ORIGINAL RESEARCH ARTICLE

LASER BEAT WAVE ELECTRON HEATING IN NANOCLUSTERED PLASMA

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ABSTRACT:

In this study, we look at how nanocluster plasma can be heated using electron Bernstein waves, which are triggered by the interaction of two super-Gaussian laser beams. When the electric fields of these laser beams interact with the electrons in nanoclusters, they create a beat wave. This beat wave produces a nonlinear pondermotive force. This force has the potential to excite the electron Bernstein wave, which then causes electron heating through a process called cyclotron damping. We developed an analytical approach to understand the unusual heating and how the electron temperature changes because of this process. Our results suggest that by adjusting the shape of the super-Gaussian laser beam and matching the beat wave's resonance with the surface plasmon frequency, we can achieve very high heating rates. The heating process can be controlled by changing factors like the laser beam width, mode index, collision frequency, cluster size, and density. This heating method could be used in toroidal fusion devices.

KEYWORDS: Electron Bernstein Wave, Nanocluster Plasma, Collisional, Anomalous Heating, Beat Wave, Supper-Gaussian Laser Beam.

1. INTRODUCTION:

Over the last few decades, beat wave excitation and heating of plasma as well as nanocluster plasma is particular field of interest due to its diverse applications in current drive experiments, terahertz radiation generation, acceleration of charge particles, and diagnostics (Malik and Uma, 2017; Peter Laqua, 1998; Ditmire, 1995). Although earlier studied of plasma excitations have been done by several groups (Kumar, 2005; Bashir, 2014; Yoon, 2014; Kumar, 2007) but cluster adds new quantity so called surface plasmons that enhance the excitation efficiency (Batani, 2001). The nanocluster plasma has unique behaviour of matter on nanometer scale regime that promises a novel tool for study the laser plasma interactions (Takeshi, 2009; Saalmann, 2006). It is generated by interactions of high intensity short pulse laser with matter (Fennel, 2010; Saalmann, 2010). Hangena *et al.* (1972) theoretical present a scheme for the cluster formation in expanding jets nozzle flow and shows the effects of nozzle size, temperature, and pressure on it. At ultrahigh laser radiation, individual clusters absorb more intense radiation than bulk materials (Ditmire, 1997). Nanoclusters have much potential to exhibit as a novel environment over the gaseous and bulk solid state of matter. Due to presence of surface plasmons in nanocluster cause the arisen of optical behaviour (Kreibig and Vollmer, 1995; Ditmire, 1996; Nosko, 2010; Milchberg, 2001). Therefore, nanocluster plasma impinges one to study the interactions of laser with it.

The plasma wave is excited by beating of two collinear laser beams in the presence of cluster that promise monotonic increase in cluster potential (Tiwari, 2006). Since the dispersion relation of electromagnetic and Langmuir waves get modified as we consider it in clustered plasma as compared to only plasma medium. The nonlinear coupling of wave is occurred by core electron in the clustered plasma. Therefore, growth rate of stimulated Raman scattering by laser in clustered plasma increases with clustered density variation (Tiwari, 2004). Antonsen 2005 et al have performed 2D and 3D electrostatic particle simulations for clustered plasma heating through intense laser radiation. They have found that resonance strong heating occurred as size dependent cluster point the boundary between hydrodynamic and kinetic cluster explosion and optical properties of heated cluster such as harmonic generation. A Gaussian laser beam with temporal and radial profile has potential for cause the Rayleigh scattering in clustered plasma which expanding by heating and hydrodynamic expansion (Kumar, 2009). Experimental results of terahertz radiation generation in argon cluster plasma by femtosecond laser depicts that emitted radiation amplified stronger than the argon gas regime (Jahangiri, 2011). Tiwari and Tripathi (2006) have reported that much enhance in third harmonic generation can be achieved when one has taken clustered radius 1.7 times than its initial radius. Parashar *et al.* (2008) proposed a theory of third harmonic generation in cluster plasma by Gaussian laser beam under paraxial ray approximation. In this, it is found that self-focusing plays an important tool for efficient harmonic generation when cluster density is three times to its critical density.

A titanium sapphire femtosecond chirped double pulse laser has potential to generate ten times more terahertz radiation in argon cluster than single pulse amplification (Mori *et al.,* 2017). The present investigation aims are to explain the electron EBWs excitation and anomalous electron heating in collisional nanocluster plasma. Hence, we have considered a gas jet target of nanocluster plasma medium which is excited by beating of two high power supper-Gaussian laser beams. The schematic of this theory is shown in Fig. 1. The nonlinear pondermotive force can drive the EBW when $\omega \sim \omega_c$ and $kv_{th}/\omega_c \geq 1$. Various factor of laser beams parameter, clustered density, and radius influencing the Bernstein wave excitation and electron heating. The nonlinear coupling of beat wave in clustered plasma is discussed in sec. 2. The anomalous heating mechanism of the electrons in cluster plasma is discussed in sec. 3. The results and discussion are given in sec. 4. Finally, conclusion of this theory is given in sec. 5.

2. NONLINEAR COUPLING:

We consider a gas jet target of nanocluster plasma medium. It has ripple of suitable wave number in the plasma. Let radius of spherical nanocluster can be taken as r_c and the total density of rippled nanocluster plasma can be written as

$$n_c = n_{c0} + n_{c\alpha}, \text{ and } n_{c\alpha} = n_{c\alpha 0} e^{i\alpha z}, \tag{1}$$

where α, n_{c0}, $n_{c\alpha 0}$ are the wave number of density ripple, equilibrium cluster density and equilibrium rippled nanocluster density respectively. This ripple can occur by using a nozzle through which nanocluster flow via gas jet. Each nanocluster has free electron density n_{ce0}. Now, suppose that two high power super Gaussian laser beams with wave numbers k_1 and k_2, frequencies ω_1 and ω_2, copropagating through this medium in z direction and polarized along y direction.

Thus, the general electric and magnetic field profile of each supper Gaussian laser can be written as

$$\vec{E}_j = \hat{y} E_0 \exp\left[-(y/a)^p\right] e^{-i(\omega_j t - k_j z)}, \tag{2}$$

$$\vec{B}_j = \left(\vec{k}_j \times \vec{E}_j\right)/\omega_j,$$

where a is the beam width parameter of laser, $j = 1, 2$, p is the index of supper-Gaussian lasers beam with hold $p \geq 2$, $\omega_{1,2} \gg \omega_c = eB_s/mc$, $\omega_p = n_0 e^2/\epsilon_0 m_e$, is the plasma frequency and n_0, e, m_e are the equilibrium electron density, electronic charge and mass respectively . When two copropagating laser beams interacted with nanocluster medium, then clusters are quickly ionized and converted into plasma balls. A schematic diagram of this mechanism has been shown in Fig. 1. The first-order equation of motion of an electron associated with nanocluster interacting with the electric field of laser beam j can be written as

$$\frac{d\vec{\mathrm{v}}_j}{dt} + \nu\vec{\mathrm{v}}_j + \frac{\omega_p^2}{3}\vec{\mathrm{r}}_j = -\frac{e}{m}\vec{E}_j, \tag{3}$$

$$\vec{F}_P^{NL} = -\frac{e^2 E_0^2 \omega_1 \omega_2}{2m\left(\omega_1^2 - \frac{\omega_p^2}{3} + i\nu\omega_1\right)\left(\omega_2^2 - \frac{\omega_p^2}{3} + i\nu\omega_2\right)}\left[-2p\frac{y^{p-1}}{a^p}\hat{y} + ik\hat{z}\right]$$

$$\times \exp\left[-2\left(\frac{y}{a}\right)^p\right] e^{-i(\omega t - kz)} + c.c. \tag{4}$$

3. ANOMALOUS HEATING OF ELECTRONS:

Since lasers beat wave driven the space charge field and it might heat the electrons cloud of nanocluster. The formula for time average heating rate per unit volume is given by

$$H = Re\left[-\frac{1}{2}n_o e\vec{E}^*_{\omega,k}\vec{v}_{\omega,k}\right], \tag{5}$$

where $\vec{v}_{\omega,k}$ is the oscillatory electron velocity due to the presence of space charge electric field $\vec{E}_{\omega,k}$ at ω, k.

4. RESULTS AND DISCUSSION:

The profile of normalized potential as the function of normalized beam direction y/a and normalized frequency has shown in Figs. 2(a)-2(b) respectively. In Fig. 2(a), comparative study of laser index is carried out for $\mathrm{p} = 2$ and $\mathrm{p} = 4$. This shows that large amplitude of normalized potential is achieved for higher index of super-Gaussian laser. Therefore, intense sharpness in gradient of laser field envelop is obtained for higher index of super-Gaussian laser as compared to low index. In this way, a strong nonlinear pondermotive force can produce high potential for higher laser index. In Fig. 2(b), comparative study of laser beam width is shown. As the beam width of beam width decreases, its normalized potential shifted to downwards. It can be noticed that maximum potential can be best fitted for $y/a{\sim}0.5$. The reason may be caused enhance in nonlinear pondermotive force because lower beam width of laser is focused on small area. In this case, beams pass maximum energy to nanocluster for excites the large amplitude surface plasmon $\left(\frac{\omega_p^2}{3}r_j\right)$ and by which it can oscillate with plasmon frequency. Hence normalized potential can be attained maximum and tuned value with make variation in beam width of laser.

The profile of normalized anomalous electron heating rate as the function of normalized beam direction y/a (cf Fig. 3(a)-3(c)). The normalized heating rate has intense multi peaks (cf Fig. 3(a)) for beam index b=4 as compared to b=2. The higher index laser beam parameter (b=4) promises intense heating as compared to low index laser beam parameter (b=2). The two intense peaks of normalized heating rate (cf Fig. 3(b)) show that heating is obtained maximum for without collision $v/\omega_p = 0$. It can be seen that heating significantly decreases by increasing the collision frequency. The cause of this decrease in heating may be arisen by nanocluster plasma spatial inhomogeneity, and electron-neutral collision in cluster. In Fig. 3(c), we can see that two peaks are appeared with normalized beam direction. The first one is appeared at $y/a{\sim}0.53$ and second is appeared at $y/a{\sim}1.01$. These two points is attributed to highest magnitude of pondermotive force. In this instant, heating becomes very intense. It is noticed that heating is become more effective as increase the n_{cq}/n_0.

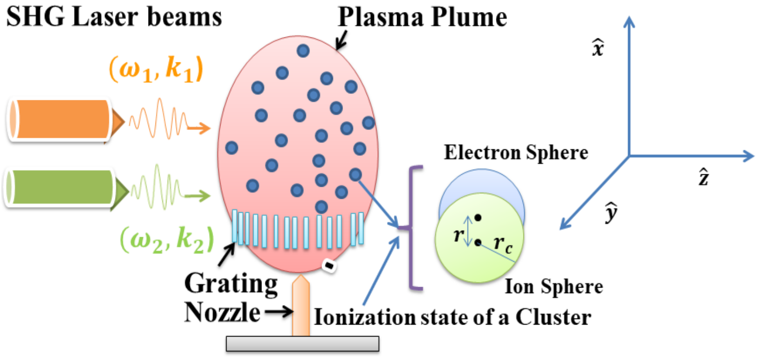

Figure 1: Schematic diagram of electron Bernstein wave aided clustered plasma heating

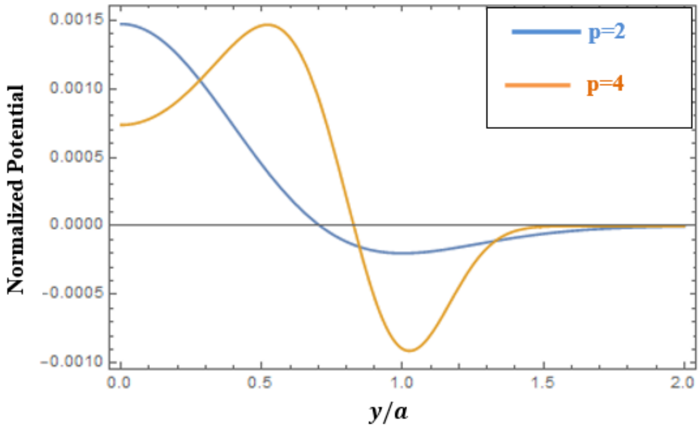

Figure 2(a): Variation of normalized potential $\frac{\phi_{\omega k}}{\phi_{00}}$ with normalized beam direction, when

$$n_{cq}/n_0 = 0.001, v/\omega_p = 0.1, \omega_1/\omega_p = 2.3, \omega_2/\omega_p = 1.8, \omega/\omega_p = 0.5, \frac{4}{3}\pi r_c^3 n_c \sim 10^{-4},$$

$$\phi_{00} = eE_0^2/2m\omega_p^2, b = k_\perp^2 v_{th}^2/2{\omega_c}^2 = 1.8$$

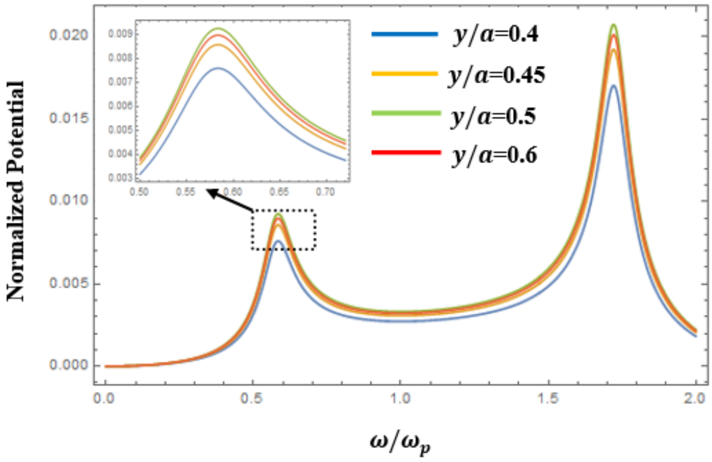

Figure 2(b): Variation of normalized potential $\frac{\phi_{\omega k}}{\phi_{00}}$ with normalized beat frequency, when

$$n_{cq}/n_0 = 0.001, \omega_1/\omega_p = 2.3, v/\omega_p = 0.1, \frac{4}{3}\pi r_c^3 n_c \sim 10^{-4}, \phi_{00} = eE_0^2/2m\omega_p^2$$

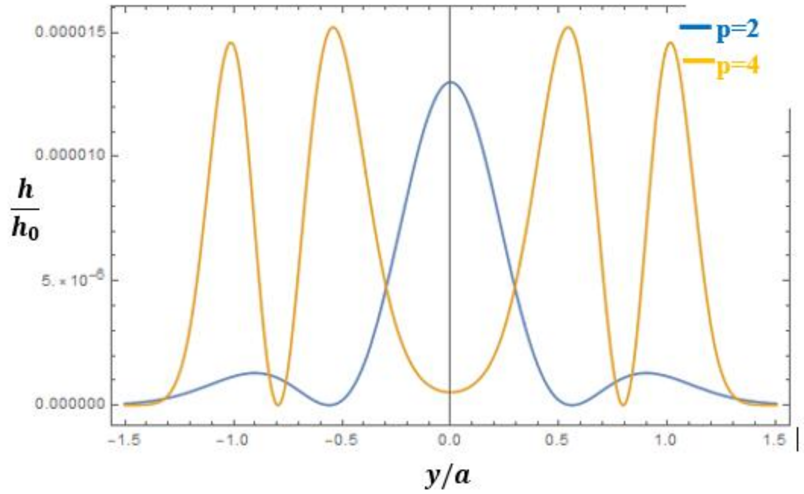

Figure 3(a): Variation of normalized anomalous heating rate with normalized beam direction for different values of p, when $n_{cq}/n_0 = 0.001$, $\omega_1/\omega_p = 2.3$, $\omega_2/\omega_p = 1.8$, $\omega/\omega_p = 0.5$, $v/\omega_p = 0.1$, $b = k_\perp^2 v_{th}^2/2{\omega_c}^2 = 1.8$

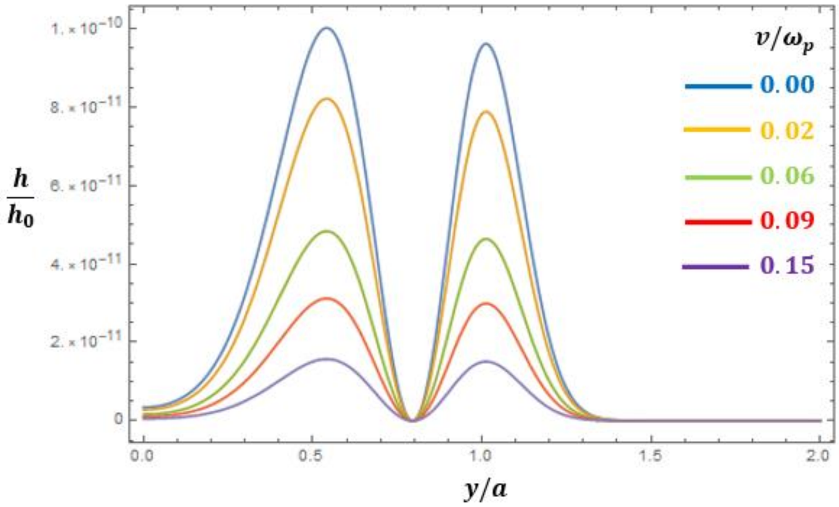

Figure 3(b): Variation of normalized anomalous heating rate with normalized beam direction for different values of v/ω_p, when $n_{cq}/n_0 = 0.001$, $\omega_1/\omega_p = 2.3$, $\omega_2/\omega_p = 1.8$, $\omega/\omega_p = 0.5$, $\frac{4}{3}\pi r_c^3 n_c \sim 0.00001$, $b = k_\perp^2 v_{th}^2/2{\omega_c}^2 = 1.8$

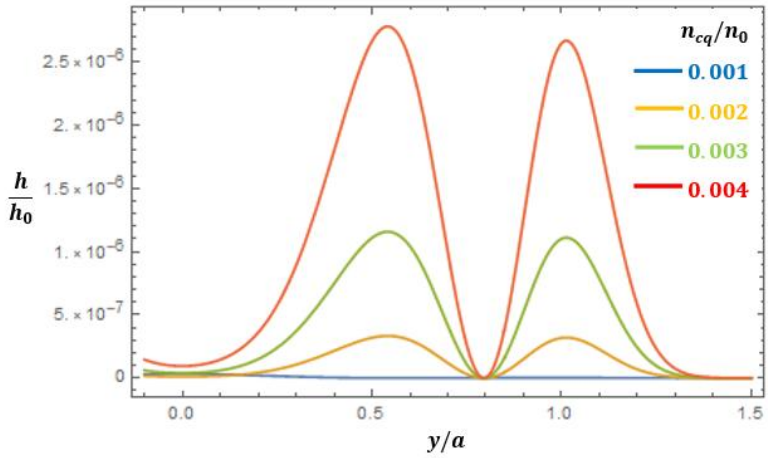

Figure 3(c): Variation of normalized anomalous heating rate with normalized beam direction for different values of $n_c \times 10^{14}(cm^{-3}) = 4,5,7$ when $\omega_1/\omega_p = 2.3$, $\omega_2/\omega_p = 1.8$, $\omega/\omega_p = 0.5$ $r_c \sim 2nm$, $v/\omega_p = 0.1$

5. SUMMARY AND CONCLUSIONS:

In this work, electron Bernstein wave assisted collisional nanoclustered plasma heating was analytically investigated by two super-Gaussian laser beams. The expression of electron dynamics in clustered plasma, nonlinear pondermotive force, and heating rate is solved by using the fluid theory. The spatial shape and multiple beams of potential, and heating profile are promising much more electron heating in clustered plasma as compared to previous results of heating in plasma wave. One may apply this theory of heating mechanism in toroidal fusion devices

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