# Langmuir wave-packet generation from an electron beam propagating in the inhomogeneous solar wind.

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**Abstract.** Recent in-situ observations by the TDS instrument equipping the STEREO spacecraft revealed that large amplitude spatially localized Langmuir waves are frequent in the solar wind, and correlated with the presence of suprathermal electron beams during type III events or close to the electron foreshock. We briefly present the new theoretical model used to perform the study of these localized electrostatic waves, and show first results of simulations of the destabilization of Langmuir waves by a beam propagating in the inhomogeneous solar wind. The main results are that the destabilized waves are mainly focalized near the minima of the density profiles, and that the nonlinear interaction of the waves with the resonant particles enhances this focalization compared to a situation in which the only propagation effects are taken into account.

**Keywords:** density fluctuations–electron beams–solar type III radio bursts
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## INTRODUCTION

The study of the beam-plasma interaction in specific solar wind conditions is a subject of great importance. It is well known that the propagation of an electron beam in an homogeneous plasma leads to the generation of Langmuir waves, that are electrostatic waves oscillating at the plasma frequency $\omega_p = (4\pi e^2 n_e/m_e)^{1/2}$, where $n_e$ is the plasma electron density, $e$ and $m_e$ the electron charge and mass respectively. This phenomena is known to be at the origin of the generation of plasma waves during type III radio bursts or close to the electron foreshock.

It is also known that density fluctuations that can be of the order of a percent of the plasma density are ubiquitous in the solar wind [2], and that the propagation of Langmuir Waves is affected by such fluctuations : in particular cases, the waves can even be trapped in density cavities [3]. The inclusion of the density variations effects in the theoretical treatment of the beam-plasma interaction in the solar wind is thus important. This understanding is crucial to the astrophysical interpretation of the wave forms measured in-situ by spacecraft, especially for the exploitation of the data provided by the TDS instrument onboard Stereo mission, that can sample electric fields on periods of 130 ms [1].

In this proceeding, we briefly present a theoretical model that we developed to study the interaction between Langmuir waves and an electron beam in a slightly inhomogeneous plasma. For reasons of simplicity, the presented model is one-dimensional and neglects the influence of the interplanetary magnetic field. Nevertheless, the observed waves are mostly linearly polarized in the direction of the magnetic field, so as the beam direction of propagation : a one-dimensional treatment thus seems reasonable.

## PRESENTATION OF THE MODEL

Here we shall consider the density fluctuations $\delta n/n$ to be of typical amplitude $\sim 1\%$, and frozen in time. This last hypothesis imposes that we consider the system's evolution on a timescale smaller than the typical time of evolution of the density fluctuations, as will be discussed in the next section. We shall not interest ourselves in their origin or stability, and shall just consider them trough a given function of space $\delta n(x)$.

The propagation of Langmuir waves in such an slightly inhomogeneous medium is described by the high frequency component of the Zakharov's equations [6], and their interaction with resonant particles can be accurately treated using a spectral method that we shall not expose in details, the use of which has already given results in the frame of the study of the interaction between resonant particles and oblique waves in homogeneous magnetized plasmas [7]

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## Set of equations solved

The main equation that is solved is the high frequency component of the Zakharov's equations, in the derivation of which we added an external charge density $-en_b(x,t)$ as a source term in Poisson equation. $n_b(x,t)$ is the density of the beam electrons that polarize the plasma and generate the Langmuir waves.

$$\nabla\left(i\frac{\partial}{\partial t}E+\frac{3\omega_p}{2}\lambda_d^2\frac{\partial^2}{\partial x^2}E-\omega_p\frac{\delta n}{2n_0}E\right) = -2\pi e n_b(x,t)\,\omega_p e^{i\omega_p t}. \quad (1)$$

In this equation, $E(x,t)$ is the electric field envelope, the actual electric field undergone by the particles being $\varepsilon(x,t)=\Re(E(x,t)e^{-i\omega_p t})$. The beam of electrons is discretized on $N$ quasi-particles, the dynamics of which are treated in a self-consistent way with the field :

$$d_t x_\alpha = v_\alpha, \quad (2)$$

$$d_t v_\alpha = -\frac{e}{m}\varepsilon(x,t), \quad (3)$$

for $\alpha = 1,...,N$.

This approach enables to reproduce all the kinetic effects related to resonant wave-particle interactions : wave destabilization and damping, particle trapping and diffusion, etc. Such an approach was firstly used in [5] to study the nonlinear interaction of a cold electron beam and a homogeneous plasma.

## Numerical method

A numerical code integrating the system of equations has been developed, using a spectral method in which two Fast Fourier Transform algorithms are performed at each time step. To check the validity of our numerical scheme, the total energy of the wave-particle system has been monitored in all the numerical simulations performed, and we adapted the time steps used so that their relative variation always stays under one percent.

The results presented in this article are obtained using a spectral grid composed of 512 points periodically distributed in Fourier space between $-k_{\max}$ and $k_{\max}$, and a periodic box of spatial dimension $L = 4000\lambda_d$, so that $\lambda_d \Delta k_{grid} = 0.0016$ and $\lambda_d k_{\max} = 0.4$.

# SIMULATION OF THE BEAM-PLASMA INSTABILITY IN THE PRESENCE OF DENSITY INHOMOGENEITIES

Here we present the results of numerical simulations of the destabilization of waves by an electron beam, firstly in the presence of a gaussian density cavity, and after in the presence of a turbulent density profile. We show that after a stage a linear instability similar to the one that would appear in an homogeneous plasma, the effect of plasmon diffusion by the density gradients combined with the nonlinear wave-particle effects tend to focalize the electric field energy in the density cavities of the plasma, generating plasma wave packets correlated with the density profile.

## Initial conditions

First of all, we consider only time-independent density profiles, to make as clear as possible the physical interpretation of the simulations results. To make this assumption realistic, the time durations $\tau_{sim}$ of the simulations presented are of taken to be of roughly $1000\omega_p^{-1}$. Admitting that the density fluctuations considered here are ion sound waves, their typical evolution time is of the order of $\tau_{\delta n} \sim \sigma_{\delta n}/c_s$, which, for the examples considered here is $\sim 4000\omega_p^{-1}$.

We want to perform simulations in a range of parameters similar to the solar type III electron beams observed at 1 A.U. Then, we chose for the normalization parameters the following typical values of the solar wind at 1 A.U. : $T_e \sim 5.10^5 K$, $n_0 \sim 5.10^6 m^{-3}$, giving $\lambda_d \sim 10m$, $f_p = \omega_p/2\pi \sim 20kHz$, and $v_{th} \sim 10^6 m/s$.

Concerning the impulsive electrons, they are launched at a velocity $v_b = 20 v_{the}$, that is $v_b \sim c/10$ which corresponds to an average velocity of the type III exciters (that ranges usually from $c/20$ to $c/3$). The observed velocity dispersion of the beam is usually quite small, and we shall take $\Delta v_b/v_b = 0.05$. The ratio of the electron beam density on the average local plasma density is taken to be $n_b/n_0 = 4.10^{-5}$, and $N = 16384$ quasi-particles are composing the beam.

## Results

We first discuss a simulation in which the electron beam propagates in a plasma with a gaussian density cavity, of depth $\delta n_{\max}/n_0 = -0.01$ and width $\sigma_{\delta_n} = 100\lambda_d$.

The figure 1 shows the number of plasmons, that is $N_p(t) = \int W(x,t).dx$ as a function of time (where the normalized electrostatic energy density is $W(x,t) = |E(x,t)|^2/8\pi n_0 k_B T_e$) the space-time profile of $W(x,t)$ and its profile at the final time of the simulation. These results are clearly showing that after a linear wave growth stage comparable to the one that would appear in a homogeneous plasma (until $\omega_p t \sim 500$), in which the waves amplitude grow exponentially and homogeneously in

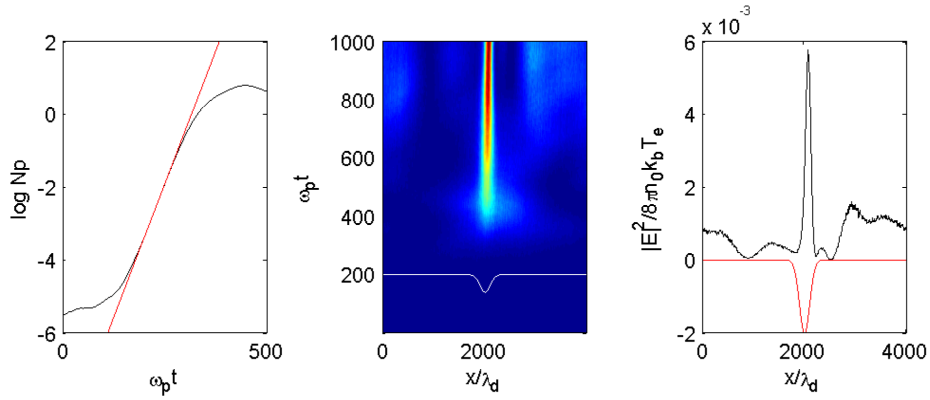


**FIGURE 1.** Left : Linear stage of a beam plasma instability illustrated by the logarithm of the number of plasmons as a function of time. The over-plotted slope is a linear fit with a slope $\gamma = 0.03\omega_p$. Middle : map of W(x,t) in linear scale showing the fast enhancement of energy in the cavity. Right : W(x) at $\omega_p t = 1000$

space, the nonlinear effects tend to focalize the energy inside the density cavity. More precisely, the maximum of energy lies in the positive gradient of the density profile, around the reflection point of the beam driven Langmuir waves.

The propagation effects of the Langmuir waves in the inhomogeneous plasma described by the Zakharov's equation can explain the focalization of the waves in the density cavities. But our model also takes into account the nonlinear effect of the resonant particles on the waves evolution. To distinguish between pure propagation effects and resonant particles effects, we performed a simulation without any beam particles (that is, the right hand term in (1) is set to zero), taking as initial condition the electric field at the saturation of the instability (that we roughly define to be $\omega_p t = 500$), and letting the field evolve until $\omega_p t = 1000$.

The results of this simulation are presented on the figure 2, and shows that the wave spatial localization effect is much more efficient in the presence of resonant particles. We shall not quantitatively investigate this phenomenon, nevertheless we can qualitatively understand it as follows : the spatial localization of the waves initially due to propagation effects generates a diffusion of the particles passing trough the wave packet, which results, as illustrated on the figure 2, in an energy transfer from the particles to the waves, and in particular in a enhancement of the wave energy spatially localized in the density hole. This effect of particle diffusion by a localized wave packet is studied in the frame of the Tokamaks physics in [4].

We first considered the case of a gaussian density cavity in order to obtain a clearly understandable physical picture. Now we investigate the more realistic case of a random density profile, with valleys and hills still having an amplitude of $\sim 1\%$ of the solar wind density. The

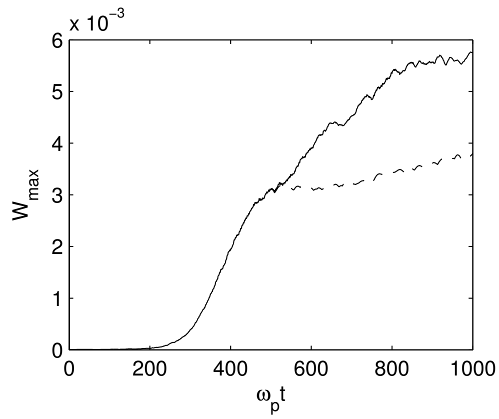


**FIGURE 2.** Time evolution of the maximum value of the electrostatic energy density $W(x,t)$ in the case where resonant particles are nonlinearly interacting with the waves (solid line) and when the evolution is only due to propagation effects of the waves in the density cavity (dashed line).

figure 3 summarizes the result of a simulation performed with beam parameters similar to the previous simulation, but with a turbulent density profile. This one was obtained by taking a gaussian power spectrum for the density $\delta n_k \propto \exp(-k^2/\sigma_k^2)$ with $(\lambda_d \sigma_k) = 10^{-2}$, and randomly distributing the phases of the Fourier components. We then take the real part of the inverse Fourier transform to obtain the density profile in space.

One sees that at the end of the simulation time $t = 1000\omega_p^{-1}$, the electrostatic energy profile is anti-correlated with the density profile : large amplitude localized wave-packets have formed in near the local density minima whereas the electrostatic energy nearly vanishes in the over-dense regions.

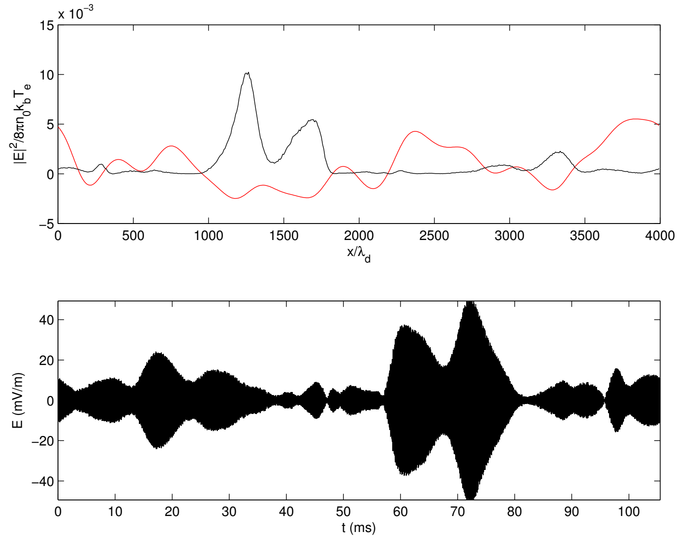


**FIGURE 3.** Normalized electrostatic energy density as a function of space at $\omega_p t = 1000$, after a beam plasma instability with the same beam parameters as figure 1. The red line shows the turbulent density profile (arbitrary units). One clearly sees the anti-correlation existing between the density profile and the electrostatic energy profile. The bottom panel shows the waveform that would measure a spacecraft located at $x = 4000\lambda_d$ for a solar wind advection velocity of $V_{SW} = 300 km/s$.

To enable a comparison of our results with the waveforms captured by the instruments onboard the WIND or STEREO spacecrafts, we show on the figure 3 the reproduced wave form that would observe a spacecraft assuming that the electric field is frozen in the state reached at the end of the simulation.

## CONCLUSIONS

We developed an analytical and numerical tool that enables a study the self consistent interaction between Langmuir waves and a resonant beam of particles in a slightly inhomogeneous plasma, based on the resolution of the high frequency component of the Zakharov's equations in which a term relative to the dynamics of the electrons composing the beam had been added.

Then we used the numerical code to investigate the destabilization of electrostatic waves by supra-thermal particles in an inhomogeneous plasma, this topic being of central interest for the understanding of the Langmuir waveforms in-situ observations by spacecrafts orbiting in the solar wind, especially during type III bursts events.

The main results is that on the typical time scale of stability of the considered density holes, we observe a spatial localization of the Langmuir wave field barely anti-correlated with the density profile. More precisely, the maximum of the electrostatic energy is located in the positive gradient regions located after the local minima of the plasma density (with respect to the beam propagation direction), that is, close to the reflection points of the beam driven waves.

Moreover, we observed that the energy of the spatially localized Langmuir waves is enhanced due to their nonlinear interaction with resonant particles, making the timescale of spatial localization of the electrostatic energy smaller than the one that would be obtained taking into account only propagation effects.

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