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ION-BEAM-DRIVEN ELECTROSTATIC ION
CYCLOTRON INSTABILITIES

By

A. Miura, H. Okuda and M. Ashour-Abdalla

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Ion-Beam-Driven Electrostatic Ion
Cyclotron Instabilities

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Abstract

We present results of numerical simulations on the electrostatic ion cyclotron instabilities driven by the ion beam parallel to the magnetic field. For the beam speed exceeding the thermal speed of background ions and the beam temperature much lower than the background ion temperature, it is found that the instability results in strong perpendicular heating and slowing down of parallel drift of the beam ions, leading to the saturation of the instability. Applications to plasma heating and space plasma physics are discussed.

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I. Introduction

Recently, there is a growing interest in the study of electrostatic ion-cyclotron (EIC) waves driven by an ion beam parallel to magnetic field. One such example is a space plasma near $1 R_E$ altitude on the auroral field line with regard to the mechanisms causing strong perpendicular heating of ions observed in situ at this altitude (e.g., Sharp et al., 1977). Another example is a fusion plasma subject to strong neutral beam injection (Stix, 1973). For the case of auroral plasmas, there are at least two energy sources driving EIC waves at this altitude (Kintner et al., 1979): one is the electron parallel drift and the other is the ion beam parallel to the magnetic field. The instability driven by parallel electron drift has been studied extensively in both linear (Drummond and Rosenbluth, 1962; Kindel and Kennel, 1971) and nonlinear (e.g., Okuda et al., 1981; Okuda and Ashour-Abdalla, 1981, 1982; Lysak et al., 1980) regimes. In contrast, the study of the ion beam driven EIC wave has remained mainly in the linear regime (Weibel, 1970; Perkins, 1976; Yamada et al., 1977; Kaufman and Kintner, 1982), although the understanding of the nonlinear consequence of the instability is essential in estimating plasma heating and beam slowing down. For the case of an auroral plasma, it has been established experimentally that the EIC waves are associated with parallel ion beam near $1 R_E$ altitude (Shelley et al., 1976; Kintner et al., 1979; Gorney et al., 1981; Cattell, 1981; Temerin et al., 1981; Mizera et al., 1982).

The purpose of this letter is to report the initial results of the particle simulation study of the EIC instability driven by the parallel ion beam. While the current-driven EIC wave is driven by the inverse electron Landau damping by the drifting electrons, the ion beam can destabilize EIC waves both by resonant (Perkins, 1976; Yamada et al., 1977) and nonresonant

(Weibel, 1970) interactions. The resonant case driven by the inverse ion Landau damping has the lowest threshold; however, the growth rate for this case is smaller than that driven by a reactive coupling between beam cyclotron modes and background ion cyclotron modes (Perkins, 1976). For the resonant case, the instability occurs at $\omega/k_{\parallel} \sim u_b$, where u_b is the ion beam velocity relative to the background ions: on the other hand, the nonresonant case is characterized by the phase velocity $\omega/k_{\parallel} \sim u_b/2$ (Yamada et al., 1977). On auroral field lines near $1R_E$ altitude, the ion beam has been observed to have a drift velocity typically a few hundred km/sec (Kintner et al., 1979; Mizera et al., 1982), suggesting that the observed ion beam is accelerated upward by a potential difference of a few KeV existing below $1 R_E$ altitude. For such a large parallel beam velocity exceeding the thermal speed of ions of ionospheric origin ($u_b \gg v_{t\parallel}$), the instability condition is easily satisfied and we expect that the parallel ion beam is a viable energy source for the EIC waves observed at $1 R_E$ altitude (Mozer et al., 1977; Kintner et al., 1979).

II. Linear Theory

The dispersion relation for the ion beam driven EIC waves (Yamada et al., 1977) in a three components plasma is given by

$$1 + \frac{1}{k^2 \lambda_{e\parallel}^2} + \frac{1}{k^2 \lambda_{t\parallel}^2} \left[1 + \sum_{n=-\infty}^{\infty} \Gamma_n \frac{\omega - n\Omega_i (1 - T_{t\parallel}/T_{t\perp})}{k_{\parallel} v_{t\parallel}} Z\left(\frac{\omega - n\Omega_i}{k_{\parallel} v_{t\parallel}}\right) \right] \\ + \frac{1}{k^2 \lambda_{b\parallel}^2} \left[1 + \sum_{n=-\infty}^{\infty} \Gamma_n \frac{\omega - k_{\parallel} u_b - n\Omega_i (1 - T_{b\parallel}/T_{b\perp})}{k_{\parallel} v_{b\parallel}} Z\left(\frac{\omega - k_{\parallel} u_b - n\Omega_i}{k_{\parallel} v_{b\parallel}}\right) \right] = 0 \quad , \quad (1)$$

where u_b is the ion beam speed, Ω_i is the ion gyrofrequency, $\Gamma_n(\mu_i) = \exp(-\mu_i) I_n(\mu_i)$, $\mu_i = k_{\perp}^2 v_{i\perp}^2 / 2\Omega_i^2 \equiv k_{\perp}^2 \rho_i^2$, $T_{t\parallel}$ and $T_{t\perp}$ are parallel and

perpendicular temperatures of background (target) ions, $T_{b\parallel}$ and $T_{b\perp}$ are parallel and perpendicular temperatures of beam ions, $v_{e\parallel} = (2T_e/m)^{1/2}$, $v_{t\parallel} = (2T_{t\parallel}/M)^{1/2}$, $v_{b\parallel} = (2T_{b\parallel}/M)^{1/2}$, $\lambda_{e\parallel} = v_{e\parallel}/\sqrt{2}\omega_{pe}$, $\lambda_{t\parallel} = v_{t\parallel}/\sqrt{2}\omega_{pti}$, $\lambda_{b\parallel} = v_{b\parallel}/\sqrt{2}\omega_{pti}$, and Z is the plasma dispersion function. In (1) we have neglected a small term due to the electron Landau damping by the assumption $\omega/k_{\parallel} \ll v_{e\parallel}$, but instead we have included the effect of anisotropic bi-Maxwellian ions by introducing parallel and perpendicular temperatures. One of the nonlinear consequences of the ion cyclotron instability is the generation of temperature anisotropy by perpendicular ion heating. Therefore, Eq. (1) may be used to determine the maximum temperature anisotropy $T_{\perp}/T_{\parallel}$ from the marginal stability condition for a given drift speed (Okuda and Ashour-Abdalla, 1981, 1982).

For the case of resonant interaction we retain only $n = 0$ for beam ions and $n = 1$ for background ions in (1). Then, assuming that $|(\omega - k_{\parallel} u_b)/k_{\parallel} v_{b\parallel}| \ll 1$ and $|(\omega - \Omega_i)/k_{\parallel} v_{t\parallel}| \gg 1$, we obtain

$$\frac{\omega - \Omega_i}{\Omega_i} = \Gamma_1^t \left(\frac{n_{ib}}{n_{it}} \frac{T_{t\perp}}{T_{b\parallel}} + \frac{n_e}{n_{it}} \frac{T_{t\perp}}{T_e} \right)^{-1}, \quad (2)$$

where n_{ib} , n_{it} , n_e are densities of beam ions, background ions, electrons, and Γ_1^t is defined by the background ions. Therefore, when the beam is cold ($T_{b\parallel} \ll T_{t\parallel}$), we find the frequency $\omega \gtrsim \Omega_i$ for $n_{it} \sim n_{ib}$.

For nonresonant interaction the instability is driven by the coupling between slow wave (negative energy wave) on the ion beam and ion cyclotron mode on background ions. Therefore by retaining $n = 1$ for background ions and $n = -1$ for beam ions and assuming $|(\omega - \Omega_i)/k_{\parallel} v_{t\parallel}| \gg 1$ and $|(\omega - k_{\parallel} u_b + \Omega_i)/k_{\parallel} v_{b\parallel}| \gg 1$, we obtain

$$\frac{\omega - \Omega_i}{\Omega_i} = -2 \left(1 - \frac{k_{\parallel} u_b}{2\Omega_i}\right) \frac{1}{1 - (\Gamma_{-1}^b / \Gamma_1^t)(T_{t\perp} / T_{t\parallel})(n_{ib} / n_{it})(T_{b\parallel} / T_{b\perp})}, \quad (3)$$

where Γ_{-1}^b and Γ_1^t are defined by beam ions and background ions, respectively, and the term from the electron shielding is neglected assuming $\omega \approx \Omega_i$. This predicts that as $T_{b\parallel} / T_{b\perp}$ approaches to zero as a result of perpendicular heating of ion beams by the EIC wave, ω approaches to Ω_i , increasing the cyclotron damping of waves by background ions. In the limit $\omega \rightarrow \Omega_i$ we obtain from (3) $\omega / k_{\parallel} \sim \Omega_i / k_{\parallel} \sim u_b / 2$. In the beam frame, the frequency is given by

$$\omega - k_{\parallel} u_b \approx \Omega_i - 2\Omega_i = -\Omega_i.$$

Therefore, in the same limit $T_{b\parallel} / T_{b\perp} \rightarrow 0$, the cyclotron damping by beam ions also increases. These results suggest that in the nonlinear stage of the nonresonant case, if the ions are heated preferentially in the perpendicular direction, the destabilizing term due to the nonresonant reactive cyclotron-cyclotron coupling is balanced by cyclotron damping of waves by background (target) ions and beam ions.

III. Simulation Results

Here we consider a three component plasma consisting of background electrons, background ions, and beam ions. We assume Maxwellian distributions for both electrons and background ions, and a drifting Maxwellian distribution for the ion beam with beam speed u_b .

The simulation code used is a one spatial dimension and 3 velocity dimensions (Lee and Okuda, 1978). This code uses the drift kinetic approximation for electrons ($k_{\perp} \rho_{Le} \ll 1$ and $\omega \ll \Omega_{ce}$), but retains the full

ion dynamics in 3-D velocity space. Parameters used in the simulations are L (system length) = 128Δ , Δ = electron Debye length, $m/M = 1/1837$, and $\omega_{pe} \Delta t = 2.0$. In accordance with the S3-3 data near 1 R_E altitude, we use $T_e = T_{it} = T_{t\parallel} = T_{t\perp}$, $T_{ib} = T_{b\parallel} = T_{b\perp} = T_{it}/16$, $k_{\parallel}/k_{\perp} = 0.1$, $n_{ib}/n_{it} = 1.0$, $\omega_{ce}/\omega_{pe} = 2.0$, and $u_b = 20 v_{t\parallel}$.

Figure 1 shows profiles in the x direction of the electrostatic potential $e\phi/T_e$ (1-a), electron density n_e (1-b), background ion density n_{it} (1-c), and beam ion density n_{ib} (1-d) at $\Omega_{it} = 160$. A coherent wave with a single wave period is seen in all profiles. Note that the variations in n_e , ϕ , and n_{ib} are almost in phase, while those between n_{it} and n_{ib} are almost out of phase. The wave amplitude in n_{ib} is larger than that in n_{it} . As we will see later, the beam ions are heated strongly with a large increase in $T_{\perp}$ by this time.

Figure 2 shows frequency spectra in the rest frame (frame of electron background) of the 1st and 3rd modes for linear phase, $0 < \Omega_{it} < 40$ (2-a,c) and for later period, $0 < \Omega_{it} < 160$ (2-b,d). In Fig. 2-a, the peak of the frequency spectrum of the 1st mode occurs below the ion cyclotron frequency. However, for the later period (Fig. 2-b), the peak of the spectrum of the 1st mode occurs at $\omega > \Omega_{it}$. This nonlinear frequency shift of the EIC wave from $\omega < \Omega_{it}$ to $\omega > \Omega_{it}$ gives rise to a perpendicular heating of background and beam ions, causing damping of the EIC wave. For the 3rd mode, the frequency spectra (Figs. 2-c and 2-d) occurs at harmonics of Ω_{it} .

Since the parallel phase velocity $\omega/k_{\parallel}$ shows us whether the instability is driven by resonant interaction or by nonresonant interaction we should check $\omega/k_{\parallel}$ by the simulation results. For the peak spectrum for the 1st and 3rd modes shown in Fig. 2-a and c, we obtain

$$\omega/k_{\parallel} = 0.38 u_b, 0.64 u_b.$$

Therefore, for the present simulation parameters with a large beam velocity, the parallel phase velocity is well below the ion beam velocity, nearly equal to one-half of the beam velocity, and the EIC waves are destabilized essentially by nonresonant interaction between beam cyclotron mode and cyclotron mode on the background ions (Weibel, 1970).

We show in Fig. 3 perpendicular and parallel velocity distributions for background ions (3-a,b) and beam ions (3-c,d). Since the electron contribution is only to give a small Landau damping, the electron velocity distribution was found to suffer a negligible change.

While the perpendicular heating of background ions remains small (Fig. 3-a), the beam ions are heated strongly (Fig. 3-c). Figure 3-d shows that the ion beam is decelerated in the parallel direction by the instability which, at the same time, caused diffusion in the beam parallel velocity.

Shown in Fig. 4 are contours of particle distribution in the velocity space ($v_x - v_{\parallel}$) for background ions (4-a,b) and for beam ions (4-c,d) at $t = 0$ and $\Omega_i t = 160$. Initially the beam is cold ($T_{ib} = T_{it}/16$) and isotropic; however, the beam ions are heated strongly in the perpendicular direction (4-d) and form an anisotropic distribution. The perpendicular temperature of beam ions at the final stage becomes about 30 times larger than its initial temperature. The background ions are also heated in the perpendicular direction (4-b) with $T_{\perp i}(\Omega_i t = 160)/T_{\perp i}(t = 0) \sim 3$. It should be noted that in the final stage the velocity spread in the perpendicular direction becomes comparable for both background and beam ions, and the equipartition of perpendicular energy between two ion components is realized.

We have shown in Fig. 3 that, along with the perpendicular heating, the

original beam velocity slows down, and the diffusion in the parallel velocity occurs by the instability. Since this slowing down of the ion beam is one important feature of the ion beam driven EIC instability (Yamada et al., 1977), we show in Fig. 5 the parallel mean velocity of beam ions u_b , the parallel mean velocity of background ions, and the parallel mean velocity of electrons multiplied by m/M . The loss of parallel momentum of the beam ions is compensated by the increase in the mean parallel velocity of the background ions with a small momentum going into background electrons. The drift velocity of the background ions reaches $0.4 v_{t\parallel}(t=0)$ and reduces the relative parallel velocity between beam ions and background ions. Since this decrease in the beam velocity is quite small $\Delta u_b/u_b \sim 0.04$, this process does not seem to be a dominant stabilizing factor, although such a beam slowing down may be a dominant stabilizing factor in the resonant case driven by a small beam velocity (Yamada et al., 1977).

If we neglect the momentum exchange between ions and electrons, we can define the parallel anomalous collision frequency between background ions and beam ions by

$$v_{\text{eff}\parallel} = \frac{1}{2} \frac{d}{dt} \langle v_{t\parallel} \rangle / (\langle v_{t\parallel} \rangle - \langle v_{b\parallel} \rangle) ,$$

which leads to the anomalous slowing down of beam ions. From Fig. 5 we obtain in the linear stage

$$v_{\text{eff}\parallel} \sim 5 \times 10^{-5} Q_i = 5.4 \times 10^{-8} \omega_{pe} .$$

Therefore the ion beam slows down with a time constant $v_{\text{eff}\parallel}^{-1} \sim 2 \times 10^4 Q_i^{-1}$.

If we compare $v_{\text{eff}\parallel}^{-1}$ with the classical electron-drag "slowing down time" t_s

for hydrogen ion (Spitzer, 1962; Stix, 1973)

$$t_s = 6.27 \times 10^8 [(kT_e)^{3/2} / n_e \ln \Lambda] \text{ sec} ,$$

where kT_e is in eV and n_e is in cm^{-3} , which is valid for $v_{t\parallel} < u_b < v_{e\parallel}$, $u_b \gg (M/m)v_e$, we obtain, for parameters near 1 R_e altitude, $n_e = 10 \text{ cm}^{-3}$, $\Omega_i \sim 600 \text{ sec}^{-1}$, $\ln \Lambda \sim 20$, $kT_e \approx 1 \text{ eV}$,

$$v_{\text{eff}\parallel} t_s \sim 10^5 .$$

Therefore the anomalous slowing down of the beam ions is 10^5 times larger than the classical value.

It is also known that under the presence of the EIC wave, the cross field diffusion of ions arises due to wave-particle resonances (Okuda et al., 1981). Since this wave-particle resonance leads to the perpendicular heating of ions, we may define the anomalous perpendicular collision frequency $v_{\text{eff}\perp}$ by

$$v_{\text{eff}\perp} = \frac{1}{T_\perp(t=0)} \frac{dT_\perp}{dt} .$$

We show in Fig. 6 perpendicular temperatures of beam and background ions normalized by their initial values as a function of time. From these curves we obtain for beam ions $v_{\text{eff}\perp}^b = 0.2 \Omega_i$ and for background ions $v_{\text{eff}\perp}^t = 0.032 \Omega_i$. Thus, the beam ions diffuse more rapidly perpendicular to the magnetic field than the background ions. Since the beam ions flowing along the magnetic field transfer their parallel momentum across the magnetic field by this anomalous cross field diffusion, there is an anomalous momentum

transfer across the magnetic field, which should be measured as a viscosity. If we define the anomalous viscosity by $\mu_{\text{eff}} \sim \rho_{\text{Li}}^2 v_{\text{eff}}^b$, we obtain $\mu_{\text{eff}} \sim 0.2 \rho_{\text{Li}}^2 \Omega_i$, which is as large as the Bohm diffusion $D_B = (1/16)(T_e/eB)$.

IV. Discussion

The present simulation study demonstrates a nonlinear consequence of non-resonant EIC waves destabilized by ion beam parallel to the magnetic field for the case of a large beam velocity ($u_b = 20 v_{t\parallel} = 0.5 v_e$). As a consequence of the instability, the beam ions are heated strongly in the perpendicular direction and suffer a strong anomalous friction via EIC waves which leads to the beam slowing down. In the linear phase, the peak frequency spectrum occurs below Ω_i . In the nonlinear stage, however, the frequency of the peak spectrum shifts to $\gtrsim \Omega_i$, causing large cyclotron damping of waves by the background (target) ions and beam ions. Since the parallel phase velocity $\omega/k_{\parallel}$ occurs at $\sim u_b/2$, the instability in the present case is destabilized essentially by nonresonant interaction between beam ion cyclotron mode and background (target) ion cyclotron mode. We find from simulation results that the anomalous slowing down of beam ions by EIC waves is much larger than that by the classical electron-drag, and the perpendicular collision frequency (viscosity) measured from the perpendicular beam heating is as large as that of Bohm diffusion which agrees with the result observed for the electron drift driven EIC instability (Okuda et al., 1981).

We should point out here that when the ion beam speed is not so large, the instability may be more favorably destabilized by resonant interaction between beam acoustic mode and background ion cyclotron mode, which is destabilized by a smaller beam speed (Perkins, 1976). Nevertheless, we expect

that two important consequences of the instability revealed by the present simulation, i.e., perpendicular heating of ions and beam slowing down, are intrinsic to the ion beam driven EIC instability and are responsible for the saturation of the instability.

Our results presented here demonstrate that the ion beam driven EIC wave is a viable mechanism to transfer the ion parallel beam energy to the ion perpendicular energy. These results are consistent with the S3-3 observations near $1 R_E$ altitude on the auroral field line, which have shown existence of upstreaming ions having an anisotropic velocity distribution or a conic distribution, in which T_{bi} exceeds greatly $T_{b\parallel}$, in close association with strong EIC waves.

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References

- Cattell, C., J. Geophys. Res., 86, 3641, 1981.
- Drummond, W. E., and M. N. Rosenbluth, Phys. Fluids, 5, 1507, 1962.
- Gorney, D. J., A. Clarke, D. Croley, Jr., J. Fennell, J. Luhmann, and P. Mizera, J. Geophys. Res., 86, 83, 1981.
- Kaufmann, R. L., and P. M. Kintner, submitted to J. Geophys. Res., 1982.
- Kindel, J. M., and C. F. Kennel, J. Geophys. Res., 76, 3055, 1971.
- Kintner, P. M., M. C. Kelley, R. D. Sharp, A. G. Ghielmetti, M. Temerin, C. Cattell, P. F. Mizera, and J. F. Fennell, J. Geophys. Res., 84, 7201, 1979.
- Lee, W. W., and H. Okuda, J. Compt. Phys., 26, 139, 1978.
- Lysak, R. L., M. K. Hudson, and M. Temerin, J. Geophys. Res., 85, 678, 1980.
- Mizera, P. F., D. J. Gorney, and J. F. Fennell, J. Geophys. Res., 87, 1535, 1982.
- Mozer, F. S., C. W. Carlson, M. K. Hudson, R. B. Torbert, B. Parady, J. Yatteau, and M. C. Kelley, Phys. Rev. Lett., 38, 292, 1977.
- Okuda, H., C. Z. Cheng, and W. W. Lee, Phys. Rev. Lett., 46, 427, 1981.
- Okuda, H., and M. Ashour-Abdalla, Geophys. Res. Lett., 8, 811, 1981; also submitted to J. Geophys. Res., 1982.
- Perkins, F. W., Phys. Fluids, 19, 1012, 1976.
- Sharp, R. D., R. G. Johnson, and E. G. Shelley, J. Geophys. Res., 82, 3324, 1977.
- Shelley, E. G., R. D. Sharp, and R. G. Johnson, Geophys. Res. Lett., 3, 654, 1976.
- Spitzer, L., Jr., Physics of Fully Ionized Gases (Interscience, New York, 1962) p. 135.
- Stix, T. H., Phys. Fluids, 16, 1922, 1973.

Temerin, M., C. Cattell, R. Lysak, M. Hudson, R. B. Torbert, F. S. Mozer, R. Sharp D., and P. M. Kintner, J. Geophys. Res., 86, 11278, 1981.

Weibel, E. S., Phys. Fluids, 16, 1922, 1973.

Yamada, M., S. Seiler, H. W. Hendel, and H. Ikezi, Phys. Fluids, 20, 450, 1977.

Figure Captions

Fig. 1. Spatial profiles in the x direction of (a) electrostatic potential $e\phi/T_e$, (b) electron density n_e , (c) background ion density n_{it} , and (d) beam ion density n_{ib} at $\Omega_i t = 160$.

Fig. 2. Frequency spectra of (a) 1st mode for $0 < \Omega_i t < 40$, (b) 1st mode for $0 < \Omega_i t < 160$, (c) 3rd mode for $0 < \Omega_i t < 40$, and (d) 3rd mode for $0 < \Omega_i t < 160$.

Fig. 3. Ion velocity distributions at $\Omega_i t = 0$ and 160. (a) perpendicular distribution of background ions, (b) parallel distribution of background ions, (c) perpendicular distribution of beam ions, and (d) parallel distribution of beam ions.

Fig. 4. Contour plots of particle distributions in the velocity space ($v_\perp - v_\parallel$) of (a) background ions at $t = 0$, (b) background ions at $\Omega_i t = 160$, (c) beam ions at $t = 0$, and (d) beam ions at $\Omega_i t = 160$.

Fig. 5. Time evolution of the parallel mean velocity of beam ions u_b , the parallel mean velocity of background ions, and the parallel mean velocity of electrons multiplied by m/M .

Fig. 6. Time evolution of the perpendicular temperatures of beam ions and background ions.

Fig. 1

Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5

Fig. 6

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