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ANOMALOUS DIFFUSION AND ION HEATING IN THE PRESENCE OF ELECTROSTATIC HYDROGEN CYCLOTRON INSTABILITIES

BY **MASTER**

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Anomalous Diffusion and Ion Heating in the Presence of Electrostatic Hydrogen
Cyclotron Instabilities

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ABSTRACT

One- and two-dimensional particle simulations have been carried out to study electrostatic ion cyclotron instabilities for a hydrogen plasma in a strong magnetic field. It is found that strong ion heating and anomalous cross-field diffusion comparable to Bohm diffusion take place associated with the instability. Implications of the instability to the recent observations in fusion devices and space plasmas are discussed.

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It is well known that the electrostatic ion cyclotron waves may be destabilized by drifting electrons along magnetic fields in an isothermal plasma ($T_e \approx T_i$) where the ion acoustic waves are damped.¹ Such waves have been observed recently in fusion devices² as well as in space plasmas along auroral field lines.³ It is important, therefore, to study the nonlinear consequences of such instabilities and, in particular, anomalous cross-field diffusion; anomalous resistivity and heating in the presence of cyclotron instabilities may be much greater than what are expected from classical theory. A number of laboratory experiments have been reported and enhanced plasma transport as well as plasma heating have been reported.^{4,5}

Here we would like to present one- and two-dimensional particle simulation studies of the hydrogen cyclotron waves for a collisionless plasma in a low β limit. The model is electrostatic and drift kinetic approximation is used for the electrons while full dynamics of ions are followed in time.⁶

Figure 1 shows the time development of the potential, $e\phi_k(t)/T_e$, for a long wavelength, $k_{\perp}\rho_i = 0.16$ (a), and a short wavelength, $k_{\perp}\rho_i = 1.2$ (b), and the frequency spectrum obtained from one of the one-dimensional simulations. Here, $m_i/m_e = 1837$, $T_e/T_i = 1$, $\Omega_e/\omega_{pe} = 5$ (electron gyrofrequency/plasma frequency), $k_{\parallel}/k_{\perp} = 0.1$, $v_d/v_{te} \approx 1.4$, and $L = 1024\Delta$ are used where v_d , v_{te} are initial electron drift speed along the magnetic field, electron thermal speed, and Δ is the computational mesh size. Note the system length L is long compared with the ion gyroradius $\rho_i = 8.6 \Delta$, and there are more than 100 unstable Fourier modes in this simulation. Both the frequency and the growth rate observed in Fig. 1 agree well with the linear theory. For $k_{\perp}\rho_i \approx 0.16$, only the fundamental cyclotron frequency is unstable, while for $k_{\perp}\rho_i = 1.2$ several higher harmonics grow in time giving rise to

modulation in amplitude due to the beating among different frequencies. This is quite similar to the satellite observations along the earth magnetic field.³

Saturation amplitudes for these modes are relatively low and are typically $|e\phi_k/T_e| \lesssim 0.2$. Nonlinear saturation is a result of electron velocity space diffusion along the magnetic field shown in Fig. 2. Clearly the diffusion flattens the positive slope of the distribution generating a plateau, and at the same time the diffusion process reverses the sign of $\partial f / \partial v_{||}$ for a region of $v_{||} > v_d$ from negative to positive, thereby destabilizing the modes which were initially stable. From many other one-dimensional simulations and also from two-dimensional simulations which include modes propagating at different angles, we find nonlinear saturation is a result of electron velocity space diffusion creating a plateau which gives the lowest level of saturation. Two-dimensional effects, such as mode-coupling among Fourier modes at different angles of propagation or scattering of ion orbits by $cE \times B/B^2$ motion,⁷ appear small for the level of saturation given by the electron velocity space diffusion. This is partly because the ion cyclotron waves are nondecay type, $\omega_{k_1+k_2} \neq \omega_{k_1} + \omega_{k_2}$, and, therefore, a large amplitude is required for mode-coupling. Also, $e\phi/T_e \sim 1$ is necessary for the scattering of ions by the fluctuating electric field⁷ which is well above the saturation level given by the electron diffusion. Associated with the instability is the anomalous resistivity η which is found $\eta/\eta_0 = 2 \times 10^{-4}$ where $\eta_0 = 4\pi/\omega_{pe}$ and $\eta = -(m_e/ne^2)(dv_d/dt)/v_d$. This value is much larger than the classical value and is comparable to the anomalous resistivity associated with ion acoustic instabilities.⁸ Since the saturation takes place via quasilinear diffusion, it is straightforward to estimate the decay rate of the electron drift along the magnetic field. From

a quasilinear equation,^{1,9} one finds

$$\frac{d}{dt} \int f v_{\parallel} dv_{\parallel} = \frac{\pi e^2}{m_e^2} \sum_k |k_{\parallel}| |\phi_k|^2 \left. \frac{\partial f}{\partial v_{\parallel}} \right|_{v_{\parallel} = \omega_k/k_{\parallel}}. \quad (1)$$

Using the observed level of fluctuations $|e\phi_k/T_e| \lesssim 0.2$ and summing over the unstable modes, we find from Eq. (1) the decay of the electron drift speed is $d(v_d/v_{te})/d(\omega_{pe}\tau) \approx 10^{-4}$ consistent with the anomalous resistivity observed in the simulations.

Figure 3 shows the decay of the average electron drift along the magnetic field for two one-dimensional simulations using $v_d/v_{te} = 1.4$ and 0.85. All the other parameters remain the same. We clearly observe that there are two distinct stages of resistivity, initial rapid decay followed by a much slower but finite decay. The initial rapid decay is clearly due to the quasilinear effects associated with the unstable ion cyclotron waves. We believe the latter part is caused by the long wavelength modes ($\omega/k_{\parallel} > v_d$) which are initially stable and become unstable as a result of velocity space diffusion.

In addition to anomalous resistivity, ion heating perpendicular to the magnetic field takes place as a result of cyclotron damping in which the Doppler-shifted frequency of an ion with the velocity $v_{\parallel}^i$ along the magnetic field, $\omega - k_{\parallel} v_{\parallel}^i$, coincides with the gyro-frequency, Ω_i . It is found that the heating of the ions can easily be (20 ~ 50)% of the initial temperature. The energy fed into the ions is roughly equal to the energy lost from the electron motion along the magnetic field and this amount is also in reasonable agreement with quasilinear theory.¹⁰

It is natural to expect enhanced cross-field particle diffusion associated with the cyclotron instability. Since the resonant electrons moving at the wave phase velocity along magnetic field experience almost the constant electric field, they suffer large diffusion by $c\mathbf{E} \times \mathbf{B}/B^2$ motion. It is estimated that the electron diffusion may be comparable to Bohm diffusion.¹ Ion diffusion is somewhat more complicated since the wave frequency is close to ion gyro-frequency and the wavelength is comparable to ion gyro-radius. Nonetheless it is natural to expect large ion diffusion since the resonant ions which satisfy cyclotron resonance, $\omega - k_{\parallel} v_{\parallel}^i = \Omega_i$, experience the constant electric field and thereby drift across magnetic field by the $c\mathbf{E} \times \mathbf{B}/B^2$ motion. Since the cyclotron resonance is responsible for ion heating, it is clear anomalous diffusion and heating are always accompanied with each other.

Using a two-dimensional model in which the variations are in (x,y) plane with the magnetic field in the (y,z) plane with $B_z \gg B_y$,⁶ one can indeed measure diffusion coefficients of both ions and electrons across magnetic field associated with the cyclotron instability.

Figure 4 plots the position of test particles, both ions and electrons, at $t = 8.2 \Omega_i^{-1}$ which were located at $x = 0$ initially. Here $m_i/m_e = 1837$, $v_d/v_{te} = 1.4$, $\Omega_e/\omega_{pe} = 5$, and $T_e/T_i = 1$ are used. It is clearly seen that the spread of the ions is greater than the spread of electrons. Diffusion coefficient defined by $D_x^{i,e} = \langle (x(t) - x(0))^2 \rangle / t$ is found $D_x^e = 4.5 \times 10^{-3} \Delta \omega_{pe}^2$ and $D_x^i = 6.0 \times 10^{-3} \Delta \omega_{pe}^2$ which are about one-half of Bohm diffusion $D_B = (1/16)(cT_e/eB) = 1.25 \times 10^{-2} \Delta \omega_{pe}^2$. This estimate is also in reasonable agreement with earlier work¹. Since the hydrogen cyclotron waves have been observed in tokamaks² and are expected from high powered neutral injection experiments, hydrogen cyclotron waves, if excited may cause not only rapid

ion heating but also anomalous plasma diffusion in addition to low frequency drift type fluctuations.¹¹

Finally we would like to emphasize that double layers have never been observed in one-dimensional simulations using a very long system. This is in sharp contrast to the ion acoustic instability simulations where double layers were almost always found.⁸ It appears hydrogen cyclotron waves observed along auroral field lines may be an effect of double layers rather than a cause for generating them.³

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Fig. 1. Temporal growth of the cyclotron waves for (a) $k_{\perp}\rho_i = 0.16$ and (b) $k_{\perp}\rho_i = 1.2$ (b) and the frequency spectrum. Both real and imaginary parts of $e\phi_k(t)/T_e$ are shown. One-dimensional simulation. (PPPL-802542)

Fig. 2. Velocity space diffusion of electrons along magnetic field. One-dimensional simulation. (PPPL-802341)

Fig. 3. Decay of the average electron drift for two different initial drifts, $v_d / v_{te} = 1.4$ and 0.85 . One-dimensional simulation. (PPPL-802342)

Fig. 4. Plot of the test particle position at $t = 3.2 \times 10^{-1}$ initially located at $x = 0$. Two-dimensional simulation.
(PPPL-802344)

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