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Energetic Particle Production, Caviton Formation,
and Nonlinear Development at a Plasma Density Maximum

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Energetic Particle Production, Caviton Formation, and Nonlinear Development at a Plasma Density Maximum

Abstract

We have investigated several phenomena of importance to laser-plasma interactions. In our studies, these are modeled by microwave and rf-plasma interactions. Our focus has been on resonant absorption of intense electromagnetic radiation at the plasma critical layer. Electron plasma wave (EPW) growth and caviton formation have been shown to be most efficient for shallow density gradients at the critical layer, where EPW convection losses are minimized. EPW electric field energies of 5000 times the plasma thermal energy, and energetic electron tails out to $5000T_e$, have been observed at the top of an inverse parabolic density profile. Ions receive delta-function-like impulses from localized electron plasma waves and wave-breaking electron ejection; the disruption of the ion fluid can only partially be described by the ponderomotive force. Our attempt is to test and illuminate some of the fundamental concepts of strong turbulence and EM wave-plasma interaction.

Introduction

The topic of electromagnetic wave-plasma interaction has been of long-standing interest, with applications to laser-fusion, nonlinear optics, space physics, and ionospheric experiments. At strong pump strengths, Langmuir turbulence results, with the concomitant production of energetic electrons. These hot electrons, while a nuisance in laser-fusion, have a number of potential practical uses, such as the development of intense compact x-ray sources and particle accelerators, or the alleviation of the ozone problem via modification of the chemistry of the upper atmosphere. The physics of the situation is rich and complex, and remains to be thoroughly understood.

Our method of studying phenomena of importance to laser-plasma interactions is to model them by microwave and rf-plasma interactions. In this way, the temporal and spatial scales are magnified four to five orders of magnitude, and detailed experimental measurements can be performed with conventional diagnostic techniques, such as various probe techniques, test particle trajectories, and optical imaging.

One important phenomenon is that of resonance absorption. The RF-plasma Small Caviton Device (SCD) experiment can produce such large wave fields at plasma resonance as to fall in a regime where analytic theories do not exist, or only apply in a borderline fashion. The most critical parameter, $W = E^2/4\pi nT_e$, is the ratio of two energy densities: that of the resonant electric field to that of the kinetic thermal motion of the plasma. For W less than the ratio of the electron mass to the ion mass, ion inertia can be neglected, a nonlinear Schrodinger equation is derived, and a variety of soliton solutions are obtained. For W greater than this ratio, but less than one, ion inertia is incorporated into a set of fluid equations, the Zakharov equations, which yield ponderomotive force driven, self-similarly collapsing, cavitons. The SCD experiment can produce $W \gg 1$ — values of 5000, and over. At these levels, kinetic effects become important, and fluid models are inadequate. We have run a particle-push computer simulation (BEPS1 by V.K. Decyk) with parameters relevant to our experiment, and have observed such kinetic effects as caviton burn-out, and, at higher power, wave breaking and clump formation. Experimental evidence also indicates such effects — particularly the production of energetic electrons as measured by a gridded energy analyzer, and by a photomultiplier tube, which observes the light emitted from neutral atoms excited by collisions with these same electrons. Fast electrons with energy up to 5000 times the initial thermal energy have been observed, in conjunction with the large wave fields.

These large electron plasma waves (EPW) are being used to investigate the basic questions of strong Langmuir turbulence. These include: the origin of observed spiky impulses to the ions (ambipolar forces not generated by

ponderomotive pressure on the electrons); quantitative checks of the convection and damping rates of large EPW, and of the trapping of EPW by density depressions (cavitons); the mechanisms responsible for caviton burn-out; the threshold levels for cavitation and caviton collapse; the characterization of the energetic electron emission; the dependence of all of these on the strength of the driving field and on the density gradient scale length.

Our attempt is to match as closely as possible experimental, theoretical, and computer simulation results, as a test of all three. The SCD experiment has a very simple geometry, and produces very clean results, and thus is highly suited for such a comparison.

Current Programs and Achievements

Our experiments have been performed in the Small Caviton Device (SCD), a cylindrical coaxial capacitor-plate device. A 200 MHz VHF burst propagates along a central rod in an azimuthally symmetric, but radially nonuniform, unmagnetized plasma. At the location where the VHF resonates with the local plasma frequency, large electron plasma waves (EPW) are excited, energetic electrons are generated, and a cylindrical shell caviton is formed. If the entire plasma is underdense, no such dramatic resonant growth of waves occurs, but other RF-plasma instabilities can nonetheless yield large EPW, and corresponding fast electrons have been observed. The operating parameters may be set to produce EPW on a density incline (eg. previous studies of the development of two dimensional caviton structures [1], and of the trapping of EPW by cavitons [2]), or at the top of a gentle, centrally located, inverse-parabolic density profile. This latter choice reduces the convection of the excited electron plasma waves [3, 4], leading to a many-fold increase in peak electric field strength, increasing the production of energetic electrons and the efficiency of cavitation [5].

Maps of the space-time evolution of the plasma density, space potential, electron temperature, and energetic tail are made with a Langmuir probe. A diagnostic low density 9 keV electron beam measures the electron plasma wave electric fields. Fast electrons and ions produced by the caviton are seen with a gridded energy analyzer. Light produced from neutral atoms excited by the fast electrons is detected with a photomultiplier tube. The VHF signal on the central rod antenna is monitored by probes at each end (at the input and output), and by crystal diodes on directional couplers. A computerized data acquisition system is used to control the experiment and to collect, process, and analyze the data. Work has begun on a Laser Induced Fluorescence optical diagnostic to improve the ion density measurements, especially during, or shortly after, the VHF pump, when the Langmuir probe is greatly disturbed by the strong high-frequency fields. Ion velocity distributions and phase-space flow may possibly also be observed, from the doppler broadening of the radiated light.

A number of technical enhancements to the SCD were made. First, the time resolution of the electron beam electric field diagnostic was improved by more than two orders of magnitude. Now electron bursts as short as 500 picoseconds can be produced, much shorter than the electron plasma wave period. This means "freeze-frame" images of the electron plasma wave can be obtained. Second, the VHF antenna was replaced with a new axisymmetric and impedance-matched VHF antenna assembly. New probes yield the exact VHF waveform on the antenna, monitored on a fast oscilloscope. The result is an order of magnitude improvement in the measurement accuracy of the incident pump field. The axisymmetry of the entire setup was substantially

increased, improving the correlation between diagnostics placed at different azimuthal angles. Third, the VHF-EPW resonance condition is very sensitive to density fluctuations, when the resonance location is placed at the top of the density profile. Shot-to-shot reproducibility was improved via modifications to the RF-plasma production system.

We have recently investigated the relative efficiency of caviton formation at the flat maximum of a density profile as compared with on a density incline. A paper on this subject has been published [5] in *The Physics of Fluids*, and is attached as Appendix A. The topic of super-strong Langmuir turbulence ($W = E^2/4\pi nT_e \gg 1$) is the current focus of our work. The energetic electron spectrum is being characterized and compared with scaling laws derived from theory and simulation [6]. The ions have been found to undergo sharp localized impulses that cannot be attributed to ponderomotive pressure of the wave on the electrons. Our results were presented at the Nineteenth Anomalous Absorption Conference (Durango, Colorado, June 1989) and at the Thirty-First Annual Meeting of the Division of Plasma Physics of the APS (Anaheim, California, November 1989) [7], and papers are being prepared for publication. The conference abstracts and a discussion of the work are appended to this report.

Publications and Conference Presentations

1. "Efficiency of Caviton Formation as a Function of Plasma Density Gradient," B.S. Bauer, A.Y. Wong, L. Scurry and V.K. Decyk, Phys. Fluids B 2, 1941, (1990).
2. "Electron Plasma Wave Breaking and Caviton Formation," B.S. Bauer, L. Scurry and A.Y. Wong, 19th Annual Anomalous Absorption Conference, Durango, Colorado.
3. "Electron Plasma Wave Breaking and Caviton Formation," B.S. Bauer and A.Y. Wong, 31st Annual Meeting of the Division of Plasma Physics, Anaheim, California. APS Bull. 34, 2150 (1989).

Education

Graduate student Bruno Bauer has performed part of his doctoral research under the grant. He has been advanced to candidacy, with the topic "Cavitation Formation and Nonlinear Development at a Plasma Density Maximum."

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