# Determination of Growth Rates on Collisional Dust-Ion Acoustic Instability in Un magnetized Dusty Plasmas

**Umo, Emem E.A.[1], Akpabio, Louis E.[2], and Antia, Akaninyene D[3]**

[1,2,3] *Department of Physics, University of Uyo, Akwa Ibom State, Nigeria*

## ABSTRACT

*In this study, the determination of growth rates on collisional dust-ion acoustic instability in un-magnetized plasmas in the presence of applied zero-order electric field $E_0$ was examined. Using the continuity and momentum equations, supplemented by the charge neutrality condition, the dispersion relation was obtained for the plasma species. Our analyses revealed that for the dust-ion acoustic instability, when the inertia terms are neglected $\delta_i = \delta_e^+ = \delta_{e^-} = 0$ and when the inertia terms are included $\delta_i = \delta_e^+ = \delta_{e^-} = 1$ with increased zero-order electric field $E_0$, the instability characteristics in the plasmas was significantly altered, which led to modified growth rates in the dust-ion acoustic wave modes. Findings obtained when the inertia terms are neglected at low energy $(\simeq 0.6eV)$ and at high energy $(\simeq 1.8eV)$ with positron-neutral cross sections $\sigma_e^+$ taken as $0.2 \times 10^{-20}m^2$ and $0.06 \times 10^{-20}m^2$respectively, showed no variation with increased electric field $E_0$, with growth rates $(\gamma < 0)$ of about $-2.2 \times 10^4 s^{-1}$. The inclusion of the inertia terms showed remarkable growth rates differences of order of magnitude $10^{-2}s^{-1}$at high energy lower than that at low energy with damping growth rates, as the electric field is increased. The inertia terms inclusion is seen to affect the ion-positron collision frequency, which modifies the instability characteristics of the dust-ion acoustic waves. These significant differences in growth rates provide valuable inputs on complexity of plasmas involving inertia and electric field to stability of dusty plasmas.*

## KEYWORDS

*dust-ion, instability, growth rates, inertia*

## I. INTRODUCTION

The study of dust-ion acoustic (DIA) wave modes in dusty plasmas was investigated with excitation of the electrons and ions in the presence of a steady-state electric field applied to the plasma [1–10]. Further investigation carried out by Merlino (1997) with the wave mode, showed that the presence of negative ion in electron-ion plasma create new wave modes [19,21,22]. Similar results were seen on the wave mode, with significant increase in growth rates and a corresponding reduction in wave (Landau damping) [11,26,27,31,32]. Instabilities in un-magnetized collisional plasma have increased the quest for further investigation by researchers on the study of dust-ion acoustic wave modes with the presence of positron inertia contrary to the three components (electron-ion-dust) plasma. [13,14,15,16,17,18,24,30] Positron inertia in plasmas has shown that the dust-ion acoustic wave modes behave quite differently [1,23,28,29,35].

The propagation of linear and nonlinear acoustic wave modes in plasma and their characteristics have given greater attention to the investigation of such behaviours (instabilities/shocks and solitons) in the plasmas with electron-ion-positron and dust particles [23,25,33,35]. Plasmas is an exciting field of study in physics with numerous applications such as in Applied Geophysics, Telecommunication, Medical field (application of lasers) etc [5,7,11,20,37]. Plasmas are found in planetary rings, cometary tails, interstellar media, galaxies, ionosphere and magnetosphere [1,5,7,25,31] They have high conductivity and are good conductors of electricity (i.e. due to the high electron mobility) [3,4,5,7,31]. In this research work, the goal is on determination of the growth rates on collisional dust-ion acoustic instability in un-magnetized dusty plasmas.

## II. MATHEMATICAL FORMULATION

We consider plasma containing ions, electrons, positrons, dust grains and neutral atom. Let the charge density of each species given by $n_j$, such that we define, ions, $\mathrm{n}_i$; electrons, $n_{e^-}$; dust grains, $\mathrm{Zn_d}$ and positrons, $n_{e^+}$, where Z is the dust charge number assumed to be fixed. Each of the charge has a mass, $m_j$ where (j = i, $e^-$, $e^+$, d) represent the ion, electron, dust and positron. If an electric field is present in the plasma, then the charged components obeys the dynamics of the fluid continuity and momentum equations and the charge neutrality condition as follows:

$$\frac{\partial n_j}{\partial t} + \frac{\partial}{\partial n}\left(n_j v_j\right) = 0 \tag{1}$$

$$n_j m_j \frac{\partial}{\partial t} v_j + v_j m_j v_j \frac{\partial}{\partial t} v_j + k_B T_j \frac{\partial}{\partial n} n_j - q_j n_j\, E_0 = -v_{jn} n_j m_j v_j \tag{2}$$

$$n_i + n_e^+ = n_e^- + Z n_d \tag{3}$$

Where E is the total electric field in the plasma including the steady-state (zero-order) electric field $E_0$. $n_j$ and $m_j$ densities and masses for the plasma species (electron, positron, ion and dust grains). $T_j$, temperature of the plasma species and $k_B$ is the Boltzmann's constant.

Note that the positron, $e^+$ is a positive electron (i.e. a particle having a positive charge), the dust grains is negatively charged. Therefore, the charged components are given by $q_i = e$; $q_e^- = e^-$; $q_e^+ = e^+$; $q_d = -eZ$. If the zero-order electric field, $E_o$ is imposed on plasma that is in a zero-order state (i.e. steady and uniform). Then $\frac{\partial}{\partial t} = 0 = \frac{\partial}{\partial x}$, the electric field $E_o$ is constant and the velocities of the charged components are also constant. Then Equations 1 and 2 reduces to Equations

$$-q_j n_j E_o = -v_{jn} n_j m_j v_{jo} \tag{4}$$

Since (( j = i, $e^-$, $e^+$, d) for ions, electrons, positrons and dust grains for the jth species. Then

Equation 4 reduces to

$$V_{jo} = \frac{q_j}{v_{jn} m_j} E_o \tag{5}$$

And charge neutrality

$$n_{io} + n_{eo}^{+} = n_{eo}^{-} + Zn_{do} \tag{6}$$

By definition $\varepsilon = \frac{n_{do}}{n_{io}}$ , we obtained from Eq. (6), and solving in terms of ions and electrons, the charge neutrality $n_{eo}^{-} = n_{io}(1-\varepsilon Z)$, hence, we obtained

$$n_{eo}^{+} = n_{io}(1-\varepsilon Z) + n_{io}(\varepsilon Z - 1) \tag{7}$$

Where the quantity $\varepsilon Z$ is the fraction of the negative charge on the dust grains, such that in the absence of dust$(\varepsilon Z = 0)$. And $\upsilon_{jn}$, in Eq. (5), are the collision frequencies for the plasma species with neutral.

## III. DISPERSION RELATIO

By linearizing the set of equations (1-2) and using the zero-order equations (5) and (7) and assuming that all the first-order quantities vary in time and space as $e^{i(kx-\omega t)}$. Let assumed that $\xi_{i1} = \frac{n_{i1}}{n_{io}}$; $\xi_{d1} = \frac{n_{d1}}{n_{do}}$; $\xi_{\substack{+\\e}1} = \frac{n_{e1}^{+}}{n_{eo}^{+}}$; $\xi_{\substack{-\\e}1} = \frac{n_{e1}^{-}}{n_{eo}^{-}}$ and $\Omega_i = w - Kv_{eo}^{+}$. Where K is the wave vector, $\boldsymbol{\omega}$ is the frequency and $\Omega_j$ is the plasma frequency for the jth species$(j = i, e^{-}, e^{+}, d)$. Then, the dispersion relation with the inertia term,$\delta_j$ for the jth species; $\delta_j = \delta_i$, $\delta_e^{+}, \delta_{e^-}$ and $\delta_d$ is obtained as;

$$\frac{1}{[-k^2 k_B T_i + m_i\Omega_i(\delta_i\Omega_i + i\upsilon_{in})]} + \frac{(\varepsilon Z - 1)}{[-k^2 k_B T_e^{+} + m_e^{+}\Omega_e^{+}(\delta_e^{+}\Omega_e^{+} + i\upsilon_{e^{+}n})]} +$$

$$\frac{(1-\varepsilon Z)}{[-k^2 k_B Te^{-} + m_e^{-}\Omega_e^{-}(\delta_{e^-}\Omega_e^{-} + i\upsilon_{e^{-}n})]} + \frac{\varepsilon Z^2}{[-k^z k_B T_d + m_d\Omega_d(\delta_d\,\Omega_d + i\upsilon_{dn})]} = 0 \tag{8}$$

Setting $\delta_d = 1$; for all cases of dust fluid. Then, Eq. (8) yields

$$\frac{1}{[-k^2 k_B T_i + m_i\Omega_i(\delta_i\Omega_i + i\upsilon_{in})]} + \frac{(\varepsilon Z - 1)}{[-k^2 k_B T_e^{+} + m_e^{+}\Omega_e^{+}(\delta_e^{+}\Omega_e^{+} + i\upsilon_{e^{+}n})]} +$$

$$\frac{(1-\varepsilon Z)}{[-k^2 k_B T_e^{-} + m_e^{-}\Omega_e^{-}(\delta_{e^-}\Omega_e^{-} + i\upsilon_{e^{-}n})]} + \frac{\varepsilon Z^2}{[-k^2 k_B T_d + m_d\Omega_d(\Omega_d + i\upsilon_{dn})]} = 0 \tag{9}$$

Considering Eq. (9), dispersion relation involving all the inertia terms $\delta_i$, $\delta_e^{+}, \delta_{e^-}$ and $\delta_d = 1$, solving for the real frequencies and growth rates dust-ion acoustic instability. By definition of relative drift velocity, $u_o = u_{eo}^{+} - u_{io}$; $u_o = u_{eo}^{-} - u_{io}$ and $\Omega_e^{-} = \Omega_i - ku_e^{-}$; $\Omega_e^{+} = \Omega_i - ku_e^{+}$ and if the electron is attached to the dust grains $(1-\varepsilon Z) = 0$. Then, from Eq. (9) letting $\Omega_i = \Omega$ such that $\Omega = \Omega_{ir} + i\,\gamma$. Solving for the real frequency $\Omega_{ir}$ (in the ion frame), we obtained as;

$$\Omega_{ir}^2 = \left(\frac{k_B T_i}{m_i}\right)k^2 + \gamma^2 + \upsilon_{in}\gamma + \left(\frac{k_B T_e^{+}}{(\varepsilon Z - 1)m_i}\right)k^2 + m_e^{+}\gamma\,\upsilon_{e^{+}n} \tag{10}$$

and the growth rate $\gamma$ (in the ion frame) as;

$$\gamma = -\frac{\upsilon_{in}}{2} + \frac{\upsilon_{e^+n}}{2(\varepsilon Z-1)^2}\frac{m_e^+}{m_i}\left(1 - \frac{ku_e^+}{\Omega_{ir}}\right) \tag{11}$$

Similarly, setting $\delta_e^+ = 1$, in Eq. (9) and if the electron is attached to dust grains $(1-\varepsilon Z) = 0$. Then Eq. (9) reduces to

$$\frac{1}{\{-k^2 k_B T_i + m_i\Omega_i(\Omega_i + i\,\upsilon_{in})\}} + \frac{(\varepsilon Z-1)}{\{-k^2 k_B T_e^+ + m_e^+\Omega_e^+(\Omega_e^+ + i\,\upsilon_{e^+n})\}} = 0. \tag{12}$$

Setting $\Omega_i = \Omega$ such that $\Omega = \Omega_{ir} + i\,\gamma$. And solving for the real frequency $\Omega_{ir}$ (in the ion frame), we obtained as;

$$\Omega_{ir} = \frac{2\, m_e^+ ku_e^+ - \{4{m_e^+}^2 k^2 u_{e^+}^2 - 4(\varepsilon Z-1)(m_i + m_e^+)\{(\varepsilon Z-1)(-m_i\gamma^2 - m_i\gamma\,\upsilon_{in} - k^2 k_B T_i) - k^2 k_B T_e^+ - m_e^+\gamma^2 - m_e^+\gamma\,\upsilon_{e^+n} + m_e^+ k^2 u_{e^+}^2\}^{1/2}}{2(\varepsilon Z-1)(m_i + m_e^+)}$$

(13) or

$$\Omega_{ir} = \frac{2\, m_e^+ ku_e^+ + \{4{m_e^+}^2 k^2 u_{e^+}^2 - 4(\varepsilon Z-1)(m_i + m_e^+)\{(\varepsilon Z-1)(-m_i\gamma^2 - m_i\gamma\,\upsilon_{in} - k^2 k_B T_i) - k^2 k_B T_e^+ - m_e^+\gamma^2 - m_e^+\gamma\,\upsilon_{e^+n} + m_e^+ k^2 u_{e^+}^2\}^{1/2}}{2(\varepsilon Z-1)(m_i + m_e^+)} \tag{14}$$

and growth rate $\gamma$ (in the ion frame) as;

$$\gamma = \frac{-\frac{\upsilon_{in}}{2}(\varepsilon Z-1) - \frac{\upsilon_{e^+n}}{2}\frac{m_e^+}{m_i} + \frac{\upsilon_{e^+n} ku_e^+}{2\Omega_{ir}}\frac{m_e^+}{m_i}}{\{(\varepsilon Z-1) - \frac{m_e^+}{m_i} - \frac{ku_e^+ m_e^+}{\Omega_{ir}\, m_i}\}} \tag{15}$$

Using the collision frequencies for ions, positrons and electrons with neutrals given as; $\upsilon_{in} = N\sigma_{in}C_i$ ; $\upsilon_{e^+n} = N\sigma_{e^+n}C_{e+}$ ; $\upsilon_{e^-n} = N\sigma_{e^-n}C_{e-}$ and for dust grains, $\upsilon_{dn} = \frac{4m_n N a^2 C_n}{md}$ respectively. Where $\sigma_{jn}$; *such that* $j = (i, e^+, e^-)$; are the cross sections for ion-neutral, positrons-neutral and electron-neutral collisions, N is density of neutral atoms, and using $C_j = \sqrt{\frac{K_B T_j}{m_j}}$ and $C_n = \sqrt{\frac{K_B T_{jn}}{m_n}}$ as thermal speeds of the species, $j = (i, e^+, e^-)$, $T_n$, temperature of the neutral, $m_n$ the mass of neutral atom, a is the radius of the neutral atom [21,22,23].

## IV. RESULTS AND DISCUSSION

The numerical solutions shown in Figure 1.0 to Figure 10.0 are calculated from the appropriate plasma parameters of references [8,12,22,34,35]. A plot of real frequency and growth rate as a function of zero-order electric field when the inertia term is neglected $\delta_i = \delta_e^+ = \delta_{e^-} = 0$ and when the inertia term is included $\delta_i = \delta_e^+ = \delta_{e^-} = 1$ at low energy ($\simeq 0.6eV$) and high energy ($\simeq 1.8eV$), for the positron-neutral cross sections are displayed in Figure 1.0 to Figure 10.0

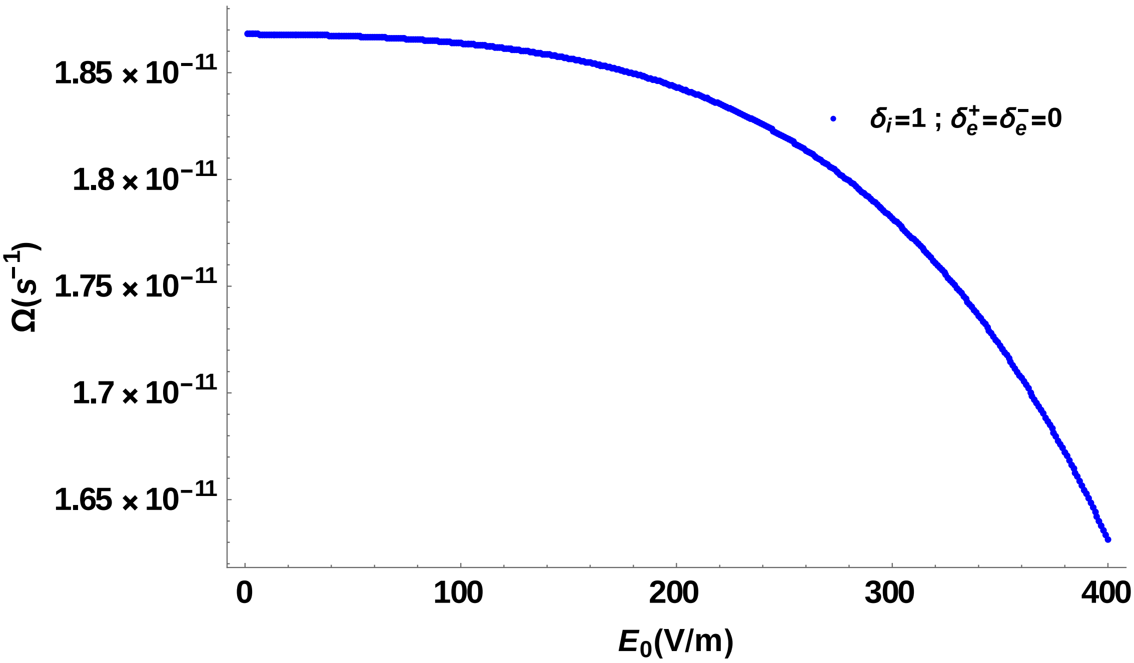


Figure 1.0: Real frequency, $\Omega_{i,r}$ (in the ion frame) as a function applied zero – order electric field $E_0$ when the inertia terms are neglected $\delta_i = \delta_e^+ = \delta_{e^-} = 0$ at low energy for dust-ion acoustic instability.

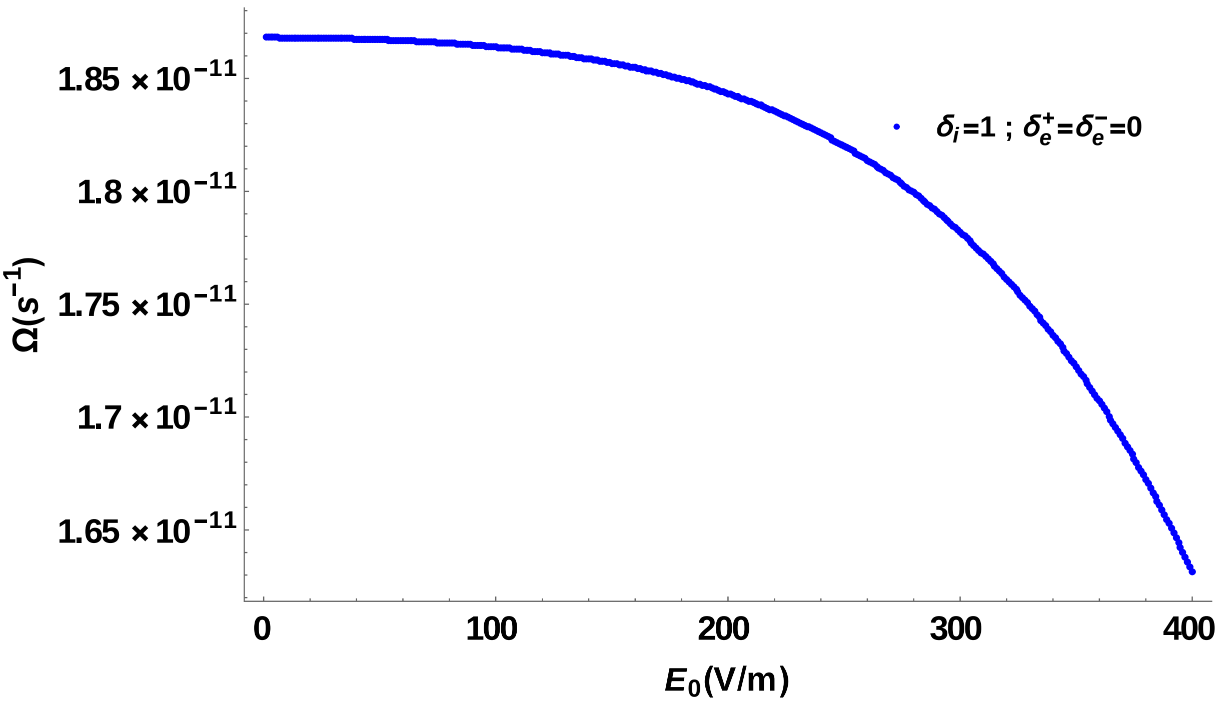


Figure 2.0: Real frequency, $\Omega_{i,r}$ (in the ion frame) as a function applied zero – order electric field $E_0$when the inertia terms are neglected $\delta_i = \delta_e^+ = \delta_{e^-} = 0$ at high energy for dust-ion acoustic instability.

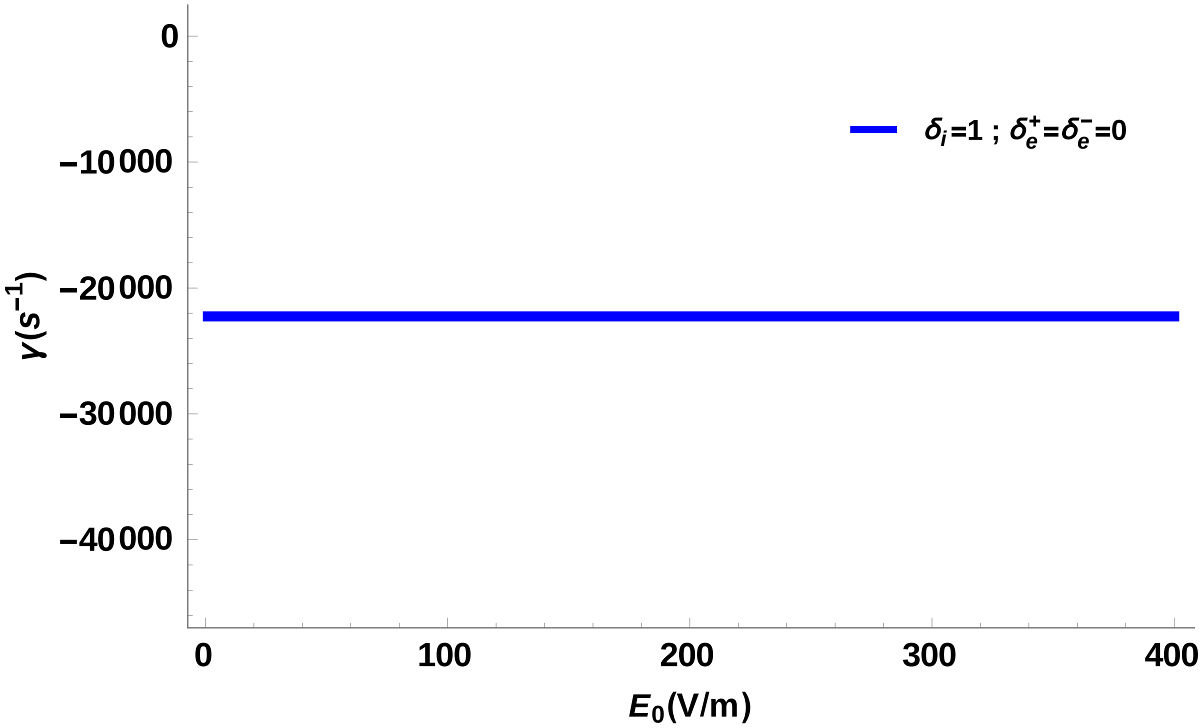


Figure 3.0: Negative growth rate, $\gamma$ (in the ion frame) as a function of applied zero − order electric field $E_0$ when the inertia terms are neglected $\delta_i = \delta_e^+ = \delta_{e^-} = 0$at low energy for dust-ion acoustic instability.

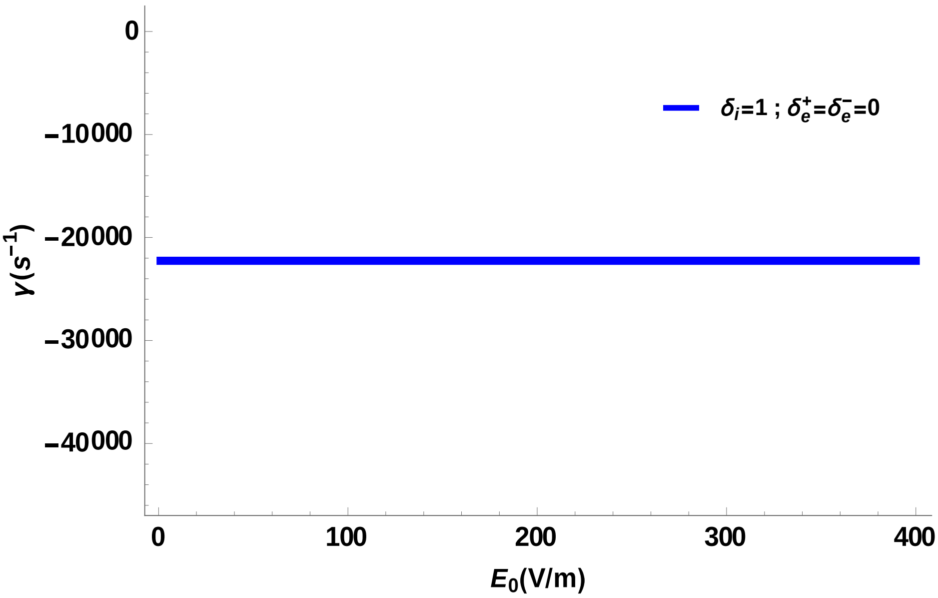


Figure 4.0: Negative growth rate, $\gamma$ (in the ion frame) as a function of applied zero − order electric field $E_0$ when the inertia terms are neglected $\delta_i = \delta_e^+ = \delta_{e^-} = 0$ at high energy for dust-ion acoustic instability.

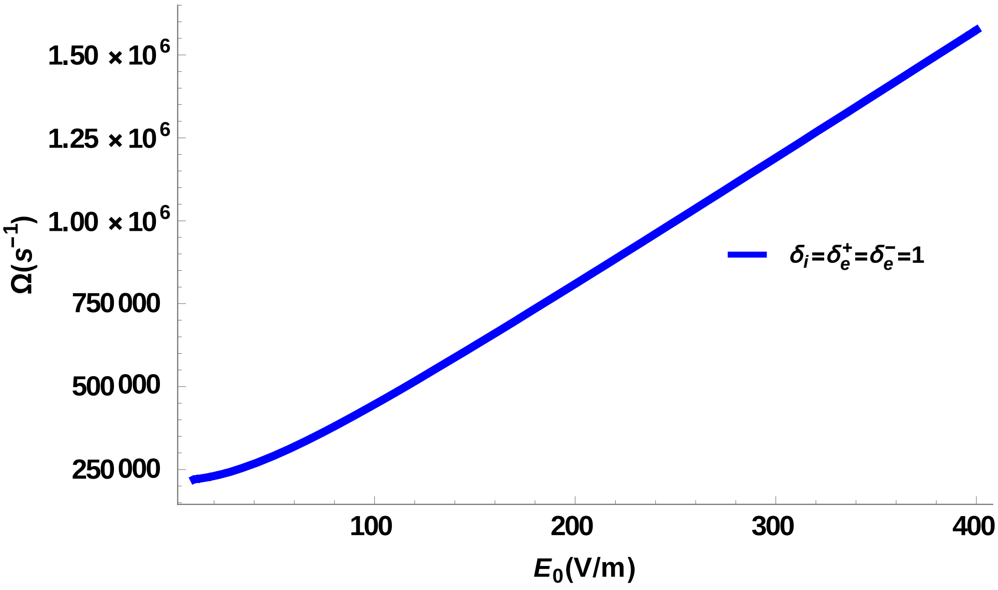


Figure 5.0: Real frequency, $\Omega_{i,r}$ (in the ion frame) as a function applied zero – order electric field $E_0$ when the inertia terms are included $\delta_i = \delta_e^+ = \delta_{e^-} = 1$ at low energy positive root for dust-ion acoustic instability.

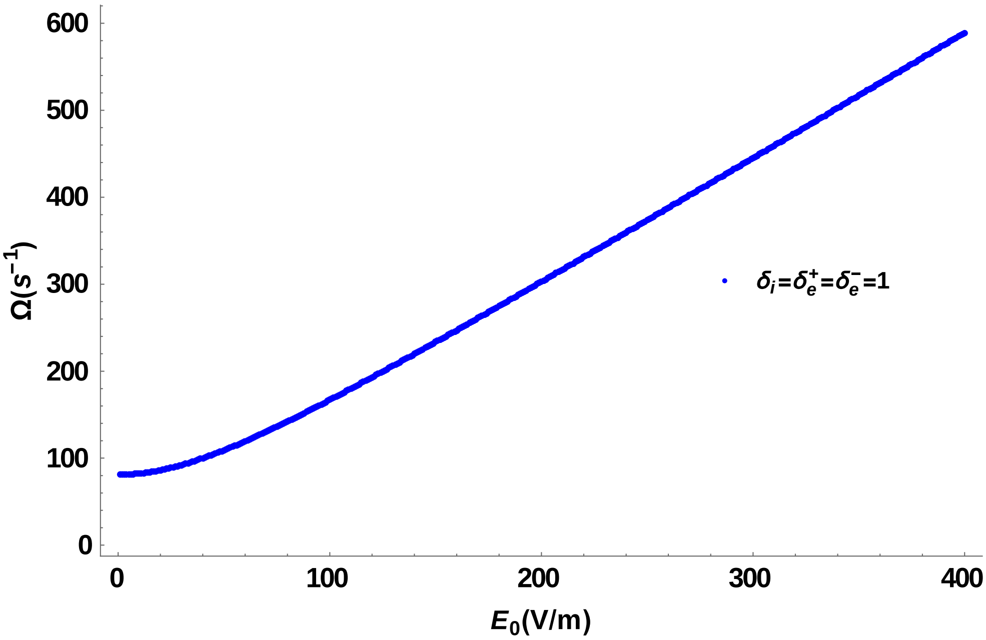


Figure 6.0: Real frequency, $\Omega_{i,r}$ (in the ion frame) as a function applied zero – order electric field $E_0$ when the inertia terms are included $\delta_i = \delta_e^+ = \delta_{e^-} = 1$ at low energy negative root for dust-ion acoustic instability.

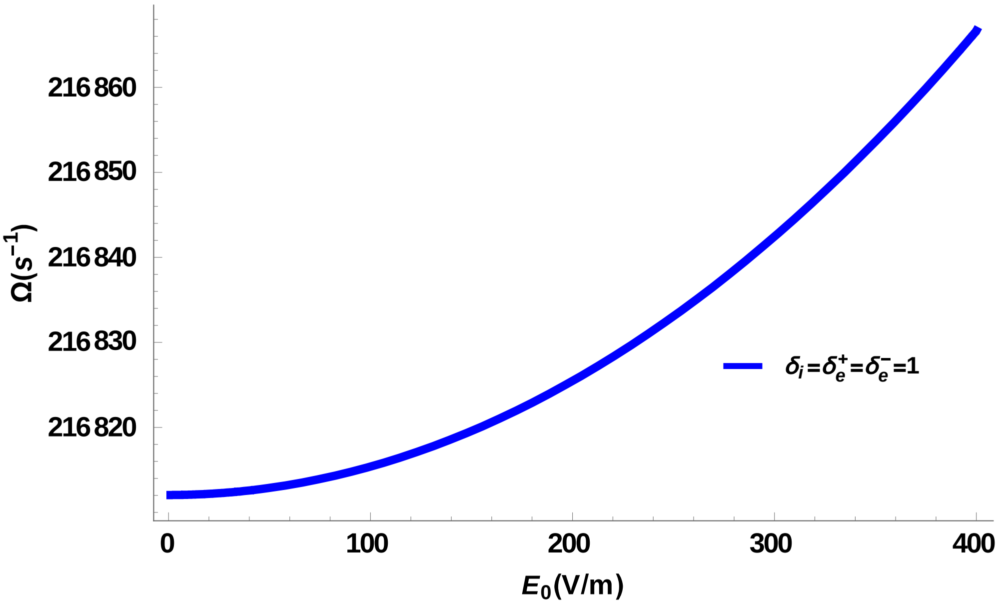


Figure 7.0: Real frequency, $\Omega_{i,r}$ (in the ion frame) as a function applied zero – order electric field $E_0$ when the inertia terms are included $\delta_i = \delta_e^+ = \delta_{e^-} = 1$ at high energy positive root for dust-ion acoustic instability.

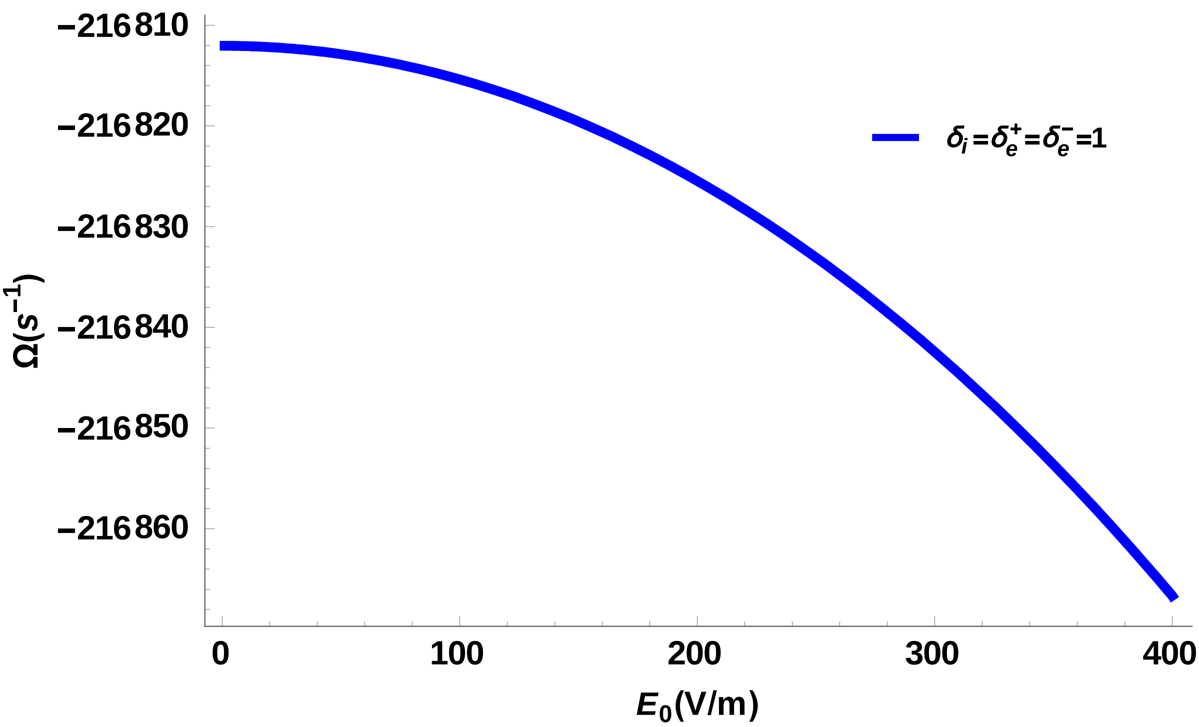


Figure 8.0: Negative real frequency, $\Omega_{i,r}$ (in the ion frame) as a function applied zero – order electric field $E_0$when the inertia terms are included $\delta_i = \delta_e^+ = \delta_{e^-} = 1$ at high energy negative root for dust-ion acoustic instability.

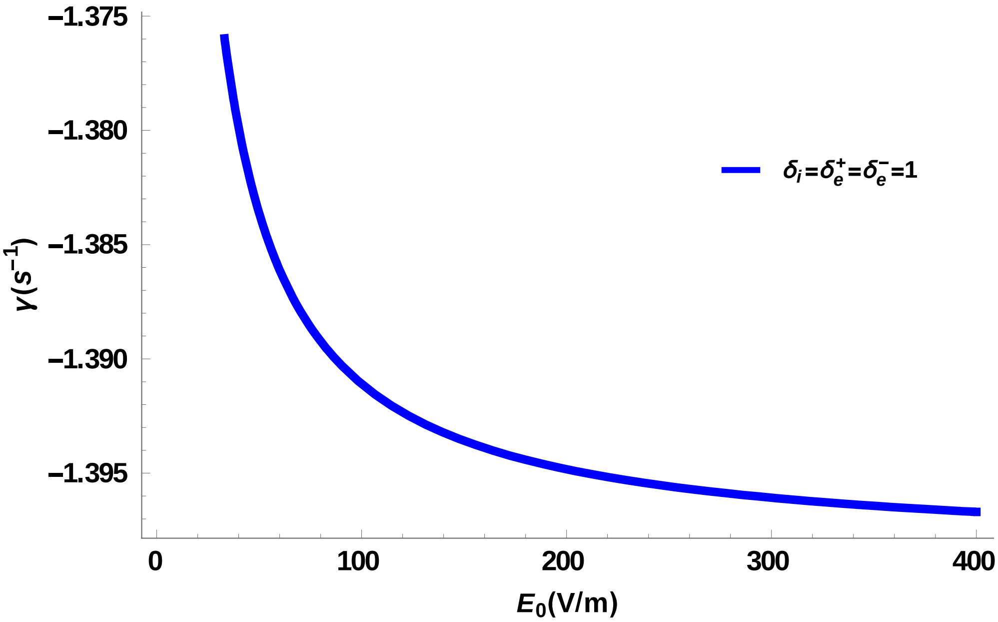


Figure 9.0: Negative growth rate, $\gamma$ (in the ion frame) as a function applied zero – order electric field $E_0$ when the inertia terms are included $\delta_i = \delta_e^+ = \delta_{e^-} = 1$ at low energy for dust-ion acoustic instability.

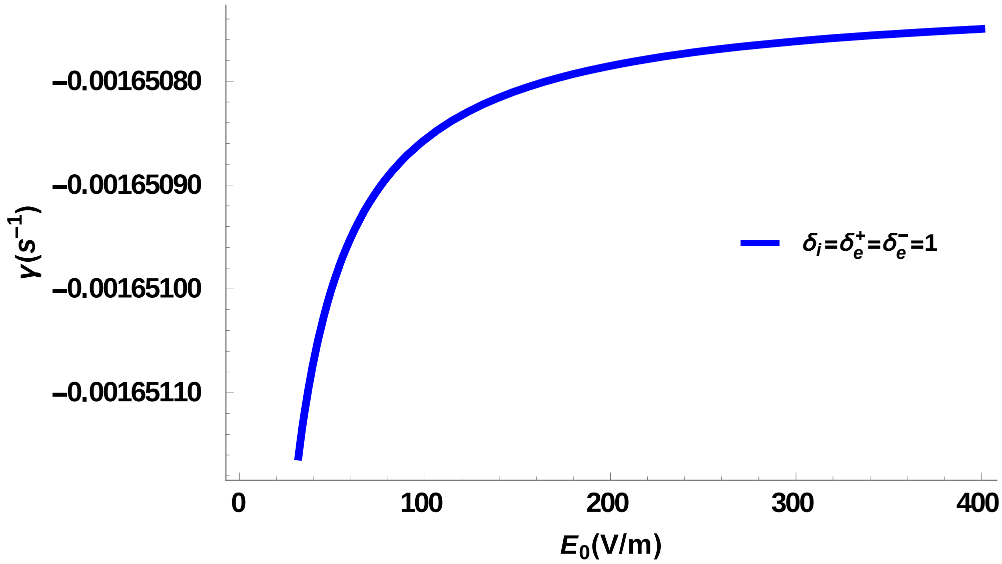


Figure 10.0: Negative growth rate, $\gamma$ (in the ion frame) as a function applied zero – order electric field $E_0$ when the inertia terms are included $\delta_i = \delta_e^+ = \delta_{e^-} = 1$ at high energy for dust-ion acoustic instability.

From the set of plasma parameters for positron-neutral cross sections [12,34,35] for the low energy ($\simeq 0.6eV$) and high energy ($\simeq 1.8eV$) and using Eq. 10 through Eq. 11 for when the inertia terms are neglected $\delta_e^+ = \delta_{e^-} = 0$ and Eq. 13 through Eq. 15 for when the inertia terms are included $\delta_e^+ = \delta_{e^-} = 1$ , have been used to obtain the plots of real frequency $\Omega_{ir}$ and growth $\gamma$ (in the ion frame) as a function of the zero-order electric field $E_0$, displayed in Figure 1.0 through Figure 10.0.

In Figure 1.0 and Figure 2.0 the real frequency $\Omega_{ir}$ (in the ion frame) displayed, shows similar plots of wave propagation with increasing electric field, $E_0$, as there is no excitation of the plasma species with increasing zero-order electric field $E_0$, showing damping of the wave at wave number $\mathrm{K} = 63\mathrm{m}^{-1}$, $\varepsilon Z = 0.8$ (i.e. fraction of negative charge on dust) for both at low energy ($\simeq 0.6eV$) and at high energy ($\simeq 1.8eV$), when the inertia terms are neglected $\delta_e^+ = \delta_{\mathrm{e}^-} = 0$. For growth rate $\gamma$ (in the ion frame) in Figure 3.0 and Figure 4.0, similar results trend are seen with increasing zero-order electric field $E_0$, as the growth rate $\gamma < 0$, negative value growth rate $\gamma$ is obtained at about $\sim 22.0\ \times 10^3 s^{-1}$ for both at low energy ($\simeq 0.6eV$) and at high energy ($\simeq 1.8eV$), showing no variations. This shows that in the absence of the inertia terms $\delta_e^+ = \delta_{\mathrm{e}^-} = 0$, there is no interaction with the ions and dust grains, which leads to stability of the plasma.

In Figure 5.0 through Figure 6.0 the plots display very large magnitudes of real frequency $\Omega_{ir}$ (in the ion frame) for the positron-neutral of cross section $\sigma_{e^+n} = 0.2\ \times 10^{-20} m^2$ at low energy ($\simeq 0.6eV$), when the inertia terms are included $\delta_e^+ = \delta_{\mathrm{e}^-} = 1$, and the wave number is reduced, $\mathrm{K} = 63\mathrm{m}^{-1}$ and negative dust concentration is increased $\varepsilon Z = 0.8$ , yields real frequency $\Omega_{i,r}$ in the order of $10^6$ $\mathrm{s}^{-1}$ with increasing zero-order electric field $E_0$, in Figure 5.0, higher than the real frequency $\Omega_{i,r}$ in Figure 6.0. This shows greater interactions between collisions frequencies and the neutral atoms cross-section.

Similarly, Figure 7.0 through Figure 8.0, plots for real frequency $\Omega_{i,r}$ (in the ion frame) for the positron-neutral of cross section $\sigma_{e^+n} = 0.06\ \times 10^{-20} m^2$ at high energy ($\simeq 1.8eV$), when the inertia terms are included $\delta_e^+ = \delta_{\mathrm{e}^-} = 1$ at reduced wave number $\mathrm{K} = 63\mathrm{m}^{-1}$and increased dust concentration $\varepsilon Z = 0.8$ in Figure 7.0 and Figure 8.0 are displayed. The real frequency $\Omega_{ir}$ (in the ion frame) is seen increasing exponentially in Figure 7.0 while in Figure 8.0, is seen negatively damping off exponentially, as the zero-order electric field $E_0$ increases. This implies that at high energy ($\simeq 1.8eV$), the positron-neutral cross section ($\sigma_{e^+n}$) impact significantly in the behaviour of the plasma. This destabilizing effect shows that as the amount of negative dust is increased, it becomes increasingly easier to excite the wave propagation at low energy ($\simeq 0.6eV$) with positron-neutral cross section $\sigma_{e^+n} = 0.2\ \times 10^{-20} m^2$ for dust-ion acoustic modes.

In Figure 9.0 and Figure 10.0, showed the plot of growth rate $\gamma$ (in the ion frame) as a function of zero-order electric field $E_0$ when the inertia terms are retained $\delta_e^+ = \delta_{\mathrm{e}^-} = 1$, for the different positron-neutral cross sections ($\sigma_{e^+n}$) at low energy ($\simeq 0.6eV$) and high energy ($\simeq 1.8eV$) when the wave number is reduced $\mathrm{K} = 63\mathrm{m}^{-1}$ and the negative dust concentration is increased $\varepsilon Z = 0.8$. There is a remarkable difference in growth rate, $\gamma$ due to the positron-neutral cross section ($\sigma_{e^+n}$) at high energy ($\simeq 1.8eV$) in Figure 10.0, showing negative growth rate in order of $10^{-3}$ smaller than that due to positron-neutral cross section ($\sigma_{e^+n}$), at low energy ($\simeq 0.6eV$) in Figure 9.0. However, in both cases the growth rates $\gamma$ (in the ion frame) when the inertia terms are included $\delta_e^+ = \delta_{\mathrm{e}^-} = 1$, showed growth rate $\gamma < 0$ (decreases), as the zero-order electric field $E_0$ increases. This explains the damping rate with increased electric field. Thus, the impact of positron-neutral cross section ($\sigma_{e^+n}$) influenced ion-positron collision frequency which in turn affects the damping growth rate in dust-ion acoustic modes.

An intriguing part of this work is on the presence of the positron inertia term, being an antiparticle of electron, which responds differently due to the positive charge. It is observed that the inclusion of positron inertia terms $\delta_e^+ = 1$, plays very crucial role in the presence of applied electric field. Plots displayed show that including the positron inertia term has great impact on growth rates in dust-ion instability, as the plasma dynamics were affected, as positron-electron interaction influences the wave propagation due to the positron-neutral cross sections. Similar results were obtained when compared to research works [18,19,21,22,23,24,27,32] dusty plasmas.

## V. CONCLUSION

In this research work, our findings on growth rates $\gamma$ for dust-ion acoustic (DIA) instability. Figure 3.0 and Figure 4.0 showed negative growth rates at low energy $(\simeq 0.6eV)$ and at high energy $(\simeq 1.8eV)$, with no variation when the positron inertia term in neglected $\delta_e^+ = \delta_{e^-} = 0$ in the presence of applied external zero-order electric field $E_0$. However Figure 9.0 and Figure 10.0 depict negative growth at low energy $(\simeq 0.6eV)$ with positron-neutral cross section $\sigma_e^+ = 0.2 \times 10^{-20} m^2$ showing that the growth rate $\gamma$ decreases with applied external zero-order electric field $E_0$ increases, the growth rates instability is affected by the ion-positron collision frequency, as the growth rate $\gamma < 0$, with zero-order electric field $E_0$, leading to damping rate. Thus, at high energy $(\simeq 1.8eV)$ with positron-neutral cross section $\sigma_e^+ = 0.06 \times 10^{-20} m^2$, the zero-order electric field $E_0 = 0\, Vm^{-1}$, showing growth rate $\gamma < 0$, with small damping rate that decreases with increasing zero-order electric field $E_0$. The inclusion of the positron inertia term $\delta_e^+ = \delta_{e^-} = 1$, shows that positron-neutral collision and the positron cross section impact can both influence the plasma dynamics and the growth rate of the dust-ion acoustic instability.

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