INFLUENCE OF THE ELECTROSTATIC PLASMA LENS ON THE EMITTANCE OF A HIGH CURRENT HEAVY ION BEAM

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We describe results of experimental emittance investigations of a high-current heavy metal ion beam focused by an electrostatic plasma lens. A pulsed beam of Cu ions with energy 16 keV, duration 100 µs, and total current up to 500mA was produced by a MEVVA type ion source. A “pepper-pot” technique was used to measure the emittance of the beam. We find that, under conditions appropriate for optimal beam focusing, the emittance corresponding to a current of 250 mA is 1.6 π·mm·mrad and is conserved in beam transport through the lens.
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1. INTRODUCTION

Plasma ion sources and ion beam technologies have matured greatly in recent years and wide-aperture, high-current, moderate-energy, heavy ion beams can now be formed relatively straightforwardly, but their use has been limited by the inability to control or manipulate them [1]. There is thus a need for an alternative to traditional vacuum beam-focusing tools for the case of high-current beams, particularly for moderate energy (10-100 keV) heavy ion beams when space-charge forces are large. The axially-symmetric electrostatic plasma lens (PL) based on the principle of magnetically insulated electrons and equipotentialization of magnetic field lines provides an attractive and unique tool for this application. This has been successfully demonstrated in a number of experiments carried out between the IP NAS of Ukraine, Kiev and the LBNL, Berkeley, USA [2]. In these experiments we have found a very narrow range of low magnetic fields for which the optical properties of the PL improve markedly. Under these conditions, the plasma noise within the lens volume is drastically reduced, and extreme beam compression can be obtained. This opens up the attractive possibility of a new generation of compact, low-cost lenses that are based on the use of permanent magnets rather than conventional current-driven field coils. Such improved lenses, having low noise and minimal spherical aberrations, could be superbly suited for use in the injection beam lines of high current heavy ion particle accelerators, where there exists a severe concern of beam space-charge blow-up. There remains, however, one very important factor that could possibly restrict the use of the PL for accelerator applications, namely the emittance of the ion beam after passage through the lens. Here we describe the results of experimental measurements of the influence of the electrostatic PL on the emittance of a high current metal ion beam.

2. EXPERIMENTAL SETUP

We use for ion beam generation a two-chamber vacuum arc MEVVA ion source 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 primary parameters as follows: beam duration τ = 100 µs, beam extraction voltage $U_{acc} \leq 20$ kV, total current $I_b \leq 500$ mA, initial beam diameter ∅ = 5.5 cm, ion species Cu, pulse repetition rate 0.5 Hz.

The parameters of the lens are as follows: input aperture D = 7.4 cm, length L = 14 cm. The highest pulsed potential applied to the central lens electrode is +5.5 kV. The magnetic field within the lens is formed by permanent magnets. The configuration of the field was determined by numerical calculations to minimize axial and radial magnetic field gradients. The magnetic induction at the center of the lens is B = 12.6 mT. According to theoretical considerations such a configuration suppresses plasma noise within the lens volume and removes spherical aberrations. The pressure in the vacuum chamber is less than 2 Ч 10^{-5} Torr. Electrons within the lens volume are generated due to secondary electron emission from the lens electrodes. The main focusing properties of this lens have been reported [3,4]. In these preliminary experiments we have found experimental conditions for which the optical properties of the lens improve drastically. The inherent plasma lens noise disappears, and at the same time good compression of the beam at the focus is observed. Measurement of the emittance of the ion beam passing through the lens were carried out under these conditions.

Peculiarities of plasma formation in a MEVVA type ion source together with the use of a repetitively-pulsed operating mode significantly restrict the techniques that can be used to measure phase characteristics of the beam. In particular, we found that the distribution of ion transverse velocities has to be measured simultaneously throughout the beam cross section. One of the methods satisfying this condition is the “pepper-pot" method (see e.g. [5]). This method is based on photographically recording the beam passed through a screen containing a regular array of identical small holes over its whole surface. The sample beamlets thus defined fall on a luminescent screen. Then the obtained image of pepper-pot emittance pattern is recorded by means of a camera.A simplified scheme of the experimental setup is shown in Fig.1.

An aluminum foil with a thickness of 20 µm was used as selection screen and the hole diameter was about 100 µm. Such a relationship was chosen to minimize scattering and collimation of the beamlets. The holes were arranged on a grid of 5 mm. The diameter of the screen was 10 cm. The central plane of the PL was equidistant from the ion source and screen.

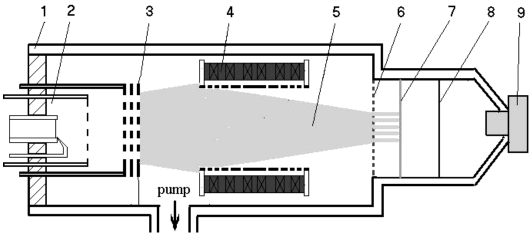

Fig. 1. Schematic of the experimental setup:
1 - vacuum chamber, 2 - ion source, 3 - ion-optical system, 4 - plasma lens, 5 - ion beam, 6 - selection screen, 7 - luminescent screen, 8 - window, 9- photo camera

The distance from the selection screen to the luminescent screen was chosen sufficiently small (3.5 cm) to exclude space charge expansion of the beamlets [5]. To investigate the possible influence of beamlet space charge and the surface charge of the luminescent screen we covered one-half of the screen by a thin tungsten grid with a transparency of 80%.

A negative film Konica Color Centuria Super 1600 was used to photograph the pepper-pot emittance patterns. Negatives were digitized with a scanner of resolution 600 dpi and then treated numerically. It should be noted that all the images were obtained in a single exposure.

All represented measurements were carried out for Cu ion beam. The experiments with Pb, Ti, C, and Al ion beams were carried out also, but Pb and Ti ions do not give rise to luminescence which is sufficient for measurements, C ions foul the screen, and Al ions damage the luminophor too quickly due its strong chemical activity.

3. RESULTS AND DISCUSSION

It is known that the two-dimensional transverse phase volume of a compensated beam expanding only due to thermal velocities has an elliptical shape. A perfect focusing system changes the orientation of the ellipse on the phase plane but does not change its area (i.e. emittance). When a moderate-energy heavy ion beam is focused by the PL, the strong influence on the phase characteristics of the beam can cause spherical and dynamic aberrations.

The pepper-pot emittance patterns obtained for various voltages supplied to the lens electrodes are shown in Fig. 2. The dimensions of the traces formed by sample beamlets allow us to determine the magnitude of the transverse velocity spread at the corresponding point of the beam cross section. Using the distance between traces we can define whether the beam is divergent or convergent. It can be seen that the PL has practically no influence on the beam parameters and that the highest compression is observed at $U_L \approx +3.5$ kV. In addition, 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 sample beamlets. This implies that both the space charge of the beamlets and the surface charge on the luminescent screen are sufficiently small and can be neglected for the emittance measurements.

To match the degree of exposure ("darkness") 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 the beamlet was calculated (expressed in units of darkness density). The current coming 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 luminophor is sufficiently low (~20 $\mu A/cm^2$) and the film darkness density created during exposure does not exceed 10% of the maximum possible. In addition, the proportionality coefficients calculated for various pepper-pot emittance patterns are only slightly different from each other.

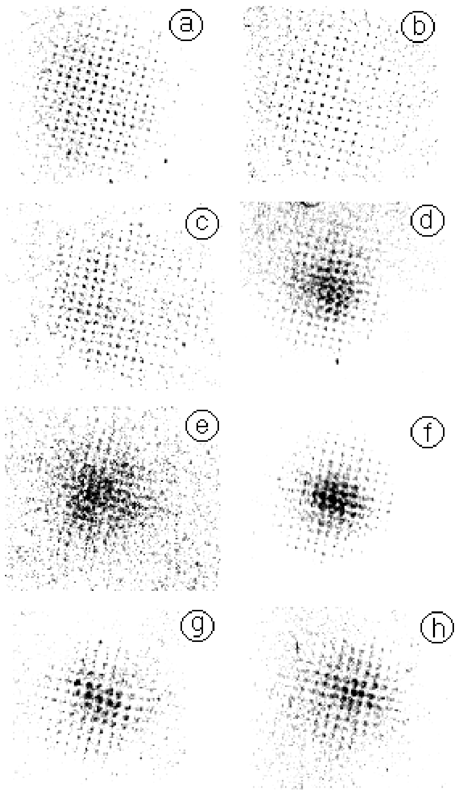

Fig. 2. Pepper-pot emittance patterns:
U_L = (a) 0, (b) 1kV, (c) 2kV, (d) 2.5kV, (e) 3kV, (f) 3.5kV, (g) 4 kV, (h) 5.5kV

The areas of phase contours that are compared should have equal ion currents. These currents can be calculated from the radial distributions of the ion current density in front of the selection screen using pepper-pot emittance patterns. Of particular interest is a comparison between the emittance with the lens off and the emittance with the lens on, (with parameters set for optimal beam focusing). Recall that in this regime the ion current density noise level does not increase, and a considerable compression of the beam is observed [3-4]. Emittance plots for these two regimes are shown in Fig. 3a and 3b.

In these figures a number of different phase space contours are shown, each corresponding to a different ion beam current. In Fig. 3b, it can be seen that the central part of the beam is almost completely focused and the ion trajectories at the periphery are distorted by spherical aberrations.

Using Fig. 3, we can derive the dependence of normalized emittance on beam current; see Fig. 4. From this dependence we can conclude that, for optimal beam focusing conditions, the normalized emittance for an ion current of 250 mA and equal to about 1.6 π·mm·mrad, and the emittance is conserved on passage through the lens.

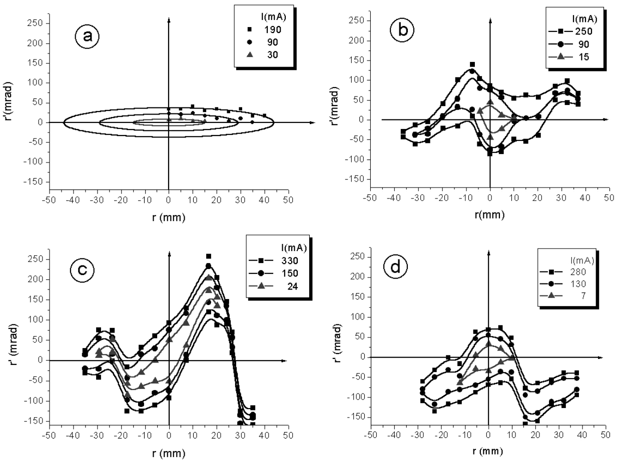

Fig. 3. Phase space contours corresponding to various beam currents. a) $U_L = 0$ (see Fig. 2a), b) $U_L = 3.5$ kV (see Fig. 2f), c) $U_L = 4$ kV (see Fig. 2g), d) $U_L = 5.5$ kV (see Fig. 2h)

Note that in a regime with considerable dynamic aberrations (Fig. 2e), almost complete loss of periodic structure on the pepper-pot emittance pattern indicates that under these conditions the emittance increases by a substantial factor.

Two additional phase contours are represented in Fig. 3c and 3d. They correspond to the conditions close to optimal. In Fig. 3c one can see that the beam is divergent, the periphery trajectories are strongly subjected to distortion, apparent axial asymmetry probably arises due to a slight misalignment of the ion source an PL optical axes. At U_L = 5.5 kV the ion beam have to be strongly divergent as, for this case, calculated focus is located practically in the lens, the observed phase contour (see Fig. 3d) indicates that, at so high voltage, qualitative rearrangement of the focused field takes place. From Fig. 4 we can conclude that within the limits of the precision of measurements the emittance is conserved for these two cases also.

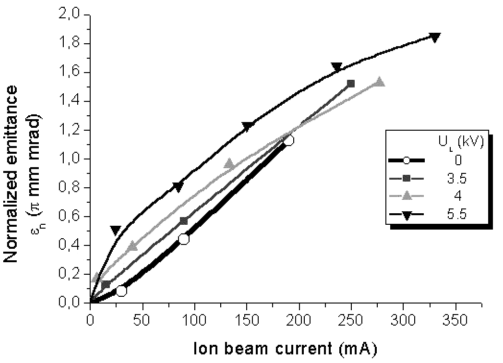

Fig. 4. Dependences of the emittance on the ion beam under the different U_L

4. CONCLUSION

This article is the first investigation of influence high current PL on emittance focused wide-aperture heavy ion beam. The emittance measurements indicate that influence of PL can be minimized. This open up possibility for novel applications PL, in part, at the injector beam lines of heavy ion linear accelerators.

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ВЛИЯНИЕ ЭЛЕКТРОСТАТИЧЕСКОЙ ПЛАЗМЕННОЙ ЛИНЗЫ НА ЭМИТТАНС СИЛЬНОТОЧНОГО ПУЧКА ТЯЖЕЛЫХ ИОНОВ

Ю.Н. Чех, А.А. Гончаров, И.М. Проценко

Представлены результаты измерения эмиттанса сильноточного пучка тяжелых ионов, сфокусированного электростатической плазменной линзой. Импульсный пучок ионов Cu длительностью 100 мкс, энергией 16 кэВ и полным током 500 мА формировался вакуумно-дуговым источником типа MEVVA. Для измерения эмиттанса использовался метод «Pepper-Pot». Показано, что в режиме оптимальной фокусировки нормализованный эмиттанс пучка, соответствующий току 250 мА, сохраняется и составляет 1.6 π·мм·мрад.

ВПЛИВ ЕЛЕКТРОСТАТИЧНОЇ ПЛАЗМОВОЇ ЛІНЗИ НА ЕМІТТАНС ПУЧКА ВАЖКИХ ІОНІВ

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Представлено результати виміру еміттансу сильнострумового пучка важких іонів, сфокусованого електростатичною плазмовою лінзою. Імпульсний пучок іонів Cu тривалістю 100 мкс, енергією 16 кеВ і повним струмом 500 мА формувався вакуумно-дуговим джерелом типу MEVVA. Для виміру еміттанса

використовувався метод «Pepper-Pot». Показано, що в режимі оптимального фокусування нормалізований еміттанс пучка, що відповідає струму 250 мА, зберігається і складає 1.6 π·мм·мрад.