Production of Fast Electrons in the Beam-Plasma Interaction*

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We have observed the generation of high-energy electrons by longitudinal electrostatic waves in a beam-plasma system. We find a direct correlation between the measured field and particle spectra.

It is well known that the beam-plasma interaction can generate a high-energy tail in the electron distribution function.[1,2] However, the mechanism by which this hot-electron component is produced is not completely understood. Numerous experiments have shown the initial quasilinear diffusion[3] and trapping[4,5] of beam electrons to be in substantial agreement with existing theory.[6,7] The agreement between theory and experiment in the later, more turbulent regime of the interaction is less complete.

The production of high-energy electrons by a resonant interaction with "whistler"-type waves has been demonstrated[8] and the mechanism has been described.[9] However, the geometry of many experiments of this type makes it difficult to interpret the resulting wave spectrum, and in some cases precludes a direct measurement of the electron distribution function.

We have measured the scattering of electrons due to beam-excited, longitudinal electrostatic waves in a strongly turbulent, magnetized, cylindrical plasma. We observed a direct correlation between the field and particle distributions. The experimental apparatus has been previously described.[10] The 70-cm-long beam-formed hydrogen plasma column has a radius of 2 cm and a peak density of approximately 10^9 cm^{-3}. The beam voltage and current range from 500 to 1500 V and 3.0 to 20.0 mA, respectively. The initial beam width is approximately 6 eV and the plasma temperature before the onset of turbulence is 3 to 7 eV. An axial magnetic field of 3400 G restricts the dynamics to one dimension.

The time-averaged wave spectrum is measured with electrostatic loops at several different axial locations, and the time-averaged electron energy distribution is measured with a retarding-field energy analyzer (RFEA). In the present series of experiments the output from the RFEA is fed to a data acquisition system which is used to differentiate numerically the measured flux curves and to calculate moments of the distributions.

The waves excited in this experiment are the longitudinal electrostatic modes with dispersion relation[11]

$$\omega_{0k}^2 = k^2\omega_{pe}^2/(p^2+k^2), \qquad (1)$$

$$k = n\pi/L, \quad n = 1, 2, 3, \ldots .$$

Here ω_{pe} is the effective plasma column frequency,[12] p is the transverse wave number, and the axial wave number k is quantized because of reflections at the ends of the column of length L. The excitation and perturbation of the cavity modes ω_{0k} by the beam have been extensively studied in the regime below the threshold for exponentially growing waves.[13] The transition to a moderately turbulent system can be accomplished without drastic changes in the background plasma. Thus a knowledge of the mode structure below threshold is useful in interpreting the turbulent wave spectrum. It is important to note in Eq. (1) that the lower frequency modes have higher phase velocities and vice versa.

A series of measured electron distributions and accompanying wave spectra is shown in Fig. 1. In this set the beam velocity is held constant and the strength of the interaction is varied by changing beam current. The effective plasma frequency of the column is roughly 350 MHz. In Fig. 1(a) beam electrons are scattered symmetrically about the mean injection energy by the single dominant mode in the spectrum. Moderate heating of the background plasma is also observed. As the beam current is increased in Fig. 1(b), several modes are destabilized by the diffused beam. We observed a merging of the beam and plasma distributions similar to that reported in recent computer simulations.[14]

In the early stages of the interaction [Figs. 1(a) and 1(b)], the instability has a pulselike character observed in other beam-plasma experiments.[15] In the later stages [Figs. 1(c) and 1(d)], the system attains a stationary secular equilibrium. As the back-filling of the distribution below the beam becomes more stationary [Fig. 1(c)], the mode spectrum shifts to higher frequencies. This

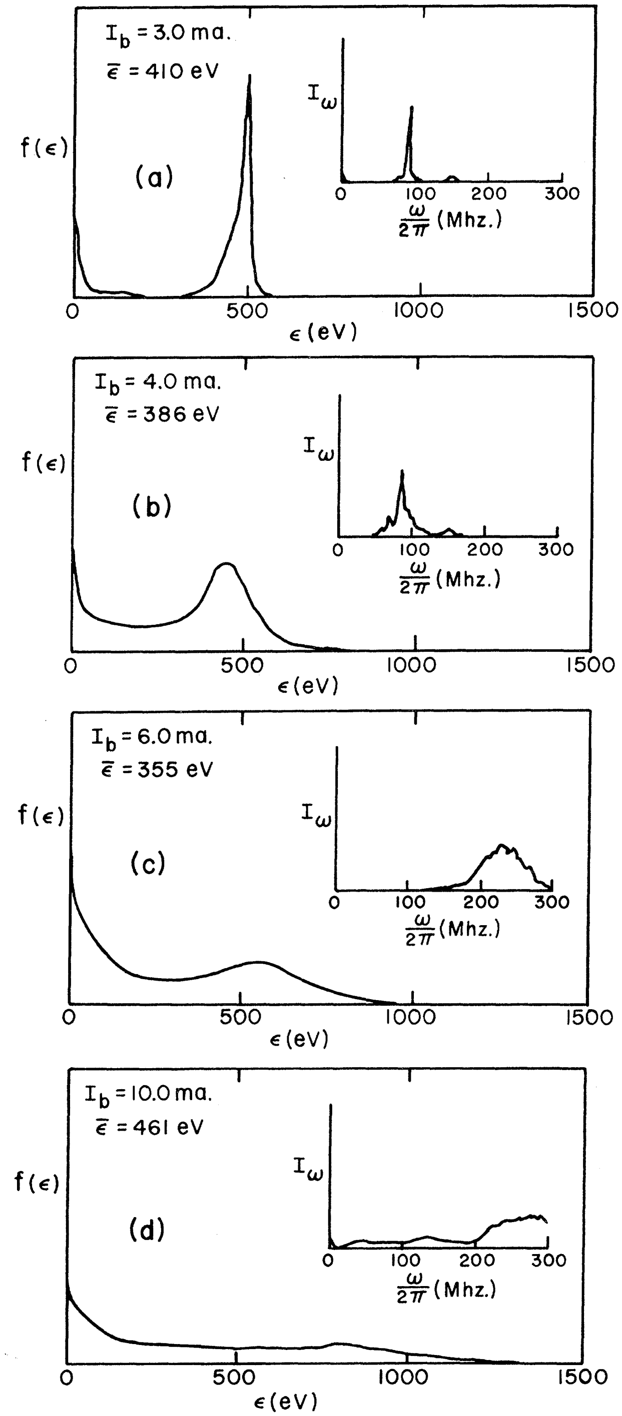

FIG. 1. Measured particle and wave spectra as the beam current is increased.

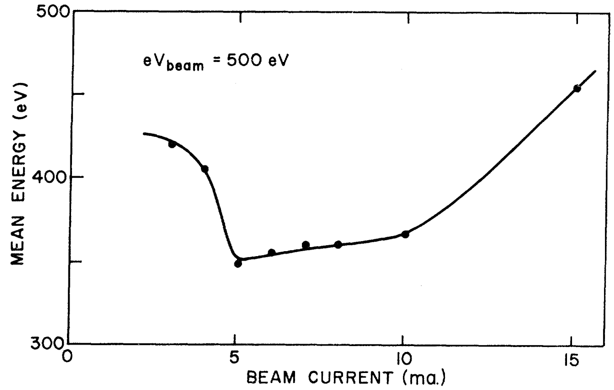

FIG. 2. Mean energy per particle for the distributions of Fig. 1 versus beam current.

shift is consistent with the fact that these higher-frequency modes have lower phase velocities [Eq. (1)] and hence are selectively excited by the slower particles. The modest increase in plasma frequency due to the increased beam current is not sufficient to account for the observed frequency shift. Finally, in Fig. 1(d) a high-energy tail appears in concert with a sudden increase in the low-frequency end of the wave spectrum. It is reasonable to associate the generation of these fast particles with the appearance of the low-frequency modes since these modes have the greatest phase velocity.

The details of the energy transfer are examined in Fig. 2, where the mean energy of the distributions of Fig. 1 is plotted versus beam current (excitation). At first the mean energy per particle decreases as energy is transferred from the beam to the waves during the quasilinear diffusion state [Figs. 1(a) and 1(b)]. As the back-filling diffusion continues [Fig. 1(c)], the mean energy remains nearly constant. Finally, the mean energy per particle increases as the energy in the wave spectrum is redistributed among the particles and the waves. It is at this latter stage that true turbulent heating commences. In any turbulent heating scheme care must be taken to insure that this stage is reached.

In conclusion, the evolution of the velocity distribution function has been shown to be directly correlated with the spectrum of the beam-excited fields. Furthermore, the generation of a high-energy tail by the low-frequency, high-phase-velocity modes of the bounded system has been demonstrated.

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Propagation of Collisionless Sound in Normal and Extraordinary Phases of Liquid ^{3}He below 3 mK*

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Measurements of attenuation and velocity of sound in the collisionless regime have been made in normal and extraordinary phases of liquid ^{3}He at several pressures. The attenuation has a frequency-independent component with a sharp maximum just below T_c and a frequency-independent component with a BCS-like temperature dependence. The velocity, frequency dependent very near T_c, becomes frequency independent at lower T and may be approaching the velocity of first sound.

In this Letter we present measurements of the attenuation and velocity of ultrasound in liquid ^{3}He at temperatures below 3 mK and at various pressures. In this temperature region and in the presence of solid ^{3}He, two new phases with extraordinary NMR properties were discovered by Osheroff *et al.*[1] In this same temperature region Webb *et al.*[2] observed a second-order phase transition, a discontinuity but not a divergence in the specific heat, over a wide range of pressure in liquid ^{3}He. This phase transition has been associated with the higher-temperature phase transition found in Ref. 1. The lower temperature phase has not yet manifested itself in our experiments. The present measurements were made in zero magnetic field at a variety of pressures from 140 lb/in.^{2} to near the melting curve and, where possible, at 5, 15, and 25 MHz. For these frequencies we have the relation $\omega\tau > 1$, where τ is a collision time, in the low-temperature region of interest. The conditions for measurement at least approximate those for propagation of zero sound[3,4] for $T > T_c$ and may approximate at our lowest temperatures the conditions for propagation of a density fluctuation mode in a superfluid neutral Fermi fluid as discussed by Leggett.[5]

The ^{3}He was cooled using an epoxy-walled, cerium magnesium nitrate (CMN)-filled, demagnetization cell of standard design[6] in which the sonic cell was lodged in a cylindrical cavity in the CMN. Sonic measurements were made using the method of Abel, Anderson, and Wheatley.[7] The nature of the experimental data and their treatment are given by Wheatley[8] (see sect. 2.4). The sound is propagated through the ^{3}He between two 5-MHz epoxy-backed X-cut quartz crystals separated by a 0.4996-cm-long×0.76-cm-i.d.