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Effect of upflowing field-aligned electron beams on the electron cyclotron waves in the auroral magnetosphere

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Abstract. The role of low density upflowing field-aligned electron beams (FEBs) on the growth rate of the electron cyclotron waves at the frequencies $\omega_r < \Omega_e$, propagating downward in the direction of the Earth's magnetic field, has been analysed in the auroral region at $\omega_e/\Omega_e < 1$ where ω_e is the plasma frequency and Ω_e is the gyrofrequency. The FEBs with low to high energy (E_b) but with low temperature ($T_{\parallel b}$) have no effect on these waves. The FEBs with $E_b < 1$ keV and $T_{\parallel b}$ (>1.5 keV) have been found to have significant effect on the growth rate. Analysis has revealed that it is mainly the $T_{\parallel b}$ which inhibits the growth rate (magnitude) and the range of frequency (bandwidth) of the instability mainly in the higher frequency spectrum. The inhibition in the growth rate and bandwidth increases with increase in $T_{\parallel b}$. The FEBs with less E_b (giving drift velocity) reduce growth rate more than the beams with larger E_b. The inhibition of growth rate increases with the increase in the ratio ω_e/Ω_e indicating that the beams are more effective at higher altitudes.

Keywords. Field-aligned electron beams; electron cyclotron waves; wave-particle interaction; auroral region.

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1. Introduction

Several workers have reported the existence of upflowing, We downflowing, and counterstreaming field-aligned electron beams (FEBs) in the auroral region [1]. FEBs are responsible for the linkage between magnetospheric and ionospheric plasmas. Klumpar and Heikkila [2] reported the upflowing FEBs at low altitudes, using the data from ISIS-2 satellite and found that these FEBs had energies of several tens of eV to a few keV and were aligned within 10° of the local magnetic field. Field-aligned currents (FACs) density associated with FEBs, in the auroral zone, is often in the range of 10–100 μA/m^2 reaching more than 1000 μA/m^2 during the magnetically disturbed conditions [3]. Upflowing FEBs have been identified as the carriers of the downward FACs [2,4]. While low energy upflowing FEBs are well-established [5], Carlson *et al* [6] from FAST satellite observations have shown the upflowing FEBs with peak energies between 100 eV and 5 keV in the auroral region with parallel temperatures of the order of 1 keV. They reported that these beams account for total downward FACs and appear more often. Cattell *et al* [7] based on statistical study of occurrence of upward FEBs from FAST observations found that more than 90% of beams have characteristic energies between 50–300 eV. It is not the intension to explore here the mechanism by which FEBs are produced.

The Earth's auroral magnetosphere is an active region for a wide variety of plasma wave activities [8–12]. The auroral plasma is characterized by $\omega_{\rm e}/\Omega_{\rm e} < 1$ where $\omega_{\rm e} = (4\pi n_{\rm e}^2/m_{\rm e})^{1/2}$ is the plasma frequency and $\Omega_{\rm e} = eB_{\rm o}/m$ is the gyrofrequency. Numerous spacecraft and ground-based observations have shown that the waves and wave–particle interaction processes are very important in the auroral region [13]. Tsurutani and Lakhina [14] have reported the basic concepts of wave–particle interaction in the collisionless plasma. Benson *et al* [10] observed natural radio wave emissions in the frequency range 150–700 kHz at ground level in the auroral region. The measurements were made during a ground-level observing program conducted near Fairbanks, Alaska, in the spring of 1986 to detect auroral cyclotron-maser generated whistler-mode waves. These emissions fall in the whistler-mode branch and overlap the frequency range of auroral kilometric radiation (AKR). Theoretical work of Wu *et al* [15] indicated that parallel propagating whistler-mode waves in the frequency range of 150–700 kHz are excited by auroral trapped energetic electrons with energies of several keV due to temperature anisotropy. These waves can easily reach the ground propagating downward along the Earth's magnetic field, since there is no cut-off frequency. Ziebell *et al* [16] studied the propagation effects on the wave amplification along the auroral field lines. Wong and Goldstein [17] extended the work of Wu *et al* [15] for relativistic calculations and for arbitrary direction of propagation and showed such effects to be quantitatively important. They found that relativistic effects tend to suppress significantly the growth rate (a factor 5) and the bandwidth ($\Delta kc/\omega \sim 0.4$–$0.6$) of this instability. Kumar *et al* [18] found that localized DC weak parallel electric fields in the direction of wave propagation enhance the growth rate and bandwidth of this instability but not significantly. In this paper, the effects of weak density FEBs with energy $E_{\rm b} < 1$ keV and varying temperature flowing upward in the opposite direction of wave propagation (downward), on the electron cyclotron waves in the frequency range of 150–700 kHz observed in the auroral region, are analyzed, which have not been reported so far. It is an interesting problem from the point of view of wave–particle interaction in the auroral region, which is a most active region of the Earth's magnetosphere for wave activities.

2. Physical model and theoretical considerations

2.1 *Physical model*

We consider here the physical model for main body of auroral plasma which is previously discussed by Wu *et al* [15]. Auroral plasma is taken as homogeneous, anisotropic and collisionless consisting of auroral trapped energetic electron density ($n_{\rm e}$) and cold background electron density ($n_{\rm c}$) of the ionospheric origin embedded in the uniform static Earth's magnetic field ($\mathbf{B}_{\rm o}$). It is well-known that fractions of the auroral electrons is reflected by a magnetic mirror effect at low altitudes and are again reflected back at high altitudes by the parallel electric field which occur frequently along the field lines [18]. They become 'trapped' along the auroral field lines. These trapped electrons form a 'bump' or a 'ring' distribution on $v_\perp$ axis as shown by Wu *et al* [15]. They suggested that the trapped electrons can lead to enhanced temperature anisotropy which gives rise to the generation of electron cyclotron waves studied here. The temperature anisotropy is the source of free energy for these waves. The ions form an immobile neutralizing background, therefore, the ion dynamics is neglected. Transfer of energy between waves and particles is assumed to be sufficiently small and localized so that non-linear effects can be ignored.

We consider that a uniform beam of electrons of density $n_{\rm b}$ (subscript 'b' denotes that it is a beam plasma) flows upward along the $\mathbf{B}_{\rm o}$ lines through the main body of the plasma. The density $n_{\rm b}$ is taken much less than the density of main body of plasma ($n_{\rm b}/n \ll 1$) and the beam energy is less to cause relativistic effects. The beam can be represented by drifting Maxwellian function [5,19] or by non-Maxwellian distribution functions such as step-like delta (δ) function [20].

2.2 *Distribution functions*

The distribution function for auroral trapped electrons is taken as a Maxwellian ring distribution [15] given by

$$f_v\left(v_\perp, v_\parallel\right) = \frac{n_e/n}{\pi^{3/2}\alpha_\parallel\alpha_\perp^2 B}\exp\left[-\left(\frac{v_\perp - v_{\rm o}}{\alpha_\perp}\right)^2 - \left(\frac{v_\parallel}{\alpha_\parallel}\right)\right], \tag{1}$$

$$B = \exp\left(-\frac{v_{\rm o}^2}{\alpha_\perp^2}\right) + \sqrt{\pi}\left(\frac{v_{\rm o}}{\alpha_\perp}\right) erfc\left(-\frac{v_{\rm o}}{\alpha_\perp}\right). \tag{2}$$

In eq. (1), the quantity $n_{\rm e}/n$ is the ratio of trapped energetic electron to the total electron density. The $v_\parallel$ and $v_\perp$ are the parallel and the perpendicular velocities with reference to $\mathbf{B}_{\rm o}$. The $v_{\rm o}$ is the drift speed. The $erfc(x)$ in eq. (2) is the complimentary error function. The $\alpha_\parallel$ and $\alpha_\perp$ are the parallel and the perpendicular electron thermal velocities, which in terms of parallel and perpendicular temperatures are given by

$$T_\parallel = \frac{m\alpha_\parallel^2}{2}$$

and

$$T_\perp = \frac{m\alpha_\perp^2}{2}\left[1 + \left(\frac{v_{\rm o}}{\alpha_\perp}\right)^2 + \frac{\sqrt{\pi}}{2B}\left(\frac{v_{\rm o}}{\alpha_\perp}\right) erfc\left(-\frac{v_{\rm o}}{\alpha_\perp}\right)\right]. \tag{3}$$

We consider here that the main body of plasma is penetrated by a low density beam of current carrying electrons drifting upward with velocity $\mathbf{v}_\mathrm{b}$ along $\mathbf{B}_\mathrm{o}$ with a distribution function [19] written as

$$f_\mathrm{b} = \left(\frac{m}{2\pi T_{\parallel b}}\right)^{1/2} \exp\left(-\frac{m(v_\parallel - v_\mathrm{b})^2}{2T_{\parallel b}}\right), \tag{4}$$

where v_b is the drift velocity of the electron beam, $v_\parallel$ is the electron beam velocity along $\mathbf{B}_\mathrm{o,}$ and $T_{\parallel\mathrm{b}}$ is the temperature of beam electrons given in the energy unit. The total electron distribution function (f_o) is given by $f_\mathrm{o} = f_\mathrm{v} + f_\mathrm{b}$ where f_v is the distribution function supporting the wave propagation (eq. (1)) and f_b is that of current carrying beam of electrons (eq. (4)). We consider here the cyclotron resonance between the electron beam and the electron cyclotron waves, which could be quite effective. The electrons of upward going beam undergo the cyclotron resonance with downward propagating electron cyclotron wave in the auroral region given by

$$\omega - k_\parallel v_\parallel = n\Omega_\mathrm{e}, \tag{5}$$

where ω and k are wave frequency and wave number.

2.3 *Dispersion relation and growth rate*

The dispersion relation for the right hand circularly polarized electromagnetic (whistler-mode) waves propagating exactly parallel to the external $\mathbf{B}_\mathrm{o}$ [15], in the auroral region having trapped energetic electron density (n_e) and cold electron density (n_c) of the ionospheric origin with the distribution function in eq. (1) is given by

$$\frac{c^2k^2}{\omega^2} = 1 + \frac{n_\mathrm{e}}{n}\left(\frac{\omega_\mathrm{e}}{\omega}\right)^2 \left[\left(\frac{\omega}{k\alpha_\parallel}\right) Z(\xi) + \left(\frac{T_\perp}{T_\parallel} - 1\right)(1 + \xi Z(\xi))\right] - \frac{n_\mathrm{c}}{n}\left[\frac{\omega_\mathrm{e}^2}{\omega(\omega - \Omega_\mathrm{e})}\right], \tag{6}$$

where $\omega = \omega_\mathrm{r} + i\gamma$ is the complex frequency, ω_r is real frequency and γ is the growth rate, k is the wave vector given by $k^2 = k_\parallel^2 + k_\perp^2$, for parallel wave propagation $k_\perp = 0$, and $Z(\xi)$ is the usual plasma dispersion function given by

$$Z(\xi) = j\pi^{1/2}\exp(-\xi^2) - \frac{1}{\xi}\left(1 + \frac{1}{2\xi^2}\right), \tag{7}$$

where

$$\xi = \frac{\omega - \Omega_\mathrm{e}}{k\alpha_\parallel}.$$

Actually we deal with two subsystems: one is a main body of plasma (n_e and n_c) and the other is a beam of field-aligned electrons which resonates with the electron cyclotron waves and whose density $n_{\rm b}$ is much less than the main body of plasma ($n_{\rm b}/n \ll 1$). The dispersion relation $D(\omega, k)$ for electron cyclotron waves propagating parallel to $\mathbf{B}_{\rm o}$ in the presence of upflowing FEBs could be taken as the sum of dispersion relations due to the main body of plasma $D_{\rm m}(\omega, k)$ and upflowing FEBs, $D_{\rm b}(\omega, k)$ written as $D(\omega, k) = D_{\rm m}(\omega, k) + D_{\rm b}(\omega, k)$. The $D_{\rm b}(\omega, k)$ is obtained by solving eq. (4), using Landau prescription for $v_{\|}$ integration, thereby accounting for singularity occurring at $v_{\|} = (\omega - \Omega_{\rm e})/k$. This indicates the Doppler-shifted resonance (eq. (6), $n = 1$ for parallel propagation) between electron cyclotron waves and FEBs moving in opposite direction to the wave propagation. The imaginary part of the solution is combined with eq. (6) to get $D(\omega, k)$. The dispersion relation $D(\omega, k)$ thus obtained for electron cyclotron waves propagating exactly parallel to $\mathbf{B}_{\rm o}$ in the presence of FEBs can be written as

$$\frac{c^2k^2}{\omega^2} = 1 + \frac{n_{\rm e}}{n}\left(\frac{\omega_{\rm e}}{\omega}\right)^2 \left[\left(\frac{\omega}{k\alpha_{\|}}\right) Z(\xi) + \left(\frac{T_{\perp}}{T_{\|}} - 1\right)(1 + \xi Z(\xi))\right] - \frac{n_{\rm c}}{n}\left[\frac{\omega_{\rm e}^2}{\omega(\omega - \Omega_{\rm e})}\right] + j\sqrt{\pi}\left(\frac{\omega_{\rm b}}{\omega_{\rm e}}\right)^2 \left(\frac{\omega_{\rm e}}{\omega}\right)^2 \left(\frac{\omega - kv_{\rm b}}{kv_{T_{\|\rm b}}}\right) f_{\rm b}(v_{\rm rb}) \quad (8)$$

The $T_{\perp}/T_{\|} - 1$ is the temperature anisotropy of trapped energetic electrons. $\omega_{\rm b}$ is the electron beam plasma frequency due to upward FEBs. The ratio, $\frac{\omega_{\rm b}^2}{\omega_{\rm e}^2} = \frac{(n_{\rm b}e^2/\varepsilon_{\rm o}m)}{(ne^2/\varepsilon_{\rm o}m)} = \frac{n_{\rm b}}{n}$, is the ratio of beam density to the total plasma density where $n = n_{\rm e} + n_{\rm c} + n_{\rm b}$. The $n_{\rm e}, n_{\rm c}$ and $n_{\rm b}$ are trapped auroral energetic, cold background and beam electron densities respectively. The $f_{\rm b}(v_{\rm rb})$ is that part of beam distribution function which resonates with waves, and $v_{\rm rb} = |(\omega - \Omega_{\rm e} - kv_{\rm b})/k|$ is the resonant beam velocity.

The growth rate is obtained by solving the dispersion relation (eq. (8)) using asymptotic expansion for $Z(\xi)$. It is assumed that real frequency is also not changed by the FEBs and is determined by cold background electrons. Using the growth rate ($\gamma/\Omega_{\rm e}$) formula

$$\frac{\gamma}{\Omega_{\rm e}} = \left.\frac{-\mathrm{Im}\, D(\omega, k)}{\Omega_{\rm e}\partial/\partial\omega(\mathrm{Re}\, D(\omega, k))}\right|_{\omega = \omega_{\rm r}}. \quad (9)$$

The expression for the $\gamma/\Omega_{\rm e}$ is found to be

$$\frac{\gamma}{\Omega_{\rm e}} = \sqrt{\pi}\frac{n_{\rm e}}{n}\frac{\omega_{\rm e}^2}{k\Omega_{\rm e}\alpha_{\|}} \exp\left(-\frac{(\Omega_{\rm e} - \omega_{\rm r})^2}{k^2\alpha_{\|}^2}\right)\left[\left(\frac{T_{\perp}}{T_{\|}} - 1\right)\frac{(\Omega_{\rm e} - \omega_{\rm r})}{\omega_{\rm r}} - 1\right] \times \left[1 + \frac{c^2k^2}{\omega^2} + \frac{n_{\rm c}}{n}\frac{\omega_{\rm e}^2}{(\omega_{\rm r} - \Omega_{\rm e})^2}\right]^{-1} - \sqrt{\pi}\frac{n_{\rm b}}{n}\frac{\omega_{\rm e}^2}{\omega_{\rm r}\Omega_{\rm e}}\left(\frac{\omega_{\rm r} - kv_{\rm b}}{kv_{T_{\|\rm b}}}\right)\exp\left(-\frac{(\omega_{\rm r} - \Omega_{\rm e} - kv_{\rm b})^2}{k^2v_{T_{\|\rm b}}^2}\right). \quad (10)$$

The first term of this expression represents the growth rate due to auroral trapped energetic electrons and cold background electrons of ionospheric origin. The second term is the contribution due to upflowing FEBs. In the absence of the second term the expression reduces to that of Wu *et al* [15].

3. Results and discussion

This study deals with linear wave-particle theory where upflowing FEBs interact with electron cyclotron waves propagating downward parallel (maximum growth rate) to the Earth's magnetic field ($\mathbf{B}_o$) as shown schematically in figure 1. The FEBs with low energy $E_b < 1$ keV and low to high energy with varying temperature $T_{\|b}$ traveling up the field lines away from the Earth in the auroral region have been reported by Menietti *et al* [21] and Carlson *et al* [6] respectively. Characteristic energies of upward FEBs mostly lie between 50–300 eV [7]. It is assumed here that upward FEBs with energies $E_b = 50$–500 eV and $T_{\|b}$ of the order of 2 keV exist in the auroral region. Since beam energy is very much less to cause relativistic effects, we restrict our analysis to non-relativistic regime of Wong and Golstein [17] or Wu *et al* [15]. The magnetic perturbations associated with field-aligned current loops may cause inhomogeneities in the $\mathbf{B}_o$, and hence mismatching of the cyclotron resonance condition that can cause the second order cyclotron resonance [22], have not been considered. For the sake of further simplification, we have considered that field-aligned currents are constant throughout the interaction region. Equation (10) indicates that the growth rate is zero for $n_e = 0$, $KT_{\|b} = 0$. The condition $n_e = 0$, shows that there are no ring electrons and $T_{\|b}$ forces beam electrons to be pure cold electrons drifting at a speed of v_b. In this case there are just cold ambient electrons and cold beam electrons. Electron cyclotron waves cannot grow within such plasmas due to no temperature anisotropy. It can also be noticed from eq. (10) that a minimum value of temperature anisotropy called critical anisotropy $A_c(T_\perp/T_\| - 1)$ is required for the excitation electron cyclotron waves or the instability of the significance ($\gamma/\Omega_e \approx 10^{-5}$). The calculated value of A_c is 4.2 in this case at $\omega_r/\Omega_e = 0.8$. In figures 2a and 2b, the normalized growth rate (γ/Ω_e) has been plotted against the normalized real frequency (ω_r/Ω_e) taking parameters from Wu

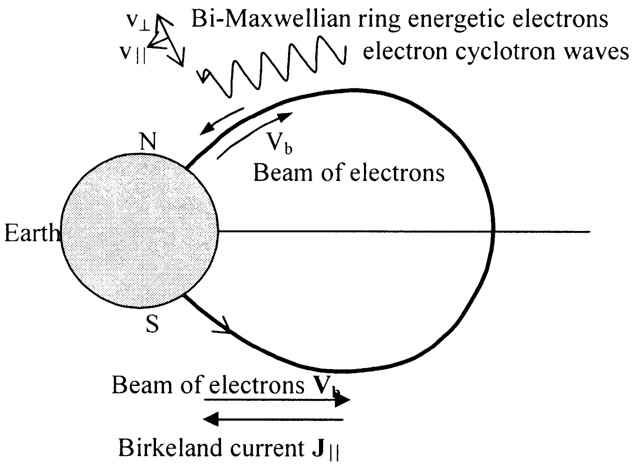

Figure 1. Diagram illustrating the region in the auroral region, where the presence of upflowing field-aligned electron beams of velocity v_b influence the growth of electron cyclotron waves.

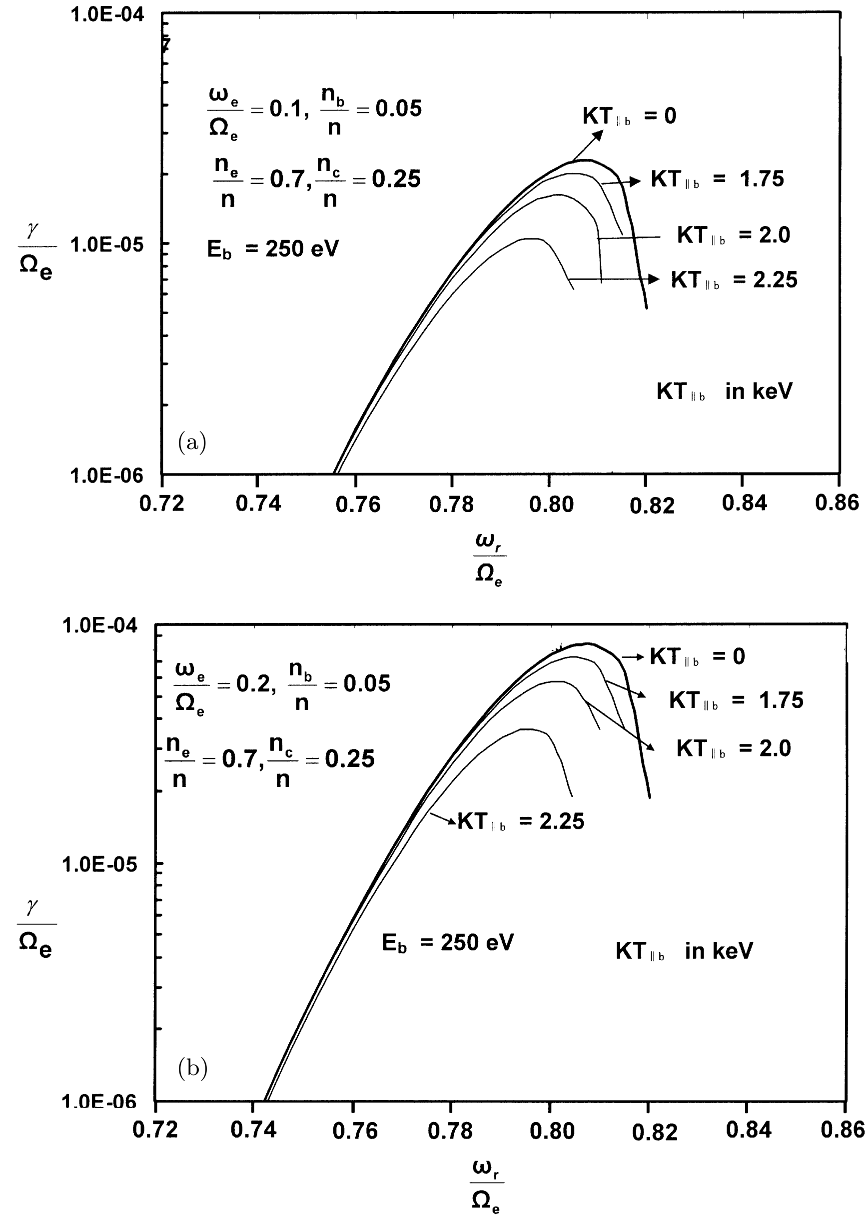

Figure 2. (**a**) Variation of normalized growth rate (γ/Ω_e) with normalized wave frequency (ω_r/Ω_e) at $\omega_e/\Omega_e = 0.1$, $\alpha_\perp/c = \alpha_\parallel/c = 0.1$, $v_o/c = 0.2$, for 70% and 25% of energetic and cold electrons in the presence of 5% upflowing FEBs with $E_b = 250$ eV and different values of $KT_{\parallel b} = 1.75$–2.25 keV. (**b**) Variation of normalized growth rate (γ/Ω_e) with normalized wave frequency (ω_r/Ω_e) for $\omega_e/\Omega_e = 0.2$. Other parameters are same as that of figure 2a.

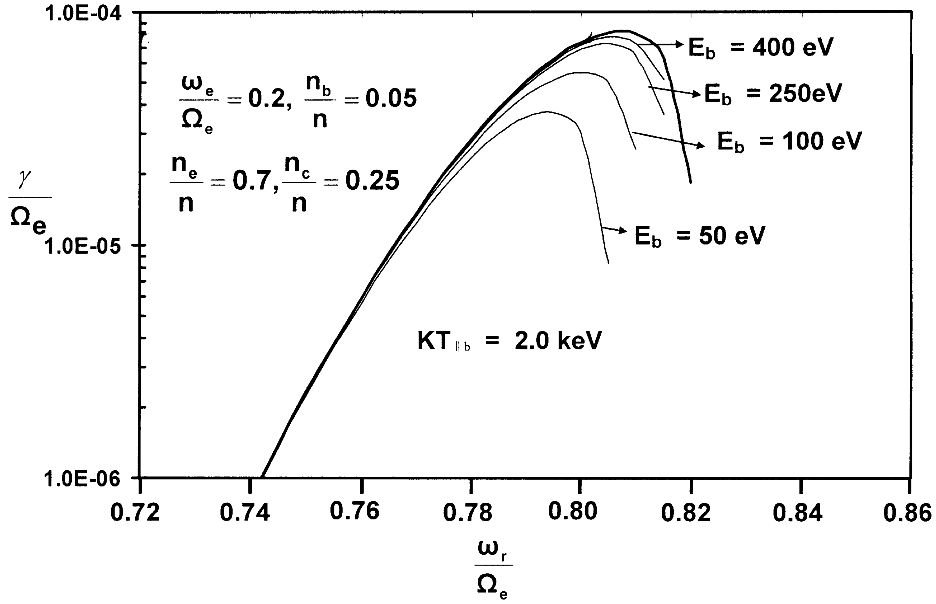

Figure 3. Variation of normalized growth rates ($\gamma/\Omega_{\rm e}$) with normalized wave frequency ($\omega_{\rm r}/\Omega_{\rm e}$) at $\omega_{\rm e}/\Omega_{\rm e} = 0.2$, $\alpha_\perp/c = \alpha_\parallel/c = 0.1$, $v_{\rm o}/c = 0.2$, for 70% and 25% of energetic and cold electrons in the presence of 5% upflowing FEBs with $KT_{\parallel{\rm b}} = 2.0$ keV and different values of $E_{\rm b}$ =50–400 eV.

et al [15] that are $\alpha_\perp/c = \alpha_\parallel/c = 0.1, v_{\rm o}/c = 0.2$ when 70% and 25% of total electrons are auroral trapped energetic electrons and cold background electrons at $\omega_{\rm e}/\Omega_{\rm e} = 0.1$ and 0.2. The growth rate without FEBs ($n_{\rm b}/n = 0$) is shown as a thick line and same pattern is used in all other figures. The beams with the thermal temperature less then 1.5 keV show no effect on the growth of waves. Calculations have been carried out for FEBs with $n_{\rm b}/n = 0.05$ (5%) for beam energy $E_{\rm b} = 250$ eV with different values of the beam temperature $KT_{\parallel{\rm b}} = 1.75$, 2.0 and 2.25 keV. The $E_{\rm b}$ and $KT_{\parallel{\rm b}}$ give $v_{\rm b}$ and $v_{T\parallel{\rm b}}$ respectively (eq. (10)). It can be seen from figure 2 that the growth rate is maximum at around $\omega_{\rm r}/\Omega_{\rm e} = 0.8$. As the beam temperature increases, the growth rate and the bandwidth decrease in the higher frequency spectrum only. The reduction in the growth rate is large compared to the enhancement in the growth rate due to parallel electric field [18]. The reduction in the growth rate is due to the resonance of beam electrons with the electron cyclotron waves that extract the wave energy. In figure 3, the plots of $\gamma/\Omega_{\rm e}$ vs. $\omega_{\rm r}/\Omega_{\rm e}$ for the same parameters as that in figure 2b for beam temperature $KT_{\parallel{\rm b}} = 2.0$ keV and different values of the beam energy $E_{\rm b} = 50$, 100, 250, 400 eV are given. At this larger parallel temperature the beams with less energy reduce the growth rate more than those with larger energy. It indicates that beams with less energy absorb more energy from waves during wave–particle interaction resonance. In the region of $\omega_{\rm e}/\Omega_{\rm e} = 0.1$–0.2 considered here, the auroral kilometric radiation (AKR), which is unobservable at the ground is generated due to the cyclotron maser instability [23]. Kazimura *et al* [24] reported that electron/electron instabilities are generated

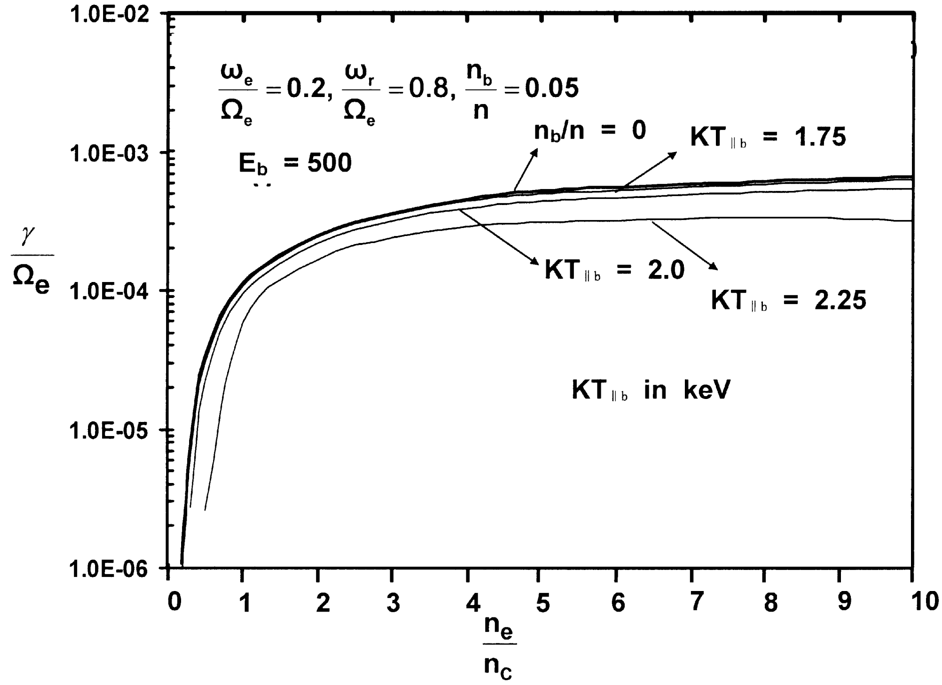

Figure 4. Variation of normalized growth rate (γ/Ω_e) with n_e/n_c at $\omega_e/\Omega_e = 0.2$, $\alpha_\perp/c = \alpha_\parallel/c = 0.1$, $v_o/c = 0.2$, in the presence of 5% upflowing FEBs with $E_b = 500$ eV and different values of $KT_{\parallel b} = 1.75$–2.25 keV.

in the auroral region at $\omega_e/\Omega_e < 1$ by tenuous electron beam propagating in the dense plasma with a sufficiently large beam relative drift velocity. Gary *et al* [25] using electromagnetic linear theory and particle-in cell simulations have studied the electron/electron beam instability driven by relatively dense and fast electron beams in the plasma with $\omega_e/\Omega_e = 1$ (polar and auroral regimes of the terrestrial magnetosphere). They found that electron/electron beam instability can account for several properties of plasma waves observed in the auroral plasmas.

The cold background electrons of ionospheric origin can play a significant role in the emission processes. To study the effects of cold plasma density n_c, we calculated γ/Ω_e as a function of density ratio energetic to cold electrons (n_e/n_c) while keeping n_b, v_b and $T_{\parallel b}$ constant. Figure 4 reveals the variation of γ/Ω_e vs. n_e/n_c for $\omega_r/\Omega_e = 0.8$, $\omega_e/\Omega_e = 0.2$ for $n_b/n = 0.05$, $E_b = 500$ eV and for different values of $KT_{\parallel b}$. It is seen from the figure that if density of cold electrons prevails ($n_e/n_c < 1$) over that of energetic electrons no emission with growth rate $>10^{-5}$ occurs. It also confirms that electron cyclotron waves can also exist in the regions where plasma frequency is less than electron gyrofrequency provided energetic electron density is larger when compared to cold background electron density [15]. The $n_e/n_c \approx 0.2$ to 2 corresponds to about 3000 and 5800 km, the range in which main amplification of these waves occurs [16]. The beams with $KT_{\parallel b} \geq 2$ keV

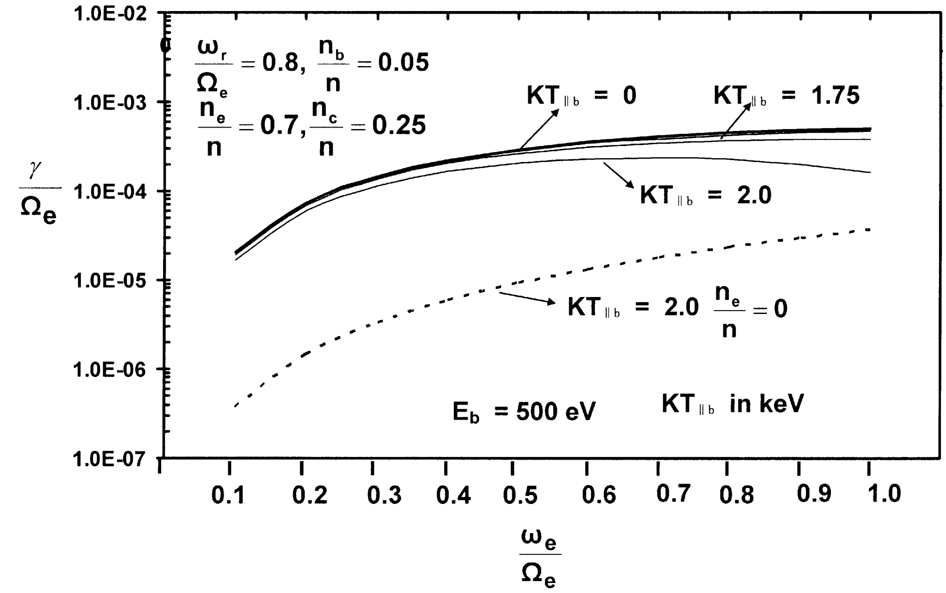

Figure 5. Variation of growth rate (γ/Ω_e) with normalized plasma frequency (ω_e/Ω_e) at $\omega_r/\Omega_e = 0.8$, $\omega_e/\Omega_e = 0.1$, $\alpha_\perp/c = \alpha_\parallel/c = 0.1$, $v_o/c = 0.2$, for 70% and 25% of energetic and cold electrons and in the presence of 5% upflowing FEBs with $E_b = 500$ eV and different values of $KT_{\parallel b} = 1.75$–2.25 keV. Dotted lime shows the reduction in growth rate due to beam with $E_b = 500$ eV and $KT_{\parallel b} = 2.0$ keV.

can suppress the waves completely under $n_e/n_c < 0.5$. The increased population of trapped energetic electrons increases the flux of energetic cyclotron resonant electrons which leads to the growth rate enhancement indicating its important role in producing such waves. The increase in the growth rate due to increase in n_e/n_c indicates that free energy required for wave growth is derived from trapped energetic electrons. Pasmanik *et al* [26] studied the amplification of whistler-mode waves in the Earth's magnetosphere by the cyclotron instability for different types of energetic distributions in the velocity space. They reported that the step-like features in the velocity space can amplify whistler-mode waves propagating along the Earth's magnetic field lines and can generate narrow band VLF emissions even if its temperature anisotropy is moderate. High frequency whistler-mode waves studied here require comparatively large value of electron temperature anisotropy and sufficient energetic electron population. The electrons which originate in the plasma sheet and are accelerated at the altitudes ranging form several thousand kilometers to a few Earth's radii carry a substantial amount of energy to cause the wave growth. Parallel electric fields therein further cause the electrons to drift into auroral zone increasing the population of energetic electrons which provide free energy to the waves. The parallel electric field mainly occurring along the auroral field lines at 3000–6000 km gradually remove the cold background electrons in the same range of altitudes [16]. The beams of field-aligned electrons extract energy from the waves during cyclotron resonance and lead to the decay of the waves. Figure 5 shows the variation of γ/Ω_e with normalized plasma frequency (ω_e/Ω_e) for $\alpha_\perp/c = \alpha_\parallel/c = 0.1v_o/c = 0.2$ for ω_r/Ω_e =0.8 in presence of FEBs with $n_b/n = 0.05$, $E_b = 500$ keV for different values of $kT_{\parallel b} = 1.75$, 2.0 and 2.25 keV. The growth rate increases with increase in ω_e/Ω_e and gets saturated at around ω_e/Ω_e =1.0. It can be said that the growth rate in the low altitude region is approximately one order larger than that in the high altitude region. Upflowing FEBs inhibit the growth rate rapidly with increase in ω_e/Ω_e. The amount of reduction in the growth rate with ω_e/Ω_e is shown by the dotted line which shows that the effect of beam increases with increase in ω_e/Ω_e.

In summary, upflowing FEBs of low energy and larger parallel temperature inhibit the growth rate and reduce the bandwidth of electron cyclotron waves mainly due to parallel beam temperature. These beams with parallel temperature of 2.0 keV can suppress these waves completely if cold plasma density prevails over energetic plasma. The low energy beams with larger temperature (thermal spread) have more effect than those with larger energy. Effect of the upflowing FEBs also depends upon the ratio of ω_e/Ω_e i.e altitude in the auroral region. A detailed analysis of the present work for beam plasma in inhomogeneous magnetic field and second-order cyclotron resonance effects will provide more insight into the problem.

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