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# INFLUENCE OF MAGNETIC FIELD STRENGTH ON THE FOCUSING PROPERTIES OF A HIGH-CURRENT PLASMA LENS

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We present results of experimental studies of the operation of the high-current wide-aperture plasma lens in the range of low magnetic fields. Investigations of focusing of copper and carbon ion beams with current up to 0,5 A and energy up to 20 keV by a plasma lens with aperture ~7 cm were conducted in Kiev; studies of focusing of tantalum, copper, zinc and carbon ion beams with current up to 0,5 A and energy up to 50 keV were studied in Berkeley. In both cases ion beams were produced by a vacuum-arc (MEVVA-type) ion source. Substantial increase of the beam current density at the focus of the lens was found for low magnitudes of the magnetic fields. A maximum in beam current density is observed for magnetic fields 5-16 kA/m, in a notably narrow range. The optimal magnetic field increases with increasing voltage applied to the lens. For a copper ion beam the optimal current density reaches ~250 mA/cm$^2$, then drops by a factor 3-4 with increasing magnetic field, after which it grows again and reaches a saturation value ~120 mA/cm$^2$ for magnetic fields exceeding 40 kA/m. The effect is observed for different distributions of the external potential of the lens electrodes. Measurement of the radial distribution of potential in the mid-plane of the lens reveals a self-consistent optimal electric field topography with minimal spherical aberrations. It is observed also in the optimum case, a drastic decrease (by a factor of more than an order of magnitude) in the amplitude of oscillations in the lens and focused ion beam. A decrease of the half-width of the ion beam at the focus is also observed.

## 1. Introduction

It is known that the operation of plasma-optical systems for control of high-current ion beams is based on the principle of electron magnetic isolation and equipotentialization of magnetic strength lines [1]. This implies naturally strong magnetization of electrons and fulfillment of the condition $\rho_e \ll R$ (here $\rho_e$ is electrons Larmor radius equal to $\rho_e = \frac{c}{H}\sqrt{\frac{2m_e\varphi_m}{e}}$, where H is a magnitude of the isolating magnetic field, $\varphi_m$ is the maximum potential difference applied to the system of typical dimension R). As a result, electrons are rigidly bound to field lines, moving freely along them. This confines the transverse mobility of electrons and enables introduction into the plasma volume of stationary electric fields suitable for control of high-current beams of non-magnetized ions. The electrostatic plasma lens is the most typical plasma-optical system. In experiments with high-current plasma lenses [2,3] it was shown that increasing magnetic field leads to an increase of the limiting electric fields introduced into the plasma of the quasi-neutral ion beam, and a decrease of electron leakage onto the lens fixing electrodes. Also it results in collective oscillations. Due to equipotentialization of magnetic field lines crossing the electrodes-fixators of the lens it is possible to manipulate over a wide range the transverse radial profile of the electric potential in the system. At the same time, due to the finite size of the electrodes and the strong magnetization of electrons it becomes more difficult to establish a parabolic radial potential distribution. Increasing magnetic field also affects the fast ion trajectories, resulting in momentum aberrations increase.

In this experimental work we describe one of the methods that leads to elimination of these difficulties. It is based on the effect of low magnetic fields for which the condition $\rho_e \leq R$ is satisfied.

## 2. Experimental set-up and approach

The experiments were carried out in Kiev on the set-up described in detail in [4], and in Berkeley in [5]. For generation of plasma and production of copper and carbon ion beams we employed in Kiev a MEVVA-type vacuum-arc ion source with two-chamber anode similar to that of used in [5]. A discharge is established between a cathode made from copper or carbon and a grid anode placed at a distance ~2 cm. Plasma drifts through the grid to the extraction electrodes in the second chamber of the source. The ion beam is formed by a three-electrode multi-aperture accelerating- decelerating ion-optical system (IOS) consisting of 84 separate ion-optical cells repetitively-pulsed mode at a frequency of 1 Hz and produces a low-divergence ion beam with duration ~100 µs, energy up to 20 keV and total current up to 500 mA. The ion source is located at a distance ~30 cm from the mid-plane of the plasma lens. The diameter of the input aperture of the lens is ~70 mm, the length is ~120 mm, and the number of fixing electrodes is 9. The electrodes are powered from a 75 kΩ RC-divider providing fixed electrode potentials over the whole range of ion beam currents. The highest potential of up to +4 kV is applied to the central electrode of the lens. Electrodes symmetric around it are coupled and connected to corresponding points of the divider. The pulsed magnetic field of the lens is varied from 0 up to

0,15 T. For measurements of the static and dynamic characteristics of the beam and plasma in the lens and drift space, we used movable Langmuir and capacitance probes. Beam current and density on the axis were measured by an axially movable sectioned collector. The residual pressure is kept at a level not higher than $2{,}7 \cdot 10^{-3}$ Pa. For these conditions, plasma is created in the lens and transport channel due to ion-electron emission from the lens walls when they are bombarded by peripheral beam ions. In the Berkeley work, low divergence beams of C, Cu, Zn and Ta ions were formed by a three-electrode system ∅10 cm. Repetitively pulsed beams with duration ~250 μs and repetition frequency up to 3 Hz were formed. The extracting voltage was up to 50 kV and the beam current up to 0,5 A. The ion source extractor was located at a distance ~34 cm from the mid-plane of the plasma lens. The diameter of the input aperture of the lens was 10 cm, length 20 cm, and the number of electrodes 9. The electrodes were powered from a 110 kΩ divider connected to a low-impedance stabilized power supply. The highest positive potential applied to the central electrode was up to +7 kV. The pulsed magnetic field of the lens was varied from 0 up to 0,08 T. The residual gas pressure was approximately $\sim 7 \cdot 10^{-4}$ Pa. The current density of the beam was measured by a radially movable Faraday cup with secondary electron suppression, which was located at a distance of 34 cm from the mid-plane of the lens.

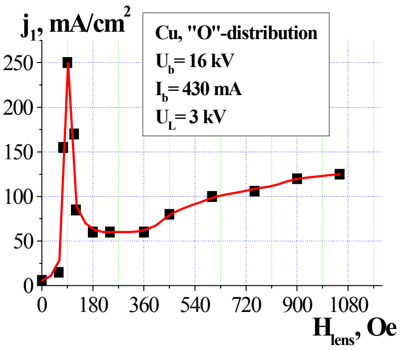


Fig.1. Dependence current density in focus on the $H_L$

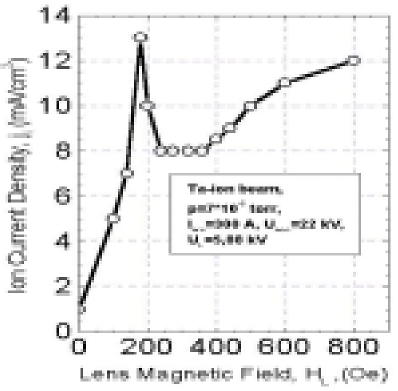


Fig.2. Dependence ion current density on the $H_L$

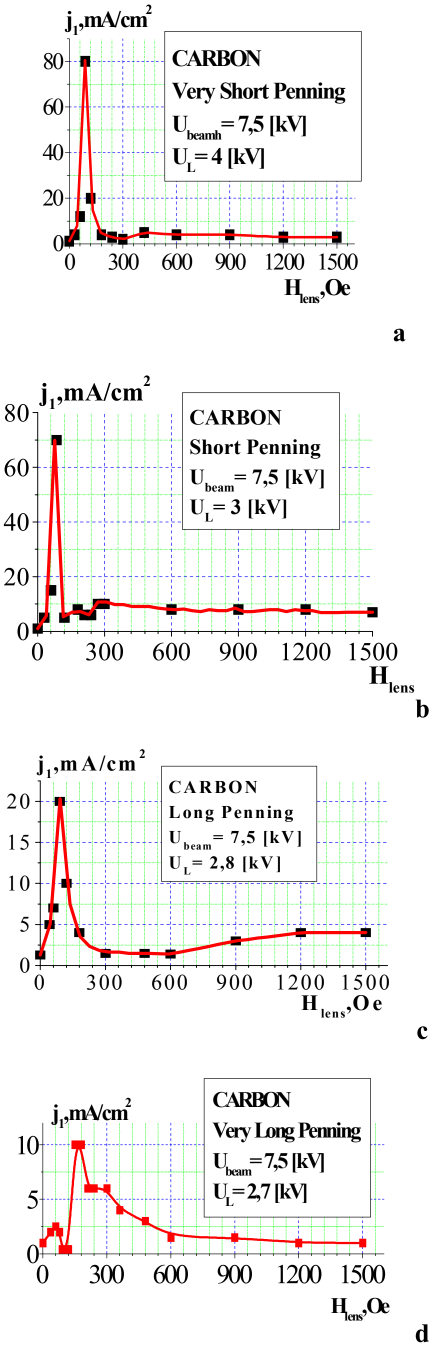


Fig.3. Dependence current density in focus on the $H_L$ for different potential distribution on lens electrodes

## 3. Results

In the course of our studies at Kiev of the plasma lens focusing properties, we found experimentally that in the range of low magnetic fields there is an optimal value of H for which is observed a sharp increase of current density on the axis of the focused ion beam. One can see in Fig. 1 that the current density of the ion beam at the focus exceeds significantly the values realized for typical magnetic fields in the lens. The existence of an optimum magnetic field, for low field strength, was noticed also in experiments with a wide-aperture plasma lens at LBNL (see Fig. 2).

Note that experiments show that the optimal magnetic field exists for different distributions of electric potential of the lens electrodes (Fig.3). The highest current density at the focus, however, may be achieved for an optimal distribution of the potential, minimizing spherical aberrations. It can be shown that the optimal magnetic field value is proportional to the square root of the potential on the central electrode of the lens (Fig.4).

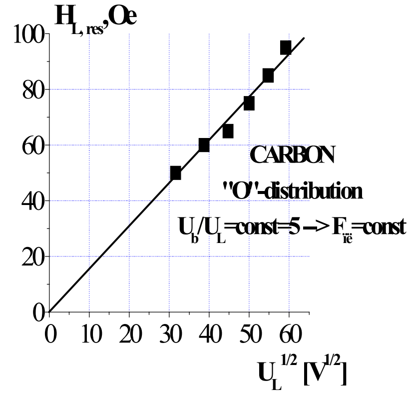


*Fig.4. Dependence optimal magnetic field on the square root of the potential on the central electrode of the lens*

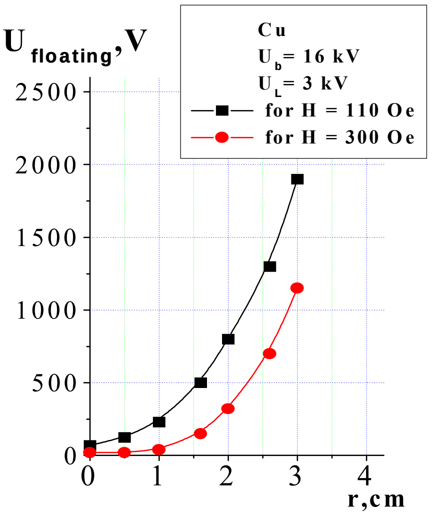
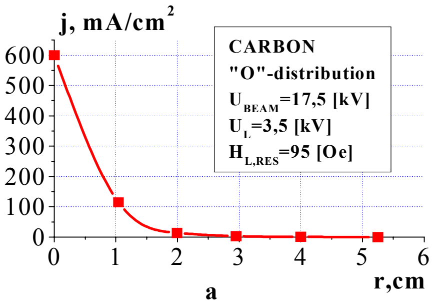


*Fig. 5. Radial distribution of the potential in the lens middle plane*

For our conditions $H_{opt}$ practically does not depend on beam energy and current. Experiments show that independent of the kind of external potential distribution of the electrodes, for the optimal magnetic field, one finds a radial distribution of potential at the mid-plane of the lens that is close to parabolic, for which spherical aberrations have to be eliminated (Fig.5.). Note that the half-width of the focused ion beam is smallest at the optimal magnetic field. As an example, shown in Fig.6 is the radial distribution of the current density for a carbon ion beam obtained at the Kiev test-stand. The current density on the axis may achieve values ~600 mA/cm$^2$ for a total beam current ~1,5 A.



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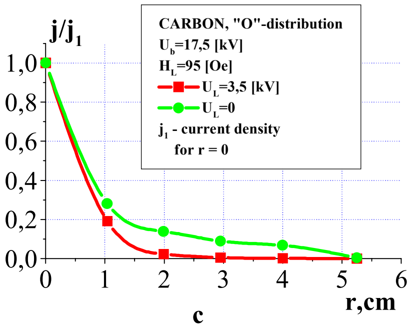

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Some interesting peculiarities may be observed in the dependence of the total current of the beam passing through the lens on the magnetic field. This dependence is observed at a current collector without suppression of secondary electrons. Whereas for high H this current approximately equals the current measured by a Faraday cup with suppression of secondary emission, for the case of low fields one can see a maximum (see Fig. 7). This maximum is especially evident for a carbon ion beam when for H~8 kA/m the current is increased by a factor of about 3. At the same time, the experiments show that the static potential on the beam axis near the collector is approximately the same for both the optimal magnetic field and fields close to it (~100 V).

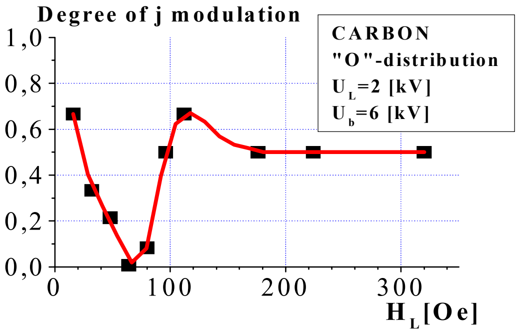

*Fig.8 Dependence of current modulation degree in focus on $H_L$*

Finally, we note that the level of oscillations in the system is significantly changed. We observe, in the optimum, a decrease by more than an order of magnitude in the oscillatory component of the beam current (see Fig. 8), and in the oscillatory signal registered by capacitive probes in the lens.

## 4. Discussion of results

The results presented here indicate that substantial improvement in the plasma lens focusing properties are obtained for a narrow range of low magnetic fields where the condition $\rho_e \approx R$ is fulfilled. Since to-date there is no good kinetic theory taking into account transfer effects and finite Larmor orbits of electrons in the complex geometry of the plasma lens, we restrict ourselves to some qualitative estimates based on clear physical mechanisms. Let us suppose that electrons appear due to secondary emission with coefficient α on the peripheral annular electrode with a square $S_c$ by input beam ions with current density $j_b'$; they move away from the volume occupied by finite Larmor circles $\rho_e > r_{ae}$ because of the transverse mobility $\mu_\perp = \dfrac{e}{m\omega_{He}^2\tau_e}$ in the strong overthermal electric field.

The condition $\varphi >> kT_e/e$ allows consideration of the transverse loss of electrons onto the central electrode with maximum positive potential as the main loss, compared to longitudinal electron leakage along the field lines onto the intermediate electrodes.

Thus we obtain the first equation. For simplicity we use cylindrical geometry.

$$(\alpha\ j_b' S_c)_I = -\mu_\perp e n_e E 2\pi r l \qquad (1)$$

From the other side, one can write a condition:

$$(\alpha\ j_b' S_c)_{II} = e n_e V_0 / \tau_e \qquad (2)$$

The expression (2) means that electrons appear on the surface of the annular electrode and go away from the volume $V_0 = \pi r^2 l$ after an average electron lifetime $\tau_e$. One can then obtain the E-field formed in the lens:

$$E \approx \frac{m_e \omega_{He}^2 r}{2e} \qquad (3)$$

It can be seen that the E-field is proportional to the radius. This means that there are no spherical aberrations. Substituting boundary conditions one obtains the following:

$$\omega_{He} \approx \left(\frac{4e\varphi_L}{m_e R^2}\right)^{1/2} \qquad (4)$$

It follows that for $\varphi_L = 3{*}10^3$ V, R=3 cm we have H≈7 kA/m. This is in agreement with the experimental value (Fig. 1).

It is possible to suppose that for the condition of electron current cut-off when $H \approx H_{\lim}$ , when the volume of the plasma lens is filled with single Larmor orbits, a self-organization of the plasma medium occurs and an isodrift regime of electron rotation around the axis is established. Under these conditions, relative sliding of layers, which causes growth of drift electron oscillations, disappears. With increasing magnetic field such a regime is quickly destroyed, leading to disturbance of the lens optical properties. Only when the H-field becomes significantly bigger than $H_{\lim}$ ($\rho_e << R$) do the plasma-optical mechanisms based on the concept of zero electron mass reveal themselves in full measure. Note that phenomena similar to that described above may be observed in related plasma-dynamical devices, for example in magnetically insulated diodes.

## Acknowledgements

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