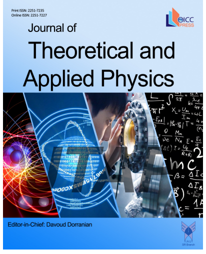

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Current filamentation instability of diluted electron beam in F-region of the ionosphere

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Original Research

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Abstract:

The current filamentation instability is one of the important instabilities in the ionosphere which plays a significant role in the amplification of magnetic fields in the ionosphere, particularly when a solar wind electron beam encounters a weakly ionized plasma. In this paper, the current filamentation instability of the interaction of an electron beam with F region of the ionosphere and the growth rate of instability has been investigated. By solving the fluid description in the presence of binary collision terms between charged and neutral particles and using the local approximation method, the dispersion relation of unstable mode has been obtained and the effect of magnetic field driven-destabilization and current-driven stabilization on the growth rate of instability has been studied. Results show the magnetic threshold for the current filamentation instability in the collisional magnetized ionosphere, in which the instability will disappear for a larger magnetic field than one. Studies show that the value of the magnetic threshold increases by increasing electron beam current density. These results could be important in the explanation of many phenomena that happened in the ionosphere.

Keywords: Current filamentation instability; Magnetic field; Weakly ionized plasma; Collision; Dispersion relation

1. Introduction

The ionosphere is a region of Earth's upper atmosphere, which is composed of a plasma consisting of positively charged ions, negatively charged electrons, and neutral particles [1]. This region of the atmosphere which extends from about 60 kilometers to over 1,000 kilometers from the Earth's surface, plays a critical role in radio communications and navigation systems, and its conditions can have significant effects on satellite positioning systems, radio antennas, and radar systems. Due to the complex interplay between various physical processes, such as solar winds, lightning discharges, radio waves, and high-energy particles, the ionosphere is susceptible to a wide range of plasma instabilities that can cause fluctuations in density, temperature, and electric field. Therefore, to understand the behavior of the ionosphere and improve the performance of radio communication and navigation systems, it is essential to investigate the various plasma instabilities that occur in this region [2–5].

One such important instability of the ionosphere is the current filamentation instability, a type of current-driven plasma instability that usually occurs in the F region of the ionosphere. When an electron beam penetrates a plasma, provided that the electron current is much higher than the Alfven limiting current, a return current is produced to neutralize the beam current, leading to various current instabilities in the beam-plasma system [6–13]. Current filamentation instability (CFI), which is excited by transverse perturbations perpendicular to the electron beam, a magnetic repulsion between the two oppositely directed currents tends to reinforce the initial transverse perturbation. Consequently, a magnetic field is produced and grows exponentially in time. The current filamentation instability plays a significant role in the amplification of magnetic fields in astrophysical systems, particularly when a solar wind encounters a weakly ionized plasma such as ionosphere. Therefore, the behavior of this instability under different

conditions in the astrophysical plasmas has been considered in recent years [14–18].
Hajisharifi et al. [15], considering collisions between charged particles and neutrals, studied the interaction of a diluted warm electron beam and weakly ionized plasma. By choosing an inhomogeneous density profile for the electron beam, the equilibrium state was satisfied. Then, the growth rate of CFI in the presence of thermal effects was obtained [15]. Their results demonstrated that increasing the beam current density expands the unstable wavelength region and increases the growth rate of CFI. Kumar et al. investigated the magnetic field amplification caused by Weibel instability in a spatially uniform, initially unmagnetized, counter-streaming electron-positron plasma beam [17], and contrasted it with the magnetic amplification in nonuniform sub-relativistic counter-streaming electron-positron pairs [18]. The findings indicated that the magnetic field produced by an inhomogeneous density distribution sustains longer than a uniform density distribution. The magnetic field energy's behavior is directly related to the density perturbation in upstream plasma flow, and the amplification of the magnetic field in the inhomogeneous distribution is attributed to temperature anisotropy. This specific density distribution is frequently reported in Gamma-ray bursts.
As it is known, according to recent experimental and theoretical studies, many astrophysical plasmas are magnetized [14, 18] and the presence of external magnetic field in current instabilities has a significant role. It can be said that in the interaction of the electron beam with the plasma, magnetization is one of the parameters to weaken the CFI. The interplay between kinetic effects and magnetic fields is crucial for determining the impact on the growth rate of CFI in magnetized plasma. This competition plays a significant role in either decreasing or increasing the growth rate of CFI in magnetized plasma. Recently, Malik studied a magnetic nozzle, where a nonuniform magnetic field is created and an ion beam is employed to provide thrust to the propulsion device having nonuniform plasma [19–21]. However, there has been limited research on the effects of density gradient, pressure distribution, and external magnetic field in magnetized astrophysical environments such as the ionosphere. Therefore, in this paper, the current filamentation instability of the interaction of a diluted electron beam having nonuniform density with the F region of the ionosphere (solar wind/ionosphere) and the growth rate of instability have been investigated. By solving the fluid description in the presence of binary collision terms between charged and neutral particles and using the local approximation method, the dispersion relation (DR) of unstable mode has been obtained and the effect of magnetic field driven-destabilization and current-driven stabilization on the growth rate of instability has been studied.

2. Model description

We consider a long and warm diluted electron beam with density n^0_{eb} and non-relativistic velocity V^0_{eb} in the x direction passing through weakly ionized plasma region of the ionosphere in the presence of an external magnetic field $\mathbf{B}_0 = B_0 x$ with cyclotron frequency $\omega_c = eB_0/cm_e$. Adopting the multi-fluid approach as well as considering the beam temperature and collisional effects, the time evolution of the system can be investigated by the continuity, momentum, and Maxwell equations, (for simplicity, hereafter on, we used the subscripts b, e, i, and n for beam, electron plasma, ion plasma, and neutral background respectively.)

$$\frac{\partial}{\partial t} n_{j,n} + \nabla\cdot(n_{j,n}\mathbf{V}_{j,n}) = 0, \quad (j = b,e,i) \tag{1}$$

$$m_j n_j\left(\frac{\partial}{\partial t} + \mathbf{V}_j\cdot\nabla\right)\mathbf{V}_j = q_j n_j\left[\mathbf{E} + \frac{\mathbf{V}_j\times(\mathbf{B}+\mathbf{B}_0)}{c}\right] - \nabla P_j - \nu_{jn} m_j n_j(\mathbf{V}_j - \mathbf{V}_n), \tag{2}$$

$$m_n n_n\left(\frac{\partial}{\partial t} + \mathbf{V}_n\cdot\nabla\right)\mathbf{V}_n = -\nabla P_n - \Sigma_j \nu_{nj} m_n n_n(\mathbf{V}_n - \mathbf{V}_j), \tag{3}$$

$$\nabla\times\mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B}, \tag{4}$$

$$\nabla\times\mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial}{\partial t}\mathbf{E}, \tag{5}$$

In Eqs. (1)-(5), q_j is the charge of species j, C is the speed of light in vacuum, and $m_{j,n}$, $n_{j,n}$, $P_{j,n}$, $\mathbf{V}_{j,n}$ are the mass, number density, pressure, and fluid velocity of charged species j, and neutral respectively. $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields and ν_{jn} (ν_{nj}) is the elastic collision frequency of charged species j (neutrals) with neutrals (charged species j). As seen in these equations, the ionization and recombination terms have been ignored. In the momentum equation, the pressure gradients of cold background species and neutrals are negligible, $\nabla P_n \cong \nabla P_i \cong \nabla P_e \cong 0$, which the pressure gradient of beam electrons can be expressed as $\nabla P_b = \gamma_b T_b \nabla n_b$ where T_b is the temperature expressed in units of energy and γ_b is the heat capacity ratio.
In the equilibrium state, considering the beam density profile as $n^0_b(x) = n^0_b(x=0)e^{-x/l}$, the charge and current neutrality condition is provided in the beam momentum transformation equation at any point in the steady state, where $l = V^2_{Tb}/(\nu_{bn\parallel} V^0_b)$ is the length of the system under consideration in the x-direction, $V_{Tb} = (\gamma_b T_b/m_b)^{1/2}$ is the electron beam thermal velocity, and $\nu_{bn\parallel}$ is the collision frequency of the beam-neutral in the direction parallel to the beam. On the other hand, regarding the higher plasma density than the beam density, $n^0_b(x) \ll n^0_p$, the local current neutrality allows us to ignore the return drift velocity of background plasma electrons at every point, $V^0_p(x) = (n^0_b(x)/n^0_p)V^0_b \sim 0$. In this regard, neglecting the collision term of neutrals with warm electrons due to the small density of electrons, the total forces acting on the unmagnetized cold plasma are equal to zero in the equilibrium state [15, 16].
Assuming quantities perturbed according to $\exp[ik_y y - i\omega t]$, with wave vector $\mathbf{k}$ perpendicular to the beam velocity, $\mathbf{k} = k_y\hat{y}$, and magnetic field parallel to the z-axis and electric field $\mathbf{E} = E_x\hat{x}$ and using local approximation method, we find the linearized equations,

$$-i\omega n^1_j + ik_y n^0_j V^1_{jy} = 0, \quad (j = b,e,i,n) \tag{6}$$

$$(-i\omega+\nu_{bn\parallel,\perp})\mathbf{V}_b^1=-\frac{\nabla P_b^1}{m_e n_b^0}-\frac{e}{m_e}\left(\mathbf{E}_1+\frac{\mathbf{V}_b^0\times\mathbf{B}_0}{c}\right)+\nu_{bn\parallel,\perp}\mathbf{V}_n^1-\nu_{bn\parallel}\mathbf{V}_b^0\frac{n_b^1}{n_b^0}, \quad (7)$$

$$(-i\omega+\nu_{en})\mathbf{V}_e^1=-\frac{e}{m_e}(\mathbf{E}_1+\frac{\mathbf{V}_e^1\times\mathbf{B}_0}{c})+\nu_{en}\mathbf{V}_n^1, \quad (8)$$

$$(-i\omega+\nu_{in})\mathbf{V}_i^1=\frac{e}{m_i}(\mathbf{E}_1+\frac{\mathbf{V}_i^1\times\mathbf{B}_0}{c})+\nu_{in}\mathbf{V}_n^1, \quad (9)$$

$$(-i\omega+\nu_n)\mathbf{V}_n^1=\nu_{ni}\mathbf{V}_i^1+\nu_{ne}\mathbf{V}_e^1, \quad (10)$$

where $\nu_{bn\parallel,\perp}$ is the effective collision frequency of beam to neutral particles in the parallel and perpendicular direction to the beam velocity, and $\nu_n=\nu_{ni}+\nu_{ne}$ is the effective frequency of the neutral collisions.
The following linearized Maxwell equations complete the description of the system:

$$\frac{i\omega}{c}\mathbf{B}_1=i\mathbf{k}\times\mathbf{E}_1 \quad (11)$$

$$i\mathbf{k}\times\mathbf{B}_1=\frac{4\pi}{c}\mathbf{J}_1-\frac{i\omega}{c}\mathbf{E}_1 \quad (12)$$

where the perturbed current density is

$$\mathbf{J}_1=\sum_j q_j n_j\mathbf{V}_j=e(n_i^0\mathbf{V}_i^1-n_e^0\mathbf{V}_e^1-n_b^0\mathbf{V}_b^1-\mathbf{V}_b^0 n_b^1). \quad (13)$$

By obtaining the densities from Equations (6) as well as the perturbed velocity of neutral particles from Equation (10) and putting them in Equations (7) to (9), the components of the perturbed velocities are obtained as

$$(-i\omega+\nu_{bn\parallel})V_{bx}^1+\frac{e}{m_e}E_{1x}-\frac{\nu_{bn\parallel}\nu_{ne}}{(-i\omega+\nu_n)}V_{ex}^1-\frac{\nu_{bn\parallel}\nu_{ni}}{(-i\omega+\nu_n)}V_{ix}^1+\frac{\nu_{bn\parallel}V_b^0k_y}{\omega}V_{by}^1=0, \quad (14)$$

$$(-i\omega+\nu_{bn\perp}+\frac{ik_y^2V_{Tb}^2}{\omega})V_{by}^1+\omega_cV_{bz}^1-\frac{e}{m_e}V_b^0B_{1z}-\frac{\nu_{bn\perp}\nu_{ne}}{(-i\omega+\nu_n)}V_{ey}^1-\frac{\nu_{bn\perp}\nu_{ni}}{(-i\omega+\nu_n)}V_{iy}^1=0, \quad (15)$$

$$(-i\omega+\nu_{bn\perp})V_{bz}^1-\omega_cV_{by}^1-\frac{\nu_{bn\perp}\nu_{ne}}{(-i\omega+\nu_n)}V_{ez}^1-\frac{\nu_{bn\perp}\nu_{ni}}{(-i\omega+\nu_n)}V_{iz}^1=0, \quad (16)$$

$$(-i\omega+\nu_{en}-\frac{\nu_{en}\nu_{ne}}{(-i\omega+\nu_n)})V_{ex}^1+\frac{e}{m_e}E_{1x}-\frac{\nu_{en}\nu_{ni}}{(-i\omega+\nu_n)}V_{ix}^1=0, \quad (17)$$

$$(-i\omega+\nu_{en}-\frac{\nu_{en}\nu_{ne}}{(-i\omega+\nu_n)})V_{ey,z}^1\pm\omega_cV_{ez,y}^1-\frac{\nu_{en}\nu_{ni}}{(-i\omega+\nu_n)}V_{iy,z}^1=0, \quad (18)$$

$$(-i\omega+\nu_{in}-\frac{\nu_{in}\nu_{ni}}{(-i\omega+\nu_n)})V_{ix}^1-\frac{\mu e}{m_e}E_{1x}-\frac{\nu_{in}\nu_{ne}}{(-i\omega+\nu_n)}V_{ex}^1=0, \quad (19)$$

$$(-i\omega+\nu_{in}-\frac{\nu_{in}\nu_{ni}}{(-i\omega+\nu_n)})V_{iy,z}^1\mp\mu\omega_cV_{iz,y}^1-\frac{\nu_{in}\nu_{ne}}{(-i\omega+\nu_n)}V_{ey,z}^1=0, \quad (20)$$

In the above equation, $\mu=m_e/m_i$ is the ratio of the electron to ion mass. By obtaining the electric field from Equation (11) and putting it in Ampere's equation, Equation (12) is obtained as follows:

$$ik_y\left(1-\frac{\omega^2}{c^2k_y^2}\right)B_{1z}-\frac{4\pi en_e^0}{c}[(1+\alpha)V_{ix}^1-V_{ex}^1-\alpha V_{bx}^1-\frac{\alpha k_y}{\omega}V_b^0V_{by}^1]=0, \quad (21)$$

where $\alpha=n_b^0/n_e^0$ is the ratio of the unperturbed beam to plasma electron number density. The dispersion relation, Dr, describing the linear dynamics of current filamentation instability of the electron beam-magnetized ionosphere under consideration can be easily derived from the coupled Equations (14) to (21) as follows:

$$Dr=\{K^4\beta_{tb}^2B_0+iC_0\bar{\omega}^2(\alpha B_3+\bar{\omega}B_1+\bar{\nu}_{bn\parallel}B_2)-K^2\bar{\omega}[\beta_{tb}^2(\bar{\nu}_{bn\perp}-i\bar{\omega})(\alpha B_3+\bar{\nu}_{bn\parallel}B_2)-(\bar{\nu}_{in}-i\bar{\omega})(\bar{\nu}_{en}-i\bar{\omega})\left(\alpha\beta^2(i\bar{\nu}_{bn\perp}+\bar{\omega})-C_0(i\bar{\nu}_{bn\parallel}+\bar{\omega})\right)]\}\{\bar{\nu}_{in}^2C_1+C_2+2\bar{\nu}_{in}[-i\bar{\omega}C_1+\bar{\nu}_{ni}(\bar{\omega}^2A+\bar{\nu}_{ne}(\bar{\nu}_{en}\bar{\omega}^2-i\bar{\omega}u+\mu\nu_{en}\Omega^2))]\}. \quad (22)$$

where the expressions of u, A, w, $B_{0,1,2,3}$, and $C_{0,1,2}$ are

$$\begin{aligned}
u&=\bar{\omega}^2-\Omega^2\\
A&=(\nu_{en}^2-2i\nu_{en}\bar{\omega}-\bar{\omega}^2+\Omega^2)\\
w&=(1-i\nu_{en}\bar{\omega}-\bar{\omega}^2)\\
B_0&=(\bar{\nu}_{bn\parallel}-i\bar{\omega})(\bar{\nu}_{bn\perp}-i\bar{\omega})(\bar{\nu}_{in}-i\bar{\omega})(\nu_{en}-i\bar{\omega})\\
B_1&=\bar{\nu}_{ne}+\mu(\bar{\nu}_{en}-i\bar{\omega})-i\bar{\omega}w-i\bar{\nu}_{ni}\bar{\nu}_{en}\bar{\omega}+\bar{\nu}_{in}w\\
B_2&=i\bar{\nu}_{ne}+i\alpha\bar{\nu}_{ne}+\bar{\omega}w+\bar{\nu}_{ni}\bar{\nu}_{en}\bar{\omega}+\mu(i\bar{\nu}_{ni}+(1+\alpha)(i\bar{\nu}_{en}+\bar{\omega}))+i\bar{\nu}_{in}w\\
B_3&=(\bar{\nu}_{en}-i\bar{\omega})(i\bar{\nu}_{in}+(1+\mu)(i\bar{\nu}_{ni}+\bar{\omega}))\\
C_0&=(\bar{\nu}_{bn\perp}^2-2i\bar{\nu}_{bn\perp}\bar{\omega}-u)\\
C_1&=\bar{\nu}_{ne}^2u+\bar{\omega}^2A+2\bar{\nu}_{ne}\bar{\omega}(\bar{\nu}_{en}\bar{\omega}-iu)\\
C_2&=(\bar{\omega}^2-\mu^2\Omega^2)[2i\bar{\nu}_{ne}\bar{\omega}(i\bar{\nu}_{en}\bar{\omega}+u)+\bar{\nu}_{ni}^2A+2\bar{\nu}_{ne}\bar{\omega}(\bar{\nu}_{en}\bar{\omega}-iu)-2i\bar{\nu}_{ni}(\bar{\nu}_{ne}(\bar{\nu}_{en}\bar{\omega}-iu)+\bar{\omega}A)-C_1]
\end{aligned}$$

The obtained DR has been expressed in terms of the following dimensionless variables:

$$K=\frac{ck_y}{\omega_p},\qquad \beta=\frac{V_b^0}{c},\qquad \beta_{Tb}=\frac{V_{Tb}}{c}$$
$$\bar{\omega}=\frac{\omega}{\omega_p},\qquad \Omega=\frac{\omega_c}{\omega_p}\qquad \bar{\nu}=\frac{\nu}{\omega_p}$$

where $\omega_p=(4\pi n_e^0e^2/m_e)^{1/2}$ is the background plasma frequency.

3. Numerical discussion

In this section, the results of numerical analysis of the dispersion relation solutions $Dr = 0$ of the collisional current filamentation instability in the ionosphere are presented. In the F region of the ionosphere, at a distance of $150-1000$ km from the earth's surface, the electron density is in the range of $10^5 - 10^6$ 1/cm^3 and the ionization degree is up to a maximum of 1%. Experimental observations indicate that the ratio of the density of penetrating electron beams to the plasma electron number density in different layers of the ionosphere can vary from 10^{-2} to 10^{-4} [1]. To analyze the current filamentation instability, by solving the dispersion equation $Dr = 0$, the normalized growth rate of the most unstable normal mode (γ/ω_p) versus normalized wave number (ck_y/ω_p) has been depicted in Fig. 1 for magnetized ionosphere with an approximate cyclotron frequency of $\Omega = \omega_c/\omega_p = 0.015$ and non-magnetized ionosphere with $\Omega = 0$. Fig. 1 also demonstrates the instability growth rate for neglecting the collision term in a non-magnetized system ($\nu = 0$, $\Omega = 0$) to ensure the accuracy of our calculations. Appropriate physical parameters of the ionosphere are the ratio of unperturbed beam to plasma electron number density $\alpha = n_b^0/n_e^0 = 4\times10^{-3}$, electron beam temperature $T_b = 3$ eV, initial electron beam velocity $V_b^0 = 0.4c$, $T_e = T_i = 0.02$ eV, neutral density $n_n = 10^{10}$ 1/cm^3, and the ionization degree $i = n_e^0/n_n^0 = 10^{-3}$.
As seen from the dot-dashed curve of this figure, in a non-magnetized system, neglecting collision term ($\nu = 0$, $\Omega = 0$), the instability growth rate of CFI increases continually with wave number until saturation at small wavelength values, in agreement with previous results reported by [15–18]. However, in magnetized and non-magnetized plasmas, collision terms result in a cut-off wave number, which is caused by the collision effects. The magnetic field can reduce the instability growth rate, in agreement with our previous results [16]. Physically, the growth rate of the instability is proportional to the deviation of the filament currents in the increase of the static magnetic field of the input disturbance. The presence of an external magnetic field in the direction of the beam prevents the deviation of electrons and excludes the increase of the filament current density, which in turn reduces the growth rate of the current filamentation instability. For further investigation, the variation of the maximum growth rate in terms of the reduced

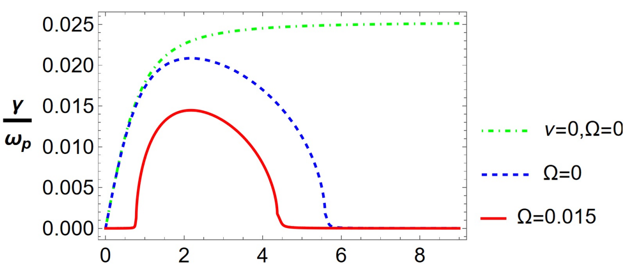

Figure 1. The growth rate of the CFI in the magnetized ($\Omega = \omega_c/\omega_p = 0.015$), unmagnetized ($\Omega = 0$) and collisionless unmagnetized ($\nu = 0$, $\Omega = 0$) regimes for $\alpha = 4\times10^{-3}$, $V_b^0 = 0.4c$, plasma density $n_e^0 = 10^6$ 1/cm^3 and $i = 10^{-3}$.

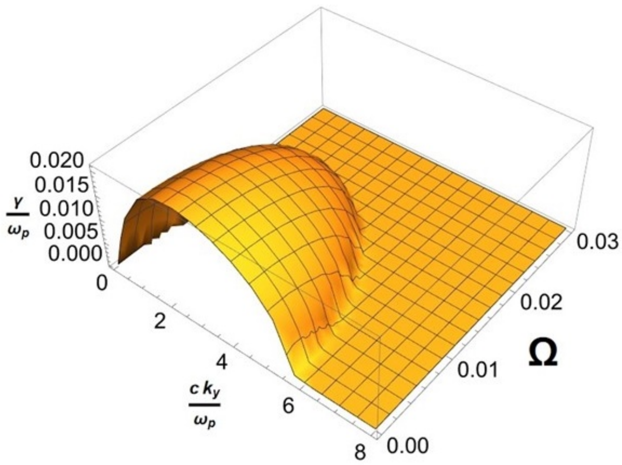

Figure 2. 3D plot of the evaluation of the normalized growth rate γ/ω_p in terms of normalized wave number ck_y/ω_p and cyclotron frequency Ω.

vector and counterplots of the growth rate versus Ω and normalized wave number is displayed in Fig. 2 and Fig. 3 for uniform magnetic field intensity $\Omega = \omega_c/\omega_p$ from 0 to 0.03. The other parameters are the same as Fig. 1.
It is found from these figures that increasing the magnetic field intensity decreases the cut-off wave number, i.e., reduction of unstable wavelength region, to stabilize the system at large Ω. Also, Ω reduces the maximum growth rate of instability at any given wavelength. On the other hand, there exists a threshold cyclotron frequency where the instability disappears for $\Omega > \Omega$th. This threshold value depends on various parameters of the beam, including the ratio of the number density of the beam to the plasma, α, and the beam velocity, β. Thus, the maximum growth rate of instability for various admissible α values and various β have been investigated in Fig. 4 and Fig. 5.

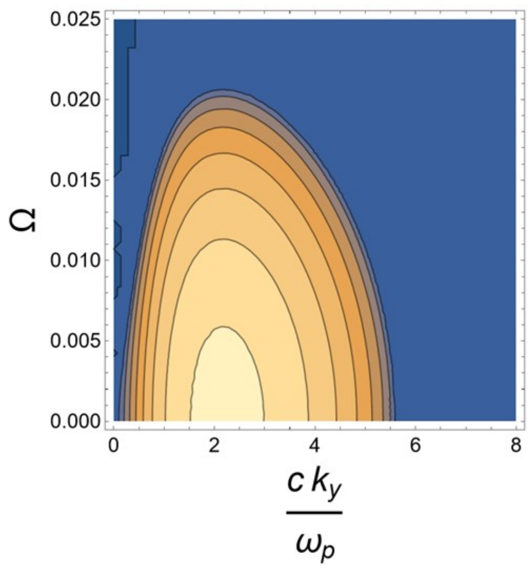

Figure 3. Contour plots of the normalized growth rate γ/ω_p versus cyclotron frequency Ω, and normalized wave number ck_y/ω_p.

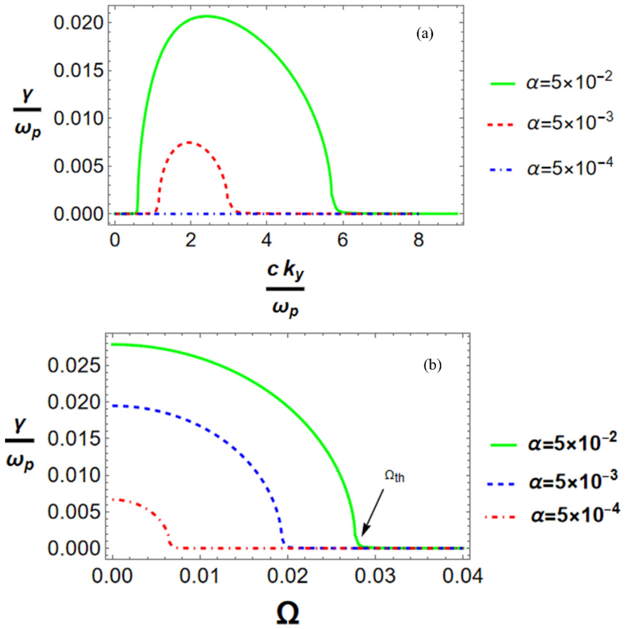

Figure 4. Dimensionless growth rate γ/ω_p in terms of (a) dimensionless wave number ck_y/ω_p, (b) cyclotron frequency Ω for three values of $\alpha = 5\times10^{-2}$, 5×10^{-3}, and 5×10^{-4}. The other parameters are the same as Fig. 1.

It is evident from Fig. 4 (a), as the ratio of beam to plasma density increases, the electron beam becomes denser, and the instability growth rate increases. Therefore, for a fixed value of magnetic field, the system becomes more unstable. Fig. 4 (b) shows that increasing α results in an increase in the cut-off wave number, which causes a broadening of unstable wavelength region, as well as an increase in the maximum growth rate of instability for any arbitrary unstable wavelength because of growing the magnetic field fluctuation with current density. The present results can be compared with the theoretical/numerical findings of Kumar [17, 18] in the competition of kinetic effects and magnetic fields. The magnetic field grows without constraint and leads to the rearrangement of particles in space. Results have shown that the magnetic pressure gradient formed during the quasilinear evolution of the CFI generates an electrostatic field component, and both the electrostatic and magnetic fields work together to redistribute particles within the spatial domain. The electromagnetic fields contribute to the thermalization of electrons. The filamentation instability demonstrates efficient mechanisms for accelerating electrons to high energy levels. On the other hand, it is found from Fig. 5 that increasing the velocity of beam, β, enhances the maximum growth rate due to the increase in current density, the main factor of instability. So, as both α and β increase, the threshold value of the magnetic field Ω_{th} also increases. Hence, larger magnetic fields are needed to prevent the excitation of current filamentation instability at high current densities and beam velocities.

4. Conclusion

In this paper, the current filamentation instability is studied in the ionosphere. The incoming solar wind electron beam interacts with different layers of the ionosphere and gives rise to several plasma unstable modes, especially the CFI. By analyzing the dispersion relation of unstable mode, the effect of magnetic field driven-destabilization and current-driven stabilization on the growth rate of instability has been studied. Results show there is a magnetic field threshold for the current filamentation instability in the collisional magnetized ionosphere, in which the instability will disappear for a larger magnetic field than ones. One can deduce that the value of the magnetic threshold increases by increasing electron beam current density, indicating that the presence of a magnetic field stabilizes the current filamentation instability. Furthermore, decreasing the magnetic field increases the unstable wavelength region as well as the maximum growth rate of the instability. On the other hand, in the magnetized ionosphere, with the increment of the velocity and density of electrons beam, the growth rate of instability becomes larger, and the system is more unstable for a fixed magnetic field. These results could be important for understanding the many phenomena that occur in the ionosphere.

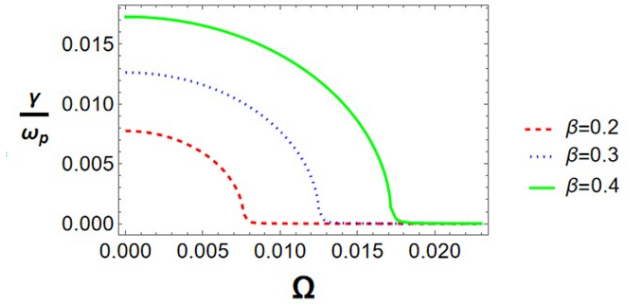

Figure 5. The plot of CFI growth rate versus cyclotron frequency for $\beta = 0.2$, 0.3, and 0.4.

Authors contributions
Samira Tajiknezhad and Kamal Hajisharifi conceived of the presented idea. Samira Tajiknezhad and Ameneh Kargarian developed the theory and performed the analytic calculations and performed the numerical simulations. Samira Tajiknezhad and Ameneh Kargarian verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

Availability of data and materials
No data was used for the research described in the article.

Conflict of interests
The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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