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Effect of the electrostatic plasma lens on the emittance of a high-current heavy ion beam

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Abstract

We describe measurements we have made of the emittance of a high-current, moderate-energy ion beam after transport through a permanent-magnet electrostatic plasma lens. The results indicate the absence of emittance growth due to the lens, when the lens is adjusted for optimal beam focusing. The measured emittance for a 16 keV Cu^{2+} ion beam formed by a vacuum arc ion source was about 0.4 π·mm·mrad at a beam current of 50 mA rising more-or-less linearly to 1.5 π·mm·mrad at 250 mA, and was conserved in beam transport through the lens. These results have significance for the application of high-current ion sources and the electrostatic plasma lens to particle accelerator injection

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Ion source and ion beam technologies have matured greatly in recent years, and heavy ion beams can now be formed relatively straightforwardly at beam current levels orders of magnitude greater than was possible just a decade or two ago. At the same time, there is a great need in modern accelerator technology for techniques for injecting high current ion beams into the low energy beam lines (LEBTs) of particle accelerators. There is a bottleneck in the application of the new high current ion sources for particle accelerator injection, in that low energy (<100 keV), high current (~10–1000 mA) ion beams, frequently of high mass ion species (e.g., titanium, uranium), are subject to severe space-charge blowup and consequent beam loss whenever the beam is passed through any of the traditional beam focusing or steering devices, because of the loss of space-charge neutralization of the beam within these beam manipulation devices. Thus there is a need for new high current ion beam manipulation devices that preserve space-charge neutralization, thereby providing a tool that can allow the high current beams to be presented to accelerator LEBTs and transported through them without severe beam loss. One such device is the electrostatic plasma lens [1-5]. The electrostatic plasma lens is an axially-symmetric plasma-optics system consisting of a set of cylindrical ring electrodes located within an externally-driven magnetic field, with field lines connecting ring electrode pairs symmetrically about the lens midplane. The basic concept of this kind of lens was first described by Morozov and coworkers [6,7], and is based on the use of magnetically insulated cold electrons to provide space-charge neutralization of the focused ion beam and maintain the magnetic field lines at equi-potentials. This is a generalization of the ideas of Gabor for employing magnetized electron clouds for ion beam focusing [8]. Electrons within the lens volume, formed for example by secondary emission following collision of beam ions with lens electrodes, are able to stream freely along the field lines, thereby tying the potential to that of the electrostatic ring electrode to which the field line is attached. Electrostatic plasma lenses have been investigated for half a century; the status of experimental investigation has been summarized in references [1-5].

Although the electrostatic plasma lens has the important characteristic of being able to focus high current ion beams without severe space-charge disruption, a critical remaining uncertainty is the possibility of sizeable emittance growth of the ion beam due to the influence of the lens. This concern has been an impediment to the application of plasma lenses for particle accelerator injection. There is a need for experimental information on the influence of the high current electrostatic plasma lens on the beam emittance as the beam passes through and is focused by the lens. We have carried out some experimental measurements of the emittance of high current ion beams that are transported through an electrostatic plasma lens. Here we report on our preliminary findings.

The ion source used for the experiments was a vacuum arc ion source [9] with a grid anode and a three-electrode, multi-aperture, accel-decel ion extraction system. The source operates in a repetitively-pulsed mode and produces moderate energy, low-divergence, broad, heavy metal ion beams with principal parameters, in the work described here: beam pulse duration $\tau = 100\ \mu s$, pulse repetition rate 0.5 pulses per second, beam extraction voltage $V_{ext} \leq 20$ kV, beam current $I_b \leq 500$ mA, initial beam diameter = 5.5 cm, ion species Cu. Copper plasma formed by a vacuum arc discharge has an ion charge state spectrum that is 16% Cu^{+}, 63% Cu^{2+}, 20% Cu^{3+}, and 1% Cu^{4+} [5], for a mean charge state of about 2.0+; thus we take the beam to be Cu^{2+} ions.

The parameters of the electrostatic plasma used lens were: input aperture D = 7.4 cm, length L = 14 cm, number of electrostatic electrodes N = 13. The potential applied to the central lens electrode was up to +5.5 kV. The lens magnetic field was formed by permanent magnets, and at the center of the lens B = 12.6 mT. The magnetic field configuration was determined by numerical calculations to minimize magnetic field gradients. According to theoretical considerations such a configuration suppresses plasma noise within the lens volume and removes spherical aberrations. The vacuum chamber pressure was $\sim 2 \times 10^{-5}$ Torr, allowing plasma formation within the lens volume by the ion beam itself by secondary electron emission from the lens electrodes. The focusing properties of this lens have been reported [10,11].

We used the "pepper pot" technique [12,13] for measurement of beam emittance. This method is based on photographically recording images of the beam cross-section after it is passed through a screen containing a regular array of identical small holes. In our setup, the multiple sampled beamlets thus defined fall on a luminescent screen, forming an array of images of the beam size which is then photographically recorded by a camera. A 20 μm aluminum foil was used as selection screen (array of small holes) and the hole diameter was about 100 μm. Such a relationship was chosen to minimize scattering and collimation of the beamlets. The diameter of the screen was 10 cm over which the holes were arranged on a grid of 5 mm. The central plane of the plasma lens was equidistant from the ion source and screen. The distance from the selection screen to the luminescent glass plate was chosen to be sufficiently small (3.5 cm) so as to minimize space-charge expansion of the beamlets [12]. To investigate the possible influence of beamlet space-charge and also of surface charge of the luminescent screen, we covered one-half of the screen by a thin tungsten grid with a transparency of 80%. A Konica Color Centuria Super 1600 camera with negative film was used to photograph the pepper-pot emittance patterns. These images were digitized with a scanner of resolution 600 dpi and then numerically processed. All of the images (emittance patterns) investigated were obtained in a single exposure of a single beam pulse. A simplified scheme of the experimental setup is shown in Figure 1.

The pepper-pot emittance patterns obtained for various lens electrodes voltages (focal lengths of the lens) are shown in Figure 2. The dimensions of the images formed by the beamlets allow us to determine the magnitude of the transverse velocity spread at the corresponding point of the beam cross section. It can be seen from the figure that the highest compression occurs at $V_L \approx 3.5$ kV. Further, the pronounced azimuthal symmetry of the images indicates that the arrangement of the grid in front of the luminescent screen does not influence the spreading of sampled beamlets;

this in turn implies that both the space charge of the beamlets and the surface charge on the luminescent screen are sufficiently small that they can be neglected for the emittance measurements.

To match the degree of exposure ("darkness") of a beamlet with the ion beam current density, the darkening profile of the axial beamlets was used. This profile was approximated by a Gaussian curve, and the total current of a beamlet was calculated (expressed in units of darkness density). The beamlet current through each hole in the selection screen is known, and we set this current to be proportional to that calculated from the Gaussian curve. Thus we assume the darkness density to be proportional to the incident ion current density. This is a valid approximation since the current density incident on the phosphor screen is sufficiently low (~20 $\mu A/cm^2$) and the film darkness density created during exposure does not exceed 10% of the maximum possible. As a confirmation of this approach, we note that the proportionality coefficients calculated for various pepper-pot emittance patterns were only slightly different from each other.

Emittance plots calculated from pepper-pot data for the cases of lens-on and lens-off are shown in Figure 3. These phase space contour plots were calculated using the pepper-pot emittance patterns shown in Fig. 2(a) and 2(f). In Fig. 2, the highest possible contrast is shown. A number of different phase space contours are shown in Fig. 3, each corresponding to a different ion beam current. It can be seen from Fig. 3(b) that the central part of the beam is almost completely focused and the ion trajectories at the periphery are distorted by spherical aberration.

From the data of Figure 3 we can derive the dependence of normalized emittance on beam current; see Figure 4. From this dependence we can conclude that, under optimal beam focusing conditions, the normalized emittance for was about 0.4 π·mm·mrad at a beam current of 50 mA rising more-or-less linearly to 1.5 π·mm·mrad at 250 mA, and was conserved in beam transport through the lens. Note however that in the focusing regime with considerable dynamic aberrations (Fig. 2(e)), almost complete loss of periodic structure on the pepper-pot emittance pattern is observed, indicating that the emittance increases by a substantial factor under these conditions.

The results of our investigations show that the emittance of a high current ion beam (up to 250 mA of Cu^{2+} ions at 16 keV) is not changed in transport of the beam through the electrostatic plasma lens, for the case when the lens is optimally focused. This result has potentially important implications for the application of the high current electrostatic plasma lens as a tool that could allow the use of modern high current ion sources on particle accelerator injection beam lines without severe beam loss. Moreover, we have demonstrated that the high current electrostatic plasma provides an ion beam tool for high current beam focusing without beam space-charge blowup and without an associated beam emittance growth.

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References

1. A. Goncharov, A. Dobrovolsky, A. Zatuagan, and I. Protsenko, IEEE Trans. Plasma Sci. **21**, 573 (1993).
2. A. Goncharov, Rev. Sci. Instrum. 69, 1150 (1998).
3. A. Goncharov, I. Protsenko, G. Yushkov, and I. Brown, Appl. Phys. Lett. **75**, 911 (1999).
4. A. Goncharov, I. Protsenko, G. Yushkov, and I. Brown, IEEE Trans. Plasma Sci. **28**, 2238 (2000).
5. A. A. Goncharov and I. G. Brown, IEEE Trans. Plasma Sci. **32**, 80 (2004).
6. A. Morozov, Dokl. Acad. Nauk USSR 163, 1363 (1965).
7. A. Morozov and S. Lebedev, in *Reviews of Plasma Physics*, edited by M. Leontovich, (Consultants Bureau, New York, 1975).
8. D. Gabor, Nature 160, 89 (1947).
9. I. G. Brown, Rev. Sci. Instr. **65**, 3061 (1994).
10. Yu. Chekh, A. Goncharov, and I. Protsenko, *Proc. Int. Conf. Physics of Low Temperature Plasma,* Kyiv (2003).
11. Yu. Chekh, A. Goncharov, and I. Protsenko, Rev. Sci. Instr. **75**, 1668 (2004).
12. C. Lejeune and J. Aubert, *Emittance and Brightness: Definitions and Measurement,* in: *Applied Charged Particle Optics*, edited by A. Septier, **13A**, 159 (1980).
13. I. G. Brown, J. E. Galvin, R. Keller, P. Spädtke, R. W. Müller and J. Bolle, Nucl. Instr. Meth. Phys. Res. A **245**, 217 (1986).

Figure Captions

Fig. 1. Simplified schematic of the experimental setup.

1 - vacuum chamber, 2 - ion source, 3 – ion beam extraction system, 4 - plasma lens, 5 - ion beam, 6 - pepper-pot selection screen, 7 - luminescent screen, 8 - window, 9- camera.

Fig. 2. Pepper-pot emittance patterns for various lens central electrode voltages V_L.

V_L = (a) 0, (b) 1kV, (c) 2kV, (d) 2.5kV, (e) 3kV, (f) 3.5kV, (g) 4 kV, (h) 5kV.

Fig. 3. Phase space contours corresponding to various beam currents.

(a) $V_L = 0$, (b) $V_L = 3.5$ kV.

Fig. 4. Dependences of emittance on ion beam current, with the lens turned off and on.

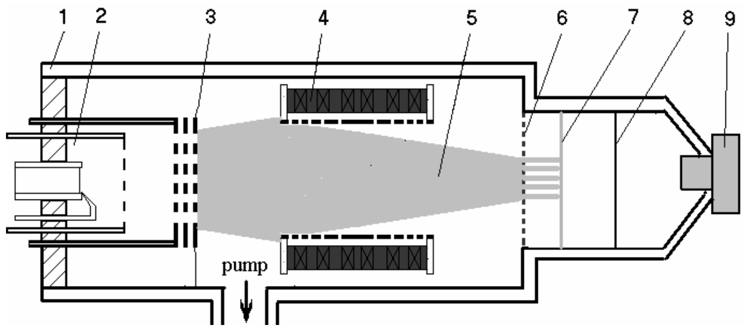

Fig. 1

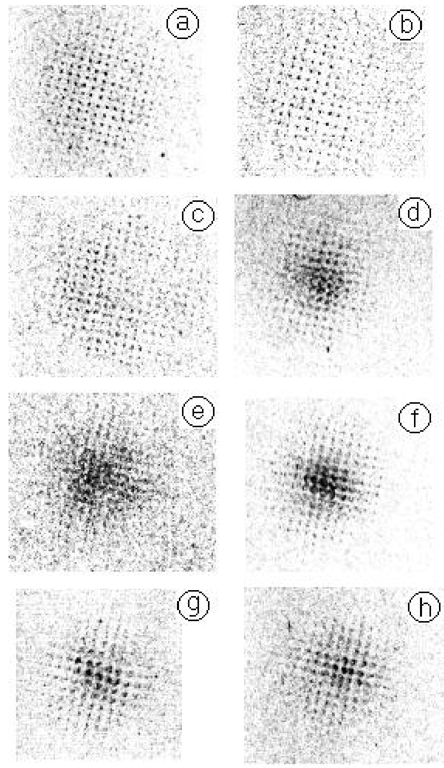

Fig. 2

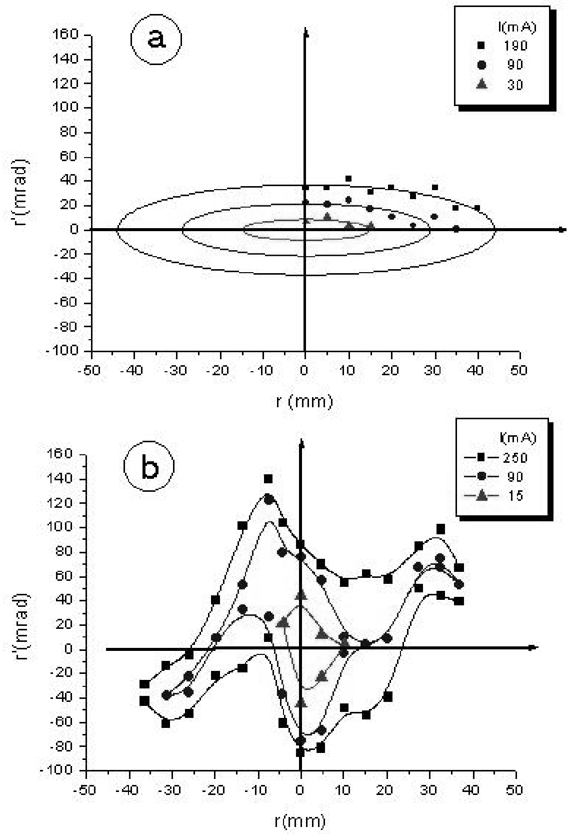

Fig. 3

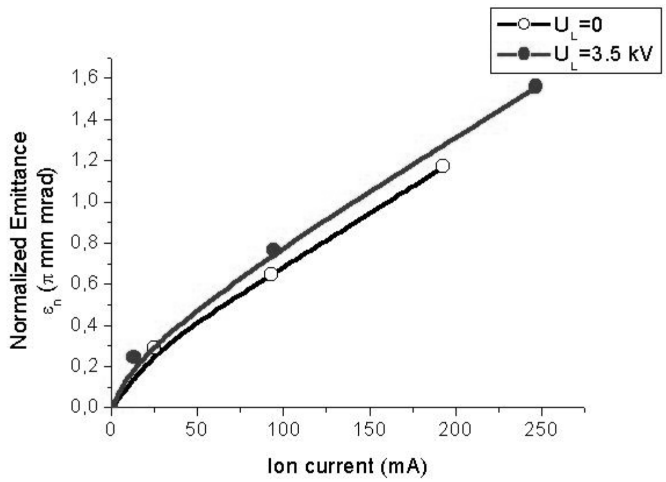
U_L=0
U_L=3.5 kV
Normalized Emittance
ε_n (π mm mrad)
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0
50
100
150
200
250
Ion current (mA)

Fig. 4