EXPERIMENTAL INVESTIGATIONS OF THE VORTEX-CHAIN GENERATED IN THE TWO-COMPONENT PLASMA WITH THE SHEARED FLOW OF MAGNETIZED ELECTRONS

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We present further experimental results on the observation of electron vortices in an electrostatic plasma lens at the strong radial gradient of electron density. Anharmonic low frequency ($\nu_{ci} << \nu \sim \nu_{pi} << \nu_{pe}, \nu_{ce}$) large-amplitude ($\varphi_{osc} >> k_{Bol}T_e/e, k_{Bol}T_i/e$) potential waves propagating in azimuth direction are observed. The recently observed results give additional confirmation that the observed waves are the manifestation of the vortex-chain generated at the azimuthal sheared flow of magnetized electrons compensating ion beam.

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1. INTRODUCTION

In the theory of plasma physics, plasma is often assumed to be quasineutral. The deviation from this rule is possible for beam plasmas [1], diode plasma systems [1, 2], various plasma-optical devices [3, 4], plasmas with high-frequency electromagnetic oscillations, and obviously in one-component plasmas [5]. Recent researches of tokamak plasma also reveal the fact that the assumption of quasineutrality does not allow to analyze all the variety of tokamak operation regimes correctly [6, 7]. We investigated the possibility for nonneutral vortices to be formed in the two-component low-temperature low-density collisionless ion beam plasma consisting of positive unmagnetized ions of medium-energy beam and magnetized electrons. Such a medium can be formed in the electrostatic plasma lens (**PL**) [3, 4, 8]. This lens is the axially symmetric plasmaoptical device intended for positive ion beam manipulation. In fact, it is an electron trap, where electrons are retained in longitudinal and radial directions by the electrostatic and magnetostatic fields, respectively. Electrons are generated by the peripheral ions through the ion-electron emission from electrodes of the lens, some part of these electrons remains in the lens providing equipotentialization of magnetic field lines [3, 4]. In the used experimental conditions magnetic field is strong enough to magnetize electrons, but practically has no effect on ions. Similarly, the voltage applied to the lens electrodes is sufficiently high to realize overthermal space-charge electric field but it is still small for ion trajectories to be effectively bended. The electric field of the negative space charge in the lens and externally applied magnetic field results in the azimuthal drift of electrons with the velocity

$$\boldsymbol{V} = [\boldsymbol{E} \times \boldsymbol{B}]/B^2, \qquad (1)$$

where $\boldsymbol{E}$ is the electric field intensity, $\boldsymbol{B}$ is the magnetic field induction. It is known that the radial gradient of the drift velocity (or shear) causes the excitation of strong instability [9-11]. This gradient may arise due to the presence of radial magnetic field gradient or nonuniform distribution of electron density. The excitation of instability results in the bunching of electrons and their self-consistent electric fields cause additional vorticity of electron trajectories. As it was shown theoretically [10,11], these bunches, having approached some density, can create the chain of electron vortices with closed trajectories of electrons. In [12] we represented the first experimental results on the observation of nonlinear stage of the instability at large radial gradients of electron density where large-scale electron vortices were observed. In this paper we present some addition results, which were not placed in [12] as well as experimental results obtained recently.

2. EXPERIMENTAL SETUP AND APPROACH

A vacuum arc ion source [13] with a grid anode and three-electrode, multi-aperture, accel-decel ion extraction system was used (see Fig. 1). Ion beamlets extracted from emission holes widen during propagation in the space between source and lens to form practically uniform ion beam current density at the lens inlet aperture.

The source operates in a repetitively-pulsed mode and produces moderate-energy, broad, heavy metal ion beam with principal parameters for the work described here: beam pulse duration – 100 μs (0.5 pps), beam extraction voltage φ_{acc} – 12 and 24 kV, beam current I_b = 150 and 400 mA, Cu ion species.

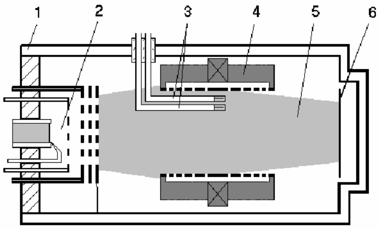

Fig. 1. Scheme of experimental setup:
1 – vacuum chamber; 2 – ion source;
3 – capacitive or Langmuir probes; 4 – plasma lens;
5 – ion beam; 6 – collector

The electrostatic plasma lens (Fig. 2) had an input aperture diameter of 7.4 cm and a length of 16 cm. The maximum positive potential φ_L = 1 kV was applied to the central lens electrode and several symmetrically arranged adjacent pair electrodes, the other electrodes being grounded. Most experiments were performed at high voltage applied to the central electrode and one pair of adjacent electrodes. In [12] we used DC potential φ_L, in the present work we used repetitively pulsed feeding of electrodes. In the latter case the lens electrodes where connected to the source of accelerating voltage of the ion source through a resistive divider. The repetitively pulsed feeding of electrodes is needed to eliminate the self-sustaining discharge in the lens [14]. Also using this regime simplifies measuring the electric potential at low frequencies by capacitive probes. The magnetic field with the induction of 40 mT at the PL center was created by permanent magnets. The vacuum chamber pressure was $\leq 1.5 \times 10^{-5}$ Torr, allowing plasma formation within the lens volume by the beam itself via ion-electron emission from the lens electrodes.

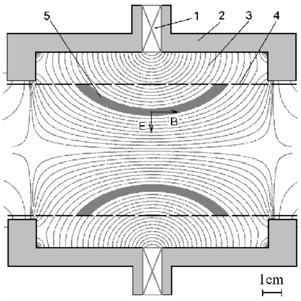

Fig. 2. Plasma lens:
1 – permanent magnets; 2 – magnetic conductor;
3- magnetic field lines; 4 – electrodes; 5 – approximate localization of electron layer

The azimuthal and radial distributions of electric potential were measured using a system of capacitive probes. The scheme of probes used in [12] is represented in Fig. 3a. The shields of these probes are not fully enclosed, and we assume that this is the reason for incorrect probe operation at low frequency range. This force us to use Langmuir probes to measure long time variation of electric potential which we call "background" potential in [12]. Now we use fully enclosed probes represented in Fig. 3b. This enables us to measure simultaneously high and low frequency dynamics of electric potential using capacitive probes only.

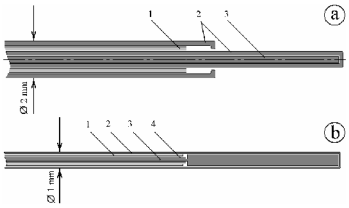

Fig. 3. Schemes of cylindrical capacitive probes:
a) previous version [12]; b) wholly isolated probe;
1 - metal shield, 2 - glass insulator;
3 - copper conductor; 4 - lacquering

The probes were introduced nearly parallel to the system axis, their sensitive tips being placed in the central cross section of the PL.

3. EXPERIMENTAL RESULTS

We used high voltage applied to the neighboring electrodes for annular electron density distribution to be created. Electrons emitted from the lens electrodes have to equipotentilize magnetic field lines, following to step-like potential distribution over the electrode system applied externally. In turn, the step-like radial potential distribution corresponds to the mentioned above annular electron density distribution.

As it was anticipated, the maximum amplitude of the waves was observed in the rage of localization of the potential step. The observed large-amplitude anharmonic waves (Fig. 4) were found to propagate in the $E \times B$ drift direction with the constant angular velocity (E is the background electric field).

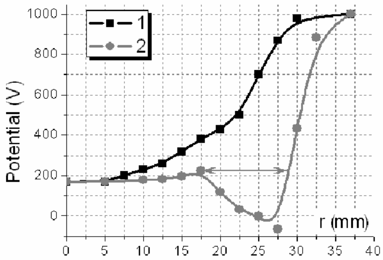

Fig. 4. Radial potential distributions in the PL central cross section; 1 – background potential; 2 – lowest potential achieved during the oscillation period; the radial dimension of the vortex is denoted by a double-headed arrow;
I_b = 400 mA, φ_{acc} = 12 kV, φ_L = 1 kV (DC), m_θ = 5

For the conditions observed, electron and ion Langmuir frequencies are $\nu_{pe} \approx 300$ MHz, $\nu_{pi} \approx 1.7$ MHz and gyrofrequencies equal to $\nu_{ce} \approx 1.4$ GHz, $\nu_{ci} \approx 20$ kHz, respectively, while the observed frequencies of oscillations $\nu \approx (1\ldots2)$ MHz therefore the conditions $\nu_{ci} << \nu \sim \nu_{pi} << \nu_{pe}, \nu_{ce}$ is satisfied. The frequency of rotation $\nu^* = \nu/m_\theta$ of the constant-phase regions around the PL axis, as well as the number of wavelengths (m_θ) within the 360° azimuthal angle interval, depend on the distance of a potential step (created by electrodes) from the axis and on the magnitude of this potential step. For the same electrode potential $\varphi_L = 1$ kV, the frequency ν^* was found to change within 200…500 kHz, while m_θ being within 4…6, depending on the potential distribution over electrode system. The temperature of electrons emitted from lens electrodes is near $T_e \approx 10$ eV while the effective temperature of ions $T_i \approx 100$ eV [8], therefore the amplitude of potential oscillations $\varphi_{osc} >> k_{Bol}T_e/e$, $k_{Bol}T_i/e$, where k_{Bol} - Boltzmann constant, e – electron charge.

We imply that a "**vortex**" is localized structure with closed trajectories, i.e. the vortex has to have separatrix. In the investigated conditions electrons are strongly magnetized, and we can omit the inertial terms in the equation of motion for electrons. As the electron plasma in the PL is low-temperature and collisionless, we can use simple drift equation of motion, which has the solution (1). Equation (1) defines the one of the main principles of plasmaoptics: the magnetic field lines have to be equpotential, also from this equation it follows that equipotentials of electric field correspond to electron trajectories [3]. Thus we can clearly recognize formation of vortices by the presence of local extrema of the potential distribution in the plane, which is normal to magnetic field. Local minima correspond to vortex-bunches with the local excess of electrons, and maxima correspond to vortex-holes with the luck of ones. Fig. 4 indicates the presence of electron vortex-bunches displaced in the radial direction approximately between 17 and 28 mm, that is the radial size of the separate vortex is near 1 cm. The small maximum near r = 17 mm on the distribution 2 in Fig. 4 is just saddle point which does not represent the vortex. The mode number m_θ = 5 represents the number of vortices in the “chain” displaced along the azimuthal direction.

The curve 2 in the Fig. 4 was obtained through calculations from distributions of the “background” potential and oscillation amplitude measured with Langmuir probe and capacitive probe, respectively. As it was mentioned above, using repetitively-pulsed voltage φ_L and capacitive probe represented in Fig. 3b, we have measured dynamics of the electric potential without splitting it on long time (background) variations and high frequency oscillations (see Fig. 5). From Fig. 5 one can conclude that there is the local minimum of radial potential distribution near r = 25 mm revealing the chain of electron vortex-bunches.

It should be noted that the considered conditions are far beyond the optimal ones of PL operation at low magnetic fields.

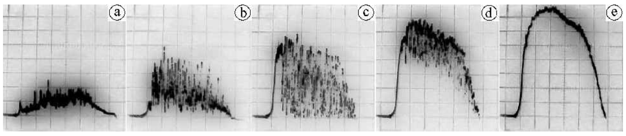

Fig. 5. Oscillograms of electric potential obtained in the PL central cross section at various distances from the PL axis with the capacitive probe represented in Fig. 3b; vertical sweep – 135 V/div; horizontal sweep – 20 μs/ div; a) r = 0, b) r = 20 mm, c) r = 25 mm, d) r = 30 mm, e) r = 35 mm; I_b *= 150 mA,* φ_{acc} *= 24 kV,* φ_L *= 1 kV (pulsed)*

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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ ВИХРЕВОЙ ЦЕПОЧКИ ГЕНЕРИРУЕМОЙ В ДВУХКОМПОНЕНТНОЙ ПЛАЗМЕ СО СДВИГОВЫМ ПОТОКОМ ЗАМАГНИЧЕННЫХ ЭЛЕКТРОНОВ

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Представлены новые результаты по исследованию электронных вихрей в электростатической плазменной линзе, возникающих при наличии значительного градиента электронной плотности. Исследуются ангармонические низкочастотные ($\nu_{ci} << \nu \sim \nu_{pi} << \nu_{pe}, \nu_{ce}$) волны потенциала большой амплитуды ($\varphi_{osc} >> k_{Bol}T_e/e,\ k_{Bol}T_i/e$). Представленные результаты являются дополнительным подтверждением того, что наблюдаемые волны являются проявлением вихревой цепочки в азимутальном сдвиговом потоке замагниченных электронов, компенсирующих ионный пучок.

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ВИХОРОВОГО ЛАНЦЮЖКА У ДВОКОМПОНЕНТНІЙ ПЛАЗМІ У ПОТОЦІ ЗАМАГНІЧЕНИХ ЕЛЕКТРОНІВ ЗІ ЗСУВОМ ШВИДКОСТІ

Ю.М. Чех, О.А. Гончаров, А.М. Євсюков

Представлено нові результати з дослідження електронних вихорів у електростатичній плазмовій лінзі, які виникають за присутності значного градієнту електронної густини. Досліджуються ангармонічні низькочастотні ($\nu_{ci} << \nu \sim \nu_{pi} << \nu_{pe}, \nu_{ce}$) хвилі потенціалу великої амплітуди ($\varphi_{osc} >> k_{Bol}T_e/e,\ k_{Bol}T_i/e$). Представлені результати є додатковим підтвердженням того, що ці хвилі є проявом ланцюжка вихорів у азимутальному потоку зі зсувом швидкості замагнічених електронів, які компенсують іонний пучок.