Permanent magnet plasma lens

A. Goncharov, V. Gorshkov, S. Gubarev, A. Dobrovolsky, I. Protsenko, and I. Brown

Citation: Review of Scientific Instruments **73**, 1001 (2002); doi: 10.1063/1.1431414
View online: http://dx.doi.org/10.1063/1.1431414
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/73/2?ver=pdfcov
Published by the AIP Publishing

REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 2 FEBRUARY 2002

Permanent magnet plasma lens

A. Goncharov,[a)] V. Gorshkov, S. Gubarev, A. Dobrovolsky, and I. Protsenko
Institute of Physics NASU, 46 pr. Nauki, Kiev 03039, Ukraine

I. Brown
Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720

(Presented on 6 September 2001)

We have designed and fabricated, for the first time, a simple, compact, and low-cost electrostatic plasma lens based on the use of permanent magnets rather than an electrically driven solenoid to establish the magnetic field. Characteristics of the focused ion beam passed through the lens have been measured. Some of the beam characteristics depend strongly on the applied magnetic field strength and the precise form of the external potential distribution applied along the lens electrodes. The experimental results obtained at the Institute of Physics (Kiev) and at the Lawrence Berkeley National Laboratory (Berkeley) show that this plasma optical device can be used beneficially for focusing and manipulating moderate energy, large area, heavy metal ion beams. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1431414]

I. INTRODUCTION

The electrostatic plasma lens (PL) is an axially symmetric plasma-optic device consisting of a set of cylindrical ring electrodes located within a magnetic field region. The basic features[1,2] of ion beam focusing by this kind of device have been demonstrated in a number of experimental investigations.[3–7] It was found,[3,4] in particular, that the characteristics of the PL depend strongly on the beam current passing through the lens. In work preliminary to that described here,[5–7] experimental investigations of the focusing of moderate energy (10–100 keV), high current (up to 1 A), large area (diameter ~10 cm), heavy ion (Cu, Mo, Ta) beams by PL were performed at the Institute of Physics in Kiev and at the Lawrence Berkeley National Laboratory (LBNL) in Berkeley. In these experiments the focusing of broad heavy metal ion beams was demonstrated using a lens in which the magnetic field was provided by a conventional current-driven electromagnetic coil. Substantial increase in the beam current density (J_b) at the focus of the lens for specific low magnetic field was noted in these experiments. Here we describe our first experimental results of the focusing properties of a simple and compact PL based on the use of small permanent magnets.

II. EXPERIMENTAL SETUP AND APPROACH

The experiments were carried out at Kiev using the setup described in detail in Ref. 3 and at Berkeley described in Ref. 6. For the generation of plasma and production of heavy metal ion beams we used a metal vapor vacuum arc-type vacuum arc ion source with a two-chamber anode. The ion beam was formed by a three-electrode multi-aperture extraction system. Both sources operate in a repetitively pulsed mode and produce moderate energy, low-divergence broad heavy metal ion beams with main parameters as follows. Kiev: beam duration $\tau = 100\ \mu$s, beam extraction voltage (U_{acc})$\leqslant$25 kV, total current (I_b)$\leqslant$700 mA, initial $\varnothing = 5.5$ cm, ion species Cu, distance (d) from ion source extractor to midplane of the PL~30 cm. Berkeley: $\tau = 250\ \mu$s, $U_{acc} \leqslant 50$ kV, $I_b \leqslant 200$ mA, $\varnothing = 6$ cm, ion species Ta, C, Cu, $d = 34$ cm.

The main parameters of the lenses used were as follows: Kiev: $\varnothing_{inp}$ of the input aperture 7.4 cm, length (1) 14 cm, number of electrostatic electrodes (N) 13; the electrodes were fed via a 100 kΩ RC divider that provided fixed electrode potentials for the duration of the ion beam, and the highest potential (U_L) applied to the central electrode was +4.7 kV. The maximum strength (B_0) of the magnetic field, formed by the Fe–Nd–B magnets, at the center of the lens was 360 G. Berkeley: $\varnothing_{inp} = 10$ cm, $1 = 15$ cm, $N = 11$; the electrodes were fed by a 110 kΩ resistive voltage divider. The $U_L \leqslant +10$ kV, and the $B_0 = 300$ G.

The magnetic field shape required for each PL and the corresponding disposition of magnets needed to establish the magnetic field were determined by computer simulation (Fig. 1). The simulation results are in excellent agreement with the experimental results. The B_0 could be varied by changing the number of small magnets used and also by employing iron pieces to shunt some of the field.

Radially movable Langmuir probes were used for measurement of the plasma in the lens volume and drift space. The 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 $\varnothing = 3$ mm (at Berkeley), located at a distance ~30 cm from the lens midplane. The base pressure in the vacuum chamber was less than 1×10^{-5} Torr.

III. RESULTS AND DISCUSSIONS

The experimental results indicate that the PL focusing properties are determined by the detailed features of the magnetic field shape formed by the permanent magnet struc-

[a)]Electronic mail: gonchar@iop.kiev.ua

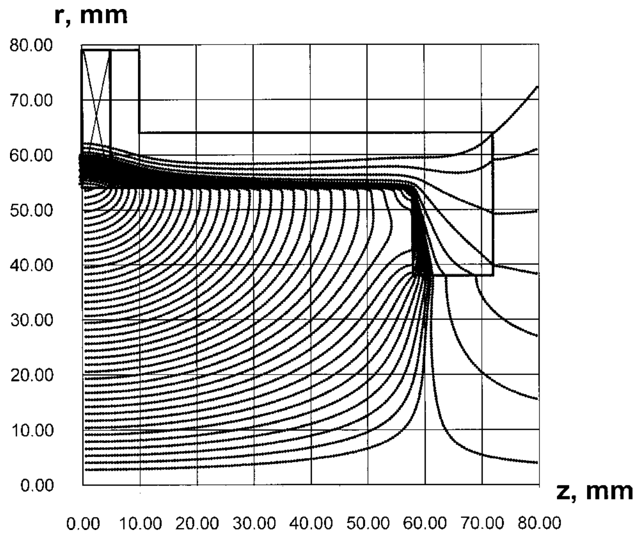

FIG. 1. Optimal magnetic field line configuration obtained by computer simulation.

ture. In addition, there is a strong dependence on the externally applied potential distribution along the lens electrodes $U_L(R,z)$ (Fig. 2). The optimum $U_L(R,z)$ needs to be empirically determined on a case-by-case basis so as to minimize the lens for spherical aberrations. The potential distribution required can be significantly different from the optimal $U_L(R,z)$ as determined by plasmaoptic theory[1] and for which $\Phi(R,z) \sim B_z(0,z)$. When the $U_L(R,z)$ distribution is empirically optimized, the PL properties remain good for a wide range of parameters of the focused ion beam (Fig. 3). The maximum beam compression at the focus is a factor of 15–25, depending on the transported I_b. The compression decreases somewhat with increasing I_b. The $J_{b\max}$ of the focused ion beam, for the case of Cu ions, was 120 mA/cm^2 for a $I_b = 700$ mA, $U_{\mathrm{acc}} = 16$ kV, and using an optimal $U_L(R,z)$. For these conditions the radial potential distribution at the midplane of the lens was as shown in Fig. 4. Also shown are the results of a computer simulation calculated for the same case. Good agreement between experiment and theory can be seen.

The experiments made at LBNL show that the lens properties are similar to those measured in the Kiev experiments. For the case when the experimental optimum $U_L(R,z)$ is used, we see a strong dependence $J_b(U_L, U_{\mathrm{acc}})$, as shown in Fig. 5. The maximum compression, for a Ta ion beam, was a factor of 5–7, with good repetition from pulse to pulse and

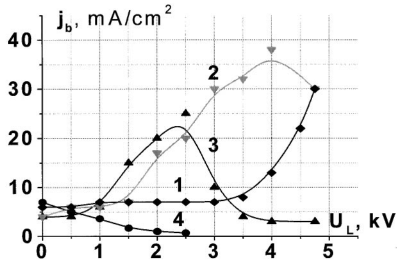

FIG. 2. Copper ion beam current density J_b as a function of lens central electrode voltage, U_L, for several different potential distributions along the lens electrodes. $U_{\mathrm{acc}} = 16$ kV, $B = 200$ G, $z = 18$ cm, $I_b = 300$ mA.

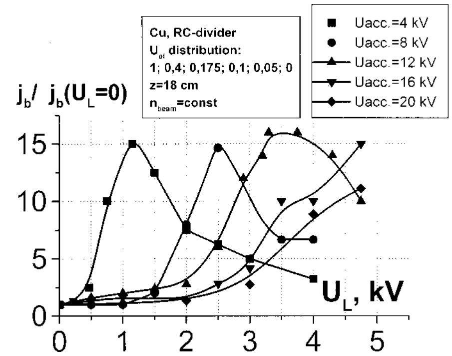

FIG. 3. Ion beam compression factor vs lens electrode voltage for various beam energies. The beam current density was kept constant throughout (optimal lens electrode potential distribution).

maximum J_b up to 14 mA/cm^2. Importantly, the $J_b(U_L, U_{\mathrm{acc}})$ variation measured here and shown in Fig. 5 is similar to that obtained previously [for the optimal $U_L(R,z)$] for the case of a magnetic field formed by a current-driven solenoid. The lens operating regime could be changed from focusing to defocusing (Figs. 6 and 7) by varying the $U_L(R,z)$ along the PL electrodes. Note that the defocusing regime follows naturally for given configuration of magnetic field lines. It can be seen in Fig. 2 how the focusing regime is destroyed by moving from a very short potential distribution to a very long potential distribution [for further discussion of the $U_L(R,z)$ see Refs. 6 and 7]. Beam focusing and defocusing is also evidenced by the radial profile of the J_b with the lens on and the lens off (see Fig. 6). One can see that in the defocusing regime the beam profile is flatter and broader.

We have investigated the focusing properties of the lens as a function of the B_0. We noted first that there is a very narrow range of B_0 for which the focusing characteristics of the PL change drastically. We found that for a $B_0 = 96$ G the focused J_b varied by more than an order of magnitude from pulse to pulse. By decreasing the B_0 to 80 G the lens operation was completely lost. The focusing characteristics of the lens became more stable with increasing B_0. We observed the same dependencies at LBNL as at Kiev. It was noted that

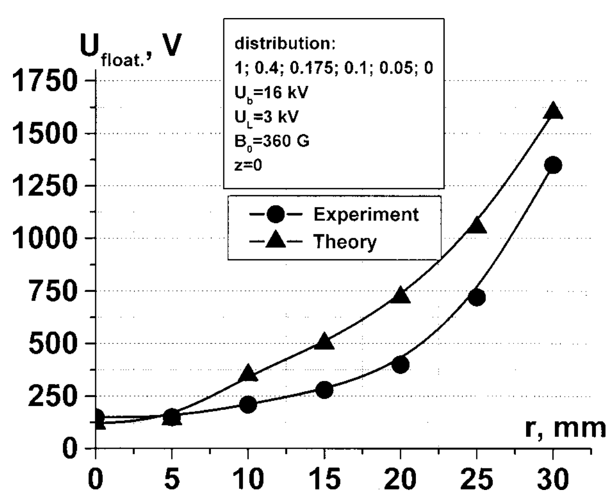

FIG. 4. Radial potential distribution at the midplane of the lens for optimal focusing conditions.

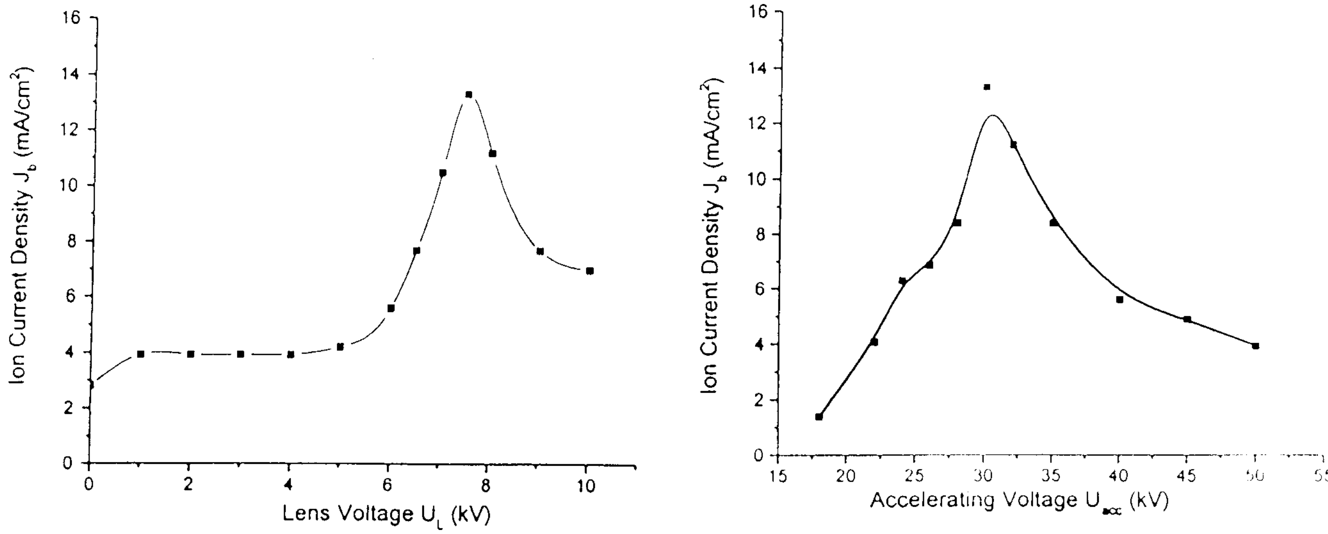

FIG. 5. Tantalum ion beam current density at the Faraday cup location vs lens voltage, for a beam extraction voltage $U_{\mathrm{acc}}=30$ kV, (upper); and vs ion source extraction voltage, for a lens voltage of 7.5 kV (lower). Optimal lens electrode potential distribution: $B_0=200$ G, $I_d=400$ A.

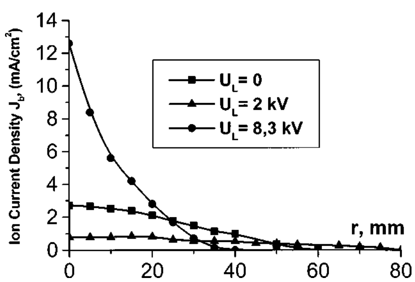

FIG. 6. Radial beam profile at the Faraday cup location: for the optimal potential distribution curve (1) $U_L=8.3$ kV, $B_0=300$ G, $U_{\mathrm{acc}}=30$ kV, $I_d=400$ A, Ta; curve (2) lens off $U_L=0$. For very long potential distribution curve (3) $U_L=2$ kV.

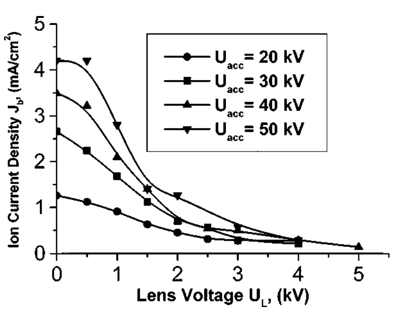

FIG. 7. Tantalum ion beam current density at the Faraday cup as a function of lens voltage for different values of ion source extraction voltage U_{acc}. Very long potential distribution: $B_0=300$ G.

in the range of favorable magnetic fields (150–200 G) there are two clear regimes in the focused I_b for a single pulse. One of these maximum occurs at the beginning of the pulse, for a $U_L \sim 5$ kV, $U_{\mathrm{acc}}=40$ kV, and $\tau \leqslant 100$ μs. The second has a maximum at approximately two times greater lens voltage.

These early results demonstrate the successful operation of a low-cost, simple, and effective PL based on the use of permanent magnets rather than of conventional current-driven coils. Such lens characteristics are similar to the characteristics of the current-driven lens, with no substantial loss of focusing properties.

ACKNOWLEDGMENTS

This work was supported by the Science and Technology Center in the Ukraine under Project No. 1596.

[1] A. Morozov, Dokl. Akad. Nauk UzSSR **163**, 1363 (1965).
[2] D. Gabor, Nature (London) **160**, 89 (1947).
[3] A. Goncharov, A. Zatuagan, and I. Protsenko, IEEE Trans. Plasma Sci. **21**, 578 (1993).
[4] A. Goncharov, A. Dobrovolsky, A. Zatuagan, and I. Protsenko, IEEE Trans. Plasma Sci. **21**, 573 (1993).
[5] A. Goncharov, I. Protsenko, G. Yushkov, and I. Brown, Appl. Phys. Lett. **75**, 911 (1999).
[6] A. Goncharov, I. Protsenko, G. Yushkov, and I. Brown, IEEE Trans. Plasma Sci. **28**, 2238 (2000).
[7] A. Goncharov, I. Protsenko, G. Yushkov, and I. Brown, Rev. Sci. Instrum. **71**, 1401 (2000).