# NON-LINEAR ELECTRON STRUCTURES IN HIGH-CURRENT PLASMA LENS

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We describe the experimental investigations of the dispersion characteristics of the electron oscillations excited owing to drift instability in high-current plasma lens (PL). The experiments were carried out using the heavy ion beams of copper or carbon with energy up to 18 keV, beam current up to 0,5 A, duration 100 mks produced by the MEVVA kind ion source. It is shown that the noise electrostatic potential oscillations arise in middle plane of the lens under passing ion beam through plasma lens. These noises in range of 0,25÷2 MHz have a regular structure with stationary amplitude depending on ion beam current value. On their background a comparable low-intensity high-frequencies noises in range 20÷50 MHz is also observed. We show that the regular structure is represented by waves that drift along azimuth and have a clear spatial localization on considerable radius from plasma lens axis. Experimental results are in accordance with theoretical analysis showing an appearance of nonlinear electron vortices structures for these conditions.

## 1. Introduction

The trapped electron cloud in static electric and magnetic fields is a very attractive subject for state-of-art basic investigations in plasma physics, fluid dynamics and atomic physics. This is very good confirmed by the paper of T.M. O'Neil publicated not too long ago [1].

By origin the electrostatic plasma lens is modification of Penning trap configuration with nonhomogeneous magnetic field, B=B(r, z), for creation in the PL volume over thermal electric fields for focusing high-current ion beams. This mean that in the PL volume quasi-neutral plasma medium is formed by fast ion beams with density $n_b$ and compencated electrons with density $n_e$. It is obvious that $n_e \geq n_b$ because of formation the volume E-field perpendicular to external magnetic field for focused ion beam. Therefore, in the PL volume in focusing mode we have some like nonneutral trapped electron plasma. In this case, the presence of ion beam and the nonremovable radial gradient $B_z$ leads to growth of drift electron instability even under $n_e$=const. This instability is modified diocotron-like instability of pure non-uniform electron cloud.

This instability was observed firstly in the experiments [2]. There was investigated also the theoretical linear stage of this instability. In these experiments the high-current electrostatic PL with a two-component quasi-neutral plasma formed by the repetitively-pulsed wide-aperture beam of hydrogen ions with a current up to 2 A, energy up to 20 keV, duration 100 μs and the electrons of secondary ion-electron emission was studied. It was shown in the investigations that under passing ion beam along the PL the noise small-scaled turbulence oscillations arise in the range of frequencies 20÷50 MHz. The results of analysis of linear dispersion equation of oscillations could qualitatively explain the integral characteristics of the noises observed in the experiments. At the same time, in these experiments we could not obtain any data about the increments, the excited frequencies, the wave numbers of these oscillations and observed frequencies.

To understand further the mechanisms determining evolution of the PL medium instability one need to study nonlinear dynamics, first of all, the electron component because of relatively small time the staying of fast beam particles in the PL volume.

As linear theory predicts, the excited frequencies are in range of Langmuir frequency of ion beam.

Therefore, use of more heavy ion beams in experimental investigations is preferable.

Here are the results of our further experimental and theoretical investigations of this instability with heavy ion beams.

## 2. Experimental conditions and approach

The experiments were carried out on the set-up which scheme is given in the [3]. For ion beam creation we use two-chamber MEVVA-like ion source with grid anode and three-electrode multi-aperture ion optical system elaborated and proposed in [4]. Such ion source provides repetitively pulsed wide-aperture (∅5.6 cm) low-divergent metal ion beam with energy up to 18 keV, current up to 500 mA and duration 100 μs. The ion source is at the distance 31 cm from the middle plane of the PL.

The beam of copper or carbon ions passed through the 9-electrode plasma lens of diameter 7 cm and length 12 cm. The maximum potential on the lens electrodes could be regulated up to 3,5 kV. The electrodes disposed symmetrically around the central one were connected in pairs. The strong of magnetic field on a lens axis could vary up to 0,17 T. The experiments were conducted with usage of radially and azimuthal movable capacitive probes disposed in mean plane of the lens. The signals from them were measured by memory oscilloscope with pass band 50MHz. In the experiments we used the optimum configuration of the *H*-field found in [2]. The beam current and density on-axis after lens were measured by an axially movable sectioned collector. Before collector the radially and axially movable Langmuir probe were placed. The residual gas pressure in a vacuum chamber was at the level of 1÷2×$10^{-5}$ Torr. This provided the plasma creation in the PL volume by secondary ion-electron emission.

## 3. Experimental results

Experiments show that copper or carbon ion beam passing through the PL leads to growth of regular electrostatic potential waves rotated around the PL axis. These waves with the frequency in the range of 0,2÷2 MHz have the nonharmonic shape. The values of these frequencies are comparable with ion beam Langmuir frequency (fig. 1). As it is seen from fig.2,3 there are also nonregular of turbulent small-scale noises comparable low-intensity in range 20÷50 MHz. The azimuthal potential waves are observed starting from the radius r=5 mm and have a clear maximum amplitude up to 700 V at the r≈20 mm from an axis of PL. These oscillations were observed under different potential distribution on fixing electrodes of the lens. The phase of these waves doesn’t depend on radius. The oscillations rapidly arise and reach stationary level for some (2÷4) periods of oscillations. Under low ion beam currents (≈20 mA) the oscillations are observed with mode m=1, then, with increasing of current the modes increase (up to m=4 in experimental conditions), as well as the frequency. The azimuthal phase velocity also slightly grows. This can be seen on fig.4. Under the same experimental conditions some modes can be excited with adjacent different frequencies and phase velocities. The photos of oscillograms of signals from capacitive probes, for modes m=1 and m=3 are exhibited in figures 2,3. It should be noted that the direction of phase velocity changes with changing of the lens magnetic field direction. We note also that natural noises originate from MEVVA-like ion source can be enhanced under passing the ion beam through lens plasma medium. The degree of current density modulation on collector grows along radius of focused beam and can reach 20%.

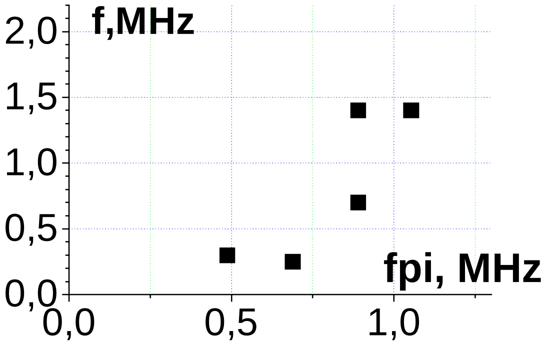
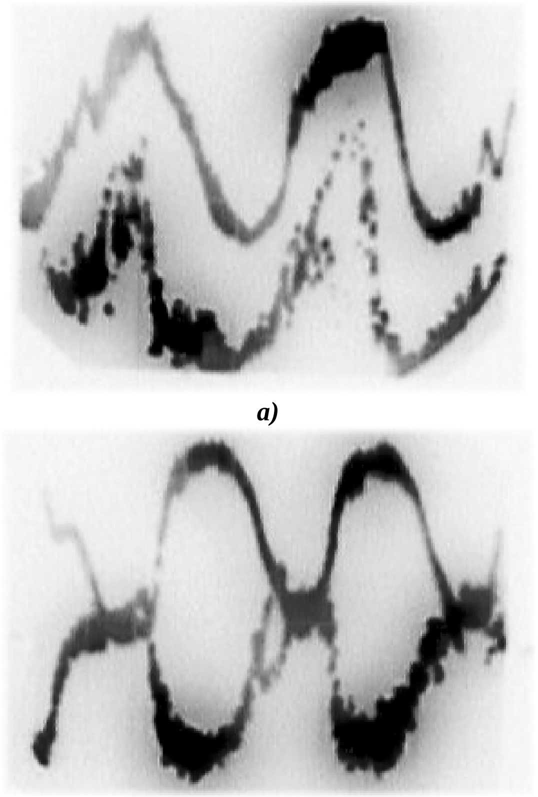


*Fig. 1. Dependency of oscillation frequency on Langmuir frequency of ion beam.*
*Cu,"O"-distribution, $U_b$=6 kV, $U_L$=2,7 kV, $B_L$=75 mT, U-=-3 kV.*



*a)*

*b)*

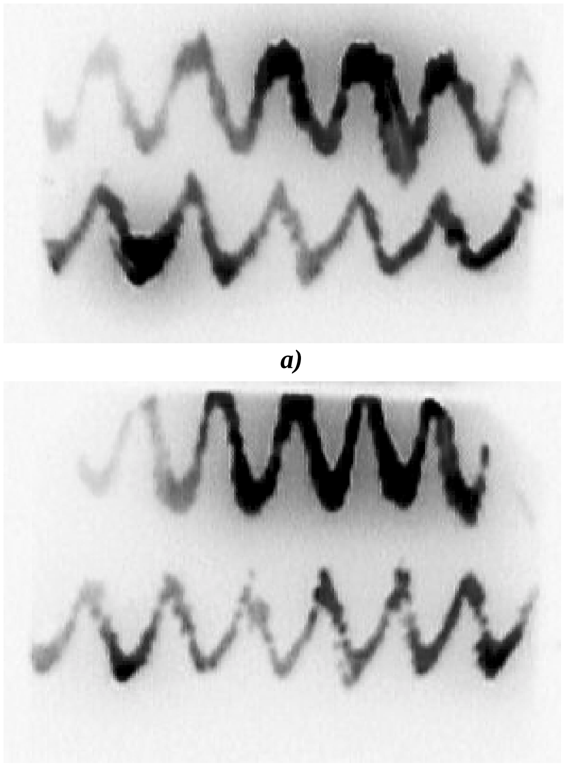
*Fig. 2. The typically oscillograms of signals from capacitive probes for modes m=1 under some azimuthal angles β between them:*
*Cu,"O"-distribution,$U_b$=6 kV,$U_L$=2,5 kV,$B_L$=60 mT, U-=-3 kV, $I_b$=40 mA, scan duration = 10 μs, amplitude oscillations 600 V, f=200kHz*
*a) β=0°, b) β=180°.*

## 4. Discussion

The experiments presented here prove that use of heavy copper ions instead of light hydrogen ions enables to distinguish the low- and high-frequency oscillations, which appear in the process of evolution of drift instability on the big radii from the axis in the PL volume, and thus, to distinguish regular low-frequency waves propagating azimuthally. This can be understood as from analysis of linear dispersion equation of small oscillations for such system a development of instability on the frequencies close to the beam ion Langmuir frequency follows. It will be right to the point to present here a dispersion equation of the linear oscillations of such system (for more simplicity we consider it for the Cartesian coordinates):

$$1-\frac{\omega_{bi}^2}{(\omega-k_z v_b)^2}-\frac{\omega_{pe}^2}{(\omega-k_y v_d)^2}\cdot\frac{k_z^2}{k^2}-\frac{\alpha\omega_{bi}^2 k_y}{k^2(\omega-k_y v_d)\omega_{Bi}P}=0 \qquad (1)$$

where $\omega_{bi}$ and $\omega_{pe}$ are the ion beam and electron Langmuir frequency correspondingly, $\omega_{Bi}$ – an ion cyclotron frequency, α= $n_e/n_b$ ($n_b$ is the concentration of ion beam, $V_b$- ion beam velocity.



a)

b)

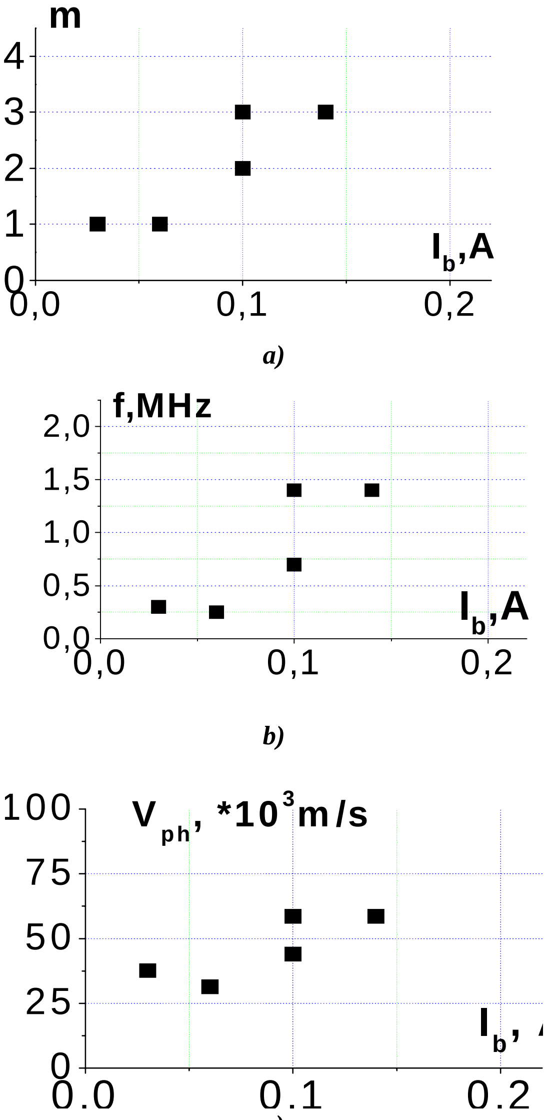
*Fig. 3. The typically oscillograms of signals from capacitive probes for modes m=3 under some azimuthal angles $\beta$ between them: Cu,"O"-distribution,$U_b$=6 kV,$U_L$=2,5 kV,$B_L$=60 mT, U-=-3 kV, $I_b$=70 mA, scan duration = 5 μs, amplitude oscillations 300 V, f=1MHz*
*a) $\beta$=0°, b) $\beta$=60°.*

This equation describes both volume oscillations, which appear due to azimuthal electron stream with a velocity $v_d = cE/B$ and gradient oscillations connected with space inhomogeneity of electron concentration $n_e(r)$ and axial component of the magnetic field $B_z(r)$ describing by function P.

An analysis and experimental data testify uniquely that volume oscillations in the conditions of a curvilinear geometry of a B-field will not take place. That is why one can suggest that $k_z$=0. With this approximation the equation was solved in [2].

An analysis of dispersion equation enables to determine a space localization of oscillations, increment times, wave numbers and frequencies of excited oscillations. It follows from solutions that maximal increments and frequencies are comparable, they are within a range of the ion beam Langmuir frequency. With a help of the linear dispersion equation it is not possible to explain a high-frequency part of the excited noises spectrum. This can be done with a help of a nonlinear analysis of a dynamics of excited electron oscillations. In [5] non-linear equation for the potential, describing electron dynamic had been received. It has the following form:

$$\frac{\partial \Delta\varphi}{\partial t} - \frac{e}{m}\nabla_y \varphi \Delta\varphi \frac{\partial}{\partial x}\left(\frac{1}{\omega_{ce}}\right) + \frac{e}{m\omega_{ce}}\{\varphi, \Delta\varphi\} = 0$$



a)

b)

c)

*Fig. 4. The dependency of mode, oscillation frequency and phase velocity on beam current: Cu, "O"-distribution, $U_b$=6 kV, $U_L$=2,7 kV, $B_L$=75 mT, U-=-3 kV.*

Numerical and analytical solutions of this equation have shown existence of small-scaled electron vortex structures that may lead to creation of high-frequencies noises. For computer modeling of appearing and evolution of large-scaled vortex structures we can represent this equation in form:

$$\frac{\partial \Omega}{\partial t} + v_x \frac{\partial \Omega}{\partial x} + v_y \frac{\partial \Omega}{\partial y} = 0$$

$$\Omega = c\frac{\Delta\varphi}{H(x)}, \quad v_x = -\frac{c}{H(x)}\nabla_y \varphi, \quad v_y = \frac{c}{H(x)}\nabla_x \varphi$$

which was solved on base of Lacks scheme for azimuth perturbation type $\delta\varphi=\varphi_0 sin(k_y y)sin(\omega_0 t)$. We take initial values of all parameters so that they are close to experimental conditions in order to compare further numerical results with experimental data for $k_y$=2π/3, $\omega_0$=1MHz, $\varphi_0=10^{-5}\Phi_0$,*on* $r=2/3R$. Results of computer simulations show that for a short period of time the instability region in the plasma lens is covered by small-scaled electron bunches, which create craters rotating about their axes and moving along the axis $y$ for the case of stationary distribution of the electrostatic potential. This created bunches merge together into one stable vortex. It has practically unchanged amplitudes and is shifted along the axis $y$ with a velocity $u$~0,4$v_d$. Rotation speed of this structure may be estimated by the formula $v_{вр}\sim e\varphi_{max}/m\omega_{he}r_0$, where $r_0$ is a calculated radius of a structure, which is equal approximately to 0,2$R$. Then $v_{вр}$ ~1,2 $v_d$, and from this fact the conclusion follows that such kind structure is a stable vortex which has spin velocity much higher then shift velocity along the y-direction. The spin rate can be estimated as $\omega_{вр}= v_{вр}/r_0\sim 20\omega_0$, so if $\omega_0$~1MHz, that means $\omega_{вр}$~20MHz.

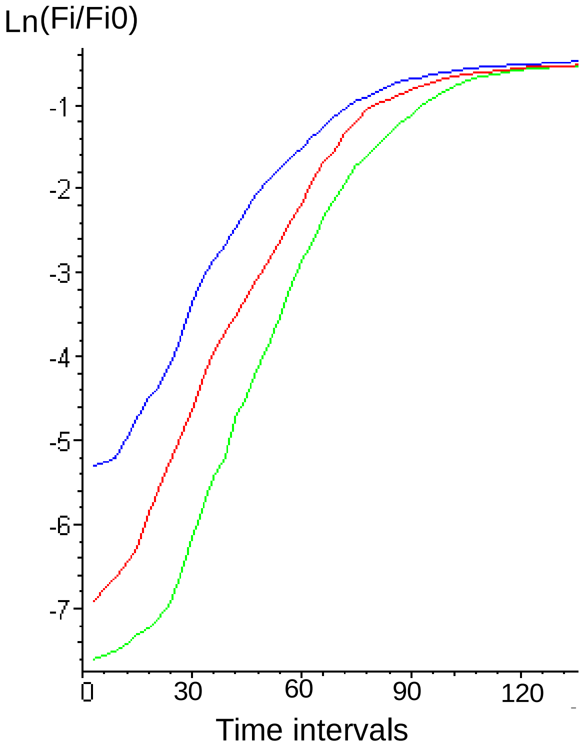


*Fig. 5. Potential (ln scale) vs time for different initial perturbations. Upper case- $\varphi_0=0.005\Phi_0$ , middle case- $\varphi_0=0.001\Phi_0$ , lower- $\varphi_0=0.0005\Phi_0$ (single time interval ~ 0.28•$10^{-7}$ c)*

On the Fig. 5 the logarithmic dependency of the potential amplitude on time is shown for different initial amplitudes of perturbations $\varphi_0$ (calculations were made for the mode 3/2). One can see at first the amplitude is growing rapidly, changing its value by orders during a very small period of time, and then it reaches a saturation value during the time of about 1-2 periods of oscillations ($10^{-6}$ sec). The higher is the amplitude of initial perturbation, the faster the saturation value is reached; the saturation value does not depend practically on initial values of perturbation amplitudes.

Fig. 6 presents results of simulation appearance and evolution vortex structure ($k_y$=2π/3, $\omega_0$=1Мгц, $\varphi_0=10^{-5}\Phi_0$, $r=2/3R$.) Using this mode 3 is because of the only possibility to compare the numerical results to experiments. One can see that vortex structure appears just after 90 intervals. Its amplitude has fast growing and reaches saturation.

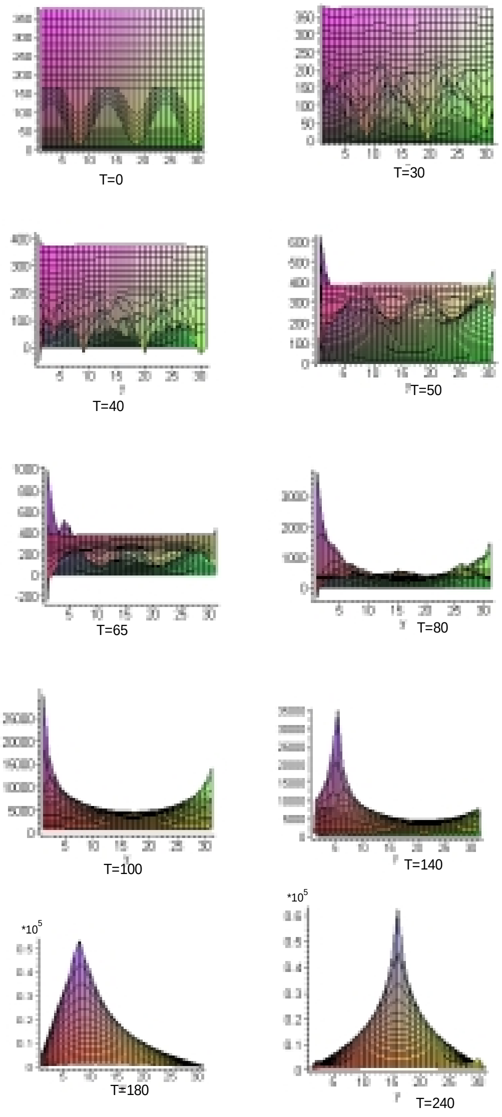


*Fig.6. Modeling of arising process for a vortex structure (y-fraction, x = 0, time interval ~ 0.28•$10^{-7}$s, $\varphi_0=10^{-5}\Phi_0$)*

It is very difficult to distinguish evolution of a separate mode in the conditions of the presented experiment where modes are excited spontaneously and the multi-mode regime is realized in fact. At the same time, one can suppose that observed high-frequency bursts of turbulent noises appearing most frequently in the regions of variable potential minimums may be connected with passing of vortexes in the place of probes allocation.

## Conclusion

Thus, it is shown in the paper that low-frequency electron-wave structures have increment times and frequencies corresponding to the linear theory of a drift instability of electrons that take place in the presence of fast particles of the ion beam and non-removable radial gradient of the axial component of a magnetic field. Observed bursts of high-frequency noises may be connected with creation of non-linear electron vortex structures, which were predicted theoretically.

## Acknowledgements

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