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Wakefields generated by collisional neutrinos in neutral-electron-positron-ion plasma

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A classical fluid description is adopted to investigate nonlinear interaction between an electron-type neutrino beam and a relativistic collisionless unmagnetized neutral-electron-positron-ion plasma. In this work, we consider the collisions of the neutrinos with neutrals in the plasma and study their effect on the generation of wakefields in presence of a fraction of ions in a neutral-electron-positron plasma. The results obtained in the present work are interpreted and compared with previous studies. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4937418]

I. INTRODUCTION

We study in the present work the generation of nonlinear structures in an electron-positron-ion plasma containing a large fraction of neutrals. We consider a beam of neutrinos passing through this plasma and undergoing collisions only with the neutrals of this plasma. The neutrinos entering in collision with neutrals are considered to have a mass and an induced charge. This allows the neutrinos to have electromagnetic properties.[1,2] Indeed, according to previous works (cf. Refs. 1 and 2), the neutrinos are assumed to have a non-zero charge. It is stated also in Refs. 3 and 4 that a neutrino propagating in a plasma acquires an induced charge. This charge is due to the interaction between the neutrino and the electrons in the plasma. In an electron-positron plasma, the electron-type neutrino induced negative charge, pushes the electrons, and the positrons are attracted by this charge. The resulting charge imbalance due to the charge separation creates finite amplitude wakefields in the plasma (cf. Ref. 4). Though small, this charge permits neutrinos to undergo processes such as Cherenkov emission or absorption of a photon. The works proving the existence of the mass and the charge of neutrinos (cf. Refs. 1–6) justify also the assumption of possible existence of collisions between neutrinos and neutrals. In this paper, we find the expressions of the electric field and the electric potential associated with the wakefield generated by the interaction of neutrinos with neutral-electron-positron-ion plasma taking into account the collision between neutrinos and neutrals in this plasma. The paper is organized as follows: in Sec. II the problem is exposed and resolved, in Sec III the results and interpretation are discussed, and conclusions are provided in Sec. IV.

II. THEORY

In this paper, we study the generation of large amplitude plasma waves in a neutral-electron-positron-ion plasma. In this work, the collective neutrino-plasma interaction $G_{\sigma\nu}$ occurs due to the effective neutrino weak charge (cf. Ref. 4)

$$G_{\sigma\nu} = \sqrt{2}G_F[\delta_{\sigma e}\delta_{\nu\nu_e} + (I_\sigma - 2Q_\sigma \sin^2\theta_w)],$$

where $G_{\sigma\nu} = -G_{\bar{\sigma}\nu}$,which leads to the coupling of neutrinos to the plasma fluid. Here, σ denotes the electron e^-, the positron e^+, and ion "i" species of the plasma, G_F is the Fermi weak interaction coupling constant; it is given by $\frac{G_F}{(\hbar c)^3} \approx 1.2\times 10^{-5}\mathrm{GeV}^{-2}$ (cf. Ref. 7), θ_w is the Weinberg mixing angle $\sin^2\theta_w \approx 0.23$, I_σ is the weak isotopic spin of the particle of the species σ, and $Q_\sigma = \frac{q_\sigma}{e}$ is the particle normalized electric charge.

The dynamics of the neutrinos can be described by

$$\frac{\partial N_\nu}{\partial t} + \nabla.\vec{J}_\nu = 0, \tag{1}$$

$$\frac{\partial \vec{p}_\nu}{\partial t} + \left(\vec{V}_\nu\,.\,\nabla\right)\vec{p}_\nu = \sum_\sigma G_{\sigma\nu}\left(\vec{E}_\sigma + \frac{\vec{V}_\nu}{c}\times\vec{B}_\sigma\right) - \nu_{c,\nu}\vec{p}_\nu\,. \tag{2}$$

We note that we have added the collisional term $\nu_{c,\nu}\vec{p}_\nu$ in (2), where $\vec{p}_\nu = \gamma_\nu m_\nu \vec{V}_\nu = \left(\frac{\vec{V}_\nu}{c^2}\right)E_\nu$. m_ν and $\vec{V}_\nu$ are, respectively, the mass and the velocity of the neutrino and $\gamma_\nu = 1/\sqrt{1-V_\nu^2/c^2}$. $\nu_{c,\nu}$ is the frequency of collision between the neutrinos and neutrals. E_ν is the neutrino energy.

The first term in the right hand side of (2) represents the weak force, $\vec{F}_\nu$, acting on a single neutrino due to the plasma, where $\vec{E}_\sigma = -\nabla N_\sigma - \left(\frac{1}{c^2}\right)\left(\frac{\partial \vec{J}_\sigma}{\partial t}\right)$ and $\vec{B}_\sigma = c^{-1}\,\vec{\nabla}\times\vec{J}_\sigma$ are, respectively, the electric and magnetic fields (cf. Ref. 8). $\vec{J}_\nu = N_\nu \vec{V}_\nu$ and $\vec{J}_\sigma = N_\sigma \vec{V}_\sigma$ are the neutrino and σ species currents, respectively. In this work, all quantum mechanical effects and strong magnetic fields are neglected.[4] The plasma particles dynamics is described by the continuity and momentum equations, which are, respectively,

$$\frac{\partial N_\sigma}{\partial t} + \nabla.\vec{J}_\sigma = 0, \tag{3}$$

$$\frac{\partial \vec{p}_\sigma}{\partial t} + \left(\vec{V}_\sigma\,.\,\nabla\right)\vec{p}_\sigma = \frac{q_\sigma\vec{E} - \vec{\nabla}P_\sigma}{N_\sigma} + \sum_\nu G_{\sigma\nu}\left(\vec{E}_\nu + \frac{\vec{V}_\sigma}{c}\times\vec{B}_\nu\right), \tag{4}$$

where $\vec{p}_\sigma = \gamma_\sigma m_\sigma \vec{V}_\sigma$ is the momentum of the particle species σ (electrons or positrons or ions) and $\gamma_\sigma = 1/\sqrt{1-V_\sigma^2/c^2}$, $\vec{V}_\sigma$ being the velocity of the electron, the positron, or the ion.

The right hand side of Equation (4) represents the total force acting on the plasma due to neutrinos, where

$\vec{E}_\nu = -\nabla N_\nu - \left(\frac{1}{c^2}\right)\left(\frac{\partial \vec{J}_\nu}{\partial t}\right)$ and $\vec{B}_\nu = c^{-1}\vec{\nabla}\times\vec{J}_\nu$ are the weak electromagnetic fields.[4] In this set of equations N_σ represents the number density of the species σ (electrons or positrons or ion). $P_\sigma = N_\sigma K T_\sigma$ is the kinetic pressure, where T_σ is the temperature of the species and K is the Boltzmann constant.

We precise that a neutral-electron-positron-ion plasma can be found most likely in the ambient interstellar medium in active galactic nuclei (AGNs), which is considered as a partially and weakly ionized plasma (with a possibility of recombination) containing electrons, positron, ions, and a large fraction of neutral atoms.[9,10] In writing the above equations we have neglected the collisions between electrons, positrons, ions, and neutrals. In this paper, we consider only the collisions between neutrinos and neutrals and we neglect the collisions between neutrinos and electrons, positrons, and ions because the fraction of electrons, the fraction of positrons, and the fraction of ions in the plasma considered are very small compared with the large fraction of the neutrals found in astrophysical mediums as in (AGNs).[9]

For reason of simplicity, we consider only the electron-type neutrino supposed to move along the x-direction with the velocity $\vec{V}_\nu$ close to the light velocity c. We suppose also the motion of the other charged species of the plasma unidirectional and its direction is x. In this paper, we neglect also the contribution of the anti-neutrinos. The plasma is supposed to be relativistic, collisionless, cold, and unmagnetized. The energy and the density of neutrinos do not change significantly when interacting with the plasma. We assume also that a small part of the energy of the neutrino is transferred to the plasma. In the frame of these assumptions, Equation (2) can be rewritten as

$$\frac{\partial E_\nu(x,t)}{\partial t} + c\frac{\partial E_\nu(x,t)}{\partial x} \approx \sqrt{2}G_F c\left(\frac{\partial}{\partial x}(N_{e^+} - N_{e^-}) + \frac{1}{c^2}\frac{\partial}{\partial t}(J_{e^+} - J_{e^-})\right) - \nu_{c,\nu}E_\nu(x,t). \tag{5}$$

To obtain this last equation, we have considered the fact that the ions contribution to the plasma force acting on the electron-type neutrino fluid is negligible. In fact, the effect of the ions on the neutrino effective weak-interaction charge $G_{i\nu}$ is very small compared with the other species' effects.

The relation between the electron, positron, and ion fluid currents is given by

$$\vec{J}_i + \vec{J}_{e^+} - \vec{J}_{e^-} = \frac{1}{4\pi e}\frac{\partial \vec{E}}{\partial t}$$

since we are interested in the generation of electrostatic waves. The electric field $\vec{E}$ is associated with the wakefield generated in the plasma. Hence, Equation (5) becomes

$$\frac{\partial E_\nu(x,t)}{\partial t} + c\frac{\partial E_\nu(x,t)}{\partial x} \approx \sqrt{2}G_F c\left(\frac{\partial}{\partial x}(N_{e^+} - N_{e^-}) + \frac{1}{4\pi e}\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - \frac{1}{c^2}\frac{\partial \vec{J}_i}{\partial t}\right) - \nu_{c,\nu}E_\nu(x,t). \tag{6}$$

In other hand, Equations (1) and (3) give

$$\frac{\partial N_\nu}{\partial t} + c\frac{\partial N_\nu}{\partial x} \approx 0, \tag{7}$$

$$\frac{\partial N_{e^-}}{\partial t} + \frac{\partial J_{e^-}}{\partial x} = 0, \tag{8}$$

$$\frac{\partial N_{e^+}}{\partial t} + \frac{\partial J_{e^+}}{\partial x} = 0, \tag{9}$$

$$\frac{\partial N_i}{\partial t} + \frac{\partial J_i}{\partial x} = 0. \tag{10}$$

From (8), (9), and (10), we can deduce the following expression:

$$(N_{e^+} - N_{e^-}) = \frac{-1}{4\pi e}\frac{\partial E}{\partial x} - N_i.$$

In this work, we consider the ions motion very slow because of their inertia ($\vec{V}_i$ and $\vec{J}_i = N_i\vec{V}_i$ are very small). Therefore, the motion equation (4) written earlier for ions takes the following form:

$$eE - \frac{\gamma K T_i}{N_i}\frac{\partial N_i}{\partial x} = 0,$$

where γ is the adiabatic coefficient; it is equal to $\gamma = 1$ in the isothermal case.

To render appropriate the rest of the calculus, a new independent variable $X = (x - V_\phi t)$ is used, where V_ϕ is the wave phase speed. In the following, we consider $E(X)$ and $E_\nu(X)$ as functions of the variable X only.

Hence, Equation (6) becomes

$$(c - V_\phi)\frac{dE_\nu(X)}{dX} + \sqrt{2}G_F c\frac{1}{4\pi e}\left(1 - \beta_\phi^2\right)\frac{d^2E(X)}{dX^2} + \nu_{c,\nu}E_\nu(X) + \sqrt{2}G_F c\frac{eE(X)}{\gamma K T_i}N_i = 0, \tag{11}$$

where $\beta_\phi = \frac{V_\phi}{c}$.

A. Determination of the electric field $E(X)$ and the electric potential $\varphi(X)$ associated with the wakefield when E_ν is assumed to be constant

We assume that during the interaction of the electron-type neutrinos with the plasma, their local energy E_ν does not change significantly and we set $E_\nu \approx$ constant. We put therefore $\frac{dE_\nu}{dX} \approx 0$ in Equation (11) and we find

$$\sqrt{2}G_F c\frac{1}{4\pi e}\left(1 - \beta_\phi^2\right)\frac{d^2E}{dX^2} + \sqrt{2}G_F c\frac{eE}{\gamma K T_i}N_i + \nu_{c,\nu}E_\nu = 0. \tag{12}$$

We assume also that $\nu_{c,\nu}, N_i$, and T_i are constants and find the expressions of $E(X)$ and $\varphi(X)$. In this case, we have to resolve the following differential equation:

$$\frac{d^2E}{dX^2} + C\frac{N_i}{T_i}E + \alpha = 0, \tag{13a}$$

where

$$\alpha = \frac{4\pi e \nu_{c,\nu} E_\nu}{\sqrt{2} G_F c \left(1 - \beta_\phi^2\right)} \tag{13b}$$

and

$$C = \frac{4\pi e^2}{\gamma K \left(1 - \beta_\phi^2\right)}. \tag{13c}$$

We find the following expressions of $E(X)$ and $\varphi(X)$:

$$E(X) = c_1 \cos\left(\sqrt{\frac{CN_i}{T_i}} X\right) + c_2 \sin\left(\sqrt{\frac{CN_i}{T_i}} X\right) - \frac{\alpha T_i}{CN_i} \tag{14}$$

and

$$\varphi(X) = \sqrt{\frac{T_i}{CN_i}} \left(c_2 \cos\left(\sqrt{\frac{CN_i}{T_i}} X\right) - c_1 \sin\left(\sqrt{\frac{CN_i}{T_i}} X\right)\right) + \frac{\alpha T_i}{CN_i} X + c_3, \tag{15}$$

where c_1, c_2, and c_3 are three constants of integration.

B. Comparison with other works

From the relations (14) and (15), we remark that the electric field $E(X)$ and the electric potential $\varphi(X)$ associated with the wakefield depend on the value of X, E_ν, $\nu_{c,\nu}, N_i$, and T_i. Therefore, the generation and the evolution of the wakefield are affected by the values of these physical quantities. For a given value of E_ν, $\nu_{c,\nu}, N_i$, and T_i, we remark also from the relation (13b) that for $\beta_\phi = 1$ (which implies $V_\phi = c$) $E(X)$ is finite and $\varphi(X) = \frac{\alpha T_i}{CN_i} X + c_3$. We see that this result is different from the one found in Ref. 11, and this is due to the introduction of ions to the neutral-electron-positron plasma considered in this previous work. In the work (cf. Ref. 11), we found that for $\beta_\phi = 1$, $E(X)$ and $\varphi(X)$ become infinite, and this leads to the generation of infinitely large wakefields in the plasma. The presence of ions in a neutral-electron-positron plasma, therefore, considerably modifies the results. However, in the work of Serbeto *et al.*,[12] the electric potential $\varphi(x,t)$ associated with the wakefield is calculated without taking into account the collisions between the neutrinos and the unmagnetized plasma particles (which are electrons and ions). $\varphi(x,t)$ is given by[12]

$$\varphi(x,t) = -\sigma_0 \frac{(E_0 - E_\nu)}{E_0} [1 - \cos(k_e x - \omega_e t)] \tag{16}$$

with

$$\sigma_0 = E_0 / \sqrt{2} G_F n_0 (2 - \beta_\phi). \tag{17}$$

In the other hand, the nonlinear interaction between an electron-type neutrino burst and a collisionless magnetized electron-positron plasma without including the collisions between the neutrino and the plasma particles is studied in the work of Serbeto *et al.*[1] The authors find the following expression for the electric field E:

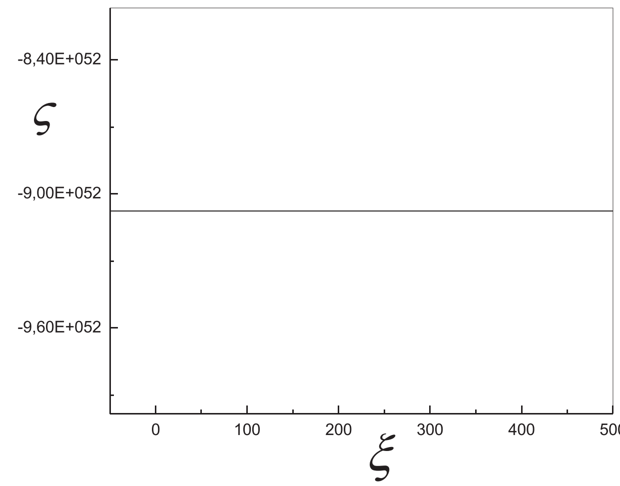

FIG. 1. The normalized electric field ς in function of the normalized distance (phase) ξ.

$$E(x,t) = 3\frac{\omega_p^3}{\omega^3} S_\nu \left(\frac{\Omega_c^2}{2}(kx - \omega t) + \sin(kx - \omega t)\right), \tag{18}$$

where

$$S_\nu = \frac{E_0 (1 - \beta_\phi)}{\sqrt{2} G_F N_0} \frac{\Delta E_\nu}{E_0}. \tag{19}$$

Here, N_0, ω_p, Ω_c, and E_0 are the equilibrium electron(positron) number density, the plasma frequency, the normalized gyrofrequency, and the initial neutrino energy, respectively.

III. RESULTS AND INTERPRETATION

In Figures 1 and 2, we have represented the variation of the normalized electric field $\varsigma = \frac{c\beta_\phi eE}{2\pi m_e c^2 f_p}$ (we use the relations (14) and (15) where $c_1 = c_2 = 1$, $c_3 = 0$, $\beta_\phi = 0.5$, and $E_\nu = 18.8$ MeV according to Bahcall and Krastev[13]) in function of the normalized distance (phase) $\xi = \frac{2\pi f_p}{c\beta_\phi} X$ and the normalized collision frequency $\frac{\nu_{c,\nu}}{f_p}$, respectively (f_p is the

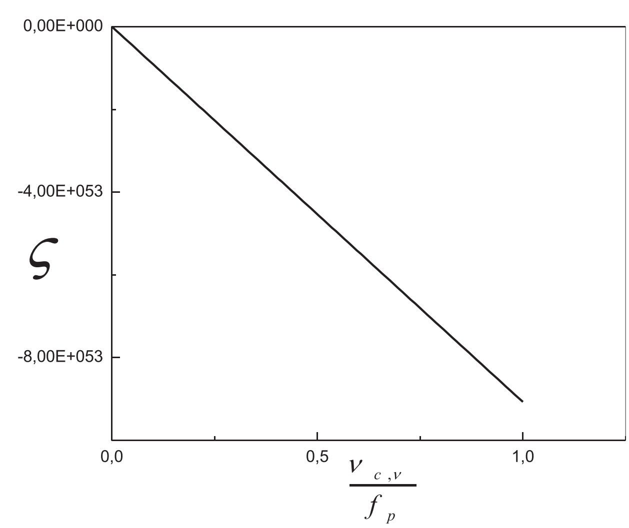

FIG. 2. The normalized electric field ς in function of the normalized collision frequency $\frac{\nu_{c,\nu}}{f_p}$.

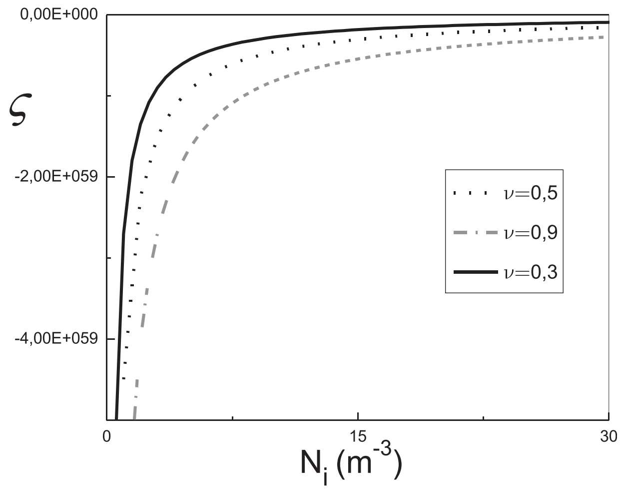

FIG. 3. The normalized electric field ς in function of the ions density N_i for different values of the normalized collision frequency ($\nu = \frac{\nu_{c,\nu}}{f_p} = 0.3$, 0.5, and 0.9).

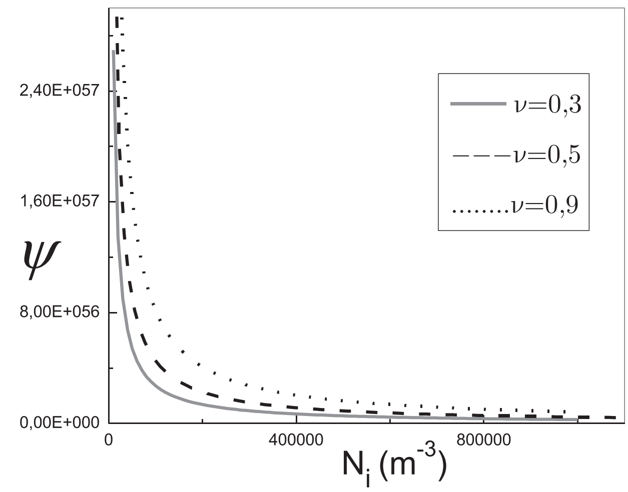

FIG. 5. The normalized potential ψ in function of the ions density N_i for different values of the normalized collision frequency ($\nu = \frac{\nu_{c,\nu}}{f_p} = 0.3$, 0.5, and 0.9).

plasma frequency; it is taken to be equal to 9×10^9Hz according to Chen[14]). In Figure 2, we have fixed the value of $\xi = 100$, $N_i = 10^6\,\mathrm{m}^{-3}$, and $T_i = 10^6\,^\circ$K to obtain the graph of ς in function of the normalized collision frequency $\frac{\nu_{c,\nu}}{f_p}$. In Figure 3, we plot ς in function of the ions density N_i for a temperature $T_i = 10^6\,^\circ$K and $\xi = 100$ for different values of the normalized collision frequency ($\nu = \frac{\nu_{c,\nu}}{f_p} = 0.3$, 0.5, and 0.9). From these three figures, we deduce that the electric field is quasi constant with respect to the distance X because the term $\left(-\frac{\alpha T_i}{CN_i}\right)$ in Eq. (14) is dominant. We remark also that the electric field decreases when the collision frequency increase, especially for the small values of N_i. For the large values of N_i, this field remains constant. In Figure 4, we plot ψ in function of the normalized distance (phase) $\xi = \frac{2\pi f_p}{c\,\beta_\phi}X$; for this we take $N_i = 10^6\,\mathrm{m}^{-3}$, $T_i = 10^6\,^\circ$K, and $\frac{\nu_{c,\nu}}{f_p} = 0.1$. In Figure 5, ψ is represented in function of the ion density N_i for different values of the normalized collision frequency ($\frac{\nu_{c,\nu}}{f_p} = 0.3$, 0.5, and 0.9) taking $\xi = 100$ and $T_i = 10^6\,^\circ$K. In Figure 6, we have fixed the values of $N_i = 10^6\,\mathrm{m}^{-3}$, $\xi = 100$, and $T_i = 10^6\,^\circ$K to obtain the graph of ψ in function of the normalized collision frequency $\frac{\nu_{c,\nu}}{f_p}$. On these three last figures, we find that the electric potential increases when the distance X and the frequency collision $\nu_{c,\nu}$ increases in the case of small values of N_i; in contrast, the potential remains constant for large values of N_i.

IV. CONCLUSION

In conclusion, we have presented a hydrodynamic description, to study the large amplitude wakefield plasma waves generated by intense electron-type neutrinos beams in a neutral-electron-positron-ion plasma, taking into account the collisions between neutrinos and neutrals. Physically, the generation of wakefields in this plasma is attributed to the induced negative charge that electron-type neutrinos acquire

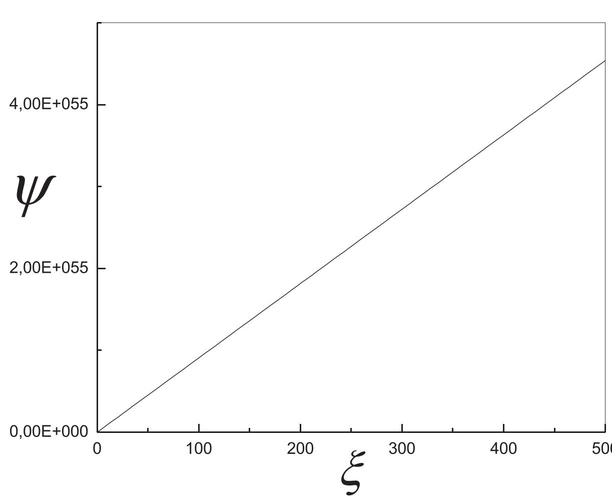

FIG. 4. The normalized potential ψ in function of the normalized distance (phase) ξ.

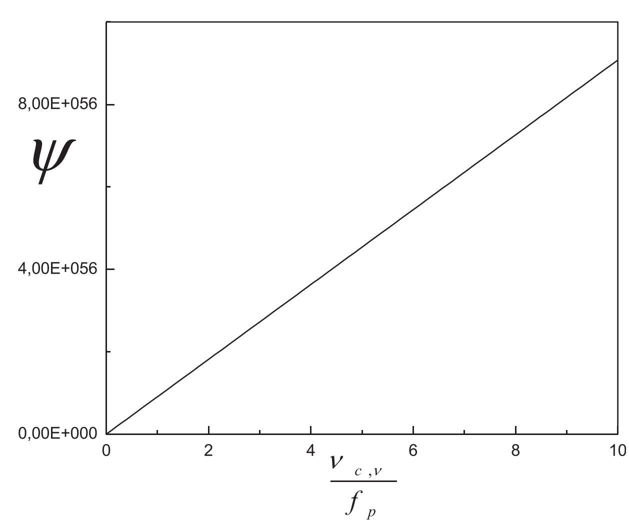

FIG. 6. The normalized potential ψ in function of the normalized collision frequency $\frac{\nu_{c,\nu}}{f_p}$.

when they pass through the plasma. The induced negative charge pushes the electrons and attracts the positrons. The resulting charge imbalance due to the charge separation, in turn, produces finite amplitude wakefields. In this work, we establish the differential equation that expresses the variation of the electric field and the electric potential associated with the wakefield. This work is mainly an attempt to study the effect of the neutrinos collisions on the wakefields generated in the plasma containing ions besides neutrals, electrons, and positrons. We find that the electric field and the electric potential depend essentially on the value of the collision frequency $\nu_{c,\nu}$ and the ions density N_i and their temperature T_i since E_ν remains approximately unchanged during the interaction neutrinos-plasma. Therefore, the generation and the evolution of the wakefield are considerably affected by the value of the collision frequency $\nu_{c,\nu}$ and the ions density N_i and their temperature T_i.

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