Plasma Lenses for Heavy Ion Beam Focusing*

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Abstract

At the German heavy-ion accelerator facility SIS/ESR at GSI in Darmstadt intense heavy-ion beams are used to achieve high-energy deposition power in matter. For efficient use of available beam power, beams have to be focused to small spot sizes on the target. One key problem is the fine-focusing of heavy-ion beams in order to achieve a focus radius of typically 100 μm. Besides conventional methods using quadrupoles also advanced novel focusing techniques are under consideration. Various types of current-carrying, "active" plasma lenses, characterized by a symmetric high-gradient magnetic field distribution, have been tested experimentally. The focusing properties of a z-pinch as well as a wall-stabilized discharge plasma lens have impressively been demonstrated.

1 INTRODUCTION

The goal of our research project is to study matter under extreme conditions of temperature and pressure [1]. The potential of intense heavy-ion beams to heat small samples of matter, and to produce dense plasmas is critically linked to beam parameters such as emittance, current, and energy. When the beam intensity is above a critical threshold such that typically some eV per target atom are deposited in the target material, then the deposition power P of the beam is the appropriate yardstick to estimate the temperature of ion beam heated targets. This quantity is proportional to the beam energy E_k and current I_b, and inversely proportional to the achievable spot size area $r_{sp}^2\pi$ on the target and the projectile range R in matter

$$P = \frac{E_k \times I_b}{r_{sp}^2 \pi \times R}. \qquad (1)$$

For an ideal focusing system the spot size radius r_{sp} scales for a given initial beam radius with the beam emittance. Conventional focusing systems with magnetic quadrupoles soon arrive at principal (and budget!) limitations, since it is very difficult to obtain a flux density at the pole tips above 1 Tesla.

A plasma lens is formed by a cylindrically symmetric plasma column through which a high pulsed current flows in axially direction. With a homogeneous current density such a "wire lens" is characterized by an azimuthal magnetic field which, inside the column, rises linearly in radial direction. The obvious advantages of plasma lenses are:

- simultaneous first order focusing in both transversal planes,
- high magnetic field gradients of several hundred teslas per meter across a lens aperture of several centimeters,
- compensation for space charge effects,
- negligible absorption of particles to be focused.

The crucial point is, however, to achieve a sufficiently homogeneous current density distribution. So far, only few applications of plasma lenses in accelerators have been reported [2, 3, 4].

2 PLASMA LENS BEAM FOCUSING EXPERIMENTS

In first proof-of-principle experiments we tested the performance of plasma lenses by using the heavy ion beam from the linear accelerator UNILAC at GSI with a beam energy of 11.4 MeV/amu. The set up is schematically shown in Fig. 1. Almost parallel heavy ion beams propagated axially through the discharge quartz vessel filled with some mbars of gas. To exclude beam interaction with solid windows, and to enable a 10-mm-wide aperture for the propagating beam, the installation of an efficient differential pumping system was required. The beam spot was observed shortly downstream of the plasma on a fast plastic scintillator. The beam-emitted light was monitored employing fast streak and framing photography.

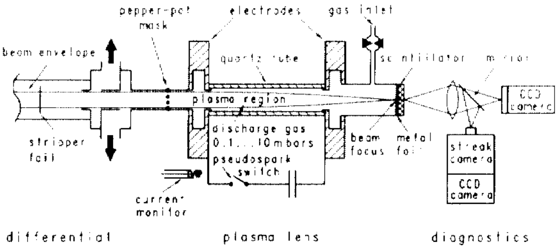

Figure 1: Scheme of plasma lens focusing experiments.

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2.1 "Z-Pinch" Discharge Plasma Lens

The focusing properties of a fast z-pinch discharge were tested which was not optimized for a plasma lens but served as a plasma target [5] for stopping power measurements. The pinch time was designed to occur near the zero-crossing of the oscillating discharge current. Nonetheless a strong focusing effect acting on the traversing argon ion beam has been found, as it is summarized in Fig. 2 [6, 7].

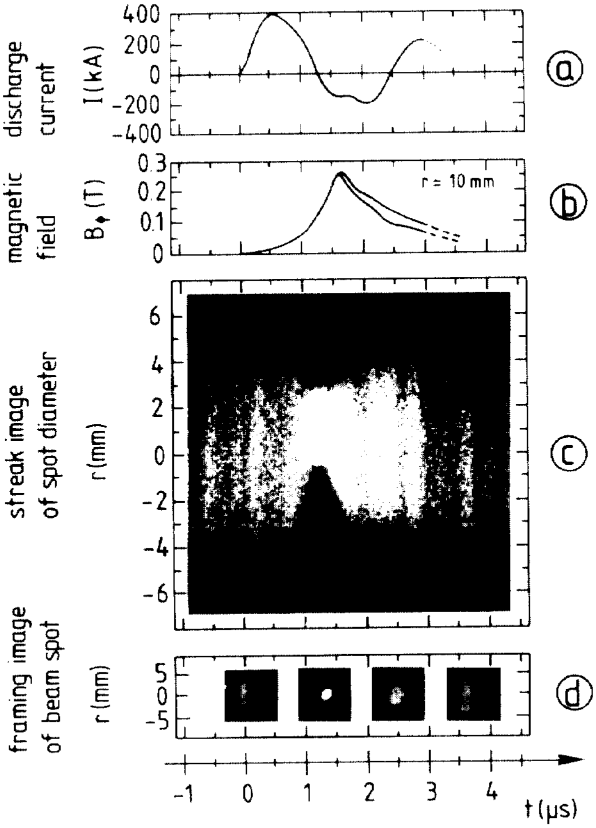

Figure 2: Overview on focusing results obtained with z-pinch plasma lens. Presentation of (a) discharge current, (b) magnetic field, (c) streak image, and (d) framing images. Time zero coincides with discharge begin.

2.2 "Wall-Stabilized" Discharge Plasma Lens

A different type of plasma lens system was designed [8] attempting to avoid plasma dynamical effects and to enhance the focusing efficiency. In contrast to the z-pinch this concept employs a "wall-stabilized" discharge mode inside an insulator tube with a cross section that matches the unfocused incident beam profile. If the skin depth of the plasma current is larger than the tube diameter, the current flow covers the entire cross section. A gold ion beam was used to check the beam-optical properties of this lens. The experimental results are presented in Fig. 3.

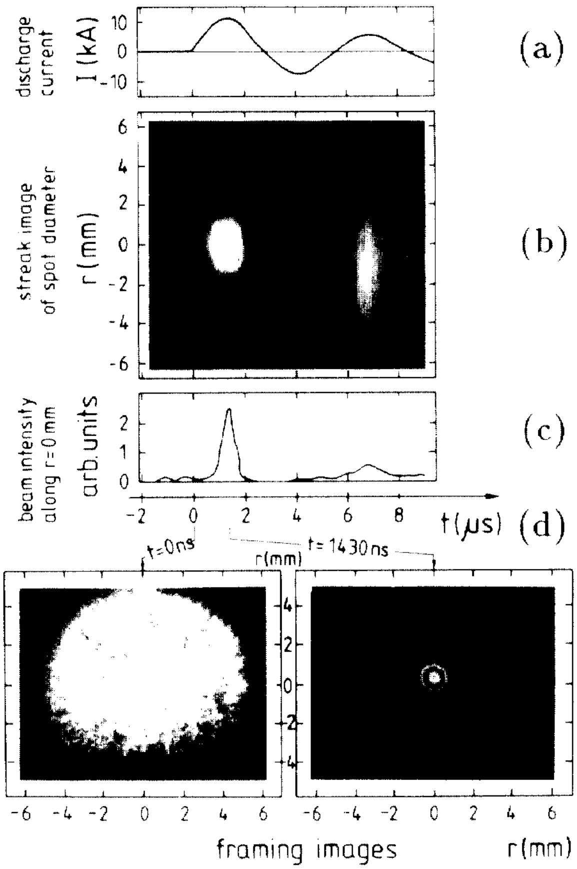

Figure 3: Overview on focusing results obtained with wall-stabilized plasma lens. Presentation of (a) discharge current, (b) streak image, (c) beam intensity along optical axis, and (d) framing images of unfocused beam at t = 0, and focused beam at t = 1.4 μs. Time zero coincides with discharge begin.

At ignition of the discharge the focal length of the plasma lens reduces from infinity to a distance of several centimeters behind the lens. The maximum focusing effect coincides with the current maximum at about 1.4 μs. In Fig. 3(d) framing images of the beam at t = 0 and t = 1.43 μs are illustrating the difference in cross section of the unfocused and focused beam. With decreasing current the focal length increases again to infinity at current zero. The magnetic field in the plasma lens is alternating between periods causing a focusing or a defocusing effect which corresponds to the time behavior of the oscillating damped discharge current in Fig. 3 (a).

With an energy of 200 J, initially stored in the capacitors, and a peak current of 22 kA, a magnetic field gradient of 123 T/m was achieved. The maximum discharge current corresponds to the maximum beam convergence angle of 36 mrad which results in a spot radius of about 125 μm, at 90 mm behind the lens, in agreement with theoretical calculations. The focused beam intensity is equally increased by a factor of more than 1000. Detailed presentation of the results are given in a second paper presented at this conference [9].

The main features of the discharge concepts tested for a plasma lens are compared in Table 1. For a fine-focusing lens the wall-stabilized discharge concept seems favorable compared to the z-pinch discharge, however, it is still uncertain if the wall-stabilized mode works stable also at a current level well above 100 kA.

Table 1: Comparison of features of z-pinch and wall-stabilized plasma lens

feature	z-pinch	wall-stabilized
current	high (1000 kA)	low (100 kA)
radius	large(40 mm)	small (10 mm)
gradient	high (1000 T/m)	medium (200 T/m)
duration	short (100 ns)	long (1000 ns)
repetition rate	single shot	high (100 Hz)
accuracy	low	high

3 APPLICATION FOR HIGH ENERGY DENSITY EXPERIMENTS

For intense beam-target experiments with the SIS/ESR beams a high-energy-density target area has been designed, as it is shown in Fig. 4 [10]. Beam pulses of maximum intensity bunched to 100 ns pulse length and stored in the SIS synchrotron are focused to a small spot size by a fine-focusing quadrupole system [11]. For a beam emittance of 0.5 π mm mrad a spot size radius of 100 μm is anticipated. At a typical SIS heavy ion beam energy of 300 MeV/amu the magnetic rigidity of the ions is about 6 Tm after having been reduced by electron stripping before entering the final focusing section. Target plasma temperatures of some eV will allow for fundamental studies of problems related to inertial confinement fusion driven by heavy-ion beams. It is planned to install a plasma lens at the end of the quadrupole system to focus even higher emittance, but more intense, beams onto sub-mm spot sizes. The quadrupole system then will work as a matching section for the SIS beam to the plasma lens. Typical parameters of a future SIS plasma lens are also listed in Table 2.

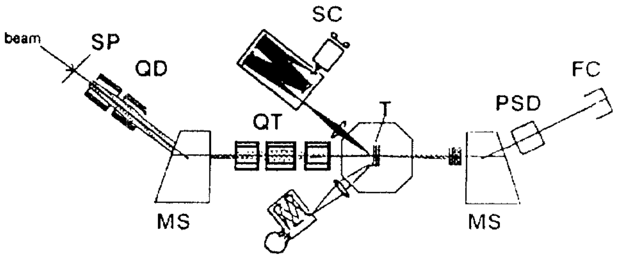

Figure 4: Target area at the SIS/ESR facility for high-energy-density experiments. SP, stripper point; QD, QT, quadrupole doublet and triplet; MS, dipole magnet; T, target; SC, streak camera; PSD, position-sensitive detector; FC, faraday cup.

Table 2: Comparison and performance of tested plasma lens parameters for SIS beams with 6 Tm rigidity

Parameter	z-pinch	wall-stabilized	SIS lens
current (kA)	12.5	22	300
gradient (T/m)	25	123	1670
focal length (mm)	1133	509	94
length (mm)	200	100	60
radius (mm)	10	6	6
duration (ns)	100	1000	100
spot size (μm) at			
10 π mm mrad	1235	850	100
0.5 π mm mrad	60	50	<50

4 CONCLUSIONS

Beam-optical properties of two different plasma lens designs have been tested with heavy ion beams. Quantitative measurements have been performed with both types, a z-pinch discharge and a wall-stabilized discharge plasma lens. Heavy-ion beams were focused with high efficiency from initially 10 mm to spot sizes below 300 μm. The ideal focusing characteristics of plasma lenses greatly advace present-day conventional focusing techniques. Further applications of plasma lenses for antiproton [12] or positron capture [13] are reported at this conference.

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