2D SIMULATION OF THE TRANSVERSELY RESTRICTED MODULATED ELECTRON BEAM DYNAMICS IN THE HOMOGENEOUS PLASMA

I.O. Anisimov, M.J. Soloviova
Taras Shevchenko National University of Kiev, Radio Physics Faculty, Kiev, Ukraine
E-mail: ioa@univ.kiev.ua

Dynamics of the transversely restricted modulated electron beam moving through the homogeneous plasma was studied via computer simulation using PIC method. 2D-simulation demonstrated the concurrence between non-resonant beam-plasma instability at the modulation frequency and resonant instability at the Langmuir frequency of background plasma. In comparison with 1D simulation new effects were obtained such as beam's transversal filamentation and expansion as well as beam electrons' longitudinal and transversal focusing. Transversal filamentation is hypothetically caused by instability of the oblique space charge waves in the beam that can be confirmed by theoretical calculations.

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1. INTRODUCTION

Dynamics of the modulated electron beam in plasma is of great interest in various branches of plasma electronics. Among them are: electron beams' using as emitters of electromagnetic waves in ionosphere [1-2], transillumination of plasma barriers for electromagnetic waves using electron beams [3-5], inhomogeneous plasma diagnostics via transition radiation of electron beams and electron bunches [6] etc.

Evolution of the modulated electron beam in supercritical plasma barrier was studied experimentally in [4, 7]. It was shown that signal at the modulation frequency reached its maximum inside the barrier, and magnitude of this maximum was directly proportional to the initial beam modulation depth. These results were explained in [8] by the concurrence between non-resonant (signal) and resonant (noise) modes of the beam-plasma system. But calculations presented in [8] correspond to the initial problem, whereas results of experiments [4, 7] correspond to the boundary problem.

Later, in our previous works [9-11] dynamics of the modulated electron beam in plasma for the initial-boundary problem was studied via computer simulation using PIC method [12-13]. The problem was solved for various ranges of parameters such as: initial modulation depth, beam current density etc., also different barrier's profiles were studied (homogeneous and Gaussian shape). Simulation results [9-11] demonstrated modes' concurrence in the beam-plasma system predicted in [8] and observed in [3-4] as well as some other effects. But all these results were obtained in one-dimensional approach. In fact, 1D 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.

In this paper results of electrostatic simulation of the stripped modulated electron beam interaction with homogeneous plasma in 2D plane geometry are presented. Initial-boundary problem is solved and results obtained are compared with results of experiments and previous simulations.

2. SIMULATION PARAMETERS

Warm isotropic collisionless plasma with initial homogeneous density profile was studied. Simulation was carried out via particle-in-cell method using modified program package PDP2 [14-15]. Rectangular area 0.2×0.05 m filled with fully ionized hydrogen plasma was treated. Difference Poisson equation was solved on the rectangular grid of 1024×512 cells. Plasma consisted of number of large electrons ($N_{large,e} = 6\cdot10^5$) and large ions ($N_{large,i} = 6\cdot10^5$).

Dirichlet boundary conditions were applied on the left and right borders of simulation region, and periodic boundary conditions were applied on the top and bottom borders: $\varphi(x = 0) = \varphi(x = L_x) = 0$, $\varphi(y = 0) = \varphi(y = L_y)$. Other simulation parameters are presented below.

Simulation parameters

Initial plasma density……………..	10^{10} cm^{-3}
Plasma electrons' and ions' thermal energy……………………	10 eV
Beam electrons velocity…………..	$2\cdot10^9$ cm/s
Beam density……………………...	$1.5\cdot10^7$ cm^{-3}
Beam modulation frequency……...	$5\cdot10^9$ rad/s
Beam modulation depth…………..	0.3
Simulation time step……………...	10^{-12} s

Thin ($L_b = 0.1\cdot L_y$) density-modulated electron beam was injected into plasma from the left electrode:

$$\rho(t) = \rho_0(1 + m\cdot\cos\omega t), \qquad (1)$$

where *m* is the modulation depth. Modulation frequency was selected in such way that $\omega_{mod} < \omega_{pe}$. Electrodes absorb both plasma and beam particles.

The simulation was carried out during the time interval of approximately 200 electron plasma periods. During this time electron beam reached the opposite electrode and quasi-stationary regime was settled.

3. SIMULATION RESULTS

3.1. INITIAL STAGE OF THE BEAM EVOLUTION: FILAMENTATION

Fig.1 demonstrates the spatial evolution of electron beam density and electric potential. One can see from Fig.1 that initially the injected beam is transversally homogeneous. But at some distance from injector beam filamentation is observed. Just after focusing of electron bunches in the beam this process depresses noticeably, and after second focusing it disappears.

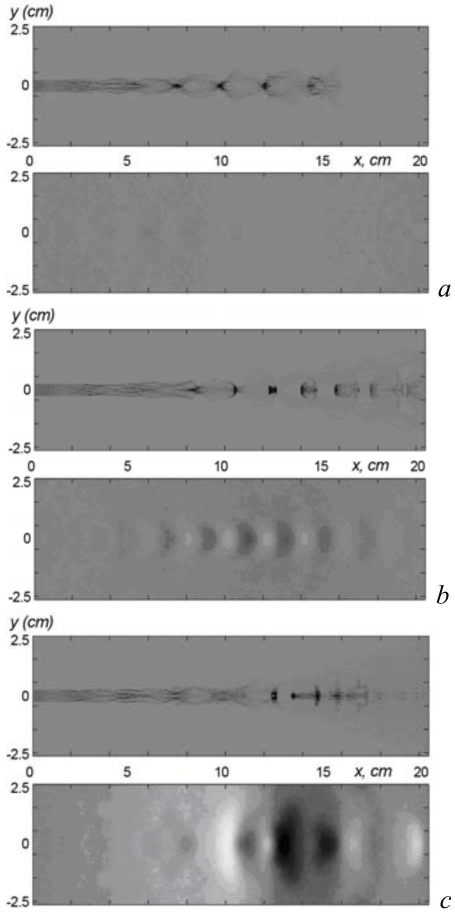

Fig.1. Spatial distribution of electron beam density (top) and electric potential (bottom) in sequential time points: t=7.5 ns (a); t=30 ns (b); t=100 ns (c)

Theoretical calculations in hydrodynamic approximation with assumption about small perturbations' magnitude demonstrated that solution for electric potential in the beam-plasma system is:

$$\varphi(x,y,t)=\begin{cases}\left((-1)^l\dfrac{k_x}{k_y}\cos\left(k_y y\right)+e^{-k_x a}ch\left(k_x y\right)\right)\times\\ \times\dfrac{\varphi_0\cdot e^{i\omega t-ik_x x}}{ch\left(k_x a\right)},\ |y|\le a;\\ \varphi_0 e^{-k_x y}e^{i\omega t-ik_x x},\ y>a;\\ \varphi_0 e^{k_x y}e^{i\omega t-ik_x x},\ y<-a;\end{cases}\qquad(2)$$

where a is beam width, φ_0 is the potential amplitude, $k_y=\pi(2l+1)/2a$, l is the mode number, and complex longitudinal wave number k_x can be obtained from the dispersion equation:

$$\omega\left(\omega-k_x v_0\right)\left(k_x^2+k_y^2\right)\times$$
$$\times\left(\left(\omega-k_x v_0\right)^2\left(\omega_p^2-\omega^2\right)+\omega^2\omega_b^2\right)=0.\qquad(3)$$

Formula (2) was obtained in the assumption that beam density perturbations vanished on its borders (this is true for small distances from injector, see Fig.1). Only symmetric oscillation modes, that are really excited in the system, were taken into account.

So wave increment doesn't dependent on the transversal wave number and waves with different transversal wave numbers grow in space with the same rates. Obviously spectrum of transversal wave numbers is defined by the fluctuations of beam electrons' density near injector.

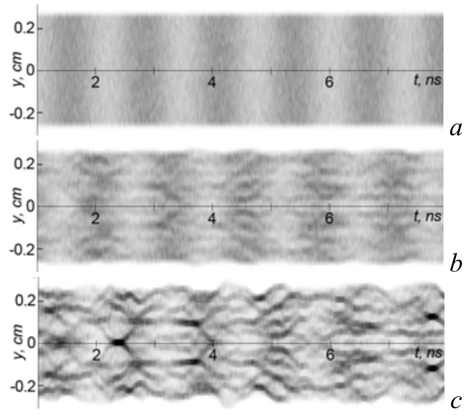

Fig.2. Temporal evolution of beam electrons density distribution in transversal direction on small distances from injector: 0.1 cm (a); 1 cm (b); c – 2 cm (c)

For detailed analysis of the beam filamentation temporal evolution of the beam electrons' density distribution in the transversal direction on several distances from injector (Fig.2) was obtained. Change of the strips color along the time axis is caused by initial beam modulation, time period of the strips is about 1.25 ns, they correspond to initial modulation frequency $\omega=5\cdot10^9$ rad/s.

Filamentation can be noticeable as early as at distance about 1…2 cm from the injector. Transversal beam perturbations are not regular; they change in time in a random way that corresponds to the conclusions obtained in analytic approach. At first several filaments appear in the beam, but later (in those parts of the beam where the most significant expansion takes place) shell with cavity inside is formed.

3.2. BEAM'S TRANSVERSAL EXPANSION AND BEAM ELECTRONS' LONGITUDINAL FOCUSING

Beam's transverse expansion is the second prominent effect after beam's focusing. Really, modulated (artificially or as a result of beam-plasma instability development) beam produces quasi-periodic potential relief. This relief disappears on great distances from system axis [15]. Beam electrons move in this potential so they are collected in minimums of potential energy (longitudinal and transverse focusing) and also rolled up from maximums (beam's swelling in transversal direction).

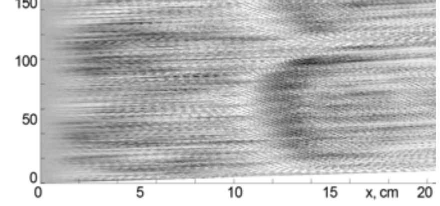

Fig.3. Space-time distribution of beam electrons density on x-axis (y=0)

On late stages, where field of excited wave of potential moves to the injector and interaction of the beam with electric field is the most effective; electron bunches formed in the beam start to decelerate relatively to peripheral beam parts. At the initial moment they are located on boundaries of the regions of the beam expansion, but later they get closer to the centers of these regions (see Fig.1,b). At the same time parts of the beam which are expanded start to overlap, and maximal amplitude of potential wave is reached in the region where bunches' density is maximal.

Fig.1,c corresponds to the time point of plasma transillumination for the beam (compare with Fig.3), when distance from injector to the maximal beam focusing grows substantially.

3.3. EVOLUTION OF INITIAL BEAM'S MODULATION AND ITS DISAPPEARANCE AFTER BUNCHES' FOCUSING

On Fig.4 spatial evolution of spectra of electric potential along x-axis (y=0) is shown. Although this dependency can't demonstrate the whole spatial dynamics, but it can be used for comparison of 2D simulation results with previous 1D simulation's results [9-11].

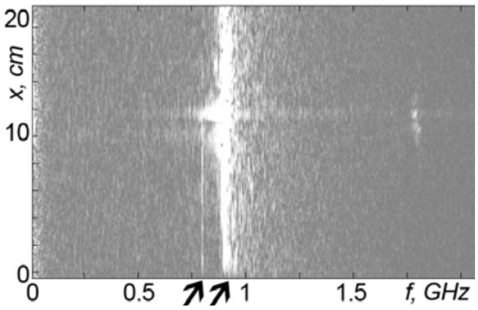

Fig.4. Spatial evolution of spectra of electric potential on x-axis (y=0). Arrows mark initial modulation frequency (left) and resonant frequency (right)

From Fig.4 one can see that concurrence between non-resonant beam-plasma instability at the modulation frequency and resonant instability at the Langmuir frequency of background plasma is completed by trapping of the beam electrons by resonant mode and suppression of the signal mode on modulation frequency. Initial modulation is preserved till some distance from injector, where maximal bunches' focusing occurs. After this moment beam "loses the memory" about its initial modulation.

CONCLUSIONS

Similar to 1D simulation effects were obtained: modes' concurrence completed by trapping of the beam electrons by resonant mode and suppression of the signal mode on the modulation frequency. These results correspond to laboratory experiments [4,7].

Several essentially new effects were observed in comparison with simulations in 1D model: transversal and longitudinal focusing of the beam, beam's transverse filamentation, which is hypothetically caused by instability of the oblique space charge waves in the beam, and beam's transverse expansion.

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ДВУМЕРНОЕ МОДЕЛИРОВАНИЕ ДИНАМИКИ ПОПЕРЕЧНО ОГРАНИЧЕННОГО МОДУЛИРОВАННОГО ЭЛЕКТРОННОГО ПУЧКА В ОДНОРОДНОЙ ПЛАЗМЕ

И.А. Анисимов, М.И. Соловьёва

С помощью компьютерного моделирования методом крупных частиц исследуется динамика поперечно ограниченного модулированного электронного пучка, движущегося в однородной плазме. Двумерное моделирование показало, что в системе плазма-электронный пучок происходит конкуренция между нерезонансной плазменно-пучковой неустойчивостью на частоте модуляции и резонансной неустойчивостью на ленгмюровской частоте фоновой плазмы. В сравнении с одномерным моделированием были получены новые эффекты, среди которых расслоение (филаментация) и расширение пучка в поперечном направлении, а также поперечная и продольная фокусировки электронов пучка. Поперечная филаментация, вероятно, вызвана неустойчивостью косых волн пространственного заряда в пучке, что подтверждается теоретическими расчетами.

ДВОВИМІРНЕ МОДЕЛЮВАННЯ ДИНАМІКИ ПОПЕРЕЧНО ОБМЕЖЕНОГО МОДУЛЬОВАНОГО ЕЛЕКТРОННОГО ПУЧКА В ОДНОРІДНІЙ ПЛАЗМІ

І.О. Анісімов, М.Й.Соловйова

За допомогою комп'ютерного моделювання методом крупних частинок досліджується динаміка поперечно обмеженого модульованого електронного пучка, що рухається крізь однорідну плазму. Двовимірне моделювання показало, що в системі плазма-електронний пучок відбувається конкуренція між нерезонансною плазмово-пучковою нестійкістю на частоті модуляції та резонансною нестійкістю на ленгмюрівській частоті фонової плазми. В порівнянні з одновимірним моделюванням було отримано ряд нових ефектів, серед яких розшарування (філаментація) пучка та його розширення в поперечному напрямку, а також поперечне та повздовжнє фокусування електронів пучка. Поперечна філаментація, ймовірно, спричинена нестійкістю косих хвиль просторового заряду в пучку, що підтверджується теоретичними розрахунками.