Investigations on a Plasma Lens for Fine Focusing of Heavy-Ion Beams

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Abstract

Within the framework of the "High Energy Density in Matter" program, a plasma lens has been designed to focus a heavy-ion beam onto a very small spot. A spot diameter of 200 µm (FWHM) is desired to get the necessary energy density on the target to create a plasma by means of a heavy-ion beam. This diameter is determined by the parameters of the SIS-accelerator at GSI-Darmstadt: beam rigidity, 6 Tm; particle energy, 300 MeV/amu; emittance, 10 π mm mrad; and total particle number > 10^{11}. The calculated current in an ideal plasma lens is between 300 and 400 kA for an emittance limited spot, dependent on initial beam radius and distance of the spot from lens exit. A flexible system has been designed in order to investigate the various discharge mechanisms and their influence on the focusing properties at these high currents.

1. Introduction

Focusing high energy particles by conventional quadrupole multiplets is subject to fundamental limitations [1]. The main reason is that the focusing effect in such devices is second order, *i.e.* there is always one focusing and one defocusing plane. Therefore multiplets are necessary, leading to a rather long system length. On the contrary, the field configuration of a "wire lens", characterized by an axially symmetric and radially linear rising magnetic field, represents a perfect ideal lens. This field configuration is produced by a homogeneous axial current density in a plasma. The beam particles traverse this plasma which has densities between 10^{-6} and 10^{-10} g/cm^3. Scattering is negligible at these densities.

For an ideal lens the spot diameter of a beam with a given emittance scales inversely with the focusing angle α. A spot diameter of 200 µm (FWHM) is desired to get the energy density on the target necessary to create a plasma by means of a heavy-ion beam with the given beam parameters of the SIS-accelerator at GSI-Darmstadt. Therefore α is fixed and the initial beam diameter at the lens entrance and the distance of the spot from the lens exit determine the current and length of the plasma column. Calculations for different target distances and initial beam diameters yield to currents between 300 and 400 kA for a beam with 6 Tm rigidity at a particle energy of about 300 MeV/amu.

The main task of this experiment is the creation of a homogeneous current density distribution in the gas discharge during the focusing phase in order to get no lens aberration. One possibility to create a plasma cylinder with variable diameter and high discharge current is the dynamic Z-pinch [2]. The selected approach is the "wall stabilized discharge" where the contraction of the current-carrying sheath is inhibited. This system has shown very good focusing properties with currents up to 30 kA [3].

2. System design

The plasma lens pulse generator is composed of up to six exchangeable capacitor banks. These units are connected to the plasma lens by flexible low-inductance HV pulse cables, enabling an easy in-place adjustment of the plasma lens. The parameters are: capacitance, 13 - 80 µF; charging voltage, 5 - 20 kV; discharge current, 10 - 400 kA; current halfwave, 6 - 9 µs. The whole lens is surrounded by the target chamber, enabling vacuum in the chamber while low-pressure gas in the lens system is contained by 100 to 300 µm thick titanium windows.

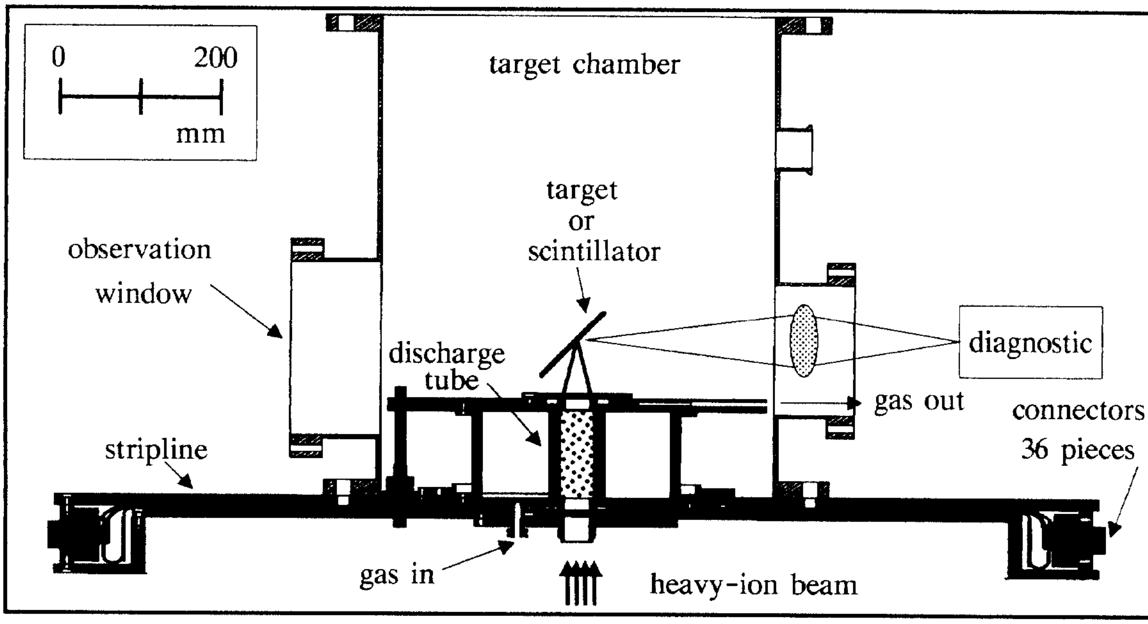

Fig. 1: schematic drawing of the plasma lens with the target chamber

3. Experiments

After completion of the plasma lens and the first capacitor bank the system was tested at the GSI UNILAC accelerator with a beam rigidity of 1.6 Tm, emittance of 5 π mm mrad and discharge currents up to 90 kA. For this parameter set no aberrations of the plasma lens have been observed, *i.e.* no deviation from the homogeneous current density distribution occured. The measured spot diameter of 350 μm (FWHM) agrees well with the 330 μm of the calculated emittance-limited focus [4].

In addition laboratory experiments with optical and spectroscopical measurements of the plasma are carried out to get scaling laws for the plasma behaviour of a wall stabilized discharge at these high currents. Unfortunately these experiments are limited because with currents exceeding 100 kA the quarz tubes are destroyed by the discharge. For the beam experiments we used alumina tubes.

The plasma development is similar for all investigated currents between 45 and 90 kA. The homegeneous ignition over the discharge volume is followed by a contracting shock wave. The time to reach the axis is about 1 μs, nearly independent of the discharge current. This shock wave is probably produced by the heating and desorbtion of adsorbates on the insulator tube. After a short expansion of the shock produced dense plasma on the axis, a second contraction phase is visible. The velocity is increasing with increasing current. This is the pinching of the current layer due to the magnetic fields. The pinch is expanding again and during current maximum a homogeneous plasma cylinder is visible. With these results it is possible to adjust the tube diameter and the gas pressure such that the diameter of the plasma is slightly greater than the incoming beam diameter.

This encouraging first tests were followed by two beam experiments at the GSI SIS/ESR facility, with 6 Tm beam rigidity and plasma currents up to 200 kA, in November 1993 and June 1994. The task was to verify the good focusing properties. The ion beam was the probe to determine the evolution of magnetic field distribution at these current levels.

The time-dependent development of the focus on plastic and quarz scintillators was detected by short time photography. The principle arrangement of a plasma lens and the diagnostic is described in [5]. The spacial resolution was 60 μm in vertical and 160 μm in horizontal direction. The diameter of the incoming beam was 14 mm and the plasma column during best focusing was between 14 and 16 mm depending on the peak current and the gas pressure.

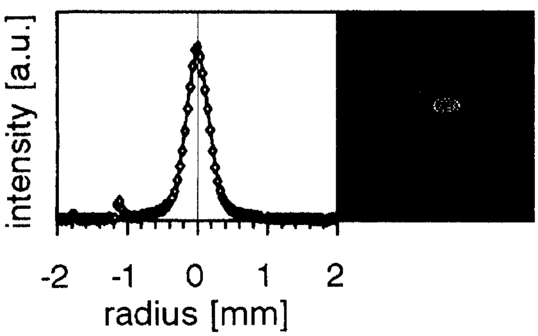

Fig. 2: Focus on the scintillator and vertical spot profile

Figure 2 shows the focused beam and the vertical beam profile at a target distance of 59 mm from the end of the plasma column. The diameter of the spot for this parameter range is 400 μm. The minimum spot diameter was 390 μm at a target distance of 53 mm.

The measurement of the beam emittance is very difficult and the accuracy is only ±50%. Therefore we tried to determine the beam emittance by measuring the spot size at different target distances. As long as the focus is only emittance-limited one should find a linear dependence of the spot diameter as a function of the focal length. It is well known that the beam has about a factor of two higher emittance in the horizontal than in the vertical plane. The focus diameter as a function of focal length is shown in figure 3.

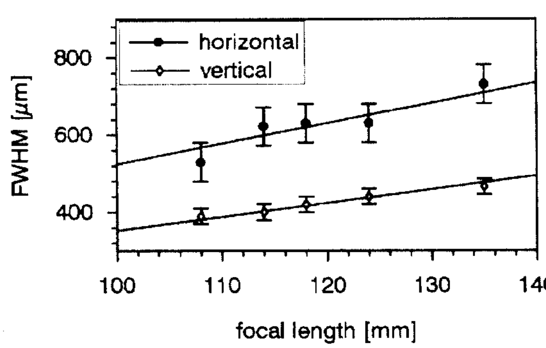

Fig. 3: focus diameter as a function of focal length for the horizontal and vertical beam profile

These results yield to 13±1 π mm mrad horizontal and 8.5±0.5 π mm mrad vertical emittance (FWHM). The reproducibility of focus diameter and focus position for several shots was 100% within the error of measurement.

4. Conclusion

The accuracy and reproducibility of wall stabilized plasma lenses at currents up to 200 kA have been demonstrated. Lens aberrations have not been detected. The next step is to increase the current to 300 kA by increasing the charging voltage of the capacitor banks. In laboratory the feasibility of the alumina discharge tubes and the thin titanium windows to withstand these higer currents has to be shown. We hope to reach the designed currents in autumn 1994. The lens with increased focusing power will then be tested again at the SIS-beam. This optimized plasma lens should reach spot diameters very close to 200 μm if the emittance of the SIS-beam is within the designed values.

5. References

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