Laser and plasma wave evolution in laser-plasma-based accelerators

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The interaction of an intense, short-pulse laser propagating in an underdense plasma is of fundamental interest in plasma physics with applications to fast ignition fusion, harmonic generation, x-ray lasers, and laser-plasma accelerator concepts. The electron plasma wave ponderomotively-driven by an intense laser pulse supports large electric fields (several orders of magnitude greater than conventional accelerators) with relativistic phase velocities and can be used to efficiently accelerate charged particles. Such laser-driven plasma-based accelerators [1] have attracted considerable attention as compact sources of high-brightness electron beams for light source and collider applications.

The energy gain in a single stage of a laser-plasma accelerator can be limited by the laser-plasma or beam-plasma interaction lengths. For typical laser-plasma parameters, diffraction is the most severe limitation, and limits the interaction length to on the order of a few laser Rayleigh ranges. This limitation can be overcome through a combination of preformed plasma channel guiding, relativistic self-focusing, and ponderomotive self-channeling. With diffraction overcome by laser guiding, the beam energy gain in the plasma wave can be limited by slippage between the beam position and the phase of the plasma wave. The slippage results from the difference between the beam velocity and the plasma wave phase velocity and is referred to as electron dephasing. The dephasing limitation may be overcome by spatially tailoring the plasma density (i.e., plasma tapering). In the weakly-relativistic regime, the exact density variation required to phase-lock the electron beam to the phase of the accelerating and/or focusing forces may be derived [2]. Laser, and consequently plasma wave, evolution will ultimately limit the single-stage energy gain in a laser-plasma accelerator, and a fundamental limit to the laser propagation distance is the transfer of laser energy into the plasma wave (i.e., laser energy depletion) [3].

In this talk we examine the evolution of a short-pulse (duration resonant with plasma frequency), intense ($>10^{18}$ W/cm^2, such that the electron quiver velocity becomes relativistic) laser propagating in an underdense plasma. Typically, the evolution of a resonant laser pulse proceeds in two phases. In the first phase, the pulse steepens, compresses, and frequency red-shifts as energy is deposited in the plasma. The second phase of evolution occurs after the pulse reaches a minimum length at which point the pulse rapidly lengthens, losing resonance with the plasma. Expressions for the rate of laser energy loss, rate of pulse steepening and compression, and rate of laser frequency red-shifting are derived and are found to be in excellent agreement with the direct numerical solution of the laser field evolution coupled to the plasma response. These processes are shown to have the same characteristic length-scale (pump depletion length). An analytic expression for the nonlinear pump depletion length for a nearly-resonant Gaussian pulse is derived, and, in the high intensity limit, this scale length is shown to be independent of laser intensity. The resulting evolution of the nonlinear plasma wave amplitude is also derived and found to be in excellent agreement with numerical solutions.

The plasma wave phase velocity determines the slippage between the beam and the plasma wave and therefore the energy gain. In the weakly-relativistic regime, the phase velocity is approximately the group velocity of the laser pulse. In this talk, we investigate the nonlinear velocity of the laser propagating in an underdense plasma. We present expressions for the nonlinear group velocity and intensity transport velocity. Expressions for the nonlinear plasma wave phase velocity, which contains contributions from the laser propagation velocity and laser evolution, are also derived and found to be in agreement with numerical solutions of the coupled laser and plasma response.

Implications of the laser and plasma wave evolution on the design of a 10 GeV laser-driven plasma-based accelerator will be discussed.

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