EVOLUTION OF ELECTRONS' DISTRIBUTION FUNCTION DURING THEIR INTERACTOIN WITH PLASMA: NUMERICAL SIMULATION

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One-dimension numerical simulation of the beam-plasma system was carried out using the big-particles-in-cells method. Instantaneous velocity distribution of the beam electrons depending of the distance from injector was received. The distribution function was found to be oscillating and strongly irregular. This result corresponds with the data of the previous calculations and laboratory experiments. After averaging over the sufficiently long time interval the distribution function becomes smoothed and similar to a plateau that was observed in the laboratory experiments.

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1. INTRODUCTION

The quasilinear theory created at the beginning of the 1960-th [1-3] has foreseen that electron beam having interacted with plasma acquire the electron's energy distribution function with the plateau due to the electrons' diffusion in the velocities' space. Some experimental investigations carried out in the same time confirmed fully this prediction [4-7]. But some disagreement between the prerequisites of the quasilinear theory and conditions of the experiments gave rise to the uncertainty [8]. Later analytic calculation [9] and numerical simulation [10-12] showed that the instantaneous distribution function should be highly non-monotonic. Experimental measurements confirmed this conclusion [13]. Consequently the problem of the agreement between the theory and experiment has not yet been solved.

This article presents results of the numerical simulation of the electron beam interaction with plasma. Temporal and spatial evolution of the instantaneous distribution function of the beam electrons was studied. Averaging of this function over the sufficiently long time interval gives the possibility to explain the experimental results mentioned above.

2. PROGRAM DESCRIPTION

One-dimension numerical simulation of the beam-plasma interaction was carried out using the big-particles-in-cells method (without external magnetic field). The modified PDP1 package [14] was used. The program is based on the 32-bit Windows operating system. There are no implicit restrictions for the number of large particles. This number is specified for every type of particles separately. The intermediate results of the simulation can be preserved for the posterior treatment.

The developed diagnostic modules give the possibility to observe 3D plots of the spatial dependencies of the instantaneous and averaged velocity distribution functions for all types of particles (particularly for the beam electrons and for the plasma electrons separately).

3. PARAMETERS SELECTION

The data mentioned below was obtained for such parameters of the beam-plasma system:

– density of the background plasma was $n_e=10^{14}m^{-3}$, corresponding Langmuir electron frequency was $\omega_p=5.6510^8 s^{-1}$;
– initial beam velocity was $v_0=10^7 m/s$, corresponding electrons' energy was $275eV$;
– current density of the beam was $j=0.1A/m^2$, corresponding ratio of the beam density to plasma density was $n_b/n_e=6\cdot 10^{-4}$.

Distance from the injector and the time were normalized as $x'=x\omega_p/v_0$ and $t'=\omega_p\ t/2\pi$, respectively. The time point t' corresponds to the beginning of the beam injection.

These parameters correspond to some real experimental conditions and give the clearest picture of the effects observed in our numerical simulation.

4. PHASE PORTRAIT OF THE BEAM-PLASMA SYSTEM

Fig.1 represents the phase portrait of the beam interacting with plasma for $t'=63$.

Near the point of origin one can observe the linear growth of the oscillations' magnitude. Further linear regime converts quickly into the regime of the wave front tipping over. For larger distances from injector the picture becomes more complicated. At the distance $x'>100$ the electrons' trajectories get mixed up and one could not follow their course.

This result is similar to the numerous results of the previous simulation (see, e.g., [15]).

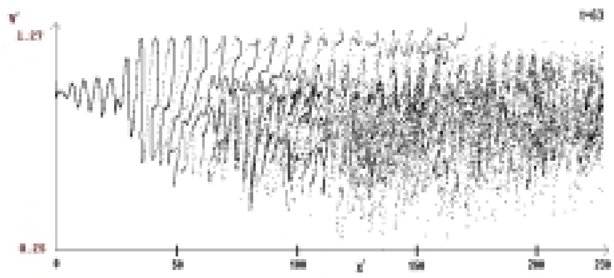

Fig.1. Phase portrait of the beam electrons for $t'=63$

5. INSTANTANEOUS VELOCITY DISTRIBUTION FUNCTION

Fig.2 demonstrates the three-dimensional plot of instantaneous velocity distribution function of the beam electrons for $t'=63$ from their injection in the plasma. The datum lines correspond to the coordinate x', normalized velocity $v'=2\pi v/v_0$ and number of electrons n

per the phase cell $\Delta x \cdot \Delta v$ (in the arbitrary units). This diagram is a kind of 3D analog of the phase portrait shown on fig.1. It shows the number of particles corresponding to each cell of the phase space.

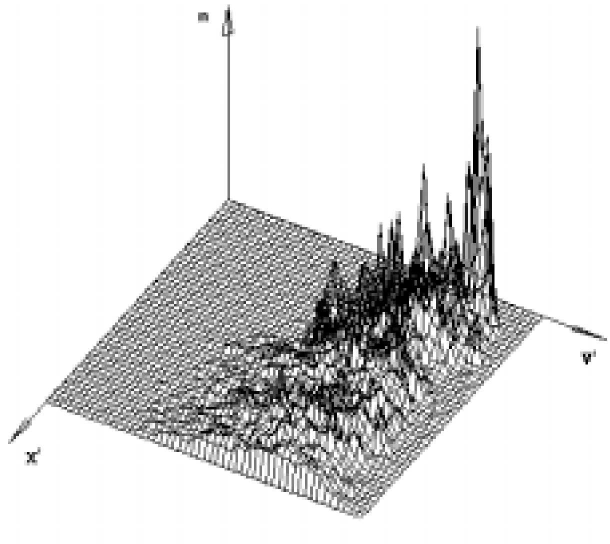

Fig.2. Instantaneous velocity distribution function of the beam electrons depending on the distance from injector for t′=63

The results presented on fig.2 are partially similar to the data obtained in [8].

Observing on the display the time evolution of the plot similar to fig.3 for the initial stage of the beam injection one can see the motion of the forefront from the injector. The highest peaks correspond to the velocities less then v_0 because the beam looses its energy during the interaction with plasma.

The cross-sections of the plot shown on fig.2 (for different x') are presented on fig.3a-d.

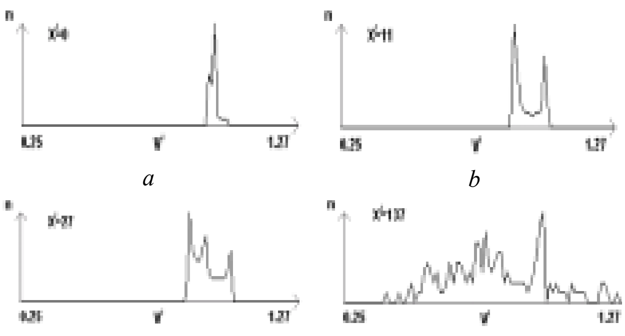

Fig.3. Instantaneous velocity distribution function of the beam electrons at different distances from injector (noted at the plots) for t′=63

At a small distances from injector one can observe the single peak that corresponds to the apart lines on the phase portrait (fig.3a). After the wave front tripping over the number of peaks is increased (see fig.3b-c). For larger distances from injector separate peaks unite into the continuos indented curve. The intensity of the spectrum is decreased with the distance from injector, and it expands both to the sides of larger and smaller velocities.

The general picture of the velocity distribution evolution is similar to the calculation for the stationary case [9] and to the experimental results [13].

6. THE AVERAGED DISTRIBUTION FUNCTION

Fig.4 shows the spatial dependence of the velocity distribution function of the beam electrons averaged over some tens of the Langmuir frequency periods. One can see that the time averaging results to the smoothing of the distribution function (compare fig.4 and fig.3).

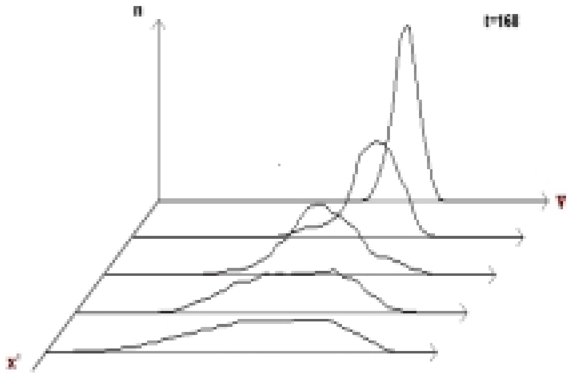

Fig.4. The averaged velocity distribution function of the beam electrons depending on the distance from injector

The results presented on fig.4 are very much similar to the experimental measurements [4-7]. At the large distances from injector one can see some kind of plateau. But this plateau is not formed due to the quasi-linear beam relaxation in plasma. It appears due to the time lag of the measuring elements that result to the time averaging of the data.

7. CONCLUSION

Simulation of the beam-plasma interaction was carried out using bib-particles-in-cells method. The spatial and temporal evolution of the instantaneous velocity distribution function of the beam electrons was studied. The results obtained coincide to the results of the previous simulation and laboratory experiments.

Averaging of the instantaneous velocity distribution over the interval of some tens of the Langmuir frequency periods results to the smoothing and formation of some kind of plateau at the large distances from injector. This effect explains the plateau formation for monokinetic electron beams that was observed in the laboratory experiments [4-7].

REFERENCES

1. Ю.А.Романов, Г.Ф.Филиппов. Взаимодействие потоков быстрых электронов с продольными плазменными волнами // *ЖЭТФ*. 1961, т.40, №1, с.123 - 132.
2. А.А Веденов, Е.П.Велихов, Р.З.Сагдеев. Квазилинейная теория колебаний плазмы. // *Ядерн. синтез*. 1962, прилож. 2, с.465 - 475.
3. W.E.Drummond, D.Pines. Non-linear stability of plasma oscillations // *Nuclear Fusion*. 1962, Suppl. 3, p.1049 - 1057.
4. И.Ф.Харченко, Я.Б.Файнберг, Р.М.Николаев, Е.Ф.Корнилов, Е.И.Луценко, Н.С.Педенко. Взаи-

модействие пучка электронов с плазмой в магнитном поле // *Ядерн. синтез*. 1962, Прилож. 3, с. 1101 - 1106.

5. C.Etievant, M.Perulli. Instabilite et amortissement dans un systeme faisseau - plasma // *Compts rendue*. 1962, vol.255, №5, p.855 - 857.
6. С.М.Левитский, И.П.Шашурин. Пространственное развитие плазменно-пучковой неустойчивости // *ЖЭТФ.* 1967, т.52, №2, с.350 - 355.
7. S.M.Levitsky, I.P.Shashurin. Electron-beam relaxation in a plasma. // *Nuclear Fusion.* 1971, v.11, №1, p.111 - 117.
8. Ю.С.Сигов, В.Д.Левченко. Когерентные явления при релаксации размытых электронных пучков в открытых плазменных системах // *Физика плазмы*. 1997, т.23, №4, с.325-342.
9. А.И.Рогашкова, И.Ф.Харченко, М.Б.Цейтлин, И.Т.Цицонь. Развитие нелинейных колебаний при взаимодействии модулированного электронного пучка с плазмой // *Изв.ВУЗов, сер. Радиофизика*. 1972, т.15, №8, с.1121-1131.
10. О.В.Батищев, Н.Г.Белова, Ю.С.Сигов. *Численное моделирование бесстолкновительной релаксации размытого электорнного пучка, инжектированного в максвелловскую плазму*. Москва, ИПН АН СССР: Препринт № 21, 1972, 28 с.
11. А.С.Бакай, Ю.С.Сигов. О бесстолкновительной релаксации плазмы с неустойчивой функцией распределения электронов // *Докл. АН СССР,* 1977, т.237, №6, с.1326-1329.
12. С.М.Криворучко, В.А.Башко, А.С.Бакай. Бесстолкновительная релаксация инжектированного а плазму размытого электронного пучка с подкритической плотностью // *ЖЭТФ.* 1981, т.80, №3, С.579-585.
13. В.А.Лавровский, И.Ф.Харченко, Е.Г.Шустин. Исследование механизма возбуждения стохастических колебаний в пучково-плазменном разряде // *ЖЭТФ*. 1973, Т.65, №6(12), с.2236-2249.
14. Ch.K.Burdsall, A.B.Langdon. Plasma Physics, via Computer Simulation. McGraw-Hill Book Comp. 1985.
15. G.V.Lizunov, O.V.Podladchikova. On the problem of bursty generation of Langmuir waves by “monoenergetic” electron beam. // *Ukrainian Physical Journal*. 1998, v.43, p.182-187.