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High Current Heavy Ion Beams in the Electrostatic Plasma Lens*

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High Current Heavy Ion Beams in the Electrostatic Plasma Lens

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Abstract – **We describe applications of the electrostatic plasma lens for manipulating and focusing moderate energy, high current, broad, heavy ion beams. Use of a plasma lens in this way has been successfully demonstrated in a series of experiments carried out collaboratively between IP NASU (Kiev) and LBNL (Berkeley) in recent years. Here we briefly review the plasma lens fundamentals, peculiarities of focusing heavy ion beams, and summarize some recent developments (experiments, computer simulations, theory). We show that there is a very narrow range of low magnetic field for which the optical properties of the lens improve markedly. This opens up some attractive possibilities for the development of a new-generation compact lens based on permanent magnets. Preliminary experimental results obtained at Kiev and Berkeley on the operation of a permanent magnet plasma lens for manipulating wide aperture high-current heavy ion beams are presented and summarized.**

Index Terms **– Plasma lens, heavy ion beams, ion beam focusing, ion manipulation, high current ion beams, plasma optics**

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I. INTRODUCTION

High-current heavy ion beams are used widely throughout basic research and high-technology applications. This kind of beam can be viewed as a drifting, quasi-neutral, plasma medium, since the high space charge forces of the positive ions demand that the beam be space-charge-neutralized, by a background of cold electrons, to a very high degree in order to propagate at all. The necessity that the space charge compensation (i.e., the presence of cold, background electrons) must be maintained at all times, and this is the basic reason why there is a notable lack of tools for manipulating such beams. The electrostatic plasma lens provides an attractive and unique tool for this application.

The fundamental concept of the plasma lens is based on the use of magnetically insulated electrons and equipotentialization of magnetic field lines. This plasma-optical concept was first described in [1,2]. The electrostatic plasma lens is an axially-symmetric plasma-optical device with a set of cylindrical ring electrodes located within the magnetic field region, with magnetic field lines connecting ring electrode pairs symmetrically about the lens mid-plane. Steady-state electric fields are introduced into the plasma volume for the control of high-current beams of non-magnetized ions (Fig.1). A number of devices of this kind have been developed and demonstrated for various applications [2].

The electrostatic plasma lens has been investigated for more than half a century. This background work is characterized by a steady increase in the beam current I_b and the beam potential parameter $I_b/4\pi\varepsilon_0 V_b$, where ε_0 is the permittivity of free space and V_b is the beam velocity.

In the work leading up to that described here, a plasma lens was used for focusing wide-aperture, repetitively-pulsed beams of hydrogen ions with total current up to 2 A and energy up to

25 keV [3-6]. Under these conditions it was noted that favorable lens operation in the high current regime occurs when the beam potential parameter is greater than the maximum externally applied lens voltage (voltage applied to the lens electrodes). The results of these experiments provided a good demonstration of the main plasma-optical principles and the ability of the lens to effectively manipulate high current ion beams. It was found that the static and dynamic characteristics of the lens depend on the throughput ion beam current. The lens has a high optical strength and spherical aberrations can be controlled over a wide range, to some extent thus allowing aberrations to be minimized. Investigations of the peculiarities of focusing of wide-aperture, low-divergence, hydrogen ion beams show that the maximum compression (ratio of current density at the focus to beam current density) of such beams is not very high (2-5) and decreases with increasing beam current. In the absence of spherical aberrations the maximum compression of low-divergence beams may be restricted by a finite phase volume, uncompensated beam space charge, and momentum aberrations due to a finite azimuthal twist of beam particles in the lens magnetic field. Estimates made in [3,8] show that the main reason for the low compression of the light hydrogen ion beams, under the experimental conditions employed [3,4], are momentum aberrations. For heavy ions the role of momentum aberrations, that lead to space charge separation and limitation of beam compression, decreases rapidly for higher ion mass and energy. Thus one can expect that for typical conditions, for example for copper ions with energy 20 keV, a beam compression in the range 500 – 1000. The first two factors lead to limiting on the similar levels.

Moderate energy, large area, high current, heavy ion beams can be focused in this way, as has been well demonstrated in a number of experiments carried out at Kiev and at Berkeley in recent years [7-8]. The lens used in these experiments employed a magnetic field that was established by conventional current-driven electromagnetic coils. In these experiments we noted an increase in the focused ion beam current density for specific low magnetic field strengths. This suggested to us the possibility of a plasma lens based on the use of permanent magnets.

The first experimental investigations of the focusing properties of a lens based on permanent magnets for establishing the required magnetic field configuration were carried out collaboratively both at the IP NASU (Kiev) and at the LBNL (Berkeley) [9-10].

Here we summarize some recent developments of the static and dynamic characteristics and focusing properties of electrostatic plasma lenses based on the use both of conventional current-driven coils and small permanent magnets.

II. EXPERIMENTAL CONDITIONS AND APPROACH

The experiments were carried out at Kiev using the set-up described in detail in [6] and at Berkeley described in [7,8]. For ion beam formation we use a two-chamber MEVVA ion source with grid anode and a three-electrode, multi-aperture, accel-decel ion extraction system. Both sources operate in a repetitively-pulsed mode and produce moderate energy, low-divergence, broad, heavy metal ion beams with primary parameters as follows. Kiev: beam duration $\tau = 100$ μs, beam extraction voltage $U_{acc} \leq 25$ kV, total current $I_b \leq 800$ mA, initial beam diameter $\phi = 5.5$ cm, ion species Cu and C, distance from ion source extractor to mid-plane of the lens ~30 cm. Berkeley: $\tau = 250$ μs, $U_{acc} \leq 50$ kV, $I_b \leq 500$ mA, initial $\phi = 6$ and 10 cm for two different extraction systems, ion species Bi, Pb, Ta, Nb, Mg, Cu, and C, distance $d = 34$ cm. The basic parameters of the lenses with current-driven coils were as follows. Kiev: input aperture $D = 7.4$ cm, length $L = 12$ cm, number of electrostatic electrodes $N = 9$; the electrodes were fed via an RC-divider that provided fixed electrode potentials for the duration of the ion beam, and the highest potential (U_L) applied to the central lens electrode was +4.7 kV; the maximum strength of the pulsed magnetic field formed by a number of coils surrounding the lens was $B = 1000$ G.

Berkeley: D = 10 cm, L = 20 cm, N = 9; the electrodes were fed by a 110 kΩ resistive voltage divider across a low-impedance stabilized power supply; $U_L \leq$ +10 kV, B = 800 G.

The parameters of the lenses used with permanent magnets were as follows. Kiev: input aperture D = 7.4 cm, length L = 14 cm, number of electrostatic electrodes N = 13; the maximum strength of the magnetic field formed by the permanent Fe-Nd-B magnets at the center of the lens was B = 360 G. Berkeley: D = 10 cm, L = 15 cm, N = 11; B = 300 G. The magnetic field shape required for each plasma lens was determined by computer simulation and experimental tests. The simulation results were in excellent agreement with the experimental data. Radially and azimuthally movable Langmuir and capacitive probes were used for measurement of the plasma parameters in the lens volume and in the beam drift space (in the Kiev setup). I_b and J_b were measured by an axially-movable sectioned collector (at Kiev) and by a radially-movable, magnetically-suppressed Faraday cup with entrance aperture 3 mm (at Berkeley), located at a distance ~30 cm from the lens mid-plane. The base pressure in the vacuum chamber was less than 1×10^{-5} Torr, allowing formation of plasma within the lens volume by the ion beam itself and by secondary electron emission from the lens electrodes.

III. RESULTS AND DISCUSSIONS

The static and dynamic characteristics and focusing properties of these lenses were explored as a function of externally applied electrode potential distribution, magnetic field strength, and manner of establishing the magnetic field (i.e., solenoid or permanent magnets), total ion beam current transported, initial beam diameter, and the ion species. The experiments confirm that the plasma lens is effective in focusing large area (up to D = 10 cm), high-current (up to 1 A), heavy metal ion beams with moderate energy (5 – 100 keV). The focusing properties of the lens are similar, under the same parametric conditions, for both the cases when the lens magnetic field is established by a current-driven solenoid and with a permanent magnet array.

The experiments show that for a large-area ion beam the focusing properties are more distinct when initial beam diameter equals the lens input aperture diameter. The maximum compression for a tantalum ion beam was a factor of 5 – 7 for the optimal lens potential distribution, for the case of beam with initial diameter 6 cm. For the case of tantalum beam with diameter 10 cm, the maximum beam compression at the lens focus was approximately a factor of 30, with current density up to 32 mA/cm^2. Similar results were obtained for a copper ion beam on the Kiev set-up, where the compression was a factor 15 – 25 depending on the total ion beam current passing through the lens and the current density was up to 170 mA/cm^2 (see [6-8] for details).

The experimental results depend on the particular externally-applied potential distribution along the lens electrodes (see [8] for more details). The optimal "O"-distribution minimizes lens spherical aberrations, as established empirically. This distribution is significantly different from the theoretical optimum potential distribution obtained by plasma optics principles.

Focusing of different ion beams species (Bi, Pb, Ta, Nb, Mg, Cu, C) was investigated. Better results were obtained for the case of the heavy ion beams Bi, Pb, and Ta. In Fig. 2 one can see good bismuth beam compression for the case of the experimental optimal electrode potential distribution. The maximum ion beam compression for Bi was up to a factor of 30, and the low-noise focused beam current density was up to 45 mA/cm^2. At the same time the total transported ion beam current increased by up to 30%. The experimental results imply that the maximum beam compression factor is restricted by non-removable spherical aberrations because of the finite width of the lens electrodes.

These results with the appropriate experimental conditions were used for theoretical analysis and computer simulation of the processes of formation of the plasma medium within the high current electrostatic plasma lens (see [11] for more details). We show only some of these results, obtained by the PIC (particle-in-cell) method, in Figs. 3 and 4. These data show the formation within the lens volume of layered electron structures (Fig. 3) due to finite width of the ring lens electrodes. This means that the presence of spherical aberrations restricted the maximum compression of the focused ion beam. This is confirmed by Fig. 4, which models ion beam focusing for the experimental conditions presented here. The maximum compression obtained by computer simulation is in good accordance with experimental results.

There is yet another important factor that can degrade the ion beam focusing. This is connected with a drift instability arising in inhomogeneous crossed $E \perp B$ fields in the lens volume. These collective processes were first observed in experiments [3]. When a hydrogen ion beam was transported through the lens, small-scale turbulent oscillations arise in the 20 – 50 Mhz frequency range. A linear dispersion equation of two-dimensional oscillations was obtained that allowed us to explain qualitatively the regularities observed in the experiments. Further understanding of the instability mechanisms require studying the nonlinear dynamics of electrons within the plasma lens medium. A nonlinear equation for the perturbation electric potential has been obtained [12], describing the dynamics of the generation and evolution of electron wave vortex-like structures within the lens. This equation describes the development of both large scale, low frequency, vortex structures and small scale, high frequency, vortices. Using heavy ion beams we could distinguish regular low frequency (0.2 – 2 Mhz) electrostatic potential waves rotating around the lens axis, and irregular small scale noise in the 20 –50 Mhz frequency range [13].

The ion beam noise (beam current fluctuation level) inherent to the MEVVA ion source can be enhanced when the beam transits through a region of oscillating fields in the lens volume. We found experimentally that there is a very narrow range of low magnetic fields, with $\rho_e \leq R$, for which the focusing properties of the lens improve dramatically. At the same time in this range the turbulence level in the lens volume and in the focused ion beam decrease by more than an order of magnitude (Fig. 5). Here we show data obtained for carbon ions on the Kiev setup for one particular experiment for which the effect was most distinct. Similar results were also observed for copper ions at Kiev and for tantalum ions at Berkeley. Under these conditions the maximum beam compression significantly exceeds that obtained for typical lens magnetic fields. These results are in good accordance with theoretical analysis of the excitation and evolution of electron vortex-like structures in the high current plasma lens [14].

This preliminary work suggests new possibilities for the development and application of a new compact plasma lens based on permanent magnets rather than on electrically driven coils surrounding the lens region

IV. CONCLUSION

The experimental results, theoretical analyses, and computer simulations described here indicate good prospects for the permanent-magnet electrostatic plasma lens for focusing high current, moderate energy, large area, heavy ion beams. The simple design, robust construction, the need for only a single power supply, and the high efficiency are all attractive advantages of a lens using permanent magnets rather than current-driven coils At this stage of the investigations, this plasma-optical device could be used, for example, for high dose ion implantation and in particle accelerator beam lines. Further experimental and theoretical efforts are needed to develop an optimized plasma lens with minimal spherical aberrations, in part by optimization of the magnetic field configuration in the low magnetic field range.

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Figure Captions

Fig. 1 Schematic of the plasma lens.

1 – magnetic coils; 2 – cylindrical electrodes; dashed lines – equipotentials; solid lines – magnetic field lines.

Fig. 2 Radial ion beam current density profile at the Faraday cup location.

Fig. 3. Electron space charge distribution in the plasma lens volume for the two lens potential distributions shown in Fig.1.

(*a*) theoretical; (*b)* experimental. The background ion space charge is 0.43 CGSE units/cm^3. Shaded areas – electron space charge density ($\rho_e \geq 0.86$ CGSE units/cm^3).

Fig. 4. Ion beam particle trajectories for the case of Fig. 3(a)

Fig. 5. Characteristics of plasma lens in the low magnetic field regime.

Upper: ion current density at collector as a function of lens magnetic field strength.

Middle: capacitive probe signal (noise amplitude) within the lens volume as a function of lens magnetic field.

Lower: amplitude of modulation in ion current density (noise amplitude) as a function of lens magnetic field.

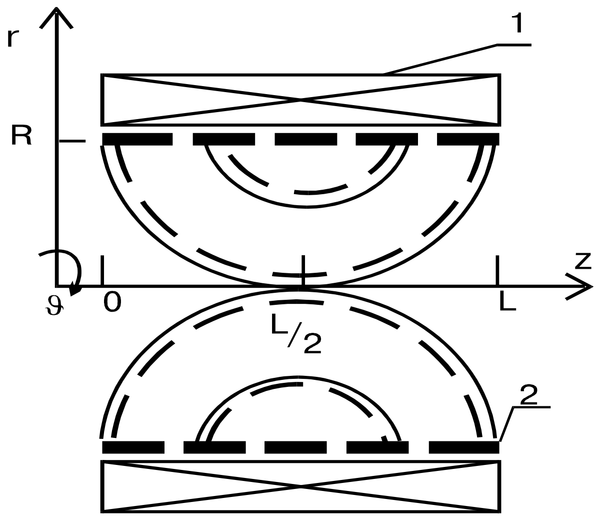


Figure 1

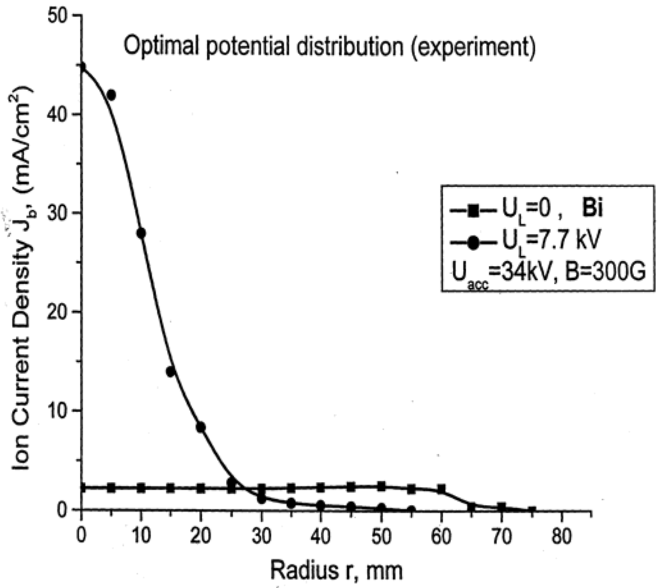

Optimal potential distribution (experiment)
Ion Current Density J_b, (mA/cm^2)
Radius r, mm
U_L=0 , Bi
U_L=7.7 kV
U_{acc}=34kV, B=300G
0
10
20
30
40
50
60
70
80

Figure 2

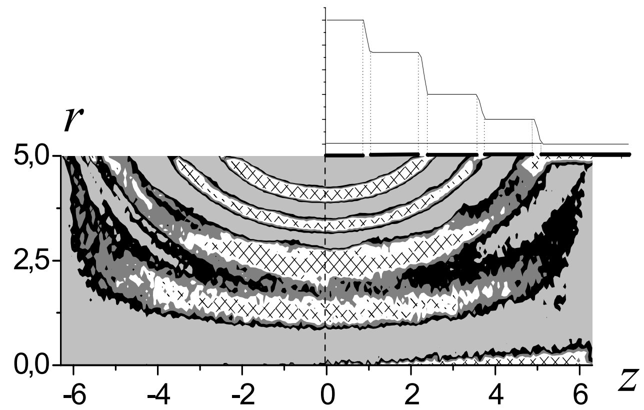


Figure 3(a)

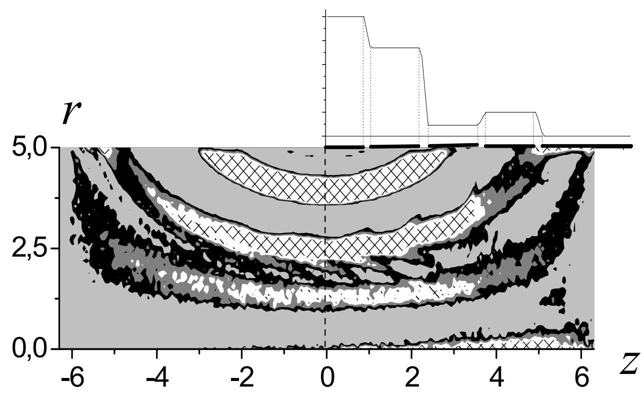


Figure 3(b)

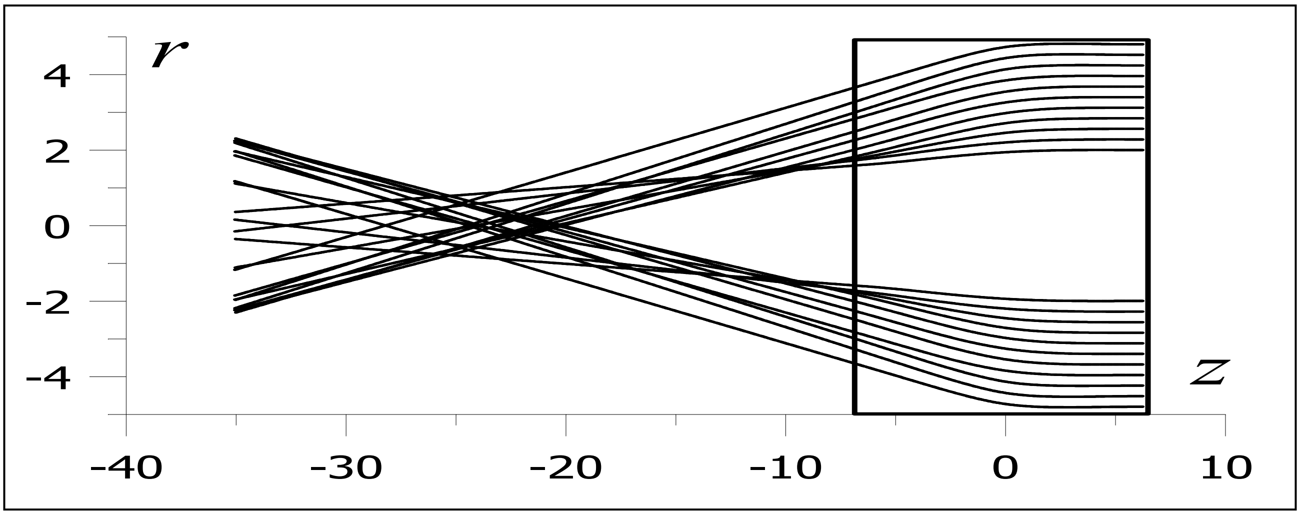
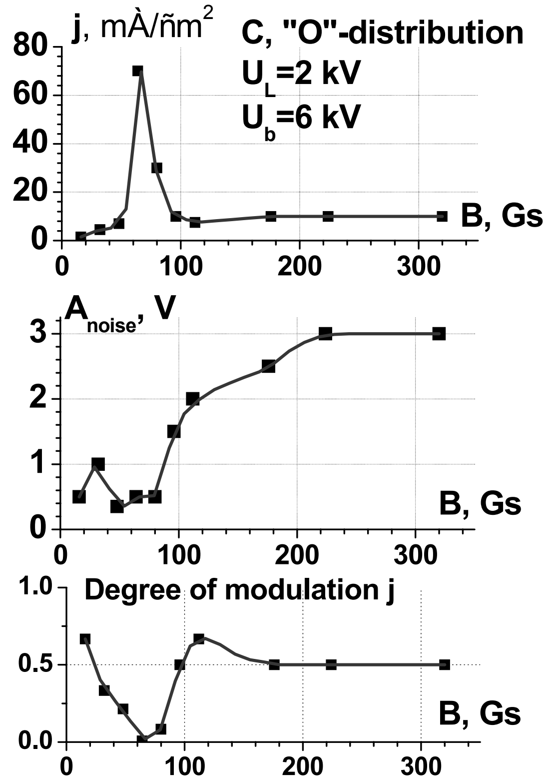


Figure 4



j, mÀ/ñm2
C, "O"-distribution
UL=2 kV
Ub=6 kV
80
60
40
20
0
B, Gs
0
100
200
300
Anoise, V
3
2
1
0
B, Gs
0
100
200
300
1.0
Degree of modulation j
0.5
0.0
B, Gs
0
100
200
300

Figure 5

Authors' Bios

Alexey A. Goncharov is a Leading Physicist at the Institute of Physics, National Academy of Sciences in Ukraine, Kiev, from which he also received the Doctor of Science degree. His research involves the development of high current plasma optical devices for their application in basic sciences and plasma-based technologies. He has been a Researcher at the Institute of Physics NASU since 1965. He is author/co-author of over 130 experimental and theoretical research programs, resulting in over 65 peer-reviewed papers published in refereed journals and presented at national and international conferences. His fields of interest include high current ion beams, magnetic isolation, plasma optics and collective processes in the plasma-beam system. Since 1985 he has focused on the investigation of high-current electrostatic plasma lenses for applications in high dose ion implantation and in heavy ion linear accelerators. Dr. Goncharov is a Member of the Ukrainian Physical Society and the American Physical Society.

Ian G. Brown is a Senior Physicist with the Lawrence Berkeley National Laboratory. His research interests include the development of plasma and ion beam sources and their application for materials synthesis and modification. He has held research and teaching positions at Sydney University, Princeton University, the University of California, Berkeley, and the Max-Planck Institute for Plasma Physics, Garching, Germany. His work on vacuum arc ion sources and materials surface modification has won two R&D-100 awards. He is a Fellow of the American Physical Society, the Institute of Physics (U.K.), the Australian Institute of Physics, as well as of the IEEE; and a Member of the American Vacuum Society, the Materials Research Society, and the Society for Biomaterials, and the Bohmische Physical Society.