# Electric Field Spectra beyond the Strong-Turbulence Regime of Relativistic Beam-Plasma Interactions

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Using a Stark-effect diagnostic, we have explored a new regime of relativistic beam-plasma turbulence, $\langle E^2\rangle > nT_e$. Measurements of $E$ and of the plasma frequency used nonperturbing optical techniques during the electron-beam pulse. Fields up to 150 kV/cm display an exponential spectrum, $\exp(-E^2/E_0^2)$ with $E_0=85$ kV/cm. This spectrum does not resemble that given by strong-turbulence theory, and involves stronger fields than are dealt with in current theory.

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Strong beam-plasma instability can produce large density fluctuations, compact electric field structures, and powerful microwave emission.[1-15] The great body of theory[3-10] and the smaller number of experiments[1,2] have studied regimes in which the ratio of the electric field and plasma energy densities, $W=(E^2/4\pi nkT)$, is less than 0.1. This regime applies to type-III solar bursts[1,5] and much weak-beam laboratory work[1,4] but not to the conditions of strong beams.[2,7,13] The region $W>1$ is unexplored; yet some nonlinear beam theory predicts such values for strongly driven beam-plasma systems.[6,7,13] The regime $W>m/M$, the electron-ion mass ratio, is often termed "strong turbulence." Kato, Benford, and Tzach[14] studied $W>0.1$ and termed it "superstrong turbulence," relating it to electromagnetic emission far above the plasma frequency $\omega_p$. Here we discuss the first experiments in a regime with $W>1$.

We present direct measurements of the turbulent Langmuir waves during strong, relativistic beam-plasma interaction. These are the first detailed observations of the amplitude $E$ made with a nonperturbing diagnostic and throughout the entire beam pulse. This allows detailed study of the turbulent $E$ spectrum.

We employ the same beam-plasma system as in earlier work.[2] We fire a 1-$\mu$s, 15-kA, 700-keV relativistic electron beam from a vacuum diode, into a 1.5-m drift tube filled with 5–7 mTorr of He. The beam is warm in the sense that the angular spread exceeds $1/\gamma$, with $\gamma$ the Lorentz factor. At the peak of the beam pulse $n_b/n=0.01$, driving very strongly unstable streaming instabilities. An electron-emitting brush ring produces a low-density plasma that allows good beam propagation. The beam then ionizes the helium, yielding a plasma density in the range $n=5\times10^{13}$ cm$^{-3}$, leaving enough neutral He atoms for the optical spectroscopy. We measured $n$ using a microwave interferometer and also by an optical technique. This used the fact that oscillating Langmuir electric fields induce optical emission in the vicinity of forbidden transitions, causing an emission line with frequency difference $\omega_p$. Both this method and the interferometer gave values of $n$ which always agreed to within 20% or less. The uniform beam propagates with a 3-cm radius. A 1-kG magnetic field suppresses magnetohydrodynamic beam instabilities. An extensive microwave-detection system provides further correlations between turbulent fields and electromagnetic emission.[12]

We detect Stark shifts in neutral He within the beam volume, using optical fluorescence. To get nonzero shifts from rapidly oscillating Langmuir fields we used a quadratic Stark system in singlet He, the $3\,^1P_1$ and $3\,^1D_2$ levels.[16] Radiative emission from the transitions $3\,^1D_1 \rightarrow 2\,^1P_1$ (6678 Å) and $3\,^1P_1\rightarrow 2\,^1S_0$ (5015 Å) appeared with Stark shifts.[17] Shifts up to 9 g cm$^{-1}$ implied rms fields up to 120 kV/cm.

Earlier spectroscopic study of beam-plasma turbulence[16] used hydrogen lines and found no fields higher than 20 kV/cm. They made no measurements of the probability distribution of electric fields. Those experiments found that electric fields decayed throughout their 100-ns beam pulse. In contrast, we find that the mean field strength is constant throughout the pulse.

Typical electric-field spectra for a single shot (Fig. 1) display fast spiky features which arise from single photon events. Figure 1 used the 5015-Å line, with each channel covering 0.4 Å (1.6 cm$^{-1}$). We checked noise levels in the system by looking at channels away from the He line with the beam on, and also by looking at the He line position without the beam. Both cases gave an average of one count per channel per ten shots. This is far below the observed signals in each channel where shifts are reported. Null tests with the fiber optic disconnected gave the same noise levels.

To be sure that we were seeing Stark shifts, we looked to the red side of the unshifted $3P$ line and the blue side of the unshifted $3D$ line. Both checks gave only noise levels for frequencies beyond the instrumental broadening of about 0.2 Å. This confirms the asymmetry of a true shift. We also tested whether plasma motion or other effects could give a misleading Doppler shift. The $3P$ line shifted to higher energy and the $3D$ to lower energy, whereas a Doppler effect would give shifts of the same sign for both. Also, lines which should have no Stark

 

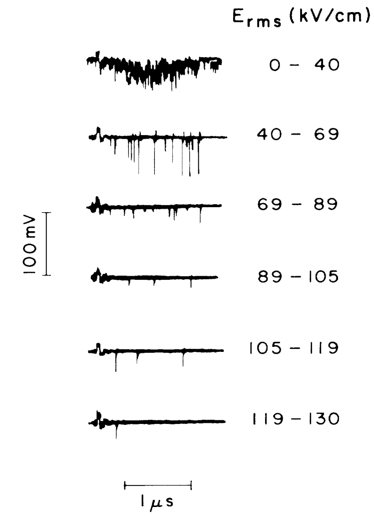


FIG. 1. Oscilloscope traces of six channels of one shot using the 5015-Å line. The electric field range of each channel is indicated. The positive square pulse at the beginning of each trace is a time marker.

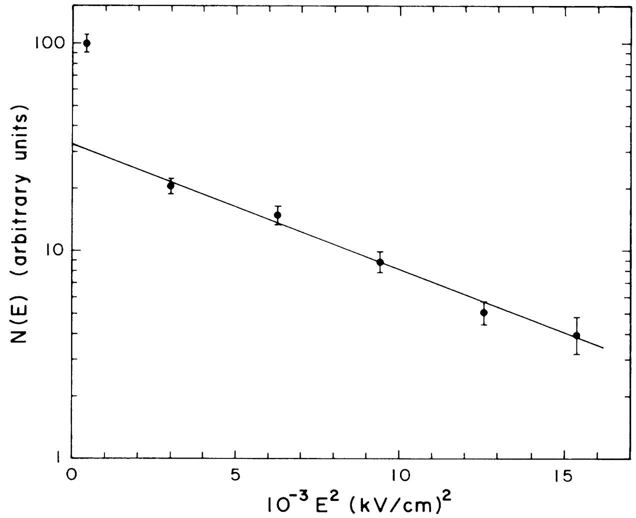


FIG. 2. The number of pulses $N(E)$ at each channel, corrected to a constant channel width in $E$, as function of $E^2$. Data were gathered from 70 beam shots, averaged over the 400 ns centered on the beam current peak.

shifts showed no counts above the noise level in channels beyond the instrumental broadening.

Note how many more events there are at lower $E$ in Fig. 1. We believe this arises from two effects. First, our optical system samples uniformly across the entire plasma column radius, giving no spatial resolution. Since the beam occupies only the inner 6 cm of the 20-cm-diam plasma column, we necessarily get contributions from the expected strong beam-plasma interaction zone (high $E$) plus the plasma halo around it (low $E$). This probably gives a two-component picture, with a substantial contribution of low $E$ from the 14-cm halo. We would then expect the low $E$ counts to be enhanced by a ratio of about 20:6.

We counted the number of counts for each $E$ bin, $N(E)$. We identify these as proportional to the probability of finding a field strength $E$ in the emitting volume within the focus of the light-gathering system.

Figure 2 shows the spectrum $N(E)$, which fits a curve $N(E) \propto \exp[-(E/E_0)^2]$, with $E_0 = 85$ kV/cm and $E$ in kV/cm. These data represent 70 separate shots of the beam, taken near the peak of beam current in order to probe the strongest beam-plasma interactions. We averaged over the 400 ns centered on the peak of the 1000-ns beam current pulse. As expected, there is an excess of counts in the lowest $E$ bin by a factor of about 3.

Few aspects of Fig. 2 can be reconciled with the general concepts of strong-turbulence theory. We do not see a power-law cascade of energy to shorter wavelengths (higher $E$), as occurs in the canonical models of energy transport in turbulent plasmas.[11] The usual picture envisions electrostatic wave energy built up at the beam-plasma resonant $k_0 = \omega_p/v_b = (6\text{ cm})^{-1}$, which then acts as a pump wave for parametric instabilities. In our very strong beam case, the modulational instability should shift energy in an inertial power-law cascade to the region above the Debye length, $\lambda_D \approx 10^{-3}$ cm. In this region theory usually assumes that each entity contracts individually. The cascade can run down a factor of about 100 before electron Landau damping dissipates the fields near $k\lambda_D = 0.1$, while greatly steepening the power law.

The customary way to find the relation between $E$ and $k$ is to invoke conservation of energy for separate self-compressing regions of intense electric field ("cavitons").[11] We write the volume of each zone as $V \propto k^{-D}$, with $k$ the mean wave number of the entity and $D$ the dimension of the entity. We assume energy conservation, $VE^2 = \text{const}$. This means our observed $N(E)$ would scale in $\mathbf{k}$ space as $\exp(-k^D)$, whereas usual strong turbulence theory yields a power law in $k$. An exponential behavior is not compatible with the usual picture underlying collapse scenarios[11] and suggests we are observing a new regime of very strong turbulence.

We immediately see that this is so, since

$$W = 2\left(\frac{E}{20\text{ kV/cm}}\right)^2 \left[\left(\frac{n}{10^{13}\text{ cm}^3}\right)\frac{T_e}{10\text{ eV}}\right]^{-1}, \quad (1)$$

so that Fig. 2 describes turbulence with $W > 1$, well beyond the limits of existing theory.

The only quantity we do not directly measure in $W$ is $T_e$, the background electron plasma temperature. The prepared plasma has about 1-eV temperature, but beam-plasma interaction can heat it considerably. This we fix by calculating the beam-plasma heating, including both electron and ion Landau damping and Ohmic dissipation of the plasma return currents.[18] Numerical solution yields values of $T_e$ in the range 30–70 eV, with convective loss along the field lines the primary cooling term. The calculations also give the ionization rate and predict an increase in plasma density of about 20% during the pulse. This agrees with our optical forbidden line measurements of the plasma frequency while the beam was on as well. Still, even though Ohmic heating describes the overall heating rate, $T_e$ might be higher near self-collapsing regions. With this caveat, we shall assume that the values of $W$ from Eq. (1) are approximately correct.

Figure 2 thus suggests we are exploring a new regime of strong plasma turbulence, since (i) $W>1$ and (ii) none of the simple scaling laws of so-called "strong" turbulence apparently work.

Our high values of $W$ confirm and extend earlier work[2] in which study of the microwave emission implied $W>m/M$. For the present experiments the influence of a kilogauss imposed axial magnetic field must be included in the nonlinear dispersion relation, which yields

$$\omega^2=\omega_p^2\left[1+3k^2\lambda_D^2+\left(\frac{\omega_c}{\omega_p}\right)^2\left(\frac{k_\perp}{k}\right)^2-W\right], \quad (2)$$

where $\omega_c$ is the electron cyclotron frequency and $k$ is the wave number perpendicular to $B$. As the beam current increases, numerical solution of energy-cascade equations[17,19] shows that $W$ increases rapidly. Our observations (Fig. 1) confirm the rapid rise of $E$. The "weak"-turbulence condition $W>(k_0\lambda_D)^2\cong 10^{-5}$ occurs in a nanosecond. Supersonic collapse begins within 10 ns, when $W>m/M\cong 10^{-4}$. Anisotropy from the magnetic field plays a role in ponderomotive collapse until about 50 ns into the microsecond beam pulse. By this time $W>(\omega_c/\omega_p)^2\approx 0.01$, after which theory says that self-compression of cavitons proceeds isotropically.[7] Thereafter, we expect that three-dimensional isotropic calculations should apply.

We cannot measure lifetimes of any underlying entities because we have too few photons to identify separate events. The lifetime for supersonic collapse,

$$t_{ss}<\omega_p^{-1}(3W\,\mu s)^{-1/2}\sim 1\text{ ns})W^{-1/2},$$

given by "strong"-turbulence theory[11] would be undetectable in any case. The same theory yields $k\lambda_D\approx 0.1W^{-1/2}$, which implies a picture of dissipation on scales $k\lambda_D\sim 0.1$. A further piece of evidence for a self-compressed picture is that the highest $E$ values appear in the beam pulse only after about 400 ns, a time compatible with the time for ion motions to form deep cavities through motions over scales $\sim 1$ cm$\sim k_0^{-1}$ at sound speed $C_s$.

The broad picture of energy transport and nonlinear stabilization of the beam-plasma instability by modulational transfer[11] gains some support from both the strength and spectrum of $E$. The highest observed fields, $W\approx 10$, are still an order of magnitude smaller than those prediced by the trapping of relativistic beam electrons in the troughs of unstable, large-amplitude waves.[13] This agrees with the initial starting point of "strong"-turbulence theories, in which modulational coupling from $k_0$ to $k$ happens faster than the nonlinear trapping state can form. Further, a trapping model demands a sharp $E$ spectrum, unlike the spectrum of Fig. 2.

Earlier calculations of dynamical screening models[17,19] for turbulent plasmas yield an exponential $E^2$ spectrum, but apply only for values of $W\ll 1$. In these models the $\exp(-E^2)$ scaling arises from Debye shielding. Since $W>1$ undermines many of the assumptions compatible with the usual Debye-length calculation, this region of $W$ demands a new explanation, possibly involving long-range correlations. Our observed fields are about a thousand times the Holtzmark field $e/b^2$, with $b$ the interparticle separation.[17] Thus, changes in the theoretical picture would be unsurprising.

In summary, we have explored a new regime of beam-plasma turbulence, using a Stark-effect diagnostic to directly measure the strength and frequency of Langmuir fields. Values of $W>1$ are common. The observed Gaussian spectrum of the turbulent field $E$ does not fit conventional "strong"-turbulence theory and may imply correlations over distances greatly exceeding a Debye length.

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