Beam test of a Plasma Lens for Heavy Ion Beam Focusing*

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Abstract

First beam tests of an "active" current-carrying plasma lens were performed at the GSI linear accelerator UNILAC using a 11.4 MeV/u gold beam. A variety of discharge parameters have been tested. Very stable and reproducible performance characteristics of this novel lens were found. In a pulsed operation with a peak current of 22 kA a ion beam with an initial diameter of 10 mm was focused for 300 ns to a spot size of less than 300 μm. By means of temporally and spatially resolved diagnostics an almost 100 % focusing efficiency was measured resulting in an increase of intensity on the focal spot by more than a factor of 1000. The spot size is mainly limited by the beam emittance and not by lens-related aberration effects. Plasma lenses are under consideration to be used at the SIS/ESR facility of GSI to produce small beam spots on targets in order to achieve a high energy density in matter.

Table 1: Data of GSI plasma lens

electrical circuit	capacity	4 μF
	inductance	400 nH
	charging voltage	10 kV
	peak current	22 kA
	stored energy	200 J
plasma	length	100 mm
	diameter	12 mm
	current density	20 kA/cm^2
	discharge gases :	
	argon	0.05 ... 30 mbar
	helium	0.6 ... 7 mbar
	hydrogen	0.5 ... 4 mbar
focusing properties	beam aperture	10 mm
	peak magnetic field	0.74 T
	peak field gradient	123 T/m

1 INTRODUCTION

Focusing of heavy-ion beams is one key issue that has to be addressed to study the interaction of powerful ion beams with targets to prove the feasibility of heavy ion beam driven inertial confinement fusion. For beams from the GSI heavy ion syncrotron (SIS) with energies up to 1 GeV/u and a typical magnetic rigidity of 6 Tm novel focusing concepts are considered to minimize the focal spot size to about 100 μm radius for a beam of 10 π mm mrad emittance. Another task is to compensate for space charge effects in the region of the focal spot. Both problems can be solved using strong first-order focusing of a plasma lens instead of second-order focusing of quadrupole multiplets and completely neutralize space charge inside the final focus lens and in the target chamber. The plasma lens concept has successfully been demonstrated at CERN for efficient collection of antiprotons [1].

2 SET UP OF THE EXPERIMENT

The lens was tested at the GSI linear accelerator UNILAC using a 2.2 GeV (11.4 MeV/u) Au^{24+} beam which was prepared to be circular and parallel at the entrance of the lens. To perform a spatially resolved diagnostic of the focusing properties a "pepper pot plate" was inserted at the entrance of the lens to prepare a pattern of individual parallel beamlets. The plasma lens consists of two hollow electrodes and a quartz discharge tube with an inner diameter of 12 mm and a length of 100 mm. The discharge gas is flowing continuously through the tube. At the entrance of the lens a differential pumping system was installed to separate the discharge gas from the vacuum in the beamline. At a variable distance behind the lens the focused beam was visualized on a plastic scintillator with fast decay time (NE 102A). The light output of the scintillator was either imaged with a fast gated CCD camera system resulting in two dimensional pictures of the beam cross section or it was imaged on the slit of a streak camera system giving a time-resolved evaluation of the beam diameter. Data for the discharge circuit can be taken from table 1, a graphical representation of the set up is given in [2].

3 RESULTS OF FOCUSING EXPERIMENTS

Fig. 1 shows a comparison between the unfocused beam and the focal spot at a distance of 90 mm behind the lens. A very high reproducibility of the focusing effect was found. Typical deviations of focus diameter and fo-

*This work has been funded by the German Federal Minister of Research and Technology (BMFT) under Contract No. 06 MM 312 and 06 AC 301 I.

cus position were below 30 μm which is 0.3 % of the lens aperture. The incoming beam is focused from an initial diameter of 10 mm down to a spot of 250 μm. This is a reduction in radius of more than a factor of 30 and, at the same time, the intensity in the focus was increased by more than a factor of 1000. A direct measurement of this increase is difficult since it exceeds the dynamical range of

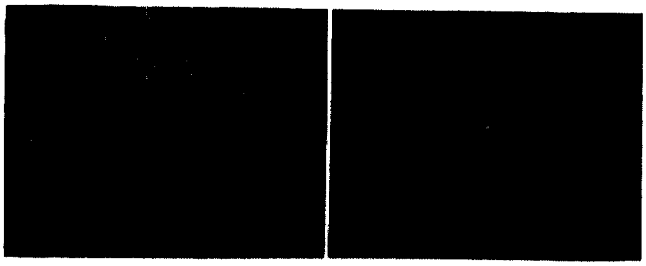

Figure 1: Snap shots of the unfocused (left) and focused (right) beam

our camera systems and the light output of the scintillator is not necessarily linear over such a large range. Therefore it is important to investigate the homogenity and symmetry of the focusing over the whole lens aperture, to prove that particles from every region of the incoming beam are focused in the same spot.

Since the focusing properties of a pulsed device such as the plasma lens are varying with time a scintillator was placed at a fixed distance of about the minimum focal length behind the lens and the light output was recorded with a streak camera to get the necessary time resolution. The information on the homogenity and linearity of the discharge was achieved by using not the whole beam aperture but only several beamlets masked out of the incident parallel beam.

By adjusting the entrance slit of the streak camera in line with three beamlets, as it is sketched in Fig. 2, the time-dependent variation of the beamlet position was monitored. The observed oscillation of their positions with time, seen in Fig. 2, corresponds to the oscillating strength of the magnetic field which is correlated to the oscillating discharge current $I(t)$. Assuming a homogeneous current density profile inside the plasma the resulting time-dependent function of the radial distance $r(t)$ of one beamlet from the optical axis observed at a fixed distance d behind the lens was calculated analytically and compared to the measured pattern. The theoretical waveform is given by the following expression

$$r(t) = r_0 \cos[\Phi(t) - \Phi(t)\, d\, \sin \Phi(t)/l], \qquad (1)$$

where r_0 is the initial distance of a beamlet from the optical axis at t = 0, and $\Phi(t) = l\sqrt{Ze\mu_0 I(t)/(2p\pi r_l^2)}$ is the phase with the ion charge state Z, the electron charge e, the particle momentum p, the lens radius r_l, and the damped oscillating discharge current waveform $I(t) = I_0 \exp(-\delta t) \sin 2\pi t/T$ with amplitude I_0 at $t = 0$, the damping coefficient δ, and the period of the current signal T. Using these measured data for the calculation of Eq.

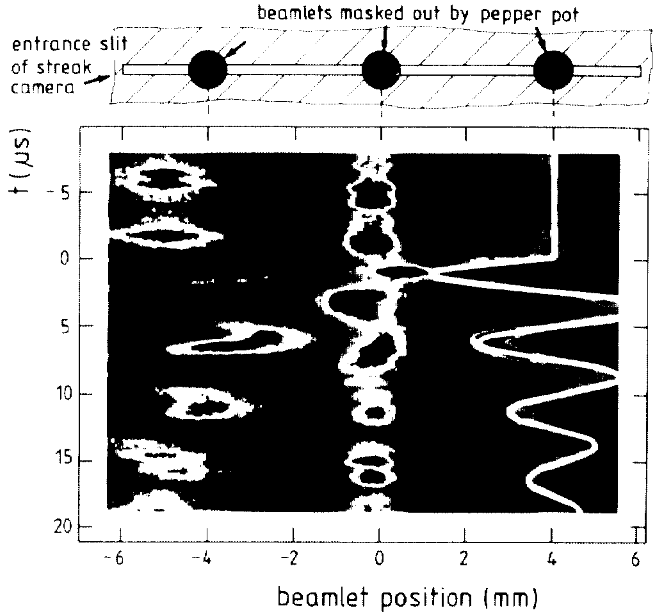

Figure 2: Streak image of three beamlets. The white solid curve represents the theoretically calculated position of the right beamlet.

(1) the white solid curve in Fig. 2 is drawn for the initial position $r_0 = 4$ mm and overlaid to the corresponding measured pattern. As the direction of the discharge current is inverted after every half wave period, phases of focusing and defocusing are alternating. The good agreement of the experimentally observed oscillation with the calculated curve confirms the assumption of a homogeneous current density distribution in the discharge.

The homogenity of the discharge over the whole beam aperture can be shown by taking photos of eight beamlets arranged on a circle with 8 mm diameter time-integrated over the first half wave period of the discharge. These eight beamlets are merging on straight lines to one common focal spot as can be seen from Fig. 3. During merging the diameter of each individual beamlet is also reduced from initially 400 μm to about 300 μm.

4 DISCUSSION OF POSSIBLE LENS ABERRATIONS

Table 2 shows a listing of possible aberration effects and their dependence on the focusing angle δ. The relative

Table 2: Limitations of focal spot size and their dependence on the focusing angle δ

limitation	δ-dependence of r_s
emittance of incoming beam	$\sim 1/\delta$
emittance caused by scattering	$\sim 1/\delta$
spherical aberration	$\sim \delta^3$
chromatic aberration	$\sim \delta$
space charge	$\sim \exp(-\delta^2)$

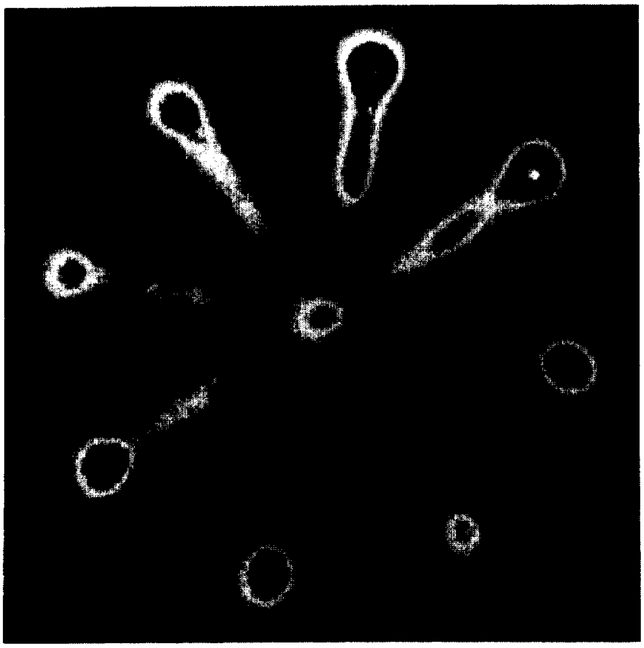

Figure 3: Time inegrated image of eight merging beamlets

strength of the different effects and their δ-dependence define an optimum for the focusing angle. To minimize the enlargement of the focal spot caused by emittance effects the focusing angle has to be increased until effects of spherical and chromatic aberration become dominant. A further increase of the focusing angle then again leads to an enlargement of the spot radius. Space charge effects are negligible in the neutralizing background plasma.

The most important limitation of the spot size in our experiments is given by the beam emittance which was measured to be 5 π mm mrad for the UNILAC beam and which will be about 10 π mm mrad for a future SIS application. Since emittance is a conservation quantity the spot size is emittance-limited to $r_s = \epsilon/\delta$, with the beam emittance ϵ. This gives an emittance-limit of 139 μm for a focusing angle of $\delta = 36$ mrad and is close to the measured spot size. An enlargement of the beam emittance by small angle scattering in the discharge gas, mainly in the differential pumping section, has to be considered at UNILAC energies of 11.4 MeV/u. To avoid this effect either low-Z gases (i.e. hydrogen or helium) have to be chosen or the filling pressure has to be kept small. At SIS energies of up to 1 GeV/u scattering can be neglected.

Chromatic aberrations are caused by two different effects namely the momentum spread of the incoming beam and the charge state spread of the ions in the lens. The magnitude for the focal spot enlargement for these effects can be calculated by Eqs. (2) and (3):

$$\text{momentum spread}: \quad r_s = \delta l \frac{\Delta p}{p} \quad \frac{\sin\Phi + \Phi\cos\Phi}{2\Phi\sin^2\Phi} \tag{2}$$

$$\text{charge states}: \quad r_s = \delta l \frac{\Delta q}{q} \quad \frac{\sin\Phi + \Phi\cos\Phi}{2\Phi\sin^2\Phi}, \tag{3}$$

with radius of the focal spot r_s, radius of the incoming beam r_0, the relative momentum spread $\Delta p/p$, the phase Φ of the betatron oscillation that the ions have reached at the end of the lens, the focusing angle δ, the equilibrium charge state of the ions in the plasma q, and the width of the charge state spread Δq. For the UNILAC beam a phase $\Phi = 0.29\pi$ and a momentum spread $\Delta p/p = 0.3\%$ leads to a spot radius limitation of $\leq 10\mu$m which can be neglected. Due to the charge spread an increase of the spot radius of 66 μm is expected for $q = 65$ and $\Delta q = 1$.

Spherical aberrations are very critical because of their δ^3-dependence. Nevertheless no signs of aberrations could be detected in the pepper pot images of the focusing process.

The dependence of the spot radius on the focusing angle (Fig. 4) shows that the radius scales inversely with the angle over the whole range of experimental data. This shows that there are no lens related aberration effects detectable.

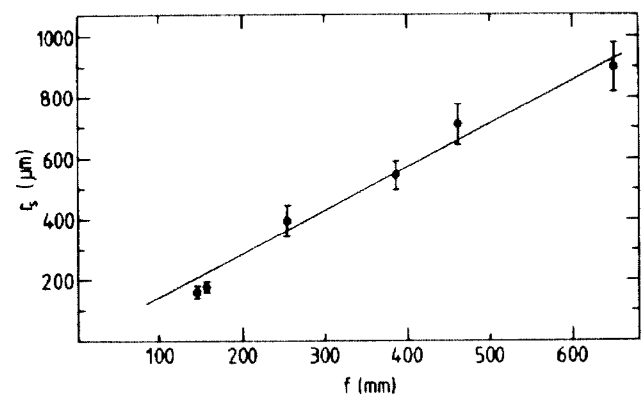

Figure 4: Dependence of the focal spot size on the focal length of the lens

5 CONCLUSIONS

The accuracy and reproducibility of a plasma lens for heavy ion beam focusing has been successfully demonstrated by focusing parallel beams down to the emittance limit. No lens related aberrations could be detected. The plasma lens device itself is small and easy to handle and the low energy input allows for high repetition rates needed in other applications for accelerators [3]. For a future SIS fine-focus lens the discharge current has to be increased into the 100-kA-region.

6 REFERENCES

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