FOCUSING OF ION BEAMS BY PERMANENT MAGNET PLASMA LENS

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1. INTRODUCTION

The electrostatic plasma lens (PL) is based on the introduction of controlled electric fields and equipotentialization of magnetic field lines within the lens volume. Moderate energy, large area, high current, heavy ion beams can be focussed in this way, as has been well demonstrated in a series of experiments carried out at Kiev and at Berkeley in recent years [1-4]. 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 focussed 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 PL 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). This work has been reported [5].

Here we describe some further investigations of the focusing properties of a simple and compact PL based on the use of small permanent magnets.

2. EXPERIMENTAL CONDITIONS AND APPROACH

Experiments were carried out at Kiev using the set-up described in detail in [1] and at Berkeley described in [4]. For ion beam creation we use a two-chamber MEVVA ion source with grid anode and three-electrode multi-aperture accel-decel ion optical 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 τ = 100 μs, beam extraction voltage $U_{acc} \le 25$ kV, total current $I_b \le 800$ mA, initial beam diameter $\varnothing$ = 5.5 cm, ion species Cu, distance d from ion source extractor to mid-plane of the PL ~ 30 cm. Berkeley – τ = 250 μs, $U_{acc} \le 50$ kV, $I_b \le 200$ mA, initial $\varnothing$ = 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 used were as follows. Kiev – input aperture D = 7.4 cm, length L = 14 cm, number of electrostatic electrodes N = 13; 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 electrode was + 4.7 kV; 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; the electrodes were fed by a 110 kΩ resistive voltage divider; $U_L \le +10$ kV, B = 300 G. The magnetic field shape required for each PL and the corresponding disposition of magnets need to establish the magnetic field were determined by computer simulation and experimental tests. The magnetic field strength B could be varied by changing the number of magnets used and also by employing iron pieces to shunt a part of the magnetic field, allowing the field strength to be changed by increments of 17 G.

Radially movable Langmuir probes were used for measurement of the plasma in the lens volume and in the beam drift space. 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 x 10^{-5} Torr, allowing formation of plasma within the PL volume by the ion beam itself and by secondary electron emission electrons from the lens electrodes.

3. RESULTS AND DISCUSSIONS

In work [5] preliminary to that described here, we investigated the cases of a copper ion beam with initial beam diameter 5.5cm (Kiev) and a tantalum ion beam with initial diameter 6cm (Berkeley). Note that the input aperture of the Berkeley PL was 10cm. Here we describe some experimental results obtained for large area ion beams with initial diameter 10cm.

The experiments show that for a large area ion beam with initial beam diameter equal to the input aperture of the PL, the focusing properties are more distinct. The maximum compression for the 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. At the same time for the case of tantalum beam with diameter 10 cm, the maximum beam compression at the PL focus was approximately a factor of 20, with and current density up to 32 mA/cm^2. Note that 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 (see [5] for details). Note also that similar results were observed when beams of this type were focussed using a PL with conventional current-driven coils [4].

The experimental results depend on the particular externally-applied potential distribution along the lens electrodes. The optimal distribution minimizes lens spherical aberrations, as established empirically for a PL

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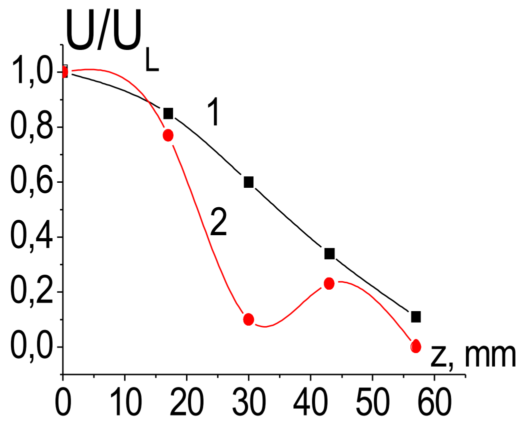


Fig. 1. The optimal PL electrode potential distribution.
1-theoretical U(R,z)~B(0,z); 2-experimental

with an input aperture of 10 cm, and as shown in Fig. 1 (curve 2). One can see that this distribution differs significantly from the theoretical optimum distribution obtained by plasma optic 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 optimal distribution. Fig.3 show that the radial profile of the focused Bi ion beam depends on the PL operation, for case of electrode potential distribution corresponding to Fig. 1 (2). Note that 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 45mA/cm^2.

These results and experimental conditions were used for computer simulation of the processes of formation of the plasma medium within the electrostatic high current PL. One can see some of these results in Figs. 4 to 6. Analysis of these data show the formation within the PL volume of layered electron structures (Fig. 4) owing to finite width of the ring lens electrodes. This means that the presence of spherical aberrations restricted the maximum compression of the focussed ion beam. This is confirmed by Fig. 6, which models ion beam focusing for the experimental conditions presented here. The maximum compression obtained by computer simulation is in the range 35-150x. This value depends markedly on the collector radius, the lens potential distribution, and the width of the ring electrodes, in good accordance with experimental results.

4. CONCLUDING REMARKS

The experimental results and the computer simulation results described here both indicate good prospects for the use of the permanent-magnet electrostatic plasma lens for manipulating 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 the PL based on

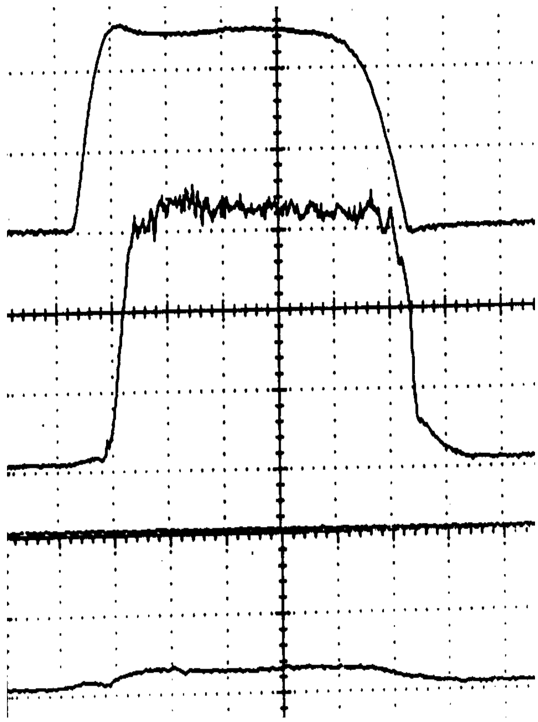


Fig.2. Oscillograms of bismuth beam current measured by an on-axis Faraday cup, for the case of maximum compression and the experimental optimal PL potential distribution. Beam accelerating voltage U_{acc} = 34kV, U_L=7.7kV, B=300G. Upper trace – ion source arc current (200A/cm); middle trace – ion beam current density for cases PL on; lower trace - PL-off. Vertical scale: 14mA/cm^2 per cm. Horizontal scale: 50μs/cm.

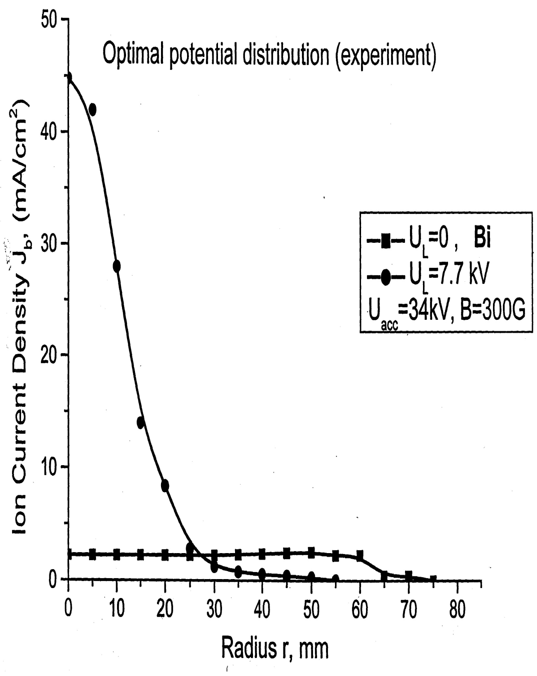
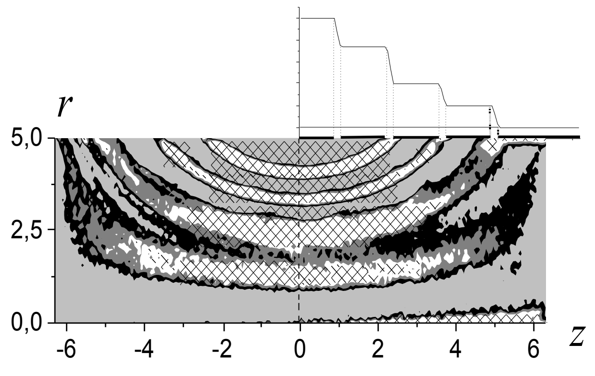
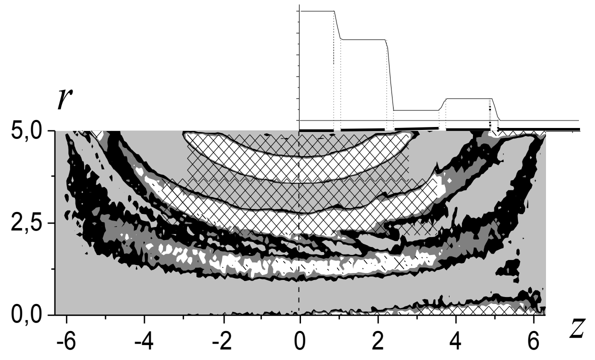


Fig. 3. Radial ion beam current density profile at the Faraday cup location.

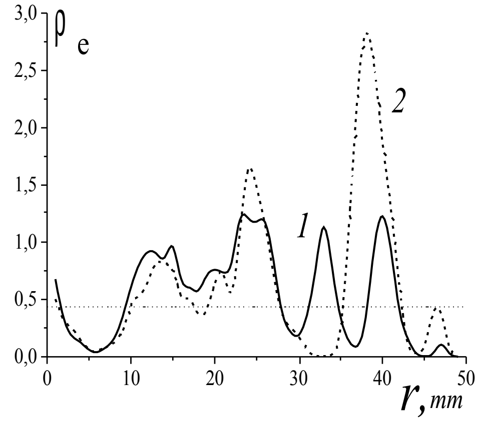


a



b

Fig. 4. Electron space charge distribution in the PL 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.*



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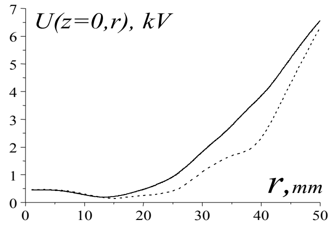

b

Fig.5. Radial distribution of (a) electron space charge, and (b) potential, at the lens mid-plane. Solid lines - for the case of Fig. 4(a); dotted lines - for the case of Fig. 4(b). Horizontal line in (a) - ion space charge background

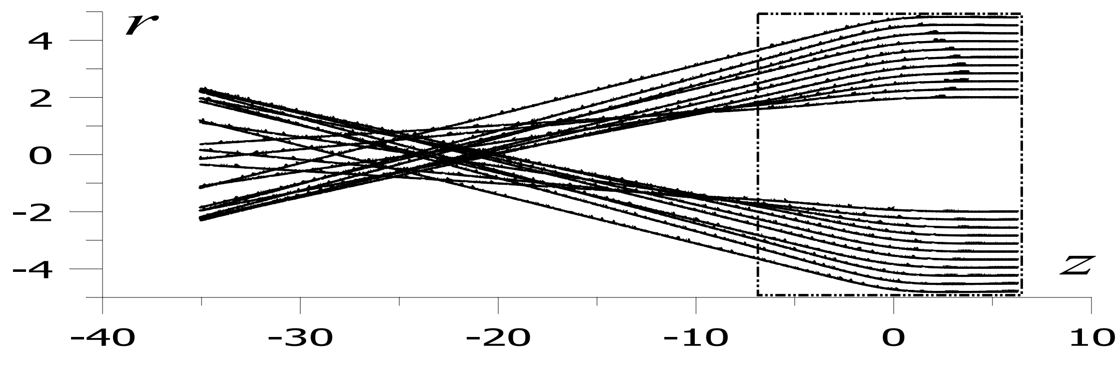

Fig. 6. Ion beam particle trajectories for the case of Fig. 4(a)

the use of permanent magnets rather than of conventional current-driven coils. At this stage of the investigations, this plasma-optical device could be used, for example, in particle accelerator beam lines and for high dose ion implantation. Further experimental and theoretical efforts are needed on forming an optimized PL without spherical aberrations, in part by optimization of the magnetic field configuration in the low magnetic field range.

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