ADVANCED ELECTROSTATIC PLASMA LENSES ON PERMANENT MAGNETS

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In the paper we summarize the recent results on the wide-aperture electrostatic plasma lenses using permanent magnets (in particular, the lenses with minimized magnetic field gradients). The lenses are investigated at the focusing of the pulsed medium-energy (~20 keV) high-current (up to 0,5 A) beams of heavy ions (Cu), generated by multi-aperture vacuum-arc ion source. The obtained static and dynamic characteristics of focused ion beams enable to determine the main factor, which determines the restriction of the maximum compression factor of the ion beams at low magnetic fields. In the range of strong magnetic fields we establish the possibility for large-scale electron vortices to be generated in a plasma lens.

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1. INTRODUCTION

Electrostatic plasma lenses (PL) proposed by A.I. Morozov [1,2] through many years demonstrate convincing advantages compared to traditional ion-optical systems. In recent years the investigations of the plasma lenses are more often used not only for fundamental researches but in applications also [3-5]. The new attractive field of PL application is high-current heavy-ion linear accelerators [6-9]. One of the main parameters that define the possibility for the PLs to be used in the beam transport line of accelerators is the effect of the lenses on the emittance of the focused beam. The emittance can be distorted due to the development of instabilities in the plasma medium of the lens or due to effect of aberrations. Therefore, there is a great need to study the properties of instabilities as well as to find the way for aberrations to be minimized. One of the most dangerous instability is one arisen due to radial inhomogeneities both the longitudinal magnetic field and electron density. Theoretical and experimental examinations have shown, that the development of this instability can even give rise to the large-scale electron vortices [10-12].

Traditionally externally applied magnetic field in the plasma lenses was created by current driven coils. In this case it is rather difficult to minimize the magnetic field gradient [13]. The reasonable alternative is the use of permanent magnets, that enable to reduce this gradient by an order of magnitude rather easily. We have shown previously [14] that there is a very narrow range of low magnetic field for which the optical properties of the lens improve significantly. As well as for the lenses with current driven coils, we have found experimental conditions where the inherent plasma lens noise is reduced to a very low level and for which good beam compression is observed for the permanent magnet plasma lens with minimized magnetic field gradients (see preliminary results reported in [15]). Under these conditions the emittance of a broad-area ion beam passing through the lens was measured [7-9], with the results indicating, in particular, that there are optimal conditions of lens operation for which the emittance is preserved on beam transport through the lens, for a copper ion beam current as high as 250 mA.

As it was mentioned above, the radial gradient of electron density has to be minimized for corresponding instability as well as spherical and dynamical aberrations to be eliminated. For this purpose we use optimized electrode system consisting of thin electrodes and interelectrode dielectric spacers. In the range of low magnetic fields the use of this system give impressive results allowing to achieve maximum ion beam current density limited by the emittance of the beam only. We are planning to test this system at strong magnetic fields in the nearest future. Although for this range it is unlikely to anticipate the near perfect focusing as for the range of low magnetic fields. From numerical calculations it follows that at strong magnetic fields the electron density may be sufficiently nonuniform, even smooth potential distribution over electrode system being used [16]. The nonuniform electron distribution gives rise to the spherical aberrations and instability excitation that in turn results in the dynamical aberrations. These effects eventually define the fact that for the range of strong magnetic fields the observed compression factors are more than an order of magnitude lower.

2. EXPERIMENTAL DEVICES AND APPROACH

The experimental setups are shown in Fig.1. A two-chamber vacuum-arc ion source (MEVVA) [17] with a grid anode and a three-electrode, multi-aperture, accel-decel extraction system was used for obtaining a wide-aperture ion beam. The extractor contains 84 individual beamlet holes ∅ 4 mm, spanning an overall diameter of 55 mm. 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 beam duration was 100 μs (0.5 pps), extraction voltage φ_{ext} was varied within the range 12…16 kV, total current I_b up to 0.5 A (Cu). Copper plasma formed by a MEVVA has the following ion charge state spectrum: 16% Cu^{+}, 63% Cu^{2+}, 20% Cu^{3+}, and 1% Cu^{4+} [17]. We optimized the ion source output by varying its operating parameters so as to obtain maximum total ion beam current with minimum beam divergence and hence also minimum emittance. Residual pressure $p<1.5\cdot10^{-5}$ Torr, allowing plasma formation within the lens volume by the beam itself via ion-electron emission from the lens electrodes.

A 13-electrode systems with 74 mm input aperture diameter were used (Fig.2). Vortex structures were studied with the use of the lens represented in Fig.2,a, magnetic induction B = 40 mT (at the center of the lens) was formed by permanent magnets, the maximum DC voltage φ_L = 1 kV was applied to the central electrode and adjacent pair of electrodes, the others being grounded. During investigations of the lens with minimized magnetic field gradients (Fig.2,b,c) the magnetic induction B at the center of the lens was 12.6 mT, the maximum DC or pulsed voltage φ_L up to 5.5 kV was applied to the central electrode only. The lens represented in Fig.2,b was used for emittance measurements. The best focusing properties were achieved with the lens represented in Fig.2,c. In this lens a metal grid with 80% transparency was used to enhance the space charge compensation of the ion beam.

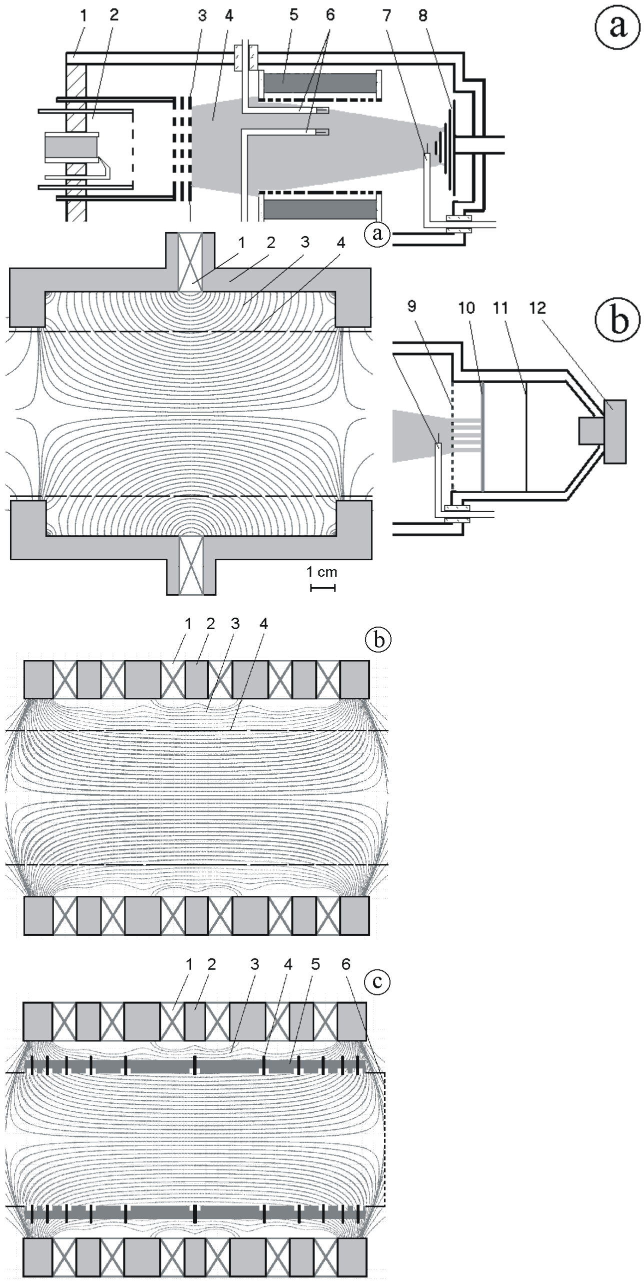

Fig.1. Schemes of experimental setups

ВОПРОСЫ АТОМНОЙ НАУКИ И ТЕХНИКИ. 2006. № 5.
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a) for investigations of the lens with minimized magnetic field gradients, and vortex structures;
b) for emittance measurements;
1 – vacuum chamber; 2 – ion source; 3 – ion beam extraction system; 4 – ion beam; 5 – plasma lens; 6 – grid; 7 – Langmuir probe; 8 – pepper pot selection screen, 9 – luminescent screen; 10 – window; 11 – camera

We used the "pepper pot" technique [18] for the measurement of the beam emittance. This method is based on photographically recorded images of the beam cross-section after it is passed through a screen containing a regular array of identical small holes. In our setup, the multiple sampled beamlets thus defined fall on a luminescent screen, forming an array of images of the beam size which is then photographically recorded by a camera. All of the images were obtained in a single exposure of a single beam pulse. The technique was described in more details in [8].

A Langmuir probe introduced near sectioned collector and Pepper-Pot selection screen was used to measure the ion beam density distribution. The probe tip was molybdenum wire 4.5 mm long and ∅ 0.3 mm. We assume the ion beam current that is incident on the probe to be a part of the current that would be accepted by a circular collector of diameter 4.5 mm = $2r_c$.

Fig.2. Permanent magnet plasma lenses
a) PL used for the investigations of vortex structures in the range of strong magnetic fields at nonuniform distribution of electron density;
b), c) PLs with minimized magnetic field gradients;
c) PL with modified electrode system
1 – permanent magnets; 2 – magnetic conductor; 3 – magnetic field lines; 4 – electrodes; 5 – interelectrode insulating spacers; 6 – metal grid

In the characterization of plasma lens focusing properties, a compression factor K_j is often used; this parameter is the ratio of ion beam density with the lens turned on and off. A current efficiency E_c [19] is another parameter used to quantify the lens efficiency as an optical element. The current efficiency is the fraction of the total beam current that reaches the collector. This parameter is measured during a single beam pulse and therefore is independent of the ion beam divergence and electron emission from the collector.

The azimuthal and radial distributions of electrostatic potential were studied using a system of capacitive probes. The azimuthal profile of the wave potential was derived from the voltage time series measured by the probes. The azimuthal wave velocity was calculated from a time shift of the phase of oscillations detected by two probes spaced by a definite azimuthal angle. The radial electric wave field was measured by a pair of double capacitive probes spaced by 5 mm, each probe sensor having a diameter of 1 mm and length of 5 mm.

The measuring circuits had equal (within the limits of ~ 10%) transmission coefficients in a frequency band from 100 kHz to 15 MHz. The distributions of potential could not be adequately determined on a time scale of the beam pulse duration due to some factors of the circuits, therefore the constant (within ≈20 μs) potential component in the PL was determined using a single Langmuir probe that could be moved in the radial direction. The constant potential component was measured in the time interval between electron bunches. In these intervals the plasma medium is least perturbed by the fields of electron bunches. For this reason, we denote the potential distribution and corresponding electric field distribution measured by the Langmuir probe as "background". All probes were introduced nearly parallel to the system axis, their sensitive tips being placed in the central cross section of the PL. The signals were measured using an S8-14 oscillograph with a working bandwidth of 50 MHz.

3. RESULTS AND DISCUSSION

3.1. FOCUSING PROPERTIES OF THE ELECTROSTATIC PLASMA LENSES WITH MINIMIZED MAGNETIC FIELD GRADIENTS AT LOW MAGNETIC FIELD

An important advantage of the electrode system used here is the suppression of "focusing disruptions", observed in the range of small magnetic fields [15]. In the optimal regimes the lens does not significantly degrade the beam emittance (Fig.3).

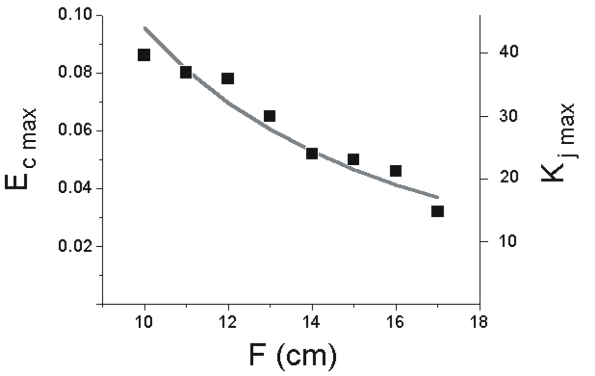


Fig.3. Dependencies of emittance and normalized emittance on the ion beam current enclosed within corresponding phase contours at various φ_L;
φ_{ext} = 16 kV, I_b = 0,5 A (Cu), B = 12.6 mT
(1) - 0 kV, (2) - 3.5 kV, (3) - 4 kV, (4) - 5.5 kV

The large initial emittance of the ion beam generated by the multi-aperture vacuum-arc source is determined by the ion source extraction system [7]. An effective temperature corresponding to the measured initial emittance can be calculated as T_i (eV) ≈ $\varepsilon_n^2 m_i c^2/(2R_L^2)$, where ε_n is the normalized emittance, m_i is the ion mass, c is the velocity of light, R_L - radius of the lens. In this way we obtain T_i > 110 eV.

The observed large emittance restricts the maximum ion current density that can be obtained at the focus. From [19], the maximum current efficiency depends on the focal length as

$$E_c = 1 - (1 - \beta) \exp[-\beta\Phi/(1 - \beta)], \quad (1)$$

where $\beta = r_c^2/(R_L^2 + F^2)$, $\Phi = W_b/T_i$, r_c is the collector radius, $W_b = Ze\varphi_{ext}$ is the ion beam energy, Z is the ion charge state (we take Z =2), e is the electron charge, and F is the lens focal length. This relationship is a generalization of Langmuir's formula for maximum current density [19]. The best agreement between the experimental results and Eq.(1) is obtained for T_i =140 eV (Fig.4).

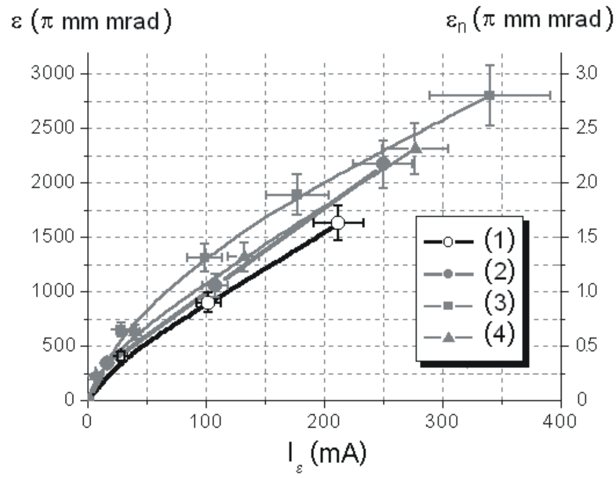


Fig.4. Dependencies of current efficiency E_c and compression factor K_j on focal length (current density 120…300 mA/cm^2); dots correspond to the measured values, curve corresponds to Eq.(1) for T_i = 140 eV; φ_{ext} = 16 kV, I_b = 0,5 A (Cu), B = 12.6 mT

Thus we obtain nearly the same values of effective transverse ion temperature from emittance measurements and from measurements of the maximum current efficiency as a function of focal length. This is evidence for the maximum ion current density to be restricted by the initial emittance of the beam.

In Fig.5 one can see that the relative level of current density noise modulation (fractional beam noise) at the focus is not increased significantly. The corresponding radial distribution of ion beam current density is shown in Fig.6. Periodically we observed a very high beam current density up to 400 mA/cm^2 (Fig.7), probably due to accidental flattening of the plasma boundaries in the ion source extraction system.

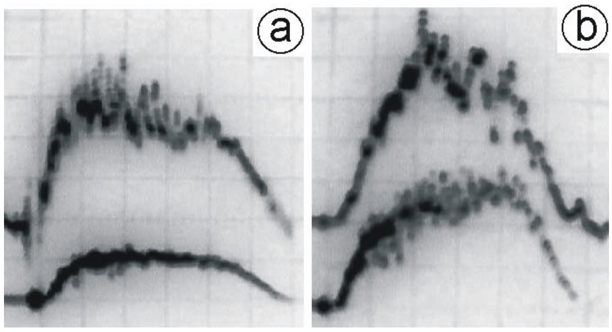


Fig.5. Oscillograms of ion beam current density j and total ion beam current I_b; upper oscillograms is j, lower oscillograms is I_b; sweep speed 20 μs/div;
a) φ_L=0 (j – 2.5 mA/cm^2 /div);
b) φ_L = 4.7 kV (j – 62 mA/cm^2 /div); for both cases vertical scan for I_b is 0.2 A/div;
φ_{ext} = 16 kV, Cu ions, B = 12.6 mT

These results open up, in part, the novel possibility of using this kind of lenses for application in linear accelerators of heavy ion beams in the LEBT between ion source and RFQ system.

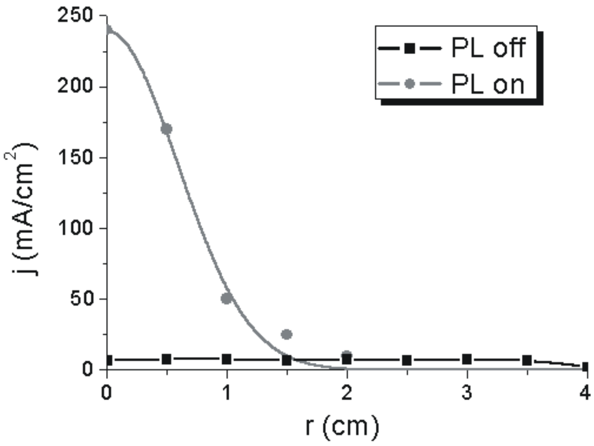
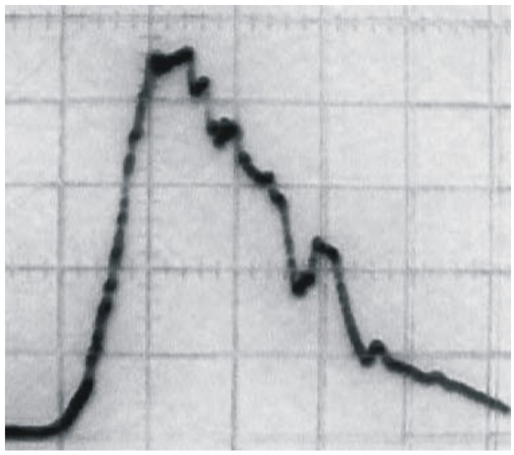


Fig.6. Radial distributions of ion beam current density corresponding to the conditions described in the cap-



tion to Fig.5

Fig.7. Oscillogram of ion current density at the beam focus for maximum compression, high frequency noise being removed; vertical scan 86 mA/cm²/div; sweep speed 20 μs/div; φ_{ext}=12 kV, I_b =0,4 A (Cu), B=12.6 mT

3.2. ELECTRON VORTICES IN ELECTROSTATIC PLASMA LENS WITH STRONG MAGNETIC FIELD

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 equipotentialize 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 above mentioned annular electron density distribution. This method enables to localize the region of instability excitation, as well as to manipulate its spatial position.

As it was anticipated, the maximum amplitude of the waves was observed in the rage of localization of the potential step (Fig.8). The observed large-amplitude anharmonic waves (Fig.9) were found to propagate in the ***E***×***B*** drift direction with the constant angular velocity (***E*** is the background electric field).

For the conditions observed, electron and ion Langmuir frequencies are $\omega_{pe} \approx 2\cdot10^9$ s^{-1}, $\omega_{pi} \approx 1\cdot10^7$ s^{-1} and cyclotron ones equal to $\omega_{ce} \approx 1\cdot10^{10}$ s^{-1}, $\omega_{ci} \approx 1\cdot10^5$ s^{-1}, respectively, while the observed cyclic frequencies of oscillations $\omega \approx (0.6\ldots1.4)\cdot10^7$ s^{-1} therefore the conditions $\omega_{ci} << \omega \sim \omega_{pi} << \omega_{pe}, \omega_{ce}$ is satisfied. The frequency of rotation $\nu = \omega/(2\cdot\pi\cdot m_\theta)$ 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 from the axis and on the magnitude of this potential step. For the same electrode potential φ_L = 1 kV, the frequency ν was

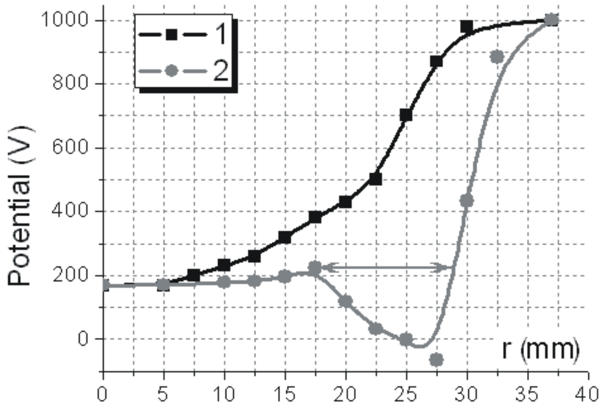


Fig.8. Radial potential distributions in the PL central cross section 1 – background potential; 2 – lowest potential achieved during the oscillation period; the radial dimension of the vortex is denoted by arrow; φ_L =1 kV, B = 40 mT, m_θ = 5

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, 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.

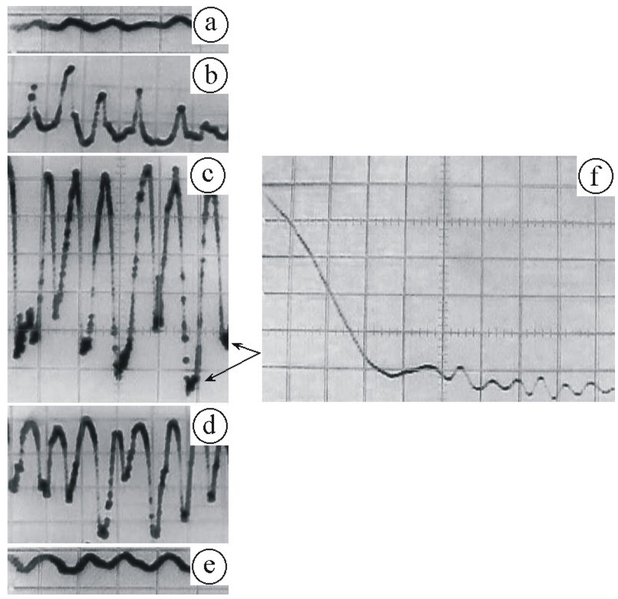


Fig.9. Oscillograms of potential oscillations in the PL central cross section measured using capacitive probes at r = 5 (a), 20 (b), 27.5 (c, f), 30 (d), and 32.5 mm (e). Sweep: 140 V/div (vertical); 0.5 μs/div (horizontal), except for (f) – 0.02 μs/div. Conditions are the same as for the Fig.8

Further we consider the way to define whether the electron bunches are the vortices or not. We imply that "**vortex**" is localized structure with closed trajectories, i.e. the vortex has to have separatrix. In the investigated conditions electrons are strongly magnetized (i.e. their typical Larmor radius is much less than the characteristic dimensions of considered structures), 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 for electrons, which has the solution

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

where ***E*** is the electric field intensity, ***B*** is the magnetic field induction. Therefore electron vortices can be formed due to the balance of Coulomb and Lorentz forces. Equation (2) defines the one of the main principles of plasmaoptics: the magnetic field lines have to be equipotential, also from this equation it follows that equipotentials of electric field correspond to electron trajectories [1]. 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, in the strict sense it have to be elliptic point on the surface corresponding to the distribution of electric potential in the central plane of the lens. Local minima correspond to vortex-bunches with the local excess of electrons, and maxima correspond to vortex-holes with the luck of ones. Fig.8 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 azimuthal size is just a little bit longer. The small maximum near *r* =17 mm on the distribution 2 in Fig.8 is just saddle point which does not represent the vortex. The mode number m_θ=5 corresponding to the conditions of Figs.8,9,10 represents the number of vortices in the "chain" displaced along the azimuthal direction. It is possible to show that bunches are the vortices through the comparison of background electric fields with those of waves, but it is more complicated way. We just note that the radial electric field of waves is significantly (up to three times) exceeds the background field in the regions where these fields are directed oppositely (Fig.10).

In addition, we performed numerical simulations of electron trajectories in the central cross section of the PL using the experimentally measured field distributions. The results of these calculations indicate that the conditions of trapping are well satisfied and the chain of vortices-bunches is actually formed in the PL. In these vortices, electrons rotate with a high velocity that is much greater than that of electron bunch moving as a whole around the PL axis. The calculated rotation frequency of electrons in the vortices was found to be in satisfactory agreement with the observed small-scale oscillations in the regions of minimum potentials of the waves (see regions indicated by arrows in Fig.9,c, one of such regions is shown on a greater time scale in Fig.9,f). It should be noted that the frequency of electron rotation around the system axis in the background distribution is ≈ 10 MHz. Therefore, the velocity of the azimuthal motion of the observed structures is significantly lower than both the background electron drift velocity and electron rotation velocity in bunches. Such vortices can be classified as “slow” [11].

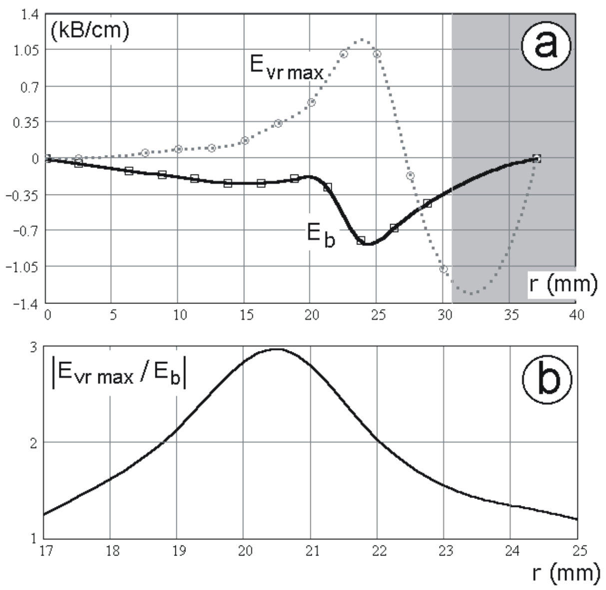


Fig.10. Parameters of radial electric fields in the PL center;
a) distributions of background electric field E_b and maximum electric field of the waves $E_{vr\,max}$;
b) absolute value of $E_{vr\,max} / E_b$ ratio in the range r=17… 25 mm. Darkened area corresponds to the region, where electrons are unmagnetized. Conditions are the same as for the Fig.8,9

Thus, we can ascertain that the observed anharmonic potential waves of large amplitude are the manifestations of the large-scale, “slow” nonneutral electron vortices in the two-component ion beam plasma, which are generated during the development of beam-drift instability in the presence of nonuniform electron density distribution. This statement is confirmed by the whole body of data, including the following: (i) the existence of regions of the potential extrema, where the potential wave field is significantly greater than the background field; (ii) the formation of localized vortex-bunches revealed by the simulations of electron trajectories using the experimentally measured field distributions; (iii) satisfactory quantitative agreement of the frequency of small-scale oscillations with the calculated frequency of vortex rotation; and (iv) the fact that the electron rotation velocity in a bunch is much greater than the velocity of the electron bunch moving as a whole. It should be noted that the potential at the vortex center is close to the potential of an electrode from which the field lines, passing through these regions, originate (see Fig. 8), in the given case, this electrode is grounded. This implies that, under the studied experimental conditions, electrons trapped in the vortex decrease the potential in this region down to the ground level and acquire the ability to go to the electrodes along magnetic field lines. As a result, the space charge accumulation ceases and the vortex amplitude is stabilized. The vortex amplitude can also be stabilized at the expense of electron loss in the direction across the magnetic field, provided that the sum of the inertia and Coulomb forces exceeds the Lorentz force (this case corresponds to the high electron density or low magnetic field). In this case, the vortex has to widen and in the limit of weak magnetic field extends over the entire PL volume [11]. However, with the use of the appropriate estimates it can be shown that under the experimental conditions studied the number of electrons accumulated in vortices is insufficient for this to be the case, and the amplitude is stabilized by the first mechanism.

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ПРОДВИНУТЫЕ ЭЛЕКТРОСТАТИЧЕСКИЕ ПЛАЗМЕННЫЕ ЛИНЗЫ НА ПОСТОЯННЫХ МАГНИТАХ

Ю. Чех, А. Гончаров, И. Проценко

В статье мы подытожили последние результаты по широко аппертурным электростатическим линзам, использующим постоянные магниты (в частности, линзы с минимизированными градиентами магнитного поля). Линзы исследованы при фокусировке импульсов средней энергии (~ 20 кэВ), сильноточных (до 0,5 А) пучков тяжелых ионов (Cu), генерируемых широко аппертурным вакуумно-дуговым ионным источником. Полученные статические и динамические характеристики сфокусированных ионных пучков дают возможность определить основной фактор, который определяет ограничение фактора максимальной компрессии ионных пучков при низких магнитных полях. В области сильных магнитных полей мы установили возможность генерации крупно масштабных электронных вихрей в плазменной линзе.

ПРОДВИНУТІ ЕЛЕКТРОСТАТИЧНІ ПЛАЗМОВІ ЛІНЗИ НА СТАЛИХ МАГНІТАХ

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У статті ми підсумували останні результати з широко апертурних електростатичних лінз, що використовують сталі магніти (зокрема, лінзи з мінімізованими градієнтами магнітного поля). Лінзи досліджені при фокусуванні імпульсних середньої енергії (~ 20 кеВ), сильнострумових (до 0,5 А) пучків важких іонів (Cu), що генеруються широко апертурним вакуумно-дуговим іонним джерелом. Отримані статичні і динамічні характеристики сфокусованих іонних пучків дають можливість визначити головний фактор, котрий визначає обмеження фактора максимальної компресії іонних пучків при низьких магнітних полях. В області сильних магнітних полів ми встановили можливість генерації велико масштабних електронних вихорів у плазмовій лінзі.