Space Charge Lens for Focusing of Negative Ion Beams

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Abstract. In the report brief review of the results of experimental and theoretical studies of the space charge lens for focusing negative ion beam is presented. An idea of such lens was formulated earlier by the first two authors. For the present time, two versions of the lens are studied experimentally and calculated numerically. In the first version focusing space charge is formed in the lens in result of gas ionization by the negative ion beam itself; in the second version - in result of gas ionization by both the beam ions and the electrons with energy of about 100 eV introduced from the special emitter placed in the lens volume. In both regimes focusing field values of about 100 V/cm are reached, which enable obtaining focal length of less or about 20 cm. However, in the first case working gas (argon, krypton, xenon) pressure comprises about 10^{-3} Torr. At such pressure significant portion of negative ions is lost due to collisions with neutral particles. Introduction of additional ionizer enables essential lowering of the working gas pressure and avoiding losses of the ions.

Calculations performed by means of particle-in cell method are in a good agreement with the experiment.

The developed lens represents the simplest device - 3 electrodes with a voltage applied between them, which is one order of magnitude less than that at the ion source. Power consumed by the lens in the first regime is 2-3 orders of magnitude less than the beam power.

INTRODUCTION

In the injectors of neutral particles the beam of negative ions commonly passes short way to recharging target, where it is converted to a flow of neutral particles. In such case an attention is usually paid just to initial forming of the beam with intention of obtaining minimum angle of the beam divergence at exit of forming system. However, in a number of tasks of nuclear physics and technology it is necessary to use the beams of small diameter, which should be transported at relatively long distance. In such case lenses should be used for the beam focusing.

The use of conventional “classic” lenses is optimum far from all cases. Electrostatic lenses are satisfactory only at small beam current values, and magnetic ones – only at small energies and masses of the ions. The only suitable “classic” device, which is sufficiently versatile and does not consume unreasonable amount of electric power is represented by magnetic quadruple lens. There may be an alternative option for it represented by the space charge lens, which essentially less expensive and more versatile.

An idea of the space charge lens for focusing of the beam of negative ions was proposed by the two first authors in [1,2]. One can easily recognize this idea, if one will look at Fig.1 exhibiting the dependence of potential at stationary negative ion beam axis on pressure of neutral gas, which is passed through by this beam. The main peculiarity of presented dependence consists in existence of a point of the potential crossing zero value. At this point space charge of the beam is completely compensated by positive ions formed in result of the gas ionization by fast beam ions. Concentration of electrons formed at that in result of ionization has value smaller by several orders of magnitude due to huge mobility of the electrons. At the left of this point the beam space charge is undercompensated, and at the right it is overcompensated.

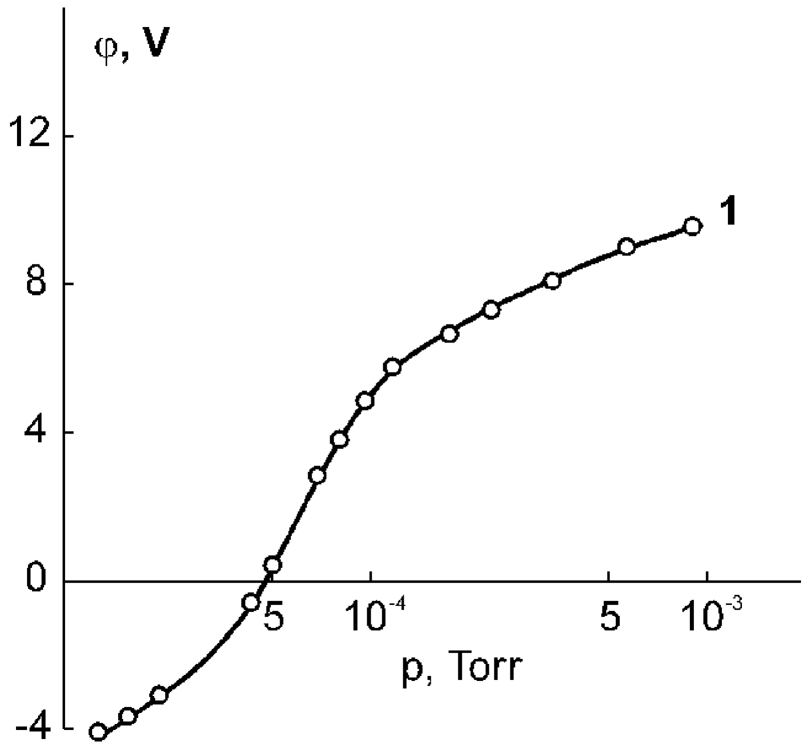


Figure 1. Dependence of potential on air pressure. Beam current is 5 mA, beam energy is 15 keV.
Note: potential in the beam center is considered with respect to grounded chamber walls.

Exactly the last case is of interest for creation of the lens. In this regime the so called "gas" focusing of the beam is observed, however, this effect is small, because focusing fields are limited by the temperature of plasma electrons. As long as the pressure increases, concentration of positive ions n_i grows up, however, concentration of electrons n_e also grows up, so that the system is practically quasi-neutral one. An idea of the lens consists in removal of electrons from the beam by longitudinal electric field in regime of high pressure values, when $n_i >> n_-$ (n_- is the concentration of negative beam ions). In the simplest case the lens is represented by three cylindrical electrodes placed sequentially along the axis. Outermost electrodes are grounded, and negative potential is applied to the middle one. As a result, electrons formed in the lens volume leave onto the outermost electrodes along the axis. Positive ions formed in result of gas ionization leave onto the middle electrode, however, due to their huge inertia the regime is formed, at which $n_i >> n_e$, and $n_i > n_-$. As well, in the initial works [1,2] it has been demonstrated that by means of such device one could create focusing field in the beam of ~ 100 V/cm and obtain focal length of the lens of less than 20 cm. Drawback of such device consisted just in fact that even in heavy gases (argon, krypton, xenon) mentioned focusing fields were created only at pressures of ~ 10^{-3} Torr. At such pressures portion of the beam might be lost due to recharging.

For excluding this negative effect it was proposed to increase the rate of gas ionization and thus to lower working pressure in the lens essentially. It can be realized by introduction of electrons with energy of ~ 100 eV, which provide efficient gas ionization, into the lens volume.

In the present work the results of experimental and numerical studies of the lens are given, both for the regime of gas ionization by the beam itself, and for the regime with additional ionizer.

DESCRIPTION OF THE SETUP

The experiments were performed at the setup, schematic diagram of which is presented in Fig.2. The beam of hydrogen negative ions with energy of ~ 10÷12 keV and current of 10÷30 mA was extracted through the slit with 0.5 mm × 15 mm dimensions from the source of surface-plasma type 1. Preliminary forming and turning of the beam was provided by magnetic field with induction value of 2 kGs formed by electromagnets 2. After passing through lens electrodes 3-4 the beam came to the collectors 7 and 8. Collector 7 with 10 cm diameter served for measurement of total beam current, and collector 8 with 2 cm diameter – for measurement of the beam compression degree. Distance from emission slit of the source to the first electrode of the lens comprised 20 cm. Distance from output plane to the collector comprised ~ 30 cm. The lens consisted from three electrodes: central one (3) represented a cylinder with 15 cm diameter and 10 cm length, outermost ones had 5 cm diameter and 1.5 cm length and were placed coaxially with central electrode with 0.5 cm gap. (In some experiments central electrode represented a cylinder with 5 cm diameter). Potential of cylindrical electrode was varied in range from 0 V to –2000 V, and outermost electrodes were grounded. Working gas was supplied either through the hole in central electrode, or through the emitter.

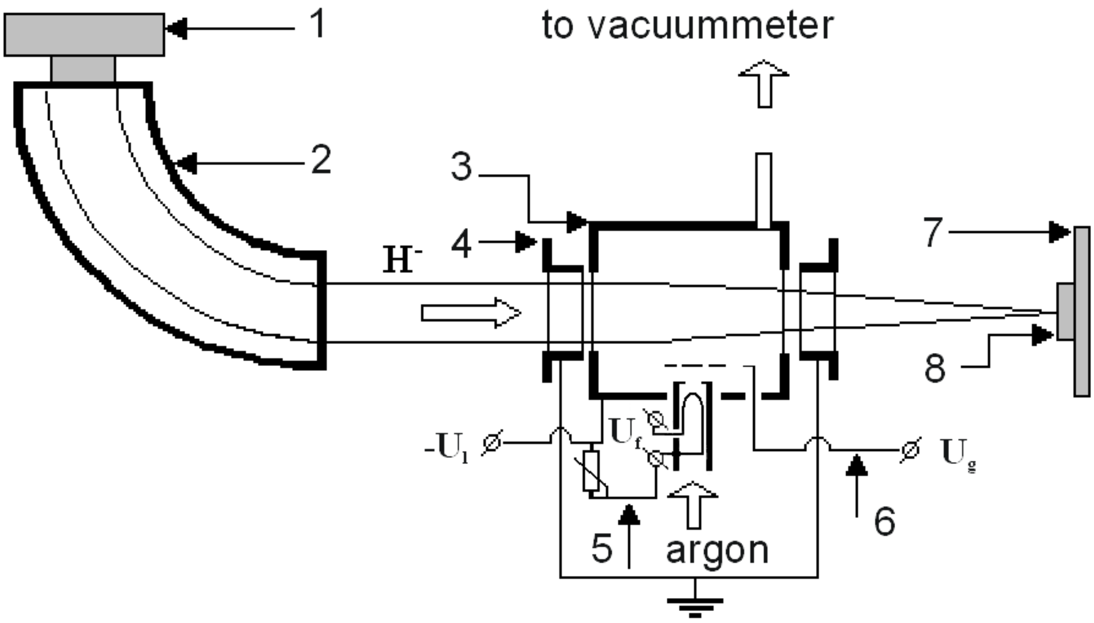


Figure 2. Schematic drawing of the experiment: 1 – pulsed source of hydrogen negative ions, 2 – beam turning magnets, 3 – lens cabinet, 4 – grounded entrance and exit electrodes of the lens, 5 – circuit of electron emitter filament, 6 – circuit of the grid for electron current control, 7 – collector of the beam current, 8 – collector of the beam current density. Gas is supplied through the electron emitter.

Gas pressure in the lens was varied in range of $1 \cdot 10^{-4} \div 1.5 \cdot 10^{-3}$ Torr, and pressure value in a region of the beam transportation was lower by one order of magnitude. Emitter of the electrons was placed in a hole in central electrode of the lens and consisted from two electrodes: 1) cathode made of tungsten wire with 7 cm length and 0.3 mm diameter wound in a helix of 1 cm length, and 2) grid with supplied 100 V potential value relatively to the cathode.

Since working gas was supplied to the lens through the emitter of electrons, non-self-maintained discharge was ignited in a gap between the cathode and the grid. It enabled removal of limiting the electron current value by the space charge, and obtaining electron current from the emitter into the lens volume of up to 200 mA.

EXPERIMENTAL RESULTS

Focusing effect of the proposed device is demonstrated in the most convincing way by Fig.3, which exhibits dependence of the beam compression coefficient (ratio of current value onto small collector in regime with the lens being turned on to that in regime with the lens being turned off) on the value of negative potential applied to central electrode of the lens. One can see that at low pressure, as it might be expected, negative potential supply does not result in the beam focusing. Only at pressure value being higher than certain critical one, it leads to the focusing effect, at that the effect increases with the pressure value growth, that is with the increase of formation rate of positive ions. As to dependence of the focusing effect on negative potential at the lens, this dependence exists up to certain point, when major portion of electrons is effectively removed from the lens volume onto the outermost electrodes, so that space charge of electrons remaining in the lens is inessential. Particularly, for the lens with 5 cm diameter of central electrode lowering the potential value below $V \approx -300$ V already does not cause essential changes in focusing features of the lens.

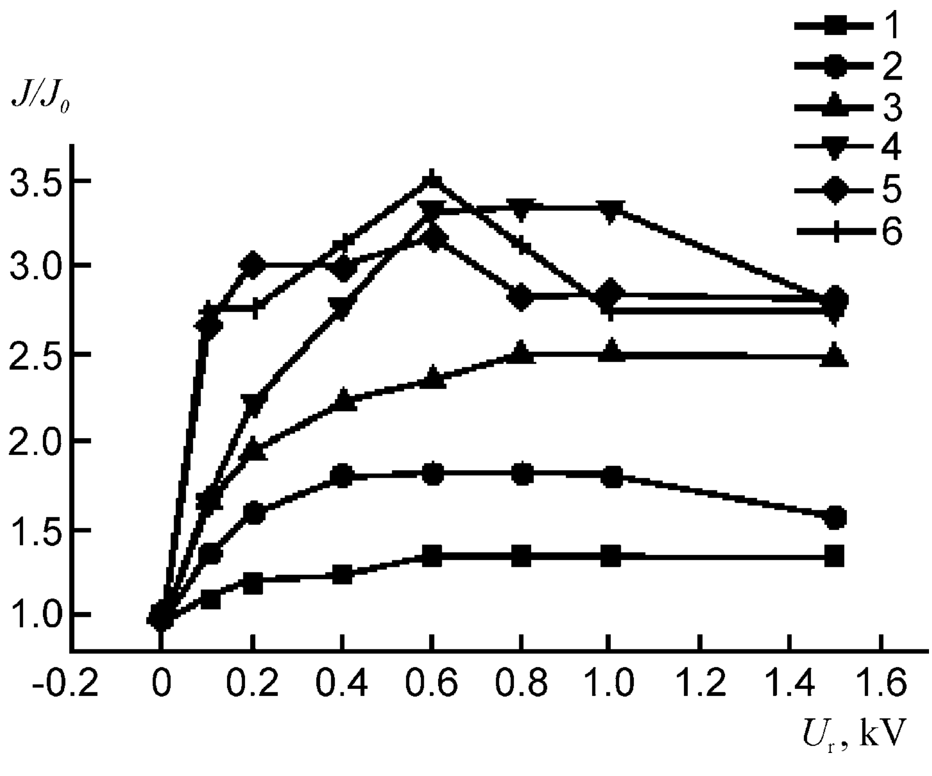


Figure 3. Dependence of hydrogen negative ion beam compression (J/J_0) from negative potential of retarding cylinder. Argon pressure in the lens: 1 - $3\cdot10^{-4}$; 2 - $7.6\cdot10^{-4}$; 3 - $1.5\cdot10^{-3}$; 4 – $2.2\cdot10^{-3}$; 5 – $3.6\cdot10^{-3}$; 6 - $6.4\cdot10^{-3}$ Torr. Diameter of central electrode of the lens is 5 cm.

Reported considerations are also confirmed by dependencies of the beam compression coefficient on gas (argon, krypton, xenon) pressure presented in Fig.4. One can see that at increase of the atom mass (ion inertia), as it might be expected, optimum focusing is reached at lower pressure. Optimum compression degree does not depend on the gas type. It gives evidence to fact that at optimum pressure the best focusing is achieved at ion collector cross section, so that further increase of focusing field will lead to overfocusing. Small compression degree (by factor of 4-6) is probably due to fact that the beam used in the experiments was not axially symmetric one. Negative influence might also be provided by the beam current oscillations due to the plasma instability in the ion source.

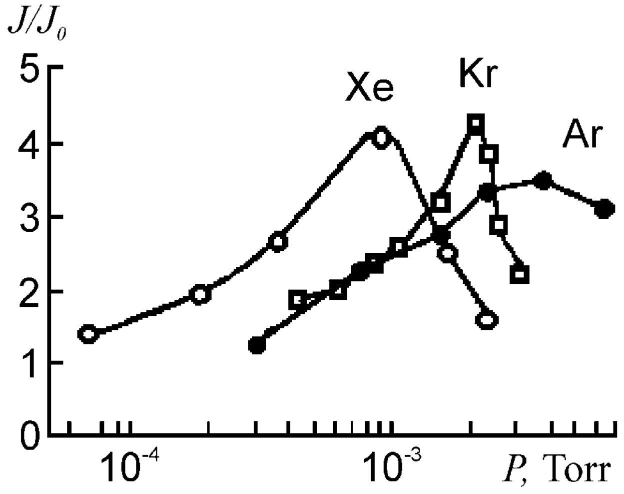


Figure 4. Dependencies of hydrogen negative ion beam compression (J/J_0) on gas pressure in the space charge lens for different gas filling (Ar, Xe, Kr). H^- beam current is 15 mA; beam energy is 10 keV. Diameter of central electrode of the lens is 5 cm.

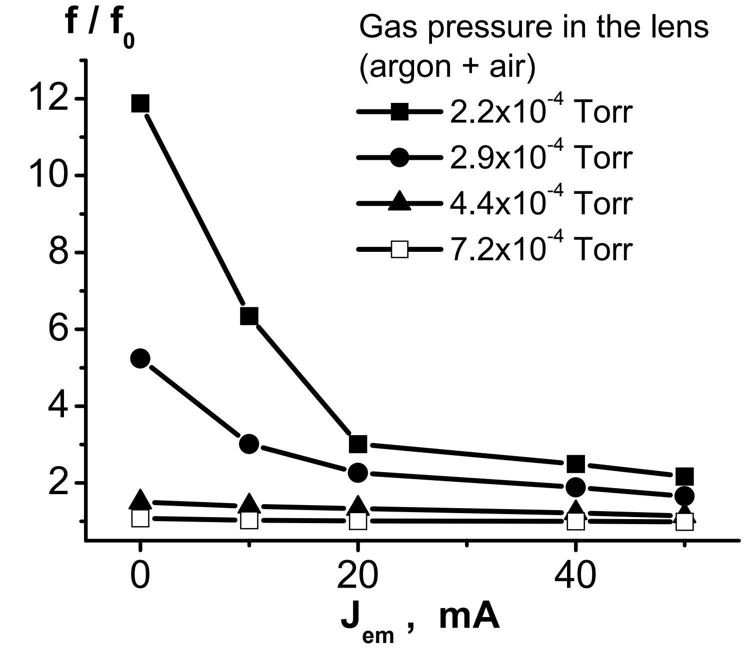
One can easily estimate that at optimum current value at collector 8 (the beam is compressed to a maximum extent) lens focal length comprises ~ 20 cm. For that purpose focusing fields of ~ 100 V/cm are required. Evaluative calculations show possibility of achieving such parameters if contribution of the electrons to space charge of the system is inessential.

As one can see from the figures, optimum beam compression is reached at pressures of ~ 10^{-3} Torr. It is easy to demonstrate that at such pressure negative ion losses due to recharging already become essential.

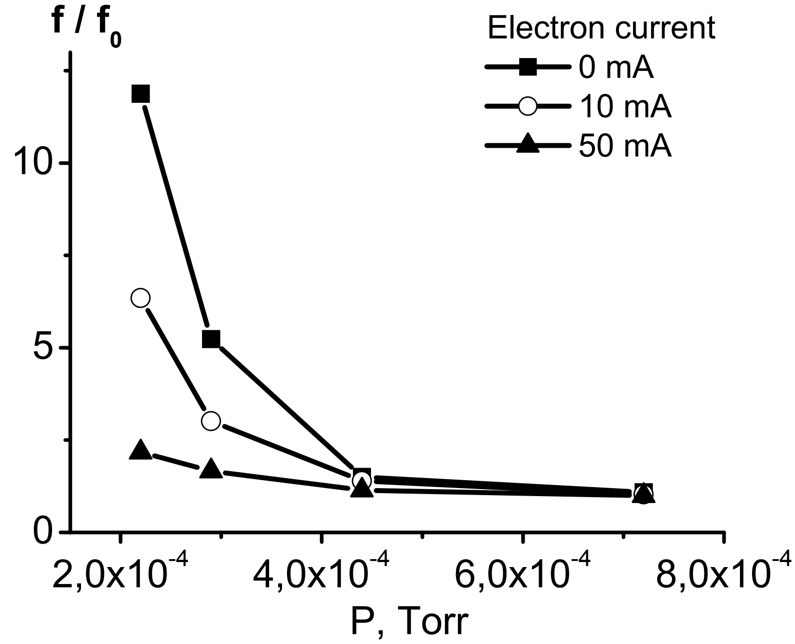
For lowering the working pressure value it was proposed to introduce additional ionizer for the increase of ion forming rate. Such ionizer was represented by electron flow with initial energy of ~ 100 eV.

Results of the experiments with additional ionizer are presented in Figs. 5a and 5b, which exhibit dependencies of the lens focal distance ratio to optimum one achieved at high pressure on electron current (5a) and gas pressure (5b). One can see that introduction of the electrons essentially increases the lens power, at that the effect increases with pressure decrease. Particularly, at emission current of 50 mA even at pressure $P=2\cdot10^{-4}$ Torr focal length is just twice longer than the optimum one. At such pressure ion losses in lens region are inessential. Thus, an efficient device is created for focusing of intense negative ion beams with the device cost being incomparably smaller than that of currently existing lenses for ion beam focusing.

Physical processes taking place in the lens will be considered in details below at the discussion of results of numerical calculations.



(a)



(b)

Figure 5. Dependencies of relative value of focal length of the lens for H^- ion beam on electron current from the emitter (a) and gas pressure (b). The lens potential $U_l = -1400$ V. The beam current is 15 mA, energy is 12 keV.

NUMERICAL CALCULATIONS

Numerical calculations were performed by the “particle-in-cell” method. Geometry of the system used in the calculations is presented in Fig.6 and corresponds to experimental one. A thread having 14 cm length was considered as electron emitter. At 1 cm distance from it grid electrode with 2 cm width and 12 cm diameter was placed. Potential of the grid with respect to the tread comprised 0÷100 V; electron current was 0÷100 mA. The calculations were performed for potential difference values of -1500 V and –2000 V between central and outermost electrodes. Current of hydrogen negative ions was chosen to comprise 10 or 15 mA, and the beam energy – 12 or 15 keV. Forming of positive ions in the lens volume was provided due the process of gas (argon) ionization by both the beam ions and electrons from the emitter. Forming of electrons occurred due to mentioned ionization process, as well as in result of recharging of the beam ions.

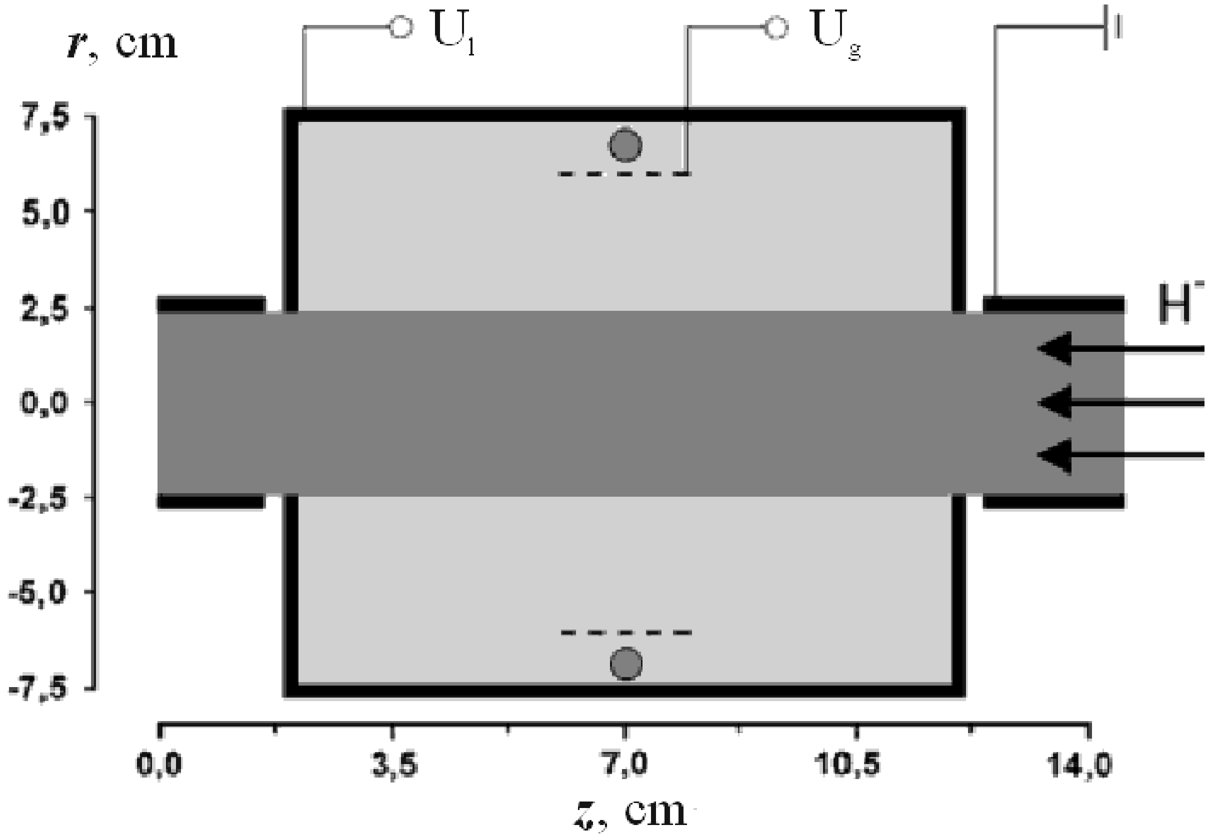
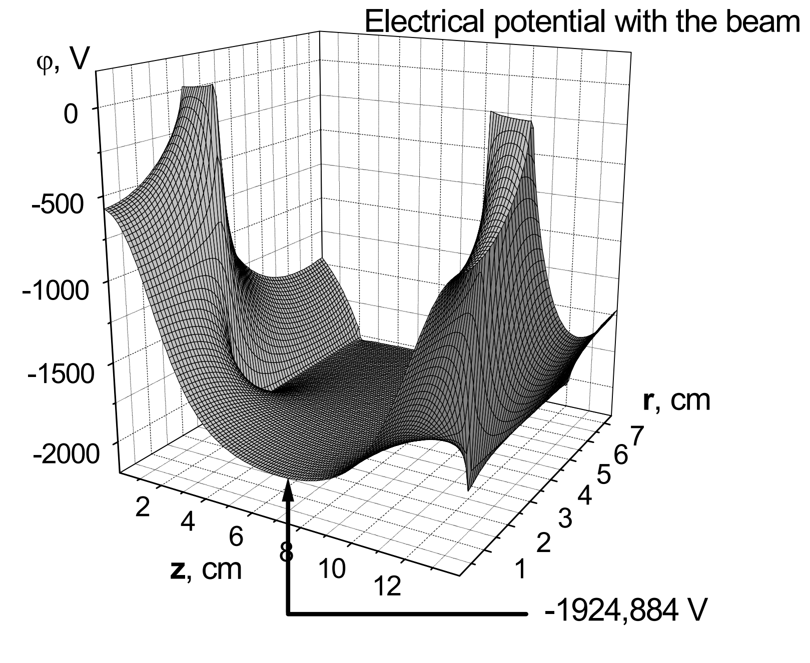


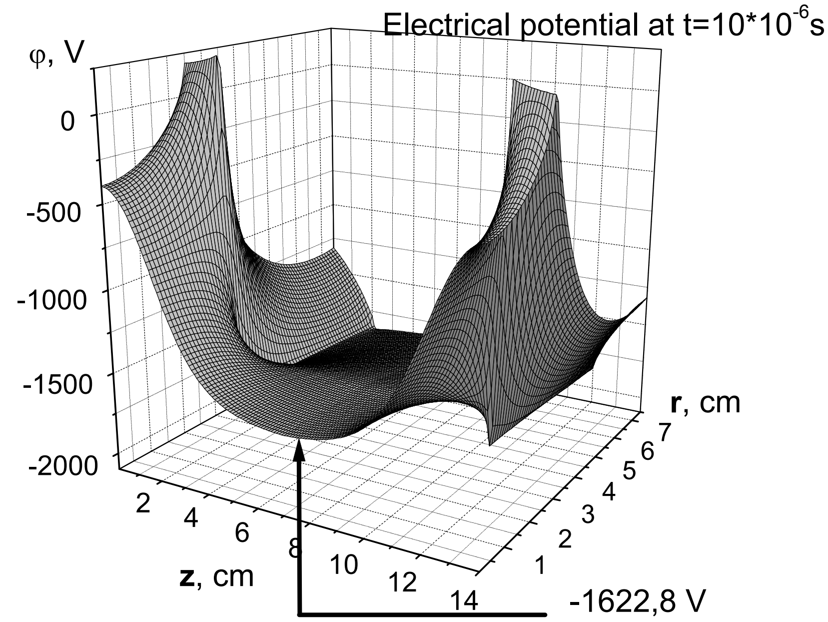
Figure 6. Model of the lens for numerical experiments. Schematic drawing of longitudinal cross section. Electrodes are shown by bold black line. In central transverse plane the electron emission source is installed (depicted as a circle near the electrode), and closer to the axis coaxial grid electrode with 2 cm width is placed.

Initial energies of the electrons were calculated in the same way as in [3], and initial energies of the ions were supposed to be equal 1 eV with uniform angular distribution. Place of origin of each new particle in the lens volume was determined by random number generator. Coordinates of the new and already trapped particles were determined from motion equation which included value of the field produced by space charges of all particles and potential of the electrodes.

Time step comprised 10^{-11} s. After 10^{-9} s time period with the use of coordinates of all particles the space charge distribution **ρ(*z,r*)** for electrons, argon positive ions and the beam ions was calculated by the “cloud-in-cell” method. On a base of determined **ρ(*z,r*)** the potential distribution **φ(*z,r*)** was found for each point of spatial grid (***Δr =0.1 cm*, *Δz=0.1 cm***). Then introduction of the new particles was performed again, and procedure of the calculations was repeated. Stationary state was usually reached within a couple of microseconds, and calculated time never exceeded 10 μs.



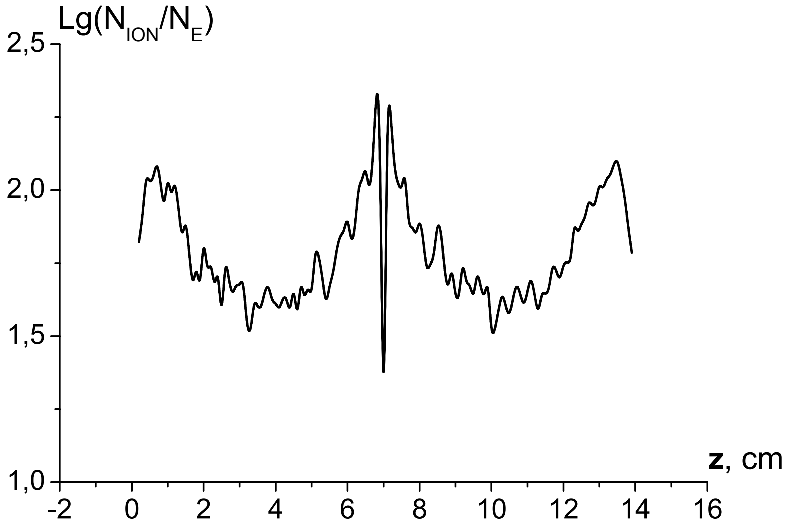
(a)



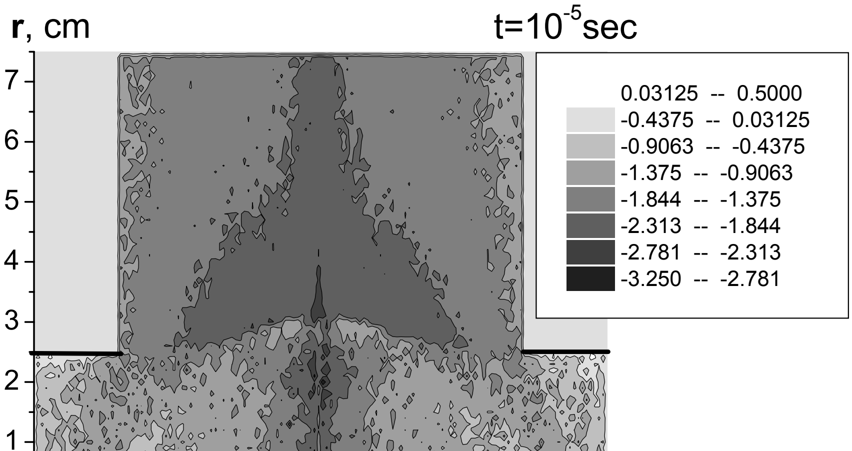
(b)

Figure 7. Distribution of potential in the lens at gas ionization by the beam. H^- negative ion beam possesses current of ~ 10 mA and energy of ~ 12 keV.
a) Initial distribution of electric field potential formed by electrodes in the lens with H^- negative ion beam.
b) Distribution of electric field potential in the lens in stationary regime at $t = 10 \cdot 10^{-6}$ s.

Let us consider at first the results of calculations in absence of additional ionizer. Fig.7a exhibits potential distribution in the lens at initial time point, and Fig.7b – at stationary operation regime of the lens. One can see that potential at the lens center increased by about 300 V due to positive space charge of the ions. All formed ions left the lens volume onto the central electrode, and all electrons – onto the side electrodes. At that electron concentration at all points of the lens was at least one order of magnitude less than the concentration of positive ions.



(a)



(b)

Figure 8. Distribution of ratio of concentration of positive ions to that of electrons at the lens axis (a) and in its volume (b). H^- negative ion beam possesses current of ~ 10 mA and energy of ~ 12 keV. Ionization is provided by the beam.

It is confirmed by Figs.8a and 8b which present the distribution of ratio of electron concentration to ion one at lens axis and in its volume. Fig.9 represents trajectories of the beam ions in the lens and in drift region. One can see that the beam is focused, and focal length comprises 18 cm value, which is close experimentally measured one.

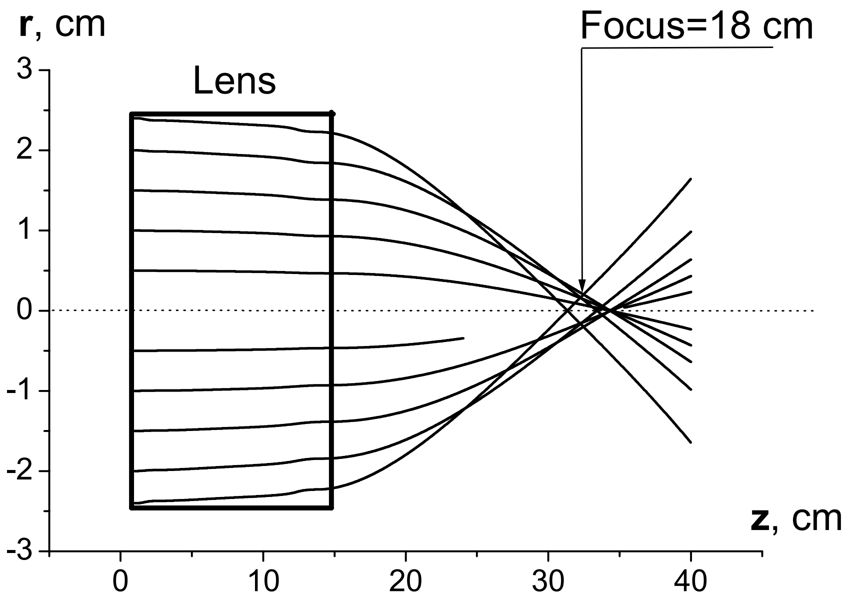


Figure 9. Trajectories of the beam particles inside the lens and outside it. H^- negative ion beam possesses current of ~ 10 mA and energy of ~ 12 keV. Ionization is provided by the beam.

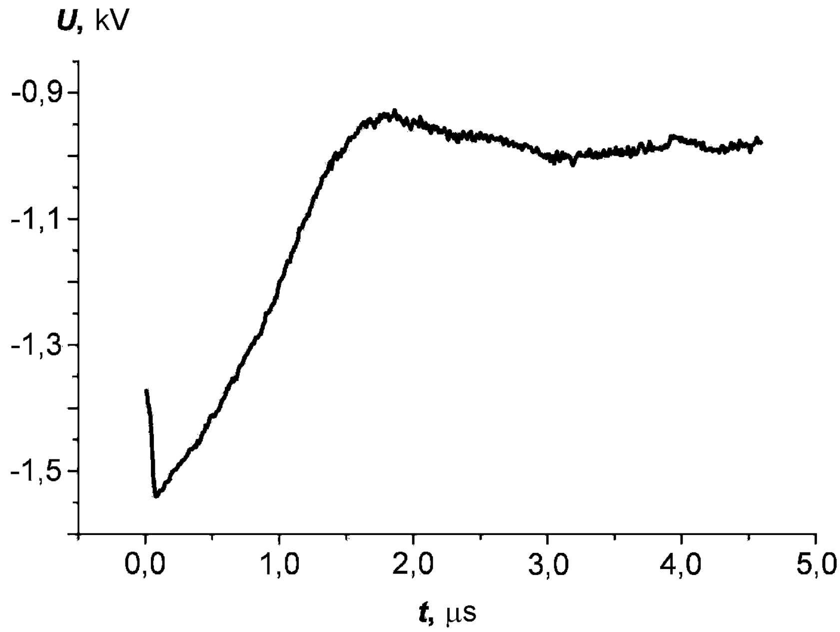


Figure 10. Dependence of potential at the lens center on time. H^- ion beam possesses current of 15 mA and energy of 15 keV. Current of the electron emitter comprises 100 mA.

We should note that calculated ration of the increase of current onto the collector comprises 25, which is significantly higher than experimental value. Such discrepancy, as it was mentioned above, may be due to non-ideal character of the beam used in the experiments, particularly, due to its asymmetry. With presence of additional ionizer the system behavior is more complex. Let us consider in details the process of establishing of operation regime of the lens at electron emission current of 100 mA, energy of 100 eV and gas pressure of $7\cdot10^{-4}$ Torr. In Fig.10 temporal dependence of potential at the lens center is presented. At initial stage (***$t=0\div0.5\cdot10^{-6}$ s***) potential value in the lens decreases, because space charge of positive ions is not yet able to compensate space charge of the beam negative ions and the electrons from emitter. With a lapse of time space charge of positive ions starts to be accumulated in the lens, and potential in the beam starts its growth. At this stage electrons from emitter are already able to perform ionization, at that contribution of electrons to the ionization increases with the growth of potential at the lens center. This positive feedback leads to rapid growth of potential, so that the accumulation process is finalized in $0.5\cdot10^{-6}$ s by reaching stationary state, in which formation rates of the ions are exactly equal to respective leaving rates. At that all positive ions leave onto central electrode of the lens, electrons formed in a process of gas ionization leave onto side electrodes, and electrons from emitter mainly leave onto the grid (just a small portion of them leaves onto side electrodes). As well as in the case without additional ionizer, concentration of positive ions in the lens in stationary state exceeds concentration of electrons, however as it follows from Fig.11, this excess is not so significant as in the case without additional ionizer.

It should be also noted that radial distribution of potential in stationary regime is close to parabolic one, that is, spherical aberrations are at their minimum, and focal length comprises 25 cm.

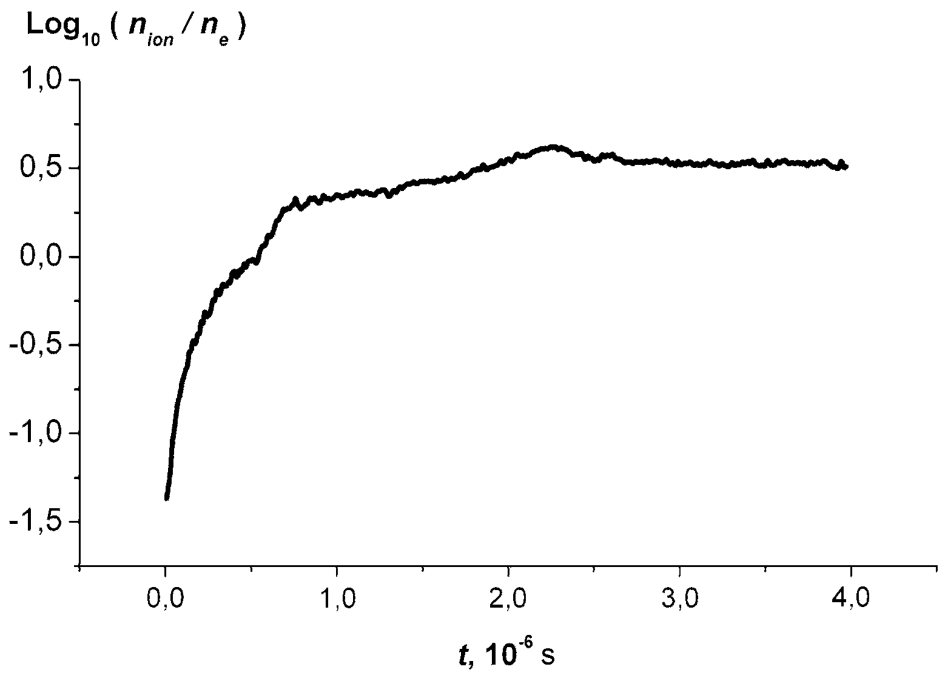


Figure 11. Dependence of logarithm of ratio of concentrations of positive ions and electrons in the lens on time. H^- ion beam possesses current of 15 mA and energy of 15 keV. Current of the electron emitter comprises 100 mA.

In the present work a set of numerical experiments was performed for different values of argon pressure and emission current. The results are presented in Fig.12 in form of ratios of the focal length value to its optimum one at different values of emitter current. One can see that, as well as in the laboratory experiment, additional ionization of the gas by electron flow results in significant increase of the lens power, at that influence of the electrons increases with pressure diminishing and electron current growth. Calculated dependencies are close to experimentally obtained ones.

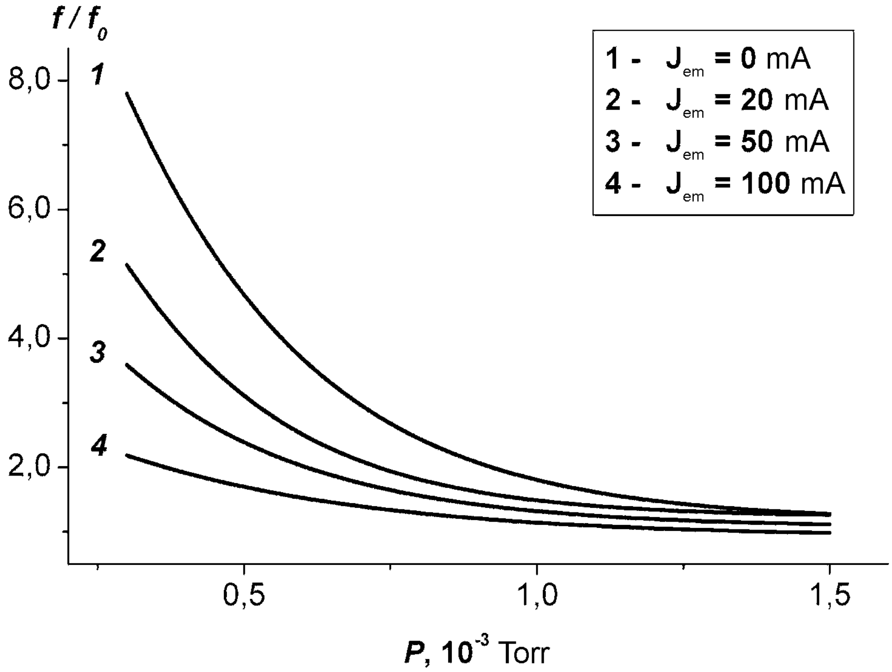


Figure 12. Dependence of relative focal length of the lens on pressure for different values of emission current. Here f_0 = 20.0 cm.

BRIEF CONCLUSIONS

In result of accomplished experimental and numerical investigations a simple and efficient space charge lens for focusing negative ion beam is created. The focusing is provided by supply of potential onto central electrode of the lens with value being one order of magnitude less than the ion source potential. Power loss in the lens is as well essentially less than that to be consumed at the focusing by means of known lenses, particularly, quadruple ones. Introduction of additional gas ionization by an electron flow enabled realization of the beam focusing at sufficiently low value of working gas pressure.

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