NUMERICAL SIMULATION OF THE BEAM-PLASMA TURBULENCE SPECTRUM EVOLUTION FOR WEAK BEAMS

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The results of the numerical simulation of weak non-relativistic monochromatic beam interaction with plasma are introduced. The modified PDP1 package for one-dimensional plasma systems simulation was used. Evolution of the phase portrait and electric field distribution during beam-plasma turbulence was investigated. Plasma oscillations spectra were obtained. Their temporal and spatial evolution was studied.

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1. INTRODUCTION

The accurate analytical model of beam-plasma systems was build only for initial and boundary problems [1,2]. It does not correspond with the real experiment conditions [3]. For this reason a lot of numerical emulations of such systems were done. There are two basic approaches in simulation of kinetic processes in plasma. The first one is based on Vlasov-Poisson set of equations [4]. The second one directly uses charged particle motion equation and Poisson equation. Such approach is used, for instance, in the PDP1 program package. The modified version of this package was used in our research.

Most of the researchers took an interest in quasi-linear regime of beam relaxation (see, e.g., [4]), or strong relativistic monochromatic beams' interaction with plasma [5]. But there are some problems in plasma electronics (such as plasma barriers' transillumination for electromagnetic waves by means of electron beams [6]) where weak beams are used. Therefore we concern weak non-relativistic beams in beam-plasma instability investigations. In particular, information about spatial and temporal evolution of the beam-plasma turbulence spectra in such systems is presented.

2. MODIFIED PDP1 PACKAGE

As was mentioned above, one of the widely used methods for computer simulation of the beam-plasma systems is the big-particles-in-cells method [7]. It is used, e.g., in the well-known package PDP1 [8], which can simulate initial-boundary problem for one-dimensional model.

We have created the modified package PDP1 [9] that has some advantages in comparison with the original version. Some main features of the modified program are listed below.

Program is realized for 32-bit Windows operation systems (Windows 95/98/NT/2000/XP). There are no implicit limitations on the big particles' number. This number is specified for each type of particles separately and limited only by the size of computer memory.

Program gives the possibility to save the intermediate results of simulation in the text files or binary files. Spatial distribution of the electric field and potential, charge density, current density, phase trajectory of single particle, particles' coordinates and velocities can be saved. It helps to obtain, e.g., frequency spectrum of oscillations at various coordinates.

More comfortable way for assignment of the number of real particles in one big particle is developed. In our program this numbers can vary for each type of particles. It gives the possibility to assign a small beam electrons' concentration in comparison with bulk plasma electrons' concentration.

3. SIMULATION PARAMETERS SELECTION

It was already noted that initial-boundary problem was considered in our simulation (beam starts injecting at the initial moment from the left side of the system). Plasma was initially homogenous and isothermic. Plasma particles are reflected by the walls. The electron beam was monoenergetic (without initial modulation). The beam current was selected so that the transition processes due to the beam forefront were negligible [10]. The plasma quasineutrality violation caused by the beam was insignificant.

The values of the simulated system basic parameters (which fulfill above-listed conditions) are:

$L/\lambda_D = 10^3$, where L is the system length, λ_D is Debye length;

$V_b/V_t = 8$, where V_b is the beam velocity, V_t is the thermal velocity of the plasma electrons;

$n_b/n \sim 10^{-4} – 10^{-2}$, where n_b is the beam electrons' concentration, n is the plasma electrons' concentration.

The number of big particles was about 10^5 for every type of particles. The number of cells in the system was 10^3.

Selected parameters correspond to moderate turbulence regime ($\tau_c/\tau_{NL} \equiv \Omega/\gamma = 8.6$; $W/nT = 1.6\cdot10^{-2}$) [4].

4. QUALITATIVE DESCRIPTION OF THE BEAM-PLASMA INSTABILITY EVOLUTION

At the beginning of the injection of relatively weak beam ($n_b/n = 7.8\cdot10^{-5}$) slight modulation appears (fig.1).

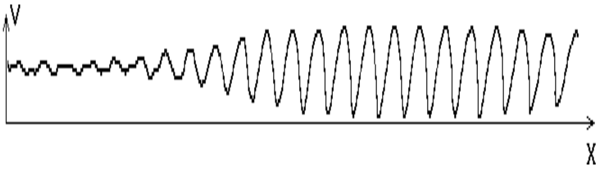


Fig.1. Linear stage of the beam-plasma instability evolution: phase plane ($\omega_p t = 165$, $n_b/n = 7.8\cdot10^{-5}$)

Oscillation increment does not depend on time and coordinate at this case. Later the front tipping over appears on the beam phase plane (fig.2). At the same time electric field magnitude oscillates in space (fig.3). This effect corresponds with spatial (stationary) problem solution [1].

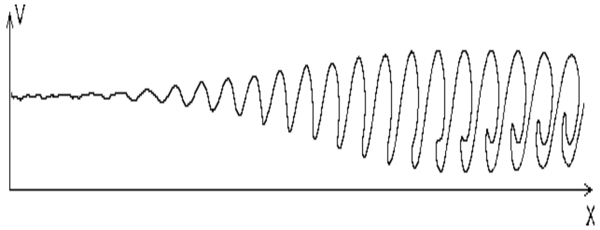


Fig.2. Front tipping over in the beam phase plane ($\omega_p t = 255$, $n_b/n = 7.8\cdot10^{-5}$)

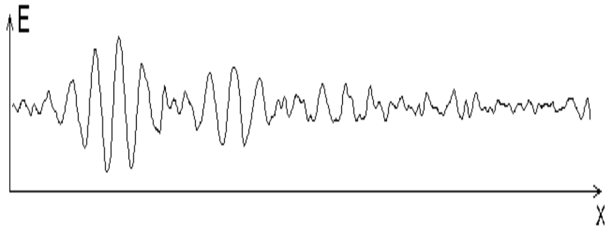
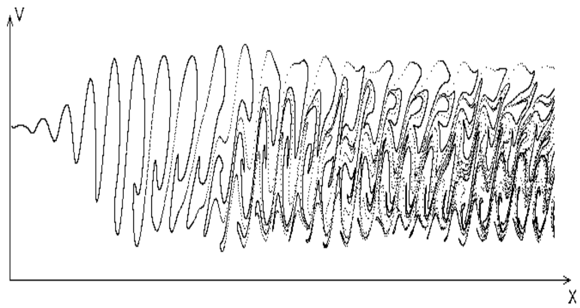
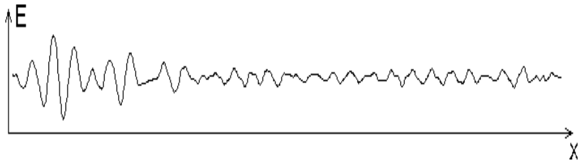


Fig.3. Electric field spatial distribution at the beginning of the nonlinear stage of beam-plasma instability ($\omega_p t = 1128$, $n_b/n = 7.8\cdot10^{-5}$)



a



b

Fig.4. Beam phase plane (a) and electric field spatial distribution (b) at the turbulence stage of the beam-plasma instability ($\omega_p t = 1612$, $n_b/n = 7.8\cdot10^{-5}$)

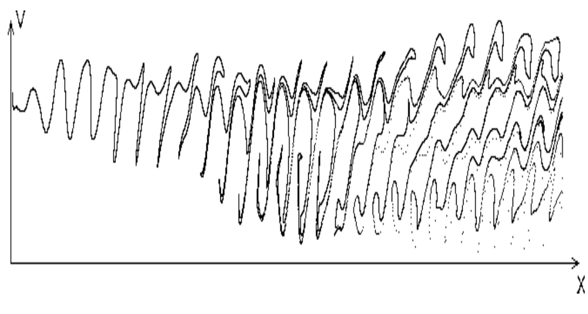


Fig.5. Plasma transillumination for electron beam ($\omega_p t = 7876$, $n_b/n = 7.8\cdot10^{-5}$)

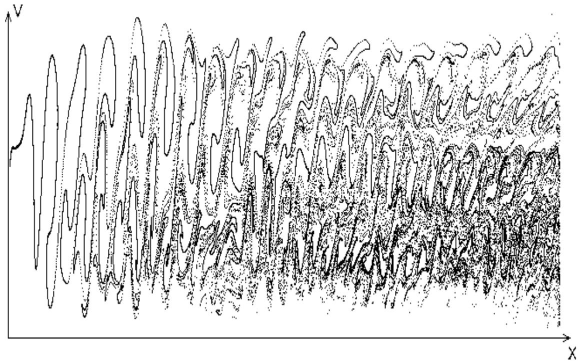


Fig.6. Beam phase plane at the turbulence stage of the beam-plasma instability ($\omega_p t = 828$, $n_b/n = 7.8\cdot10^{-4}$)

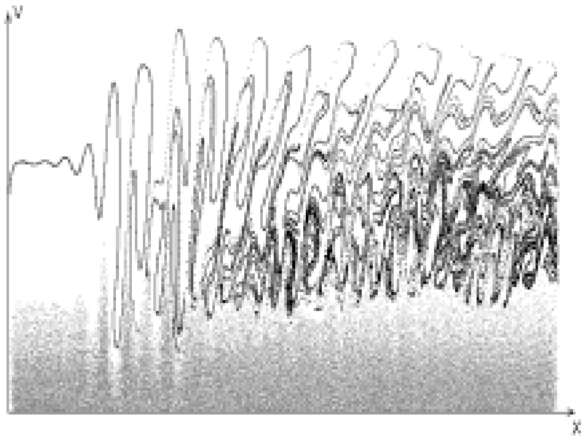


Fig.7. Bulk plasma electrons' acceleration by the beam electrons ($\omega_p t = 164$, $n_b/n = 6.9\cdot10^{-3}$)

For the next moments the beam electrons' motion becomes more chaotic (fig.4a). Depth of the electric field modulation decreases (fig.4b). Fig.4b demonstrates lack of the full trapping of beam electrons by the wave. One can see on the phase plane both trajectories of finite motion (corresponding to the electrons trapped by the wave) and trajectories of infinite motion (corresponding to the drift particles). Chaotic motion of electrons is caused by trajectories' instability near the separatrix between those trajectories types [11]. Later chaotic region of beam's phase plane moves towards the injector. At the late stage ($\omega t \sim 8\cdot10^3$) transillumination of plasma for beam near injector can be observed, so the beam electrons' motion becomes less chaotic (fig.5).

Increasing of the electron beam current leads to the faster transition from regular dynamics to chaotic one. So the distance between injector and chaotic region decreases (fig.6). Sufficiently dense beam ($n_b/n \geq 10^{-2}$) could lead to the well-known [10] effect of bulk plasma electrons acceleration (fig.7). Very dense beams cause an appreciable quasineutrality violation, so the virtual cathode could appear.

5. BEAM-PLASMA TURBULENCE SPECTRA

Oscillation spectra as a function of distance from injector were obtained by processing of simulation results. Time interval used by the Fourier transform was almost a thousand Langmuir periods long. It starts from the moment when the oscillations' magnitude maximum stops moving towards the injector. Spectra of electric field and current density were almost identical. Oscillation spectrum is concentrated at the narrow band near the plasma frequency ($\Delta\omega/\omega \sim 0.03$ at the level 0.1 of maximal magnitude). This effect can be easily explained: plasma acts as a high-Q resonator, so it suppresses all oscillations except the eigenmodes. Detailed

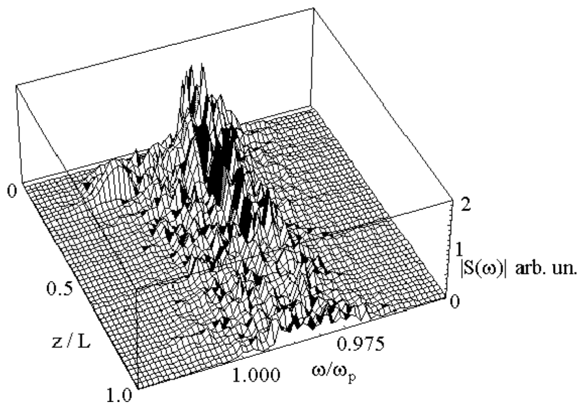
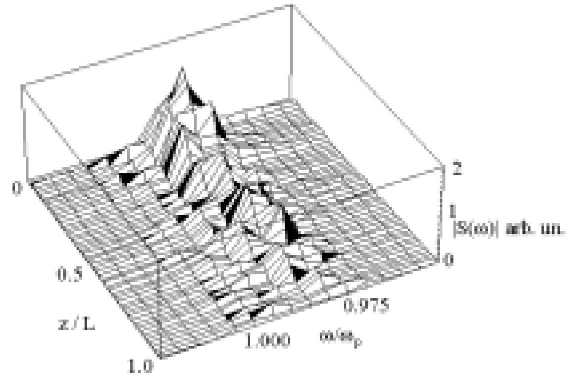
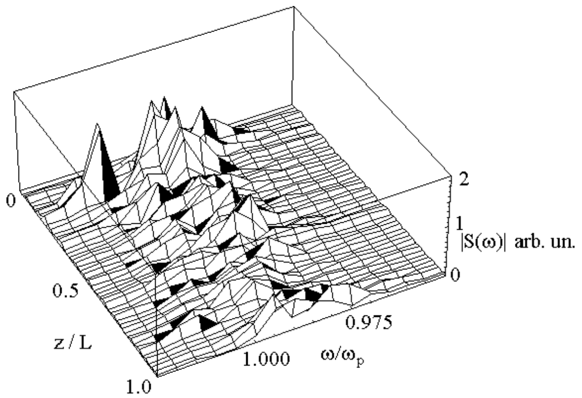


Fig.8. Spatial distribution of the beam-plasma instability spectrum at the interval from $\omega_p t$ = 1128 to $\omega_p t$ = 5640 ($n_b/n = 7.8 \cdot 10^{-5}$)



a



b

Fig.9. Time evolution of the spatial distribution of the beam-plasma instability spectrum ($n_b/n = 7.8 \cdot 10^{-5}$): a – time interval from $\omega_p t$ = 1128 to $\omega_p t$ = 2256; b – time interval from $\omega_p t$ = 4512 to $\omega_p t$ = 5640

analysis shows that the spectrum maximum is not sharp but has a complex indented shape. It was no significant widening of the spectrum along the system. Gradual decrease of the spectral intensity and increase of the peaks' number were observed instead (fig.8).

Note that the shape of the obtained spectrum qualitatively corresponds with the radiation spectra of the beam-plasma discharge (for relatively weak currents) [3].

Time evolution of the spectrum was also investigated. The whole time interval was divided on four equal parts. The spectrum was found to be essentially non-stationary. At the first time interval it has the sharp peak near the injector that expands and decreases at some distance from it (fig.9a). At other time intervals spectrum comes down and expands, it becomes more homogenous along the system (fig.9b).

6. Conclusion

Numerical simulation using the big-particles-in-cells method gives the possibility to study the spatial and temporal evolution of the beam-plasma system in case of weak non-relativistic electron beams.

Simulation results contradict the analytical theory of the nonlinear stage of the beam-plasma instability [1,2]: stationary oscillations were not observed even for the weak beam. For any beam current the moderate turbulence regime [4] appeared at some distance from injector.

In fact the analytical theory does not take into account plasma modification due to the energy taken from the beam. This effect results to the non-stationarity of the beam-plasma interaction in the model examined.

Analysis of oscillation spectra spatial distribution at late stage of the beam-plasma turbulence shows that in case of weak beam the oscillation frequencies are concentrated in relatively narrow band near the electron Langmuir frequency. It is no significant widening of the spectrum along the system. At the same time there is a smooth changing of spectrum. It becomes more homogeneous along the system.

Obtained spectrum of beam-plasma turbulence qualitatively corresponds with the experimental data.

Note that one-dimensional simulation cannot reproduce all the possible effects observed in experiments. E.g., we could not observe the effect of plasma extrusion from the electron beam volume caused by high-frequency pressure of electric field [3]. Also the excitation of "oblique" waves (with respect to beam direction) is impossible for this model. At least two-dimensional model must be used to simulate such effects.

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