EXCITATION OF GOULD-TRIVELPIECEMODE BY AN ION BEAM IN MAGNETIZED DUSTY PLASMA

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ABSTRACT- Excitation of Gould-Trivelpiece (TG) mode byan ionbeam via Cerenkov interaction in a magnetized dusty plasma is investigated. The unstable wave's frequencyenhanced with wave number and δ (relative density of negatively charged dust grains). Moreover, the growth rate of the unstable mode found to be enhanced with increase inδ as well asthe density of the ionbeam. The growth rate scales as the (1/3)rdpower of the beam density. Our study may useful in a Plasma-filled backwardwave oscillator.

***KEYWORDS* -Ion-beam, dust grains, Growth rate, Cerenkov interaction**

I. INTRODUCTION

Gould-Trivelpiece (TG) waves are electrostatic in nature and are observed in the range of frequency between ion plasma frequency and electron cyclotron frequency.TG wave has been investigated theoretically and experimentally [1-5] due to its fascinating property [6]. Excitation of TG waves by low-energy electron beam [7]; observed TG mode in plasma filled rippled resonator[8];observation of the TG mode in Plasma-filled backward wave oscillator[9]; instability of electrostatic TG mode along with electromagnetic instability in neutrino-driven plasma [10]; existence of TG mode alongside helicon mode [11] are some of the investigations done by the researchers .

Dusty plasma is the vast and fascinating arena over the decades.Ion-acoustic wave is observed by Barkan et al. [12] in magnetized dusty plasma. Rosenberg observed dust ion-acoustic and dust acoustic instabilities in an unmagnetized dusty plasma [13]. The effect of negatively charged dust grains on excitation of ion-acoustic waves [14] and dust acoustic waves by an ion-beam in a plasma cylinder have been studied [15].

In this work, we have developed a model in which the excitation of Gould-Trivelpiece (TG) mode by ion beam in magnetized dusty plasmas is examined. Section II contains the instability analysis. Using linear first order perturbation theory, the response of the ion beam industy plasma is obtained and growth rate of instability is derived. Section III gives the results and discussion of instability. The results of work are concluded in Section IV.

II INSTABILITY ANALYSIS

Let us consider the plasma column having dust grains and the equilibrium electron density n_{e0}, ion density n_{i0}, and dust grains density n_{d0}. The column is held in the static magnetic field B_s in the z-direction. The electrons are defined by ($-e$, m_e, T_e), ions by (e, m_i, T_i) and dust particles by ($-Q_{d0}$, m_d, T_d).Consider an electrostatic wave, say, Gould-Trivelpiece (TG) mode, propagating perpendicularly to the external magnetic field (propagation vector **k**) in the x-z plane. The ion beam is taken which is travelling along z-axis through the plasma column along the magnetic field with density n_{b0} and equilibrium velocity $\upsilon_{b0}\hat{z}$. Before perturbation, the system of beam and plasma is quasi-neutral, $(-n_{e0}+n_{i0}+n_{b0}-n_{d0}=0)$ since it has been taken that the plasma density is much more greater than the beam density. This equilibrium is perturbed due to electrostatic perturbation and potential associated with it is given by

$$\phi=\phi_0\exp[-i(\omega t-k_x x-k_z z)]. \quad (1)$$

The species (plasma, dust and beam particles) are taken as fluids and consider the equation of motion and equation of continuity. Further, on linearization the equations of motion and continuity leads to the perturbations inelectrondensity, ion density, dust density and beam density and given by the following Eqs:

$$n_{1e}=-\frac{n_{e0}e\phi}{m_e}\left[\frac{k_x^2}{\omega^2-\omega_{ce}^2}+\frac{k_z^2}{\omega^2}\right], \quad (2)$$

where $\omega_{ce}\{=eB_s/m_e c\}$ is the electron-cyclotron frequency,

$$n_{1i} = \frac{n_{i0} e\phi}{m_i}\left[\frac{k_x^2}{\omega^2 - \omega_{ci}^2} + \frac{k_z^2}{\omega^2}\right], (3)$$

where $\omega_{ci}\{= eB_s / m_i c\}$ is the ion-cyclotron frequency,

$$n_{1d} = -\frac{n_{d0} Q_{d0} \phi k^2}{m_d \omega^2}, (4)$$

and

$$n_{1b} = -\frac{n_{b0} e k_z^2 \phi}{m_e(\omega - k_z \upsilon_{b0})^2}. (5)$$

In this case, dust is taken as unmagnetized since $\omega >> \omega_{cd}$ with $\omega_{cd}\{= Q_{d0} B_s / m_d c\}$ (dust cyclotron frequency). Further applying the probe theory to a dust grain, Q_d (dust grain's charge) is said to be well-balanced with the plasma currents present on the grain surface [16,17].

Then, the equation written below is express the term 'charge fluctuation'

$$\frac{dQ_{1d}}{dt} + \eta Q_{1d} = -|I_{eo}|\left(\frac{n_{1i}}{n_{i0}} - \frac{n_{1e}}{n_{e0}}\right), \quad (6)$$

Substituting the values of n_{1e} and n_{1i} from (2) and (3) in (8), we obtain

$$Q_{1d} = \frac{|I_{e0}|}{i\,(\omega + i\eta)}\left[\frac{k_x^2\phi}{(\omega^2 - \omega_{ci}^2)m_i} + \frac{k_z^2\phi}{m_i\omega^2} + \frac{k_x^2\phi}{m_e(\omega^2 - \omega_{ce}^2)} + \frac{k_z^2\phi}{m_e\omega^2}\right]. \quad (7)$$

Under the view of overall charge neutrality in equilibrium, we can write, $-en_{i0} + en_{e0} + Q_{d0}n_{d0} = 0$ or $n_{d0}/n_{e0} = \{\delta - 1\}\{e/Q_{d0}\}$, where $\delta = n_{i0}/n_{e0}$ Using Poisson's equation $\nabla^2\phi = 4\pi(n_{1e}e - n_{1i}e - n_{1b}e + n_{d0}Q_{1d} + Q_{d0}n_{1d})$ and substituting the values from (2)- (5) and (7) in it, and taking $\omega << \omega_{ce}$, we obtain

$$1 + \left(\frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{k_x^2}{k^2} - \frac{\omega_{pe}^2}{\omega^2}\frac{k_z^2}{k^2} - \frac{\omega_{pi}^2}{(\omega^2 - \omega_{ci}^2)}\frac{k_x^2}{k^2}\right) - \left(\frac{i\beta\omega_{pe}^2(m_e/m_i)}{(\omega + i\eta)(\omega^2 - \omega_{ci}^2)}\frac{k_x^2}{k^2} + \frac{i\beta\omega_{pe}^2(m_e/m_i)}{(\omega + i\eta)\omega^2}\frac{k_z^2}{k^2}\right)$$
$$+ \left(\frac{i\beta\omega_{pe}^2}{(\omega + i\eta)\omega_{ce}^2}\frac{k_x^2}{k^2} - \frac{i\beta\omega_{pe}^2}{(\omega + i\eta)\omega^2}\frac{k_z^2}{k^2} + \frac{i\beta\omega_{pe}^2}{(\omega + i\eta)\omega^2}\frac{k_z^2}{k^2}\frac{\omega_{pd}^2}{\omega^2}\right) = \frac{\omega_{pb}^2}{(\omega - k_z\upsilon_{b0})^2}\frac{k_z^2}{k^2}, \quad (8)$$

where $\omega_{pe}^2 = \frac{4\pi n_{e0} e^2}{m_e}$, $\omega_{pi}^2 = \frac{4\pi n_{i0} e^2}{m_i}$, $\omega_{pd}^2 = \frac{4\pi n_{d0} e^2}{m_d}$, $\omega_{pb}^2 = \frac{4\pi n_{b0} e^2}{m_b}$ and

$\beta\left(= \frac{|I_{e0}|}{e}\frac{n_{d0}}{n_{e0}}\right)$ is the dust plasma coupling parameter.

Using charge neutrality condition by Prakash and Sharma [18], we can also write dust plasma coupling parameter as $\beta = 0.397(1-1/\delta)(a/v_{te})\omega_{pi}^2(m_i/m_e)$, where $v_{te} = \sqrt{T_e/m_e}$ is the thermal velocity of electron. The dust charging rate can be given by $\eta = 0.79a\left(\frac{\omega_{pi}}{\lambda_{Di}}\right)\frac{1}{\delta}\left(\frac{m_i T_i}{m_e T_e}\right) \approx 10^{-2}\,\omega_{pe}\left(\frac{a}{\lambda_{De}}\right)\frac{1}{\delta}$.

Further, on neglecting the effect of the ion beam and dust grains i.e., $n_{b0}=0$, $\delta=1$, $\beta=0$, (8) gives

$$1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{k_x^2}{k^2}-\frac{\omega_{pe}^2}{\omega^2}\frac{k_z^2}{k^2}-\frac{\omega_{pi}^2}{(\omega^2-\omega_{ci}^2)}\frac{k_x^2}{k^2}=0. \qquad (9)$$

Considering (9) and applying conditions essential for TG wave, we obtain

$$\omega_{pi} << \omega << \omega_{ce},\ \omega = \left(\omega_{pe}k_z\right)/k_\perp \quad (10)$$

as$(\omega_{pe}/\omega_{ce})$<<1 where $k=\sqrt{k_\perp^2+k_z^2}$, $k_z << k_\perp$. Equation (10) is the standard dispersion relation of TG mode [19, 20] in the infinite geometry. Equation (10) can be rewrite as

$$\left(1+\frac{i\beta\omega_{tg}^2}{(\omega+i\eta)\omega_{ce}^2}\frac{k_x^2}{k^2}\right)\omega^4+\left(\begin{array}{l} -\omega_{ci}^2-\omega_{tg}^2\frac{m_i}{m_e}\frac{k_z^2}{k^2}+\omega_{tg}^2\frac{k_x^2}{k^2}-\frac{i\beta\omega_{tg}^2}{(\omega+i\eta)}\frac{k_x^2}{k^2}\\ +\frac{i\beta\omega_{tg}^2}{(\omega+i\eta)\,\delta}\frac{k_z^2}{k^2}+\frac{i\beta\omega_{tg}^2(m_i/m_e)\omega_{ci}^2}{(\omega+i\eta)\omega_{ce}^2}\frac{k_z^2}{k^2}\\ +\frac{i\beta\omega_{tg}^2(m_i/m_e)}{(\omega+i\eta)}\frac{k_z^2}{k^2}+\frac{\omega_{pd}^2}{\tilde{K}}\end{array}\right)\omega^2 \qquad (11)$$

$$+\left(\omega_{tg}^2\omega_{ci}^2\frac{m_i}{m_e}\frac{k_z^2}{k^2}-\frac{i\beta\omega_{tg}^2\omega_{ci}^2}{\left(\omega+i\eta\right)\delta}\frac{k_z^2}{k^2}\left(1-\frac{m_i}{m_e}\right)-\frac{\omega_{pd}^2}{\tilde{K}}\omega_{ci}^2\right)=\frac{\omega_{pb}^2\omega^2(\omega^2-\omega_{ci}^2)}{(\omega-k_z\upsilon_{b0})^2}\frac{k_z^2}{k^2},$$

where,

$$\omega_{tg}^2=\omega_{pi}^2/\tilde{K},\ \tilde{K}=1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{k_x^2}{k^2}.$$

Equation (11) gives

$$(\omega^2-\xi_1^2)(\omega^2-\xi_2^2)(\omega-k_z\upsilon_{b0})^2=\omega_{pb}^2\omega^2(\omega^2-\omega_{ci}^2)\frac{k_z^2}{k^2}, \qquad (12)$$

where

$$\xi_1^2=\frac{\left(\frac{\omega_{tg}^2\omega_{ci}^2k_z^2m_i}{k^2m_e}-\frac{i\beta\omega_{tg}^2\omega_{ci}^2k_z^2}{(\omega+i\eta)\delta k^2}+\frac{i\beta\omega_{tg}^2\omega_{ci}^2m_ik_z^2}{(\omega+i\eta)m_ek^2}-\frac{\omega_{pd}^2\omega_{ci}^2}{\tilde{K}}\right)}{\left(\begin{array}{l}\omega_{ci}^2+\frac{\omega_{tg}^2m_ik_z^2}{m_ek^2}+\frac{\omega_{tg}^2k_x^2}{k^2}+\frac{i\beta\omega_{tg}^2k_x^2}{(\omega+i\eta)k^2}+\frac{i\beta\omega_{tg}^2k_z^2}{(\omega+i\eta)k^2}\\ +\frac{i\beta\omega_{tg}^2k_z^2}{(\omega+i\eta)\delta k^2}+\frac{i\beta\omega_{tg}^2\omega_{ci}^2m_ik_x^2}{(\omega+i\eta)\omega_{ce}^2m_ek^2}+\frac{i\beta\omega_{tg}^2m_ik_z^2}{(\omega+i\eta)m_ek^2}-\frac{\omega_{pd}^2}{\tilde{K}}\end{array}\right)}$$

and $\xi_2^2 = \dfrac{\omega_{ci}^2}{1+\dfrac{k^2}{k_z^2}\dfrac{m_e}{m_i}}$.

Here, in Eq. (12) $\omega \approx \xi_1$ associates with TG mode, $\omega \approx \xi_2$ associates with ion-cyclotron mode and $\omega = k_z\upsilon_{b0}$ associates with beam mode. We are seeking for the solution when $\xi_1 \approx k_z\upsilon_{b0}$ (i.e., when beam mode is in Cerenkov resonance with the TG mode). Here, the two factors on the LHS of the equation (12) will become zero simultaneously, when ion beam is not present.

From (12), in the absence of ion beam and putting $\delta\left(= {n_{i0}}\big/{n_{e0}}\right)$=1, i.e., $\beta \to 0$, we will recover the expressions as

$$\omega^2 = \omega_{tg}^2\left(1+\frac{m_i}{m_e}\frac{k_z^2}{k^2}\right), \qquad \omega_{tg}^2 = \omega_{pi}^2\Bigg/\left(1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{k_x^2}{k^2}\right)$$

where, ω_{tg} is the frequency of TG mode.

Further, ξ_1^2 in Eq. (12)can be modified and rewrite as

$$\xi_1^2 = \frac{l_1l_3+l_2l_4}{l_3^2+l_4^2} + i\,\frac{l_1l_4+l_2l_3}{l_3^2+l_4^2} .$$

$$\xi_1 = \left[\left(\frac{l_1l_3+l_2l_4}{l_3^2+l_4^2}\right)^2 + \left(\frac{l_1l_4+l_2l_3}{l_3^2+l_4^2}\right)^2\right]^{1/4} \qquad (13)$$

where, $l_1 = \omega_{ci}^2\omega_{tg}^2\dfrac{k_z^2}{k^2}\dfrac{m_i}{m_e} + \dfrac{\beta\eta\omega_{tg}^2}{(\omega^2+\eta^2)}\omega_{ci}^2\dfrac{k_z^2}{k^2}\left(\dfrac{1}{\delta}+1\right) - \dfrac{\omega_{pd}^2\omega_{ci}^2}{\tilde{K}}$,

$$l_2 = \frac{\beta\omega\omega_{tg}^2}{(\omega^2+\eta^2)}\omega_{ci}^2\frac{k_z^2}{k^2}\left(\frac{1}{\delta}+1\right),$$

$$l_3 = \omega_{ci}^2 + \omega_{tg}^2\frac{m_i}{m_e}\frac{k^2}{k_z^2} - \frac{\omega_{pd}^2}{\tilde{K}}$$

$$+\frac{\beta\eta\omega_{tg}^2}{(\omega^2+\eta^2)}\left(\frac{k_x^2}{k^2}+\frac{k_z^2}{k^2}\frac{1}{\delta}+\frac{m_i\omega_{ci}^2}{m_e\omega_{ce}^2}\frac{k_x^2}{k^2}+\frac{m_i}{m_e}\frac{k_z^2}{k^2}\right)$$

and

$$l_4 = \frac{\beta\omega\omega_{tg}^2}{(\omega^2+\eta^2)}\left(\frac{k_x^2}{k^2}+\frac{k_z^2}{k^2}\frac{1}{\delta}+\frac{m_i\omega_{ci}^2}{m_e\omega_{ce}^2}\frac{k_x^2}{k^2}+\frac{m_i}{m_e}\frac{k_z^2}{k^2}\right).$$

In the presence of beam, we expand frequency ω as $\omega = \xi_1 + \delta'' = k_z\upsilon_{b0} + \delta''$, where δ'' is the small frequency discrepancy due to the finite value on RHS of Eq. (13).

According to Mikhailovski [21], the growth rate of the unstable mode is given as

$$\gamma = \operatorname{Im}\delta_1 = \frac{\sqrt{3}}{2}\left[\frac{\omega_{pb}^2 k_z^2 \xi_1(\xi_1^2 - \omega_{ci}^2)}{2(\xi_1^2 - \xi_2^2)k^2}\right]^{1/3} . \tag{14}$$

The real part of unstable mode's frequency is

$$\omega_r = k_z\left[\frac{2eV_b}{m_i}\right]^{1/2} - \frac{1}{2}\left[\frac{\omega_{pb}^2 k_z^2 \xi_1(\xi_1^2 - \omega_{ci}^2)}{2(\xi_1^2 - \xi_2^2)k^2}\right]^{1/3} , \tag{15}$$

where $\upsilon_{b0}\left[=\left(\frac{2eV_b}{m_i}\right)^{1/2}\right]$ is the beam velocity, eV_b is the ion beam energy and $k^2 = k_x^2 + k_z^2$.

The phase velocity of the unstable mode

$$v_{ph} = \frac{\omega_r}{k_z} = \left[\frac{2eV_b}{m_i}\right]^{1/2} - \frac{1}{2k_z}\left[\frac{\omega_{pb}^2 k_z^2 \xi_1(\xi_1^2 - \omega_{ci}^2)}{2(\xi_1^2 - \xi_2^2)k^2}\right]^{1/3} . \tag{16}$$

III.NUMERICAL ANALYSIS

In the present work we have taken common dusty plasma parameters for calculations. Using (13), we plot the dispersion curvesof Gould-Trivelpiece (TG) mode in Fig.1 for different values of $\delta\left(=n_{i0}/n_{e0}\right)$. The parameters used for calculations are: ion plasma density $n_{i0}=10^9$ cm^{-3}, electron plasma density $n_{e0}=0.1\times10^9$-1×10^9 cm^{-3}, $m_d=10^{12}m_p$ (for the size of 1μm grain, a mass of density of ~1g cm^{-3}),temperatures of electron and ion is taken equal to 0.2eV, beam radius r_b=1.5 cm, guide magnetic field $B_s=4\times10^3$ G, dust grain density $n_{d0}=1\times10^4$ cm^{-3}, $m_i/m_e=7.16\times10^4$ for potassium plasma and the average dust grain size a=5μm. The 1st zero of the Bessel function (i.e., mode number=1) is taken.

Further, we have plotted the ion beam mode with beam velocity=7×10^6 cm/sec (beam energy=1000eV). The velocity of ion beam is taken such that it intersects with the TG mode and transfers its energy to the wave and make the wave unstablehence it grows, here the condition which must be achieved is $k_\perp = k$, $k_z << k_\perp$ for the TG mode to exist. It is found that the frequencies of unstable TG waves increase with the wave numberfor all the values of $\delta\left(=n_{i0}/n_{e0}\right)$ (cf.Fig.1). Our theoretical results resembles with the experimental outcome of Chang [22].The intersection points of beam mode and the TG mode are written in Table I.

Now, Using Eq. (14) and taking values from Table I we have plotted Fig.2 which shows the growth rate of the unstable wave as a function of δ (relative density of negatively charged dust grains). From Fig. 2,it can be clear that as the values of δ increases the growth rate of the instability also increases. The reason for this enhancement in the growth rate is the disturbance in proportion of negative charge per unit volume which is inherent by dust grains due to the decrease in the number of electrons (n_{e0}). For δ=1 i.e., β=0 i.e., without dust grains the value of the growth rate $\gamma=0.02\times10^6$ sec^{-1}. The experimental observation of Barkan et al. [12] indicatesthat the growth rate increases withδ. As the wave damping decreases withδ, the wave grows, therefore growth rate increases.

Again,the growth of unstable mode has been investigated by taking different values of beam density. Using (14) we have plotted Fig.3 in which we have taken the growth rate of the unstable wave $\gamma(\sec^{-1})$ as the function of relative density of negatively charged dust grains for the different values of beam density for e.g.,n_{b0}= 2×10^6cm^{-3}, 6×10^6cm^{-3} and 8×10^6cm^{-3}, keeping all other parameters constant. From Fig.3, it can be seen that the growth rate of the unstable mode increaseswithδ as the value of beam density increases. Since the number density of ion beam increases more and more energy will be supplied by the beam through electrons in the dusty plasma.The unstable mode's growth rate uplifted with the beam density which shows the fine settlement with the experimental interpretation by Chang [22].

Eq. (15) shows that the unstable mode's real frequency varies as square root of the beam voltage (V_b). Our results are similar with the experimental findings of Chang [22], without dust. Also, Eq. (16) shows that the phase velocity of the TG mode also increases with the beam energy.

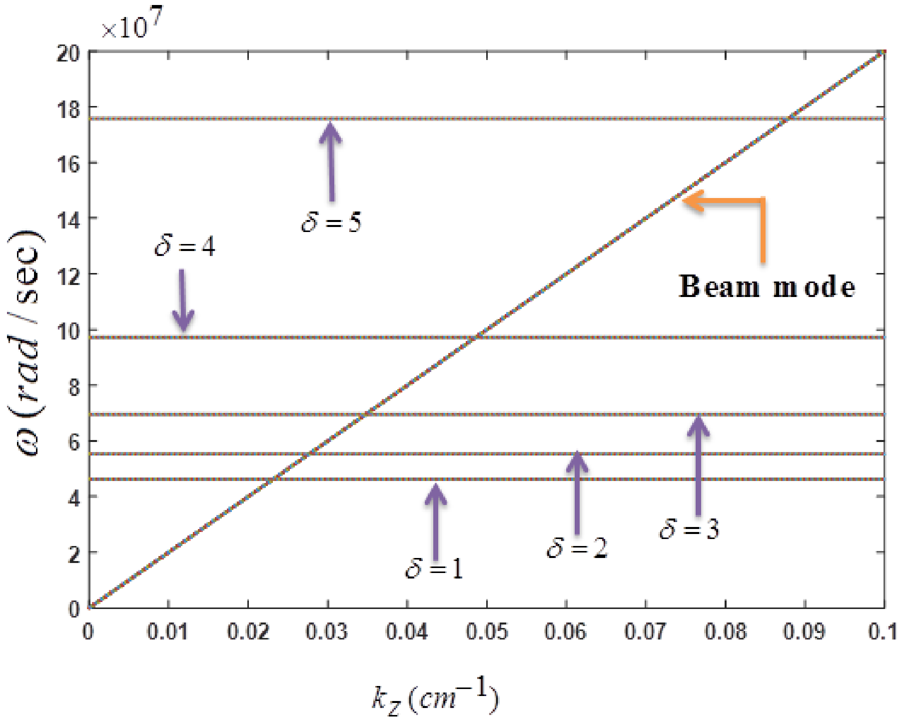

FIG.1 Dispersion curve of Gould-Trivelpiece mode in presence of negatively charged dust grains and a beam mode.The parameters are given in the text.

TABLE IFrom Fig.1 (ion beam+ plasma containing negatively charged dust grains) we acquire the values of frequencies of unstable mode and axial wave number $k_z(cm^{-1})$ for different values of δ

$\delta(= n_{i0}/n_{e0})$	$\omega(rad/\sec)\times 10^7$	$k_z(cm^{-1})$
1	4.5	0.020
2	5.9	0.029
3	7.1	0.035
4	9.7	0.051
5	17.6	0.092

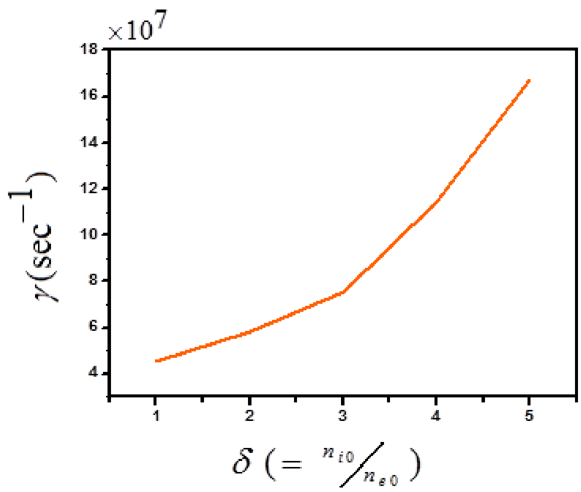

FIG.2 Growth rateγ(sec^{-1})as a function of δ

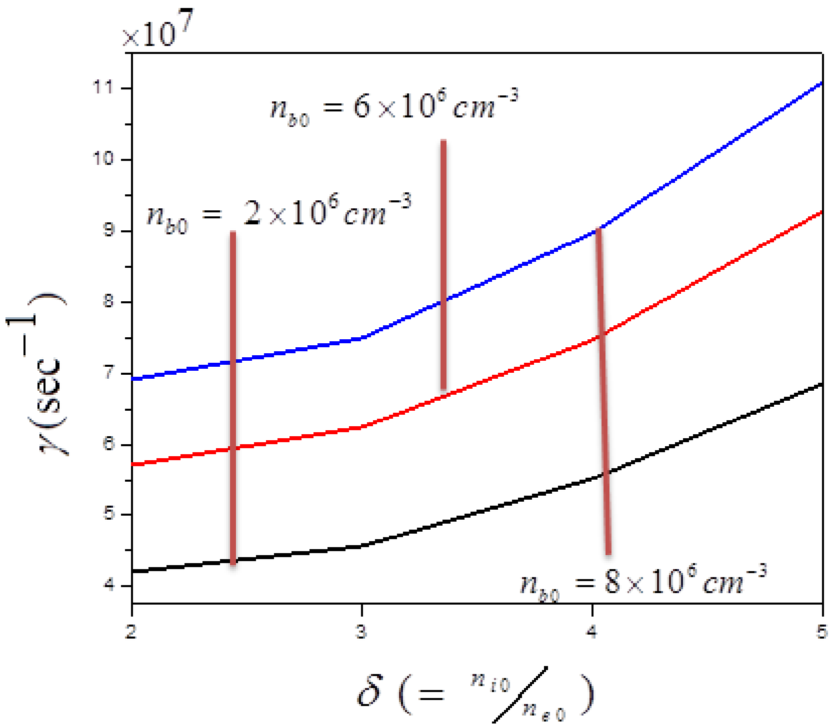

FIG.3 Growthγ(sec^{-1}) rateas a function of δfor different values of beam density.

IV CONCLUSION

The excitation of Gould-Trivelpiece mode driven to instability by an ion beam in dusty plasma. Theinstability is due to excitation of ion beam via Cerenkov interaction. The frequency of unstable TG mode uplift with the negatively charged dust grains. It is observed in the present work that the enhancement in the growth rate of instability is found to be increase when the density of ion beam increases. The growth rate scales as the (1/3)rdpower of the beam density [cf. Eq. 14]. The growth rate results of our work are found to be qualitatively resemble the experimental observations and theoretical outcomes of many researches [Refs.12, 22].Thus the instability of Gould-Trivelpiece wavemodifies due to the presence of beam and dust grains. This work may advantageous in a Plasma-filled backward wave oscillator [9].

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