2D ELECTROSTATIC SIMULATION OF THE MODULATED ELECTRON BEAM INTERACTION WITH INHOMOGENEOUS PLASMA

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Electrostatic plasma simulation code for 2D rectangular geometry is presented. Main distinguishing feature of the code is its orientation on the beam-plasma interaction. The code and its graphical interface were developed using MATLAB programming language. Simulation results of inhomogeneous plasma interaction with modulated electron beams of different width are compared. In case of wide beam the front of Langmuir waves generated in point of local plasma resonance is planar and in case of thin beam (or ribbon beam) the front has approximately half-circular form.

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1. INTRODUCTION

Beam-plasma interaction is the object of scientific interest for many years. Deeper understanding of this phenomenon would cause a progress in a large number of applications from space weather prediction to plasma electronic devices construction.

Interaction of inhomogeneous plasma with modulated electron beams in 1D geometry is studied both theoretically and via numerical simulation (see, e.g., [1-2]). In fact, this model with the beam of infinite transversal length corresponds to plasma with the strong magnetic field parallel to the density gradient. But for real beams of finite radius the radial component of electric field appears causing the electrons' and ions' radial motion. 1D models do not describe this effect.

The report presents electrostatic simulation of the modulated electron beam interaction with inhomogeneous plasma in 2D plane geometry. The simulation was performed using large particles' method. Large particles interact electrostatically and can move in two dimensions freely or driven by external forces. The code gives possibility of charged particles' beam injection into inhomogeneous plasma.

2. ALGORITHM AND COMPUTER CODE

Particle in cell (PIC) algorithm [2] lies in the base of presented code. This algorithm considers plasma as a set of charged particles that consists of large number of elementary particles. The big particles interact with each other not directly but through a grid – an object that appears after breaking a simulating volume on the set of cells. FFT method was used for difference Poisson's equation solving [3].

The above described algorithm is coded using the language for technical computing MATLAB. The core of the code is a cycle in which the operations of particles' charge weighting, electrical field calculation and particles coordinates and velocities updating are consequently repeated.

Modular architecture is laid in the basis of the developed code. The main routines such as routine of Poisson's equation for electrical field solving, particles' charges weighting routine and others are independent building blocks of the program.

The other distinguishing feature of the presented code is a presence of graphical interface which makes the code operation easier for a user. The interface includes a number of dialogues for putting simulation parameters into the code and graphical window for system state visualization during a simulation.

3. NUMERICAL SIMULATION OF MODULATED BEAM INTERACTION WITH INHOMOGENEOUS PLASMA

Simulation of beam-plasma interaction was performed using electrostatic 2D computer code. The simulated volume is bounded by two pairs of parallel planes with L_x=4cm, L_y=1cm. The rectangular grid is introduced in system with 1024x256 cells. The volume is filled with plasma which is modeled as a number of large electrons ($N_{big} = 10^6$) with temperature T_e = 0.5 eV and a motionless positive background charge. The large particle in the 2D rectangular geometry is an infinite uniformly charged rod which moves perpendicularly to its axis. The linear density of the large particle in the presented simulations is $8{\cdot}10^3$ elementary particles per meter for beam electrons and $2.56{\cdot}10^6$ m^{-1} for plasma electrons. The plasma concentration is constant along *y* coordinate and changes linearly along *x* coordinate from $3.2{\cdot}10^{15}$ m^{-3} on the left electrode to $9.6{\cdot}10^{15}$ m^{-3} on the right electrode. Plasma particles are reflected from the left and right boundaries and translated into the simulated volume by adding or subtracting L_y from their *y* coordinate if they have crossed bottom or top boundary.

Boundary conditions of the Dirichlet type on the left and right electrodes and periodic boundary conditions on the top and bottom electrodes were used for the Poisson's equation solving:

$$\phi(x=0)=\phi(x=L_x)=0\,,\ \phi(y=0)=\phi(y=L_y)\,.$$

The time step of simulations dt=$5{\cdot}10^{-11}$ is two order less than the period of plasma oscillations T_p=$1.1{\cdot}10^{-9}$ s in the maximal density region at x=L_x (T_p>>dt). The Debye length L_d and size of cell dx are one order less then the wave length λ_L of generated Langmuir waves dx:L_d:λ_L=1:2.4:24 at x=0. Number of particles in the Debye sphere (Debye cylinder in the 2D geometry) is $N_d = \pi{\cdot}k_b{\cdot}T_e{\cdot}\varepsilon_0/(e^2{\cdot}\lambda)=8.5$, where $\lambda=2.56{\cdot}10^6$m^{-1}– linear density of the large particles.

Modulated beams of different width were injected into the volume and their interaction with plasma in the point of local resonance was investigated.

3.1. BEAM-PLASMA INTERACTION IN QUASI 1D GEOMETRY

In this section results of simulation of inhomogeneous plasma interaction with modulated beam which width is equal to L_y are reported. Due to periodicity of boundary conditions on the top and bottom electrodes the interaction in this case can be thought as quasi one-dimensional.

Beam particles are injected into the plasma with $v_x=27v_T=8\cdot10^6$m/s, $v_y=0$. Beam density is modulated with frequency $f_m=7.5\cdot10^8$ Hz, modulation depth m=1 and maximal value $n_b=5\cdot10^{13}$ m^{-3}.

Perturbation of plasma electrons density for 5 subsequent time moments is shown on Fig.1.

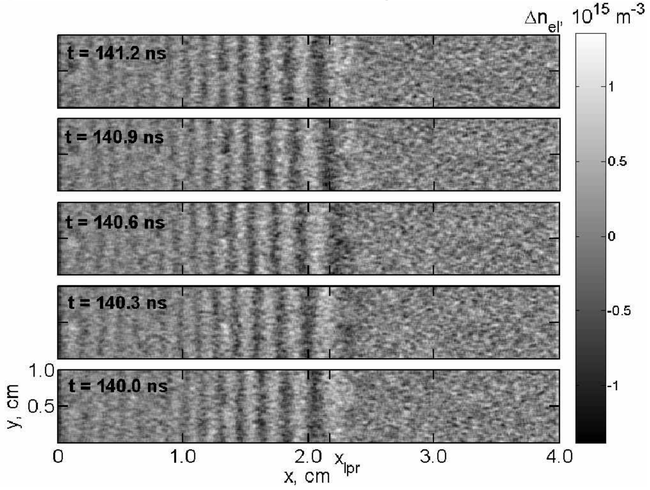

Fig. 1. Planar Langmuir waves generation generated in quasi 1D beam-plasma interaction

It can be easily observed that Langmuir waves are generated in the point of local plasma resonance x_{lpr} and propagate leftwards. Phase velocity of the waves decrease with plasma density decreasing. Wave front is planar, and plasma electrons density is roughly constant along *x* axis.

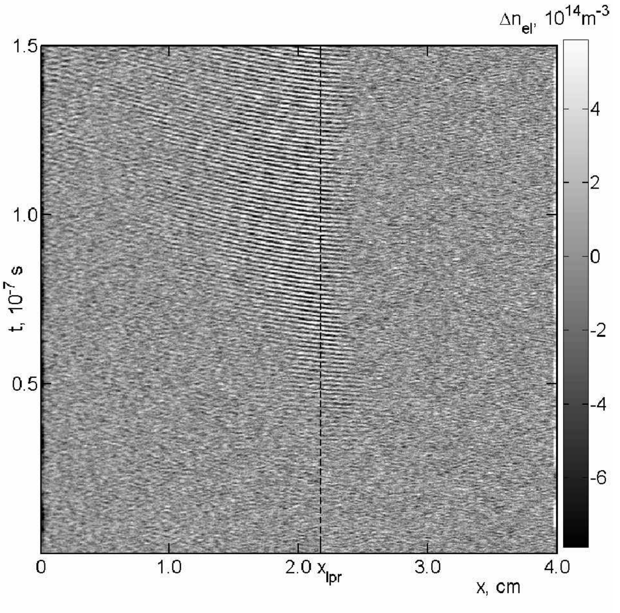

Fig. 2. Time dependence of plasma electron density perturbation on the axis of the system for quasi 1D beam-plasma interaction

Time development of wave process on the axis of the system (y=0.5 cm) is shown on Fig. 2. Dashed line marks the point of local plasma resonance calculated theoretically. From this point waves of plasma density propagate toward left electrode, and trajectories of their maxima are shown by white color.

Density of beam electrons is shown on Fig. 3. It changes from 0 to $-6\cdot10^{13}$ m^{-3} due to modulation. It can be easily observed that the beam becomes “fibrous” during its motion toward the right electrode.

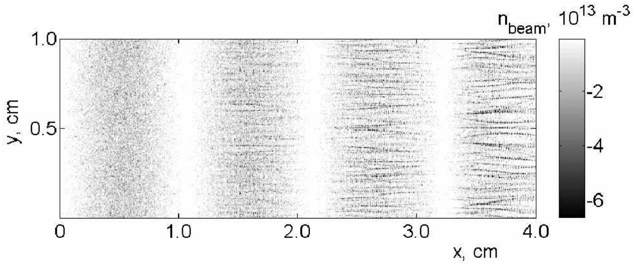

Fig. 3. Beam density for t = 140 ns. Simulation for quasi 1D interaction

3.2. SIMULATION OF PLASMA INTERACTION WITH THIN (RIBBON) BEAM

In this section results of simulation of inhomogeneous plasma interaction with thin modulated beam are reported. The fact that beam density is not constant along *y* axis makes the simulation essentially two-dimensional.

The beam width is $L_b=L_y/20=0.05$cm, maximal beam density $n_b=1\cdot10^{15}m^{-3}$, so the total current in the system is equal for both simulations. Modulation frequency and depth are also remained unchanged.

Perturbation of plasma electron density at 5 subsequent time moments during one Langmuir period is shown on Fig.4.

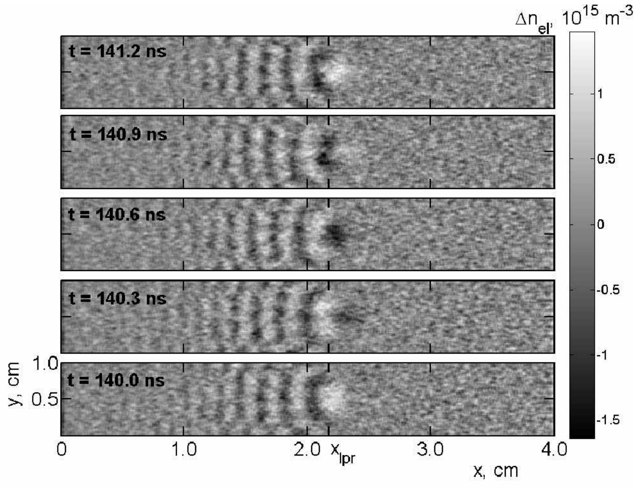

Fig. 4. Spherical (cylindrical) Langmuir waves generated by thin beam

Intensive oscillations of plasma electrons' density can be observed in the local plasma resonance point. Oscillations with the period equal to the beam modulation period propagate in regions of lower plasma density. Wave front has approximately half-circular form. The explanation of this effect is that the region of intensive beam-plasma interaction can be treated as point-like source.

Time development of the plasma density oscillations on the axis of the system (*y*=0.5cm) is shown on Fig.5. At the early stage (t<20 ns) the waves of space charge density that propagate rightwards are visible. These waves are caused by non-compensated beam charge.

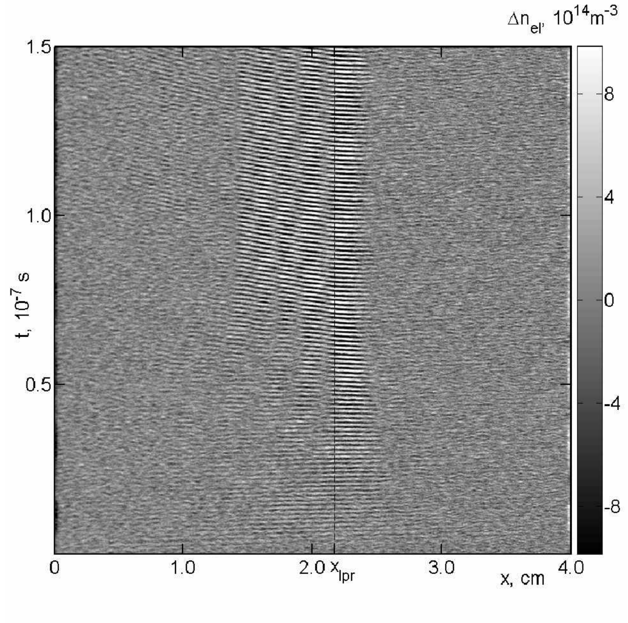

Fig.5. Time dependence of plasma electron density perturbation on the axis of the system for inhomogeneous plasma interaction with thin beam

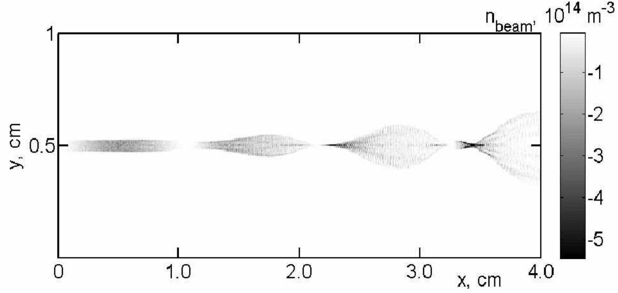

Fig. 6. Spatial distribution of the beam electrons' density for t = 140 ns

Later charge density waves start interfering with Lanmuir waves that propagate leftwards. On Fig. 5 this interference appears as a spatial beating of plasma density that is predicted theoretically [4-6].

Density of beam electrons is shown on Fig. 6. Non-compensated beam charge causes beam widening .

4. CONCLUSIONS

Two simulations of modulated electron beam interaction with inhomogeneous plasma interaction for different beam width were performed. The first simulation deals with quasi 1D beam-plasma interaction, when the beam width is equal to the length of the system along *y* direction. Langmuir waves propagation from the region of local plasma resonance to the regions of lower plasma density was observed. The “fibrous” beam structure was discovered.

The second simulation deals with essentially 2D beam-plasma interaction. Beam is thin in comparison with system length along *y* direction. Langmuir waves with quasi half-circular wave front were observed in this case. The effect of spatial beating between waves of space charge driven by beam and Langmuir waves generated in region of beam-plasma resonance was established during the simulation.

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ДВУМЕРНОЕ ЭЛЕКТРОСТАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ВЗАИМОДЕЙСТВИЯ НЕОДНОРОДНОЙ ПЛАЗМЫ С МОДУЛИРОВАННЫМ ПУЧКОМ ЭЛЕКТРОНОВ

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Представлен компьютерный код для моделирования плазмы с электростатическим взаимодействием в двумерной геометрии. Главной особенностью представленного кода является его возможность моделировать взаимодействие плазмы с пучком. Код и графический интерфейс разработан в среде программирования MATLAB. Сравниваются результаты моделирования взаимодействия неоднородной плазмы с модулированными пучками разной ширины. В случае широкого пучка фронт ленгмюровских волн, которые генерируются в точке локального плазменного резонанса, является плоским; в случае же тонкого (или ленточного) пучка фронт приблизительно является полукругом.

ДВОВИМІРНЕ ЕЛЕКТРОСТАТИЧНЕ МОДЕЛЮВАННЯ ВЗАЄМОДІЇ НЕОДНОРІДНОЇ ПЛАЗМИ З МОДУЛЬОВАНИМ ПУЧКОМ ЕЛЕКТРОНІВ

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Представлений комп’ютерний код для моделювання плазми з електростатичною взаємодією в двовимірній геометрії. Головною особливістю представленого коду є його можливість моделювати взаємодію плазми з пучком. Код і графічний інтерфейс розроблений в середовищі програмування MATLAB. Порівнюються результати моделювання взаємодії неоднорідної плазми з модульованими пучками різної ширини. У випадку широкого пучка фронт ленгмюрівських хвиль, які генеруються в точці локального плазмового резонансу, є плоским, у випадку ж тонкого (або стрічкоподібного) пучка фронт приблизно є півколом.