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NOVEL GENERATION OF PLASMAOPTICAL DEVICES: FUNDAMENTAL RESULTS AND APPLICATIONS

A.A. GONCHAROV, V.I. GUSHENETS, A.N. DOBROVOLSKIY, I.V. LITOVKO, E.M. OKS, A.S. BUGAEV

The paper considers the current status of ongoing research and development of an electrostatic plasma lens for focusing and manipulating wide aperture high current electron beams. The first experimental and theoretical investigations of intense electron beams focusing due to a plasma lens with an axially symmetric positive space charge cloud produced by the cylindrical anode layer and magnetic electron insulation accelerator are presented.

Keywords: plasma lens, high-current beam.

1. INTRODUCTION

The fundamental concept of the novel plasma devices are based on application of plasma optical principles of magnetic insulation electrons and equipotentialization magnetic field lines for the control of over thermal electric fields introduced into the plasma medium for manipulating non-magnetized ions. The axially symmetric electrostatic plasma lens is a well-explored tool for manipulating and focusing high-current large-area, moderate energy positive heavy ion beams where the concern of a beam space charge neutralization is critical [1]. A numerous of effective plasma lenses for positive ion beams focusing were made and tested in NASU Institute of Physics, considerable quantity in collaboration with LBNL (Berkeley, USA). The electrostatic plasma lens is an axially symmetric plasma-optics device with a set of cylindrical ring electrodes located within the magnetic field region, with field lines connecting ring electrode pairs symmetrically about the lens middle plane. The robust construction, low energy consumption and high cost effectiveness make these tools attractive for applications in high dose implantation facilities, linear heavy ion accelerators, heavy ion fusion and other high technology.

The crossed electric and magnetic fields inherent plasma lens configuration provides the attractive method for establishing a stable plasma discharge at low pressure. Using plasma lens configuration in this way several cost-effective, low maintenance, high reliability plasma devices using permanent magnets were developed. In part, it was proposed and created cylindrical plasmaoptical magnetron sputtering device with virtual anodes and target utilization factor up to 100% and cylindrical plasma production device for the ion treatment of substrates with complicated cylindrical shape. These devices can be applied both for fine ion cleaning and activation of substrates before deposition and for sputtering. These plasma tools can be operated as stand-alone plasma devices, or as part of a single technological cycle together with a sputtering system [2].

One particularly interesting result of this background work was observation of the essential positive potential at the floating substrate. This suggested to us the possibility of an electrostatic plasma lens for focusing and manipulating high-current beams of negatively charged particles, electrons and negative ions that is based on the use of the cloud of positive space charge in conditions of magnetic insulation electrons. The idea of the plasma lens based on electrostatic electron isolation for these aims was first proposed in [3]. Later it was proposed to use magnetic electron insulation for creation of a stable positive space charge cloud [4].

Here we describe the recent results of investigations the focusing wide aperture intense electron beam by positive space charge plasma lenses based on the ideas of magnetic electron insulation.

2. PLASMA LENS WITH MAGNETIC ELECTRON INSULATION

The lens is a cylindrical plasma accelerator with an anode layer and used as a device with magnetic insulation of electrons for creation of the dynamic cloud of positive space charge. The scheme of the plasma lens with magnetic insulation used for creation of the dynamic cloud of positive space charge is shown in Fig.1.

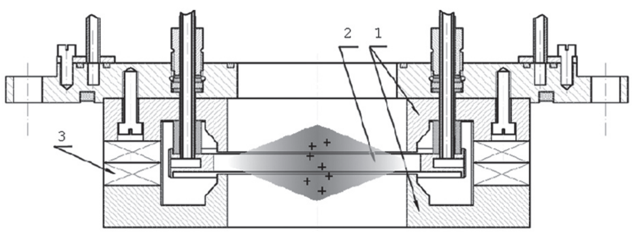

Fig.1. Scheme of the PL with magnetic electron insulation: 1 – cathode; 2 – anode; 3 – magnetic system based on permanent magnets

The beam of positively charged argon ions formed by the device converged to the system axis whereas electrons were magnetized in the anode layer. The plasma device described in those papers was adapted for focusing of intense negatively charged particle beams. The lens has a system of permanent magnets that produces an axially symmetric magnetic field between the poles of a magnetic circuit serving as a cathode. The magnetic field is controlled by varying the number of magnets or by using magnetic shunts. Because the magnetic field configuration is typical of the single magnetic lens configuration, the lens will focus the transported electron beam. When a positive potential is applied to the anode, a discharge in the axial magnetic and radial electric crossed fields is ignited between the anode and the cathode. The electrons thus drift along closed trajectories in the azimuthal direction, repeatedly ionize atoms of the working gas, and gradually diffuse to the anode. Thus the ions formed are accelerated in the strong electric field created by the electron space charge and leave the ion source through a hole in the acceleration channel. The axially converging ion beam creates a positive space charge. In the experiments, the energy of the converging beam could reach 2,5 kV. Maximum potential will be in the center on cylindrical axis. Ions are stored in the cylinder volume until their own space charge creates a critical electric field. This field forces ions to leave the volume and the system comes to dynamic equilibrium after some relaxation time.

In Fig. 2 profiles of the floating potential measured in the central lens section at the pressure of $5\cdot10^{-5}$ Torr and normalized to the corresponding anode potentials are shown. Reducing the magnetic field at the lens axial area doesn't change essentially shapes of floating potential distributions. Double-humped potential distribution is observed. Humps are formed in the paraxial area that indicates the influence of momentum aberrations on the converging positive ion beam dynamics. With anode potential growing, the anode potential to floating potential transfer efficiency decreases [5].

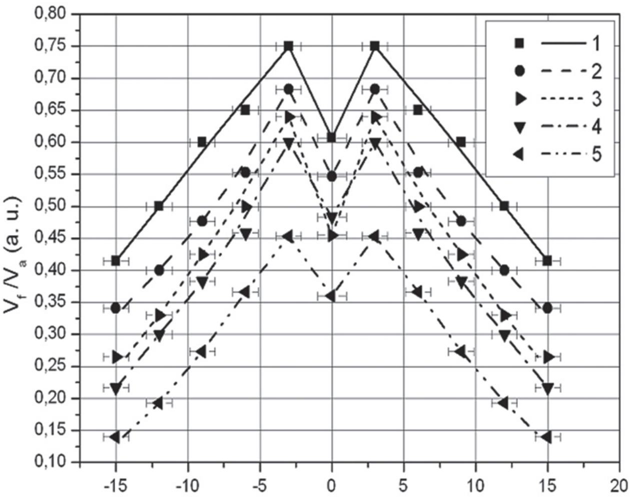

Fig. 2. Floating potential profiles normalized to corresponding anode potentials at pressure $5\cdot10^{-5}$ Torr, z = 0, discharge voltage: 1 – 700 V; 2 – 850 V; 3 – 1000 V; 4 – 1200 V; 5– 1500 V

The electric field radial component E_r in the center of the lens at different anode potentials had been calculated by using floating potential profiles (see Fig. 3). One can see that the electric field magnitude reaching 400 V/cm depends weakly upon anode potential in the range of 700-1500 V at a given pressure in the lens.

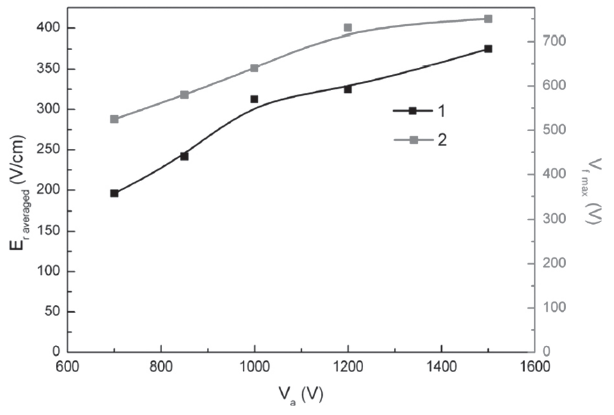

Fig 3. Averaged radial electric field (1) and maximum floating potential (2) in the plasma device volume vs. anode potential at pressure 5·10-5 Torr

2.1. Computer Simulation Results

The set of equations describing positive space charge accumulation process in plasma lens in the cylindrical coordinate system includes the Poisson (1), particles motion (2) and continuity law (3) equations:

$$(1/r)\partial\left(r\,\partial U/\partial r\right)/\partial r+\partial^2 U/\partial z^2=4\pi q_i n_i\,, \qquad (1)$$

$$M_i\frac{dv_i}{dt}=q_iE+\frac{1}{c}\left[v_i\times B\right] \qquad (2)$$

$$V\cdot div(j_{out})=S\cdot j_{in}\,. \qquad (3)$$

Here M_i, q_i, v_i are ion mass, charge and velocity respectively, E – electric field: $E_r=-\partial U/\partial r$, $E_z=-\partial U/\partial z$, U – potential, B – magnetic field, n_i – ion density, V –cylinder volume for this case, j_{in} – current density at the boundary of current-collecting surface S of radius r and height h, and j_{out} – the ion current density leaving the volume V. Knowing the space charge distribution we can determine the expulsive force acting on the particle on the boundary of space charge volume and calculate ions trajectories.

$$\oint_S E_s dS=\int_V \rho dV\,. \qquad (4)$$

The simplest analytical solutions of (1)-(3) were obtained [6] and was shown that ion density that could accumulate around the system axis reaches $0.1\cdot10^{10}$ to $0.27\cdot10^{11}$ cm^{-3} and electric field could reach 600V/cm. Equations (1)-(4) were solved numerically by PIC-method. Every time interval Δt (real time is approximately $8\cdot10^{-8}$ sec) N new particles of charge q_i and mass M_i come to the volume. The magnitudes of N, Δt, q_i satisfy the considered relation: $Nq_i/\Delta t=j_iS$. Equation of motion (2) was solved both for "new" particles and for those that are still left in the volume (time step $\Delta\tau<<\Delta t$). After time Δt the distribution of the ion space charge was determined. The Poisson equation has been solved and potential electric field $U(r, z)$ has been calculated. We have considered in our simulations that ions Ar^+ in the beam with the total current 20 mA and energy distribution from 0 to E_{max} move with angular distribution in the magnetic field similar to the experimental . The results of calculations of the potential distribution are shown in Fig. 4.

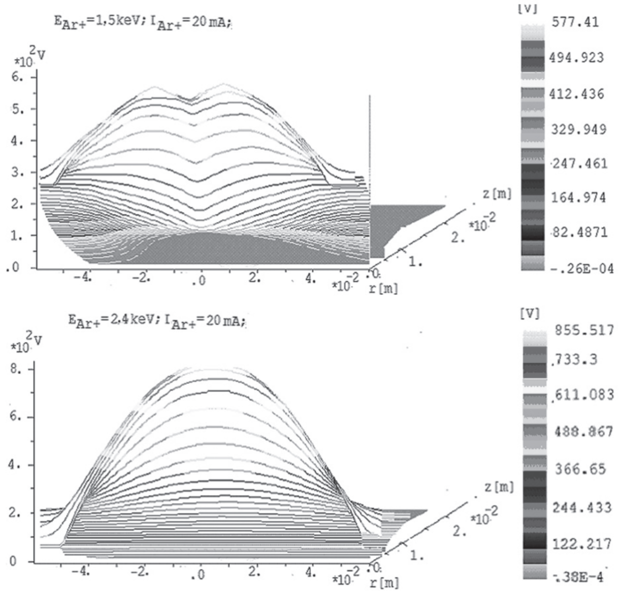

Fig. 4. Potential distribution in plasma lens midplane for Ar+ ion beam with total current 20mA and E_{max}= 1.5keV (top) and 2.4keV(down)

We can see that with ions energy increasing, the spatial distribution shape changes markedly. Whereas maximum of potential for the ion beam energy 0-1.5 keV (Fig.4 top) is double-humped situated in the coaxial region around the axis, the maximum for energy 0-2.4 keV (Fig. 4 down) is single-humped onto the axis. The results of the calculations of the potential distribution for Ar^+ and Xe^+ ion beams with maximal energy about 1.8 keV are shown in Fig. 5. One can see that the spatial distribution shape changes markedly with the ion mass increasing also. The maximum of potential for Ar ion beam (Fig. 5a) is in the coaxial region around the axis, but the maximum for heavier Xe ions (Fig. 5b) is at the axis. This can be explained by a smaller influence of the momentum aberration on the converging Xe ion beam dynamics.

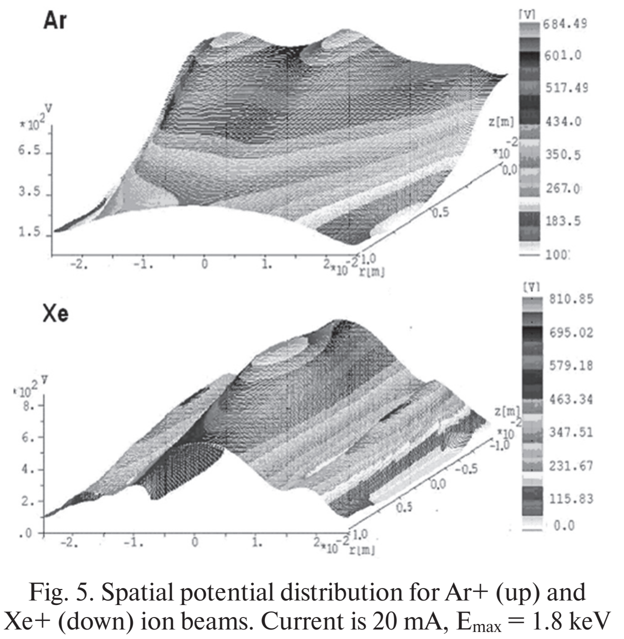

Fig. 5. Spatial potential distribution for Ar+ (up) and Xe+ (down) ion beams. Current is 20 mA, E_{max} = 1.8 keV

The calculated electric field could reach 600V/cm. Thus the obtained experimental and simulation results confirmed that in the region of positive space charge, an electrostatic plasma lens arises, being suitable for focusing beams of negatively charged particles, including electrons.

3. ELECTRON BEAM FOCUSING BY SPACE CHARGE PLASMA LENS (LOW-CURRENT MODE)

The plasma electron source based on electron extraction from vacuum arc discharge with a hollow anode was used for generation of the beam. The scheme of the experimental setup is shown in Fig. 2. The beam source (1-4) was assembled on the lens. The PL(5-7) was located in the vacuum chamber under pressure of $1,3 \cdot 10^{-2}$ Па. The cathode and chamber wall were grounded. An electron beam (8) from the plasma electron source passes through the positive space charge cloud of Argon ions in the lens volume to the sectioned collector (9-13).

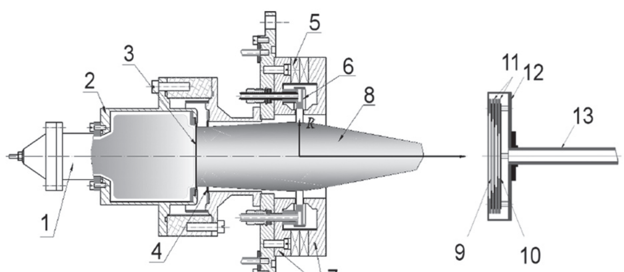

Fig. 6. Scheme of the setup: 1 – plasma cathode, 2 – hollow anode, 3 – emission grid, 4– accelerating electrode. 5 – permanent magnets, 6 –anode, 7 – cathode, 8 – electron beam, 9,10 – collector rings, 11 – isolators, 12– shield, 13 – slide rod

Electron beam focusing experiment

The pulsed wide-aperture plasma electron source based on the vacuum arc discharge on a dielectric surface was used. It produces an electron beam with current of 200-400 mA, energy up to 25 keV and pulse duration of 120 mks. The beam diameter is 6 cm on the extractor outlet. The maximum lens anode potential is 2 kV. The lens discharge current is up to 20 mA, Ar pressure is $10\text{-}5\text{-}10^{-4}$ Torr. The magnetic field on the axis is H_0 =100 Oe.

The radial distribution of the electron beam current with energy (E_b) of 8 keV is shown in Fig. 7. and the beam compression factor is shown in Fig. 8.

One can easily see the effect of electrostatic PL in this case is weak, especially as compared with the effect of the magnetic field in the lens volume. Here we observed the combined effect of electrostatic and magnetic lens, which created difficulties of separating electrostatic and magnetic focusing. One of the simplest ways to separate the influence of E- and H-lenses is to decrease H-field at the volume propagated electron beam the another way is to increase lens voltage. The optimal solution should be combining both ways so far as every have some physical restrictions.

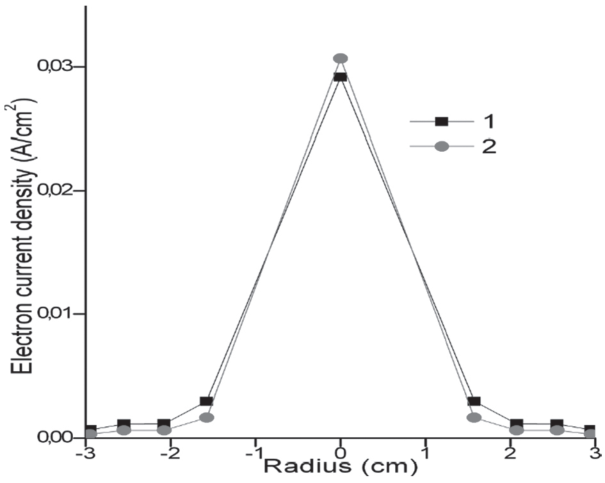

Fig. 7. The radial current density distribution of the electron beam. 1-PL-off,2- PL-on.(U_L=1,5kV)

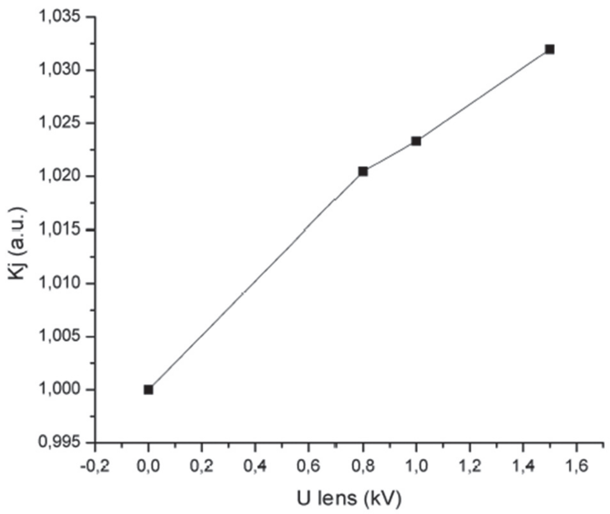

Fig. 8. The beam compression factor on lens voltage (magnetic field — 0,017 T)

Thus the lens was optimizes on some parameters [7]. At first – decreasing magnetic field value in channel allows reducing its impact on the ion's trajectories and restricted their momentum aberrations as well as to lower magnetic field influence on electron beam focusing. However, it has no significant effect on the operation of the discharge, forming convergent ion beam on the axis. At second – changing the construction of the anode lens allowed to increase the maximum potential of the anode is almost twice. This led to an increase the optical strength of the lens and reduced ion's twisting in transverse magnetic field of the accelerator. Due to these modifications the electrostatic focus location of electron beam was separated from magnetic and arrangement before it.

The results of experimental measurement are shown on Fig. 9, 10. The electron beam current density distribution on the axis after plasma lens passing is shown in Fig. 9. Ones can see that plasma lens operation (curve 3) lead to focus distance decreasing and additional beam compression in comparison with only magnetic lens action (curve 2). The beam current density at the focus increase up to 5 time as compared with lens off and almost twice in case beam focusing by magnetic field only. The focus distance is 150 mm for electron beam energy 10 keV passing through plasma lens with anode potential 2.4 keV with according to experimental measurements.

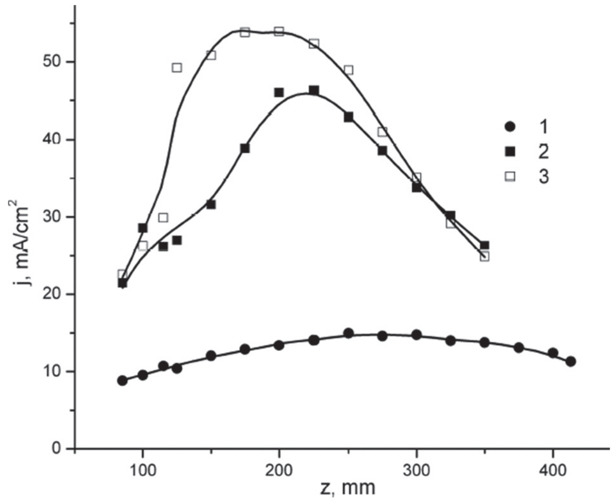

Fig.9. Beam current density distribution along Z axis (R=0). Beam energy 10 кeV, current – 200 мA. 1 – magnetic field off, anode lens potential – 0 V; 2 – magnetic field on, anode lens potential – 0 V; 3 – magnetic field on, anode lens potential2400 V.

The compression factor for electron beam current density is shown in Fig.10.

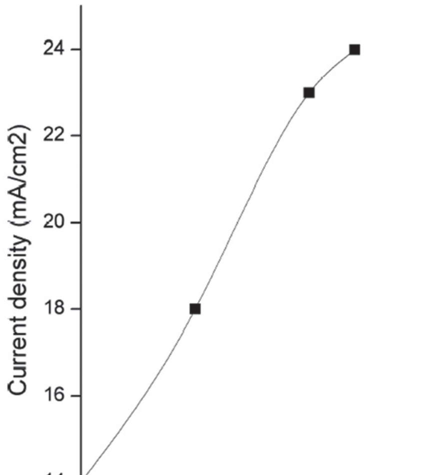

Fig. 10. Compression factor for electron beam current density, magnetic field on and beam energy is 18kV, beam current – 380 mA (Magnetic field — 0,005 T)

One can see that compression factor is significantly increased in comparison with the previous lens model (See Fig. 8). Thus optimizing lens construction allows to improve focusing of lens possibilities substantially.

Simulation electron beam focusing results

We investigated transport electron beam (energy from 5 to 20 keV) through the positive space charge cloud in plasma lens. For correct description of such system we must solve equations for ions and electrons parts together. Thus previous equation system (1)-(4) has been modified and equations for electron's motions and the law of charge conservation $\nabla \cdot j = 0$ have been added. Poisson equation had been changed to form: $\Delta\varphi = {}^{\rho}\!/_{\varepsilon}$, where φ – is the electric potential, c = $(\rho_i - \rho_e)$ – space charge density, ρ_i, ρ_e – ion and electron density, ε – the permittivity.

The Ar+ ion beam with total current 20 mA and maximal energy 2 keV (with narrow energy and angle distribution) had been used for stable positive charge cloud creation. Simulation box had been chosen as cylinder with diameter 100 mm and length 600 mm. Modeling PL has diameter 80 mm and length 10mm and has been placed in begin of the box. For computer experiment the magnetic field changed from H_0 =100 Oe to 50 Oe on the axes, thus magnetic focus lies near electrostatic focus at first case and behind it – at second. The maximal potential in cloud was reaching about 800V. The electron beam with energy 10 keV (transverse – 0.5 eV) and 0.1- 1.0 A currents passing through such PL were investigated. Results on computer experiment are shown in Fig. 11, 12.

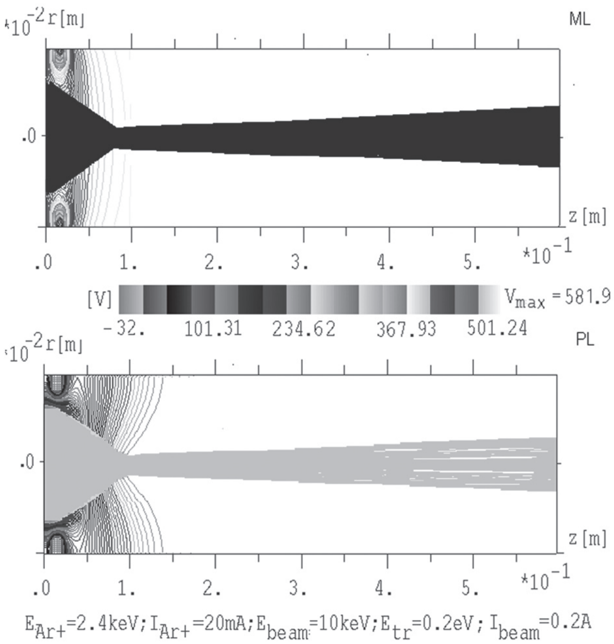

Fig.11. Electron beam trajectories: top – beam focusing by magnetic field; down – beam focusing by PL with the same magnetic field

In the Fig 11 are shown beam trajectories for electron beam with energy 10kev and total current 200mA passing through magnetic lens only (top) and positive space charge plasma lens with the same magnetic field that reach about 100 Oe on the axes . Ones can see that in this case switching plasma lens didn't change substantially beam focusing parameters. Focusing distance (about 8.5 cm) and beam cross-section diameter (about 20 mm) are almost the same in both cases that correspond with theory [8]. In the pictures Vmax =581.9V is maximal cloud potential before beam passing; under beam passing maximal cloud potential reduced to 501V. In Fig 12 are shown beam trajectories when magnetic field was reduced twice.

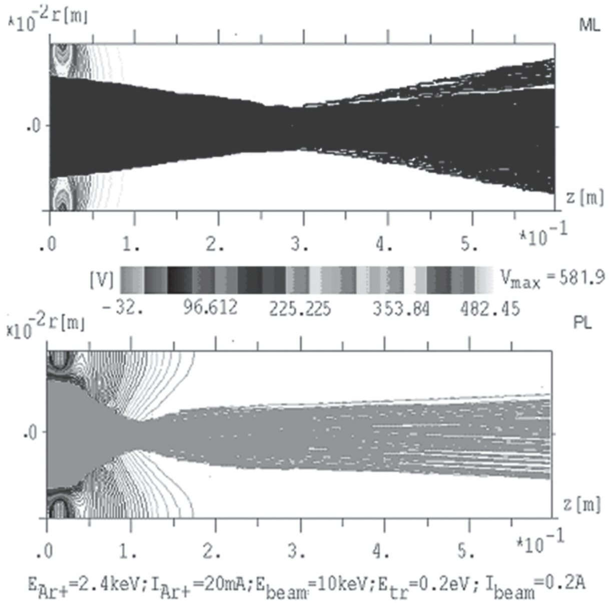

Fig.12. Electron beam trajectories for reducing magnetic field: top – beam focusing by magnetic field; down – beam focusing by PL with the same magnetic field

One can see that in this case space charge cloud lead to additional visible beam compression and moving focus closer to lens. If focus distance for magnetic lens was about 28 cm and beam radius 22mm, than switching lens on leads to shift focus distance to 15 cm and beam radius reducing up to 14 mm. Thus it is seen that the switch on the positive space charge electrostatic lens leads to improvement of electron beam focusing. The simulation results are in a good agreement with experimental data.

4. ELECTRON BEAM FOCUSING BY SACE CHARGE PLASMA LENS (HIGH-CURRENT MODE)

The scheme of experimental setup is shown in Fig. 13. The electron beam was extracted from the plasma of a hollow anode discharge through a fine grid.

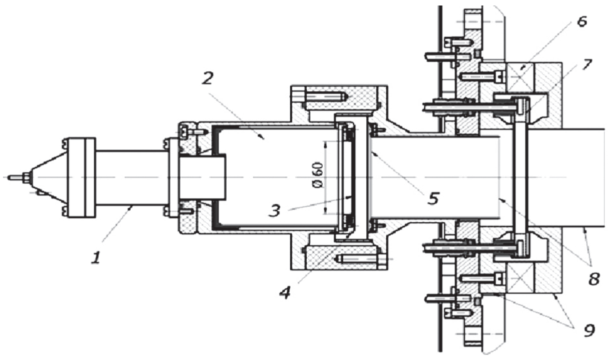

Fig. 13. Experimental setup with the plasma electron source and plasma lens: 1– plasma source cathode, 2 – hollow anode, 3– emission grid, 4 – emission electrode, 5 – extraction electrode, 6 – magnet, 7 – lens anode, 8 – Ti foil cylinder, 9 – lens cathode

The beam current is up to 100 A (high-current mode). Energy is up to 20keV, the lens discharge current is above 100 mA, pressure above $4x10^{-4}$ Torr.

In the Fig. 14 is shown vacuum arc plasma generator. Plasma generators of this type are distinguished for their design simplicity, rather high reliability, and incredibly wide range of parameters such as operating pressure, discharge current amplitude and pulse duration

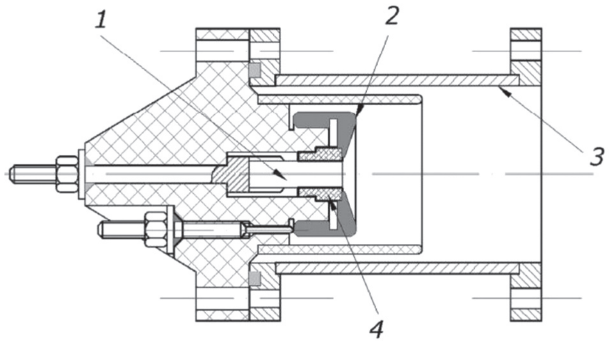

Fig. 14. Vacuum arc plasma generator. 1– cathode; 2 – igniter electrode; 3 – anode; 4 – insulator

Numerical simulation shows that at an electron beam current of 1 A, the potential in the positive space charge region decreases and the region collapses [9]. This breaks down the electrostatic focusing, and only the magnetic focusing of the beam survives. Oscilloscope recordings of the voltage across the electrodes and the discharge current in the lens show that at the instant of electron beam passage, a high-current discharge is ignited in the lens and the discharge operating voltage decreases from several kilovolts to several tens of volts. The discharge in the lens added stability to the pulse shape of the electron beam current, decreasing its fluctuation amplitude and enhancing the current transport. The lens positive influence ones can see from comparison of oscillogram 2 and 3 in Fig. 15 showing respectively the beam currents before ignition and after ignition of the discharge in the lens at a discharge current of 100 mA. It is seen that the higher the discharge current in the lens, the more the fluctuations are suppressed.

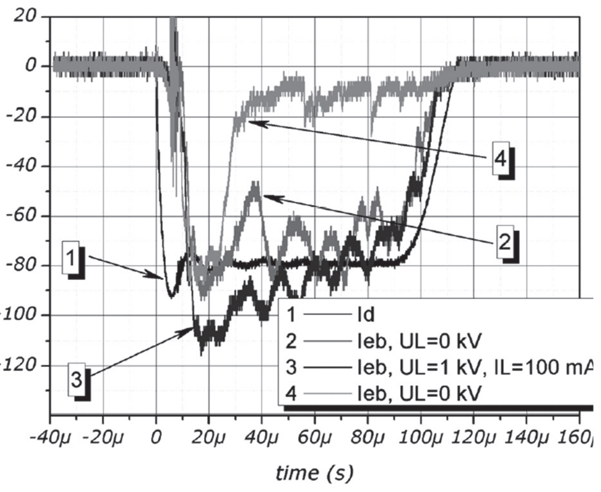

Fig.15. Oscillogram of the discharge current (1) and electron beam current before switching on the lens (2), with lens switched-on (3), after switching off(4).

In these experiments the plasma lens operate in the plasma mode and provide plasma density required for the accelerating, formation and stable transport of the intense pulsed electron beam. The beam was focused solely by the magnetic field of the lens. It allowed compressing the electron beam from its initial diameter of 6 cm to a diameter of 1 cm; the current density thus increased more than 30 times and was larger than 100 A/cm^2.

5. CONCLUSION

At the first time was experimentally demonstrated the focusing of intense electron beam with wide aperture by electrostatic plasma lens with positive space charge and magnetic insulation of electrons. It should be noted that in the case of negative ion beam focusing effect of the magnetic field on the beam is much smaller because of the large difference in the masses of electrons and ions. Efficiency electrostatic focusing on the mass of the particle is independent, so negative ion beam must focus PL is as effective as the electron beam, although the level of maximum compression of the beam at the focus may be different due to the nature of generation, formation and transport of electrons and negatively charged ions. At the same time, the proposed lens is, essentially, a thin transparent plasma sheet for passing and focusing beam of negative particles. Estimates show that in these conditions should not be a significant loss of beam due to overcharging. This allows as to talk about the prospects of using electrostatic PL to focus and control intense beams of negatively charged particles, electrons and negative ions.

For relatively low-current mode for which electron beam space charged less than positive space charged plasma lens it realize electrostatic focusing passing electron beam.

In case of high-current mode when electron beam space charge much more than space charge plasma lens the lens operates in plasma mode to create transparent plasma accelerating electrode and compensate space charge propagating electron beam. The lens magnetic field in this case use for effective focusing beam.

The experimental results are in accordance with computer calculation results.

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В статье рассмотрено современное состояние и дальнейшее развитие исследований электростатической плазменной линзы для фокусировки и управления широкоапертурными сильноточными электронными пучками. Представлены первые экспериментальные и теоретические результаты фокусировки интенсивного электронного пучка плазменной линзой с облаком аксиально-симметричного положительного пространственного заряда, созданного цилиндрическим ускорителем с анодным слоем и магнитной изоляцией электронов.

Ключевые слова: плазменная линза, сильноточный пучок.

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У статті розглянуто поточне становище та напрямок розвитку досліджень електростатичної плазмової лінзи для фокусування та керування широко апертурним сильнострумовим електронним пучком. Представлені перші експериментальні та теоретичні результати дослідження фокусування інтенсивного електронного пучка плазмовою лінзою з хмарою аксіально-симетричного позитивного просторового заряду, створеного циліндричним прискорювачем з анодним шаром та магнітною ізоляцією електронів.

Ключові слова: плазмова лінза, сильнострумовий пучок.

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