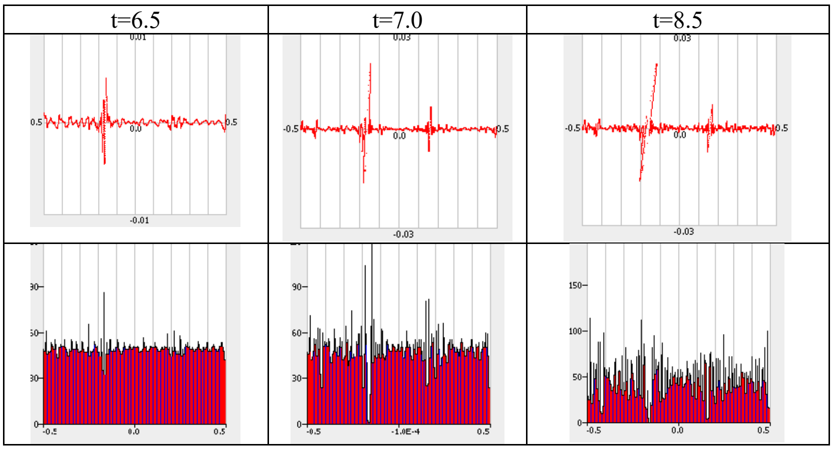

Figure 3. Phase plane (velocity, coordinate) and plasma density at different times for Silin's hybrid model. The number of spectrum modes is 201, the number of particles simulating ions is 10,000 [11]

4. FORMATION OF SPATIAL PLASMA DENSITY DISTRIBUTIONS IN SYSTEMS WITH A LARGE NUMBER OF PARTICLES SIMULATING IONS

Generally speaking, it remains unclear whether the emerging caverns move in space. In other words, do the phases of the amplitudes of charge density and ion density varying slowly with time $\nu_{in} = en_{in}$ and n_{in}. In addition to explaining their dynamics, this circumstance, as shown below, affects the process of synchronization of the Langmuir spectrum of instability. In the calculations, only the obvious condition $n_{i,-n} = (n_{i,n})^*$ was assumed to be satisfied. However, as shown by model calculations for a large number of spectrum modes (the number of which is 1001) and a large number of particles simulating ions, equal to 50,000, phase changes for the spectral components of the plasma density were not noticed. The caverns practically did not change their position, changing only their amplitude (see Fig. 4).

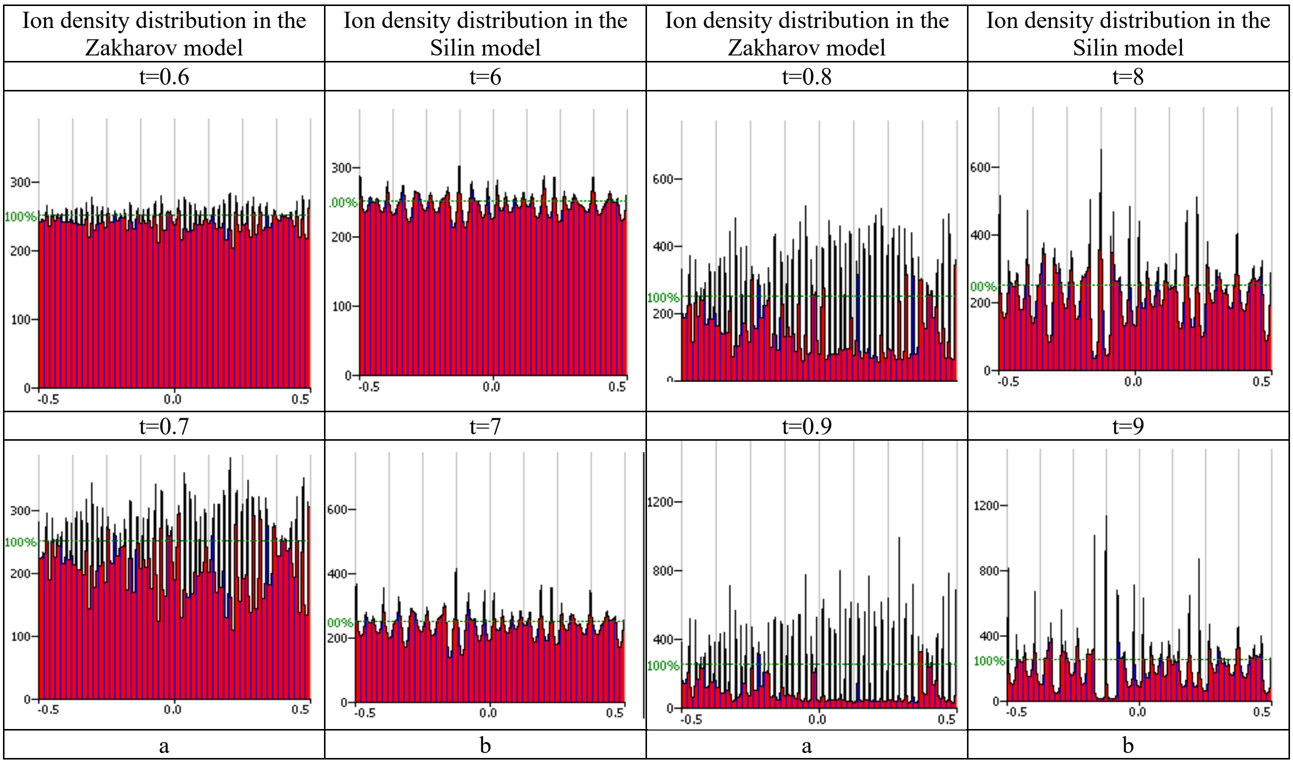

Figure 4. Plasma ion density distribution in the Zakharov (a) and Silin (b) models, the number of particles simulating ions is 50000, the number of spectra modes is 1001. Absorption in the system is 0.05. [11]

5. PHASE SYNCHRONIZATION MECHANISMS IN THE ZAKHAROV AND SILIN MODELS

The process of phase synchronization of short-wavelength Langmuir waves of the instability spectrum $E_n = |E_n| \cdot \exp\{i\varphi_n\}$ can be illustrated as follows. From equations (7), (10) at the initial stage of instability in the Zakharov model, one can obtain a simple equation for the phase of an individual mode of the RF Langmuir spectrum

$$\frac{\partial \varphi_n}{\partial t} - \Delta_Z = R_Z \cdot \ \mathrm{Cos}\{\phi - \varphi_n\} \tag{18}$$

where $\Delta_Z = \dfrac{\omega_{pe}^2 - \omega_0^2 + k^2{}_0 n^2 v_{Te}^2}{2\omega_0}$ and $R_Z = \dfrac{\omega_0 n_{in} E_0}{2 n_0 E_n}$. Obviously, in the absence of changes in the position of the caverns, and at a significant value of $R_Z \propto E_0 / E_n >> 1$, the phases of the RF spectrum modes are able to synchronize.

Accordingly, equations (2), (5) in the initial stage of instability for the phases of the RF modes of the Langmuir spectrum $E_n = |E_n| \cdot \ \exp\{i\varphi_n\}$ can be written as

$$\frac{\partial \varphi_n}{\partial t} - \Delta_S = R_S \cdot \mathrm{Sin}\{\phi - \varphi_n\}, \tag{19}$$

where $\Delta_S = \dfrac{\omega_{pe}^2 - \omega_0^2}{2\omega_0}$, $R_S = \dfrac{4\pi\omega_{pe} v_{in}}{k_0 n E_n} J_1(a_n) \propto J_1(a_n)/E_n$, and $J_1(a_n)/E_n >> 1$ for rapidly growing modes of the HF spectrum allows the phases of the spectrum to be synchronized.

Despite the development of small-scale modulation of the plasma density in the Zakharov and Silin models, the nature of the formation of cavities, even on small scales, is largely associated with mode locking. This process is illustrated in Fig. 5, which shows the formation of small-scale caverns.

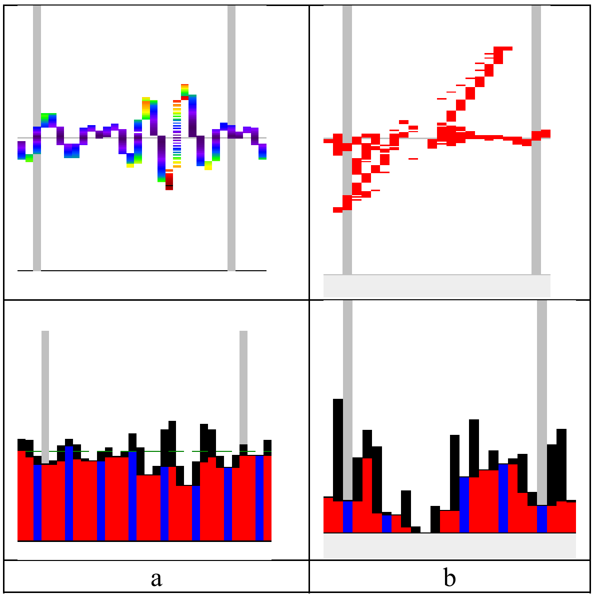

Figure 5. Formation of small-scale plasma ion density caverns in the Zakharov (a) Silin (b) hybrid models. The upper fragments illustrate the phase (velocity and coordinate of particles) space near the caverns, the lower fragments illustrate the particle density distribution [11]

In Zakharov's model for a nonisothermal plasma, expression (13) is valid for the components of the low-frequency field strength, and expression (8) is valid for Silin's cold plasma model. It is important to note that the right-hand sides of these expressions contain terms, the number of which is significant for wide spectra of short-wave disturbances in hybrid models. Therefore, the RF pressure is very high in this case, especially in the Silin model for cold plasma. Perhaps this is why the formation of the small-scale cavity shown in Fig. 5b demonstrates such a dynamic character. In addition, the particle extrusion mode is implemented here, which expands the cavity. It is also possible to switch to the mode of intersection of particle trajectories, which destroys the cavity, as can be seen in [5].

6. CONCLUSION

The paper considers the instability of intense Langmuir oscillations in nonisothermal (Zakharov's model) and cold (Silin's model) 1D plasma. The main attention is paid to the formation of plasma density caverns in the hydrodynamic and hybrid (electrons are described hydrodynamically, ions are described by model particles) representations.

In the hydrodynamic representation, with a small number of spectrum modes, large-scale plasma density caverns are formed, which rapidly deepen. This process is supported by the appearance of small-scale perturbations, and phase synchronization of the Langmuir waves of the instability spectrum is observed (Section 5). This phase synchronization of the spectrum modes is quite capable of fulfilling the role that was previously proposed to be given exclusively to the effect of extrusion of particles from the cavity by the field.

In hybrid models, where ions in the region of consideration are described by model particles, the number of which in the one-dimensional case $10^4 \div 5 \cdot \ 10^4$ (which in the three-dimensional case corresponds to the number of particles $10^{12} \div 10^{14}$)

the initial spectrum of perturbations is very wide and rather intense, which leads to an explosive growth of perturbations in the Zakharov model [8] and a rapid development of instability in Silin's model. In this case, in the developed instability regime, the formation of many small-scale plasma density caverns is observed. It is important to note that the caverns practically do not change their position; phase changes for the spectral components of the plasma density were not observed. It is the presence of this small-scale modulation due to the Fermi effect that rapidly forms the normal velocity distribution of ions [7]. In this case, the effect of particle heating due to Landau damping loses its primacy [9]. Only individual small-scale caverns demonstrate dynamics (see Fig. 5) similar to the development of caverns in the hydrodynamic representation.

Thus, the notions that plasma density caverns, which form during the instability of intense Langmuir oscillations, first appear on a large scale and only then deepen due to the extrusion of particles by the HF field or due to the development of energy motion along the spectrum are only partly true. In fact, when describing ions by particles due to the wide initial spectrum (due to the discreteness of the ionic component), many small-scale cavities immediately appear and the appearance of large deepening cavities becomes unlikely.

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ПРО МЕХАНІЗМИ ФОРМУВАННЯ КАВЕРН ЩІЛЬНОСТІ ПРИ НЕСТІЙКОСТІ ІНТЕНСИВНИХ ЛЕНГМЮРІВСЬКИХ КОЛИВАНЬ У ПЛАЗМІ

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У роботі розглянуто нестійкість інтенсивних ленгмюрівських коливань у неізотермічній (модель Захарова) та холодній (модель Силіна) 1D плазмі. Основна увага приділена процесу формування каверн щільності плазми у гідродинамічному та у гібридному (електрони описані гідродинамічно, іони – модельними частинками) представленнях. У гідродинамічному поданні при невеликій кількості мод спектру спостерігаються великомасштабні каверни щільності плазми, які швидко поглиблюються. Цей процес підтримується появою дрібномасштабних обурень, причому спостерігається синхронізація фаз ленгмюрівських хвиль спектра нестійкості. Ця синхронізація фаз мод спектру цілком здатна виконати ту роль, яку раніше пропонували віддати виключно ефекту видавлювання полем частинок з каверни. У гібридних моделях у області розгляду іони описані модельними частинками, число яких у одновимірному випадку $10^4 \div 5 \cdot 10^4$ (що у тривимірному випадку відповідає числу частинок $10^{12} \div 10^{14}$). Початковий спектр обурень дуже широкий і досить інтенсивний, що призводить до вибухового зростання збурень у моделі Захарова та швидкого розвитку нестійкості у моделі Силіна. При цьому в розвиненому режимі нестійкості спостерігається формування безлічі дрібномасштабних каверн щільності плазми. Саме наявність цієї дрібномасштабної модуляції за рахунок ефекту Фермі швидко формує нормальний розподіл іонів за швидкостями. В цьому випадку ефект нагрівання частинок за рахунок згасання Ландау втрачає першість. Показано, що каверни мало змінюють свого становища, фазові зміни для спектральних компонентів щільності плазми помічені не були. Тільки окремі дрібномасштабні каверни демонструють динаміку, подібну до розвитку каверн у гідродинамічному представленні.

Ключові слова: інтенсивні ленгмюрівські коливання, моделі опису Захарова та Силіна, дрібномашабні малорухливі каверни щільності плазми, синхронізація фаз.