Scattering of Relativistic Electrons on Electric Field Concentrations in a Turbulent Plasma

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The angle and energy distribution of a 800-keV, 6-kA, 100-ns electron beam have been measured in an experiment in which this beam interacts with an initially cold hydrogen plasma of density 7×10^{19} m^{-3}. Towards the end of the beam pulse both distributions become Gaussian. They are explained by the assumption of collisions of beam electrons with three-dimensional "blobs" containing fields with amplitudes of 10^8 V/m. Spectroscopic measurements give average fields of 10^6 V/cm. These observations are interpreted as evidence for the occurrence of Langmuir collapse.

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Experiments[1-3] have demonstrated the capability of electron beams to generate spiky turbulence, i.e., spatially localized areas in which waves of large amplitude ($\approx 10^4$ V/m) are trapped. In these experiments electron beams (≈ 1 keV, ≈ 100 A m^{-2}) are injected into tenuous plasmas with densities around $n_e = 10^{15}$ m^{-3}. We report measurements that extend observations on strong turbulence to plasma densities that are a factor of 10^5 higher. In our case turbulence is generated upon the injection of an 800-keV, 10^7-A$\cdot$m^{-2} relativistic electron beam into a plasma with $n_e = 7\times10^{19}$ m^{-3}.

In the low-density experiments only a few density cavities are generated by the beam. In our case the beam generates an ensemble of such "blobs." We observe the influence of many random collisions between beam electrons and the blobs. The result is a broadening of the beam distribution in energy[4] and in opening angle.[5] The measurements show all kinds of odd energy distributions during the first 50 ns of the beam shot. After 60 ns ($\cong 500/\omega_{pi}$, where ω_{pi} is the ion plasma frequency), however, the distribution shows a dominance of random collisions and a statistical analysis is applied. This lead to fields $E_t \approx 10^8$ V/m.

Spectroscopic measurements yield an estimate for the beam-generated high-frequency electric fields. We obtain $E_k \approx 1$ MV/m. The difference between E_k and E_t then is indicative of the collapse of Langmuir waves into blobs.

The occurrence of solitonlike structures has been invoked earlier. Radiation at plasma frequency harmonics in current-driven turbulence[6] was explained by soliton fields of 6×10^7 V/m.[7] However, we believe that we present more direct evidence of Langmuir collapse in a dense plasma.

A relativistic electron beam (REB) ($V_b = 0.8$ MV, $I_b = 6$ kA, $\tau_b = 100$–150 ns, $\phi_b = 3.5$ cm) is injected into a cylindrical drift tube of 2.5 m length and 0.12 m diam.[8] The beam is extracted from a cold carbon cathode sphere of 2.5 cm diam, and passes through a Ti anode foil of 18 μm thickness. Beam-current rise time is 30 ns. The beam is guided by a magnetic field of 0.21 T.

Background pressure is 10^{-6} Torr. Plasma is created by striking a discharge[4] between the wall and two annular electrodes of 6 cm diam, placed 0.48 and 1.92 m downstream from the anode. Hydrogen gas working pressure is 10^{-3} Torr. The beam is injected 50 μs after initiation of the discharge. Measurements by probes, 8-mm microwave cutoff, and H^0 beam attenuation give a plasma density $n_e = 7\times10^{19}$ m^{-3} $\pm$ 30%. During the REB shot the density does not change by more than 10%.

Diagnostics include Rogowski coils, ten-channel Thomson-scattering and optical-spectroscopy setup at $z = 1.22$ m,[5] a four-channel beam-angle analyzer[9] placed at $z = 0.66$ m, and an eight-channel beam-energy analyzer[10] situated 2 m beyond the collector. Only those electrons which have their velocity angle within a cone of 1 deg with respect to the guide field are detected by the energy analyzer. Data are recorded by a twelve-channel digital data-acquisition system. Figures presented in this paper result from a numerical integration over 16 ns. All diagnostics have a time resolution better than this.

In Fig. 1 we present results of measurements with the angle analyzer. For three successive beam shots are given the mean velocity angle $\bar{\theta}$, found by comparing the measured distribution with the distribution predicted by multiple-scattering theory,[9] and the least-squares deviation Δ of the measured from the calculated distribution. It is seen that $\bar{\theta}$ increases whereas Δ decreases during the first 50 ns. It was found that $\bar{\theta}$ is not appreciably larger at

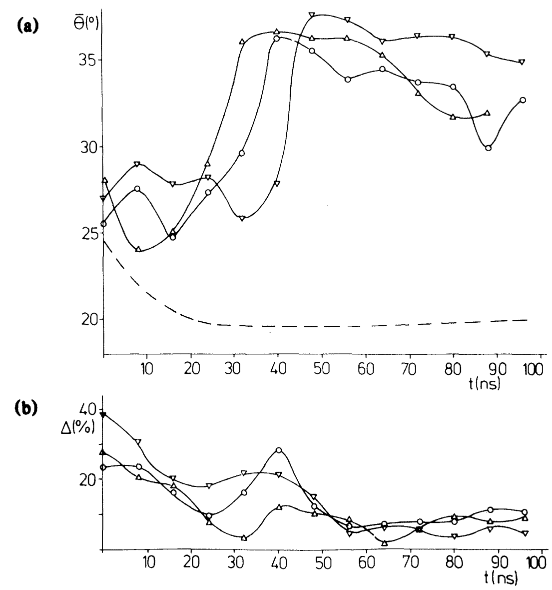

FIG. 1. The mean angle $\bar{\theta}$ of the velocities of the beam electrons, and the rms deviation Δ of the angular distribution function from the prediction by multiple scattering theory Δ. These reduced quantities are presented for three shots of the REB through an 18-μm titanium foil into a plasma with density $n_e = 7\times10^{19}$ m^{-3}. The analyzer was placed at $z = 66$ cm. The dashed line in (a) represents the average angle $\bar{\theta}$ for injection of the REB into vacuum.

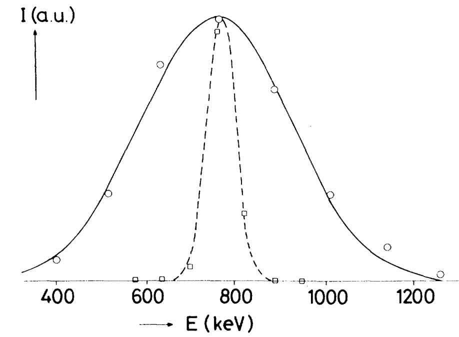

FIG. 2. Parallel energy distribution of the beam electrons. The circles give the distribution at $t = 50$ ns after the beginning of the REB pulse, upon injection of the REB into a hydrogen plasma with density $n_e = 7\times10^{19}$ m^{-3}. The full curve is a least-squares fit of a Gaussian to the measured points. The dashed line is the Gaussian fit to the measured energy spectrum in case the beam is injected into vacuum.

greater distances from the diode.

Figure 2 shows a beam energy distribution measured at $t = 50$ ns. The energy width of each detector is ≈ 20 keV. The full curve is a Gaussian distribution, $F_b(E_{\parallel}) \propto \exp\{-(E_{\parallel}-E_0)^2\}$, fitted to the experimental points. The dashed curve is the same for the case in which the beam is injected into vacuum. Figure 2 shows an increase in width (full width at half maximum) from 80 to 400 keV.

With the optical spectrograph,[5] having a resolution of 0.23 Å, satellites on the H_β line were observed. The intensity of such satellites is a measure for the strength of high-frequency fields, whereas their displacement corresponds to the field frequency. In a beam-plasma system one expects the excitation of waves at the electron plasma frequency ω_{pe}. The measured displacement of the satellite $\Delta\lambda$ then leads, according to $\Delta\lambda = \lambda^2\omega_{pe}/2\pi c$, to a plasma density of $(6\pm2)\times10^{19}$ m^{-3}, in agreement with density measurements. The strength of the high-frequency fields is obtained by comparing the measured satellite intensity with calculated intensities.[11] The result is shown in Fig. 3.

In addition to satellites, forbidden lines were observed in a He plasma at a working pressure of 10^{-3} Torr. We determined the ratio of the intensities of the 3^1P-2^1P line at 6632 Å and the 3^1P-2^1S line at 5015 Å. Comparison with calculated ratios[12] yields electric field strengths. These results are also shown in Fig. 3.

In spectroscopic measurements a small volume of

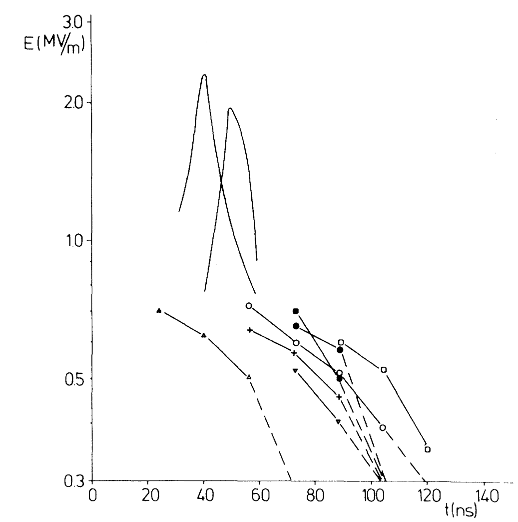

FIG. 3. Time dependence of the field strength of the high-frequency electric fields during the REB pulse. The two curves at the upper left result from the measurement of forbidden-line intensities in helium. The other curves result from the measurement of satellites of the H_β line in a hydrogen plasma. The density in all shots is $n_e = (7-10)\times10^{19}$ m^{-3}. The measurements were done at $z = 122$ cm.

plasma, with an area of 0.1×10 mm^2, is imaged onto the slit of the polychromator. Satellite intensities (Fig. 3) show that within this volume Langmuir oscillations are present with amplitudes of at least 0.8 MV/m. Forbidden-line intensities corroborate this conclusion.

Thomson-scattering data show that at $t\approx50$ ns, the electron temperature reaches a maximum value of ≈100 eV.[4] With this temperature and a field $E_k=2$ MV/m (see Fig. 3), the normalized field energy density

$$W=\tfrac{1}{4}\epsilon_0|E|^2/(nkT_e) \tag{1}$$

becomes $W_k=8\times10^{-3}$.

The largest field amplitudes in a beam-plasma system can be expected to occur for the quasihydrodynamic interaction. Theory[13] predicts a saturation field $E_{sat}=20$ MV/m. This field should occur at a distance from the diode corresponding to some six growth periods, $z_{sat}\approx6\beta c/\Gamma\approx0.1$ m. At further distances the waves decay by one of several mechanisms.[14,15] In agreement with this picture the measured fields have a smaller value than the maximum predicted by theory.

The measured beam distributions result from the interaction of individual electrons with waves along their path in the plasma. Interpretation of data is only possible if measurements show evidence of statistical behavior. The distribution fulfills this demand for $t\geqslant50$ ns.

Strong-turbulence theory[15] gives an order-of-magnitude expression for the scattering of beam electrons. Scattering over an angle of 1 rad takes place in a time

$$\tau_D=(\omega_{pe}W_a)^{-1}(mc^2/kT_e)^{3/2}, \tag{2}$$

where W_a is the field energy density to be obtained from the measurements with the angle analyzer. In Fig. 1 we observe an increase in the mean angle $\overline{\theta}$ from 20° (at all z in vacuum) to 35° at $z=0.66$ m, for $t\geqslant40$ ns. The increase in angle $\delta\theta=15°$ occurs in a time $z/\beta c\cos\overline{\theta}\approx2.7$ ns. Consequently, $\tau_D\approx11$ ns. Inserting this value in Eq. (2), we obtain $W_a\approx70$ and $E_a\approx1.7\times10^8$ V/m. It is possible that the scattering over $\delta\theta=15°$ took place on a shorter distance than 0.66 m. Then W_a would be larger. Experimental constraints do not allow measurement at a shorter distance.

We explain the energy spectra by assuming that a beam electron collides N times with a blob. On traversing the blob the beam particle approximately stays in phase with respect to the confined Langmuir waves, and it is continually accelerated or decelerated, depending on the particular value of the phase on entering the blob. So many collisions result in a symmetric broadening of the beam energy distribution, as is indeed observed. If on the average the beam-particle energy changes by an amount ΔE during a collision with a blob, then a random-walk process results in the following distribution:

$$F_b(E)\propto\exp\{-(E-E_0)^2/2N(\Delta E)^2\}. \tag{3}$$

An upper estimate for N is obtained by assuming that a blob arises on each Langmuir wavelength[1] $\lambda_p=2\pi\beta c/\omega_{pe}=3.7\times10^{-3}$ m. Then $N_{max}=L_e/\lambda_p$, where L_e is the length of plasma column over which blobs are generated. We take $L_e=0.66$ m, because the angle analyzer measurements showed no further increase in $\overline{\theta}$ for $z>0.66$ m. The experimental width of the distribution of 400 keV and $N_{max}=175$ lead to $\Delta E=13$ keV in Eq. (3). The dimensions of the blobs are considered to be of order $10\lambda_D$,[16] where $\lambda_D=13$ μm is the Debye length. The mean blob field amplitude experienced by beam particles is $E_e=\Delta E\sqrt{2}/10\lambda_D=1.3\times10^8$ V/m, for $T_e=100$ eV. Thus the field amplitudes obtained with the beam energy or angle diagnostic are both of order 10^8 V/m.

The fields of the Langmuir oscillations are sufficiently large that the criterion for strong turbulence, $W_k>>(k_0\lambda_D)^2$, where k_0 is the wave number of the Langmuir spectrum, is fulfilled. Substituting the appropriate values we find

$$W_k=8\times10^{-3}>>(k_0\lambda_D)^2\approx(v_{te}/c)^2=4\times10^{-4}.$$

The fields belonging to the Langmuir oscillations are two orders of magnitude smaller than the blob fields. A possible explanation is the collapse of Langmuir waves. If we assume that wave energy is conserved during collapse, and that the collapse is n dimensional, then the field energy density must increase in proportion to r^{-n}, where r is the typical length. The size varies from λ_p to $10\lambda_D$, which is by a factor of 30. The energy density changes from W_k to W_a, which is by a factor of at least 3×10^3. We tentatively conclude that $n=3$. So if collapse takes place then the Langmuir waves contract in three dimensions.

Measurements on the return current show that the plasma resistance is only a factor 8 larger than the classical resistance. This supports the picture in which Langmuir waves collapse into blobs of very small size, leaving the greater part of the plasma in a quiescent state.

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