e}{dx}$$

$$\omega'_{pi} = \left(\frac{4\pi e^2 (n_{ib} + n_{it})}{m_i} \right)^{1/2} = \left(\frac{4\pi e^2 n_e}{m_i} \right)^{1/2}$$

This inequality is equivalent to the condition that the ion diamagnetic drift velocity is larger than the perpendicular phase velocity of the fundamental ion Bernstein mode. For typical experimental parameters ($n_{ib} \approx n_{it}$, $\omega_{ci}/\omega_{pi} \approx .25 - .07$, $\kappa \rho_i > .6 \rightarrow .14$), Eq. (7) is easily satisfied at the beam edge.

Figure 3 presents results of numerical calculations of the dispersion relation of the ion cyclotron drift wave for $\kappa \rho_i = 0.5$, $n_{ib} = n_{it} = 10^9 \text{ cm}^{-3}$. In analogy to the beam-plasma interaction, one obtains unstable ($\gamma > 0$) waves near the intersection points of the ion Bernstein dispersion curves with $\omega/k_y \approx v_{di}^* / (1 + k_y^2 \lambda_{di}^2)$, where we have used the assumption $k_y \gg k_x$. Thus, the frequency spectrum of this wave slightly depends on the average density and the radial density gradient of the beam.

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 Fig. 3. Dispersion curve of ion cyclotron drift wave. Frequency vs. azimuthal wave number. Broken lines are real part of the dispersion curve in unstable regime; dotted lines show growth rates. $B = 4$ kG, $n_{bi} = n_{ti} = 10^9$ cm $^{-3}$, $\kappa \rho_i = 0.5$.

(ii) For $T_{b\parallel} \ll T_o$, Eq. (5) becomes:

$$1 + \frac{k_{De}^2}{k^2} \frac{\omega_e^*}{\omega} + \frac{k_{Di}^2}{k^2} \left[1 - \frac{\omega}{\omega - \omega_{ci}} I_1(\lambda) e^{-\lambda} - \frac{n_{ib}}{n_{it}} \frac{\omega_{ci} - \omega_{bi}^*}{\omega - \omega_{ci}} I_1(\lambda) e^{-\lambda} \right] = 0 \quad (8)$$

Note that to first order the temperature ratio drops out of the approximation and the resultant stability requirement is the same as Eq. (7) except for a numerical factor.

Thus the theory predicts a parallel ($k_z \neq 0$), resonant instability inside the (homogeneous) beam and a nonresonant transverse ($k_z \approx 0$) diamagnetic drift instability on the edge of the (inhomogeneous) beam, both occurring near the ion cyclotron frequency.

3. EXPERIMENTAL APPARATUS AND RESULTS

3.1 Apparatus

The experiments were performed on the thermally ionized potassium plasma of the Princeton Q-1 device, Fig. 4. The plasma column (diameter 3.2 cm, confining field 2-7 kG) was divided by a negatively biased mesh (with grid spacing $< \lambda_{Debye}$) which prevented electron flow. The beam-source (end) plate was biased positively and the target-plasma-source plate was grounded. There can be no electron flow through the mesh, therefore, the entire potential drop occurs across the mesh, accelerating the ions into the target plasma.^{16,18} A mechanical aperture of variable diameter creates a well defined beam; the beam and target plasma densities can be varied independently by regulating

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Fig. 4. Sketch of experimental set-up.

the neutral fluxes impinging on the ionizer plates. The density gradient is much steeper at the edge of the beam than at the edge of the target plasma and the beam is injected coaxially so that the target density gradient is negligible in the beam region. Ion-ion collisions are negligible since $\lambda_{mfp} \gg L$ (L = machine length) and the plasma is highly ionized so that ion-neutral collisions can also be ignored. For the target plasma, $n_i \approx 10^9 \text{ cm}^{-3}$, $T_o = T_{i\perp} = T_{i\parallel} = T_{e\perp} = T_{e\parallel} \approx .35 \text{ eV}$, $u_t = (4T_o/m_i)^{1/2}$. For the beam, $n_{ib}/n_{it} \approx .1-5$, $E_b/T_o = 0-10^3$, $T_{b\perp} = T_o$. Probes measure T_e , T_i , n_{it} , n_{ib} , instability amplitudes and frequencies and their radial and axial profiles. An ion energy analyzer (2 mm diam., 1 mm aperture) which measures the distribution of background and beam ions can be turned into the beam, target and perpendicular directions and moved radially. Wavelengths are obtained from phase shift vs. rotation of a double probe (λ_y) or vs. distance of an axially or radially moving probe (λ_z , λ_x).

When an ion beam of sufficient density ($n/n_t \gtrsim .2$) is injected, two kinds of instabilities with frequencies close to the ion cyclotron frequency are excited. Figure 5a is a typical spectrum of the two instabilities, obtained with a probe located at the beam edge. The lower frequency wave has maximum amplitude at the center of the beam with spectral peak slightly lower than the ion cyclotron frequency and is identified as a resonant ion cyclotron wave. The higher frequency mode with $\omega = \omega_{ci} + \Delta$ occurring at the periphery of the ion beam (Fig. 5b), is an ion cyclotron drift wave destabilized by the density gradient of the beam.

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Fig. 5a. Typical spectra of two cyclotron instabilities.
 5b. Radial profile of wave amplitude. 1 - Resonant ion cyclotron wave with $m=0$. 2 - Resonant wave and nonresonant drift wave both with $m \neq 0$.

3.2 Resonant Ion Cyclotron Instability

Soft onset of an instability with a frequency slightly below the ion cyclotron frequency is observed as the beam velocity is increased above about twice the target ion thermal velocity. With further increase of the beam velocity, waves with higher harmonic frequencies (up to $n = 3$) also appear, in agreement with the theory.

Figure 6a shows measurements of instability frequency vs. B for constant beam velocity, taken well above onset. The observations are in agreement with the theory which includes Doppler shift due to the drifting target plasma. In the lab frame, the frequency of the mode near the fundamental cyclotron frequency is predicted to be:

$$\omega \approx \omega_{ci} [1 + I_1(\lambda) e^{-\lambda}] \frac{u_b}{u_b + u_t}$$

Figure 6b gives instability frequency vs. beam energy. At onset, the frequency lies about 35% below ω_{ci} . As the beam energy is increased the frequency approaches ω_{ci} when the target drift becomes negligible compared to the beam velocity ($u_t \ll u_b$). A calculation of u_t based on these frequency measurements gives a value in good agreement with the ion sound velocity, i.e., the predicted target drift velocity.¹⁹ The solid (theory) line includes measured changes of $k_{\perp} \rho_i$.

Parallel wavelengths were measured with an axially moving probe which was aligned to move parallel to the magnetic field with an accuracy of $\theta \leq 0.2^\circ$. In Fig. 7 typical correlation

Fig. 6a. Frequency vs. magnetic field strength. $u_p = 7 \times 10^5$ cm/sec.
 6b. Frequency vs. ion-beam energy. $u_t = \sqrt{2} v_i$, i.e. sound velocity.
 The calculated peak frequency is based on optimum values between 0.7 and 2.0 for $k_{\perp} \rho_i$. See Fig. 1. $B = 5$ kG.

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Fig. 7. Results of interferometer measurements of the parallel wavelength for various beam velocities. Correlation of signal from axially moving probe and reference probe signal are plotted vs. distance.

measurements of the parallel wavelength are shown. Resonant coupling of the wave with the ion beam is demonstrated in Fig. 8a. The wave phase velocity is about 5 -15% below the beam velocity, in agreement with the computer calculation shown by the solid line. Figure 8b displays the parallel wavelength vs. B for constant beam energy and indicates the predicted behavior of $\omega/k_z \approx 0.9 u_b$ and (for constant u_b) $\lambda_z \propto \omega_{ci}^{-1}$. The radial wavelength was comparable to the beam size (~ 5 mm). The azimuthal propagation was often found to correspond to a mode number $m=0$, but when $m \neq 0$ the propagation was in the same direction as the ion gyro-motion. The range of perpendicular wavelengths corresponds to $k_{\perp} \rho_i = 0.7-2.0$.

The wave is well confined to the interior of the beam. Spatial growth was measured with the axial probe. The observed spatial growth rate $k_i \approx 0.05 - 0.1 \text{ cm}^{-1}$ agrees with the calculated value using $k_i = \gamma / \frac{\partial \omega}{\partial k_z}$, Fig. 9. In the calculation, for a resonant ion cyclotron wave with $m \neq 0$, we include the effects of the diamagnetic drift due to the inhomogeneous ion beam. The maximum wave density fluctuation at saturation was found to be $\tilde{n}/n \approx 0.10 - 0.15$. The dependence of the threshold beam velocity (normalized by v_i) on the ratio of beam to target densities for constant B is shown in Fig. 10. The beam energy at onset is minimized for approximately equal beam and target densities. The solid line is the computer calculation which includes both the beam and target acoustic terms for $k_{\perp} \rho_i = 1.7$. Experiment and theory agree within the accuracy of the n_b/n_0 measurements.

Since the wave is excited at the expense of the parallel ion-beam energy (inverse Landau damping), one expects velocity

Fig. 8a. Parallel phase velocity of resonant ion cyclotron waves vs. beam velocity. Both axes normalized by $v_i = (2T_o/m_i)^{1/2}$. Solid line is theoretical curve. $n_{bi} \approx n_{ti}$. $B = 5$ kG. Broken line is cyclotron-cyclotron mode ($p=1$, $q=-1$).

8b. Parallel wavelength vs. B . $E_b \approx 20$ eV, $n_{bi} \approx n_{ti}$.

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 Fig. 9. Spatial growth of instabilities. Theoretical curve is calculated for resonant ion cyclotron mode with $\omega_i^* \neq 0$, $\kappa\rho_i = 0.2$, and $k_y\rho_i \approx 1$ ($m=3$). $n_{bi} \approx n_{ti}$.

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 Fig. 10. Threshold beam energy vs. relative beam density. If the beam diameter is 5 mm, the predicted modes have $k_{\perp}\rho_i = 0.8$ or $k_{\perp}\rho_i = 1.7$. Solid line computed for $k_{\perp}\rho_i = 1.7$ $(\omega - k_z u_b)/k_z u_{b''} \leq 0.5 \sim 3.1$.

space diffusion to occur at saturation: When the wave grows to large amplitude, the fluctuating fields scatter plasma and beam ions and cause diffusion in velocity space. Figure 11 presents the normalized parallel energy spread of the ion beam vs beam energy, both with and without instability. As the wave amplitude grows we observe flattening at the lower energy side of the beam's distribution function, where the resonant particles are located.

To evaluate this non-linear effect semiquantitatively, we calculate the quasi-linear diffusion time of the beam ions in the parallel velocity coordinate. We express the particle diffusion in three dimensional velocity space as ²⁰

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial \vec{v}} \cdot \vec{D}_v \cdot \frac{\partial}{\partial \vec{v}} f, \quad (9a)$$

where the diffusion tensor is given by

$$\vec{D}_v = 2\pi \left(\frac{e}{m}\right)^2 \sum_{\vec{k}} |E_k|^2 \frac{\vec{k} \vec{k}}{k^2} \delta(\vec{k} \cdot \vec{v} - \omega). \quad (9b)$$

Then the time constant for quasi-linear diffusion of the beam ions in the parallel velocity coordinate is found:

$$\tau_R \approx \frac{\left\langle \delta\left(\frac{\omega}{k_{\parallel}}\right) \right\rangle^2}{D_{v_{\parallel}}} = \frac{\left\langle \delta\left(\frac{\omega}{k_{\parallel}}\right) \right\rangle^3 k_{\parallel}}{2\pi \left(\frac{e}{m}\right)^2 \cdot \frac{k_{\parallel}^2}{k_{\perp}^2} (E_{k_{\perp}}^2)_{\text{at peak}}}, \quad (10)$$

where $\delta(\omega/k_{\parallel})$ is the parallel phase velocity interval occupied by waves, $\delta(\frac{\omega}{k_{\parallel}}) \approx v_{b_{\parallel}}$. Substituting experimental values,

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Fig. 11. Beam-energy spread with onset of instability. a) Beam-energy distribution before onset and with saturated instability. b) Beam-energy spread (normalized by spread at $E_b = 1$ eV) and instability amplitude vs. beam energy. Filled circles: $n_b/n_t \approx 2$, instability present; crosses: $n_b/n_t \approx 7$, instability absent.

$e\phi/T_0 \approx 0.1$, $\delta(\omega/k_{\parallel}) \approx 0.3 v_i$, $v_{ph}/v_i \approx 5$, we obtain

$$\tau_R \approx \frac{2}{\pi} \cdot \left(\frac{T_0}{e\phi}\right)^2 \cdot \left(\frac{v_{ph}}{v_i}\right) \left(\frac{\delta(\frac{\omega}{k_{\parallel}})}{v_i}\right)^3 \cdot \frac{1}{\omega_{ci}} \approx \frac{10}{\omega_{ci}} \quad (11)$$

This time is shorter than the transit time of the beam ions in the device ($\approx 100/\omega_{ci}$). Thus the observed flattening of the energy distribution of the injected beam ions is interpreted as the result of quasi-linear velocity space diffusion. The instability produces anomalous friction forces which effectively slow down the beam ions.

3.3 Ion Cyclotron Drift Instability

As indicated above, a steep density gradient in a radially inhomogeneous ion beam can excite ion cyclotron drift waves, which were predicted by Mikhailovskii and Timofeev¹⁷ for a plasma without beam or current, and experimentally identified by Hendel and Yamada^{21,22} in current-driven plasmas. In the present case, we observe such ion cyclotron drift waves with frequencies of $1.2 \omega_{ci}$ and $n\omega_{ci} + \Delta$ propagating in the ion diamagnetic direction in the density gradient region of the beam, in the absence of electron current. Figure 12 shows the peak frequencies versus magnetic field strength. As predicted, the most unstable waves have frequencies $1.10 \sim 1.25 \omega_{ci}$, with amplitudes more than 40 dB above the thermal fluctuation level of the plasma, and $\frac{\tilde{n}}{n} \approx 0.1$. At very high beam density ($n_b/n_t \geq 5$), the resonant modes described earlier are suppressed.

Fig. 12. Peak frequencies of an ion cyclotron drift wave vs. magnetic field strength. $n_{bi} = n_{ti}$. Probe located at beam edge, $r = 3$ mm; the spectrum agrees with the theory for $\kappa\rho_i = 0.8$.

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Unlike the resonant instability, the drift wave is independent of the beam's parallel energy and exists even when $E_b < T_o$ as long as criterion (7) is satisfied. The parallel wavelength was measured by both axial and fixed probes aligned with the B field. The results indicate that the wave is a standing wave with $\lambda_z \approx 2L$ (L =machine length) and is independent of any parallel properties ($E_{b\parallel}$, $T_{b\parallel}$) of the beam, $\omega/k_z \sim 6 \times 10^7$ cm/sec $> v_e$. Electron Landau damping generates a stabilizing effect on these waves.

The azimuthal wavelength was measured by a rotational double probe inserted radially^{21,22}, with the separation of the probe tips comparable to the perpendicular wavelength. Fig. 13 shows the dependence of the azimuthal wavelength on B, the solid line indicates $k_\perp \rho_i \approx 5$. In most drift wave experiments $\kappa (= 1/n \, dn/dx)$ is independent of B and therefore $v_{di}^* = \kappa c T_o / eB$ is inversely proportional to B. In the present work, however, $\kappa \propto B$, since the steepness of the density gradient of the injected ion beam is limited by ρ_i ; thus v_{di}^* is independent of B. Figure 14 compares v_{di}^* calculated (using measured parameters) with measured azimuthal phase velocity and confirms the prediction that both should be independent of B and the relation $v_{di}^* \geq \frac{\omega}{k_\perp}$. This ion cyclotron drift wave in a similar geometry (20 kV beam produced plasma) was observed by Gabovich and Soloshenko²³ but a complete comparison of the experimental dispersion relation with theory was not attempted.

Because of the long parallel wavelength, ion cyclotron damping and the resultant ion heating cannot occur. Electron Landau damping could lead to the appearance of a tail in the parallel electron velocity distribution but was not observed due to

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Fig. 13. Azimuthal wavelength vs. magnetic field strength. $n_p = n_i = 10^9 \text{ cm}^{-3}$; probe position $r = 2 \text{ mm}$. The solid line is the theoretical curve.

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Fig. 14. Comparison of azimuthal phase velocity with ion diamagnetic drift velocity. Closed circles, measured phase velocity; open circles, diamagnetic drift velocity calculated from static plasma parameters.

the good thermal conductivity of the electrons and their short transit time.

No obvious deterioration of the plasma confinement due to the presence of this instability was observed. Non-linear radial beam diffusion was looked for but could not be conclusively demonstrated. These results are not surprising since this short wavelength instability is not expected to produce a strong anomaly in the diffusion coefficient ($D_{\text{anom}} \propto \gamma/k_{\perp}^2 \sim 10^2 \text{ cm}^2/\text{sec}$): Confinement (1 msec) is determined by the high parallel losses in the present experiment.

4. CONCLUSIONS

Two distinct electrostatic ion cyclotron instabilities driven by an ion beam injected parallel to the confining magnetic field have been observed in an inhomogeneous, isothermal plasma. One of them, a parallel, resonant instability driven by inverse Landau damping of the beam was identified by measurements of ω and $\vec{k}$ and of threshold beam energy as function of relative beam density. The experiment is shown to be in good agreement with numerical calculations extended from Perkins' analysis of counterstreaming beams to include a beam of variable velocity and density, injected into a plasma flowing opposite to the beam with the velocity of sound. A nonlinear flattening of the beam's parallel velocity distribution by wave-particle interaction was observed and demonstrates enhanced energy transfer from the beam to the target plasma. This observation of velocity space diffusion is interpreted by quantitative quasi-linear calculations of the time necessary for this energy spreading to occur. The second instability observed is an ion cyclotron (diamagnetic) drift wave excited by the steep density gradient

of the beam, independent of the beams parallel energy. The measurements of frequency, wavenumber and its density dependence agree well with the predictions for this inhomogeneous plasma instability ($k_z \approx 0$) and no deleterious effects due to this instability on either the beam or target plasma were observed.

Neutral beams presently used for tangential injection into tokamaks^{1,2,25} are neither intense nor localized enough ($\Gamma = n_b E_b / (n_e T_e + n_{it} T_{it}) \lesssim 1$, $n_{bi}/n_{ti} \ll 1$, $u_b/v_i \sim 4$, $\kappa \rho_i < 0.1$) to excite the instabilities discussed above. However, these instabilities may occur in future high intensity neutral beam injection heating and colliding beam Tokamaks²⁴ during the transient switch-on of the beam. Immediately after injection, the velocity distribution of the (charge-exchanged) ions has a sharp peak at the injected velocity and it takes time ($t \leq \tau$ slowing down) to spread this peak by Coulomb-collisional slowing-down processes. Since the instability growth time may be much shorter than the collisional slowing-down time, instabilities may play a major role in the energy transfer from beam to plasma during this initial period. Detailed understanding of ion beam driven instabilities and their anomalous effects in fusion devices is essential for the optimization and control of neutral beam energy-deposition.

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