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THE SPACE-TIME EVOLUTION OF THE NONLINEAR TWO-STREAM INSTABILITY

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Abstract

A cold electron beam penetrating a cold plasma is electrostatically unstable. The instability produces a growing electric field that saturates when the beam electrons are suddenly trapped by a single wave. During trapping a significant amount of energy is transferred from the beam to the field and ultimately to the plasma. At Los Alamos experiments are being performed that demonstrate this anomalous beam-driven plasma heating.

The heating efficiency is a function of the phase velocity of the trapping wave. According to our generalization of a previous calculation, the instability is absolute and its wave form evolves in both space and time. Modifying trapping theory to account for the space and time evolution of the two-stream instability, we find that the heating efficiency should change in time. This prediction is in agreement with results from one-dimensional PIC simulations.

Introduction

For years there has been an interest in using relativistic electron beams (REB's) to heat plasmas to thermonuclear temperatures via an anomalous beam-plasma interaction. At Los Alamos, for instance, the Anomalous Intense Driver (AID) experiment [1,2] is presently being upgraded to include the capability of firing a 5-MeV, 10-kJ REB into not only a neutral gas but also into a preformed $n_p \approx 10^{17}$ cm^{-3} density plasma. Recently we have performed numerical simulations in which the efficiency of beam-to-plasma energy transfer changes in time during the beam pulse increasing to as much as 30-50%, twice its initial value, before reaching a maximum and decreasing. This efficiency enhancement occurs when beam electrons are trapped by two-stream instability produced waves whose phase speeds are less than the phase speed of the most rapidly growing wave.

In this report we define a beam-to-plasma energy transfer efficiency ε as the ratio of beam energy density lost ΔE to the initial total beam energy density $n_b mc^2 \gamma_b$ so that $\varepsilon = \Delta E/(n_b mc^2 \gamma_b)$. Possibly a more meaningful definition of efficiency is the ratio of beam energy density lost to initial kinetic energy $\varepsilon\gamma_b/(1 - \gamma_b)$. Here we use the parameter ε because it has been suggested [3,4] that ε is a function not of the relativistic beam factor γ_b and beam-to-plasma density ratio n_b/n_p independently but only of a single strength parameter S, where S is a simple function of γ_b and n_b/n_p. We find that, although ε can be parameterized with S for specially prepared periodic simulations and that S can be generalized to include space-time dependence, the strength parameter is not an adequate parameter for the aperiodic simulations most relevant to laboratory experiments.

Strength Parameter Scaling

Consider a cold beam penetrating a homogeneous plasma. It is two-stream unstable and produces a spectrum of growing waves. When one of these waves of phase speed $v_\phi = \beta_\phi c$ becomes strong enough to trap, say, a fraction f_T of the beam electrons between wave crests, these electrons reflect elastically and coherently from the downstream wave crest. In this "rigid rotation" model, the trapped electrons suffer momentum reversal but no energy loss in the wave frame. Taking into account relativistic effects, the model leads to the general expression for energy loss in the lab frame

$$\varepsilon = f_T\, S/(1 + S) \quad , \tag{1}$$

where $S = 2\beta_b \gamma_b^2 \Delta\beta$ and $\Delta\beta = \beta_b - \beta_\phi$ assuming the wave phase speed is relatively close to the beam speed so that $\Delta\beta \ll \beta_b$.

If the trapping wave is the wave of maximum growth rate calculated from linear fluid equations $\Delta\beta = (\beta_b/2\gamma_b)(n_b/2n_p)^{1/3}$ and $S = \beta_b^2 \gamma_b (n_b/2n_p)^{1/3}$. In this context, Thode argued that the fraction of electrons trapped $f_T = 1/(1 + S)^{3/2}$. This results in an efficiency $\varepsilon = S/(1 + S)^{5/2}$ [3]. Subsequently, the shifted S scaling $\varepsilon = 1.5\, S/(1 + 1.5\, S)^{5/2}$ was shown to agree somewhat better with results from full and partial particle-in-cell (PIC) simulations [5]. The latter fully simulate the beam but treat the plasma as a linear medium.

Here we use fully nonlinear relativistic PIC simulations to test these S-scaling laws. In later sections, we consider cases when the trapping wave has a phase speed less than the wave of maximum growth rate. In all cases the simulations were performed with the code BIGONE [6] modified to be purely electrostatic. Energy conservation is always better than 5% and usually better than 2%.

Figure 1 presents ε versus $S = \beta_b^2\gamma_b(n_b/2n_p)^{1/3}$ for some 30 periodic simulations with wavelength equal to that of the most unstable linear mode. The simulations cover a wider range of parameters than previously published: $10^{-4} \lesssim n_b/n_p \lesssim 10^{-1}$ and $2 \lesssim \gamma_b \lesssim 16$ with $0 < S < 2$. The simulation transfer efficiency ε was defined in terms of the minimum beam energy during the first trapped particle oscillation. Note that while the simulation data roughly follows the scaling $\varepsilon = 1.5\ S/(a + 1.5\ S)^{5/2}$, the lowest density simulations follow the $S/(1 + S)$ curve and achieve higher efficiencies than the higher density ones. For example, $\varepsilon \cong 27\%$ for $n_b/n_p = 10^{-4}$, $\gamma = 12$, and $S = 0.4$, as opposed to $\varepsilon \cong 18\%$ predicted by the $\varepsilon = 1.5\ S/(1 + 1.5\ S)^{5/2}$ curve.

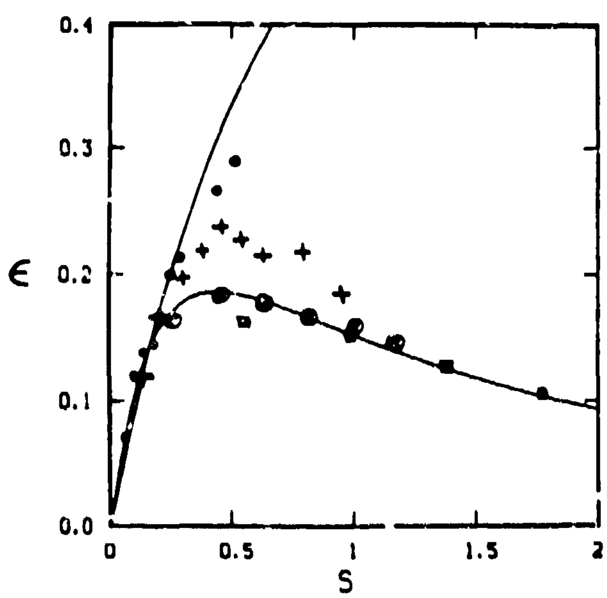

Fig. 1. Efficiency $\varepsilon = \Delta E/(n_b mc^2\gamma_b)$ versus strength papameter $S = \beta_b^2\gamma_b(n_b/2n_p)^{1/3}$ where ΔE is the beam energy lost to the plasma and field in one-dimensional, periodic, PIC simulations with simulation lengths equal to the wavelengths of the most unstable mode. Parameters for the various simulations are in order of increasing S: ● $n_b/n_p = .0001$, $\gamma_b = 2,3,4,5,6,7,8,12,14$; + $n_b/n_p = .001$, $\gamma_b = 2,3,4,5,6,7,8,10,12$, ⊗ $n_b/n_p = .01$, $\gamma_b = 2,3,4,5,6,7$; ■ $n_b/n_p = .1$, $\gamma_b = 2,3,4,5$.

Phase Velocity Dependence

For regions of phase space in which the transfer efficiency ε is an increasing function of the strength parameter, it should be possible to increase ε for a beam of definite γ_b and n_b/n_p by decreasing the phase speed β_ϕ of the trapping wave so that $\Delta\beta$ $(\beta_b - \beta_\phi)$ and consequently S increases. Later we argue that this can happen naturally in time in aperiodic and laboratory systems. Here we demonstrate the principle in periodic systems by calculating ε for a particular beam interacting with waves of various wavelengths, various phase speeds, and less than maximum growth rates.

In Fig. 2 these transfer efficiencies are plotted versus S where $\Delta\beta$ is determined with linear theory for each wavelength simulated. Three different sets of data corresponding to various wavelengths for each of three different pairs of beam

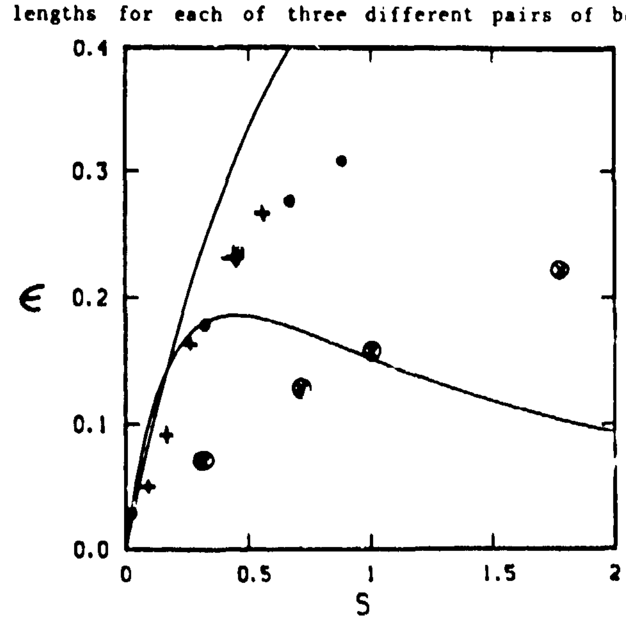

Fig. 2. Efficiency $\varepsilon = \Delta E/(n_b mc^2\gamma_b)$ versus strength papameter $S = 2\beta_b\gamma_b^2\Delta\beta$ where ΔE is the beam energy lost to the plasma and field in one-dimensional, periodic, PIC simulations, simulation lengths are equal to several wavelengths for each set of beam parameters, and $\Delta\beta$ is the phase velocity shift $(\beta_b - \beta_\phi)$ for each wavelength. Parameters for the various simulations are in order of increasing S: ● $n_b/n_p = .001$, $\gamma_b = 6.0$, LC/ω_p = 6.6220, 6.2364, 6.1940*, 6.1449, 6.0972; + $n_b/n_p = .01$, $\gamma_b = 2.0$, LC/ω_p = 6.2832, 5.8178, 5.3840*, 4.9474, 4.7242; ⊗ n_b/n_p = .01, $\gamma_b = 6.0$, LC/ω_p = 6.4775, 6.2832, 6.1879*, 6.0069. Wavelengths marked with an asterick are the wavelengths of maximum growth rate.

parameters γ_b and n_b/n_p are shown. In each set the point corresponding to maximum growth rate when $S = \beta_b^2\gamma_b(n_b/2n_p)^{1/3}$ is identical to the corresponding point plotted in Fig. 1. Note that, surprisingly, not only does decreasing the phase velocity and consequently increasing $\Delta\beta$ and S increase ε in the region of parameter space where $1.5\ S/(1 + 1.5\ S)^{5/2}$ is increasing but ε increases with S in all cases. While this result is encouraging for heating experiments, it also indicates that there is no S-scaling of ε good for all the different ways of changing S, a result that is also supported by results reported in the last section.

Space-Time Dependence

In aperiodic simulations and laboratory experiments the complete spectrum of instability produced waves is allowed to grow and interact with the beam. Because the beam-stationary plasma type of two-stream instability is absolute, there are unstable waves with phase speeds and growth rates less than those of the most unstable wave that can trap the beam upstream of the point of initial trapping after the time of initial trapping [7].

Specifically, consider a spectrum of waves forming a wave packet generated by the beam-plasma instability from a localized noise source at the space-time point $z = 0$, $t = 0$. The envelope of the wave packet $E(z,t)$ has a space-time dependence of

$$E(z,t) \propto \exp\{z^{2/3}(V_bt - z)^{1/3}\} \tag{2}$$

for $0 < z < V_bt$ and $[n_b/(n_p\gamma_b^3)]^{1/3} \ll 1$ [8,9] There is a phase speed β_ϕ associated with every space-time point in this packet such that the phase velocity lag $\Delta\beta = \beta_b - \beta_\phi$ is given by

$$\Delta\beta = \left(\frac{\beta_b}{2\gamma_b}\right)\left(\frac{n_b}{n_p}\right)^{1/3}\left(\frac{V_bt - z}{z}\right)^{1/2} \tag{3}$$

through leading order in $\Delta\beta/\beta_b$ [10]. Since the wave amplitude necessary to trap a beam of particular energy and density, γ_b and n_b/n_p, remains constant in time, the position of trapping z decreases in time t as

$$z^2(V_bt - z) = z_0^2(V_bt_0 - z_0) \quad , \tag{4}$$

where z_0 and t_0 with $z_0 = 2V_bt_0/3$ describe the position and time of initial trapping. Combining Eqs. (3) and (4) and the definition of strength parameter $S \equiv 2\beta_b\gamma_b^2\Delta\beta$ we arrive at a strength parameter

$$S = \beta_b^2\gamma_b\left(\frac{n_b}{2n_p}\right)^{1/3}\left(\frac{3t}{t_0} - 2\right)^{1/2} \tag{5}$$

that increases in time.

Since the increase of S with t as defined in Eq. (5) is caused by the decrease in the phase speed of the wave trapping the beam, the ε versus S curves as determined from aperiodic simulations of particular beam-plasma interactions in Fig. 3 should be similar to the ε versus S curves of Fig. 2 determined from a series of periodic simulations with the same parameters γ_b and n_b/n_p but varying wave phase speed. The points in Fig. 3 are from the simulation produced numbers, t_0--the time of initial trapping, t--the subsequent times at which ε is measured, ε an average efficiency over a 100-200 ω_p^{-1} interval centered on t,

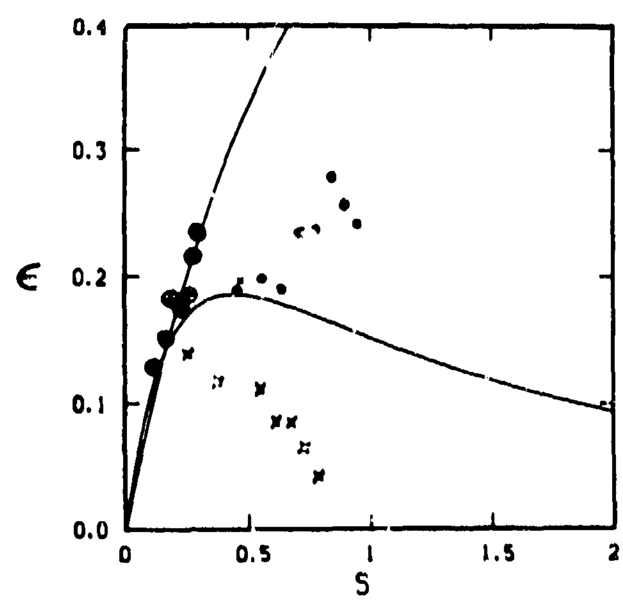

Fig. 3. Efficiency $\varepsilon = \Delta E/(n_bmc^2\gamma_b)$ versus strength parameter S where ΔE is the beam energy lost to the plasma and field in one-dimensional, aperiodic PIC simulations and S is determined from Eq. (5). Parameters for the various simulations are in order of increasing S: ● $n_b/n_p = .001$, $\gamma_b = 6.0$, $t_0\omega_p = 1300$, $t\omega_p = 1300, 1500, 1700, 1900, 2100, 2300, 2500, 2700$; + $n_b/n_p = .01$, $\gamma_b = 2.0$, $t_0\omega_p = 250, 350, 450, 550, 650, 750, 850, 950$; ⊗ $n_b/n_p = .001$, $\gamma_b = 2.0$, $t_0\omega_p = 350$, $t\omega_p = 350, 450, 550, 650, 750, 850, 950$.

and the definition of S(t) in Eq. (5). The points in Figs. 2 and 3 with $\gamma_b = 6$, $n_b/n_p = .001$ do indeed roughly lie along similar curves indicating the observed efficiency enhancement is caused by trapping with low-phase velocity waves. Late in time, however, some of the efficiencies reach a peak and begin to decline. The cause of this decline is not yet understood.

Acknowledgments

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