Laser driven in-situ evolution and resonant control of plasma currents in non-isothermal warm plasma

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Abstract- Generalized treatment on investigation of resonant plasma dynamics is carried out in non-isothermal weakly collisional plasma to study the in-situ evolution of plasma current densities due to propagation of moderate intensity pico-second (*ps*) lasers. The resonance condition for generation of maximized non-linear plasma current is obtained and further tuned in a controlled manner. Treatment is nonrelativistic as lasers are moderately intense and laser strength parameter is less than unity i.e. $a << 1$. In this regime, ponderomotive nonlinearity is dominated over nonlocal heat transport. The effect of collision frequency, resonant frequency and thermal motion of plasma electrons on dielectric constant of plasma and subsequent plasma current densities are analyzed through adjustment and fine tuning of plasma density ripples in a controlled manner.

Keywords: density; dielectric constant; non-thermal plasma; laser plasma interaction

Abbreviations: PF, ponderomotive force; ps, pico second; LSP, laser strength parameter

1. INTRODUCTION

Plasma being a fourth state of matter has a wide range of distinguished properties in terms of its plasma parameters. Interaction of different intensity lasers with plasma have opened up several fields of applications ranging from nuclear fusion reactor[1] to table top accelerators[2], from compact THz radiation sources[3] to advance photonics based optical devices[4] and many more etc. Laser plasma interactions involve highly complex nonlinear processes depending on the intensity of interacting laser, their intensity distribution profile or shapes and durations[5]. Laser pulses of different pulse duration i.e. nano-second (*ns*), pico-second (*ps*), femto-second (*fs*) and atto-second (*as*) pulses etc. give rise to different regimes of interaction. Giulietti *et al.*[6] compared *ns* and sub-*ps* laser interaction regimes at moderate laser intensity and observed that the laser field itself undergoes self-phase modulation (SPM) due to modified refractive index of plasma which strongly affects the laser plasma interaction in different regimes. Hassan *et al.*[7] considered relativistic nonlinearity in the plasma with very short ($\tau_L << 1/\omega_p$) intense laser ; τ_L is laser pulse duration. But, in present article laser pulse is longer enough (few sub-*ps*) therefore it takes longer time to interact with plasma and hence thermal effects become considerably accountable. Nowadays ultra-short, ultra-intense pulses are generated by chirped pulse amplification (CPA) technique which is very promising technology for the development of next generation compact, table top laser driven multi stage plasma accelerators. Unlike conventional RF accelerators, in table top accelerators plasma electrons are accelerated to energy levels of several GeV in the bubble regime however betatron oscillations inhibit the electron acceleration. That's why it becomes essential to study laser plasma dynamics in much more detail to understand the selective several underlying mechanisms like wakefield excitation[8], unifocal terahertz radiation[9], multifocal terahertz[10] and their characterization in different interaction regimes due to beat wave mixing. Besides above mentioned concurrent mechanisms, there exist modified plasma dynamics of wave mixing and phase conjugation in weakly collisional plasma[11] as well as kinds of stimulated scattering contributed by collisions in the plasmas[12]. Sharifian *et al.*[13] investigated mechanism of terahertz emission by beating of two spatial-Gaussian lasers whereas other group has employed superGaussian lasers in collisional plasma[14].

Many other research groups have studied gas and plasma dynamics using molecular dynamics simulation (MDS) to investigate close interactions amongst charged species, neutral species and the electric field, including space charge[15] for a better insight in plasma medicine to treat cancer[16]. In this regard, table top compact radiation sources are being developed for medical field therefore it become essential to study laser plasma dynamics. In addition, MDS is good to investigate surface plasma interaction which is highly complex due to interplay of many simultaneous mechanisms. MDS provides insight of some of the time and length scales processes and the availability of suitable force fields but to low-temperature non-thermal plasmas[17]. But, there is, probably, not much confidence at present in the capability of low-temperature plasma physics simulations through MDS[18] therefore, analytical studies have their own importance and reliability in such a context of surface plasma interaction as well as laser plasma interaction.

In view of medical applications, terahertz sources are much popular than the conventional radiation sources because of their non-ionizing, safe and low photon energy level. Laser plasma interaction is the most viable method to develop terahertz sources hence it become essential to understand laser plasma dynamics for the sake of development of table top, broadband, amplitude and frequency tunable sources. Since, collisions are integrated in non-isothermal plasma therefore in the present analysis we assumed weakly collisional plasma. Many studies have been performed to analyze the dynamics of collisional plasma but none of them have considered the effects of thermal motion of plasma electrons for beat wave mixing of laser pulses in rippled density plasma with controlled resonance. In this regard, the present study gives a good insight to the researcher dealing with moderate intensity laser plasma interaction. The article is organized as follows: in the first section theoretical model is presented to study the electron nonrelativistic motion under nonlinear PF regime by beating of two Gaussian lasers in the weakly collisional plasma. Further, discussion on the resonant excitation of nonlinear plasma currents and phase matching condition to achieve tunable resonance is presented. At last, results are discussed and conclusion is presented.

2 METHODOLOGY AND FORMALISM

2.1 Schematic and Geometry

The beating of two linearly polarized Gaussian lasers of frequency ω_1, ω_2 and wave numbers k_1, k_2 is considered in non-isothermal weakly collisional plasma. The laser is polarized in y direction and beat wave oscillations propagate along z direction in the plasma. The effective electric field of the lasers is represented as Equation (1).

$$\vec{E} = \{E_{L1} e^{-\left(y/b_w\right)^2} e^{i(k_1 z - \omega_1 t)} + E_{L2} e^{-\left(y/b_w\right)^2} e^{i(k_2 z - \omega_2 t)}\}\hat{y}, \tag{1}$$

Where, E_{L1}, E_{L2} ($E_{L1} = E_{L1} = E_{0L}$) is field amplitude and b_w is beam width of beating lasers respectively. The considered plasma is preformed, weakly collisional where electron-neutral collisions of frequency - ν exists (collision frequency is normalized with plasma frequency ω_p) and non-isothermal with initial electron temperature - T_0. The ions in the plasma are assumed to be excessive cold and immobile because of their heavy mass, hence their motion is not taken into account. Ions create a uniform background for electron dynamics in nonrelativistic regime. The incident lasers are short duration (few sub-*ps*) and carry moderate momentum and amplitude which corresponds to laser strength parameter $a \approx 0.015$ ($a = eE/mc\omega$) when $E_{0L} = 5\times10^8$V/m and e, m, c are electronic charge, mass and speed of light. The electron dynamics are relativistic when $a >> 1$ and nonrelativistic for $a << 1$. Thus, it is quite obvious for chosen set of parameters, the present approach is applicable for nonrelativistic regime of laser plasma interaction. The geometry and detailed schematic of the mechanism is shown in Figure 1. The illustration shows that the two co-propagating slightly differ frequency lasers creates a beat wave that further modify the motion of plasma electrons in the wake of beat wave propagation through weakly collisional non-isothermal plasma and setup nonlinear redistribution of plasma electrons.

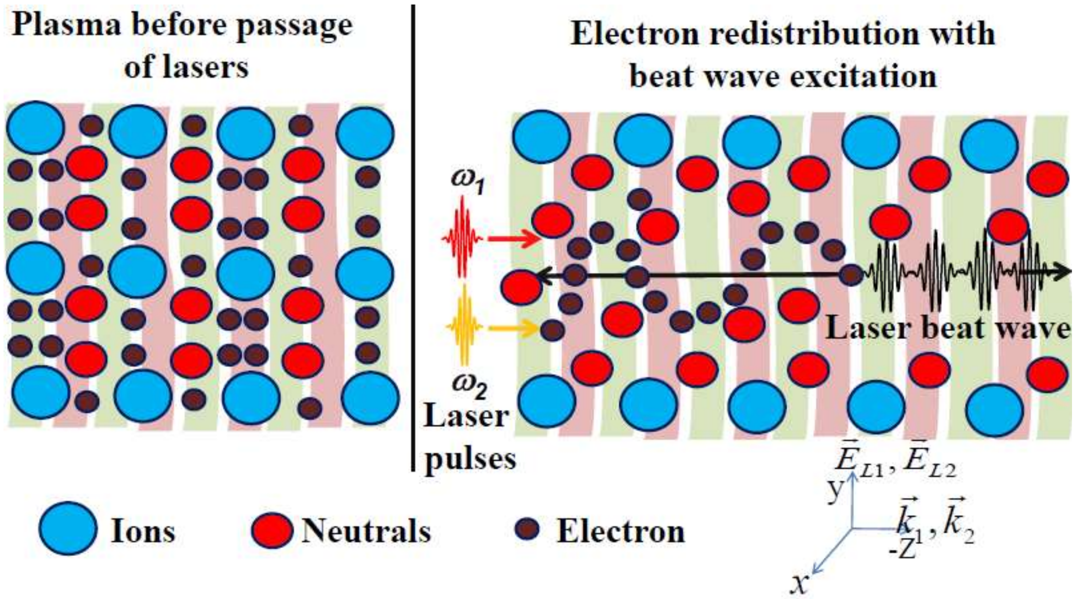

FIGURE 1. Illustration of electron motions in plasma with passage of lasers.

2.2 Plasma dynamics in nonlinear ponderomotive force regime

Initially, before passage of lasers, the plasma maintains its equilibrium state but with passage of lasers, the electrons come under the influence of laser and get drift velocity with lasers' field. In order to understand the dynamics of plasma electrons, force equation is used to compute electron quiver velocity with both lasers simultaneously, such that

$$m_e\, \partial \vec{\upsilon}_1 / \partial t = -e\left[E_{L1} e^{-\left(y/b_w\right)^2} e^{i(k_1 z - \omega_1 t)} \right] - m_e \nu \vec{\upsilon}_1 \tag{2}$$

$$m_e\, \partial \vec{\upsilon}_2 / \partial t = -e\left[E_{L2} e^{-\left(y/b_w\right)^2} e^{i(k_2 z - \omega_2 t)} \right] - m_e \nu \vec{\upsilon}_2 . \tag{3}$$

The collisional forces at once offers damping to the electron oscillations imparting resultant quiver velocities, expressed as $\vec{\upsilon}_1 = e\vec{E}_{L1} / m_e(i\omega_1 - \nu)$, $\vec{\upsilon}_2 = e\vec{E}_{L2} / m_e(i\omega_2 - \nu)$ from Equation 2 and Equation 3 respectively. With passage of lasers, the ponderomotive potential $\phi_p = -(m_e/2e)(\vec{\upsilon}_1 \cdot \vec{\upsilon}_2 *)$ is developed due to inhomogeneous redistribution of plasma electrons which correspondingly generates nonlinear ponderomotive force. $\vec{\upsilon}_2 *$ is the complex conjugate of $\vec{\upsilon}_2$. As laser field is oscillating in *y* direction only, hence we will emphasize only on the transverse (*y*) component of force though longitudinal (*z*) component also exists but have feeble magnitudes. The *y* component of ponderomotive force is calculated

$$F_{py}^{\;NL} = \frac{e^2 E_{0L}{}^2 \times e^{-2\left(y/b_w\right)^2}}{2m_e(i\omega_1 - \nu)(i\omega_2 + \nu)} \frac{4y}{b_w^2} e^{i\{kz - \omega t\}} \tag{4}$$

PF is realized at the beat wave frequency $\omega = \omega_1 - \omega_2$ and wave number $k = k_1 - k_2$. There are fair chances of an energy exchange from laser to plasma electrons leading to nonlocal electronic heat transport which causes nonlinear heating effect that severely affect the excitation of nonlinear current densities in the plasma. To discuss more on this possibility, Shukla *et al.*[19] studied nonlinear interaction of an intense electromagnetic wave with an unmagnetized electron positron plasma and proposed an approximation, when effective charge ratio is greater than the mean free path i.e. $Z_i^{5/4} >> k\lambda_{mfp}$ where, $Z_i = q_i / e$ and mean free path $\lambda_{mfp} = \upsilon_{th} / \nu$. He approximated that the electromagnetic waves in a weakly collisional plasma causes nonlocal electron heat transport which plays a very important role specifically to enhance the damping rate of the plasma wave, in addition also produces thermal modulation nonlinearity which even exceeds the ponderomotive force nonlinearity. But, in our approach the situation is contrary, lasers used are moderately intensed therefore ponderomotive force nonlinearity arises mainly in nonrelativistic regime instead of temperature redistribution in the plasma however, electron thermal motion plays a significant role to the excitation of plasma currents with added non-linear density perturbations caused via pressure gradient forces.

The ponderomotive force is highly specialized oscillating nonlinear force which causes redistribution of plasma electrons to create pressure gradient forces result an increased nonlinear dynamics of plasma electrons. In this situation, finite temperature of plasma electrons also adds on the nonlinearities to the electrons motion because of their thermal motion in collaboration with collisions of electrons with neutrals. Therefore, the transverse component of nonlinear velocity $\vec{\upsilon}_y^{NL}$ of plasma electrons and developed nonlinear current density in the plasma is computed using the following force equation

$$m\left(\partial \upsilon_y^{NL} / \partial t\right) = F_{Py}^{NL} - m_e \nu \upsilon_y^{NL} - k_B T_0 \left(\nabla_y N^{NL} / N_0\right) \tag{5}$$

and equation of continuity

$$\partial N^{NL} / \partial t + N_0 (\partial \upsilon_y^{NL} / \partial y) = 0\,, \tag{6}$$

which yields non-linear velocity $\upsilon_y^{NL} = \omega F_{py}{}^{NL} / \left[m_e \nu \omega - i\left(m_e \omega^2 - k^2 \upsilon_{th}^2\right)\right]$ and non-linear density perturbation $N^{NL} = -\chi_e N_0 \vec{\nabla} \cdot \vec{F}_p{}^{NL} / m_e \omega_p{}^2$,respectively, where $\upsilon_{th}^2 = k_B T_0 / m_e$ is thermal velocity, $\chi_e = -\omega_p{}^2 / \left[(\omega^2 - k^2 \upsilon_{th}^2) + i \nu \omega\right]$, is electrical susceptibility and $\varepsilon_r = 1 - \omega_p{}^2 / \left[(\omega^2 - k^2 \upsilon_{th}^2) + i \nu \omega\right]$ is dielectric constant of plasma. The relative magnitudes of dielectric constant for range of collision frequency at different thermal velocities of electrons are compiled in the Table 1.

TABLE 1. Values of dielectric constant (ε_r) of plasma with varied collision frequency (normalized with plasma frequency ω_p) at different electron thermal velocity (normalized with speed of light c)

υ_{th}/c	ν/ω_p	ε_r
0.0	0	0.2439
	0.1	0.2495
	0.5	0.3641
0.03	0	0.2432
	0.1	0.2489
	0.5	0.3637
0.3	0	0.1691
	0.1	0.1766
	0.5	0.3235
0.5	0	-0.0082
	0.1	0.0052
	0.5	0.2454

If one look at the variation of dielectric constant for respective range of collision frequency, it increases with increased collisions but respective values decreases for corresponding increased thermal motion of plasma electrons. Though, such behavior remains same for lower thermal velocity but toggles when thermal velocity reaches close to speed of light because of relativistic effects prominence then. Similar effect on refractive index also may be predicted which leads to the self-focusing of laser when thermal motion is close or higher than $\upsilon_{th} \geq 0.5c$. Indeed, the present approach gives insight that in non-isothermal weakly collisional plasma for lower range of thermal motion, the dielectric constant occupies such moderate values for which self-focusing effect may be ignored.

2.3 Non-relativistic plasma currents and resonance

The resultant transverse nonlinear electron velocity under the combined action of forces which also takes the contribution of resultant non-linear electron density perturbation is obtained by using following Equation.

$$m_e(\omega+i\nu)\frac{\partial \upsilon_y^{'}}{\partial t}=\left[1+\frac{\omega_p^2}{\omega(\omega+i\nu)(1+\chi_e)}\right]iF_{py}^{NL} \tag{7}$$

On substitution of χ_e and F_{py}^{NL} in the Equation 7, we get

$$\upsilon_y^{'}=\frac{\{\omega^2(\omega+i\nu)^2-k^2\upsilon_{th}^2[\omega(\omega+i\nu)+\omega_p{}^2]\}}{m_e\omega(\omega+i\nu)^2[\omega(\omega+i\nu)-(\omega_p{}^2+k^2\upsilon_{th}^2)]}\frac{ie^2E_{0L}{}^2\times e^{-2\left(y/b_w\right)^2}}{2m_e(i\omega_1-\nu)(i\omega_2+\nu)}\frac{4y}{b_w^2}e^{i(kz-\omega t)} \tag{8}$$

On rearranging the terms, we obtain resultant nonlinear velocity such as

$$\upsilon_y{}'=\frac{Q}{2m_e{}^2\omega(\omega+i\nu)^2}\frac{ie^2E_{0L}{}^2\times e^{-2\left(y/b_w\right)^2}}{(i\omega_1-\nu)(i\omega_2+\nu)}\frac{4y}{b_w^2}e^{i(kz-\omega t)} \tag{9}$$

Where $Q=\dfrac{\{\omega^2(\omega+i\nu)^2-k^2\upsilon_{th}^2[\omega(\omega+i\nu)+\omega_p{}^2]\}}{[\omega(\omega+i\nu)-(\omega_p{}^2+k^2\upsilon_{th}^2)]}$.

Now correspondingly nonlinear oscillatory current densities are evaluated in presence of uniform density (N_0) plasma i.e. $\vec{J}^{NL}=-N_0e\upsilon_y{}'$, yielded as

$$J_y{}^{NL}=-\frac{N_0}{m_e{}^2\omega(\omega+i\nu)^2}\frac{ie^3E_{0L}{}^2\times ye^{-2\left(y/b_w\right)^2}}{(i\omega_1-\nu)(i\omega_2+\nu)b_w^2}Q\times e^{i\{kz-\omega t\}} \tag{10}$$

If modulated density plasma is considered where density ripples are created along z direction (same as the laser propagation direction) of modulated density $N = N_0 + N_\alpha e^{i\alpha z}$, where N_α, α, N_0 is the ripple density amplitude, ripple wave number and ambient density respectively. The non-linear oscillatory current density is yielded as

$$J_y{}^{NL}=-\frac{N_\alpha}{m_e{}^2\omega(\omega+i\nu)^2}\frac{ie^3E_{0L}{}^2\times ye^{-2\left(y/b_w\right)^2}}{(i\omega_1-\nu)(i\omega_2+\nu)b_w^2}Q\times e^{i\{(k+\alpha)z-\omega t\}}. \tag{11}$$

One can realize the importance of rippled density plasma in place of uniform density plasma for laser interaction in view of excitation of nonlinear currents through Equation 9 and 10. In uniform density plasma, currents oscillate with wave number k while in modulated density plasma it oscillates with $k + \alpha$. The mechanism of excitation of nonlinear currents may be tuned to a wider range of wave number with added parameter α in the latter case. Therefore, the resonance condition to achieve largest magnitude of nonlinear currents may be controlled experimentally. Hence, modulated density plasma is preferred over uniform density plasma.

For cold plasma, where no thermal motion is involved i.e. $\upsilon_{th}=0$, this Equation 11 takes the form which has been obtained[8]. The nonlinear current densities are mainly caused by pressure gradient forces in addition to the ponderomotive force driven density in nonrelativistic regime. It can be seen that J_y^{NL} is modified due to contribution of the finite thermal motion of the plasma electrons. Present scheme is different from Etehadi & Shokri[20] studies in the context of modification of laser field profile, electron density and temperature distribution inside plasma due to nonlinear heating by laser. Whereas, in the present scheme heating effects are suppressed due to prevailing ponderomotive force effects though electron redistribution occur on account of pressure gradient and ponderomotive force altogether.

3. RESULTS AND DISCUSSION

It is evident from the expression of nonlinear current that J_y^{NL} oscillates at the frequency ω and wave number $k + \alpha$ whereas ponderomotive force oscillate at the frequency ω and wave number k. Thus, wave number of nonlinear current is needed to be matched with ponderomotive force which is consistent with the application of periodicity of the density ripples as proposed by Antonsen *et al.*[21]. Clearly the dielectric constant and resonance condition for excitation of plasma currents has been modified due to the finite thermal motion of electrons in the presence of weak collisions which further lead to the modification of dispersion relation of laser in the plasma. Here comes the need of employing rippled density plasma for resonant excitation of plasma currents through dispersion relation.

3.1 Controlled Resonance and its Tunability

Further, in order to obtain the maximize amplitude of plasma current, the importance of phase matching through following dispersion relation condition $k'^2 - (\omega^2/c^2)\varepsilon_r = 0$ is justified. Dispersion relation of laser pulse in plasma is needs to be matched to obtain resonant excitation of plasma currents such that

$$k' = \frac{\omega}{c}(\varepsilon_r)^{1/2} = k + \alpha \tag{12}$$

On substitution of value of dielectric constant (ε_r) in the Equation 12, we obtain

$$k + \alpha = \frac{\omega}{c}\left[1 - \frac{\omega_p{}^2}{\left[(\omega^2 - k^2 \upsilon_{th}^2) + i\nu\omega\right]}\right]^{1/2} \tag{13}$$

$$\left(\frac{\alpha c}{\omega_p}\right) = \frac{\omega}{\omega_p}\left(1 - \frac{\omega_p^2}{\{\omega(\omega + i\nu) - k^2 \upsilon_{th}^2\}}\right)^{1/2} - \frac{ck}{\omega_p} \tag{14}$$

From Equation 14, real part of normalised ripple wave number is obtained as $(\alpha c/\omega_p) = \frac{\omega}{\omega_p} \times \left[\left(1 - \omega_p{}^2(\omega^2 - k^2\upsilon_{th}^2)/\{(\omega^2 - k^2\upsilon_{th}^2)^2 + \omega^2\nu^2\}\right)^{1/2} - 1\right]$, which is the required condition for resonant excitation of plasma currents. If we look at the resonance condition, we find that the condition $\omega = \omega_p$ obtained in the collision-less plasma is departed due to the electron-neutral collisions and thermal motion of plasma electrons in the present case and hence, the resonance condition modifies. The modified resonance condition in the present case of finite thermal motion of plasma electrons read $\omega = \sqrt{\omega_p^2 + \nu^2 + k^2 \upsilon_{th}^2}$.

3.1.1 Effect of collision frequency

In the present approach, laser intensities are moderate such that the laser spot size is comparatively much bigger than the focal spot and power of lasers is much less than the critical power $P_L << P_c$ [P_c=17$(\omega_L/\omega_p)^2$] where P_L, P_c, ω_L and ω_p are power of lasers, critical power, laser frequency and plasma frequency etc. Therefore, self-focusing, self-phase modulation and relativistic effects are not important. It is already described that ponderomotive force exceeds the nonlocal electron heat transport under the approximation therefore it become essential to understand the behaviour of nonlinear ponderomotive force.

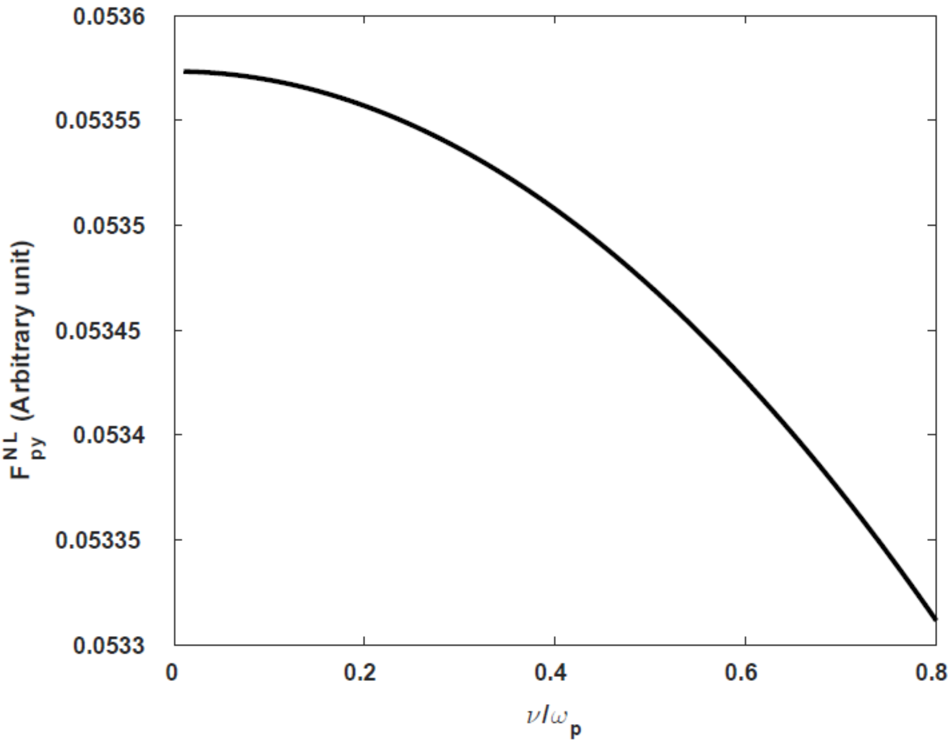

FIGURE 2. Variation of ponderomotive force with normalized collision frequency when $\omega_1 = 2.4\times10^{14}$ rad/s, $\omega_p = 2.0\times10^{13}$ rad/s, b_w= 0.01cm, $y = 0.8b_w$, $N_\alpha = 0.2N_0$, $E_{0L} = 5.0\times10^8$ V/m and ω =1.15 ω_p.

Figure.2 demonstrates the variation of nonlinear ponderomotive force with normalized collision frequency. The plasma is weakly collisional such that the electron neutral collisions are more probable than electron ion collisions i.e. $\nu_{en} >> \nu_{ei}$ though the collision frequency is much lower than the plasma frequency. There is a clear dependence of ponderomotive force with collision frequency and it decays sharply with increased collisional rates. This decay can be attributed to the collisional damping forces which resist the electron motion in the wake of inhomogeneous intensity distribution of laser pulses. The present study is performed in low temperature non-isothermal plasma while Bobin[22] studied Ponderomotive pressure effects in laser driven high-temperature plasma.

3.1.2 Role of density ripples

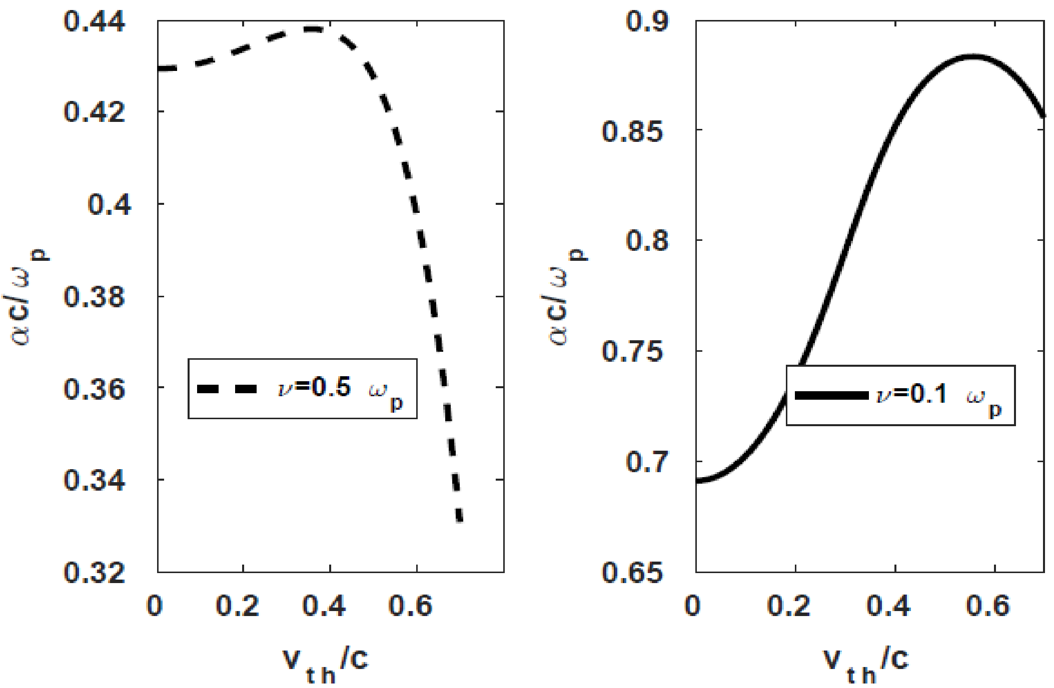

FIGURE 3. Variation of normalized ripple wave number with normalized thermal velocity when ω_1 = 2.4×10^{14} rad/s, ω_p = 2.0×10^{13} rad/s, b_w= 0.01cm, y = 0.8b_w, N_α = 0.2N_0, E_{0L} = 5.0×10^8 V/m and ω =1.15 ω_p.

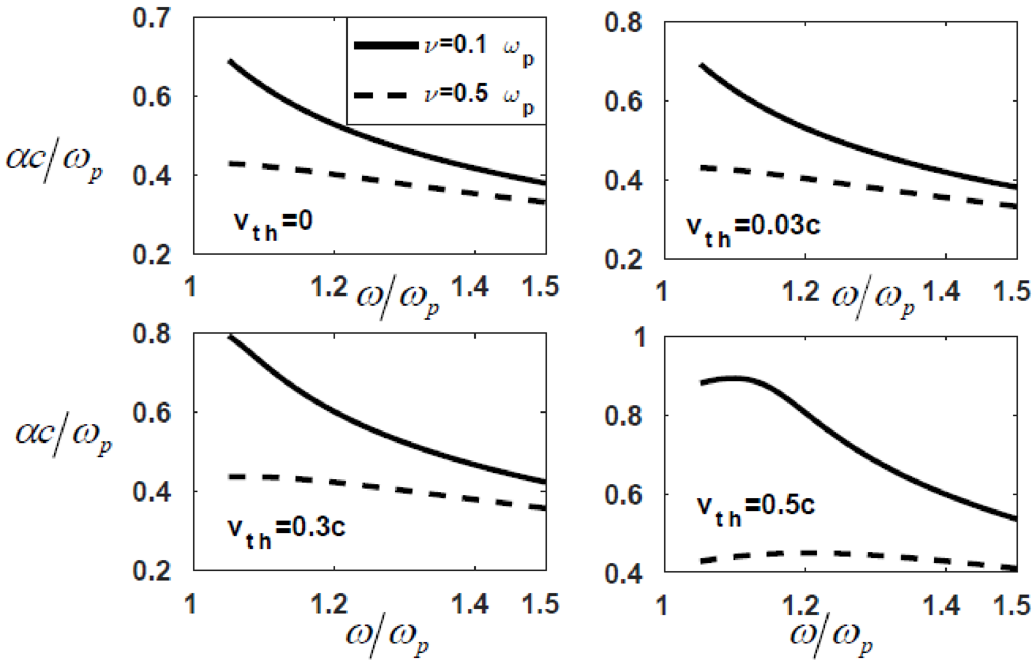

FIGURE 4. Variation of normalized ripple wave number with normalized resonance frequency when $\omega_1 = 2.4\times10^{14}$ rad/s, $\omega_p = 2.0\times10^{13}$ rad/s, b_w= 0.01cm, $y = 0.8b_w$, $N_\alpha = 0.2N_0$, $E_{0L} = 5.0\times10^8$ V/m and $\omega = 1.15\ \omega_p$.

Since, ponderomotive force is oscillatory in nature that along with pressure gradient forces bring out nonlinear oscillation of plasma electrons which ultimately sets up nonlinear oscillatory plasma currents of same frequency of oscillations though wave numbers are different which is matched through rippled density plasma. The variation of normalized ripple wave number with normalized thermal velocity of plasma electron is plotted with different collision frequency in the Figure 3. There is a wide range of tuning of density ripple size and periodicity in the presence of weak collision of the order $\nu = 0.1\omega_p$ than the high order of electron neutral collision frequency $\nu = 0.5\omega_p$ for lower thermal velocity of plasma electrons in nonrelativistic ponderomotive force regime. The situation becomes relativistic with increased thermal velocity and hence the entire mechanism is altered and present approach is not applicable.

The effect of normalized resonant frequency on the ripple wave number tuning through different thermal velocity along with different collision frequency is elaborated through Figure 4. It is seen that the variation of normalized ripple wave number is flat for high collision frequency while steepness is observed for lower values. This again validates that the tuning of ripples is applicable to wider range at lower collisional rate to achieve resonance.

Thus the mentioned approach is applicable for only weakly collisional plasma but fails in case of highly collisional plasma. The same result follows for non-relativistic case when thermal velocities are much lower than the speed of light. For the case of thermal velocity $\upsilon_{th} \geq 0.5$c, the results get modified as relativistic effects become more important and come into the picture.

3.1.3 Effect of thermal motion

In the entire mechanism of laser plasma interaction, resonance is very important and governing criteria to ensure controlled plasma dynamics otherwise scatterings and energy loss dominance take place . So far, resonance is found to be tuned with wave number matching to ensure maximum amplitude of excited nonlinear plasma currents. These currents are further important to study other mechanisms like betatron, synchrotron and terahertz radiation emission etc. The variation of amplitudes of nonlinear plasma currents with normalized collision frequency is plotted in the Figure 5 for different thermal velocity at varied normalized plasma frequency. If we compare the graphs corresponding to the $\omega = 1.05\omega_p$ and $\omega = 1.15\omega_p$, the former frequency is closer to the resonance than the latter frequency for υ_{th} = 0, 0.03c and 0.3c. Whereas, for $\upsilon_{th} = 0.5c$ the latter frequency is closer to the resonance. Thus, resonance frequency is modified with thermal motion of plasma electrons in collisional plasma. The resonance is sharp at low collision frequency while flat resonance is obtained for high range of frequency. There is an observance of anomalous behaviour of plasma currents when $\upsilon_{th} \geq 0.5c$ as thermal velocity approaches the speed of light because of relativistic effects become prominent in picture. Similar behaviour can also be seen from Table1 corresponding to the value of dielectric constant for υ_{th} =0.5c. Garcia *et al.*[23] also obtained modified Vlasov equation and dispersion relations for a relativistic radiating electron plasma but present case is non-relativistic under approximation.

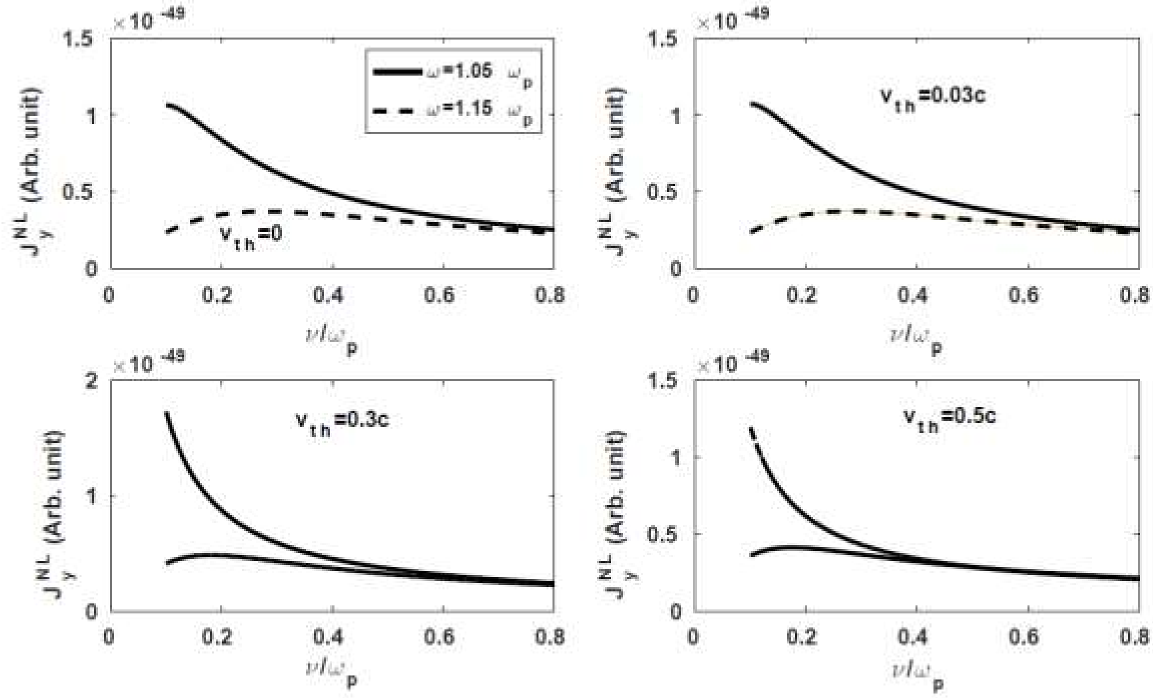

FIGURE 5. Variation of nonlinear plasma currents with normalized collision frequency when ω_1 = 2.4×10^{14} rad/s, ω_p = 2.0×10^{13} rad/s, b_w= 0.01cm, y = 0.8b_w, N_α = 0.2N_0, E_{0L} = 5.0×10^8 V/m.

3.2 Implication on non-linear plasma currents

Figure 6 is plotted to demonstrate the variation of plasma current with normalized thermal velocity and to understand the behaviour of resonant plasma current in a more lucid manner. Current magnitude is maximum for $v = 0.1\omega_p$; $\omega = 1.05\omega_p$ and $v = 0.1\omega_p$; $\omega = 1.15\omega_p$ for their optimum thermal velocity $\upsilon_{th} = 0.3c$ and $\upsilon_{th} = 0.5c$ respectively. But, there is no resonance for $v = 0.5\omega_p$, and $\omega = 1.15\omega_p$ as the graph is completely flat rather the role of thermal velocity become insignificant for this case.

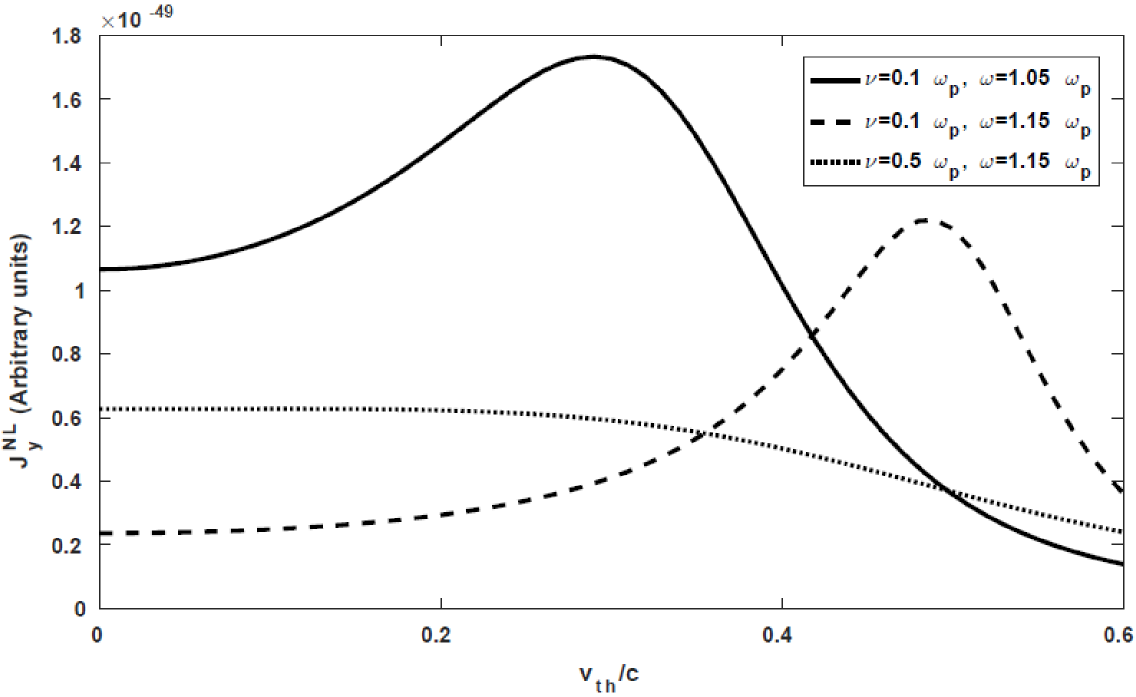

FIGURE 6. Variation of nonlinear plasma currents with normalized thermal velocity when $\omega_1 = 2.4\times10^{14}$ rad/s, $\omega_p = 2.0\times10^{13}$ rad/s, b_w= 0.01cm, $y = 0.8b_w$, $N_\alpha = 0.2N_0$, $E_{0L} = 5.0\times10^8$ V/m.

The magnitudes of current are higher for $\omega = 1.05\omega_p$ than $\omega = 1.15\omega_p$ that implicates the closeness of mechanism to the resonance for former frequency than the latter. However, the nature and behaviour of current for both frequencies is similar. One can see the resonant peaks can be tuned with the help of normalized beat wave frequency as well as thermal velocity of plasma electrons. Thus, it is very important to study resonant excitation of plasma currents in nonlinear PF regime of non-isothermal weakly collisional plasma with modulated ripple density plasma.

4. CONCLUSION

The nonlinear plasma currents developed in nonrelativistic ponderomotive force regime are highly characterized with respect to the thermal motion of electrons in presence of weak electron neutral collisions. Under the approximation, ponderomotive force nonlinearity is predominated over nonlocal heat transport and resonance is modified due to the thermal motion of plasma electrons in the non-isothermal weakly collisional plasma. Ripples in the modulated density plasma helps to achieve and tune the resonance condition in a controlled manner to ensure excitation of largest magnitudes of nonlinear oscillating currents.

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CONFLICT OF INTEREST

None

DATA AVAILABILITY STATEMENT

Data will be provided on request.

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TABLE 1. Values of dielectric constant (ε_r) of plasma with varied collision frequency (normalized with plasma frequency ω_p) at different electron thermal velocity (normalized with speed of light c)

υ_{th}/c	ν/ω_p	ε_r
0.0	0	0.2439
	0.1	0.2495
	0.5	0.3641
0.03	0	0.2432
	0.1	0.2489
	0.5	0.3637
0.3	0	0.1691
	0.1	0.1766
	0.5	0.3235
0.5	0	-0.0082
	0.1	0.0052
	0.5	0.2454

Figure Captions:

FIGURE 1. Illustration of electron motions in plasma with passage of lasers.

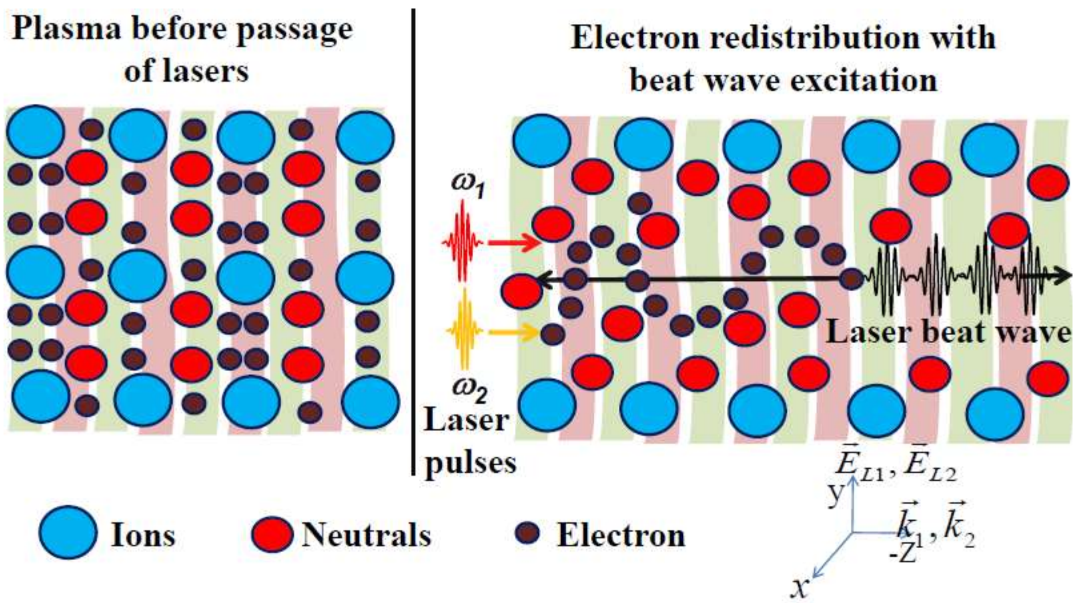
FIGURE 2. Variation of ponderomotive force with normalized collision frequency when $\omega_1 = 2.4\times10^{14}$ rad/s, $\omega_p = 2.0\times10^{13}$ rad/s, b_w= 0.01cm, $y = 0.8b_w$, $N_\alpha = 0.2N_0$, $E_{0L} = 5.0\times10^8$ V/m and ω =1.15 ω_p.

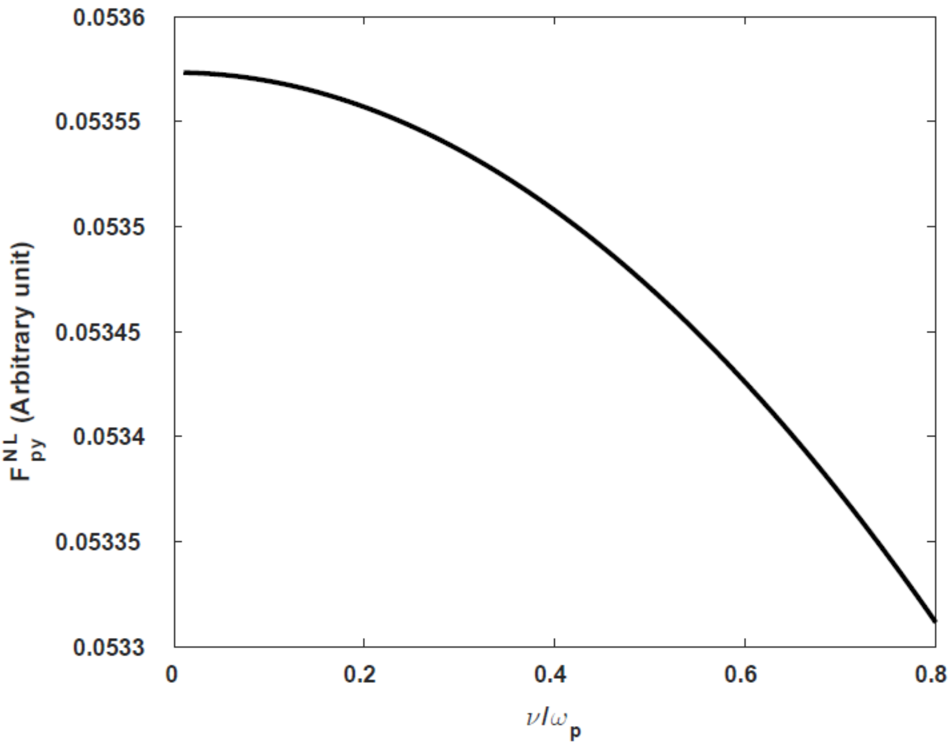
FIGURE 3. Variation of normalized ripple wave number with normalized thermal velocity when $\omega_1 = 2.4\times10^{14}$ rad/s, $\omega_p = 2.0\times10^{13}$ rad/s, b_w= 0.01cm, $y = 0.8b_w$, $N_\alpha = 0.2N_0$, E_{0L} = 5.0×10^8 V/m and ω =1.15 ω_p.

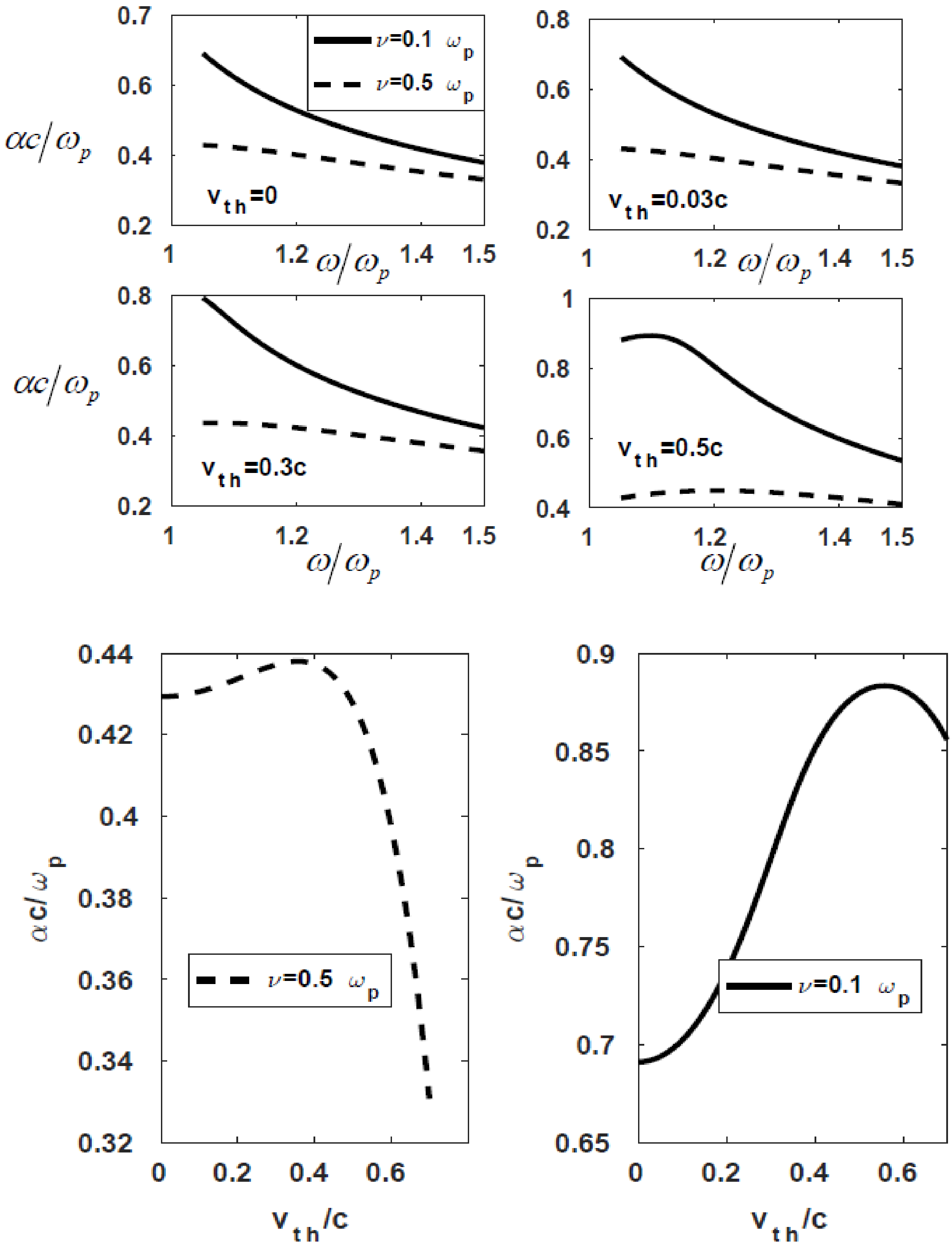
FIGURE 4. Variation of normalized ripple wave number with normalized resonance frequency when $\omega_1 = 2.4\times10^{14}$ rad/s, $\omega_p = 2.0\times10^{13}$ rad/s, b_w= 0.01cm, $y = 0.8b_w$, $N_\alpha = 0.2N_0$, $E_{0L} = 5.0\times10^8$ V/m and ω =1.15 ω_p.

FIGURE 5. Variation of nonlinear plasma currents with normalized collision frequency when $\omega_1 = 2.4\times10^{14}$ rad/s, $\omega_p = 2.0\times10^{13}$ rad/s, b_w= 0.01cm, $y = 0.8b_w$, $N_\alpha = 0.2N_0$, $E_{0L} = 5.0\times10^8$ V/m.

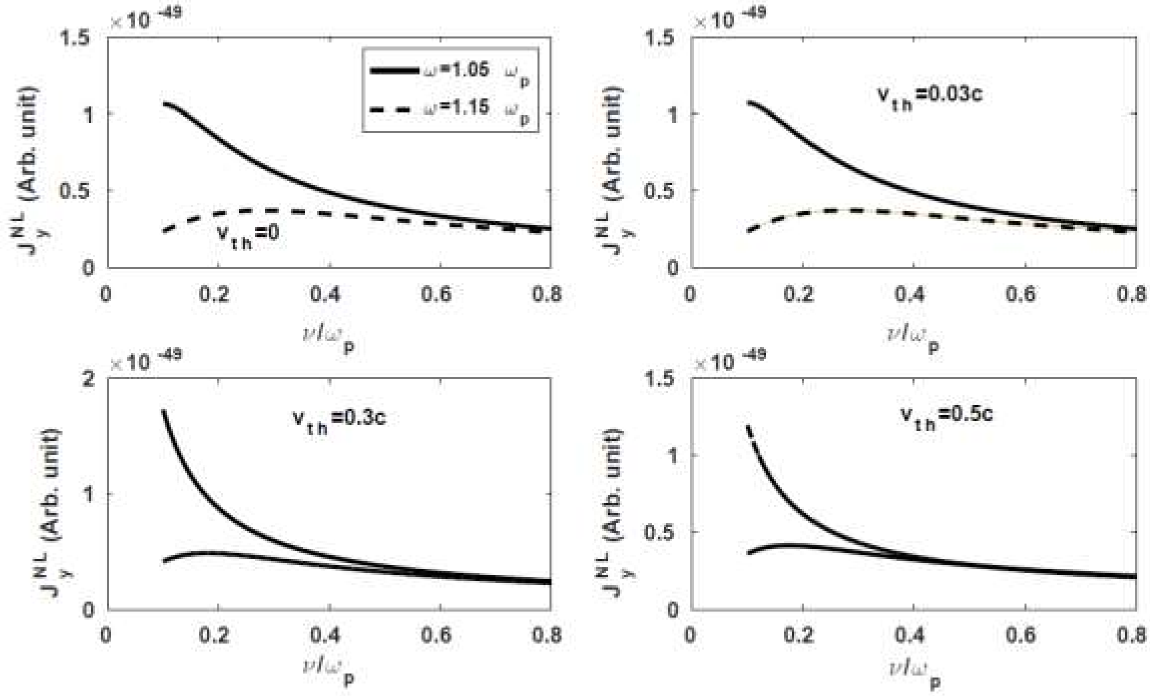
FIGURE 6. Variation of nonlinear plasma currents with normalized thermal velocity when $\omega_1 = 2.4\times10^{14}$ rad/s, $\omega_p = 2.0\times10^{13}$ rad/s, b_w= 0.01cm, $y = 0.8b_w$, $N_\alpha = 0.2N_0$, $E_{0L} = 5.0\times10^8$ V/m.

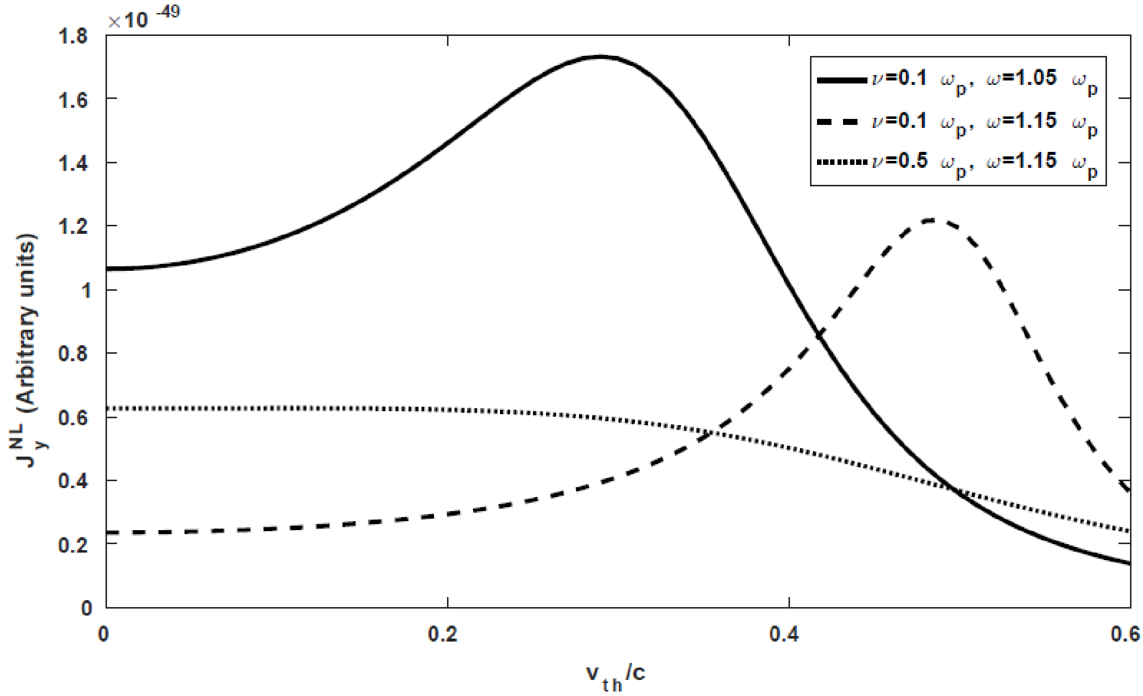

Plasma before passage of lasers
Electron redistribution with beat wave excitation
ω_1
ω_2
Laser pulses
Laser beat wave
$\vec{E}_{L1}, \vec{E}_{L2}$
y
$\vec{k}_1, \vec{k}_2$
-Z
x
Ions
Neutrals
Electron


0.0536
0.05355
0.0535
0.05345
0.0534
0.05335
0.0533
0
0.2
0.4
0.6
0.8
F_{py}^{NL} (Arbitrary unit)
ν/ω_p



ν=0.1 ω_p
ν=0.5 ω_p
$\alpha c/\omega_p$
ω/ω_p
v_{th}=0
v_{th}=0.03c
v_{th}=0.3c
v_{th}=0.5c
v_{th}/c


×10^-49
ω=1.05 ω_p
ω=1.15 ω_p
v_th=0
v_th=0.03c
v_th=0.3c
v_th=0.5c
J_y^NL (Arb. unit)
ν/ω_p


×10^-49
ν=0.1 ω_p, ω=1.05 ω_p
ν=0.1 ω_p, ω=1.15 ω_p
ν=0.5 ω_p, ω=1.15 ω_p
J_y^NL (Arbitrary units)
v_th/c