SELF-FOCUSING DYNAMICS OF COSH-GAUSSIAN LASER BEAMS IN ABSORPTIVE COLD QUANTUM PLASMA UNDER RELATIVISTIC AND PONDEROMOTIVE NONLINEARITIES

Deepak Tripathi[1], Nisha Singh Rathore[2], Vinit Kakkar[3], Keshav Walia[4]*

[1]Physics Department, USAR/USBS, Guru Gobind Singh Indraprastha University, East Delhi Campus, Delhi, India-110032
[2]Department of Applied Sciences, KCC institute of Technology and Management, Greater Noida, India
[3]Department of Physics, Lotus Valley International School, Sector-50, Gurgaon, India
[4]Department of Physics, DAV University Jalandhar, Punjab, India
*Corresponding Author e-mail: keshavwalia86@gmail.com

The current study examines self-focusing behavior of Cosh-Gaussian laser beams in absorptive cold quantum plasma, incorporating merged influence of relativistic mass variation and ponderomotive effects. Applying WKB approximation in combination with paraxial theory, 2nd order propagation equation describing variation of beam width as a function of normalized distance is derived incorporating effect of linear absorption. The numerical solution of resulting differential equation is obtained by 4th order Runge-kutta method. Further, a comprehensive parametric study is performed to access effect of laser-plasma parameters such as beam intensity, plasma density, initial beam radius, decentered parameter and absorption coefficient on beam dynamics. The results show that relativistic and ponderomotive nonlinearities enhance self-focusing, whereas absorption reduces it. Comparison with classical relativistic plasma underscores the key role of quantum effects in laser propagation through dense plasmas.

Keywords: *Self-focusing dynamics; Cosh-Gaussian beam; Relativistic mass variation; Ponderomotive effects; Linear absorption*
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1. INTRODUCTION

Laser beam self-focusing in plasma is a fundamental nonlinear phenomenon attracting interest from theoretical/experimental groups. This phenomenon was first time reported by Askar'yan in 1962[1]. In self-focusing, the intensity of laser beam alters the refractive index of plasma medium, thereby causing beam to self-focus without any external optical components. This intrinsic focusing tendency plays a pivotal role in many advanced applications including laser driven fusion, X-ray lasers, high energy particle acceleration and nonlinear optical experiments [2-9]. It has been confirmed from past literature that self-focusing phenomenon may arise in distinct nonlinear media including plasmas, atomic clusters and related materials. There exist many mechanisms that lead to self-focusing in plasma media. These mechanisms include relativistic self-focusing, ponderomotive self-focusing and thermal self-focusing. In relativistic self-focusing, an intense laser beam induces an effective increase in electronic mass, thereby modifying plasma's dielectric response. In addition to relativistic effects, ponderomotive and thermal self-focusing also contribute significantly to beam's convergence. Each of these mechanisms induces refractive index modifications, thereby enhancing the beam's focusing. Early work in this area was conducted by Hora and Siegrist [10-11]. Relativistic and ponderomotive nonlinearities are often studied separately, through both can co-exist depending on pulse duration. Relativistic effects dominate for $\tau < \tau_e$, while for $\tau_e < \tau < \tau_i$, both act together. In this regime, ponderomotive nonlinearity strengthens relativistic self-focusing and plasma density modulation. Self-focusing often triggers secondary nonlinear phenomena including harmonic production, filamentation, and parametric instabilities, which are critical in high intensity laser plasma interactions [12-27].

Recent developments in plasma physics have focused on laser interactions with quantum plasmas, which are characterized by high electron densities and low temperatures. In quantum plasmas, some effects such as electron degeneracy, quantum tunneling and wave-function becomes significant. While classical plasmas are governed by Maxwell-Boltzmann statistics, whereas electrons in quantum plasmas obey Fermi-Dirac statistics, and their behavior is best described through Wigner formalism [28-32]. Quantum effects become dominant when electron De-Broglie wavelength is comparable to or greater than inter-particle spacing, leading to pronounced modifications in plasma properties. Quantum plasmas are of interest for astrophysical/cosmological systems, dense plasma devices, semiconductor systems, quantum dots, and inertial confinement fusion experiments [33-40].

Most previous studies on laser propagation in quantum plasmas have focused on cylindrical symmetric Gaussian beams, which provide limited control over beam's intensity profile [41-43]. Cosh-Gaussian (ChG) laser beams offer a more general and flexible intensity profile, with adjustable intensity distribution that better represents realistic laser pulses. Unlike conventional Gaussian beams, ChG beams provide extra control via decentered parameter, allowing precise manipulation of self-focusing. The enhanced control improves energy localization, reduces diffraction, and strengthens laser plasma interactions. Linear absorption further affects beam's energy distribution, altering plasma dielectric response and overall propagation. Understanding these effects is crucial for accurately modeling laser-plasma interactions under

practical experimental conditions. In this study, we investigate self-focusing of ChG laser beams in absorptive cold quantum plasma to achieve a more realistic description of laser-plasma dynamics. Both relativistic modification of electron mass and ponderomotive nonlinear effects are included to describe beam propagation under intense laser fields. The paper is structured as follows: Section 2 presents the derivation of governing 2nd order differential equation using WKB and paraxial approximations. Section 3 explains numerical method and discusses the influence of different parameters on beam dynamics. Finally, section 4 summarizes main results and highlights the important features observed due to quantum plasma effects.

2. NONLINEAR DYNAMICS OF LASER BEAM WIDTH

The transverse electric field distribution of a ChG laser beam at the input plane ($z = 0$) can be written as

$$E(r, 0) = E_0 \exp\left(-\frac{r^2}{r_0^2}\right) Cosh(\rho_0 r) \tag{1}$$

Where r_0 is initial beam width, r denotes radial coordinate in a cylindrical coordinate system, E_0 represents peak field amplitude. The parameter $'\rho_0'$, known as Cosh-factor, governs the deviation of beam from standard Gaussian profile. Using the identity of hyperbolic cosine function, Eq. (1) can be equivalently expressed as superposition of two laterally displaced Gaussian beams as

$$E(r, 0) = E_0 \exp\left(\frac{b^2}{4}\right)\left\{exp\left(-\left[\frac{r}{r_0} + \frac{b}{2}\right]^2\right) + exp\left(-\left[\frac{r}{r_0} - \frac{b}{2}\right]^2\right)\right\} \tag{2}$$

Where, $b = r_0\rho_0$ is denoted as decentered parameter. This parameter controls separation of Gaussian components, shaping beam profile and influencing self-focusing. During the propagation along z-direction, the ChG beam's transverse profile evolves under influence of diffraction and nonlinear plasma effects. The field distribution at an arbitrary propagation distance z is given by

$$E(r, z) = \frac{E_0}{2f} \exp\left(\frac{b^2}{4}\right)\left\{exp\left(-\left[\frac{r}{r_0 f} + \frac{b}{2}\right]^2\right) + exp\left(-\left[\frac{r}{r_0 f} - \frac{b}{2}\right]^2\right)\right\} \tag{3}$$

Where, $f(z)$ represents the normalized beam width parameter describing the dynamics of beam spot size during transition. The formulation clearly illustrates enhanced flexibility of Cosh-Gaussian beams over conventional Gaussian beams, enabling precise control of intensity distribution and nonlinear propagation characteristics in plasma media.

The transition of pump beam in plasma medium is described by wave equation for field vector. In non-uniform plasma, this equation takes the form

$$\nabla^2 E - \nabla(\nabla . E) + \frac{\omega^2}{c^2}\varepsilon E = 0 \tag{4}$$

Where, ε represents dielectric function of plasma, ω is beam's angular frequency, and c is light's speed. The second term accounts for spatial variations of dielectric function and becomes important only when the plasma inhomogeneity is strong. For slowly varying plasma density, the dielectric function changes smoothly in space. Under the condition, $\frac{1}{k^2}[\nabla^2 \ln \epsilon] \ll 1$, the contribution of second term in Eq. (4) can be neglected. Consequently, the wave equation simplifies to

$$\nabla^2 E + \frac{\omega^2}{c^2}\varepsilon E = 0 \tag{5}$$

As the laser beam propagates through cold quantum plasma, its oscillating electric field drives plasma electrons in to oscillatory motion. In the relativistic intensity regime, this motion leads to an effective increase in electron mass. The corresponding oscillatory velocity of electron is given by $v = \frac{eE}{m_0\omega\gamma}$. Here, $'\gamma'$ is relativistic Lorentz factor expressed as $\gamma = (1 + \alpha EE^*)^{1/2}$ with $\alpha = \frac{e^2}{m_0^2\omega_0^2 c^2}$ being nonlinear coefficient.

In the nonlinear regime of laser-plasma interaction, the dielectric response of medium becomes explicitly dependent on intensity of electromagnetic field. Accordingly, the dielectric function can be expressed in general form as

$$\epsilon = \varepsilon_0 + \Phi(E \cdot E^*) \tag{6}$$

Where, $\varepsilon_0 = 1 - \frac{\omega_p^2}{\omega^2}$ represents the linear, intensity-independent contribution, while $\Phi(E \cdot E^*)$ accounts for nonlinear modification arising due to relativistic electron mass variation and quantum mechanical effects induced by strong laser field. The plasma frequency is defined as $\omega_p = \sqrt{\frac{4\pi n e^2}{m}}$. For an unmagnetized cold quantum plasma (CQP), merged influence of relativistic and quantum corrections leads to dielectric function given by [44]

$$\epsilon = 1 - \frac{\omega_p^2}{\gamma\omega^2}\left(1 - \frac{\delta q}{\gamma}\right)^{-1} \tag{7}$$

Here, the parameter $'\delta q'$ measures the strength of quantum effects and is expressed as $\delta q = \frac{4\pi^4 \hbar^2}{m^2 \omega^2 \lambda^4}$. Where, $'h'$ denotes Planck's constant and λ is the wavelength of incident laser beam. In the classical limit, where quantum effects are negligible, $\delta q \to 0$, So, Eq. (6) reduces to well-known dielectric response of classical relativistic plasma (CRP).

$$\epsilon = 1 - \frac{\omega_p^2}{\gamma \omega^2} \tag{8}$$

The redistribution of electrons in plasma arises due to action of ponderomotive force associated with intense laser field. This force drives electrons away from portions of high field intensity, leading to a modification in local electron density. The resulting density variation can be expressed as [44]

$$n = n_0 \exp\left(-\frac{mc^2}{T}(\gamma - 1)\right) \tag{9}$$

By substituting modified electron density given by Eq.(9) in dielectric function expressions and combining Eqs. (6), (7) and (9), the nonlinear contribution to dielectric function is obtained as

$$\Phi(E \cdot E^*) = \frac{\omega_{p0}^2}{\omega^2}\left[1 - \left(1 - \frac{\delta q}{\gamma}\right)^{-1} \exp\left(-\frac{mc^2}{T}(\gamma - 1)\right)\right] \tag{10}$$

Where $\omega_{p0} = \sqrt{\frac{4\pi n_0 e^2}{m_0}}$.

Following [41-43], the wave Eq.(5) is solved by adopting slowly varying envelope approximation, wherein the laser field is represented as a slowly varying amplitude modulating a oscillating carrier wave. Accordingly, the electric field is represented as

$$E = E_0(r, z) \exp[i(\omega t - k(S + z))] \tag{11}$$

The corresponding intensity distribution of propagating ChG beam is given by

$$E_0(r, z) = \frac{E_{00}}{2f} \exp\left(\frac{b^2}{4}\right)\left\{\exp\left(-\left[\frac{r}{r_0 f} + \frac{b}{2}\right]^2\right) + \exp\left(-\left[\frac{r}{r_0 f} - \frac{b}{2}\right]^2\right)\right\} \tag{12}$$

The phase function $'S'$, which accounts for both curvature of wave-front and the accumulated longitudinal phase change during propagation, can be expressed as

$$S = \frac{1}{2}r^2 \frac{1}{f}\frac{df}{dz} + \Phi_0(z) \tag{13}$$

Where, $\Phi_0(z)$ denotes cumulative longitudinal phase shift accumulated by laser beam during its propagation through plasma medium. The wave number k of laser beam inside plasma is defined as

$$k = \frac{\omega}{c}\sqrt{\varepsilon_0} \tag{14}$$

The transverse dynamics of laser beam is completely described by beam width parameter $'f(z)'$, which characterizes variation of beam spot size during propagation. To simplify analysis, a normalized propagation distance $'\eta'$ is introduced. In terms of this normalized variable, the evolution of beam width $'f(z)'$ along propagation direction is governed by 2nd order nonlinear differential equation, which captures combined effects of diffraction, nonlinear plasma response and absorption of beam propagation.

$$\frac{d^2 f}{d\eta^2} = \frac{1}{f^3} - \left(\frac{\omega_{p0} r_0}{c}\right)^2 (2 - b^2)\frac{\alpha E_{00}^2 \exp(-2k_i \eta)}{2f^3}\frac{\exp\left(-\frac{mc^2}{T_e}\left[\sqrt{1 + \frac{\alpha E_{00}^2 \exp(-2k_i \eta)}{f^2}} - 1\right]\right)}{\left(1 + \frac{\alpha E_{00}^2 \exp(-2k_i \eta)}{f^2}\right)^{3/2}\left(1 - \frac{\delta q}{\sqrt{1 + \frac{\alpha E_{00}^2 \exp(-2k_i \eta)}{f^2}}}\right)^2}\left[1 + \right.$$

$$\left.\frac{mc^2}{T_e}\sqrt{1 + \frac{\alpha E_{00}^2 \exp(-2k_i \eta)}{f^2}}\left(1 - \frac{\delta q}{\sqrt{1 + \frac{\alpha E_{00}^2 \exp(-2k_i \eta)}{f^2}}}\right)\right] \tag{15}$$

Eq. (15) describes how the normalized beam waist $'f(z)'$ evolves with the normalized distance. Diffraction, represented by 1st term, causes the beam to spread during propagation, whereas 2nd term arises from nonlinear relativistic-ponderomotive effects in cold quantum plasma, which promotes self-focusing by modifying plasma response. The balance between these opposing mechanisms determines whether the beam spreads, self-focuses, or show oscillatory behavior.

3. DISCUSSION

Due to the inherent nonlinearity of Eq. (15), an exact analytical solution is not feasible. Therefore, the numerical solution is obtained using the 4th-order Runge-Kutta method. The simulations are carefully performed for a chosen range of laser and plasma parameters corresponding to realistic experimental conditions, allowing a meaningful analysis of beam propagation behavior in plasma:

$$\alpha E_{00}^2 = 3.0, 4.0, 5.0; \frac{\omega_{p0}^2}{\omega^2} = 0.6, 0.7, 0.8; k_i = 0.1, 0.4, 0.7 ; b = 1.0, 2.0, 3.0; r_0 = 10 \ \mu m, 15 \ \mu m, 20 \ \mu m$$

The propagation dynamics of beam width described by Eq. (15) arises from interplay between diffraction and nonlinear focusing. Diffraction accounts for inherent tendency of beam to spread while propagating through plasma; its dominance leads to beam divergence and leading to a broadening of lateral dimensions of beam. On the other hand, high power laser field nonlinearly modifies plasma dielectric response, producing a self-focusing effect. When this mechanism dominates, the beam contracts and its width decreases. A balanced regime is achieved, when diffraction and nonlinear focusing exactly counteract each other. In this regime, the beam propagates in a stable manner with a constant transverse width.

Figure 1 presents variation of beam width f along propagation distance η for beam intensities $\alpha E_{00}^2 = 3.0, 4.0,$ and 5.0, shown by Black, Red, and Green respectively. In each case, the beam width displays a characteristic oscillatory pattern arising from saturation of plasma's dielectric response. With increasing laser intensity, diffraction effects become more significant against the nonlinear focusing effect, diminishing beam's ability to contract. As a result, at higher intensities, the beam reaches its minimum width farther along the propagation path, clearly indicating a reduction in self-focusing effect.

Figure 2 presents variation of beam width f along propagation distance η for plasma densities $\omega_{p0}^2/\omega^2 = 0.6, 0.7, 0.8$, shown by Black, Red, and Green respectively. In each case, the beam width displays a characteristic oscillatory pattern arising from saturation of plasma's dielectric response. With increasing plasma density, nonlinear focusing effects become more significant against diffraction effects, strengthening beam's ability to contract. As a result, at higher densities, the beam reaches its minimum width at an earlier point along the propagation, clearly indicating a amplification in self-focusing effect.
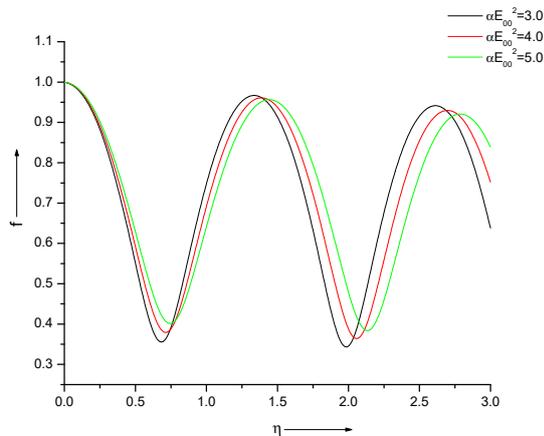

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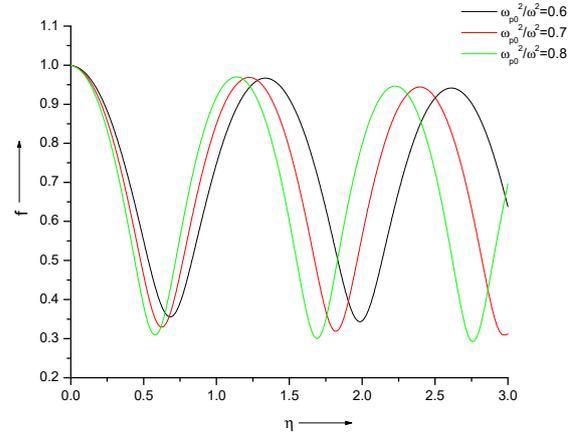
Figure 2. Variation of beam width f along propagation distance η for plasma densities $\omega_{p0}^2/\omega^2 = 0.6, 0.7, 0.8$, shown by Black, Red, and Green respectively

Figure 3 presents variation of beam width f along propagation distance η for beam radii $r_0 = 10 \ \mu m, 15 \ \mu m,$ and $20 \ \mu m$, shown by Black, Red, and Green respectively. For each scenario, the beam width shows a regular oscillatory pattern caused by nonlinear saturation of plasma dielectric properties. With higher beam radius, the influence of nonlinear focusing grows compared to diffraction, promoting stronger beam convergence. Accordingly, at elevated beam radii, the beam achieves its minimum width at a shorter propagation distance, indicating strengthened self-focusing.

Figure 4 presents variation of beam width f along propagation distance η for decentered parameter, $b = 1.0, 2.0, 3.0$, shown by Black, Red, and Green respectively. For each scenario, the beam width shows a regular oscillatory pattern caused by nonlinear saturation of plasma dielectric properties. Increasing the decentered parameter amplifies the role of nonlinear focusing relative to diffraction, promoting tighter beam focusing. A higher decentered parameter increases local beam intensity, enhancing nonlinear plasma response. This strengthens self-focusing over diffraction, leading to tighter beam contraction and stronger confinement along propagation.

Figure 5 presents variation of beam width f along propagation distance η for distinct k_i values, $k_i = 0.1, 0.4, 0.7$, shown by Black, Red, and Green respectively. The figure demonstrates that an increase in k_i reduces beam's contraction driven by enhanced energy dissipation via absorption. With increasing absorption, the gradient of plasma refractive index

weakens, weakening nonlinear focusing mechanism. Consequently, diffraction predominates, causing the beam to converge less efficiently, and maintain a wider transverse profile during propagation.
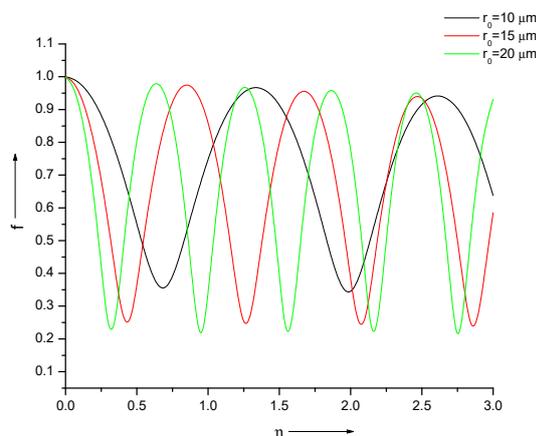

Figure 3. Variation of beam width f along propagation distance η for beam radii $r_0 = 10\,\mu m, 15\,\mu m,$ and $20\,\mu m,$ shown by Black, Red, and Green respectively
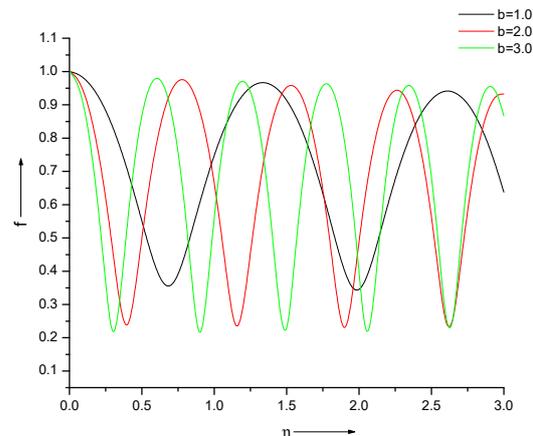

Figure 4. Variation of beam width f along propagation distance η for decentered parameter, $b = 1.0, 2.0, 3.0,$ shown by Black, Red, and Green respectively

Figure 6 presents variation of beam width f along propagation distance η for three distinct plasma regimes. The black curve depicts the combined influence of relativistic-ponderomotive cold quantum plasma (RPCQPP), while red curve corresponds to cold quantum plasma (CQP) alone, and the green curve corresponds to classical relativistic plasma (CRP) alone. Beam focusing occurs earliest in the RPCQP case, compared to both CQP and CRP. In CQP regime, the beam exhibits stronger focusing than in CRP scenario. This behavior highlights the significant role of quantum effects, which enhance the nonlinear focusing contribution relative to diffraction, thereby improving the overall focusing of beam.
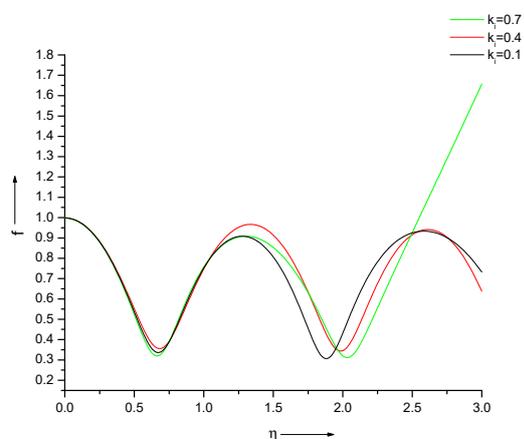

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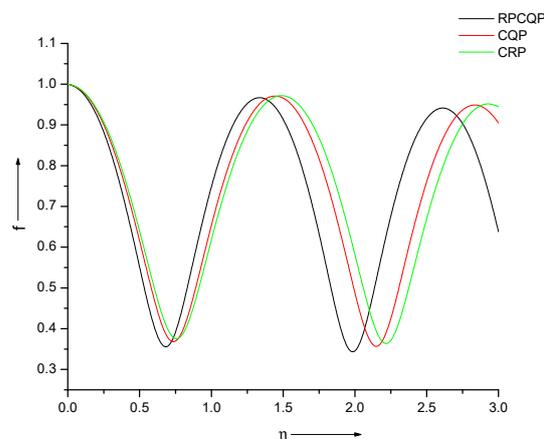

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4. CONCLUSIONS

This work presents a comprehensive study of self-focusing dynamics of ChG laser beams propagating through absorptive cold quantum plasma, incorporating RP force. Employing WKB and paraxial approximations, the self-focusing equation is derived. The results reveal that the beam's convergence is enhanced with increasing number density, beam radius, and decentered parameter, as these parameters strengthen nonlinear refractive index. Conversely, higher beam intensity reduces focusing effect. Furthermore, inclusion of quantum contribution amplifies nonlinear convergence term, leading to markedly stronger self-focusing of beam. These results help understand and control laser propagation in plasma, useful for improving laser-driven fusion and other high intensity laser applications.

Conflict of Interest

The authors declare that there are no conflicts of interest.

ORCID

⬤**Deepak Tripathi,** https://orcid.org/0000-0001-9945-4069; ⬤**Keshav Walia,** https://orcid.org/0000-0001-9547-3027

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ДИНАМІКА САМОФОКУСУВАННЯ КОШ-ГАУСІВСЬКИХ ЛАЗЕРНИХ ПРОМЕНІВ В АБСОРБЦІЙНІЙ ХОЛОДНІЙ КВАНТОВІЙ ПЛАЗМІ ПІД ДІЄЮ РЕЛЯТИВІСТСЬКИХ ТА ПОНДЕРОМОТОРНИХ НЕЛІНІЙНОСТЕЙ

Діпак Тріпаті[1], Ніша Сінгх Ратхор[2], Вініт Каккар[3], Кешав Валья[4]

[1]*Фізичний факультет, USAR/USBS, Університет Гуру Гобінд Сінгх Індрапрастха, кампус Східного Делі, Делі, Індія-110032*
[2]*Фізичний факультет, Інститут технологій та менеджменту KCC, Велика Нойда, Індія*
[3]*Фізичний факультет, Міжнародна школа Лотосової долини, Сектор-50, Гургаон, Індія*
[4]*Фізичний факультет, Університет DAV, Джаландхар, Пенджаб, Індія*

У цьому дослідженні розглядається поведінка самофокусування лазерних променів Коша-Гаусса в абсорбційній холодній квантовій плазмі, враховуючи об'єднаний вплив релятивістської зміни маси та пондеромоторних ефектів. Застосовуючи наближення ВКБ у поєднанні з параксіальною теорією, отримано рівняння поширення 2-го порядку, що описує зміну ширини променя як функцію нормалізованої відстані, враховуючи вплив лінійного поглинання. Чисельне рішення результуючого диференціального рівняння отримано методом Рунге-Кутти 4-го порядку. Далі проведено комплексне параметричне дослідження для оцінки впливу параметрів лазерної плазми, таких як інтенсивність променя, густина плазми, початковий радіус променя, параметр децентрування та коефіцієнт поглинання, на динаміку променя. Результати показують, що релятивістська та пондеромоторна нелінійності посилюють самофокусування, тоді як поглинання зменшує його. Порівняння з класичною релятивістською плазмою підкреслює ключову роль квантових ефектів у поширенні лазера через щільну плазму.

Ключові слова: *динаміка самофокусування; Кош-Гаусівський промінь; релятивістська зміна маси; пондеромоторні ефекти; лінійне поглинання*