



LASER BEAT WAVE ELECTRON HEATING IN MAGNETIZED PLASMA

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Abstract

The theoretical investigation focuses on the enhanced electron heating facilitated by the electron plasma wave-assisted beat wave generated from Hermite cosh-Gaussian and cosh-Gaussian laser beams in a magnetized collisional plasma characterized by density ripples. The interaction of this beat wave with the density-rippled plasma results in the generation of a significant nonlinear ponderomotive force acting on the plasma electrons, which in turn couples with the large amplitude electron plasma wave. An analytical expression for the anomalous electron heating rate has been derived. This enhanced electron heating rate holds potential applications in plasma fusion devices and supports normal sheath acceleration.

Keywords: Decentered parameter, Anomalous heating, Density rippled, Electron plasma wave, Beat wave, Collisional frequency, Landau damping

1. Introduction

The nonlinear interaction of electromagnetic radiation with materialistic medium (solid, liquid, gas and plasma) is promising phenomenological field of research interest owing to vast field applications such as charged particle acceleration [1], harmonic generation [2-3], Parametric instabilities, self-focusing [4] and so many more. Owing to acquires of immense electrical conductivity, plasma is acceptable candidate for interacting medium. The produced characteristics properties through this interacting media can be controlled by considering the rippled [5] and collision [6] effect in media. When two slight difference frequency laser beams interacts either counter propagation or copropagation, beat wave

generation process will be taken into the consideration. Highly energetic electron acceleration process can be achieved by lasers beat wave excitation as compared with laser wake field acceleration. The propagation properties of hyperbolic cosine-Gaussian laser beam [7] and Hermite hyperbolic cosine-Gaussian laser beam [9] was theoretically studied by considering the paraxial theory of approximation and ABCD matrix.

In these present theoretical investigations, we present a scheme of electron heating by electron plasma wave assisted beat wave of two different profile laser beams in collisional magnetized plasma with density rippled. The beat wave of two laser beams excite an immense amplitude electron plasma wave and couples with it, lead to strong electron heating via Landau damping. The possible schematic diagram of this electron heating mechanism is shown in Fig. 1. The organization of this research article is as follows. Sec. 1 provides the introduction of this theory. The theoretical formulation of nonlinear coupling of two laser beams with electron plasma wave is given in Sec. 2. Sec. 3 provide the formulation of electron heating rate equation. The results and discussion of this theory is explained in Sec. 4. Finally, Sec. 5 provides the summary and conclusion part.

2. Nonlinear Coupling

Consider a rippled density plasma of electron temperature T_e and total electron density can be written as $n_0 = n_0^0 + n_q$, where $n_q = n_{q0} e^{iqz}$, (1) where n_0^0 and n_q are the equilibrium electron density and rippled density respectively, n_{q0} stands for strength (amplitude) of density rippled at equilibrium condition and q is the wave number of rippled density. The transmission ring grating and pattern mask

technique is used for producing density rippled in plasma.

Now, suppose that two different profile high power laser beams with Hermite cosh-Gaussian (HChG) and cosh-Gaussian (ChG) laser beams profile having wave numbers k_1 and k_2 ,

$$\vec{E}_1 = \hat{y}E_{01}H_m\left(\sqrt{2}\frac{y}{w_{0H}}\right)\cosh\left(\frac{yd}{w_{0H}}\right)\exp\left(-\frac{y^2}{w_{0H}^2}\right)e^{-i(\omega_1t-k_1z)}, \quad (2)$$

The General Electric field profile of cosh-Gaussian laser [17] can be written as

$$\vec{E}_2 = \hat{y}E_{02}\cosh\left(\frac{yd}{w_{0C}}\right)\exp\left(-\frac{y^2}{w_{0C}^2}\right)e^{-i(\omega_2t-k_2z)}, \quad (3)$$

where, $j=1, 2$ assigned for two different type of laser profiles (Hermite cosh-Gaussian and cosh-Gaussian), w_{0H} and w_{0C} are the initial beam width of two laser beams respectively, d is the beam decentered parameter associated with hyperbolic cosine term, E_{01} and E_{02} are the electric field amplitude of the two laser beam at the central position ($y=z=0$) respectively, H_m denotes the Hermite polynomial function, m is the mode index related with the Hermite polynomial function.

As the two copropagating laser beams interact with collisional magnetized plasma, electron associated with this medium undergoes energized and excited. Each laser beam imparts oscillatory velocity to the plasma electrons. The equation of motion can be written a

$$m\left(\frac{d\vec{v}_j}{dt} + v_{en}\vec{v}_j\right) = -e(\vec{E}_j + \vec{v}_j \times \vec{B}_s), \quad (4)$$

where \vec{v}_j and v_{en} are the oscillatory velocity of electron and electron-neutral collisional frequency respectively. \vec{B}_s stands for applied external static magnetic field along the z-direction. In left hand side of Eq. (4), the first

\vec{F}_p^{NL}

$$\begin{aligned} &= \frac{-e^2(E_{01}E_{02}^*)(-i\omega_1 + v_{en})(i\omega_2 + v_{en})}{2m(\omega_1^2 - v_{en}^2 - \omega_c^2 + 2iv_{en}\omega_1)(\omega_2^2 - v_{en}^2 - \omega_c^2 - 2iv_{en}\omega_2)} \left[(ik)\hat{z}H_m\left(\frac{\sqrt{2}y}{w_{0H}}\right)\cosh\left(\frac{yd}{w_{0H}}\right)\cosh\left(\frac{yd}{w_{0C}}\right) \right. \\ &+ \hat{y}\left\{ \cosh\left(\frac{yd}{w_{0H}}\right)\cosh\left(\frac{yd}{w_{0C}}\right)\left\{ H_m\left(\frac{\sqrt{2}y}{w_{0H}}\right) \times -2y\left(\frac{1}{w_{0H}^2} + \frac{1}{w_{0C}^2}\right) + \left(\frac{\sqrt{2}y}{w_{0H}}\right)2mH_{m-1}\left(\frac{\sqrt{2}y}{w_0}\right) \right\} \right. \\ &+ \left. H_m\left(\frac{\sqrt{2}y}{w_{0H}}\right)\left\{ \left(\frac{d}{w_{0C}}\right)\cosh\left(\frac{yd}{w_{0H}}\right)\sinh\left(\frac{yd}{w_{0C}}\right) + \left(\frac{d}{w_{0H}}\right)\cosh\left(\frac{yd}{w_{0C}}\right)\sinh\left(\frac{yd}{w_{0H}}\right) \right\} \right] \exp\left\{-y^2\left(\frac{1}{w_{0H}^2} + \frac{1}{w_{0C}^2}\right)\right\} e^{-i(\omega t - kz)}, \quad (7) \end{aligned}$$

frequencies ω_1 and ω_2 , copropagate through magnetized collisional plasma along z-direction and polarized along y-direction. The General Electric field profile of Hermite cosh-Gaussian laser [18] can be written as

term $\left(m\frac{d\vec{v}_j}{dt}\right)$ denotes the rate change of momentum of electron; the second term denotes the damping force (due to collision between electron and neutral particles). In right hand side of Eq. (4), the first term ($e\vec{E}_j$) represents the force exerted by laser beam radiation field on electrons, the second term $-e(\vec{v}_j \times \vec{B}_s)$ represents the force exerted by static magnetic field on plasma electrons.

On solving Eq. (4), the oscillatory velocities of electrons along the laser field polarization direction can be written as

$$v_{jy} = -\frac{eE_j i\omega_j(-i\omega_j + v_{en})}{m(\omega_j^2 - v_{en}^2 - \omega_c^2 + 2iv_{en}\omega_j)}. \quad (5)$$

The nonlinear interaction of two different profile laser beams with collisional magnetized plasma causes creation of nonlinear ponderomotive force to the plasma electrons at the beat frequency $\omega = \omega_1 - \omega_2$ and beat wave number $k = k_1 - k_2$. The expression of nonlinear ponderomotive potential and force can be derived by using the following formula

$$\begin{aligned} \phi_p^{NL} &= -\left(\frac{m}{2e}\right)\vec{v}_1 \cdot \vec{v}_2^* \\ \text{and } \vec{F}_p^{NL} &= -\nabla\phi_p^{NL}, \quad (6) \end{aligned}$$

3. Anomalous heating of electrons

Since we know that the generated beat wave of two laser beams (Hermite cosh-Gaussian and cosh-Gaussian) has an efficient potential to couple and drive the electrostatic space charge wave. The two laser beat waves might be coupled and excite the electron plasma wave in magnetized collisional plasma with density rippled. Therefore, in the presence of an electron plasma wave, the beat of two laser beams leads to heat the electrons associated with magnetized collisional plasma.

$$H = \frac{\omega k'^2 n_0 e^2}{2m\omega_p^2} |\phi_{\omega,k'}|^2 \chi_{ei}, \quad (8)$$

In terms of normalized electron heating rate (h), the heating rate per electron per second can be written as

$$\frac{H}{n_0} \equiv hm\omega c^2 = \frac{\omega(k+\alpha)^2 e^2}{2m\omega_p^2} |\phi_{\omega,k'}|^2 \chi_{ei}, \quad (9)$$

where we have substituted the $\frac{\omega}{k} \approx c$.

The normalized electron heating rate can be written as

$$h = \frac{k'^2 e^2}{2m^2 c^2 \omega_p^2} |\phi_{\omega,k'}|^2 \chi_{ei}. \quad (10)$$

4. Results and Discussion

Herein, we have analytically investigated the electron heating by the nonlinear interaction of two different profile laser beams with aided of electron plasma wave in collisional magnetized plasma. The nonlinear interaction of two copropagating laser beams cause to beat wave generation and thus produces a nonlinear ponderomotive force to the plasma electrons. This nonlinear force has competent potential to drive a space charge wave and excite electron plasma wave. Our aim to assist this excited (pre-existed) electron plasma wave with laser beat wave and studied the electron heating mechanism. Since, we know that the large amplitude of electron plasma wave coupled along the two lasers beam polarization direction. The nonlinear ponderomotive force has two components along the y-direction and along the z-direction respectively. We can take y-component of the nonlinear ponderomotive force owing to have the same aligned polarization direction of laser beam. The possible schematic of electron heating mechanism by the beating of two laser beams

with the association of electron plasma wave has been drawn in Fig. 1.

In Fig. 2, we plot the normalized electron heating rate with transverse propagation distance of two laser beams from y-axis for different values of Hermite polynomial mode index m . For beam decentered parameter $d=2$ and mode index $m=0$, the two laser beams have acquired a purely cosh-Gaussian profile. At the central position of the laser beam, the electron heating rate is minimum (equal to zero). The two resonant lobes of electron heating rate are appeared around transverse propagation distance $y/w_0 \sim 0.50$ and $y/w_0 \sim 1.50$ respectively. In this, the amplitude of the second one lobe is higher than the first one lobe (approximately 112%). We can see that the electron heating rate is decreased very sharply at off-resonant position. On the other hand, if we take $d=2$ and $m=1$, the first one laser acquired Hermite cosh-Gaussian profile and the second one laser beam acquired cosh-Gaussian profile. Because of this, the two laser beams having different profiles cause two resonant lobes of electron heating rate with equal amplitude (approximately). The two resonant lobes of electron heating rate are appeared around transverse propagation distance $y/w_0 \sim 0.72$ and $y/w_0 \sim 1.66$ respectively. At the central position of laser beam, the heating rate is not minimum but it is minimum at the outer side from the central position ($y/w_0 \sim 1.19$). For the particular position of resonant condition, the lasers beat wave maximally coupled the electron plasma wave and hence leads to strong electron heating process. On comparing both $m=0$ and $m=1$ conditions, the electron heating rate is very high for higher index Hermite polynomial.

The variation of normalized electron heating rate as a function of the transverse propagation distance of two laser beams from the y-axis for different values of laser beam decentered parameter d when Hermite polynomial mode index $m=0$ is plotted in Fig. 3. In this situation, the two laser beams profile must be purely identical profile (cosh-Gaussian). The variation in the peak amplitude of electron heating rate is not much observed upto the decentered parameter $d=1.2$. However, the peaks are shifted outward from origin and have wider lobes. Beyond the values of beams decentered parameter $d=1.2$, the peaks profile of the

electron heating rate acquired two lobes and enhanced amplitude. Thus, we can see that, by tuning and controlling the values of beam decentered parameter, one can optimize the electron heating rate.

Fig. 4 shows the variation of normalized electron heating rate as a function of the transverse propagation distance of two laser beams from the y-axis for different values of laser beam decentered parameter d when Hermite polynomial mode index $m=2$. It is noticed that the electron heating rate has two resonant peaks at the particular values of beam transverse propagation distance. The amplitude of electron heating rate at the first peak is very stronger than the second peak. The increment of the electron heating rate is very large because of a small change in the laser beam decentered parameter. The field intensity profile of laser beams become much more shaper for the enhanced value of beam decentered parameter. Because of this enhanced field intensity of laser beam radiation, the nonlinearity will be much more and thus we can conclude that the beam decentered parameter associated with the hyperbolic cosine term is very sensitive to the electron heating rate.

5. Summary and Conclusions

In the present theoretical investigation, we have studied the strong electron heating by the copropagation of two different profile laser beams in collisional magnetized plasma with density rippled. Herein, the association of electron plasma wave with beating of two laser beams leads the strong resonant heating rate. This has been obtained as the lasers beat wave frequency nearly approaches to electron plasma wave frequency. The various graphical profiles depicts that electron heating rate is dependent on resonant beat wave frequency of two laser beams, beam decentered parameter, each laser beam width, Hermite polynomial mode index, transverse propagation distance of laser beams, amplitude of density rippled, electron cyclotron frequency, and electron-neutral collisional frequency. By tuning and controlling the above parameters, required electron heating can be achieved.

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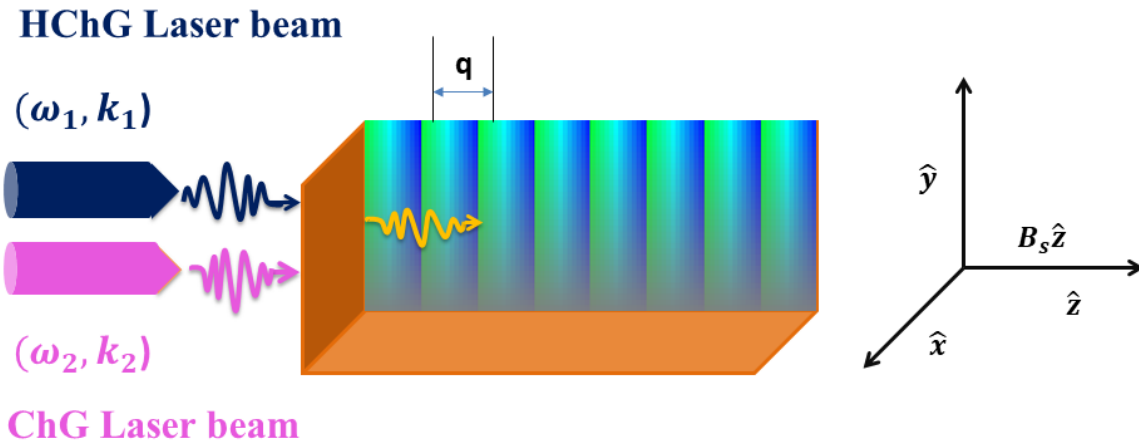


Fig. 1

Fig. 1: Schematic diagram of electron heating in collisional magnetized plasma with density rippled.

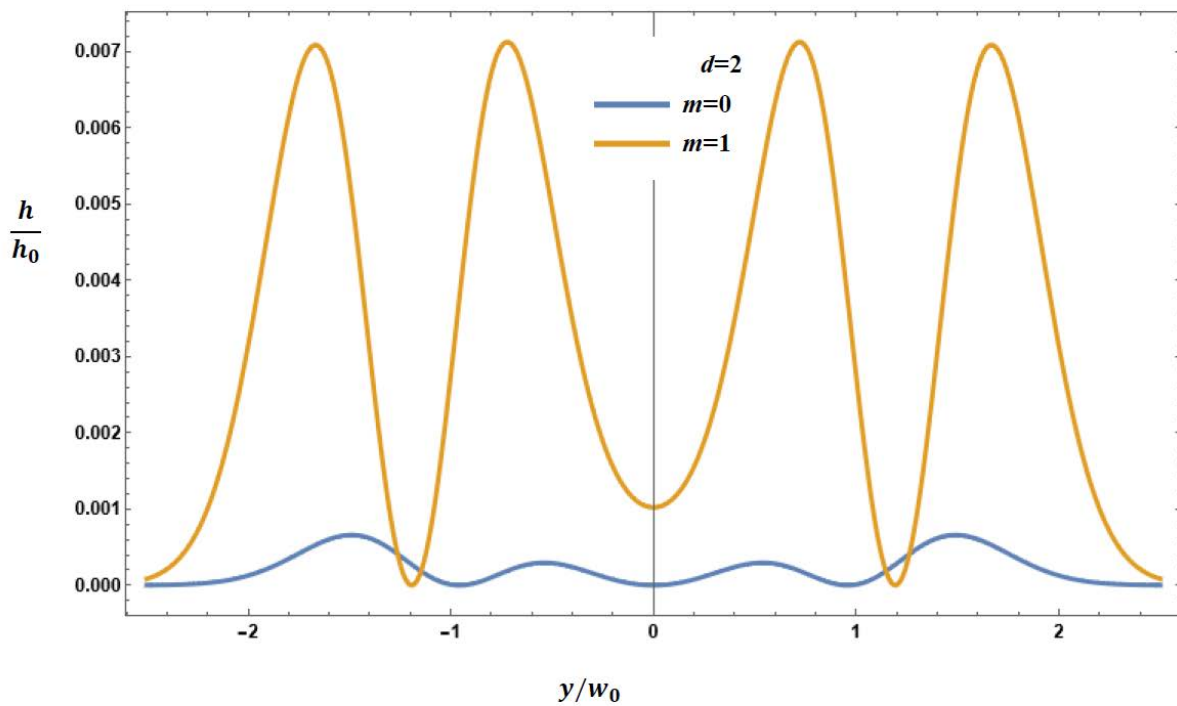


Fig. 2

Fig. 2: Variation of normalized electron heating rate with transverse propagation distance of each laser beams from y-axis for different values of Hermite polynomial mode index $m = (0, 1)$ when $d=2, n_q/n_0 = 0.1, \omega/\omega_p = 0.5, v_{en}/\omega_p = 0.01, \omega_c/\omega_p = 0.05$

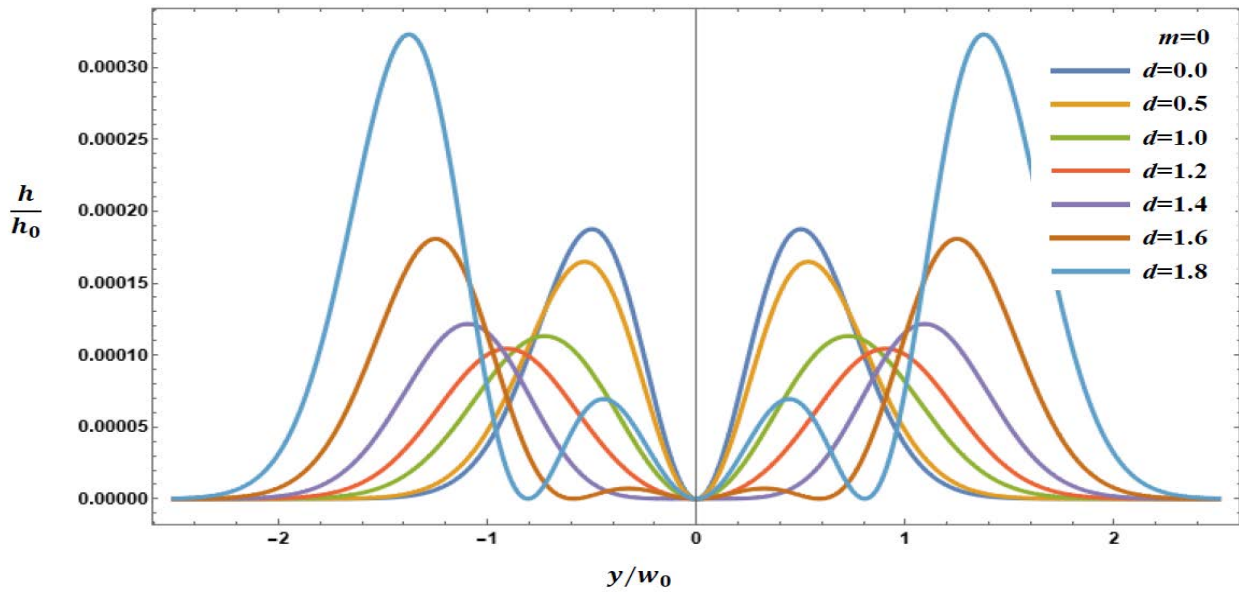


Fig. 3: Variation of normalized electron heating rate with transverse propagation distance of each laser beams from y-axis for different values of laser beam decentered parameter $d = (0.0, 0.5, 1.0, 1.2, 1.4, 1.6, 1.8)$ when $m=0, n_q/n_0 = 0.1, \omega/\omega_p = 0.5, v_{en}/\omega_p = 0.01, \omega_c/\omega_p = 0.05$

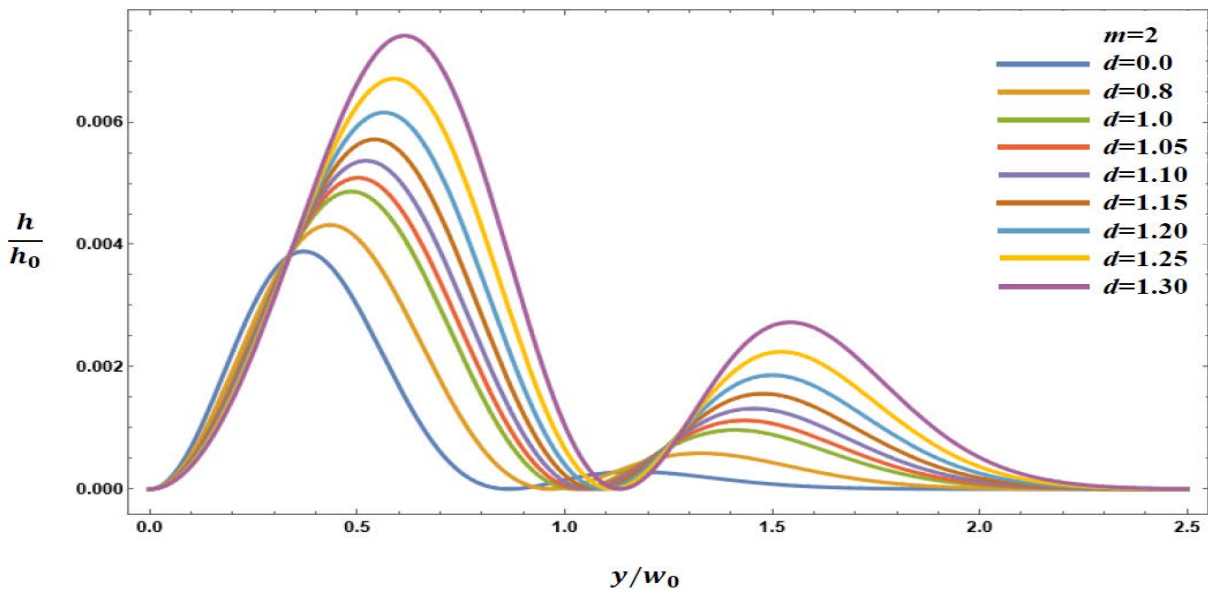


Fig. 4

Fig. 4: Variation of normalized electron heating rate with transverse propagation distance of each laser beams from y-axis for different values of laser beam decentered parameter $d = (0.00, 0.80, 1.00, 1.05, 1.10, 1.15, 1.20, 1.25, 1.30)$ when $m=2, n_q/n_0 = 0.1, \omega/\omega_p = 0.5, v_{en}/\omega_p = 0.01, \omega_c/\omega_p = 0.05$