EXCITATION OF ELECTROSTATIC PLASMA WAVE BY TWO LASER BEAMS IN NANOCLUSTERED PLASMA

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Abstract:
In this theoretical investigation, we explore the excitation of electron plasma waves (EPW) by two copropagating high-power laser beams within a collisional nanocluster plasma. The interaction of the electric field profiles of the laser beams leads to the ionization of the nanocluster, which rapidly transforms into plasma plume balls. Each super-Gaussian laser beam's electric field profile imparts an oscillatory velocity to the electrons associated with the nanoclustered plasma. This nonlinear ponderomotive force drives a self-consistent space charge wave, which has significant potential for exciting plasma waves in nanoclustered plasma. The expression for the electrostatic potential of the plasma wave is derived in nanoplasma while considering the effects of collisions. The effective surface plasmon resonance at the surface of the nanoclustered plasma is crucial for the excitation process. The tuning and control of plasma wave excitation are achieved by varying the super-Gaussian index, cluster radius, density, laser beat wave frequency, laser beam width, and collisional frequency. The plasma wave excited by electrons may have applications in nonlinear phenomena such as self-focusing and anomalous absorption.

Keywords: Plasma wave, Excitation, Super-Gaussian Laser beam, Beat wave, Cluster radius, Collisional frequency, Oscillatory velocity, Ponderomotive force

1. Introduction

In recent few years, interaction of laser beams with plasma and nanoclustered plasma is a particular field of interest due to its applications such as heating [1], charged particle acceleration [2], current drive experiments, and excitation [3]. The clusters are atomic aggregation upto several hundred atoms. These are bound by weak forces. Plasma embedded with nanocluster shows ambiguous property that aided a new dimension to study the plasma wave excitation [4-6]. When an intense laser beam interacts with material then ionization process takes place and cluster plasma is formed [7]. Another mechanism of cluster formation is possible through expanding noble gases via supersonic jets flow. The presence of effective surface plasmons oscillation on the surface of nanocluster affects the excitation property of plasma wave [7-10].

Plasma wave is a kind of electrostatic wave [10-11]. The nonlinear interaction of laser beam excites [12] the electrostatic wave and heat the plasma electrons. Owing to presence of effective surface plasmons frequency, the electron associated with nanocluster shows the enhanced heating rate [13]. Further, Kumar *et al.* [14] have studied the efficient electron heating through plasma wave aided laser beam in nanoclustered plasma.

The aim of present theoretical study is to investigate the electron plasma wave excitation by two copropagating high power SG laser beams in plasma embedded with nanocluster. The schematic diagram of this plasma wave excitation theory is shown in Fig. 1. Initially two laser beams nonlinearly interact with nanoclustered plasma and produced plasma plume ball. The plasma wave excitation is controlled by various factors such as super-Gaussian index, collisional frequency, laser beams width parameter, and clustered radius. The coupling of two laser beam in nanocluster plasma is given in Sec. 2. In Sec. 3, dispersion relation of nanoclustered plasma and potential profile of plasma wave in nanocluster is derived. Sec. 4 provides the results and discussion. Finally, summary and conclusion of our proposed theory is given in Sec. 5

2. Nonlinear Coupling

Here, we consider nanoclusters are embedded in plasma. The radius and density of cluster can be taken as r_c and n_c respectively. The two copropagating super-Gaussian laser beams withwave numbers $k_1$and k_2, frequencies ω_1 and ω_2 nonlinearly interact with nanoclustered plasmain z direction and polarized along y direction. The electric and magneticfield profile of each super-Gaussian (SG) laser can be taken as

$$\vec{E}_j = \hat{y}E_0 \exp[-(y/w_0)^p]e^{-i(\omega_j t - k_j z)}, \qquad (1)$$

$$\vec{B}_j = (\vec{k}_j \times \vec{E}_j)/\omega_j, \qquad (2)$$

where w_0 is the beam width parameter of laser, p (for $p > 2$) is the super Gaussian mode index, j=1, 2 is for each laser representation, m is the electro mass, e is the electron charge, andω_p is the electron plasma frequency.The ions are immobile owing to have large mass as compared to electron mass and during the interaction of laser beam withplasma embedded with nanocluster and only electrons are responded to thelaser beams in nanoclustered plasma.

We can write the equation of motion of electron in nanoclustered plasma as

$$\frac{d\vec{v}_j}{dt} + v\vec{v}_j + \frac{\omega_{pe}^2}{3}\vec{r}_j = -\frac{e}{m}\vec{E}_j, \quad (3)$$

where $\vec{v}_j$,$\vec{r}_j$, and$v$are the oscillatory velocity of electron, displacement, and electron ion collisional frequency respectively. The term $\omega_{pe}/\sqrt{3}$ is the effective plasmon frequency.

We canobtain theexpression ofelectron displacement and oscillatory velocityas

$$\vec{r}_j = \frac{e\vec{E}_j}{m\left(\omega_j^2 - \frac{\omega_{pe}^2}{3} + iv\omega_j\right)}, \qquad (4)$$

$$\vec{v}_j = -\frac{ie\omega_j\vec{E}_j}{m\left(\omega_j^2 - \frac{\omega_{pe}^2}{3} + iv\omega_j\right)}. \qquad (5)$$

The two copropagatingsuper-Gaussian laser beams in the nanoclusters cause a nonlinear ponderomotive force to the cluster electrons at the beat frequency $\omega = \omega_1 - \omega_2$ and beat wave number $k = k_1 - k_2$. The expression of nonlinear ponderomotive potentialcan be derived by using the following formula

$$\phi_p = -\left(\frac{m}{2e}\right)\overrightarrow{v_1}.\overrightarrow{v_2^*}, \text{and} \vec{F}_p = e\nabla\phi_p, \quad (6a)$$

The ponderomotive potential only for the plasma electrons is given as

$$\phi_p = -\frac{eE_0^2 \exp\left[-2\left(\frac{y}{w_0}\right)^p\right]e^{-i(\omega t - kz)}}{2m\omega_1\omega_2}, (6b)$$

The ponderomotive potential for the clustered electron is given as

$$\phi_p^c = -\frac{\omega_1\omega_2 eE_0^2 \exp\left[-2\left(\frac{y}{w_0}\right)^p\right]e^{-i(\omega t - kz)}}{2m\left(\omega_1^2 - \frac{\omega_{pe}^2}{3} + iv\omega_1\right)\left(\omega_2^2 - \frac{\omega_{pe}^2}{3} + iv\omega_2\right)}, (6$$

3. Plasma Wave Excitation

Let us assume that ponderomotive force have much potential to excite a space charge wave (electrostatic wave). Also, plasma wave might be driven by this space charge wave of potential $\phi = \phi_0 e^{-i(\omega t - \boldsymbol{k}.\boldsymbol{r})}$.

The electron density perturbation of the plasma electron can be written as

$$n_e = \frac{k^2}{4\pi e}\chi_{ep}(\phi + \phi_p), \qquad (7)$$

In the presence of nanoplasma, the electron density perturbation can be written as

$$n_e^c = \frac{k^2}{4\pi e}(\chi_{ep} + \chi_{ec})(\phi + \phi_p^c), \qquad (8)$$

The susceptibility ofplasmaelectrons$\chi_{ep}$and the susceptibility of nanoclusteredelectron$\chi_{ec}$is written as

$$\chi_{ep} = -\frac{{\omega_p}^2}{\omega^2}, \qquad (9a)$$

$$\chi_{ec} = -\frac{4}{3}\pi r_c^3 n_c \frac{\omega_{pe}^2\left(\omega^2 - \frac{\omega_{pe}^2}{3}\right)^2}{\left(\omega^2 - \frac{\omega_{pe}^2}{3}\right)^2 + v^2\omega^2} - i\frac{4}{3}\pi r_c^3 n_c \frac{\omega_{pe}^2 v\omega}{\left(\omega^2 - \frac{\omega_{pe}^2}{3}\right)^2 + v^2\omega^2}, \qquad (9b)$$

One can write the Poisson's equation as

$$\nabla^2\phi = 4\pi e(n_e^c), \qquad (10)$$

Further, we can write the dispersion relation as following

$$\epsilon\phi = -(\chi_{ep} + \chi_{ec})\phi_p^c, \qquad (11)$$

where ϵ is given as

$$\epsilon = 1 + \chi_{ep} + \chi_{ec}, \qquad (12)$$

4. Results and Discussion

We have theoretically studied the plasma wave excitation by beating of two high power copropagating SG laser beams in plasma embedded with nanocluster.Plasma wave can be excited by nonlinear interaction of two super-Gaussian laser beamswith beat wave frequency$\omega = \omega_1 - \omega_2$.Since ions are massive as compared to electrons. Hence, ionsmotion can be neglected as compared to electrons. During the interaction of laser beams with nanoclustered plasma, only clustered electrons are responsible for dynamics.The nonlinear ponderomotive force have much potential to excite the plasma waves. Our proposed theory is in good agreement with theoretical results in which they have excited the electron Bernstein wave in plasma by two laser beams.

Fig. 2(a) shows the variation of normalized potential amplitude profile of plasma wave as a function of normalized transverse distance of laser beat wave from y-axis for different value of super-Gaussian index p.The potential profile of plasma wave is purely Gaussian for index p=2 and super-Gaussian profile for p=4, 6. In this consideration, we can say that large amplitude of potential profile is obtained for super-Gaussian index as compared to purely Gaussian index.Fig. 2(b) shows the variation of normalized potential amplitude profile of plasma wave as a function of normalized transverse distance of laser beat wave from y-axis for different value of nanocluster radius.We can see that by increasing the nanocluster radius, the amplitude of normalized potential profile of plasma wave is increased.

The variation of normalized potential amplitude profile of plasma waves as a function of normalized laser beat wave frequency for different value of normalized plasmons frequency is shown in Fig. 3.It shows that maximum peak profile is attained at $\omega \sim 0.62\omega_{pe}$. At this particular point, plasma wave is excited much more. Also, we can see that on increasing the electron plasmons frequency, the plasma wave is also enhanced.

In Fig. 4, the variation of normalized potential amplitude profile of plasma waves as a function of normalized laser beat wave frequency for different value of normalized collisional frequency has been plotted.We can see that on increasing the collisional frequency, the peak profile of excited plasma wave is decreased. Therefore, one can say that collision effect causes the destruction effect on plasma wave excitation.

Fig. 5 shows the graph between normalized potential amplitude and normalized laser beat wave frequency for different value of nanocluster radius.As one increases the size of nanocluster, the excitation of plasma wave is increased. This occurrence due to increase in cluster radius, the effective surface region of interaction is increased and the electron associated with nanocluster plasma is increased. In this way, one can say that large effective surface area causes the much more plasma wave excitation.

5. Summary and Conclusions

In these present theoretical investigations, we study the plasma waveexcitation byusing the super-Gaussian laser beat wave frequencyin collisional nanoclustered plasma.The dependence of the plasma wave excitation on the laser beam super-Gaussian mode index, collisional frequency, laser beam width, cluster radiusis presented.The spatial shape of plasma wave potential with laser beat wave frequency and propagation distance were depicted the much excitation. The effective plasmons oscillations on the surface of nanocluster plasma plays an effective role for enhancing the plasma waveexcitation. Large amplitude of normalized potential profile of electron plasma wave is obtained in nanoclustered plasma as compared with only plasma medium. The maximum excitation is achieved at normalized laser beat wave frequency around $\omega \sim 0.62\omega_{pe}$.

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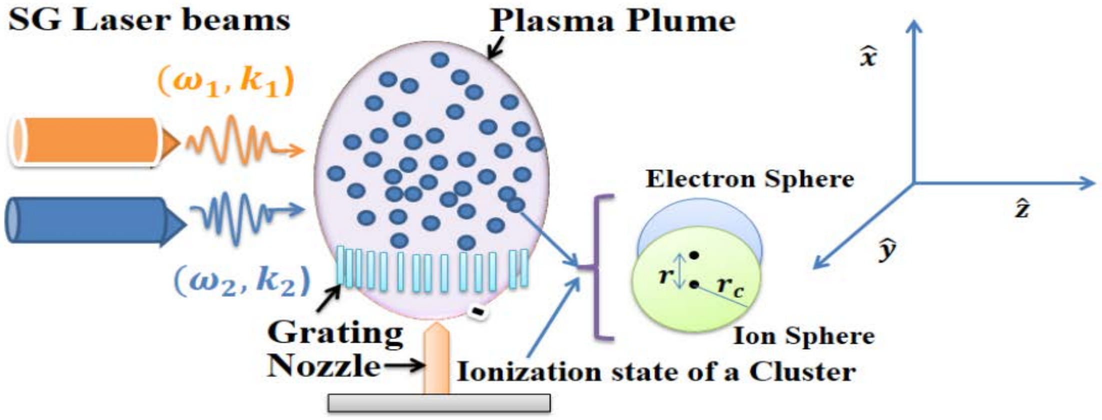

Fig. 1

Fig. 1: Schematic diagram of plasma wave excitation in a collisional nanocluster plasma

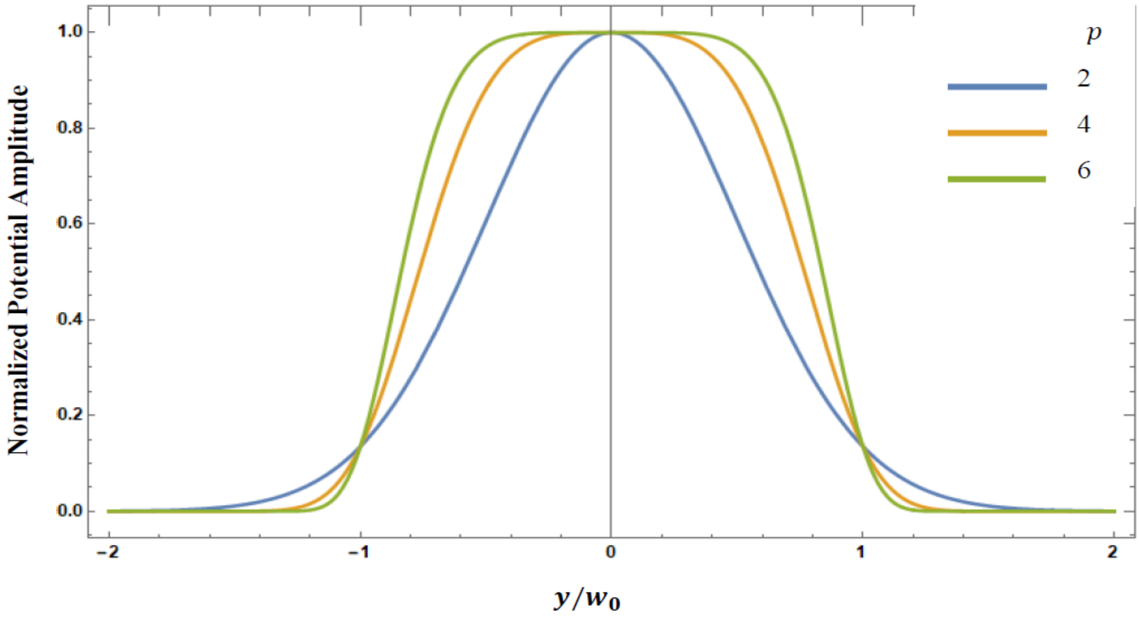

Fig. 2 (a)

Fig. 2(a): Variation of normalized potential amplitude profile with normalized beam propagation distance for different values of super- Gaussian index of laser beams p

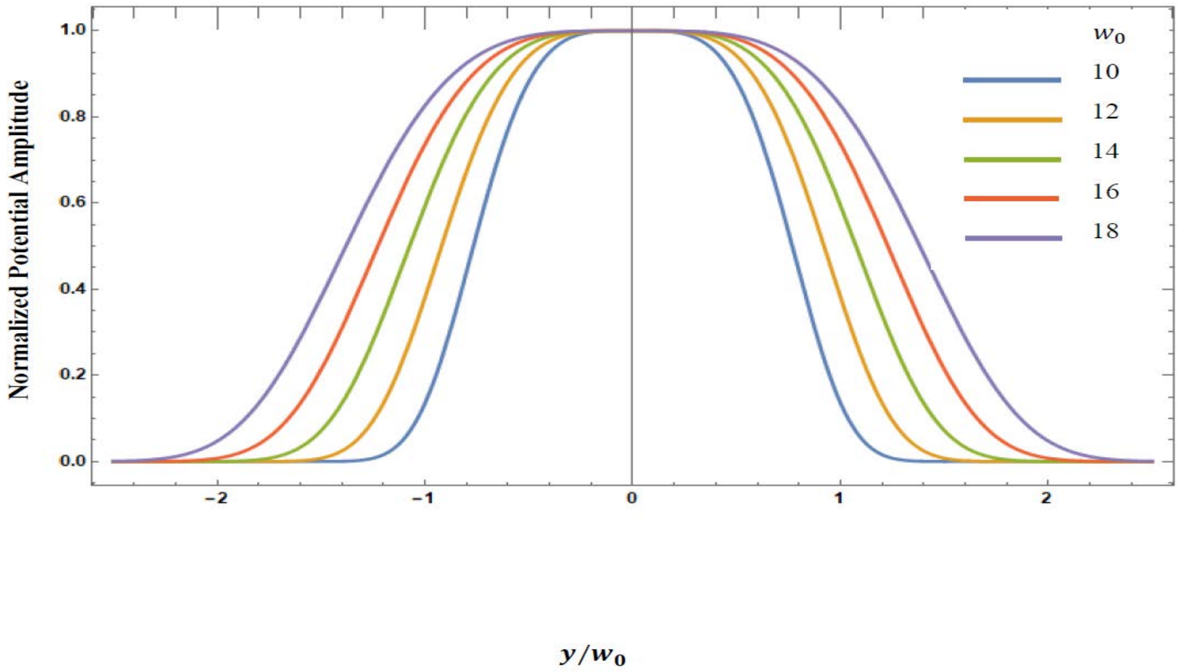

Fig. 2 (b)

Fig. 2(b): Variation of normalized potential amplitude with normalized beam propagation distance for different values of laser beam width

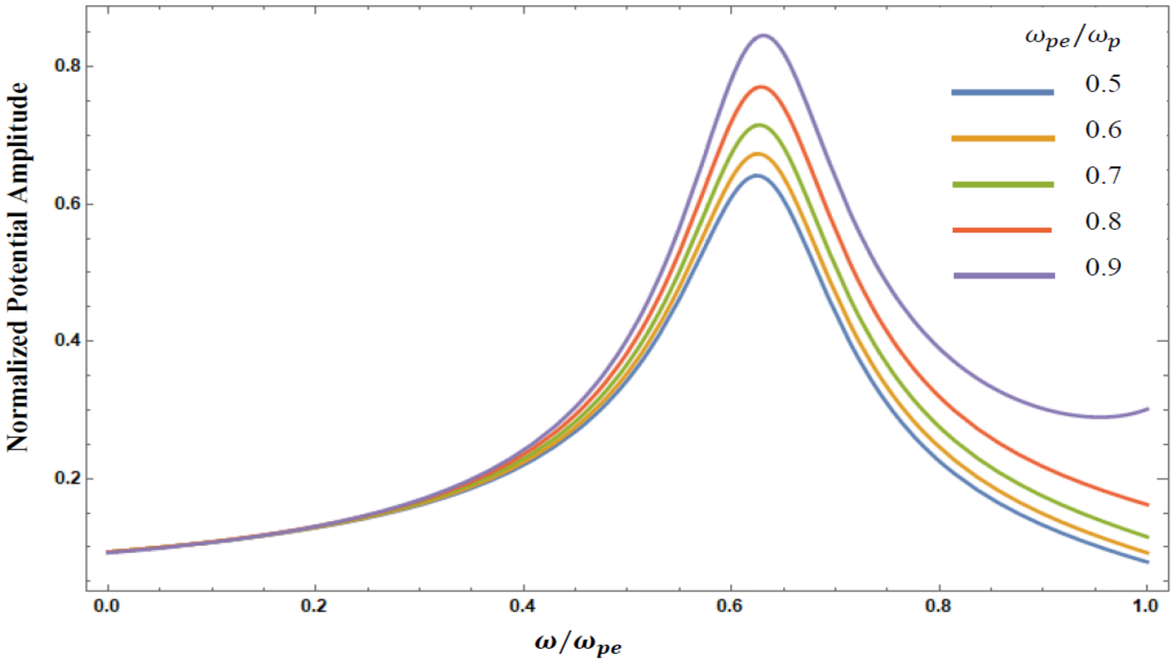

Fig. 3

Fig. 3: Variation of normalized potential amplitude profile with normalized beat frequency for different values of normalized plasmons frequency

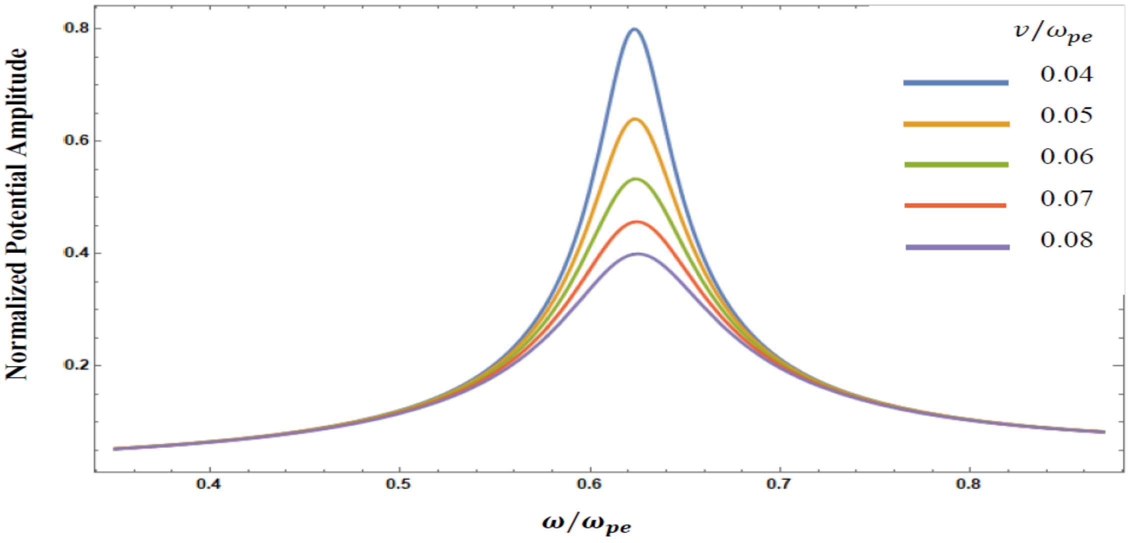

Fig. 4

Fig. 4: Variation of normalized potential amplitude with normalized beat frequency for different values of collisional frequency

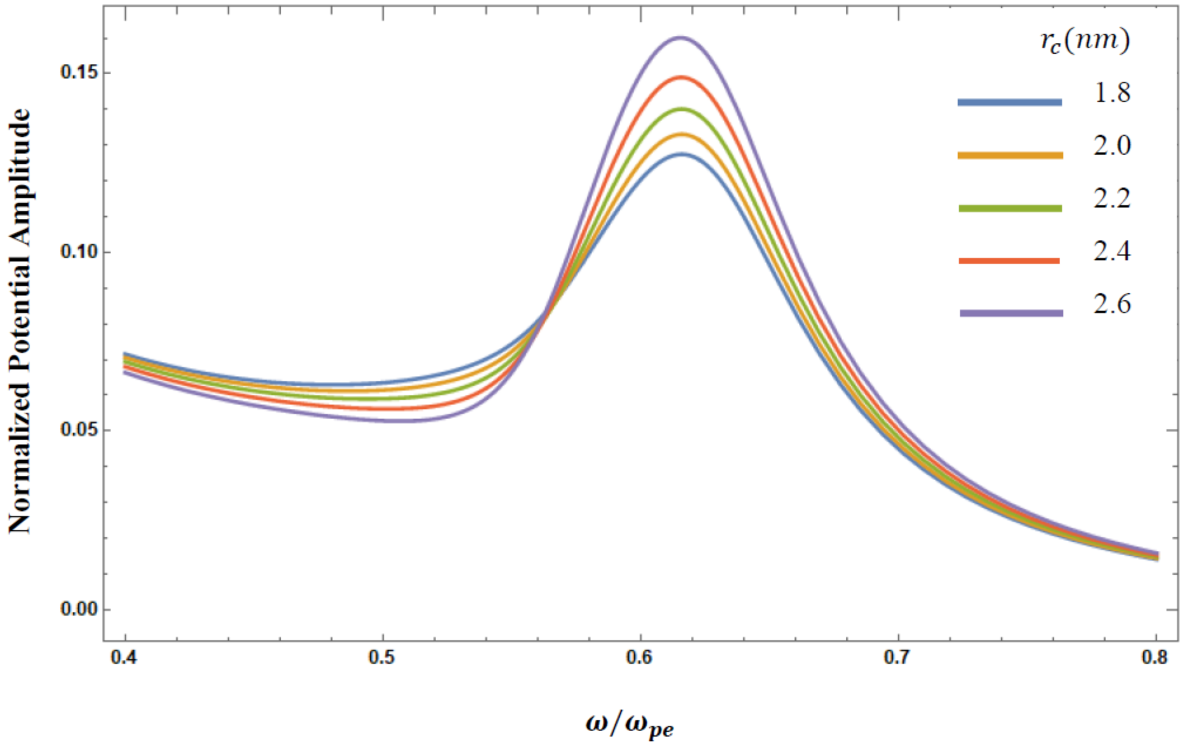

Fig. 5

Fig. 5: Variation of normalized potential amplitude with normalized beat frequency for different values of cluster radius