Focusing Properties of the Electrostatic Plasma Lens with Minimized Magnetic Field Gradients

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Abstract – We describe the results of investigations of the suitability of the electrostatic plasma lens with minimized magnetic field gradients as a focusing element in the low energy injection beam lines of particle accelerators. We investigate the focusing of high-current wide-aperture heavy ion beam. It is shown that under optimal conditions the lens does not increase the emittance or the (fractional) beam noise, and allows increasing the ion current density by a factor of 30 (up to 250 mA/cm^2). It is shown also that the lens can provide ion current density up to 400 mA/cm^2 or more if an appropriate ion source extraction system is used.

1. Introduction

There is a need in modern accelerator technology for new approaches to injecting high current ion beams into the low energy beam lines of particle accelerators. Even though ion source technologies have developed greatly in recent years, and heavy ion beams can be formed relatively straightforwardly with current much greater than was possible just a decade or two ago, there is a problem in the accelerator application of the new high current ion sources 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 when not fully space-charge-compensated. There is a substantial 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 optical elements. Thus new high current ion beam manipulation devices are needed that preserve space-charge neutralization, to provide a tool that can allow the high current beams to be presented to accelerator injector beam lines 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-optical 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 [1], 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 equipotentials. 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 in recent years especially at the Institute of Physics, Ukraine Academy of Sciences (IP NASU), Kyiv, and this work has been reported in the literature, including some collaborative work with the Lawrence Berkeley National Laboratory (LBNL) [5-8]. The experimental results indicate the suitability of the lens for applications that call for focusing of wide-aperture high-current moderate energy heavy metal ion beams such as can be formed by vacuum arc ion sources.

The results suggest the novel possibility of using this kind of lens on the low energy injection beam lines (LEBTs) in heavy ion linear accelerators, for example between the ion source and an RFQ pre-accelerator system. At the same time, a concern that could limit the application of the plasma lens for this purpose is connected with the possible negative influence of the lens on the emittance of the focused ion beam due to inherent lens noise and aberrations. We have shown previously [7] that there is a very narrow range of low magnetic field for which the optical properties of the lens improve significantly. This, in turn, allows the possibility for a new kind of compact lens based on the use of permanent magnets as opposed to current-driven magnets. As well as for the lenses with current driven coils, for plasma lens with minimized magnetic field gradients using permanent magnets, we have found experimental conditions for which the inherent plasma lens noise is reduced to a very low level and for which good beam compression is observed [9]. Under these conditions the emittance of a broad-area ion beam passing through the lens was measured [10], with the results indicating, in particular, that there are optimal conditions of lens operation for which the emittance is preserved on beam transport through the lens, for a copper ion beam current as high as 250 mA.

Here we summarize experimental investigations of the focusing properties of the plasma lens with minimized magnetic field gradients in the range of low magnetic fields.

2. Experimental devices and approach

The experimental setup is shown in Fig. 1. A two-chamber ion source of the MEVVA [11] type with a grid anode and a three-electrode, multi-aperture, accel-decel extraction system was used for obtaining a wide-aperture ion beam. The beam duration was 100 μs (1 pulse per 2 seconds), extraction voltage U_{ext} 16 kV, total current I_b up to 0.5 A (Cu), and initial beam diamter ∅ 6 cm. 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+} [11] (mean charge state about 2+). We optimized the ion source output by varying its operating parameters so as to obtain maximum total ion beam current with minimum beam divergence and hence also minimum emittance. Residual pressure was below $1.5 \cdot 10^{-5}$Torr.

In the PL, a 13-electrode system with 74 mm input aperture diameter and 16 cm length was used (Fig. 2). A maximum voltage U_L up to 5.5 kV (dc or pulsed) was applied to the central electrode. 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 minimizes spherical aberrations. In Fig. 3 one can see that magnetic field is practically uniform, the range of the uniformity in the axial direction was extended also.

For dc power feeding the electrode system, a preliminary plasma medium was formed by a low-pressure glow discharge, aiding formation of a more stable and more uniform electron column [12].

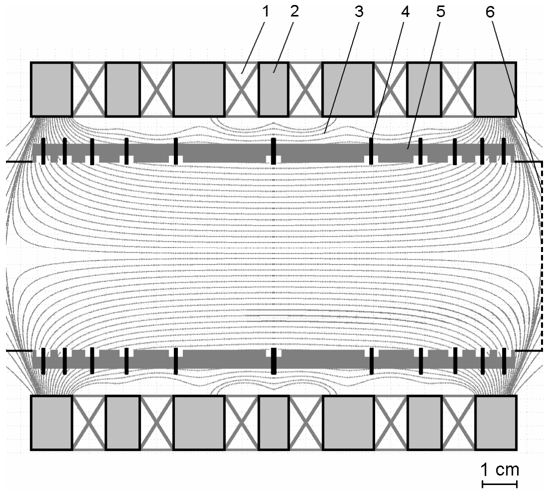

Fig. 2. Plasma lens
1 - permanent magnets; 2 - magnetic conductor; 3 - magnetic field lines; 4 - electrodes; 5 - interelectrode insulating spacers; 6 - metal grid.

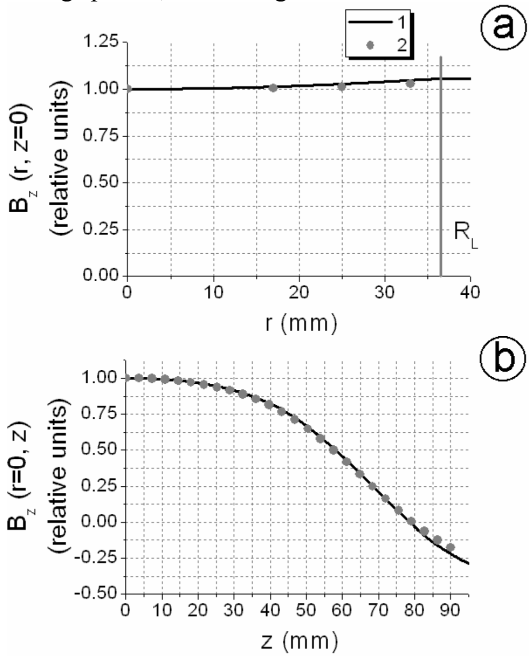

Fig. 3. Radial and axial distribution of magnetic field induction in the PL; 1 – calculated distribution, 2 – measured distribution.

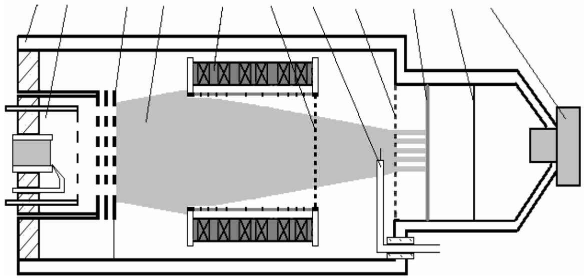

Fig. 1. Schematic of experimental setup; 1 - vacuum chamber, 2 - ion source, 3 - ion beam extraction system, 4 - ion beam, 5 - plasma lens, 6 - grid, 7 - Langmuir probe, 8 - pepper pot selection screen, 9 - luminescent screen, 10 - window, 11 – camera.

In the work described here (except for emittance measurements), we used a modified lens electrode system consisting of thin metal rings with interelectrode insulating spacers so as to increase the axial uniformity of the lens potential distribution, and a metal grid with 80% transparency at the lens exit to enhance the space charge compensation of the ion beam.

We used the "pepper pot" technique [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. All of the images were obtained in a single exposure of a single beam pulse. The technique was described in more details in [10].

A Langmuir probe was used to measure the ion beam density distribution. The probe tip was molybdenum wire 4.5 mm long and 0.3 mm diameter. We assume the ion beam current that is incident on the probe to be a part of the current that would be accepted by a circular collector of diameter 4.5 mm = $2r_c$.

In characterization of plasma lens optical characteristics, a compression factor K_j is often used; this parameter is the ratio of ion beam density with the lens turned on and off. The current efficiency E_c [14] is another parameter used to quantify the lens efficiency as an optical element; current efficiency is the fraction of the total beam current that reaches the collector. This parameter is measured during a single beam pulse and therefore is independent of the ion beam divergence and electron emission from the collector.

3. Results and discussion

An important advantage of the electrode system used here is the suppression of "focusing disruptions", observed in the range of small magnetic fields [9]. In the optimal regimes the lens does not significantly degrade the beam emittance (Fig. 4). The large initial emittance of the ion beam generated by the multi-aperture vacuum-arc source is determined by the ion source extraction system [15]. An effective temperature corresponding to the measured initial emittance can be calculated as T_i (eV) $\approx \varepsilon_n^2 m_i c^2/(2R_L^2)$, where ε_n is the normalized emittance, m_i is the ion mass, c is the velocity of light, R_L - radius of the lens. In this way we obtain $T_i > 110$ eV.

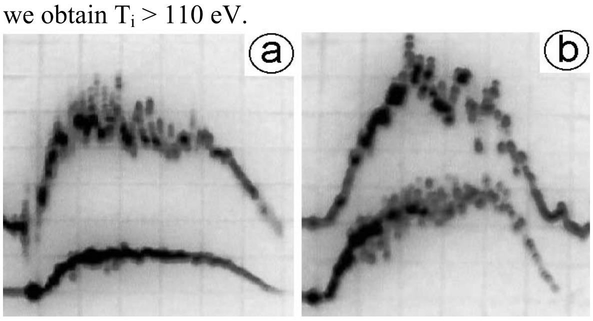

Fig. 6. Oscillograms of ion beam current density j and total ion beam current I_b; upper oscillograms is j, lower oscillograms is I_b; sweep speed 20 µs/div; a) U_L=0 (j – 2.5 mA/cm^2 /div), b) U_L = 4,7 kV (j – 62 mA/cm^2 /div); for both cases vertical scan for I_b is 0.2 A/div

The observed large emittance restricts the maximum ion current density that can be obtained at the focus. From [14], the maximum current efficiency depends on the focal length as

$$E_c = 1 - (1 - \beta) \exp[-\beta\Phi/(1 - \beta)], \qquad (1)$$

where $\beta = r_c^2/(R_L^2 + F^2)$, $\Phi = W_b/T_i$, r_c is the collector radius, $W_b = ZeV_{ext}$ is the ion beam energy, Z is the ion charge state (we take Z = 2), e is the electron charge, and F is the lens focal length. This relationship is a generalization of Langmuir's formula for maximum current density [14]. The best agreement between the experimental results and Eq. (1) is obtained for T_i = 140 eV (Fig. 5).

x

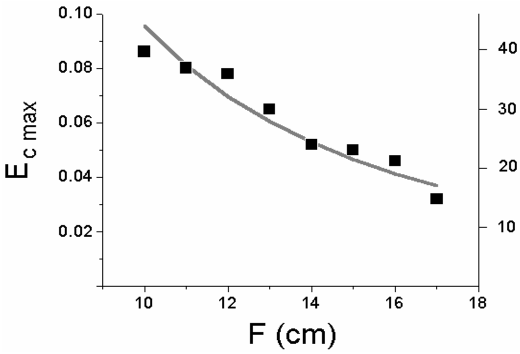

Fig. 5. Dependencies of current efficiency E_c and compression factor K_j on focal length (current density 120–300 mA/cm^2); dots correspond to the measured values, curve corresponds to Eq. (1) for T_i = 140 eV

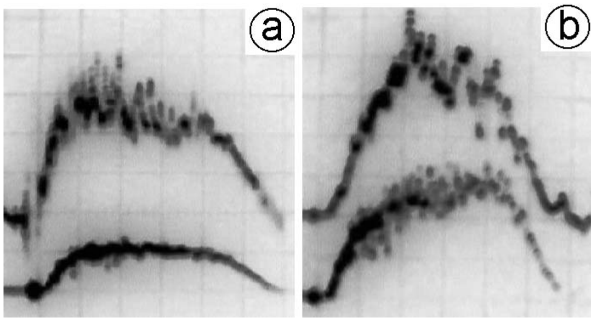

Fig. 6. Oscillograms of ion beam current density j and total ion beam current I_b; upper oscillograms is j, lower oscillograms is I_b; sweep speed 20 µs/div; a) U_L=0 (j – 2.5 mA/cm^2 /div), b) U_L = 4,7 kV (j – 62 mA/cm^2 /div); for both cases vertical scan for I_b is 0.2 A/div

Thus we obtain nearly the same values of effective transverse ion temperature from emittance measurements and from measurements of the maximum current efficiency as a function of focal length. This is evidence that the maximum ion current density is restricted by the initial emittance of the beam.

In Fig. 6 one can see that the relative level of current density noise modulation (fractional beam noise) at the focus is not increased significantly. The corresponding radial distribution of ion beam current density is shown in Fig. 7. Periodically we observed a very high beam current density of up to 400 mA/cm^2 (Fig. 8), probably due to accidental flattening of the plasma boundaries in the ion source extraction system.

These results open up, in part, the novel possibility of using these kinds of lenses for application in linear accelerators of heavy ion beams in the LEBT between ion source and RFQ system.

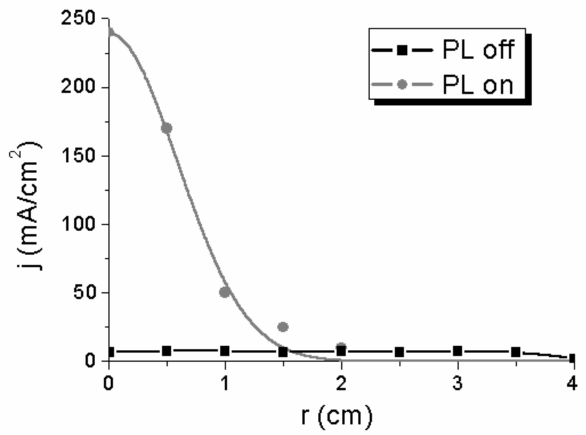

Fig. 7. Radial distributions of ion beam current density corresponding to the conditions described in the caption to Fig. 6.

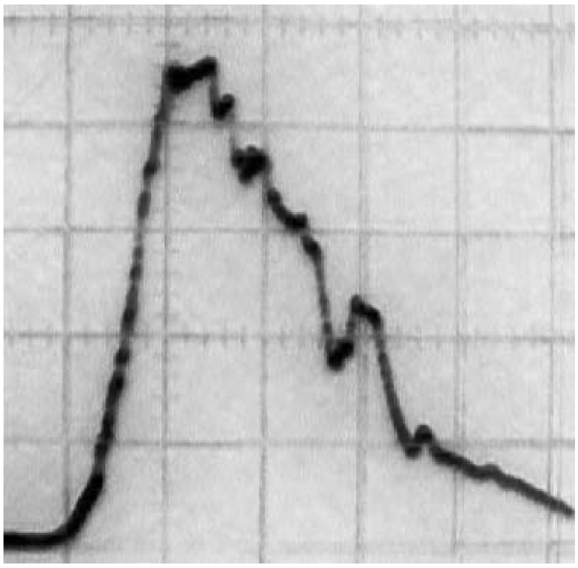

Fig. 8. Oscillogram of ion current density at the beam focus for maximum compression, high frequency noise being removed; vertical scan 86 mA/cm^2/div; sweep speed 20 μs/div.

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