PRESENT STATUS OF THE POSITIVE SPACE CHARGE LENSE FOR FOCUSING INTENSE NEGATIVE CHARGED PARTICLE BEAMS

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We describe the new experimental and simulation results of wide-aperture (6 cm) non-relativistic (up to 18 keV) intense (up to 400 mA) electron beam focusing by the positive-space-charge plasma lens. Recently we proposed and explored a new original plasma-optical tool for negative charged particle beams focusing and manipulating with a dynamic cloud of non-magnetized free positive ions and magnetically isolated electrons produced by a toroidal plasma source like an anode layer thruster. In such kind systems the electrons are separated from ions by relatively strong magnetic field in the discharge channel. The accelerated ions are weakly affected by the magnetic field owing to their mass. Focusing of the electron beam by electrostatic plasma lens was separated from magnetic focusing experimentally and the compression factor was up to about 5. The results of the computer simulation are shown good agreement with experimental data. Obtained experimental results demonstrate the possibility to create a low-cost high-effective tool for negatively-charged particle beam focusing without influence of momentum aberrations.

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INTRODUCTION

Plasma-optical principles of introducing macroscopic over thermal electrostatic electric fields in the plasma volume of an intense ion beam, proposed firstly by A. Morozov [1], resulted in essential progress in focusing and manipulating high-current, wide-aperture positive light and heavy ion beams with current values in a range of amperes [2]. The advances in plasma lens (PL) creation for positive ion beam led to idea utilize plasma lens with a positive space charge cloud for focusing high-current negatively charged particle beams. The first proposed PL with positive space charge cloud for these purposes is based on the principle of electrostatic electron isolation [3]. In experiments the radial electric field about 100 V/cm under gas pressure about 10^{-4} Torr for focusing negatively charged hydrogen ion beam was demonstrated. This lens is easily-maintained and low-cost; its dimensions and power consumption are essentially less than those for traditional magnetic lens are, but obtaining a stronger electric field is a significant problem for such kind device.

The magnetic electron insulation for creation of the positive space charge stable cloud is promising approache. The original device has been designed for this purpose. It has been investigated both experimentally and theoretically [4, 5]. It was shown this method allow to obtain stronger focusing electric field than in electrostatic isolation case (400 V/cm against 100 V/cm).

Here we describe the new experimental and simulation results of wide-aperture (6 cm) non-relativistic (up to 18 keV) intense (up to 400 mA) electron beam focusing by the positive-space-charge plasma lens. Focusing of the electron beam by electrostatic plasma lens was separated from magnetic focusing experimentally and the compression factor was up to 5.

EXPERIMENTAL SETUP AND RESULTS

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.

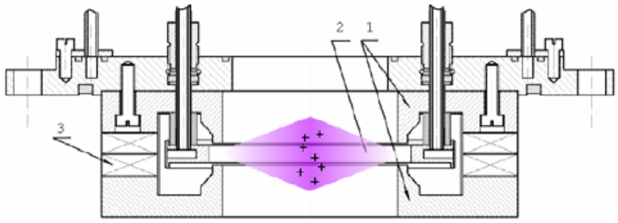

Fig. 1. Scheme of the PL with magnetic electron insulation: 1 – cathode; 2 – anode; 3 – magnetic system based on permanent magnets

The scheme of experimental setup is shown in Fig. 2. The PL (5–7) was located in vacuum chamber under pressure of 10^{-4} Torr. The cathode and chamber wall was grounded. The pulsed wide-aperture plasma electron source based on the vacuum arc discharge on dielectric surface (1–4) was located upstream the lens. An electron beam (8) from the plasma electron source propagated through the positive space charge cloud of Argon ions in lens volume to the sectioned collector (9–13). The axial movable collector had 4 symmetric rings coaxial to the symmetry axis that allowed to measure the radial distribution of focusing beam. The plasma electron source produces electron beam with current 200…400 mA, energy up to 18 keV and pulse duration 120 mks. The beam diameter is 6 cm on the extractor outlet. A detailed description and some preliminary results of the setup operation have been described previously [4-6]. There the combined effect of electrostatic and magnetic lens was obtained. The beam magnetic compression factor was up to 4. The discharge ignited under high positive potential on the lens anode and positive ions from discharge channel moved to the beam center generated the positive space charge cloud.

But combined field's action was results to 10 % beam density increasing as compared with only magnetic field focusing. As follows from theoretical estimation [5], action of the magnetic and electrostatic fields on the electron beam was the same.

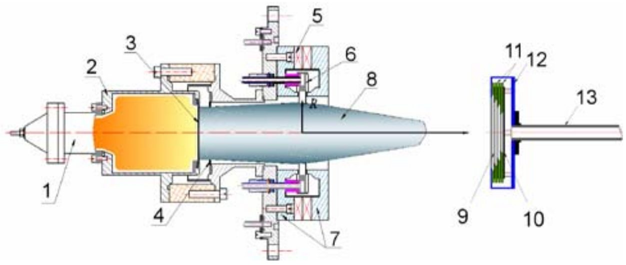

Fig. 2. Scheme of the setup: 1 – plasma cathode; 2 – hollow anode; 3 – emission grid; 4– accelerating electrode; 5 – permanent magnets; 6 – anode; 7 – cathode; 8 – electron beam; 9, 10 – collector rings; 11 – isolators; 12– shield; 13 – slide rod

In addition transverse magnetic field created conditions for momentum aberrations appearance through deflection Argon ions from linear path under their moving to system axes that complicated observing picture. It had been shown that result to such electric field profile for which focusing electron beam periphery and scattering central part. The preliminary experiments allowed to clear construction flaws of the setup and taking them into account for improvement and modernization.

The lens was optimizes on some parameters. 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 toward 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 twist 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. 3.

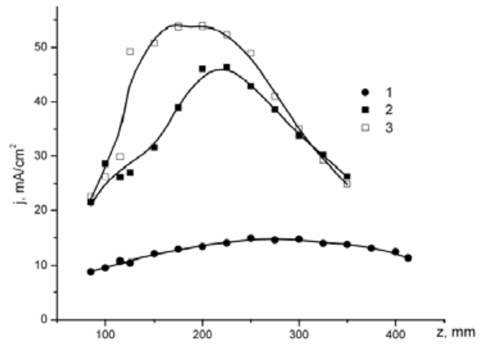

Fig. 3. Beam current density distribution along Z axis (R=0). Beam energy 10 кeV, current – 200 мA. 1 – magnetic field off, anode lens potential – 0 V; 2 – magnetic field on, anode lens potential – 0 V; 3 – magnetic field on, anode lens potential 2400 V

Ones can see that plasma lens operation (curve 3) lead to focus distance decreasing and additional beam compression in comparison with magnetic lens action solely (curve 2). The beam current density at the focus increase up to 5 times 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. The electron beam current density radius distribution in electrostatic cross-section is shown on Fig. 4. If lens off and magnetic field is absent (curve 1) – beam is spatially homogeneous. Magnetic lens action leads to beam compression (curve 2), the switching on electrostatic plasma lens leads to noticeable additional beam compression (curve 3). Thus the intensive wide-aperture electron beam focusing by positive space charge electrostatic lens with electron magnetic isolation was firstly demonstrated experimentally.

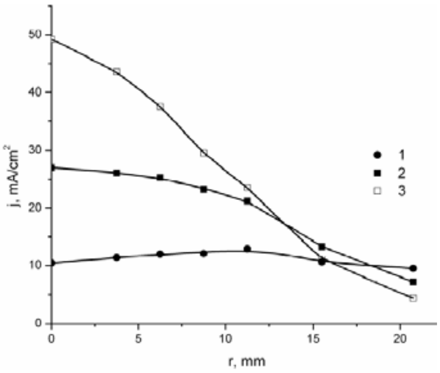

Fig. 4. Beam current density distribution on cross-section z = 125 mm. 1 – magnetic field off, anode lens potential – 0 V; 2 – magnetic field on, anode lens potential – 0 V; 3 – magnetic field on, anode lens potential 2400 V

COMPUTER SIMULATION RESULTS

For computer simulation we applied the model described before in our previous papers [3, 4] the conditions of the numerical experiment are similar to the experimental: electron beam current – 200 mA, energy -10 keV, magnet field strength in the lens center – 0,005 T, ion source current – 20 mA. Results are shown on Fig. 5 and 6. On Fig. 5 are shown trajectories of electron beam passing through lens with positive space charge cloud and magnetic field (up) and through magnetic lens only (down). One can see that 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 22 mm, than switching lens on leads to shift focus distance to 15 cm and beam radius reducing up to 14 mm. The electron beam current density distribution at the electrostatic focus cross-section is shown on Fig. 6. The red curve corresponds to the electrostatic lens with magnetic field and black – magnetic lens only. Thus it is seen that the switch on the positive space charge electrostatic lens leads to improvement of electron beam focusing. The simulation results confirmed experimental data and there are in a good agreement with them.

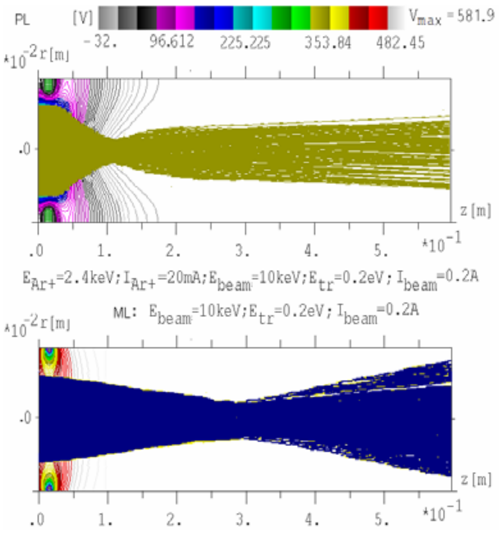

Fig. 5. Trajectories of the electron beam: top – electric and magnetic field; down – magnetic field only

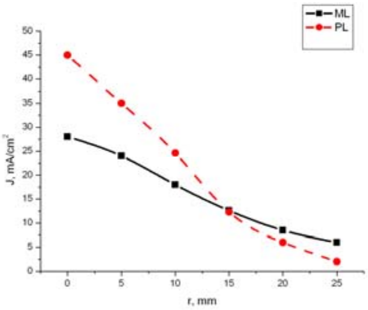

Fig. 6. The electron beam current density distribution at the electrostatic lens focus cross-section

CONCLUSIONS

At the first time was experimentally demonstrated the focusing of intense wide aperture electron beam 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 talking about the prospects of using electrostatic PL to focus and control intense beams of negatively charged particles, electrons and negative ions. The experimental results are in accordance with computer calculation results.

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ПЛАЗМЕННАЯ ЛИНЗА С ПОЛОЖИТЕЛЬНЫМ ПРОСТРАНСТВЕННЫМ ЗАРЯДОМ ДЛЯ ФОКУСИРОВКИ ИНТЕНСИВНЫХ ПУЧКОВ ОТРИЦАТЕЛЬНО ЗАРЯЖЕННЫХ ЧАСТИЦ

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Впервые наглядно продемонстрирован эффект фокусировки интенсивного широкоапертурного электронного пучка средних энергий электростатической плазменной линзой формирующей аксиально-симметричное облако положительного пространственного заряда в области прохождения пучка в условиях магнитной изоляции плазменных электронов линзы. Экспериментально измеренное фокусное расстояние плазменной линзы находится в согласии с расчетным значением. Достигнуто почти пятикратное увеличение плотности тока пучка на оси при совместном действии магнитного и электростатического полей линзы. Показана возможность четкой сепарации влияния магнитного и электрического полей на фокусировку проходящего электронного пучка.

ПЛАЗМОВА ЛІНЗА З ПОЗИТИВНИМ ПРОСТОРОВИМ ЗАРЯДОМ ДЛЯ ФОКУСУВАННЯ ІНТЕНСИВНИХ ПУЧКІВ НЕГАТИВНО ЗАРЯДЖЕНИХ ЧАСТИНОК

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Вперше наочно продемонстровано ефект фокусування інтенсивного широкоапертурного електронного пучка середніх енергій електростатичною плазмовою лінзою, що формує аксіально-симетричну хмару позитивного просторового заряду в області проходження пучка в умовах магнітної ізоляції плазмових електронів лінзи. Експериментально виміряна фокусна відстань плазмової лінзи знаходиться у згоді з розрахунковим значенням. Досягнуто майже п’ятикратне збільшення густини струму пучка на осі при сумісній дії магнітного та електростатичного полів лінзи. Показана спроможність виразної сепарації впливу магнітного і електричного полів на фокусування електронного пучка, що проходить.