Abstract

In this paper we performed a computer simulation of the nongyrotropic electron beam-plasma interaction based on observational data obtained from ISEE 1 and 2. These data indicated the existence of nongyrotropic electrons just upstream of the Earth’s bow shock. In the simulation, the electron beam is assumed to have an extreme nongyrotropy. We study the possible electromagnetic emissions and clarify effects of the nongyrotropy on nonlinear evolution of the electron beam instabilities. In the nongyrotropic case, we found that the magnetic field energy became much larger than in the gyrotropic case, indicating a strong electromagnetic wave emission.

Simulation Model

We use a particle-in-cell code, KEMPO (Kyoto University ElectroMagnetic Particle Code) developed at Radio Atmospheric Science Center (Matsumoto and Omura, 1993) that allows spatial variations along the x-direction. Since we are interested about parallel propagation, the wave vector of the modes is aligned with the x-direction, \( \hat{k} = k \hat{x} \), with the ambient magnetic field defined by \( \hat{B}_r = B_0 \hat{z} \). Figure 1 shows the reference system used in our simulations.

Figure 1 - Reference system used in our simulation. It shows an electron beam propagating parallel to the background magnetic field, both in the x-direction of the system.
For the proposed study the simulation code incorporates three species of charged particles: background electron and ions, and an electron beam with a given drift velocity. We assume the ion species to be of infinite mass, providing a neutralizing background. Both beam and plasma electrons have Maxwelliana population. For gyrotropic (subscript G) and nongyrotropic (subscript NG) cases the electrons of the beam are distributed with a pitch angle $\alpha = 60^\circ$, where $\alpha = \arctan (v_y / v_z)$ is the angle between background magnetic field and the direction of motion of the particles. For the nongyrotropic case the electron beam velocity component, $v_{NG_b}^z$, is assumed to have an additional value $v_{NG_b}^z = 16v_{th_b}^z$, $v_{NG_b}^z = v_{th_b}^z = 0$, introduced at $t = 0$. Velocity distribution functions of the moving particles, gyrotropic (top) and nongyrotropic (bottom) cases, are shown in Figure 2, at $t = 0$. We can see the formation of a ring for the electron beam, in the gyrotropic case, and an extreme electron beam nongyrotropy with gyrophase angle $\phi = 90^\circ$, in the nongyrotropic case. Boundary conditions are periodic and preexisting wave packets are not assumed, and all the waves grow self-consistently out of noise.

Electrostatic modes are investigated by observing the longitudinal wave electric fields $\hat{E}_x \parallel \hat{k} \parallel \hat{x}$ whereas the electromagnetic modes by observing the wave field components $(\hat{E}_y, \hat{E}_z)$ and $(\hat{B}_y, \hat{B}_z)$.

**Results and Discussion**

Simulation results presented in this section were obtained using the parameters shown in Table 1. Parameters were chosen based on observational data from measurements on ISEE 1 and ISEE 2 (Anderson et. al, 1985). The velocities are normalized with respect to $v_{th_b}$, where $v_{y} = \sqrt{2} v_{th_b}$ (subscript b is related to the nongyrotropic electron beam), and the frequencies are normalized with respect $|\Omega_b|$. The resulting Debye length ($\lambda_D$) is large enough (in the scale of the grid spacing) to avoid nonphysical heating of the plasma (Birdsal and Langdon, 1985).

Figure 3 presents the time evolution of electrostatic and kinetic energy for the gyrotropic (left) and nongyrototropic (right) case, both in the logarithm scale for the $y$ axis. All the energies were normalized by the initial magnetic energy $\mu_B^2 / 2 \mu_0$. The nongyrotropic case presents higher kinetic and electrostatic energies due to the introduction of $v_{NG_b}^z = 0 \parallel 16 v_{th_b}^z$. We can observe that both cases present similar behavior, the corresponding decreasing of kinetic energy appearing as an increasing of the electrostatic energy, in the beginning of simulation until $t \parallel 2 |\Omega_b|^{-1}$. After this time the kinetic energy became constant, in both cases, and the electrostatic energy decreases slowly.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
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<tr>
<td>Electron plasma frequency $\omega_{pe}$</td>
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<tr>
<td>Electron cyclotron frequency $\Omega_e$</td>
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</tr>
<tr>
<td>electron thermal speed $v_{th_e}$</td>
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</tr>
<tr>
<td>electron beam thermal speed $v_{th_b}$</td>
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<td>electron beam drift velocity $v_{db}$</td>
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<td>grid spacing $(\Delta x)$</td>
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<td>number of superparticles</td>
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<td>time step</td>
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<td>beam to plasma density ratio $(n_b / n_i)$</td>
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</table>

Figure 2 - Velocity distribution functions, at $t = 0$, for the gyrotropic (top) and nongyrotropic (bottom) cases.

Concerning the electromagnetic energy, we see that for the gyrotropic case there is no variation along the time, as

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shown in Figure 4 (left), just appearing fluctuations. For the nongyrotropic case, we see an increasing of the electromagnetic energy as shown in Figure 4 (right). The growing of electromagnetic energy starts at $t \approx 4|\Omega_b|^{-1}$ reaching the first maximum at $t \approx 10|\Omega_b|^{-1}$ (the total time run simulation). This energy gain comes from the electrostatic energy that decreases along the simulation (see the Figure 3).

The diagram $(\omega \times k)$ tells us the modes that are present in the system. We constructed the $(\omega \times k)$ diagram for the electromagnetic fields components $(E_x, E_y, B_x, B_y)$. We will show the $(\omega \times k)$ diagram for the $E_x$ and $E_y$ components. Figure 5 shows the $(\omega \times k)$ diagram for $E_x$ component (electrostatic mode) for the gyrotropic (left) and the nongyrotropic (right) cases, respectively. Colors are related to the intensity of the field component (in dB). For both cases we observe Langmuir waves, frequency close to $45|\Omega_b|$, forward and backward propagating and also the beam mode forward propagating in the nongyrotropic case.

Figure 6 shows the $(\omega \times k)$ diagram for the $E_y$ component (electromagnetic mode) for the gyrotropic (left) and the nongyrotropic (right) cases. For both cases we observe the RCP high frequency mode, forward and backward propagating. We also observe the whistler mode (RCP low frequency) in both cases. For the nongyrotropic case (right) the whistler mode emission is intensified. Colors are related to the intensity of the field component (in dB). We also observe in the nongyrotropic case the presence of an electrostatic mode due the extreme electron nongyrotropy, which behaves like a beam mode.

Figure 7 shows the distribution function of velocity, for the components $v_x$ and $v_y$ for different times. This figure illustrates a rotating nongyrotropy with frequency $\Omega_b$.

Conclusions

In this work we performed particle simulations of electron beam-plasma interaction in a one-dimensional system taken along the magnetic field. We introduced a nongyrotropy in the particle population of an electron beam drifting against the background plasma. We compare the behavior of two systems, gyroscopic and nongyrotropic. We observe that at early times, up to $t \approx 2|\Omega_b|^{-1}$, both systems have similar behavior. For times larger than $t \approx 4|\Omega_b|^{-1}$, there is an enhancement of the electromagnetic energy for the nongyrotropic case. An intensification of the emission of the whistler mode can be observed in the $(\omega \times k)$ diagram for the $E_y$ component (see Figure 6). Different gyrophase angles and density beam to plasma ratios should be investigated in the near future.

Acknowledgments

This work was supported by FAPESP- Fundação Amparo à Pesquisa do Estado de São Paulo, and UNITAU – Universidade de Taubaté, Brasil.

References

Figure 3 - Time evolution of electrostatic and kinetic energy for the gyrotrropic (left) and nongyrotrropic (right) cases.

Figure 4 - Time evolution of electromagnetic energy for the gyrotrropic (left) and nongyrotrropic (right) cases.
Figure 5 - $\omega \times k$ diagram for the electric field component, $E_x$, electrostatic, for the gyrotropic (left) and the nongyrotropic (right) cases. Colors are related to the amplitude of the component.

Figure 6 - $\omega \times k$ diagram for the electric field component, $E_y$, electrostatic, for the gyrotropic (left) and the nongyrotropic (right) cases. Colors are related to the amplitude of the component.
Figure 7 – Contour plots of the distribution function, velocity components \( v_y \) and \( v_z \), for the beam and plasma electrons for different time steps, in the nongyrotropic case.