Formation of Electric Field Spikes in Electron-Beam–Plasma Interaction

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High-frequency waves, which are driven by a strong electron beam and propagate along a density gradient, can form spatially concentrated "HF spikes" which extend typically one wavelength (1 cm) in the direction along the beam. Experiments and computer simulations show that the spike is a standing wave with nodes at boundaries to regions with propagating waves. The spikes only form in a plasma density gradient, and attempts to produce them in homogeneous plasma have failed. They form without trapping of the waves in density cavities and remain stable after the formation, i.e., there is no tendency towards collapse of the structure. [S0031-9007(96)01902-3]

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In previous papers we have reported investigations of the high-frequency (HF) oscillations driven by electron beams injected into the plasma at an electric double layer. In this case the beam density is in general much higher than in the classical beam-plasma experiments, and the wave propagates along the density gradient that surrounds the double layer [1,2]. It was found that the amplitude of the HF waves had a sharp maximum and formed a spike with a width of 1–2 cm (about one wavelength) within the region with density gradient. The growth length and the amplitude were found to agree fairly well with theoretical expectations from linear growth [3,4] and beam trapping [4,5]. However, the limited extent in the beam direction has remained unexplained. Proposed explanations which we have investigated, but cannot match our data, are Langmuir collapse, the formation of wave packets moving with a slow group velocity $d\omega/dk$, and rapid thermal Landau damping after the wave growth is saturated. In these experiments two innovations in HF probe design made it possible to achieve both an absolute amplitude calibration of electric fields up to 600 MHz and single-sweep multiple probe measurements without severe mutual probe disturbance, both features which had never been achieved before.

In this paper we report experimental observations of this HF spike in the plasma density gradient in front of a plane cathode and in computer simulations, and for the first time a physical picture, supported by both experiments and simulations, is presented of such HF spikes. The HF spikes can form for electric fields well below the threshold field for modulational instability, and the spikes form at early times long before a density cavity has formed in the simulations. A conditional sampling technique is used to obtain space-time graphs of the wave structure in the turbulent plasma, showing that the HF spike consists of a narrow standing wave with nodes at the boundaries to the neighboring regions with lower-amplitude, propagating waves. The computer simulations reproduce this wave pattern in detail, and the spike forms only when a density gradient is introduced but not when the beam is injected into homogeneous plasma. The simulations also show that the electron beam is strongly scattered in the vicinity of the stationary HF spike.

The experimental device was a large cylindrical stainless steel tank (Fig. 1). The coil on the right-hand side of the chamber produces a magnetic mirror field which is approximately constant over the interaction region and gives an electron gyro radius of about 1 mm there. The plasma was produced by a discharge between a hot Lanthanum hexaboride cathode (diameter 35 mm), and a ring-shaped anode (inner diameter 100 mm, and outer diameter 330 mm). The cathode was heated to about 1500 °C. By applying a negative voltage to the cathode we inject an electron beam through the plasma. Most of the applied voltage falls across a sheath close to the cathode. The voltage drop in the sheath is 35 V. The plasma is produced via ionization of the background gas by the electron beam. The background gas is argon at a pressure of 1×10^{-4} mbar. Electrons from the cathode must move across the magnetic field to reach the anode ring. The

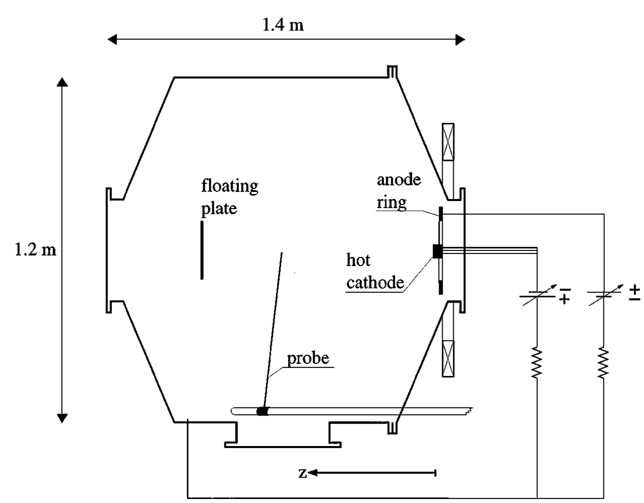

FIG. 1. The Green tank in which the experiments were performed. The electrons are accelerated in the cathode sheath and travel to the left in the figure.

beam density is about 25% of the total electron number density. The beam density was calculated from the measured current and the velocity gained from the acceleration in the cathode sheath.

The plasma potential and the plasma density as a function of the axial coordinate z are shown in Fig. 2. The plasma potential measurements were made using electron emitting probes. The density and temperature were found from analysis of Langmuir probe characteristics. Some discharge parameters are shown in Table I. The electric field of the high-frequency plasma waves was measured with double probes matched to 50 Ω [6]. To minimize the disturbance on the plasma we used naked thin spirals as probe shafts, as described in [2,7].

The maximum amplitude of the HF electric field, as measured by a probe that was moved to different positions along the beam, is shown by the solid curve in Fig. 3. Within this region the HF spike has an irregular motion back and forth with a velocity of the order of the ion acoustic velocity due to fluctuations in the turbulent plasma. To obtain the shape of the spike by simultaneous measurements we use the technique described in [1]. We have three probes, A, B, and C, where probe A is closest to the cathode, probe B is in the middle, and probe C is farther out. The recordings were triggered by a high level on probe B which was kept stationary while probes A and C were moved to different positions. The maximum amplitudes on probes A and C, within ± 10 ns (larger than the travel time of the wave between the probes) from the triggering time, were recorded. Four recordings were taken for each value of the probe separation. The crosses and rings below the solid curve in Fig. 3 shows the averages of these four. The diagram shows that the HF spike extends typically 1 cm, about one wavelength, in the beam direction. The field is axially directed over most of the plasma column cross section which is determined by the diameter of the cathode. At the radial boundary the magnitude of the field drops to very small levels.

Detailed measurements of the growth rate, amplitude, damping rate, and motion of such HF spikes were reported in [1] in a different experimental configuration with a smaller beam density. The space and time evolution of the wave form within a spike is here reported for the first time. For this purpose we have used a conditional sampling technique. A large amount of data were collected in the turbulent plasma with three probes at various distances from each other. The data were then processed in a computer to select subsets of data satisfying various selection criteria which all were based on the signal from the triggering probe B alone. A successful combination, which picks out the same frequency and wavelength, was that the wave amplitude at the position of probe B should be between 1000 and 1500 V/m, and constant within 1% over at least two wave periods. From our full data set, we used all the data that satisfied this condition. In cases where we got several "hits" for the same probe distance we used the average field from these. The result can be visualized by a plot such as is displayed in Fig. 4. It shows the electric field of the wave as a function of time and space. The standing wave at $z = 45$ mm is clearly seen. Outside the standing wave the dominating feature is a forward moving wave with a phase velocity slightly below the beam velocity, as expected by a beam-driven plasma oscillation. This wave is amplitude modulated so that an interference pattern is created, suggestive of interference with a backwards traveling wave with a lower amplitude. A line with a slope corresponding to the phase velocity of such a backwards traveling wave should trace the amplitude maxima created by the constructive interference between the two waves. The slope of such a line shows that the backward traveling wave has a phase velocity about equal to that of the forward wave.

The HF spike is found approximately between $z = 40$ mm and $z = 50$ mm in Fig. 4, where the amplitude is largest. We interpret this part as a purely standing wave.

TABLE I. Some parameters from the experiment and the simulation.

	Experiment	Simulation
Plasma density n_e	2×10^{15} m^{-3}	2×10^{15} m^{-3}
Relative density n_{beam}/n_e	20%–30%	5%
Electron temperature T_e	5–10 eV	5 eV
Beam energy W_{beam}	35 V	35 eV
Magnetic field B	7 mT	0

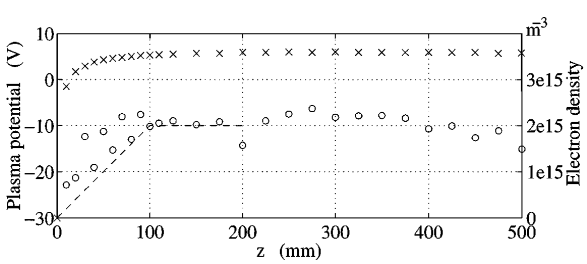

FIG. 2. Plasma potential (×) and density (○) measured along the axis of the experimental device. The dashed curve shows the initial plasma density profile in the simulation.

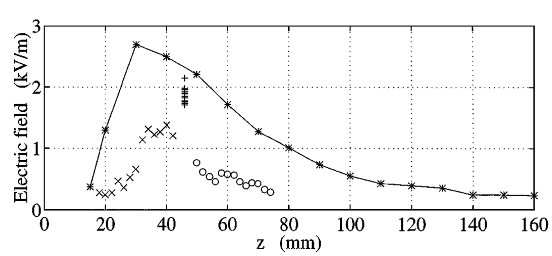

FIG. 3. The maximum electric field amplitude as a function of the axial coordinate z (solid curve). Also shown are the results of simultaneous three probe measurements. Measurements made with probe A, which is closest to the cathode, are marked "×," probe B "+," and probe C "○." There is clearly an HF spike, as in the double layer case.

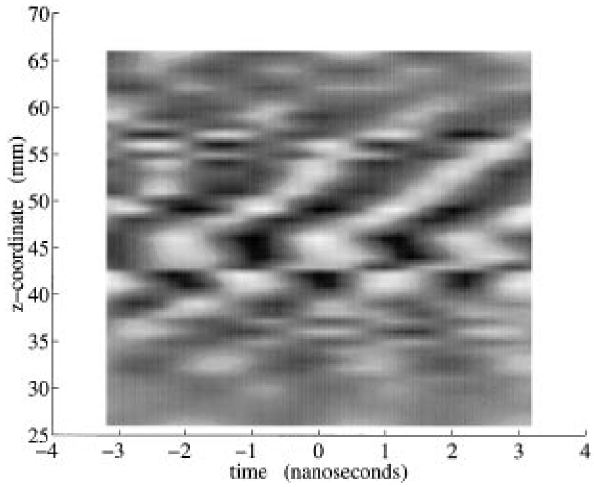

FIG. 4. Space-time diagram of the electric field, given by a gray scale with white as maximum. Dark and light stripes pointing in a direction corresponding to the phase velocity are seen, and the field spike at $z = 45$ mm is clearly seen. There are also less pronounced stripes going towards decreasing z values with increasing t values, thus indicating that a fraction of the wave is traveling backwards. The total wave pattern outside the field spike region can be considered as a superposition of a traveling and a standing wave.

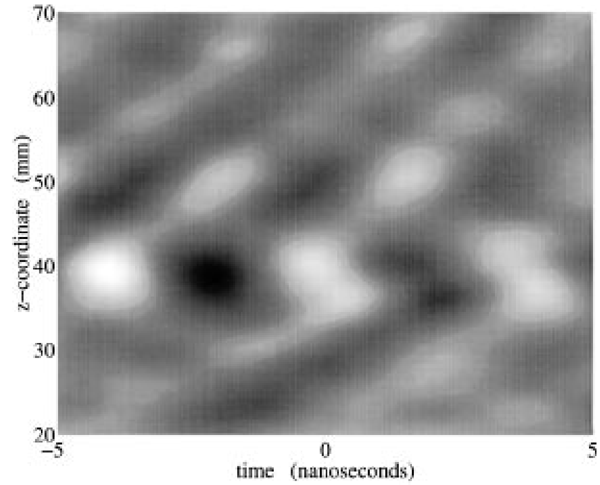

FIG. 5. The electric field of the wave as a function of time and space in the simulation. The similarity with the experimental data shown in Fig. 4 is conspicuous. Also in the simulation the total wave can be considered as a superposition of a traveling and a standing wave.

This hypothesis is tested using the particle-in-cell code, PDP1 [8].

The simulation parameters are compared to the experimental parameters in Table I. We simulated a 200 mm long plasma, whose temperature was 5 eV. The initial density was increasing linearly from zero at $z = 0$ to 2×10^{15} m^{-3} at $z = 100$ mm, and was constant and equal to 2×10^{15} m^{-3} from $z = 100$ mm to $z = 200$ mm. For reference, this profile is shown as a dashed curve in Fig. 2. The beam was not injected at the boundary but self-consistently accelerated in a cathode sheath. A half-Maxwellian distribution of electrons (current density of 20 A/m^2) was injected at $z = 0$, with a temperature of 0.15 eV. The left ($z = 0$) electrode was biased to -20 V. The voltage drop across the sheath then became about 35 V, that is, equal to the voltage drop accelerating the beam in the experiment. The plasma potential and density profiles are similar to the experimental ones shown in Fig. 2. A sheath, corresponding to the cathode sheath, forms close to the left boundary of the simulated plasma.

A grey scale plot of the electric field in the simulation as a function of time and space is shown in Fig. 5. The electric field was recorded between $t = 3.0$ μs and $t = 3.01$ μs. The similarity with Fig. 4, which shows the electric field in the experiment, is conspicuous. In both cases there is, outside the central HF spike, an interference pattern where the forward traveling wave dominates. The HF spike in both cases is a standing wave with about one wavelength extension. The simulated HF spike is centered at close to the same position as in the experiment, $z = 40$ mm. Figure 6 shows the instantaneous E field in the simulation for $t = 3.0$ μs. The dominating amplitude of the HF spike is more evident than in the grey scale plot of Fig. 5. Thus the simulation has reproduced the HF spike that was discovered experimentally [1].

The strong scattering of the beam electrons in the vicinity of the HF spike is shown in Fig. 7. After a sufficiently long time, a small depletion in the plasma density can be seen in the simulation at the same place as the peak in the electric field showing the effect of the ponderomotive force. However, the field spike is seen before the density depletion appears, and when the simulation is run for several microseconds, the peak does not change size or move. Hence we conclude that the density depletion has little or no influence on the wave itself in this case.

We have investigated the importance of a density gradient for the HF spike to appear. When running the simulation with a constant plasma density of 2×10^{15} m^{-3} without any density gradient, the waves were purely forward traveling, and were present at large amplitude in the whole plasma to the right of $z = 40$ mm where they had

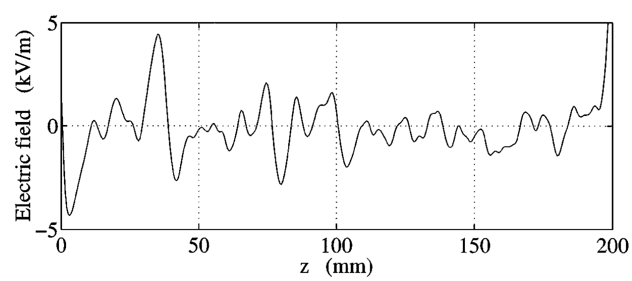

FIG. 6. The simulated electric field at time $t = 3.002\,89$ μs. The field spike is at about $z = 35$ mm. The position remains stationary, and the field oscillates between about ± 4 kV/m.

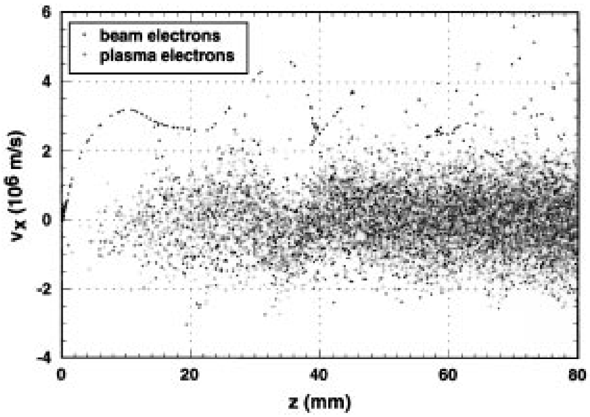

FIG. 7. Velocity phase space for beam and plasma electrons at time $t = 3.002\,89$ μs. The plot displays 80 mm of the 200 mm diode to emphasize the HF region. The position of the HF spike is about $z = 35$ mm, and the beam is strongly dispersed after passing the spike.

grown to full amplitude, and no spike appeared even for very long simulation times.

An HF spike in a density gradient was also found in an experiment where the beam was generated by acceleration of electrons in an electric double layer [1]. The similarity of the waves in the two discharges were found in spite of the very different experimental conditions. In the double layer (DL) case the electron beam was going into the magnetic mirror, whereas in the case here it goes out of it. The beam emitted from the cathode is much colder than the beam of the DL case. The relative beam density $\eta = n_b/n_0$ was 3% in the DL case, and 20%–30% in the cathode case. The main similarity was the voltage by which the beam electrons were accelerated. It was 35 V in the simulation and the cathode experiment, which is not too far from the 27 V double layer voltage.

In summary, we have shown that the field spike is formed both in two different experiments and in the simulations, and we conclude that it represents a general phenomenon, not peculiar to the experimental configuration used in this paper. In all three configurations we have observed the HF spikes only in regions with a density gradient. The HF spike represents a standing wave. The simulations show that the HF spike strongly scatters the electron beam, and accordingly it offers a new type of beam scattering mechanism which can dominate over amplitude saturation by electron trapping in a propagating wave.

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