BEAM-PLASMA INTERACTION IN THE PRESENCE OF DENSITY GRADIENTS

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Abstract

The formation of narrow high frequency electric field spikes in plasma density gradients is investigated using one dimensional particle in cell simulations. It is found that the shape of the plasma density gradient is very important for the spike formation. A coupling to the ion motion, is not necessary for the formation of hf spikes. However, the hf spike influences the ion motion, and ion waves are seen in the simulations. The spike can be seen as a coupled system of two eigenmodes of a plasma diode fed by a beam-plasma interaction. Based on a simplified fluid description of such eigenmodes, explanations for the localization of the spike, spatially and in frequency, are given. The amplitude of the oscillating density is comparable with the dc density level close to the cathode. This sets a limit for the wave amplitude in the whole system. (This paper is a short version of Ref. [1].)

1. Introduction

Beam plasma interaction occurring in density gradients can give rise to narrow (about one wavelength) high frequency electric field spikes, as shown by experiments and particle in cell simulations [2,3,4]. The hf spikes have been studied in a double layer experiment [2], through particle in cell simulations, and in an experiment with a hot cathode as source of the electron beam [3,4]. Common to these studies is that the plasma density has a gradient with increasing density in the direction of the electron beam.

The spike has an irregular motion back and forth with ion acoustic velocities due to fluctuations on the ion time scale, and time resolved measurements are neeeded to find its shape. This motion covers a distance of several half widths of the spike, and a fixed probe in this region shows strong modulations in the hf power due to the motion of the spike. The space time evolution of the electron wave amplitude has been recorded by conditional sampling of data, simultaneously obtained by three hf probes in the turbulent plasma. An interference pattern between a forward and a reflected wave appears, and, in the centre of this pattern, a narrow region with a standing wave with high amplitude is observed. A similar wave pattern is observed in the particle in cell (PIC) simulations.

2. PIC-simulations

PIC-simulations were performed using the one dimensional electrostatic code, PDP1 [5]. The plasma was simulated using a 300 mm long, short-circuited, plasma diode, with a background electron temperature of 6 eV. The initial density increased linearly from zero at the left hand boundary ($x = 0$) to a constant value ($1 \cdot 10^{15}$ m^{-3}) in the right hand part of the plasma ($x > 90$ mm). A half-Maxwellian distribution of electrons, with a temperature of 0.15 eV for the full Maxwellian distribution, was injected at $x = 0$ and accelerated in a cathode sheath that developed self-consistently. These electrons formed the beam. A narrow region of standing waves at high amplitude, the hf spike, developed at $x \approx 50$ mm. Three different simulation experiments were reported in Ref. [1].

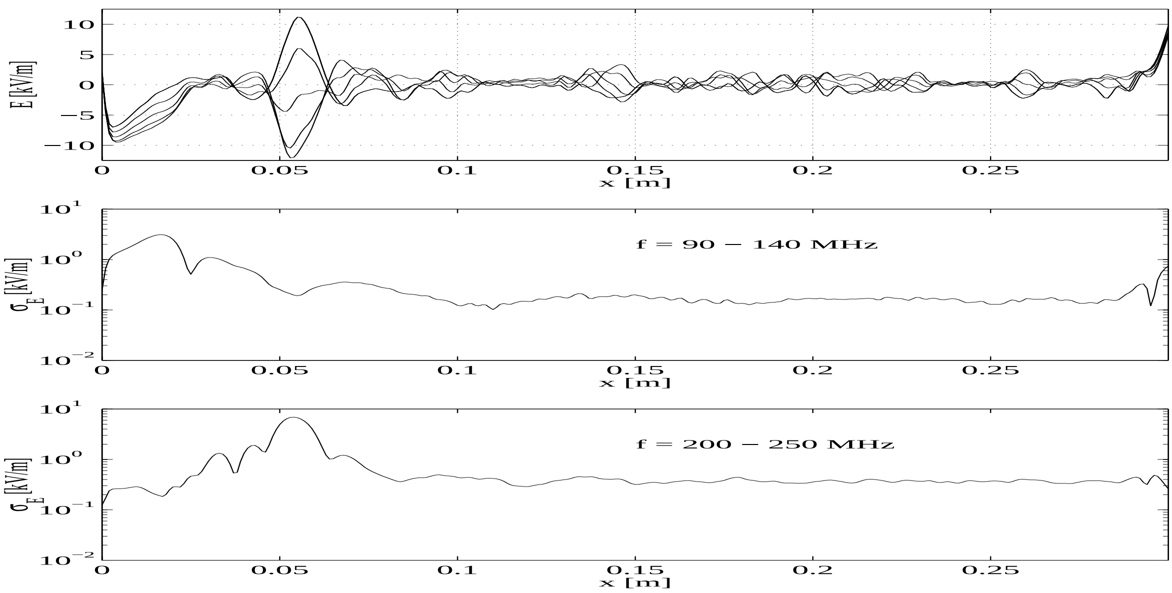

Figure 1. (a) The electric field for five times t from $t = 532$ ns to $t = 534$ ns. (b,c) A root mean square measure of the electric field in frequency bands around the dominant frequencies (seen in Fig. 2). The shown value is the standard deviation of the electric field after it has been filtered by a tenth order Butterworth bandpass filters. The original data was a 1.024 μs series with sampling frequency of 2 GHz. The standard deviation in (c) increases nearly two orders of magnitude from the cathode to the spike. The standard deviations in (b,c) have high and nearly constant values in the homogeneous plasma region where these frequencies are well below the local plasma frequency 284 MHz.

A simulation with mobile ions gives ion waves generated by the pondermotive force at the spike possition. The phase velocity of the forward travelling ion wave is estimated to 3.5 km/s, and the phase velocity of the backward wave is 5 km/s. (The sound speed for argon at 6 eV is 3.8 km/s.)

Starting from a situation with the spike, a replacement of the ions with the initial thermalized phase space distribution causes a disappearance of the spike, but a replacement of the electrons by with the initial phase space distribution causes no disappearance of the spike. A spike is also seen in simulations with rigid ions. Hence we conclude that the ion density as a function of space $n_{ion}(x)$ is important for the formation of an hf spike, and that ion motion is not necessary for spike formation.

The analysis can thus be limited to electron behaviour and the presented figures (Figs. 1,2) are based on simulations with rigid ions. The simulation results can be summarized in the following statements: **(1)** The spike is a two frequency system, the dominating frequency at the spike position and a subharmonic. **(2)** The spike is a system wide phenomenon as seen in the outer circuit current. **(3)** The density variation is small in most parts of the diode which makes it possible to find (approximative) eigenmodes with linearized equations, but **(4)** the amplitude of the oscillations is limited by the dc density level close to the cathode. This limit seems to determine the amplitude in the whole diode.

These observations lead to the following hypothesis. There are two coupled eigenmodes of the diode. The eigenmode with maximum amplitude at x_1 pre-modulates the beam, that is not yet fully accelerated. At x_2, the location of the maximum amplitude of the second eigenmode with frequency $2f_1$, i.e., twice the modulation frequency, plasma oscillations grow

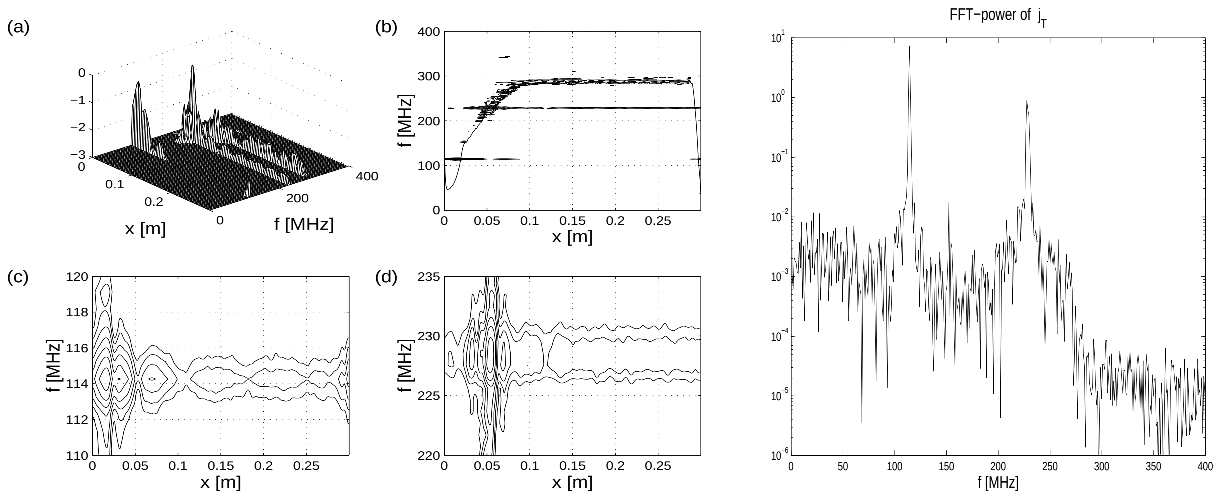

Figure 2. LEFT: FFT power of the electric field calculated from a 1.024 μs time series with 2 GHz sampling frequency. The shown values are normalized to the maximum power which corresponds to a harmonic field with amplitude of $\sim$11 kV/m. (a) The 10-logarithm of the power with the minimum limited to 10^{-3} of the maximum amplitude (for readability). (b-d) Logarithmic contour graphs, where two contours per power of ten are shown. The lowest contour shown in (b,d) is 10^{-3} and the lowest contour in (c) is 10^{-4}. The two pronounced frequencies (enhanced in (c,d)) have the maximum amplitudes a fraction of a wavelength before $f = f_p$. The local plasma frequency f_p is shown as reference in (b). Note in (c,d) that there are several spatial maxima and note also that the oscillations extend with constant amplitude into the region where $f < f_p$. RIGHT: FFT power of the outer circuit current. The two frequencies $f \sim (114, 228)$ MHz coincide with the localized spikes in the left panels.

to high amplitude. Since waves at the frequency f_2 cannot propagate into the higher density plasma at $x > x_2$ the waves are reflected, and the Langmuir wave travelling back towards the cathode feeds the pre-modulating oscillation at x_1. The growth and reflection of the forward wave, together with the damping of the backward wave account for the narrowness of the spike.

3. Fluid eigenmodes in a diode

Fully kinetic solutions of the (non-linear) beam-plasma interaction in density gradients are only reachable by the use of PIC-simulations. The PIC-simulations are too noisy and time consuming to study the frequency response of the diode, and the results are hard to interpret. As it will turn out, an understanding of the frequency response can be obtained, and some of the observations can be explained, within the framework of a fluid-model, neglecting the weak beam. Linearized dynamic equations capturing the inhomogeneities, the finite extension as well as the electrostatic fields, will be used. The solution is obtained in a two step procedure. First a static solution is found, and then those results are used as inputs in the dynamic equations.

The static electric field E_0 (index 0 on static variables) is determined from Boltzmann's and Poisson's equations and boundary conditions. For the parameters in the simulation $v(\partial/\partial x) \ll (\partial/\partial t)$ or $\partial(nvv)/\partial x \ll \partial(nv)/\partial t$, and the linearized momentum equation, continuity equation and Poisson's equation can be written as an inhomogeneous wave equation for the harmonic electric field E_1

$$\mathcal{D}E_1 \equiv \frac{\gamma k_B T_e}{m}\frac{\partial^2 E_1}{\partial x^2} + \frac{eE_0(x)}{m}\frac{\partial E_1}{\partial x} + (\omega^2 - \omega_p^2(x))E_1 = -\frac{i\omega}{\epsilon_0} j_T \qquad (1)$$

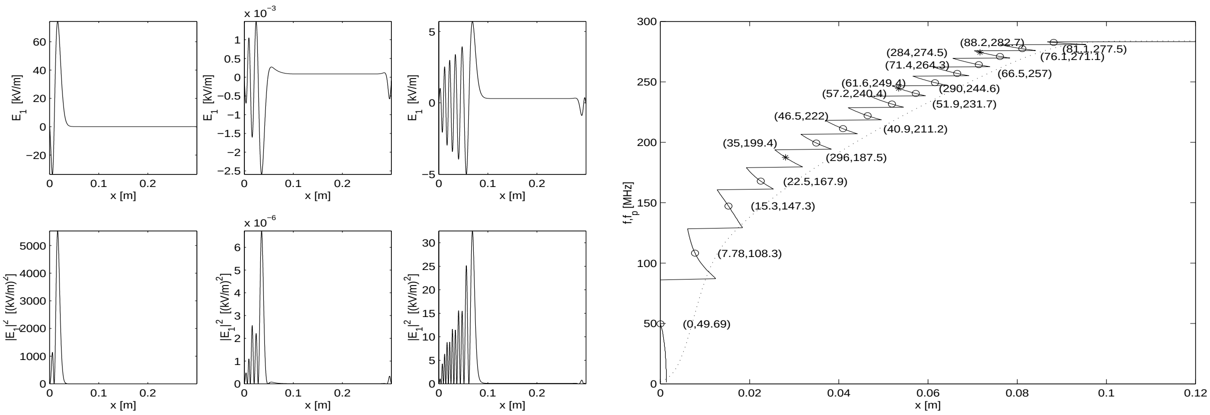

Figure 3. LEFT (six panels): The electric field E_1 in the upper panels, and $|E_1|^2$ in the lower panels. A harmonic factor $\exp(i(\omega t + \frac{\pi}{2}))$ should be multiplied with the shown value of E_1, where the reference phase is on j_T. The frequencies are $\omega = (0.5,\ 0.7,\ 0.9)\omega_{p,\max}$ in the (left, mid and right) panels, where $n_{0,\max} = 10^{15}\mathrm{m}^{-3}$ ($f_p = 284$ MHz). The total current density $j_T = 1\mathrm{Am}^{-2}$ and the electron temperature is 10 eV RIGHT: The sawtooth shaped line gives the position of the maximum field amplitude in the left part $x < 0.12$ m of the diode. The horizontal lines represent a jump in position where two local maxima, one in each end point of the line, are equal in amplitude. Resonant frequencies with a global amplitude maximum in the shown region are marked with circles and resonant frequencies with a global amplitude maximum in the anode sheath are marked with stars. The positions of the global maxima (x [mm],f [MHz]) for the resonant frequencies are given in the parenthesis. The local plasma frequency is shown as reference by the dotted line.

where j_T is the total, spatially invariant, current density $-e(n_0v_1 + n_1v_0) + i\omega\epsilon_0 E_1$ and $\omega_p^2(x) = e^2 n_0(x)/(m_e\epsilon_0)$. This equation is solved numerically with the boundary condition of no oscillating particle currents. The resonances are determined by the outer circuit condition $\int E_1 dx = 0$. Eq. 1 does not model the coupling of the resonances, neither does it capture the energy drive in the beam, but it is successful in the following cases: **(1)** As in the PIC simulation all amplitude maxima appear above of the resonant line $\omega = \omega_p(x)$ in Fig. 3. **(2)** With the same current density as in the PIC-simulation the amplitudes of the resonances closest to 228 MHz, i.e., 222 and 232 MHz become 9.6 and 11.9 kV/m which is in good agreement with the PIC field amplitude ~ 11 kV/m. **(3)** The lowest lying resonance has a spatially decaying solution with maximum at the cathode. The second resonance fits well to the lowest spike in the PIC-simulation. The resonance (232 MHz) coincides with the PIC spike spatially and roughly also in frequency. **(4)** The PIC amplitudes in the evanescent region, $\omega < \omega_p(x)$, at the two frequensies f_1 and f_2 are in good agreement with the particular solutions, $-i\omega j_T/((\omega^2 - \omega_p^2)\epsilon_0)$, predicted by the fluid model in Eq. 1.

Acknowledgments. This work was supported by the Swedish Natural Science Research Council.

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