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EARLY STAGE OF THE ELECTROMAGNETIC BEAM NONLINEAR INTERACTION WITH THE DENSE PLASMA LAYER

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Using computer simulation, the initial stage of low-power electromagnetic waves` beam nonlinear interaction with the overdense plasma layer was studied. It is shown that the peripheral part of the beam excites a Langmuir wave at the second harmonic, which propagates deeper into the plasma. It is also demonstrated that an axially asymmetric structure is formed in the near-axis region of plasma, which includes interconnected perturbations of the longitudinal and transverse electric fields, the longitudinal electron velocity, and electron density.

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INTRODUCTION

Interaction of a powerful electromagnetic waves` beam with plasma is of interest both from the perspective of nonlinear wave theory in plasma and for several applied problems—plasma barriers transillumination, laser thermonuclear fusion, and others. This effect has been the subject of numerous studies [1-14], which include results from laboratory experiments and theoretical investigations. A significant portion of the experimental results still lack a definitive explanation, and sometimes remain entirely unclear.

In our previous works [15, 16], we employed particle-in-cell (PIC) simulations to study the dense plasma barrier transillumination problem. It was determined that, for electromagnetic beams of moderate power, the formation of a channel in the plasma barrier is driven by the ponderomotive force exerted on the plasma by the inhomogeneous high-frequency electromagnetic field (the slow transillumination mode). For beams of higher power, turbulent motion arises in the plasma, leading to the redistribution of plasma density in space. As a result, the wave passes through the barrier in regions of reduced plasma density before a full channel is formed (the fast transillumination mode).

In the aforementioned works, we used direct simulation results to construct the spatial distributions of electron and ion densities in the plasma, as well as the electric and magnetic fields excited by the incident wave. These distributions were constructed in a plane containing the system's axis (based on the assumption of axial symmetry of the model).

Meanwhile, the array of simulation results allows for more complex processing. Specifically, averaging the electric fields over the period of their oscillations enables us to highlight the quasi-stationary components that arise from the nonlinear interaction of the incident beam with the plasma. It is also possible to construct distributions of electron and ion densities, components of the electric field, and electron velocities in a plane perpendicular to the system's axis.

The slow transillumination of plasma by a low-power beam can be conventionally divided into several stages. The first stage lasts from the time point the front of the beam falls on the plasma until the formation of a cavity on the barrier surface. Then, this cavity propagates into the depth of the barrier, and eventually, a waveguide channel is formed through which the incident wave passes behind the barrier.

The aim of this work is to investigate the initial stage of the nonlinear interaction of a low-power waves` beam with an overdense plasma layer, specifically the first stage of transillumination.

1. SOFTWARE TOOLS AND SIMULATION PARAMETERS USED

The PIConGPU package [17], based on the particle-in-cell method, was used for 3D simulation. Using the ParaView package [18], analysis was conducted through three-dimensional visualizations of instantaneous values. Averaged values analysis was conducted in a custom program that reads raw values in OpenPMD format.

The following simulation parameters were used: fully ionized hydrogen plasma of a density $9\cdot10^{12}$cm^{-3} (electron plasma frequency – 27 GHz); plasma temperature – 0.5 eV (isothermal plasma); the plasma layer thickness – 12.5 cm, radius – 21.5 cm; incident wave length – 3.33 cm (frequency – 9.9 GHz, i.e. plasma is opaque for this wave); pulse duration – 101 ns; pulse radius (at half maximum) – 4.9 cm; the maximum electric field amplitude is 0.964·MV/cm (4 times smaller than the amplitude of a moderate wave in [15, 16]).

2. QUASI-STATIONARY ELECTRIC FIELDS ARISING IN PLASMA AND THE PLASMA MOTION THEY INDUCE

Fig. 1,a–c shows the distribution of the axial component of the averaged electric field in the plane containing the system axis at different time points after the wave packet's leading edge impacts the plasma.

It is evident that at 0.56 ns, an electric field directed out of the plasma is formed on the plasma surface where the wave falls (see Fig. 1,a).

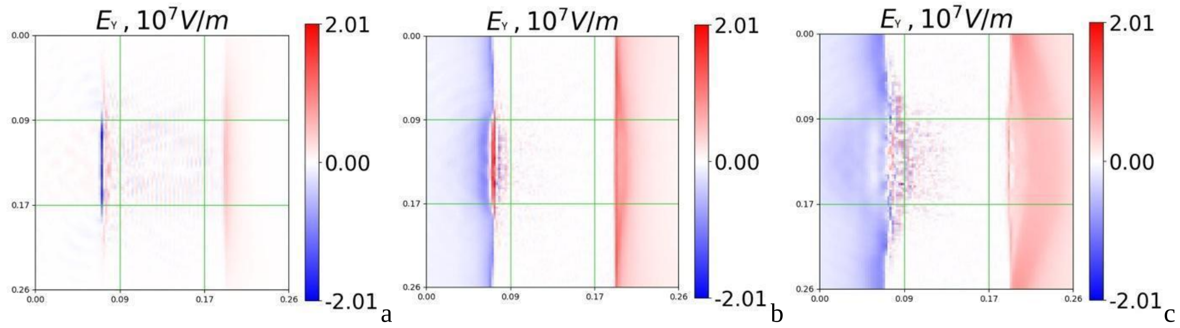

Fig. 1. Distribution of the averaged longitudinal electric field in the cross-section containing the system's axis at time points: 0.56 ns (a), 5.11 ns (b), and 10.45 ns (c)

This occurs under an action of the ponderomotive force caused by the non-uniform high-frequency field [19]. Electrons are the first to move into plasma, leading to charge separation and appearance of the mentioned field, which then pulls the ions following the electrons. At 5.11 ns, the field changes its sign to the opposite (see Fig. 1,b), and by 10.45 ns, the field virtually disappears. Thus, the characteristic time of the field change is approximately 5 ns, whereas the period of the incident wave is around 0.1 ns. Therefore, the observed field can indeed be considered quasi-stationary.

It can be assumed that one observes a kind of transient process occurring in the near-surface layer of plasma when the leading edge of the wave packet falls.

The emergence of a longitudinal electric field on both sides of the barrier, in our opinion, is an unphysical effect. This is associated with the fact that electrons escaping from plasma during the boundary erosion process are absorbed by the surfaces limiting the simulation volume in the given software package, which eventually causes the plasma to acquire a positive charge over time.

3. NONLINEAR EXCITATION OF LANGMUIR WAVES BY AN INCIDENT ELECTROMAGNETIC WAVE

Fig. 2,a demonstrates that deep within the plasma layer, at the point where the wave beam falls, regions appear where the longitudinal field periodically changes in space. This spatial field variation can be interpreted as a Langmuir wave. Fig. 2,b shows that this variation is accompanied by disturbances in the electron velocity.

It is known that when a transverse electromagnetic wave normally falls on a plasma, the electrons oscillate along the direction of the wave's electric field and simultaneously experience the influence of the magnetic field. As a result, a Lorentz force arises, directed deeper into plasma. After half a period, the directions of electric and magnetic fields reverse, so the direction of the Lorentz force remains the same. At the same time, its magnitude undergoes oscillations, with a frequency twice that of the wave. It can be assumed that these oscillations of the Lorentz force excite the aforementioned Langmuir wave. The proposed explanation is supported by the fact that the Langmuir wave frequency, found from the simulation results, is 19.8 GHz, while the frequency of the incident electromagnetic wave is 9.9 GHz.

Note that the excitation of the Langmuir wave predominantly occurs at the periphery of the incident wave beam. Over time, this effect disappears, which can be associated with the deformation of the plasma surface under the influence of the incident wave beam.

Effects of the nonlinear transformation of the incident electromagnetic wave with plasma were studied previously, namely the second harmonic excitation (see, e.g., [20]) and parametric excitation of the Langmuir wave propagating along the electric field of the incident wave [4]. The nonlinear excitation of a Langmuir wave at the doubled frequency, propagating into plasma, has not been previously discussed in the literature .

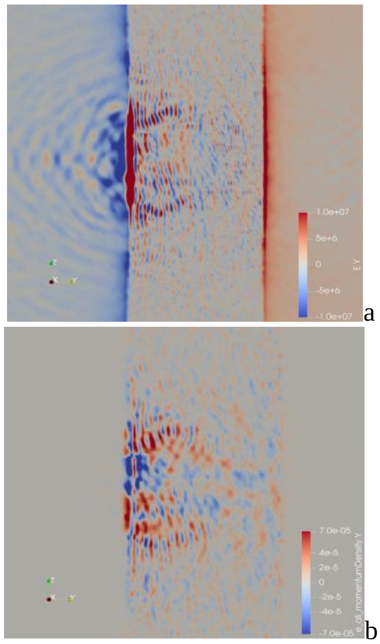

Fig. 2. Distribution of the instantaneous axial components of the electric field (a) and electron velocity (b) in the plane containing the system axis (t=4.5 ns)

4. AXIALLY ASYMMETRIC STRUCTURES FORMATION

Due to the initial axial symmetry of the model, one might assume that this symmetry would be preserved. However, as the simulation results (Figs. 3, 4) show the breaking of this symmetry. This disruption can be associated with the development of a certain parametric instability in the field of the incident wave beam, leading to the emergence of azimuthal inhomogeneity (similar, for example, to the diocotron instability in a rotating tubular electron beam).

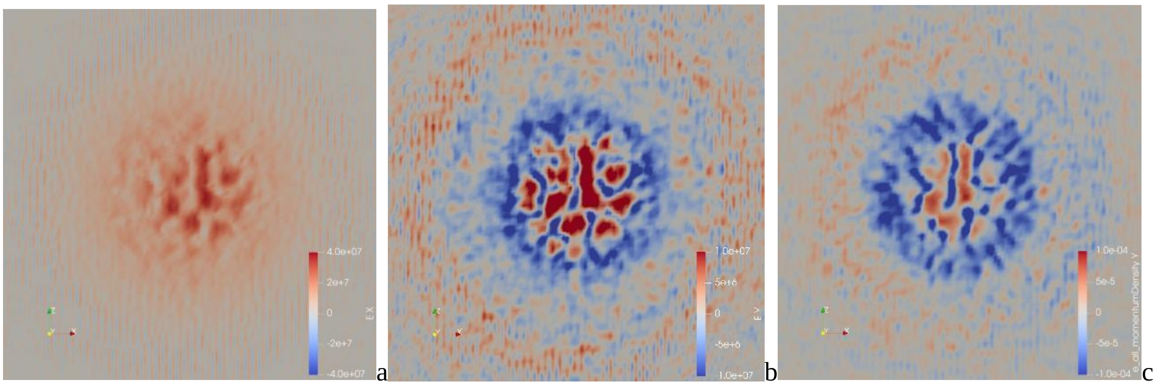

Fig. 3. Distributions of the instantaneous transverse (a) and longitudinal (b) electric fields, as well as the axial velocity of electrons (c) in the plane perpendicular to the axis of the system at a depth of 0.3 cm from the initial plasma boundary at the moment of time 4.5 ns

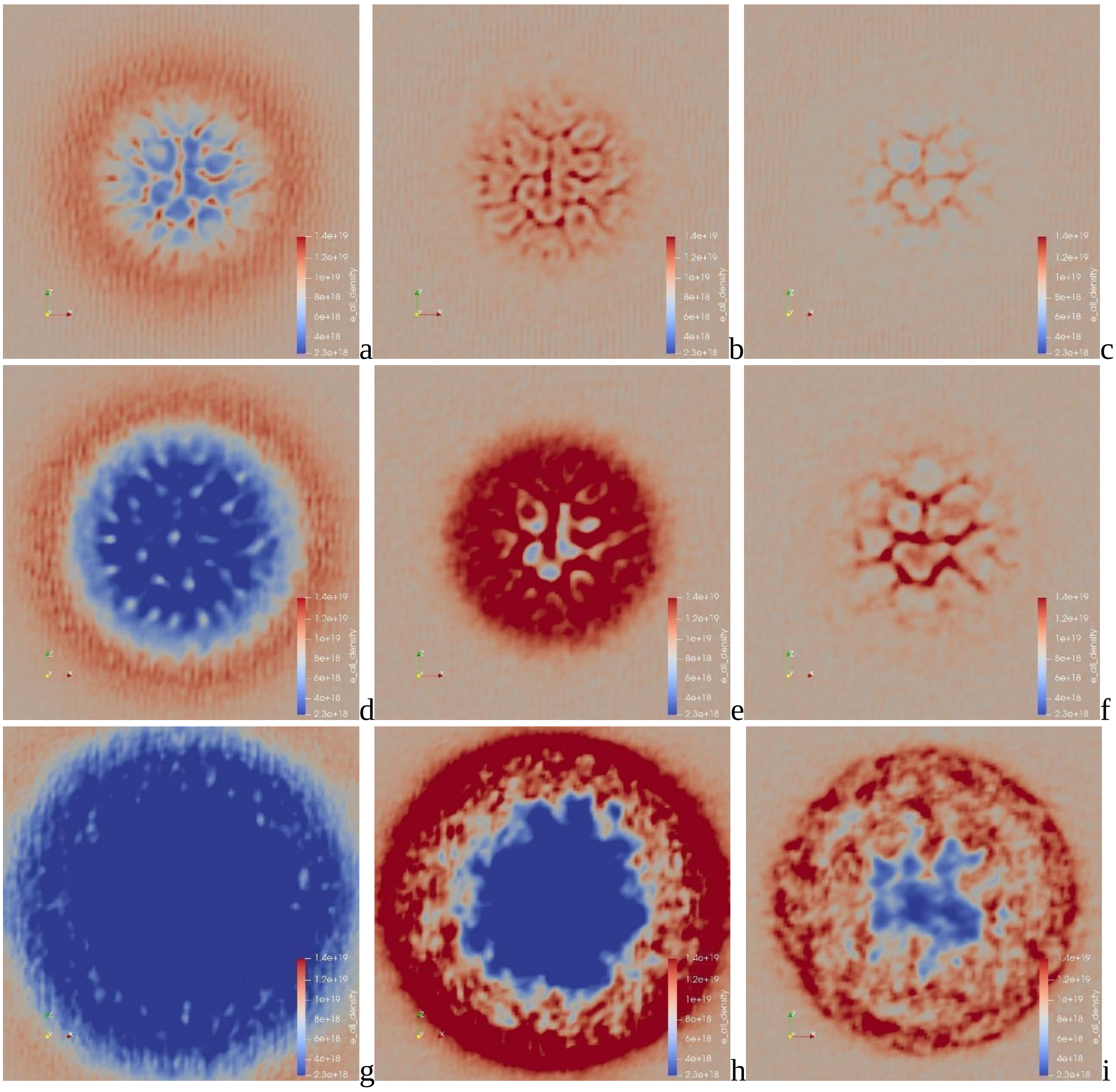

Fig. 4. Transverse distributions of instantaneous electron density at the time points: 4.55 ns (a-c), 7.59 ns (d-f), and 19.73 ns (g-i) at depths of 0.3 cm (a, d, g), 0.8 cm (b, e, h), and 1.3 cm (c, f, i) from the initial boundary of the plasma layer

In general, the shape of the regions of increased transverse (see Fig. 3,a) and positive (directed into plasma) longitudinal (see Fig. 3,b) electric fields, positive longitudinal electron velocity (see Fig. 3,c), and reduced electron density (see Fig. 4,a) generally coincide. This suggests that a ponderomotive force arises at the maximum of the transverse electric field, causing electrons to move deeper into the plasma and resulting in a corresponding redistribution of its density. In turn, the decrease in plasma density leads to an increase in its dielectric permittivity and a subsequent rise in the electric field in these regions. Finally, the motion of electrons into the plasma disrupts its charge neutrality, which leads to the appearance of a longitudinal electric field.

Maybe formation of these structures in the near-axis region causes the Langmuir wave excitation primarily at the periphery of the wave beam, where practically absent (or maintain axial symmetry) – see Fig. 2.

When such structures arise, the transverse component of the electron velocity is also disturbed (see Fig. 3,c; compare with Fig. 3,a-b and Fig. 4,a). Overall, the plasma motion in this case appears turbulent. The small disturbances at the periphery of Fig. 3,a-c can be associated with the grid used in the simulation process.

Fig. 4 shows the spatial structure of the density distribution and its evolution over time. It can be seen that at 4.55 ns, the structure is visible to a depth of approximately 1.5 cm (for the selected simulation parameters). In the near-axis region, where the electron dencity is reduced at a depth of 0.3 cm (compared to undisturbed plasma), it is increased at a depth of 0.8 cm. Indeed, the ponderomotive force generates an electron flow into plasma, so its density near the plasma surface decreases, while it increases at greater depths (Fig. 4,a-c).

At 7.59 ns, the initial disturbance structure remains only at a depth of 1.3 cm. At shallower depths (up to 0.8 cm), a deepening forms, which can be considered axially symmetric in the first approximation.

Finally, at 19.73 ns, this deepening occupies the entire original volume of the axially asymmetric structure. This time point can be conventionally considered as the end of the first stage of the nonlinear interaction of a low-power wave beam with the plasma.

CONCLUSIONS

1. In the initial time points after the wave beam falls on the plasma layer, plasma becomes polarized, and a quasi-stationary longitudinal electric field arises in the near-surface layer. Later, this field changes its sign and eventually disappears after some time. Overall, this can be described as a transient process caused by the leading front of the wave beam falling on the plasma. It can be assumed that smoothing this front will weaken or even eliminate this transient process.

2. The wave beam falling on the plasma excites a Langmuir wave with a doubled frequency, which propagates into the plasma's depth. The mechanism of transformation from a transverse electromagnetic wave into a longitudinal Langmuir wave is related to the oscillatory component of the ponderomotive force induced by the incident wave. The excitation of Langmuir waves occurs at the periphery of the incident wave beam and lasts for a limited time. The Langmuir waves excitation presence specifically at the periphery of the beam can be associated with the formation of structures near the system's axis, while the limited duration of excitation is linked to the nonlinear deformation of the plasma density's spatial distribution.

3. The analyzed model is axially symmetric. However, in the near-axis region close to the plasma surface, the axial symmetry of the system is disrupted, and structures arise where coupled disturbances of the transverse and longitudinal components of the electric field, the longitudinal velocity of plasma electrons, and their density occur. The emergence of these structures can be attributed to the development of a certain parametric instability of the plasma in the field of the incident wave, which breaks the axial symmetry of the model. Over time, these structures decay, which can also be associated with the nonlinear deformation of the plasma density's spatial distribution.

4. The initial stage of interaction between a low-power wave beam and the plasma ends with the formation of a deepening at the location of the axially asymmetric structure near the system's axis, with its surface resembling a truncated sphere.

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REFERENCES

1. Yu.Ya. Brodskiy, B.G. Yeremin, A.G. Litvak, Yu.A. Sakhonchik. Self-canalization of the strong electromagnetic waves in the dense plasma // *JETP Letter*s. 1971, v. 13, No. 3, p. 136-139.

2. G.M. Batanov, V.A. Silin. Self-action of electromagnetic wave in the dense collisionless plasma // *JETP Letters*. 1971, v. 14, No. 8, p. 445-448.

3. A.G. Litvak. Self-focusing and waveguide propagation in plasmas // *Physics-Uspekhi*. 1972, v. 107, No. 3, p.515-516.

4. G.M. Batanov, V.A. Silin. Non-linear penetration of the strong microwave field into the layer of dense collisionless plasma // *Transactions of Lebedev FIAN*. 1974, v. 73, p. 87-103.

5. A.G. Litvak, V.A. Mironov, G.M. Fraiman. On the self-action of electromagnetic waves in plasmas at the modulation instability // *JETP Letters*. 1975, v. 22, No. 7, p. 368-371.

6. B.G. Yeremin, A.V. Kostrov, A.D. Stepanushkin, G.M. Fraiman. Parametric heating of electrons in the HF field of the millimeter waveband // *Fizika plazmy*. 1976, v. 2, No. 3, p. 414 (in Russian).

7. Yu.Ya. Brodskiy, V.L.Goltsman, V.A.Mironov, S.I.Nechuyev. Experimental study of electromagnetic field interaction with the plasma layer // *Fizika plazmy*. 1978, v. 74, No. 5, p. 1636-1649 (in Russian).

8. G.M. Batanov, Yu.V. Zadiraka, S.M. Levitsky, V.A. Silin, V.A. Tsygankov. *Non-linear penetration of electromagnetic waves of various polarization into the dense collisionless plasma*: FIAN preprint No. 160. 1979, 20 p.

9. A.G. Litvak. Dynamic non-linear electromagnetic phenomena in plasmas // *Problems of plasma theory*. Moscow: Atomizdat. 1980, Issue 10, p. 164-242.

10. M.I. Brizhinev, B.G. Yeremin, A.V. Kostrov, A.D. Stepanushkin, G.M. Fraiman. Thermal transillumination of the magnetized plasma by the electromagnetic wave // *Fizika plazmy*. 1980, v. 6, No. 3, p. 559-564 (in Russian).

11. G.M. Batanov, Yu.V. Zadiraka, S.M. Levitsky, S.N. Satunin, V.A. Silin, L.V. Sin'kovskaya. Re-distribution of charges density due to the action of the strong electromagnetic wave of the microwave band on the dense collisionless plasma // *All-Union conf. on the gaseous discharge physics:* Abstracts. 1981, Part 1, p. 74-76.

12. G.M. Batanov, S.N. Satunin, V.A. Silin, L.V. Sin'kovskaya, Yu.V. Zadiraka, S.M. Levitsky. Density variation in the plasma layer due to the nonlinear transparency caused by the field of the strong electromagnetic wave // *International Conference on Plasma Physics. Proceedings, Contributed Papers*. Kiev, 1987, v. 1, p. 188-192.

13. I.O. Anisimov, L.I. Romaniuk. Transillumina-tion, quasi-transparency and information transparency of the wave barriers in the inho-mogeneous plasmas // *Ukr. Phys. Journ. Reviews.* 2010, v. 6, No. 2, p. 101-139.

14. R. Betti, O.A. Hurricane. Inertial-confinement fusion with lasers // *Nature Physics.* 2016, v. 12. p. 435-448.

15. B.R. Mykhailenko, I.O. Anisimov. Trans-illumination of the dense plasma barrier by the strong beam of electromagnetic waves: computer simulation // *Problems of Atomic Science and Technology. Series "Plasma Physics".* 2020, №6 (130), p. 64-68.

16. B.R. Mykhailenko, I.O. Anisimov. Modes of transillumination of the dense plasma layer via electromagnetic ray // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration".* 2021, №4 (134), p. 3-5.

17. M. Bussmann, H. Burau, T.E. Cowan, A. Debus, A. Huebl, G. Juckeland, T. Kluge, W.E. Nagel, R. Pausch, F. Schmitt, U. Schramm, J. Schuchart, and R. Widera. Radiative signatures of the relativistic Kelvin-Helmholtz instability // *SC'13 Proc. Int. Conf. High Perform. Comput. Networking, Storage Anal*. 2013, v. 60, No. 4, p. 1-12.

18. James Ahrens, Berk Geveci, Charles Law ParaView. *An End-User Tool for Large Data Visualization:* Visualization Handbook, 2005, p. 717-731.

19. L.F. Chernogor. *Nonlinear Radiophysics*. Kharkiv: V.N. Karazin Kharkiv National University, 2004.

20. T.A. Davydova, N.I. Chernova // *Ukrainian Journal of Physics*. 1976, v. 21, No. 10, p. 1658.

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РАННЯ СТАДІЯ НЕЛІНІЙНОЇ ВЗАЄМОДІЇ ПУЧКА ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ З ШАРОМ ЗАКРИТИЧНОЇ ПЛАЗМИ

Б.Р. Михайленко, І.О. Анісімов

Методом комп'ютерного моделювання досліджена початкова стадія нелінійної взаємодії пучка електромагнітних хвиль малої потужності з шаром закритичної плазми. Показано, що периферійна частина пучка збуджує ленгмюрівську хвилю з подвоєною частотою, яка поширюється вглиб плазми. Показано також, що у приосьовій області у плазмі формується аксіально-несиметрична структура, що включає взаємопов'язані збурення поздовжнього та поперечного електричних полів, поздовжньої швидкості електронів та їхньої густини.