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Destruction of Trapped-Particle Oscillations*

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In the small-cold-beam limit, the beam-plasma instability is identical to the interaction in a traveling wave tube. We built a traveling wave tube to investigate the late-time development of this instability. We observe five trapped-particle oscillations following the saturation of a single launched wave. These oscillations can be destroyed either by increasing the wave damping or by modulating the main wave with unstable test waves.

The predictions of the single-wave trapping model[1-3] for the nonlinear interaction between a small cold beam and a plasma agree completely with the experimental[4-8] observations through the initial trapping and up to the first amplitude oscillation. Beyond this point, experiments[4-8] universally exhibit a rapid decay of the saturated wave rather than the persistent trapped-particle oscillations predicted by the theory.[2,3] This decay is not well understood experimentally because there are many processes which may be responsible. One class of mechanisms involves the nonlinear motion of the beam electrons and the linear response of the plasma. For example, unstable sidebands[9,10] may grow to large amplitude and detrap the particles. Another class includes nonlinear processes[11-13] involving the background plasma, which occur for strong beams, typically $n_b/n_p \geq 1\%$. In addition, laboratory plasmas suffer from density gradients, which may affect the evolution of the instability, and low-frequency potential fluctuations, which can confuse the measurements.

In order to avoid effects associated with the background plasma, we have built a somewhat unconventional traveling wave tube[14] (TWT) to investigate the late-time development of the beam-plasma instability. The replacement of the plasma with a slow-wave structure allows us to isolate the effects which are due solely to the beam dynamics from those which result from the background plasma. In the small-cold-beam limit, the plasma acts essentially as a linear dielectric medium capable of supporting slow waves. Therefore, this replacement does not alter the basic features of the wave-particle interaction. This is demonstrated by the fact that the equations of the single-wave model[2-3] are identical to Nordsieck's[15] working equations for the nonlinear interaction in a TWT. The TWT, however, has the advantage that the slow-wave structure will remain linear, regardless of the wave amplitude; furthermore, it does not introduce any noise. In the past, TWT's have been thoroughly investigated[14-18] primarily for application as a broad-band amplifier. Consequently, the investigators had no compelling reasons to study the interaction much beyond saturation.

We observe over five trapped-particle oscillations following the growth and saturation of a single launched wave. We are able to destroy the trapping oscillations in a controlled manner either by increasing the wave damping or by launching a small unstable test wave at a neighboring frequency.

Measured in wavelengths and total gain, our TWT is 3–4 times longer than typical commercially available TWT amplifiers. The main element of the slow-wave structure is a BeCu-tape helix with a length $L = 3$ m, radius $a = 0.81$ cm, and pitch $p = 0.25$ cm, corresponding to a pitch angle $\psi = \tan^{-1}(p/2\pi a) = 2.8°$. It is supported in a glass vacuum jacket by three alumina rods, set 120° apart. This assembly lies concentrically in a slotted cylindrical wave guide. There are four axially movable electrostatic probes used for transmitting and receiving waves. The electron beam is confined on axis by a 440-G magnetic field which is uniform to $\pm 1\%$ in the interaction region. The beam has a 4-mm radius and is formed with apertured accelerating electrodes by immersed flow.

An electromagnetic wave on the helix can be thought of traveling along the windings at approximately the speed of light. Consequently, the axial phase velocity is reduced by $\tan\psi$. The dielectric supports also reduce the phase velocity slightly. Our dispersion relation resembles that of a finite-size plasma with a finite temperature.[4]

The result of launching a wave on the TWT in the presence of a strong beam is shown in Fig. 1. The wave power grows exponentially by a factor of over 10^3 to saturation and then executes five trapped-particle oscillations. This is in contrast to typical beam-plasma results where the wave decays away rapidly following the first oscillation. In this case, the power falls by 5 dB as a result of the finite dissipation in the slow-wave structure. The fast oscillations in Fig. 1 are at half the wavelength and are a result of the forward wave beating with a small component which is reflected by the imperfectly matched ends. The backward wave does not significantly affect the dynamics because it is far from synchronism with the beam. The frequency spectrum (measured in the range 1–500 MHz) is dominated by the fundamental mode and its first harmonic. By the end of the tube, unstable noise has grown substantially, but is still at a power level 35 dB below that of the main wave.

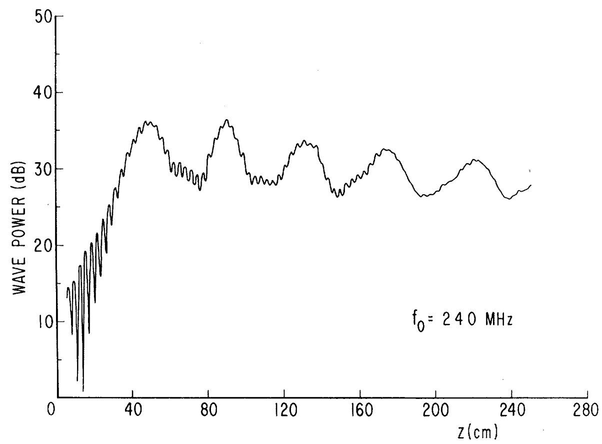

FIG. 1. Wave power (1-MHz bandwidth) vs distance from the transmitter. Beam current is 25 mA. Cathode voltage is 960 V.

The linear growth rates[18] and saturation power[17] for TWT's have been previously measured. In addition to these we have measured the bounce length and nonlinear wave phase[3] over a wide range of experimental parameters. We have also solved the working equations of Tien's model,[16] essentially the single-wave model with detuning,[19] damping, and finite-beam-strength corrections included, for parameters pertinent to our experiment. Our measurements agree with our computer solutions and will be discussed in detail in a forthcoming paper.

We have established that the trapping oscillations can persist for many bounces. We can now look for processes which destroy them. One method is to increase the dissipation in the slow-wave structure. We do this, without changing the wavelength, by adding resistive strips near the helix over the entire length of the tube. An illustrative example of the effect of dissipation on the instability is shown in Fig. 2. The dotted line shows three trapping oscillations of a single launched wave. In the absence of the beam, a wave at this frequency damps with a decrement $k_i = 2.8 \times 10^{-3}$ cm^{-1} as a result of the dissipation in the helix and supporting structure. The wave number is $k_0 = 0.77$ cm^{-1}. The solid line is the power vs z when we increase the no-beam damping rate to $k_i = 6 \times 10^{-3}$ cm^{-1}.

Prior to the first bounce, the additional damping does not significantly alter the spatial evolution of the wave. However, after the second maximum the wave power falls dramatically and fails to regrow to the previous large level. Near the deep minimum at $z = 178$ cm, the wave undergoes

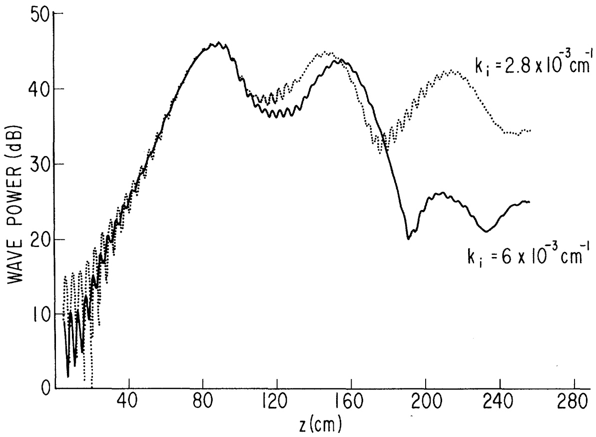

FIG. 2. Wave power (1-MHz bandwidth) vs distance. Beam current is 10.8 mA. Cathode voltage is 1 kV. $f_0 = 195$ MHz.

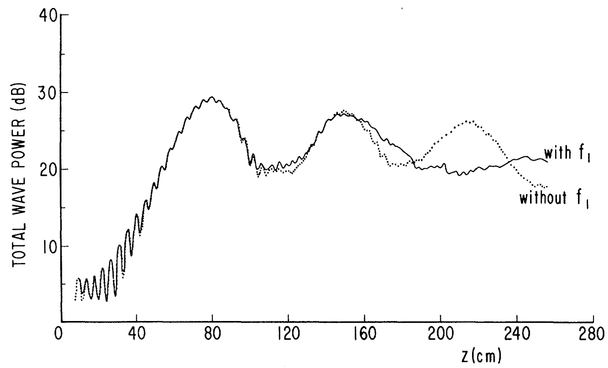

FIG. 3. Total wave power (1–400 MHz) vs distance. Dotted curve, launch $f_0 = 185$ MHz only. Solid curve, launch $f_1 = 222$ MHz at low level in addition to f_0. Beam current 10 mA. Cathode voltage 960 V.

a rapid phase shift $\Delta\theta = 130°$ (measured with a standard interferometer) within two wavelengths, corresponding to $\Delta k/k_0 = 18\%$. The main wave dominates the frequency spectrum. Although naturally occurring sidebands grow throughout the nonlinear region, their amplitudes are always more than 60 dB below the saturation power. According to our sideband experiments, this is orders of magnitude below the level at which the sidebands cause detrapping.

Our computer solutions accurately describe the evolution of the instability in the presence of damping. From our computer studies we can explain the salient features in Fig. 2 as follows. Immediately following the second maximum, the amplitude of the wave decreases as it accelerates the particles. This follows from momentum balance in the initial beam frame.[3] Since it has been attenuated, the wave is energetically incapable of forcing the particles out of the accelerating region of the wave potential before vanishing. However, when the amplitude becomes small, the wave experiences a rapid phase shift which, in effect, transfers the particles into the decelerating region and causes the wave to regrow. The phase shift is a consequence of energy balance in the initial beam frame.[3]

As a result of the reduced amplitude and the phase shifts, particles spill into adjacent wave troughs and the previously clumped particles spread in phase space. The spilled particles rotate out of synchronism with the unspilled particles and, in general, along different phase trajectories. Since the bounce frequency depends on their oscillatory energy,[20] and hence on their phase trajectories, the particles rotate at different rates and phase-mix. If a significant fraction of the particles spill at a deep amplitude minimum, the clump is rapidly destroyed. There are nearly as many particles being accelerated as there are being decelerated. Consequently, little net energy exchange will occur and the wave will remain at a low power level.

Figure 2 demonstrates that a small damping rate, $k_i/k_0 \sim 1\%$, can have a catastrophic effect on the trapping oscillations. One must be careful in applying this result to a beam-plasma system if the damping mechanism is Landau damping. The saturated wave alters the plasma distribution function near the wave's phase velocity by capturing the resonant plasma particles. Therefore, the linear Landau damping rate in the absence of the beam does not apply in the nonlinear region. On the other hand, nonlinear decay processes in a beam-plasma system may result in an effective damping of the saturated wave. In that case, we would expect a behavior similar to that described above.

The trapping oscillations can also be destroyed by launching unstable waves at neighboring frequencies. The result is shown in Fig. 3. The dotted line is the total wave power when we launch the main wave only at $f_0 = 185$ MHz. The solid line is the wave power when we launch the main wave and a smaller amplitude (by 15 dB) wave at $f_1 = 222$ MHz. The presence of the additional wave destroys the trapping oscillations in the vicinity of the second minimum. Since the two curves begin to depart near the second maximum, the disruption occurs over a short distance, i.e., a fraction of a bounce length. The wave power then remains constant at a level significantly below the power maxima. Since this is the total wave power most of the energy has stayed in the beam.

We have also measured the power in the spectral components. The wave at f_1 is unstable in both the linear and nonlinear regions. It saturates near the second maximum at an amplitude 12 dB below the saturation level of the main wave. In addition, the modes at f_0 and f_1 couple nonlinearly[21] to produce waves at frequencies $f_n = f_0 \pm n\Delta f$, where $\Delta f = f_1 - f_0$ and n is an integer. Many unstable modes grow in the nonlinear region, but the most dominant modes prior to the detrapping are f_0 and $f_0 \pm \Delta f$.

Since the dynamics are dominated by only three waves whose phases are not random, the disruption process is not statistical. We have measured the real-time wave form produced by the interference of these waves.[22] When the interference is destructive, the electric field is small. The particles within these beat minima become untrapped momentarily. The previously bunched particles spread and many spill into adjacent troughs. This results in particle phase-mixing, as described earlier, which precludes further trapping oscillations.[23]

We get a result similar to Fig. 3 by launching the main wave and broad-band noise. The unstable waves grow to moderate amplitudes and disrupt the particle trapping. However, our result with the single test wave suggests that the statistical nature of the noise is incidental and that the modulation of the main wave, be it statistical or not, is pre-eminent in destroying the trapping oscillations.

The disruption process described above does not depend on the nature of the linear slow-wave structure. Thus, we expect that noise within the instability bandwidth of a beam-plasma system would grow and destroy the trapping.

Following the phase-mixing, triggered by either method, the *time-averaged* velocity distribution is centered near the phase velocity of the main wave and has a spread roughly equal to the trapping width $\sim (e\varphi/m)^{1/2}$. This state is still unstable. We have not yet experimentally investigated its subsequent relaxation.

In summary, we have shown that the trapping oscillations in a TWT can persist for five bounces. These oscillations can be destroyed in an abrupt manner as a result of particle phase-mixing by either (1) wave damping or (2) modulation of the main wave by unstable sidebands. Since the interaction in a TWT is identical to the beam-plasma instability in the small-cold-beam limit, we expect an analogous behavior in a beam-plasma system.

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