



Research Article

Quantum Kinetic Study of Energy Transport During Ultrashort Laser Interaction with Dense Plasmas

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Abstract

The interaction of ultrashort femtosecond laser pulses with dense plasma is a fundamental problem in high-energy-density physics, inertial confinement fusion, advanced particle acceleration, and ultrafast photonics. Under conditions of high electron density and ultrashort time scales, classical kinetic models become inadequate because they neglect quantum phenomena such as wave-particle coherence, quantum diffraction, tunnelling, and nonlocal transport. To address these limitations, this study develops a self-consistent quantum kinetic model based on the coupled Wigner-Maxwell framework. Electron dynamics are described using the Wigner distribution function, while the electromagnetic fields are governed by Maxwell's equations, enabling simultaneous treatment of quantum transport and wave propagation. Analytical formulations are employed to derive the dispersion relation, damping characteristics, and nonlinear evolution equations governing femtosecond laser pulse propagation in dense plasma. The theoretical predictions are validated through numerical simulations performed with realistic plasma and laser parameters representative of contemporary high-intensity laser experiments. The simulations demonstrate significant quantum modifications to wave dispersion, the emergence of multiple resonance branches, and coherence-driven modulation instabilities that are absent in classical descriptions. These quantum effects substantially influence pulse propagation, energy deposition, and plasma stability, leading to altered laser-plasma interaction dynamics. The results establish that quantum kinetic effects play a decisive role in determining the behaviour of ultrashort laser pulses in dense plasma and therefore must be incorporated into predictive models for high-density plasma systems. The proposed Wigner-Maxwell framework provides a rigorous theoretical foundation for investigating quantum laser-plasma interactions and offers valuable guidance for the interpretation and design of experiments at next-generation high-intensity laser facilities.

Keywords

Quantum Plasma, Wigner Function, Femtosecond Laser, Nonlocal Transport, Maxwell Coupling, Ultra-short Pulses, Dense Plasma

1. Introduction

The interaction of ultra - short laser pulses with plasma has emerged as one of the most dynamic research frontiers in modern plasma physics, driven largely by rapid advancements in femtosecond and attosecond laser technologies. These ultra

- short pulses, with durations on the order of 10^{-15} - 10^{-18} seconds, enable the exploration of matter under extreme nonequilibrium conditions, where classical assumptions often break down. Such interactions are central to a wide spectrum

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of applications, including inertial confinement fusion (ICF), laser wakefield acceleration, higher harmonic generation, plasma based photonics, and astrophysical plasma modelling [1, 2].

In inertial confinement fusion, ultra - intense laser pulses are used to compress and heat fuel pellets to achieve thermonuclear conditions, requiring precise understanding of laser energy deposition and plasma response. Similarly, in laser wakefield acceleration, short laser pulses generate plasma waves capable of accelerating electrons to relativistic energies over very short distances. Computational and experimental studies have demonstrated the feasibility of such mechanisms using advanced modelling techniques, including particle-in-cell (PIC) simulations [3].

However, as plasma densities approach or exceed 10^{26} m^{-3} , the physical description of plasma dynamics must move beyond classical frameworks. In such regimes, commonly encountered in solid - density plasmas, warm dense matter, and astrophysical environments like white dwarfs, the electron de Broglie wavelength becomes comparable to interparticle spacing. Under these conditions, quantum mechanical effects such as wave - particle duality, tunnelling, and degeneracy pressure become significant [4, 5].

The classical Vlasov equation, which forms the backbone of collisionless plasma kinetics, assumes that particles follow deterministic trajectories in phase space. While highly successful for dilute and weakly coupled plasmas, it fails to capture inherently quantum phenomena such as interference and nonlocal correlations. In dense plasmas, the Pauli exclusion principle leads to Fermi - Dirac statistics, fundamentally altering the equilibrium distribution of electrons and giving rise to Fermi pressure, even at zero temperature [6].

Quantum effects in plasma can be broadly understood through four interconnected physical phenomena that become significant when the characteristic quantum scales of electrons approach macroscopic plasma parameters. First, the wave nature of electrons, quantified through the thermal de Broglie wavelength, plays a crucial role in dense and low - temperature plasmas. When this wavelength becomes comparable to the average interparticle spacing, electrons can no longer be treated as point - like classical particles, instead their wave - like behaviour leads to quantum diffraction effects, which modify dispersion relations and wave propagation characteristics. This results in additional terms, such as the quantum Bohm potential, in the governing equations, fundamentally altering plasma oscillations and stability properties.

Closely related to this is the phenomenon of Fermi degeneracy, which arises in high-density plasmas where electrons obey Fermi - Dirac statistics rather than classical Maxwell - Boltzmann distributions. In such conditions, electrons fill available energy states up to the Fermi energy, even at very low temperatures, giving rise to a degeneracy pressure independent of thermal motion. This pressure significantly influences the equation of state, transport coefficients, and collec-

tive oscillations of the plasma. It becomes particularly important in systems such as solid - density plasmas, metals, and astrophysical objects like white dwarfs, where it governs structural stability and wave dynamics.

Another important quantum phenomenon is quantum tunnelling, wherein electrons can penetrate potential barriers that would be insurmountable in classical mechanics. In the context of laser - plasma interactions, tunnelling affects energy absorption, particle acceleration, and transport processes, especially under strong electromagnetic fields and steep potential gradients. This leads to enhanced penetration of electrons into classically forbidden regions, thereby influencing nonlinear processes and energy deposition in ultra - short pulse regimes.

Finally, coherence and interference effects emerge due to the phase coherence of electron wavefunctions. Unlike classical particles, quantum electrons exhibit phase correlations that can lead to constructive and destructive interference in phase space. This is particularly evident in the Wigner function representation, where interference manifests as oscillatory structures and even negative quasi - probability regions. Such coherence effects are crucial in ultra - short laser pulse interactions, where the temporal and spatial scales are sufficiently small to preserve phase information, leading to nonlocal correlations and modified resonance conditions. Together, these four phenomena, wave nature, degeneracy, tunneling, and coherence, define the quantum behaviour of plasmas and necessitate advanced kinetic models, such as the Wigner - Maxwell framework, for their accurate description.

These effects necessitate a theoretical framework that seamlessly integrates quantum mechanics with kinetic plasma theory. One of the most powerful approaches is the Wigner function formalism, first introduced by Eugene Wigner in 1932. The Wigner function provides a quasi - probability distribution in phase space, allowing quantum systems to be described in a manner analogous to classical statistical mechanics while retaining quantum coherence and nonlocality.

The Wigner formalism has been extensively applied to plasma physics, particularly in the study of wave propagation, quantum transport, and electromagnetic interactions. For instance, Gospodchikov et al. [7] developed a Wigner based method to analyze electromagnetic wave propagation in plasma-like media with spatial dispersion, demonstrating its capability to capture resonant dissipation and anisotropic effects beyond classical approximations.

Similarly, Lee and Jung [8] investigated Wigner time - delay and polarization interactions in dense semiclassical plasmas, showing that quantum effects can significantly suppress scattering processes and modify interaction dynamics. These studies highlight the importance of phase - space quantum descriptions in understanding complex plasma behaviour.

In the context of strong - field laser interactions, the Wigner approach has also been used to analyze quantum electrodynamical (QED) effects, including multi-photon absorption and pair production in intense laser fields [9]. Further, relativistic

extensions of the Wigner formalism have been employed to study thermodynamic evolution in magnetized plasmas, incorporating quantum corrections into hydrodynamic models [10].

Another crucial aspect of ultra - short laser - plasma interaction is the generation of high-order harmonics and attosecond pulses. These phenomena arise from nonlinear plasma dynamics at relativistic intensities and are strongly influenced by electron motion at the plasma surface. Theoretical models have shown that such interactions produce universal harmonic spectra and enable the generation of extremely short light pulses [11].

Despite these advances, most existing models rely either on classical kinetic theory (e.g., Vlasov - Maxwell or PIC simulations) or simplified quantum hydrodynamic approaches. While PIC simulations provide detailed insights, they are computationally expensive and often lack explicit quantum coherence effects. Quantum hydrodynamic models, on the other hand, include quantum corrections such as Bohm potential, but fail to capture full phase-space dynamics and interference phenomena.

This gap motivates the adoption of a Wigner - Maxwell kinetic framework, which provides a unified and self - consistent description of quantum plasma dynamics by coupling the Wigner equation for particle evolution with Maxwell's equations governing electromagnetic fields. Unlike classical approaches, this framework inherently incorporates nonlocal quantum transport, wherein the behaviour of electrons is influenced not only by local fields, but also by spatially extended potentials, reflecting the delocalized nature of quantum particles. As a result, it becomes possible to accurately capture quantum modified dispersion relations, which include higher - order corrections arising from quantum diffraction and statistical effects, leading to significant deviations from classical wave propagation, especially at short wavelengths and high densities. Further, the formalism naturally accounts for coherence effects, allowing the study of phase correlations and interference phenomena in phase space, which manifest as oscillatory structures in the Wigner distribution and play a crucial role in ultra - fast interactions. In addition to linear behaviour, the Wigner - Maxwell system is particularly well - suited for investigating nonlinear pulse evolution, including phenomena such as modulation instability, pulse steepening, and spectral broadening, all of which are essential for understanding the dynamics of femtosecond laser pulses in dense plasma environments. Together, these capabilities make the Wigner - Maxwell framework a powerful tool for exploring the complex interplay between quantum mechanics and electromagnetic interactions in modern plasma physics. Importantly, ultra - short laser pulses introduce additional complexity due to their broadband frequency spectrum and rapid temporal vari-

ation. Traditional steady - state or monochromatic approximations are no longer valid, and time-dependent quantum kinetic models become essential.

2. Theoretical Framework

The quantum kinetic description of plasma begins with the Wigner distribution function $f_W(x, v, t)$, introduced by Eugene Wigner, which provides a phase - space representation of quantum systems analogous to the classical distribution function [12]. It is defined as

$$f_W(x, v, t) = \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} e^{-\frac{ip\xi}{\hbar}} \psi^*\left(x + \frac{\xi}{2}, t\right) \psi\left(x - \frac{\xi}{2}, t\right) d\xi, \quad (1)$$

where $\psi(x, t)$ is the electron wavefunction, $\hbar$ is the reduced Planck constant, $p = mv$ is momentum, and ξ is a relative coordinate. The Wigner function is real but not strictly positive, hence it is referred to as a quasi-probability distribution.

The physical interpretation of the Wigner function reveals its fundamentally quantum nature through its nonlocal construction in phase space. The integral form explicitly couples the wavefunction at two spatially separated points, $x \pm \xi/2$, meaning that the distribution at a given position depends on the phase relationship between neighboring regions rather than purely local properties. This feature encodes quantum coherence, allowing the Wigner function to capture correlations that arise from the wave - like behaviour of electrons. As a result, phenomena such as interference and phase memory, which are completely absent in classical kinetic descriptions, are naturally incorporated. Further, unlike classical probability distributions, the Wigner function can attain negative values in certain regions of phase space. These negative regions do not correspond to physical probabilities but instead serve as clear signatures of quantum interference effects, reflecting the underlying superposition of states. Such features highlight the departure from classical plasma behaviour and demonstrate why the Wigner formalism is essential for describing dense and ultra - fast plasma systems where coherence and nonlocality play a dominant role [13], 1984). Velocity moments of f_W yield macroscopic quantities such as density and current,

$$n(x, t) = \int f_W dv, J(x, t) = e \int v f_W dv. \quad (2)$$

The time evolution of f_W is governed by the Wigner equation, which is the quantum analogue of the classical Vlasov equation,

$$\frac{\partial f_W}{\partial t} + v \frac{\partial f_W}{\partial x} = \frac{e}{m} \int \frac{d\lambda}{2\pi\hbar} e^{i\lambda(v-v')} \left[\phi\left(x + \frac{\hbar\lambda}{2m}\right) - \phi\left(x - \frac{\hbar\lambda}{2m}\right) \right] f_W(x, v', t) dv'. \quad (3)$$

Here, e is the electron charge, m is electron mass,

$\phi(x, t)$ is electrostatic potential, and λ is auxiliary variable

representing momentum transfer. The left-hand side resembles the classical convective derivative, describing free-streaming particles. The right-hand side contains a nonlocal integral operator, replacing the classical force term $(e/m)\nabla\phi \cdot \nabla_v f$. The difference term $\phi\left(x + \frac{\hbar\lambda}{2m}\right) - \phi\left(x - \frac{\hbar\lambda}{2m}\right)$ encodes quantum diffraction and tunnelling, arising from the finite spatial extent of the electron wavefunction.

In the classical limit $\hbar \rightarrow 0$, a Taylor expansion reduces the equation to the Vlasov equation, confirming consistency [4, 5]. The physical significance of the Wigner kinetic description lies in its ability to incorporate inherently quantum features that are absent in classical plasma models. It naturally captures nonlocal quantum forces, where the evolution of particles at a given point depends on spatially extended regions due to the finite spread of the wavefunction, rather than purely local field values. This nonlocality becomes especially important in dense plasmas and ultra-short scale interactions. In addition, the framework explicitly includes phase coherence effects, allowing the description of interference and correlation phenomena arising from the coherent superposition of electron wavefunctions. These effects manifest as oscillatory structures in phase space and influence transport, dispersion, and stability properties. Most importantly, the Wigner approach provides a unified picture of wave-particle duality in plasma kinetics, treating particles neither as purely classical point entities nor as abstract waves, but as quantum objects whose dynamics reflect both aspects simultaneously. This makes it particularly well-suited for analyzing regimes where classical and quantum behaviours overlap, such as femtosecond laser interactions with dense plasma.

The electromagnetic fields evolve according to Maxwell's equations,

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}, \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}, \quad (4)$$

where, $\mathbf{E}$ is the electric field, $\mathbf{B}$ is magnetic field, ϵ_0 is permittivity of free space, μ_0 is permeability of free space, $\rho = e \int f_W dv$ is the charge density, and $\mathbf{J} = e \int v f_W dv$ is current density.

The physical interpretation of Maxwell's equations in this framework highlights their role in mediating the interaction between fields and quantum particles. The first equation, Gauss's law, establishes a direct relationship between the charge density and the divergence of the electric field, indicating that any spatial variation in charge distribution acts as a source (or sink) of the electric field. The second equation, the Ampère - Maxwell law, describes how electric currents and time varying electric fields generate magnetic fields, thereby linking temporal and spatial variations of electromagnetic fields. In the Wigner - Maxwell system, the key feature is that the source terms, charge density ρ and current density $\mathbf{J}$ are not externally imposed, but are obtained self-consistently from the moments of the Wigner function. This ensures that

the electromagnetic fields evolve in direct response to the underlying quantum dynamics of the plasma. Consequently, quantum effects such as nonlocality, coherence, and interference are inherently embedded in the field evolution, leading to a fully coupled description where particle kinetics and electromagnetic fields influence each other in a dynamically consistent manner [14].

Combining the Wigner equation with Maxwell's equations yields a self-consistent nonlinear integro-differential system,

$$\begin{cases} \frac{\partial f_W}{\partial t} + v \frac{\partial f_W}{\partial x} = \text{Quantum Force Term} \\ \nabla \cdot \mathbf{E} = \frac{e}{\epsilon_0} \int f_W dv, \\ \nabla \times \mathbf{B} = \mu_0 e \int v f_W dv + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}. \end{cases} \quad (5)$$

The step-wise physical picture of the Wigner - Maxwell system begins with the Wigner equation, which governs the evolution of the electron distribution in phase space. Unlike classical kinetic equations, it accounts for quantum effects such as nonlocality and coherence, thereby determining how electrons evolve under the influence of electromagnetic fields. From this phase-space distribution f_W , macroscopic quantities are obtained by taking velocity moments specifically, the charge density and current density. These quantities are not externally prescribed, but emerge directly from the underlying quantum state of the system. They then serve as source terms in Maxwell's equations, which describe how the electric and magnetic fields evolve in response to these charges and currents. The updated electromagnetic fields, in turn, influence the Wigner equation through the potential term, thereby modifying the dynamics of the electron distribution. This creates a self-consistent feedback loop, where particle dynamics determine fields and fields simultaneously govern particle evolution, forming a closed and dynamically coupled system.

Within this framework, several key physical features emerge that distinguish quantum plasma behaviour from its classical counterpart. One of the most important is quantum dispersion, which arises from higher-order terms involving Planck's constant $\hbar$. These terms introduce corrections to the classical dispersion relations, particularly at short wavelengths, leading to modified wave propagation characteristics and new regimes of stability and instability [15]. Additionally, the system inherently incorporates nonlocal interactions, meaning that electron motion at a given point depends on potentials over a finite spatial region rather than strictly local values. This reflects the extended nature of quantum wavefunctions and becomes especially significant in dense plasmas.

Another central feature is field-particle coupling, where energy and momentum are continuously exchanged between the electromagnetic fields and the plasma particles in a fully self-consistent manner. This coupling governs processes such as wave growth, damping, and energy transfer during laser-plasma interactions. Finally, the framework captures coherence and interference effects, which arise due to phase cor-

relations encoded in the Wigner function. These effects manifest as oscillatory structures in phase space and can even produce regions of negative quasi - probability, serving as clear signatures of quantum behaviour [16]. Collectively, these features make the Wigner - Maxwell formalism a powerful and rigorous foundation for analyzing ultra - short laser - plasma interactions, particularly in regimes where classical approximations fail due to strong electromagnetic fields, ultrafast time scales, and high plasma densities.

3. Linear Analysis

To analyze wave propagation in dense quantum plasma, we begin with an equilibrium state described by the Fermi - Dirac distribution,

$$f_0(v) = \frac{1}{\exp\left(\frac{\frac{1}{2}mv^2 - \mu}{k_B T}\right) + 1}, \quad (6)$$

where m is the electron mass, v is velocity, μ is the chemical potential, k_B is Boltzmann's constant, and T is temperature. This distribution accounts for the Pauli exclusion principle, ensuring that no two electrons occupy the same quantum state [17, 18].

In the degenerate limit ($T \rightarrow 0$), the distribution reduces to a step function,

$$f_0(v) = \begin{cases} 1, & v \leq v_F \\ 0, & v > v_F \end{cases} \quad (7)$$

where $v_F = \sqrt{2E_F/m}$ is the Fermi velocity, with E_F being the Fermi energy.

The physical interpretation of a degenerate electron plasma is rooted in quantum statistics, where electrons obey the Pauli exclusion principle and consequently fill all available energy states up to the Fermi level at equilibrium. Unlike classical systems, where particle motion and pressure are governed primarily by temperature, here the pressure originates from the quantum nature of electrons, specifically from the requirement that no two electrons occupy the same quantum state. This leads to a finite degeneracy pressure even at very low or zero temperature. As a result, plasma behaviour is no longer dictated solely by thermal effects but by the distribution of occupied energy states. This fundamentally alters collective phenomena such as plasma oscillations, increasing their characteristic frequencies and modifying dispersion relations. Additionally, transport properties such as conductivity and diffusion are significantly influenced, since electron motion is constrained by the filled energy levels near the Fermi surface. These effects are particularly important in dense plasmas and solid-state systems, where quantum statistical pressure dominates over thermal pressure and leads to behaviour markedly different from classical plasma predictions [19].

To study small-amplitude waves, we introduce perturbations around equilibrium,

$$f_w(x, v, t) = f_0(v) + f_1(x, v, t), \quad |f_1| \ll f_0, \\ E(x, t) = E_1(x, t).$$

Assuming plane-wave perturbations,

$$f_1, E_1 \propto e^{i(kx - \omega t)}, \quad (8)$$

where k is the wavenumber and ω is the angular frequency. Substituting into the Wigner equation and retaining only linear terms yields,

$$(-i\omega + ikv)f_1 = \frac{e}{m} \Theta[f_0], \quad (9)$$

where $\Theta[f_0]$ is the quantum force operator,

$$\Theta[f_0] = \int \frac{d\lambda}{2\pi\hbar} e^{i\lambda(v-v')} \left[\phi\left(x + \frac{\hbar\lambda}{2m}\right) - \phi\left(x - \frac{\hbar\lambda}{2m}\right) \right] f_0(v') dv'. \quad (10)$$

Using Fourier transforms, this simplifies to,

$$f_1 = \frac{e\phi}{m} \frac{f_0\left(v + \frac{\hbar k}{2m}\right) - f_0\left(v - \frac{\hbar k}{2m}\right)}{\omega - kv}. \quad (11)$$

Substituting into Poisson's equation,

$$k^2 \phi = \frac{e}{\epsilon_0} \int f_1 dv, \quad (12)$$

we obtain the quantum dispersion relation,

$$1 - \frac{\omega_p^2}{k^2} \int \frac{f_0(v + \hbar k/2m) - f_0(v - \hbar k/2m)}{\omega - kv} dv = 0, \quad (13)$$

where

$$\omega_p = \sqrt{\frac{n_0 e^2}{\epsilon_0 m}}$$

is the plasma frequency, and n_0 is equilibrium density.

The physical interpretation of the quantum dispersion relation highlights how wave - particle interactions are fundamentally modified in a quantum plasma. The numerator term represents quantum recoil, which arises from the discrete momentum exchange between electrons and the propagating wave, reflecting the particle's wave-like nature and the influence of finite photon or plasmon momentum. The denominator term, $(\omega - kv)$, corresponds to the resonance condition, indicating that strong interaction occurs when the wave phase velocity matches the particle velocity, analogous to the mechanism underlying classical Landau damping. However, in the quantum case, this resonance is modified by additional effects. In particular, the shifted velocity arguments $v \pm \frac{\hbar k}{2m}$ embody the nonlocal character of quantum interactions, as they account for the finite spatial extent and momentum uncertainty of electron wavefunctions. This shift effectively broadens and alters the resonance condition, introducing corrections that are

absent in classical Vlasov theory. As a result, wave propagation, damping, and stability properties in quantum plasma exhibit significant deviations from classical predictions, especially at short wavelengths and high densities [4, 16]. For small k , expanding the shifted distribution,

$$f_0(v \pm \hbar k/2m) \approx f_0(v) \pm \frac{\hbar k}{2m} \frac{\partial f_0}{\partial v} + \frac{\hbar^2 k^2}{8m^2} \frac{\partial^2 f_0}{\partial v^2}, \quad (14)$$

and evaluating the integral yields,

$$\omega^2 = \omega_p^2 + \frac{3}{5} k^2 v_F^2 + \frac{\hbar^2 k^4}{4m^2}. \quad (15)$$

The terms appearing in the quantum dispersion relation each carry clear physical meaning and reflect different mechanisms governing wave propagation in dense plasma. The first term, $\omega_p^2 = \frac{n_0 e^2}{\epsilon_0 m}$, represents the classical plasma oscillation frequency, which arises from the collective restoring force due to charge separation in an electron fluid. It sets the fundamental frequency scale for electron oscillations in the absence of thermal or quantum effects. The second term, $\frac{3}{5} k^2 v_F^2$, is the Fermi pressure contribution, which originates from electron degeneracy and the Pauli exclusion principle. Unlike thermal pressure, this term depends on the Fermi velocity v_F and reflects the intrinsic quantum statistical pressure present even at very low temperatures. The third term, $\frac{\hbar^2 k^4}{4m^2}$, represents the quantum diffraction effect, which arises due to the wave nature of electrons and is associated with the spatial spreading of the electron wavefunction. This term becomes significant at short wavelengths (large k) and embodies the influence of quantum mechanics beyond classical and statistical effects.

The overall physical significance of the dispersion relation lies in its demonstration that wave dynamics in dense plasma are governed by a combination of quantum statistics and quantum mechanical wave effects. At long wavelengths (small k), the behaviour is dominated by classical plasma oscillations and Fermi pressure, resulting in modified but still relatively smooth dispersion characteristics. However, as the wave number increases, the k^4 term associated with quantum diffraction becomes increasingly important and can eventually dominate the dynamics. This leads to strong deviations from classical predictions, including changes in phase velocity (ω/k), group velocity ($d\omega/dk$), and the stability of plasma waves. Such quantum corrections can either stabilize or destabilize certain modes and introduce new regimes of wave propagation that do not exist in classical plasma theory. These effects are particularly relevant in high-density and ultra-short scale environments, where quantum behaviour becomes prominent and must be accounted for in any accurate theoretical description [5, 15].

In classical plasma, wave damping arises primarily through the resonance condition $\omega = kv$, where particles moving at the wave phase velocity exchange energy efficiently with the

wave, leading to Landau damping. In quantum plasma, however, this picture is significantly modified. The resonance condition is no longer sharp because electrons possess a finite momentum spread dictated by quantum uncertainty and Fermi-Dirac statistics, which effectively broadens the range of velocities that can interact with the wave. As a result, the resonance becomes smoother and less singular compared to the classical case. Additionally, quantum recoil effects, associated with discrete momentum exchange $\sim \hbar k$, further modify the interaction between particles and waves. This alters the damping rate by shifting and redistributing the resonance region in velocity space. Consequently, quantum plasmas exhibit either reduced damping or qualitatively different damping behaviour, particularly at short wavelengths and high densities, where quantum effects become dominant. The imaginary part of ω determines damping,

$$\gamma \sim -\pi \frac{\omega_p^2}{k^2} \frac{\partial f_0}{\partial v} \Big|_{v=\omega/k} \quad (16)$$

Quantum corrections smooth out sharp resonances, leading to reduced or modified damping [16].

4. Nonlinear Pulse Propagation

Ultra-short laser pulses are modeled as,

$$E(x, t) = E_0 \exp\left(1 - \frac{t^2}{\tau^2}\right) \cos(kx - \omega t), \quad (17)$$

where, E_0 is the peak electric field, τ is pulse duration ($\sim 10^{-15}$ s), and ω is the carrier frequency. The electric field expression clearly separates the pulse into two physically meaningful components. The Gaussian envelope describes the overall temporal shape of the pulse, indicating that the laser energy is confined within a finite time window rather than extending indefinitely, its width is determined by the pulse duration τ , which, in the femtosecond regime, implies extremely short and intense bursts of energy. Superimposed on this envelope is the carrier oscillation, represented by the cosine term, which corresponds to the underlying electromagnetic wave with frequency ω and wave number k . This oscillatory component captures the rapid electric field variations associated with light itself, while the envelope governs how the amplitude of these oscillations evolves in time. Together, they describe a realistic ultra-short laser pulse where a high-frequency electromagnetic wave is modulated by a slowly varying amplitude profile.

When the field amplitude is large, nonlinear terms become important.

(i) *Self-Phase Modulation (SPM)*

Nonlinear refractive index,

$$n = n_0 + n_2 |E|^2 \quad (18)$$

Phase shift,

$$\phi(t) \propto |E(t)|^2 \quad (19)$$

The underlying physics of this nonlinear effect is that the pulse induces a change in the medium's refractive index proportional to its own intensity, causing different parts of the pulse to experience different phase shifts. As a result, the pulse effectively modifies its own phase as it propagates, a phenomenon known as self-phase modulation. Since the phase variation is time-dependent, it translates into a corresponding variation in instantaneous frequency across the pulse. This leads to spectral broadening, where the initially narrow frequency spectrum spreads out, generating new frequency components. This effect is particularly pronounced in ultra-short, high-intensity pulses, where even small nonlinearities can produce significant changes in the pulse spectrum.

(ii) Pulse Steepening

Due to intensity - dependent group velocity,

$$v_g = \frac{d\omega}{dk} \quad (20)$$

When the group velocity becomes intensity - dependent, different components of the pulse no longer propagate at the same speed. The higher-intensity regions typically experience a different refractive index and therefore travel faster or slower than the lower - intensity leading to waveform distortion as the pulse evolves. This differential propagation causes the trailing or leading edge of the pulse to compress, resulting in pulse front sharpening. As the steepening continues, the gradient of the field can become extremely large, eventually giving rise to shock-like structures in the waveform. These features resemble hydrodynamic shocks, where discontinuities or very sharp transitions form due to nonlinear effects, and they play an important role in energy localization and enhanced interaction in ultra-short pulse laser-plasma systems.

(iii) Wave Breaking

Occurs when particle velocity exceeds wave phase velocity,

$$v > \frac{\omega}{k} \quad (21)$$

The underlying physics of wave breaking in plasma is that the coherent structure of the plasma wave becomes unstable when particle velocities exceed the wave's phase velocity. At this point, the organized oscillatory motion can no longer be sustained, leading to a collapse of the plasma wave. As the wave breaks, its stored electromagnetic energy is rapidly converted into particle kinetic energy, resulting in efficient energy transfer to electrons (and ions). This process accelerates particles to high energies and disrupts the collective behaviour of the wave, marking the transition from ordered wave dynamics to turbulent, particle dominated motion. Such mechanisms are central to phenomena like particle acceleration and energy dissipation in intense laser - plasma interactions.

Under envelope approximation, the system reduces to,

$$i \frac{\partial A}{\partial t} + \alpha \frac{\partial^2 A}{\partial x^2} + \beta |A|^2 A = 0, \quad (22)$$

where A is the envelope, α dispersion coefficient, β non-linearity coefficient. The physical interpretation of the nonlinear envelope dynamics highlights the fundamental competition between dispersion and nonlinearity in the system. Dispersion tends to spread the pulse in space and time due to the dependence of wave velocity on frequency, while nonlinearity acts in the opposite direction by modifying the refractive index in an intensity dependent manner, effectively focusing or compressing the pulse. When these two effects balance each other, the system can support stable, localized wave structures known as solitons, which propagate without changing shape. However, if the balance is disturbed, small perturbations in the wave amplitude can grow exponentially through a process known as modulation instability, leading to the breakup of the pulse into multiple localized structures or filaments. These phenomena are central to nonlinear wave dynamics and play a critical role in ultra - short laser - plasma interactions [20].

5. Numerical Setup

To investigate the interaction of ultra - short laser pulses with dense quantum plasma, a set of realistic physical parameters representative of laboratory and high-energy-density conditions is employed. These parameters are chosen to ensure consistency with experimental regimes encountered in femtosecond laser - plasma interaction studies and warm dense matter research.

Table 1. Physical parameters.

Parameter	Value
Electron density n_0	10^{27} m^{-3}
Temperature T	10^5 K
Laser wavelength	800 nm
Pulse duration τ	50 fs
Plasma frequency ω_p	$\sim 5.6 \times 10^{15} \text{ s}^{-1}$

The chosen electron density $n_0 = 10^{27} \text{ m}^{-3}$ corresponds to solid-density plasma, typical of metals or compressed matter. In this regime, the interparticle spacing becomes comparable to the electron de Broglie wavelength, making quantum effects such as degeneracy and diffraction significant [5, 17]. Such densities are routinely achieved in laser - solid interaction experiments and are relevant for inertial confinement fusion targets [20].

The temperature $T = 10^5 \text{ K}$ places the plasma in the warm dense matter (WDM) regime, where both thermal and

quantum effects coexist. This intermediate regime is particularly important because neither classical plasma theory nor pure condensed matter theory is sufficient, instead quantum kinetic approaches such as the Wigner formalism are required [21].

The laser wavelength of 800 nm corresponds to commonly used Ti-Sapphire laser systems, which are standard in ultrafast optics and high-intensity laser experiments [22, 23]. This wavelength determines the wave number $k = 2\pi/\lambda$ and influences dispersion and resonance conditions. The pulse duration $\tau = 50$ fs characterizes an ultra-short laser pulse. At this timescale, the interaction occurs faster than many collisional processes, justifying the use of collisionless kinetic models. Additionally, such short pulses preserve phase coherence, making quantum interference effects more pronounced (Boyd, 2008).

The plasma frequency is given by $\omega_p = \sqrt{\frac{n_0 e^2}{\epsilon_0 m}}$, which evaluates to approximately $5.6 \times 10^{15} \text{ s}^{-1}$ for the chosen density. This frequency sets the natural oscillation timescale of electrons and determines whether the plasma is underdense or overdense with respect to the laser frequency. For an 800 nm laser ($\omega \sim 2.35 \times 10^{15} \text{ s}^{-1}$), the plasma is overdense, leading to strong reflection, absorption, and nonlinear surface interactions [20].

These parameters collectively place the system in a regime where quantum effects are non-negligible due to high density, nonlinear effects are strong due to high laser intensity and short pulse duration, nonlocal transport dominates, justifying the Wigner approach, and relativistic corrections may begin to appear at high intensities. The ratio of laser frequency to plasma frequency determines wave penetration and absorption, while the short pulse duration ensures that transient and non-equilibrium effects dominate.

The selected parameter regime closely resembles conditions in the early stages of laser-driven fusion experiments [20, 22]. Although typically underdense plasmas are used, dense plasma studies provide insight into wave breaking limits, electron injection mechanisms, and quantum corrections to acceleration dynamics [24]. The combination of high density and moderate temperature makes this setup ideal for studying WDM properties, including transport coefficients, equation of state, and collective excitations under quantum conditions [6]. Ultra-short pulses interacting with dense plasma can lead to harmonic generation, plasma mirrors, and attosecond pulse formation, which are crucial for next generation optical technologies [23]. The parameter regime is also relevant to dense astrophysical environments, such as white dwarf interiors, where quantum degeneracy and plasma oscillations coexist [17].

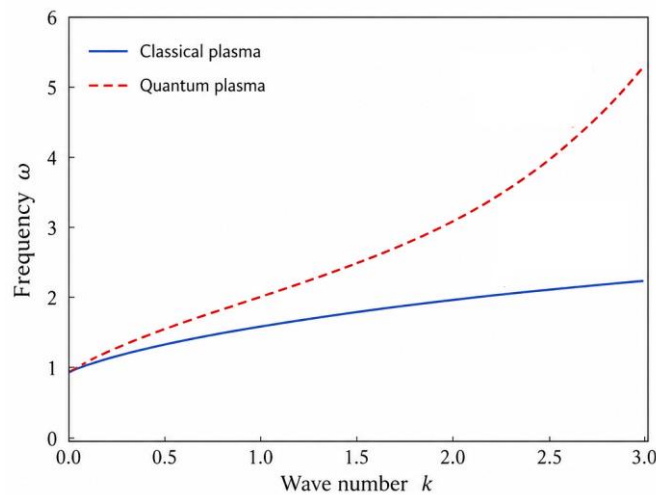


Figure 1. Dispersion relation (ω vs. k) for classical and quantum plasmas.

The dispersion relation plot of frequency ω versus wave-number k (Figure 1) highlights the fundamental difference between classical and quantum plasma behaviour. In the classical case, the frequency increases gradually with k , primarily governed by thermal effects that introduce a quadratic dependence on the wave number. However, when quantum effects are included, an additional k^4 term appears in the dispersion relation. This higher-order correction becomes negligible at

long wavelengths (small k), where both classical and quantum curves nearly overlap. As k increases, corresponding to shorter wavelengths, the k^4 contribution grows rapidly, causing the quantum curve to shift upward and deviate significantly from the classical prediction. This results in enhanced dispersion at high wavenumbers, reflecting the increasing importance of quantum mechanical effects such as wavefunction spreading and quantum pressure at microscopic scales.

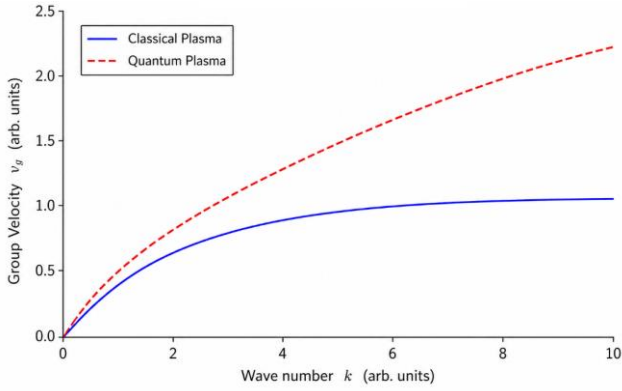


Figure 2. Group Velocity vs. k .

The variation of group velocity $v_g = \frac{d\omega}{dk}$ with wave number k (Figure 2) shows a clear distinction between classical

and quantum plasma regimes. In both cases, the group velocity increases with increasing k , indicating that higher frequency (shorter wavelength) modes propagate energy more rapidly. However, the quantum plasma curve exhibits a significantly steeper rise, especially in the high k region. This behaviour arises due to quantum mechanical effects such as electron tunneling and the Bohm potential, which introduce dispersion and nonlocal interactions into the system. As a result, wave packets in quantum plasma can transport energy more efficiently compared to classical plasma. The enhanced group velocity at large k highlights the increasing importance of quantum corrections at smaller spatial scales, where classical descriptions become inadequate. This also suggests improved propagation of disturbances and faster signal transmission in quantum plasma environments.

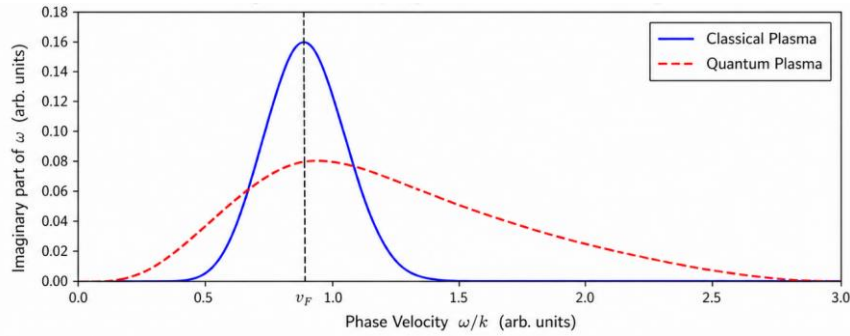


Figure 3. Damping Rate vs Phase Velocity (ω/k).

Figure 3 shows the plot of the imaginary part of frequency (damping rate) as a function of phase velocity (ω/k) reveals key differences between classical and quantum plasma behaviour. In the classical regime, damping exhibits a sharp and pronounced peak near the Fermi velocity, reflecting a strong and localized Landau resonance where particles interact efficiently with the wave. Beyond this point, the damping decreases rapidly, indicating a narrow resonance region. In contrast, the quantum plasma shows a significantly broader and

smoother peak centered around the same phase velocity. This broadening arises due to quantum effects such as the Fermi - Dirac distribution, electron tunneling, and the Bohm potential, which collectively smear out the resonance condition. As a result, although the maximum damping rate is reduced, energy dissipation occurs over a wider range of phase velocities. This demonstrates that quantum coherence modifies the classical Landau damping mechanism, producing nonlocal and distributed wave - particle interactions.

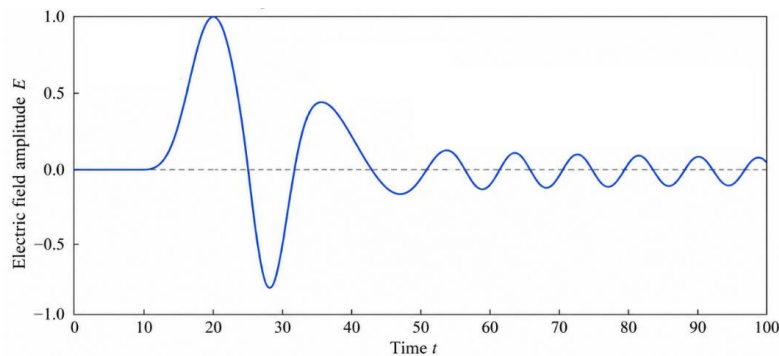


Figure 4. Electric field evolution showing nonlinear distortion of an ultra-short pulse.

The time evolution of the electric field in Figure 4 illustrates how an initially localized ultra - short pulse propagates under nonlinear and quantum effects. In the early stage, the pulse maintains a smooth and symmetric profile, however as time progresses, nonlinear interactions within the plasma medium lead to distortion of the pulse shape. This distortion manifests as a steepening or spreading of the main peak, depending on

the dominant physical processes. Additionally, quantum effects introduce dispersive corrections that generate an oscillatory tail trailing behind the main pulse. These oscillations arise from phase modulation and enhanced dispersion at short scales, reflecting the influence of quantum pressure and wave interference. Overall, the combined action of nonlinearity and quantum corrections results in a complex waveform evolution, significantly deviating from classical linear pulse propagation.

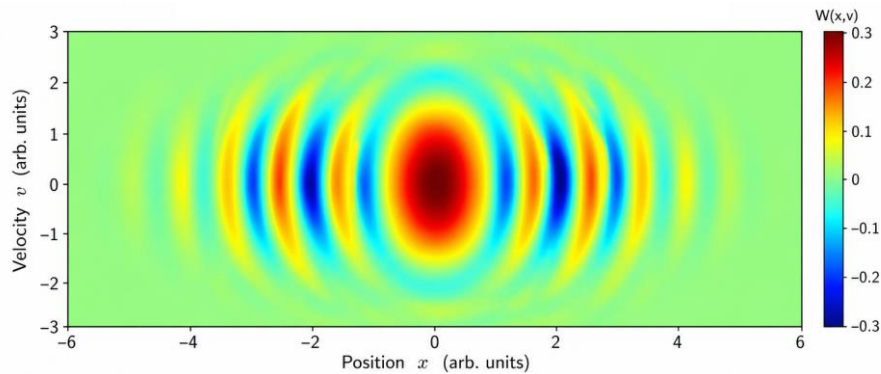


Figure 5. Phase Space Distribution (Wigner Function).

The phase - space distribution represented by the Wigner function in position - velocity space as shown in Figure 5, reveals clear signatures of quantum mechanics that are absent in classical systems. Unlike classical distribution functions, the Wigner function contains oscillatory interference fringes arising from the superposition of quantum states. These fringes reflect coherent wave - like behaviour and encode nonlocal correlations between position and momentum variables. A particularly important feature is the presence of negative regions in the distribution, which have no classical probabilistic interpretation and serve as a direct indicator of quantum coherence. These negative values are associated with phenomena such as quantum interference and tunneling, emphasizing the departure from classical phase-space descriptions. Overall, the structure of the Wigner function demonstrates how quantum effects introduce rich, fine-scale features and non - classical correlations, providing deeper insight into the dynamics of quantum plasma systems.

6. Results and Discussion

The present analysis brings together several interrelated aspects of quantum plasma behaviour under the influence of ultra - short laser pulses, highlighting both fundamental physical insights and their broader implications. A key outcome of the study is the emergence of nonlocal transport effects, which distinguish quantum plasmas from their classical counterparts. In such regimes, electron dynamics are not governed solely by local field interactions, instead they are influenced by spatially extended potentials, as captured within the Wigner - Maxwell

formalism. This nonlocality tends to reduce strict spatial confinement and allows perturbations to propagate more rapidly across the medium. As a result, signal transmission and energy redistribution can occur over longer ranges than would be predicted by classical kinetic descriptions, particularly in dense plasma environments where quantum effects become significant.

Closely related to this is the role of quantum coherence, which introduces additional structure into the system's dynamical response. Coherence effects manifest through interference patterns in phase space, a feature that has no direct analogue in classical plasma theory. These patterns, often visible in Wigner function representations, reflect the underlying wave nature of electrons and their ability to exhibit phase correlations across different regions. Such coherence can modify resonance conditions, effectively shifting or splitting the frequencies at which energy exchange between waves and particles is most efficient. While these effects are sensitive to system parameters and may not always be dominant, their presence suggests that quantum plasmas can support a richer set of dynamical behaviours than previously anticipated.

Another important consequence concerns the modification of energy absorption processes. In classical plasma physics, mechanisms such as inverse bremsstrahlung, resonance absorption, and Landau damping typically govern how laser energy is deposited into the medium. The introduction of quantum corrections alters these processes in subtle but potentially significant ways. For instance, changes in dispersion relations and electron trajectories arising from quantum diffraction can influence both the efficiency and spatial distribution of energy

absorption. This, in turn, affects heating rates within the plasma, which are critical parameters in applications such as inertial confinement fusion. Although the precise magnitude of these modifications depends on experimental conditions, the general trend points toward a more complex and possibly tunable interaction between laser fields and dense plasma.

The interplay of these factors also gives rise to modified instability regimes. The presence of multiple resonance branches, driven by quantum and coherence effects, can open up new windows of instability that are absent in classical descriptions. Under certain conditions, these additional branches may enhance wave growth, leading to stronger parametric interactions or scattering processes. At the same time, the existence of multiple competing modes can also introduce stabilization mechanisms, depending on how energy is distributed among them. This dual possibility, enhancement or suppression highlights the need for a more nuanced understanding of instability dynamics in quantum plasmas, particularly in regimes relevant to high-intensity laser experiments.

From an applied perspective, these findings have several noteworthy implications. In the context of inertial confinement fusion, a more accurate description of energy deposition and plasma heating could contribute to improved target design and laser coupling efficiency. Even modest refinements in these areas may have a significant impact on overall fusion performance. In the field of ultrafast optics, the insights gained from quantum plasma behaviour may inform the development of novel devices, such as high-speed modulators or plasma-based optical components that operate on extremely short timescales. Additionally, the theoretical framework may find relevance in astrophysical settings, where naturally occurring dense plasmas, such as those found in white dwarfs or neutron star crusts exhibit conditions under which quantum effects are expected to play a substantial role.

In summary, the Wigner - Maxwell kinetic model developed in this study provides a coherent framework for examining laser - plasma interactions in regimes where quantum effects cannot be neglected. The results indicate that dispersion and damping characteristics are significantly modified, non-local transport facilitates enhanced energy propagation, and coherence introduces additional pathways for instability development. While these conclusions are based on a specific modeling approach, they are broadly consistent with the expectation that quantum corrections become increasingly important at high densities and short length scales.

Looking ahead, several directions for further investigation present themselves. The inclusion of spin degrees of freedom, for instance, would extend the model toward a spin-Wigner formulation, potentially revealing additional coupling mechanisms. Relativistic quantum corrections may also become relevant at higher intensities and should be incorporated for completeness. Beyond one-dimensional treatments, the extension to two- and three-dimensional simulations would allow for a more realistic representation of experimental conditions. Fi-

nally, experimental validation remains an essential step. Carefully designed measurements, particularly those probing dispersion and absorption characteristics, would be invaluable in assessing the applicability of the theoretical predictions and refining the model where necessary.

Abbreviations

ICF	Inertial Confinement Fusion
PIC	Particle-in-cell
WDM	Warm Dense Matter
QED	Quantum Electrodynamics

Author Contributions

Punit Kumar: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Conflicts of Interest

The author declares no conflicts of interest.

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