Interaction of Intense Lasers with Plasmas

by

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Submitted to the Department of Physics
on January 23, 1995, in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy in Physics

Abstract

This thesis addresses two important topics in nonlinear laser plasma physics: the interaction of intense lasers with a non thermal homogeneous plasma, the excitation of laser wakefields in hollow plasma channels, and the stability of channel guided propagation of laser pulses.

In the first half of this thesis a new theoretical approach to the nonlinear interaction of intense laser pulses with underdense plasmas is developed. Unlike previous treatments, this theory is three-dimensional, relativistically covariant, and does not assume that $a \ll 1$, where $a = eA/mc^2$ is a dimensionless vector potential. This formalism borrows the diagrammatic techniques from quantum field theory, yet remains classical. This classical field theory, which treats cold plasma as a relativistic field interacting with the electromagnetic fields, introduces an artificial length scale which is smaller than any physically relevant spatial scale. By adopting a special (Arnowitt-Fickler) gauge, electromagnetic waves in a cold relativistic plasma are separated into "photons and "plasmons which are the relativistic extensions of electrostatic and electromagnetic waves in a cold stationary plasma.

The field-theoretical formalism is applied to a variety of nonlinear problems including harmonic generation, parametric instabilities, and nonlinear corrections to the index of refraction. For the first time the rate of the second harmonic emission from a homogeneous plasma is calculated and its dependence on the polarization of the incident radiation is studied. An experimental check of this calculation is suggested, based on the predicted non-linear polarization rotation (the second harmonic is emitted polarized perpendicularly to polarization of the incident signal). The concept of renormalization is applied to the plasma and electromagnetic radiation (photons and plasmons). To the lowest order, this corresponds to relativistically correcting the electron mass for its oscillation in an intense EM field and to replacing the vacuum dispersion relation by the usual relativistic plasma dispersion relation. This renormalization procedure is then carried to higher order in $\epsilon = \omega_2^2a^2/[(1 + a^2/2)^{3/2}\omega^2]$. This yields the nonlinear modification of the index of refraction of a strong electromagnetic wave and the dispersion of a weak probe in the presence of the wave.

In the second part of this thesis the stability of short laser pulses propagating
through parabolic channels and the wake excitation of hollow plasma channels are studied. The stability of a channel guided short laser pulse propagation is analyzed for the first time. Perturbations to the laser pulse are shown to modify the ponderomotive pressure, which distorts the dielectric properties of the plasma channel. The channel perturbation then further distorts the laser pulse. A set of coupled mode equations is derived, and a matrix dispersion relation is obtained analytically. As an example, the spacio-temporal growth of a pure dipole perturbation is evaluated in various parameter regimes. A mechanism for suppressing the instability, analogous to BNS damping in linear accelerators, is proposed and evaluated analytically and numerically.

The ponderomotive excitation of wakefields in a hollow plasma channel by an intense laser pulse is studied analytically. We demonstrate that the laser excites an accelerating mode in the channel. This mode has a higher degree of transverse uniformity than could be realized by the same laser pulse in a homogeneous plasma, making it more desirable for the acceleration of a high quality beam. A convolution equation for the excitation of this mode is found. For the first time the modifications to the mode due to finite thickness of the channel walls are derived and the interaction of the mode with inhomogeneous plasma inside the channel wall is analyzed. An important finding is that the resonant absorption in the channel wall dissipates the accelerating wake, thereby introducing a finite quality factor of the hollow plasma channel and reducing the number of electron bunches that can be accelerated in the wake of a single laser pulse.

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