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A Study of Plasma Lenses and Their Use as Beam Spreaders for the SSC

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Abstract

Plasma lenses are evaluated as a method of spreading the SSC beam on its way to the beam absorber. These lenses are studied first individually and then in several different geometries encompassing lenses with both steady and oscillating currents. To further enhance the evaluation, considerations such as varied beam energies and off-axis entrance of the beam to the dump are discussed.

1. Introduction

Plasma lenses have been developed for use as high gradient focussing magnets in such applications as rare particle collection. Such a device was constructed at CERN in 1989 and is used in a manner similar to the lithium lens at Fermilab to collect newly created antiprotons [1]. Another lens of a different design has been used for heavy-ion focussing at GSI [2]. Currently plasma lenses are proposed for use as a final focussing lens in linear colliders. By reversing the current direction within a plasma lens, a strong defocussing magnet is created. In this paper we investigate the use of such plasma lenses as defocussing devices for spreading the intense SSC beam before it strikes the beam absorber.

If the material of the absorber is given too much energy within too short a time, effects such as melting and cracking can occur. With the large circulating energy of 420 megajoules and small natural spot size of 0.125 millimeters in radius, a direct dump of the full 20 TeV beam from the SSC would dramatically decrease the lifetime and effectiveness of the beam absorber. The

beam must be distributed across the face of the absorber if the use of the material is to be extended.

The current proposal for spreading the beam consists of 6 meters of fast kicker magnets and 44 meters of conventional quadrupole blowup magnets. The kicker magnets are arranged to move the beam centroid in a raster pattern over the 300 microsecond beam extraction time similar to the sweeping pattern of a television; the quadrupole magnets expand this pattern on the face of the absorber.

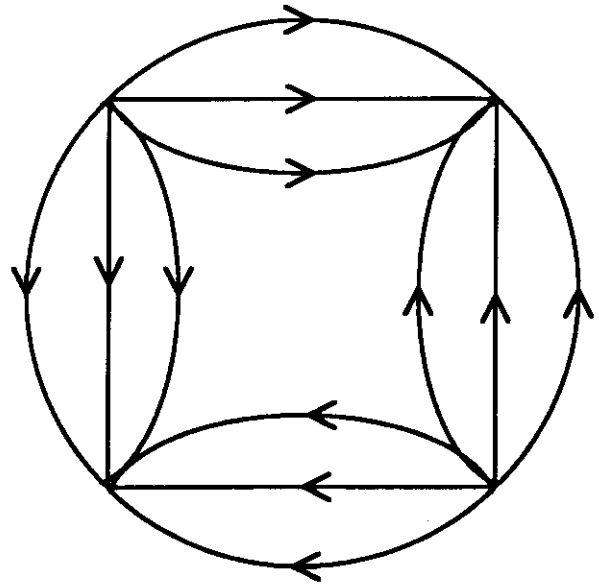
Such a system might be enhanced through the use of plasma lenses. The total magnet length could possibly be reduced due to the higher gradients of the plasma lenses. The shape of the plasma in the lens allows defocussing in all directions simultaneously. Finally they may be rapidly triggered and therefore do not need to be kept at full power at all times.

A plasma lens consists of a current run across a column of ionized gas. The current produces a magnetic field that circles the axis of the plasma column, directed tangentially at every point both inside and outside the column (fig. 1). For maximum defocussing a proton beam travelling into the page should encounter a field circling counter-clockwise created by a current running out of the page.

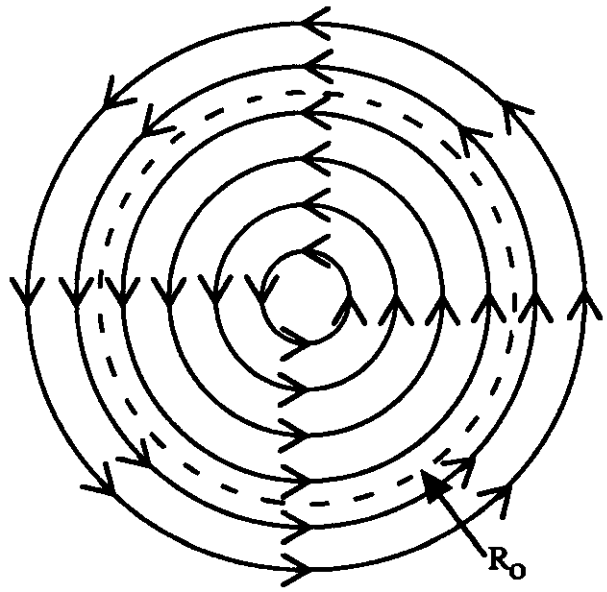
The magnitude of the field can be found using Ampere's Law:

$$\int \mathbf{B} \cdot d\mathbf{l} = \mu_0 i$$

For points outside the radius of the plasma column ($> R_0$), all of the current is enclosed, and the strength of the field is given by



Quadrupole



Plasma Lens

Fig. 1. Magnetic field lines of conventional quadrupole and plasma lens.

$$B = \frac{\mu_o i}{2\pi r}.$$

The current inside of the column is proportional to r^2/R^2, so the field becomes

$$B = \frac{\mu_o i r}{2\pi R^2}$$

This leads to a linearly increasing field strength inside the radius of the plasma and a field decreasing by 1/r outside the radius as shown in figure 2.

2. Methodology

Simulation of the beam dump lattice was done using the MARS12 fortran code by N. V. Mohkov [3]. The program was run in a Unix operating environment on a Sun workstation. MARS12 has the capacity for an arbitrary time dependent magnetic field, **B**(x,y,z,t), and easily interfaces to produce figures for the heating incurred by the beam absorber. Some additions were made to the user written subroutine BField by Brett Parker. In particular variables XCENT and YCENT were created in the main program so the magnets could be set deliberately off-center from the beam path. Also, a new magnet type (-2) was defined to calculate the magnetic field at any point inside or outside of the plasma. The input included XCENT and YCENT as well as the gradient (Tesla/meter) and the radius of the plasma (centimeters). After each run, a file containing the final beam distribution was transferred to the VAX. Using PAW, scatter plots were made to show the shape of the beam spot as it

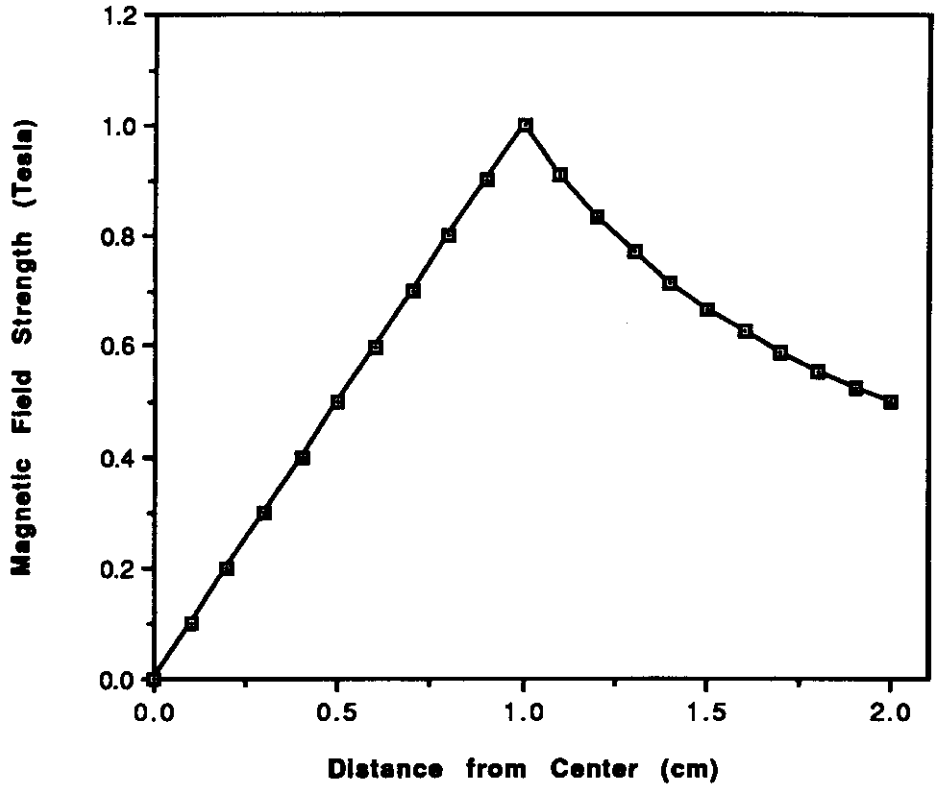


Fig. 2. Variance in magnetic field strength inside and outside a plasma column (plasma radius =1.0 cm).

had reached the beam dump. X and Y projections were also made to obtain figures for mean position and RMS spread.

3. Results

Simple Geometries

In an attempt to understand the basic focussing properties of plasma lenses, a number of runs were devoted to determining how a single lens affects the beam. A gradient of 100 T/m was defined by a current of 50 kA, which is both attainable and thought to be well below the level that would produce instabilities within the plasma. Starting with the beam entering on the axis of the magnet, a magnet first with a steady current and then with an oscillating one was offset 0.1 cm in the X direction (XCENT) for each run of the program up to 1.5 cm. The figures in Table 1 show the parameters used in these runs.

Table 1
Single Magnet Study Parameters

Beam energy	20 TeV
Beam size (SigX & SigY)	0.0125 cm
Number of particles	5000
Magnet start	375 m
Magnet length	2.5 m
Plasma Radius	1.0 cm
Z drift	1900 m

Figure 3 shows the shape of the beam as it reaches the absorber after having gone through the center of a plasma lens and drifting to 1900 meters.

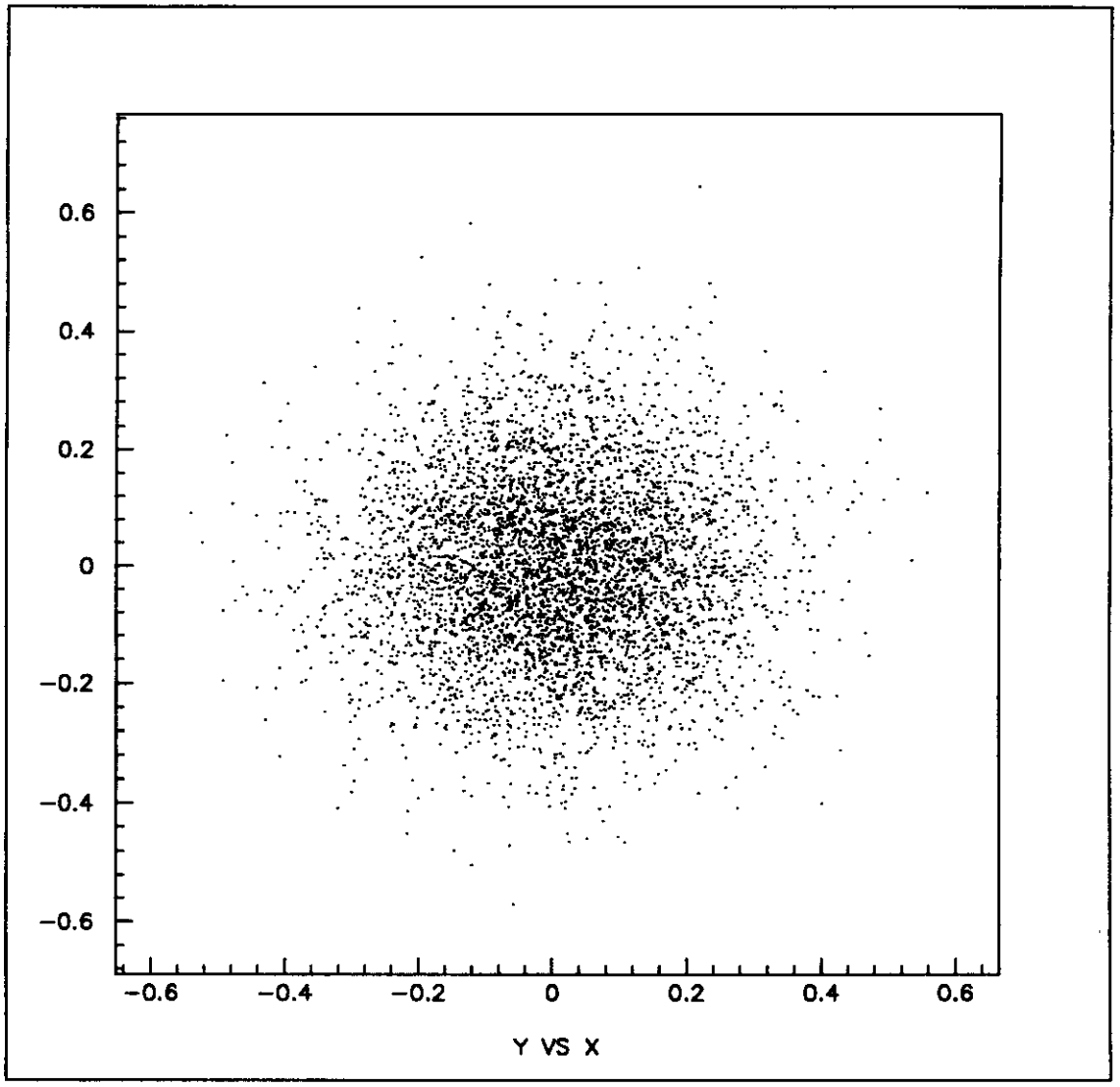


Fig. 3. The beam as it appears reaching the absorber having gone through the center of a single plasma lens. (All units are cm.)

As expected, the length of the plasma column and the RMS extent of the resulting spot are found to be linearly related (fig. 4). The radius of the plasma effects only off-center beams at this part of the tunnel; when the beam enters the lens exactly at the edge of the plasma, the beam spot becomes flattened on the side away from the axis. As the beam was moved from entering the center of the magnet to further out, X RMS showed the same linear rise and 1/r fall as the field strength; Y RMS stayed fairly constant within the plasma but dropped once outside of R. The spot shape itself is somewhat uncertain as the program seems to generate an artificial shadow that affects only the off-center single steady current lens.

The effects of oscillating the current through the plasma lenses were also studied. The idea to use an oscillating current in the plasma to avoid z-pinch instabilities was first suggested by Simon Yu of the Lawrence Livermore Laboratory. For the study of a single oscillating-current lens, all parameters are the same as before with the addition of a sinusoidal oscillation at a frequency of 60 kHz applied over a total extraction time of 300 microseconds. Such an oscillation reduces the RMS of the final spot from an on-axis run by a factor of 1.7.

If run through the oscillating lens anywhere except the axis, the beam spot takes on the bow tie shape shown in figure 5. The X and Y RMS of the spot from this lens act much the same as those of the steady-current lens, but the X RMS values are about 10 times as large, while the Y RMS values are more than half of their steady-current values. The frequency of the current oscillations and the RMS of the beam spot are unrelated.

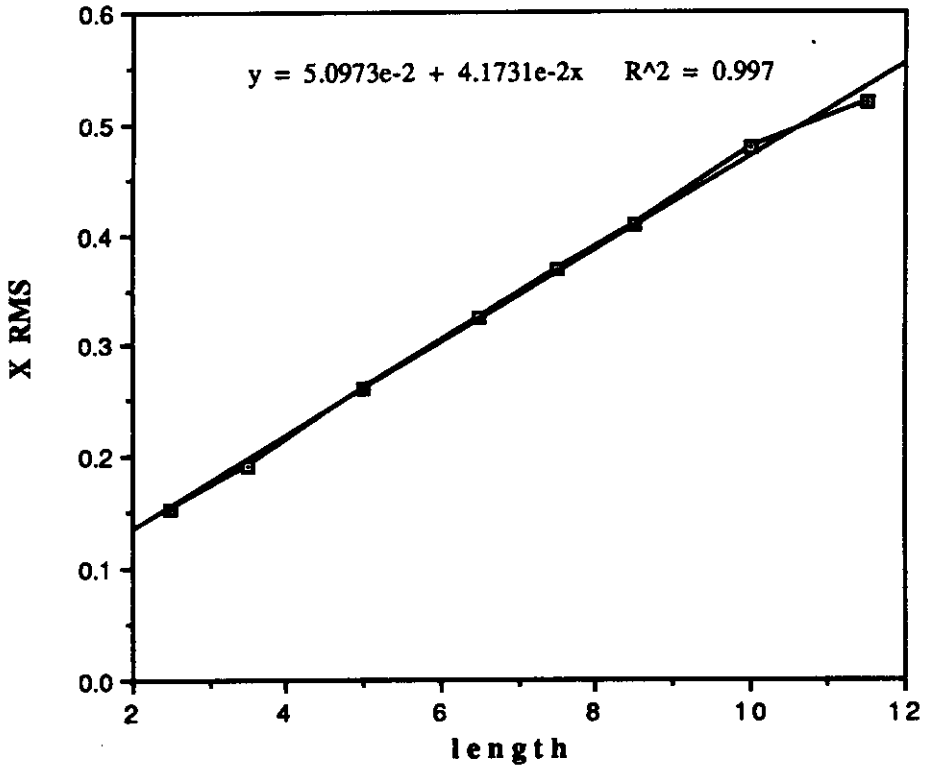


Fig. 4. Single plasma lens length to RMS relation.

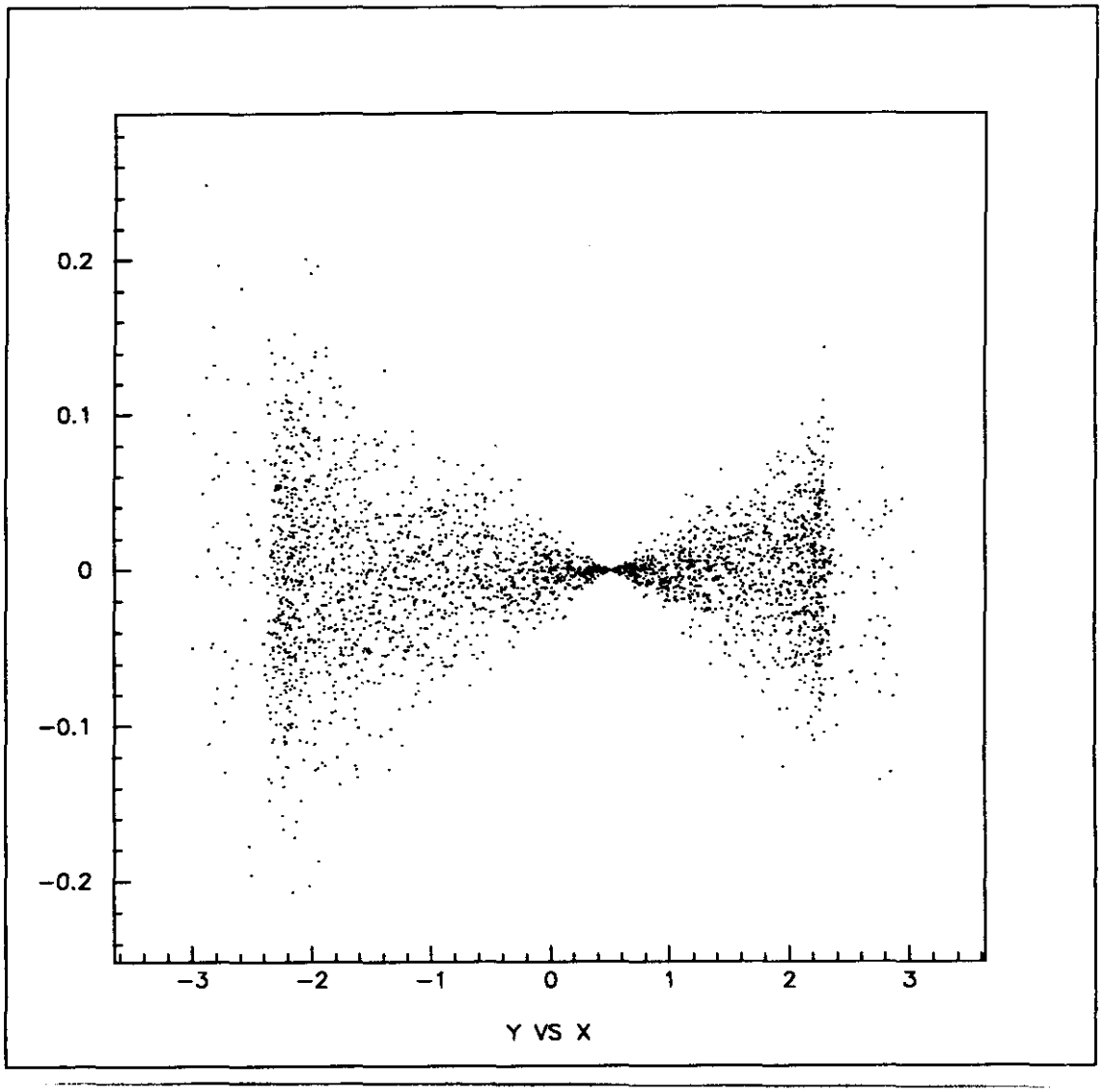


Fig. 5. Beam spot from beam travelling off-center through an oscillating plasma lens.

Complex Geometries

Combining a plasma lens with normal quadrupole kickers proved to be very challenging. A plasma lens was placed downstream of quadrupole magnets that were oscillated according to Brett Parker's raster scan [4]. For this geometry to be successful, the beam must not be allowed to enter the plasma lens outside of the plasma. Due to the change in field strength once the beam reaches the radius of the plasma, the beam spot in this case exhibits folding of the rectangular scan pattern into a circular shape (fig. 6).

Plasma lenses carry the potential of being kicker magnets because a beam entering the magnet off-axis will be deflected. The most effective way to use a plasma lens as a kicker is to combine it with other plasma lenses. Two oscillating plasma magnets placed equal amounts on either side of the beamline create two nodes of concentration and only spread the beam in one dimension. With one magnet spreading in the X direction and the other in the Y dimension, shapes from ovals to pretzels occur, still with points of large concentrations of particles. To create a more evenly spread pattern, four magnets oscillating at different frequencies are placed together offset in each direction 0.5 cm; this combination causes the plasma lenses to work much like kicker magnets. The lattice in Table 2 creates a roughly circular coverage of the absorber (fig. 7).

Table 2
Oscillating Magnet Kicker Lattice

magnet position	length	freq.	XCENT	YCENT
375.0 m	2.5 m	81.7 kHz	0.5 cm	0.0 cm
377.5 m	2.5 m	78.4 kHz	-0.5 cm	0.0 cm
380.0 m	2.5 m	80.5 kHz	0.0 cm	0.5 cm
382.5 m	2.5 m	73.9 kHz	0.0 cm	-0.5 cm

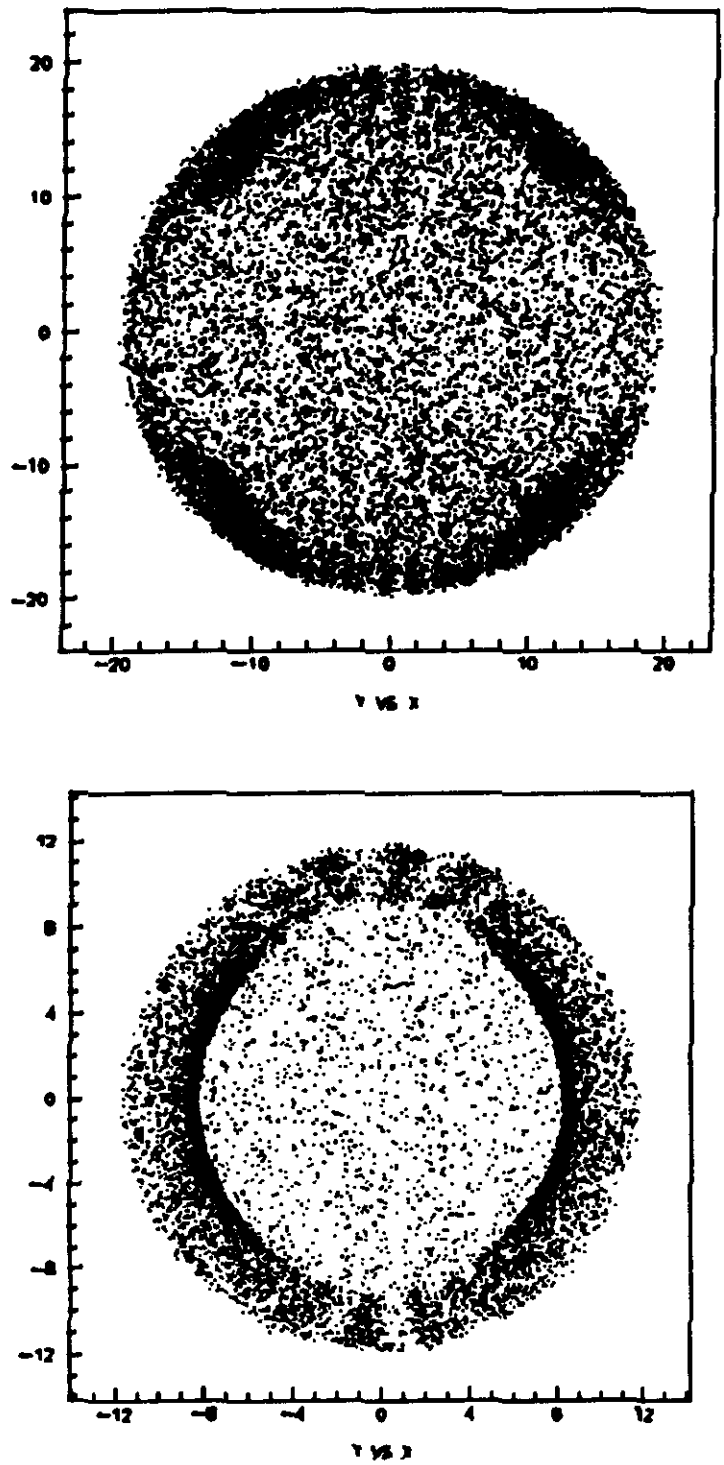


Fig. 6. Folding affects are apparent when a raster scan is aimed at a plasma lens.

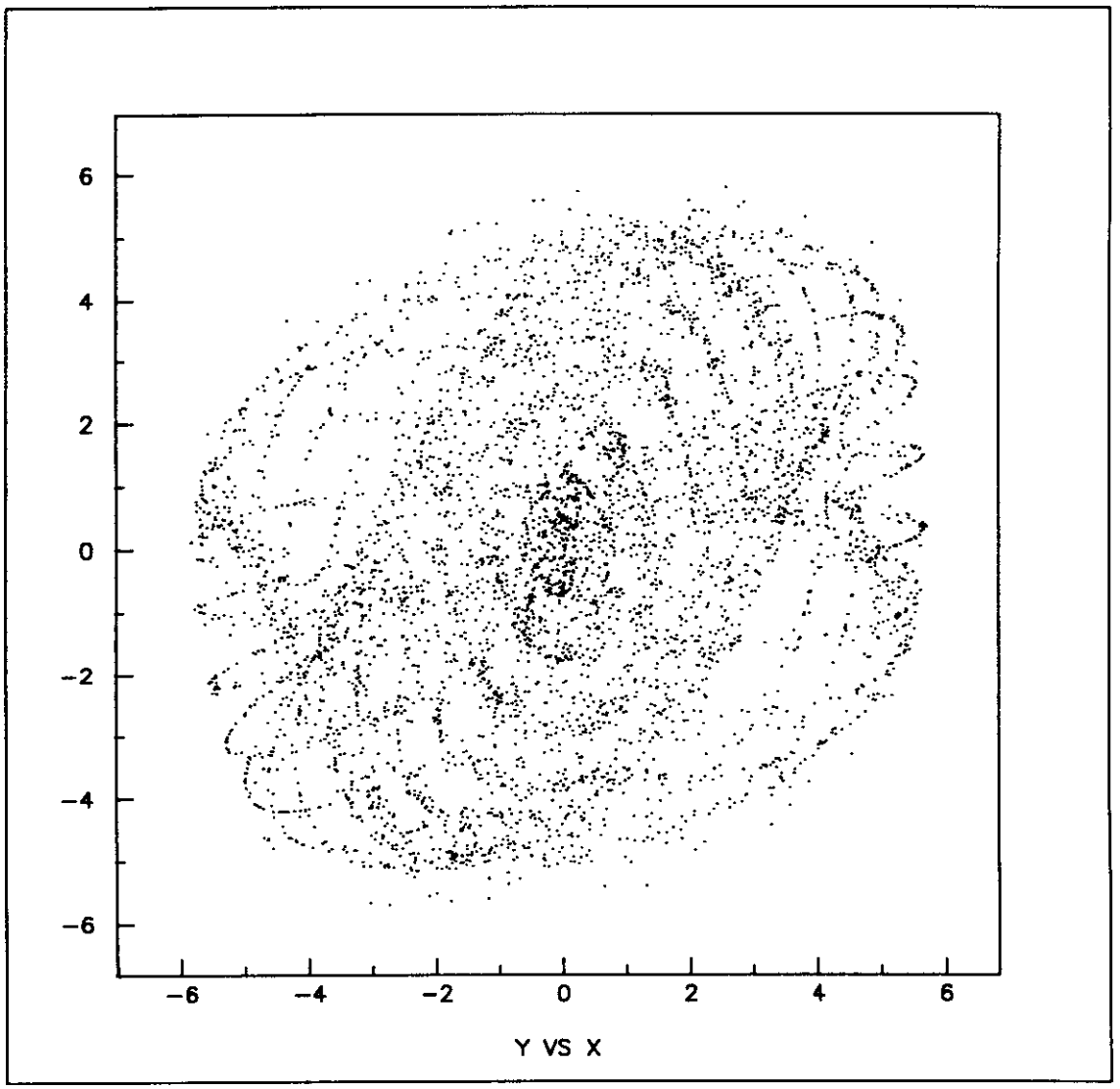


Fig. 7. Circular beam spot from a combination of four oscillating lenses.

Although the shape of the beam spot from this lattice is desirable, regions of the beam absorber reach temperatures of over 4000 K, far beyond the melting point of the absorber material. To spread the beam out more, a single steady-current lens was placed where the radius of the spot reaches 0.9 cm (fig. 8). This arrangement resulted in a beam spot 20 cm in radius and a temperature rise of less than 1000 K, which is within the capacity of the absorber to tolerate.

Another consideration for a beam dump lattice is how the beam will respond if dumped at injection energy. A 2 TeV beam sent through the lattice in figure 9 is spread too much; however, varying the strength of the field proportionally to the energy leads to a constant spread across the absorber. Changing the current in all the magnets to 5 kiloAmps converts the maximum field in the magnets to 0.1 Tesla and works effectively with a 2 TeV beam.

The major problem with this design is its intolerance to the beam entering the lattice off-center from the beam path. When the beam enters as little as 3 mm away from center, severe folding occurs in the beam spot (fig. 9). Moving the steady-current magnet closer in helps to lessen this problem but requires a longer plasma lens.

4. Conclusions

A single plasma lens could be used to spread the SSC beam, but the length that would be required for the necessary spread would also be prohibitively long. With special attention paid to z-pinch instabilities, however, an increase in current could reduce the length of this or any lens used in the beam dump. Oscillating plasma lenses seem to work most efficiently

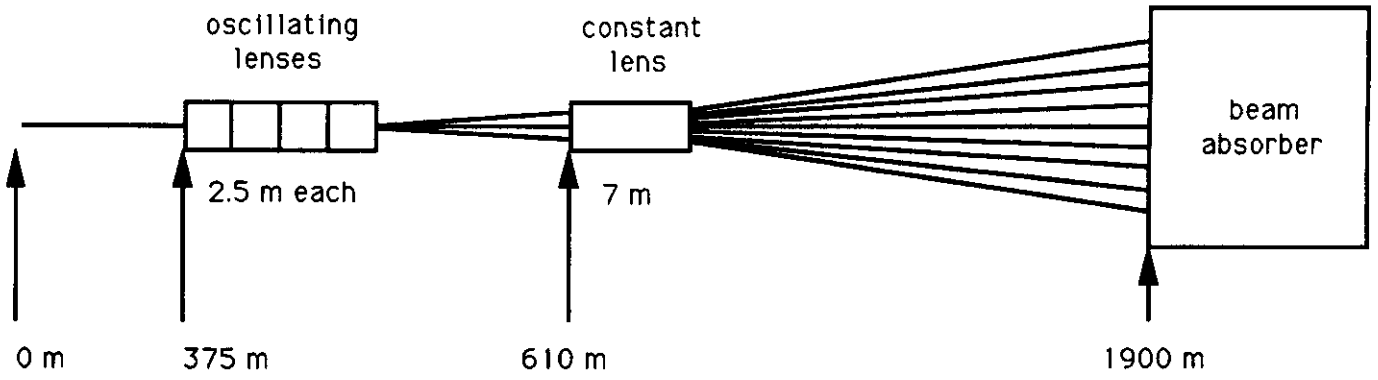


Fig. 8. A fifth lens is placed downstream from the oscillating lenses to further spread the beam on its way to the absorber.

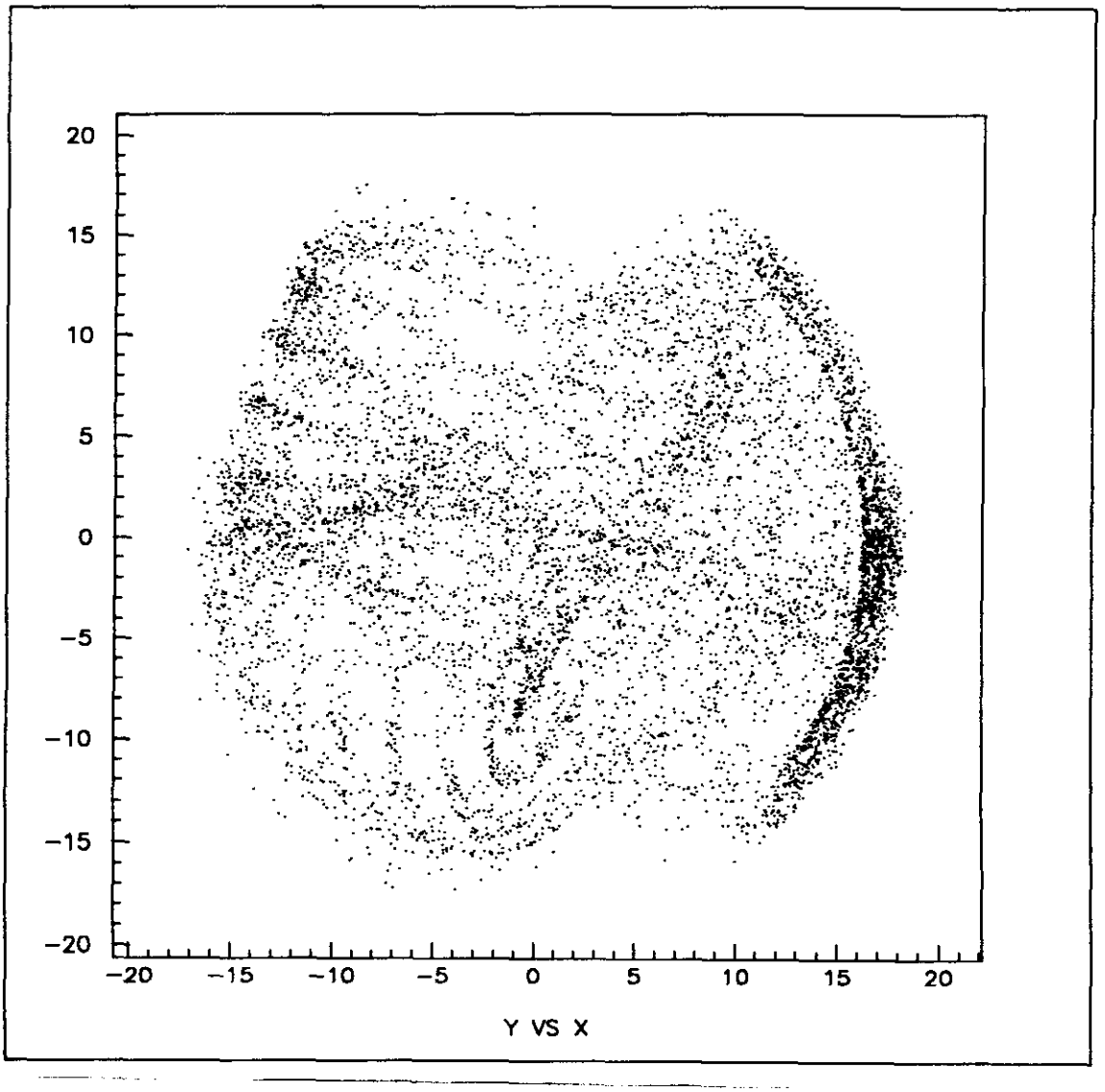


Fig. 9. A beam entering the beam dump 3 mm off-center would take this shape having travelled through the lattice in figure 8.

and perform the best when in combination. A spread can be produced with these combinations larger than that produced by a steady-current lens of equal length. The geometries are also very adaptable to differing beam energies. The main difficulty lies in creating a lattice of plasma lenses that is unbiased to the beam entering the dump off-axis.

Due to the fact that plasma has not been used extensively as a focussing agent, a lattice consisting entirely of plasma lenses may not be reliable enough for initial use in the SSC beam dump. Nonetheless, the exceptional spreading ability suggested by this study shows much hope that with further development of plasma lenses these devices could be used successfully at the SSC in the future.

Acknowledgements

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References

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