Chapter 1
Wakefield Formation Due to a Short Electron Beam in Quantum Nanowires:
Plasma Oscillations with Quantum Effects

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ABSTRACT

The basic properties of classical and quantum plasmas are discussed. Quantum plasmas behave differently due to high densities and low temperatures at nanometer scale in contrast to classical ones which are characterized by low densities and high temperatures. A literature survey is made to investigate the plasma phenomenon with quantum mechanical effects. Classical and quantum viewpoints are also presented to understand the free electron gas in metals. In particular, the excitation of stable plasmon wakefield is studied due to a short electron pulse propagating in axial direction of nanowire. The latter contains degenerate electrons and classical static ions. By using the Trivelpiece-Gould configuration and Fourier transform techniques, a general dispersion is obtained for the electrostatic plasmons and analyzed numerically. Nevertheless, an evolution equation for the wakefield is derived and carried out the stability analysis. In a gold nanowire, the amplitudes of wakefield become significantly modified by the variation of quantum diffraction, quantum exchange-correlations and mode quantization in the radial direction. The present findings may prove useful for investigating new radiation sources in the extreme-ultraviolet range.

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FUNDAMENTALS OF PLASMAS AND NANOSTRUCTURES

Classical plasmas are low-density and high-temperature plasmas, occur in many laboratory and space environments, e.g., plasmas in glow discharges and laser laboratories, in industrial processing plants and tokamaks, in magnetosphere, in ionosphere, in solar wind, in stellar interiors, in interstellar medium, etc. An ionized gas can be treated as *classical plasma* (Chen, 1984) if it holds certain criteria that impose specific conditions. These conditions not only rely on the high-temperature and low-particle density but also on the characteristic Debye length for maintaining the quasi-neutrality and collective behavior of plasma particles. First, the plasma must be a *quasi-neutral gas* on the global scale such that the dimension of a plasma system should be much larger than the characteristic Debye length, viz., $L \gg \lambda_D$, otherwise, the shielding phenomenon microscopically becomes ineffective and there would be just an ionized gas rather than a plasma gas. An immobile positive test charge in a plasma attracts electrons and gives rise to the formation of Debye-Hückel potential, i.e., $\phi_{DH} = \frac{q_T}{R}\exp\left(-R / \lambda_D\right)$, where q_T is the charge of the test particle, R is the distance of test charge from an observation point and $\lambda_D = \left(\varepsilon_0 k_B T / N_0 e^2\right)^{1/2}$ is the Debye shielding length. It is important here to note that for a distance much smaller than the Debye length, the potential is reduced to Coulomb potential while in opposite case, the potential decreases exponentially with the distance from the test charge. Second, it is the Debye shielding length, which basically characterizes a length scale at which the thermal particle energy is balanced with the electrostatic potential energy, helping us to determine the Debye sphere containing large number of plasma particles, viz., $N_D = \left(\frac{4\pi}{3} N_0 \lambda_D^3\right) >> 1$. This further implies that a plasma is generally dominated by long-range collective interactions or forces that prevail over the short-range individual interactions (i.e., the binary interactions or collisions). If this condition violates, the plasma will simply correspond to *strongly coupled state*, which behaves differently from a conventional plasma state. Third, the collisional time between the charged particles and neutrals must be larger than the inverse of plasma oscillation frequency, viz., $\tau_{en} >> \omega_p^{-1}$.

To understand the physics of a collective phenomenon that involves a plasma oscillation frequency, we zoom out a small portion of the plasma gas, as shown in Figure 1. Observe that an electric field is established if we slightly displace the electrons from their mean positions, where ions are fixed, providing a neutralized plasma background. Let's say the displacement of electrons is along the x-axis and these electrons are literally come back towards the ions due to their restoring force