*Experimental Observations of Beam Transport in Twisted Quadrupole Fields**

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ABSTRACT

In the course of phase space matching an electron beam from guide field focussing into a twisted quadrupole (stellarator) strong-focussing channel, we have developed Cherenkov imaging techniques to measure the profile and density distribution of the beam. We have imaged a 200 A, 850 keV electron beam (average radius ~ 4 mm) as it propagates through the transition from guide field focussing into a stellarator channel. With no matching lenses, the maximum excursion in major radius of the beam in the stellarator channel was ~ 40%. First attempts at matching reduced this excursion to the 24% level. Significant damping of these mismatched oscillations has been seen over the 2.5 meter length of the stellarator magnet channel. Emittance and profile data will be compared for the beam at the end of the channel with and without detailed matching.

INTRODUCTION

A strong focussing $\ell = 2$ is used in the SLIA (Spiral Line Induction Accelerator) bends to reduce the off-axis motion of the beam centroid for beam elements which are not at the matched energy for the bend radius and bending fields. There is then a transition between the longitudinal guide field transport in the straight sections of the SLIA and the toroidal, stellator, and vertical field transport of the bends. Theoretical calculations predict that if this transition is adiabatic then the beam will change from circular in the straight section to elliptical in the bends without significant envelope oscillations[1]. If the transition is non-adiabatic then the beam envelope oscillates. A matching scheme which uses one or two quadrupole coils plus a ring coil has been devised to take the circular beam from the solenoidal field in the straight section and provide the proper eccentricity and rotation for preservation of the elliptical beam profile in the stellarator fields[2].

BEAM DIAGNOSTICS

Current distribution measurements for the 1 MeV matching experiment were obtained with a Cherenkov[3] imaging system that has been cross-calibrated with a charge collector. The current distribution for a circular beam shown in Figure 1, was determined using two independent diagnostics. The first measurement was done by radially sampling the beam with a charge collector (2 mm resolution). The results of this measurement are plotted as charge density vs. radial position in Figure 2.

The second diagnostic used was the Cherenkov beam imaging system which allowed high resolution 2D information to be determined. With this system a typical beam profile is recorded by imaging the Cherenkov light created by the electron beam. From the digitized image shown in Figure 1, the 2D charge distribution can be reduced by normalizing the optical density of the image with the previous charge collector measurement. Figure 3 is a plot of optical density normalized to charge density vs. radial position. When the optical density of the digitized beam profile was compared over a range of film exposures a good fit was achieved as can be seen in Figure 4. Now that the imaging system is calibrated with direct charge collection data, contour plots and perspective plots can be used to determine the beam charge distribution and radii of an elliptical beam profile. Example contours and perspective plots are shown in Figures 5 and 6. These plots were generated from the circular beam profile shown in Figure 1.

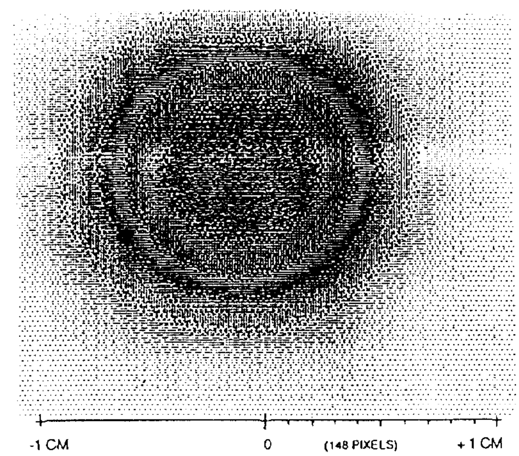

Figure 1. Digitized beam image.

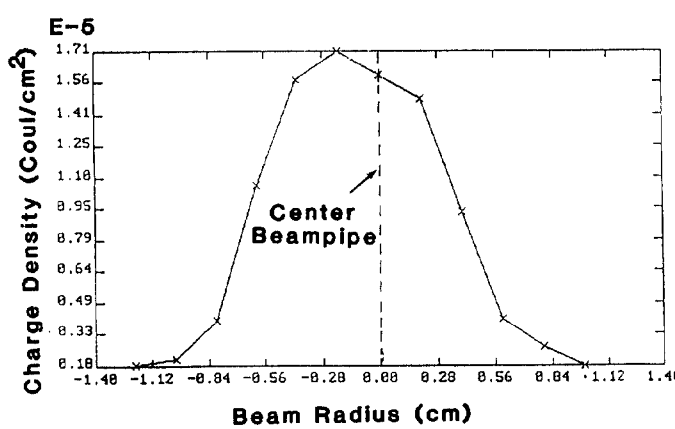

Figure 2. Radially scanned charge collector.

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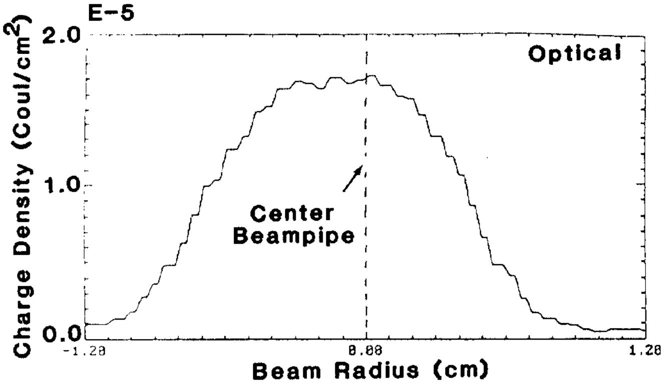

Figure 3. Line profile of Cherenkov image.

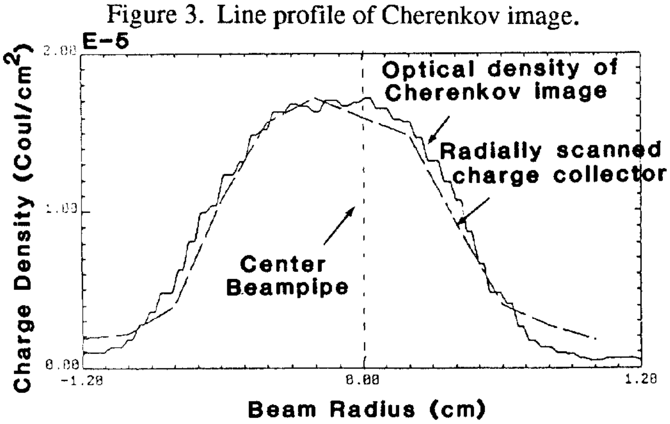

Figure 4. Otical density fit with charge density.

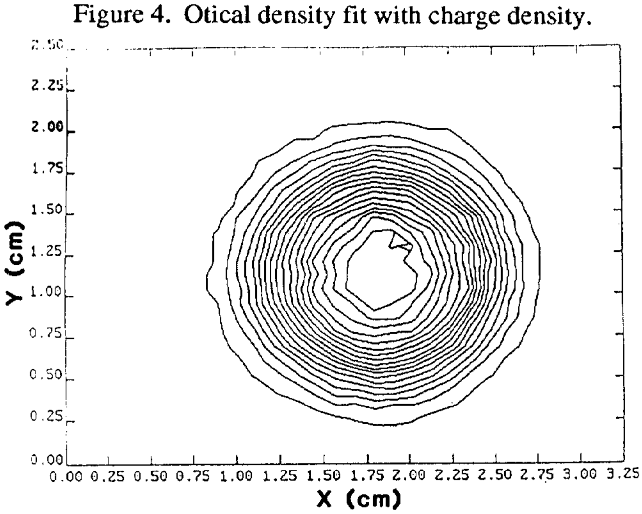

Figure 5. Contour plot of Cherenkov image.

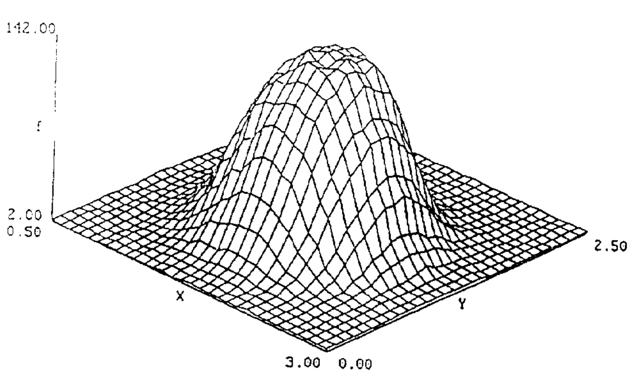

Figure 6. Perspective plot of Cherenkov image.

MATCHING EXPERIMENTS

The Cherenkov imaging technique described above has been used to investigate the beam behavior caused by the transition on and off the stellarator field both with and without matching elements. The beam kinetic energy was 848 kV and the current was 200 A. The 200 A current was chosen to simulate the beam space charge effects in the first POCE (proof-of-concept experiment) bend (4 MeV, 10 kA). The beam was extracted from a field-free diode and inserted into a short solenoid (45 cm) before entering the solenoidal (262 cm) plus stellarator field (251.3 cm) region. Another short solenoid (45 cm) was at the end of the stellarator field region. The long solenoid plus stellarator coil had the same pitch length for the windings (L = 62.83 cm) and length (4L or 251.3 cm) as the first POCE bend. The nominal solenoidal field was 1.48 kG and the on-axis stellarator field gradient was 68.5 G/cm.

No matching lenses were used in the first set of experiments shown in Figures 7 and 8. In the short straight before the stellarator field section the beam was circular and had a diameter of 6.8 mm. To first-order the beam was elliptical and rotated with the stellarator winding pitch as seen in Figure 7.

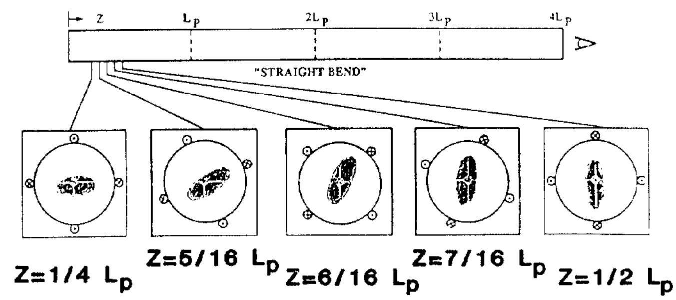

Figure 7. Beam rotation with stellarator coil.

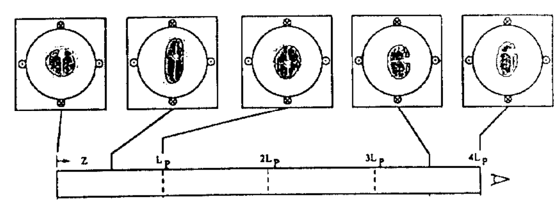

Figure 8. No matching elements.

With no matching lenses the maximum excursion in major radius of the beam in the stellarator channel during the first pitch length was ~ 40%. Significant damping of the mismatch oscillations can be observed over the 2.5 meter length of the stellarator field in Figure 8 and corresponding plot of major and minor radii in Figure 9.

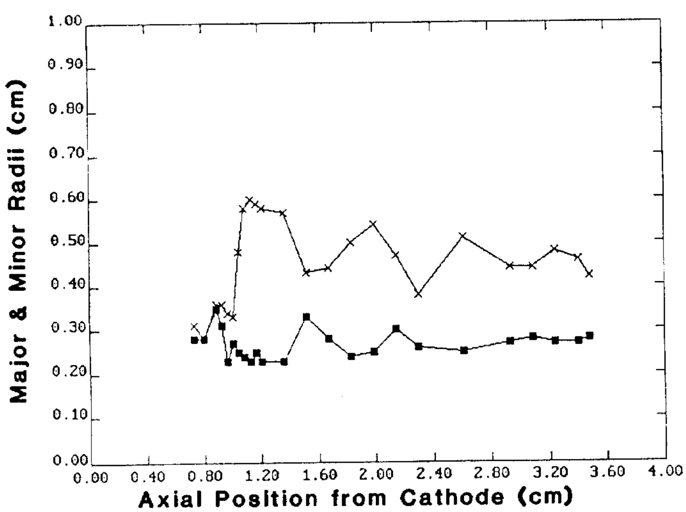

Figure 9. Radius versus position.

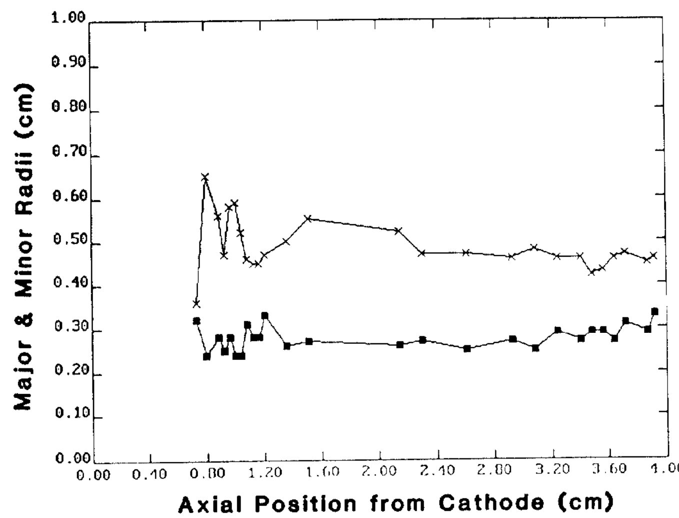

Figure 11. Radius vs. position.

During the last stellarator pitch length the maximum excursion was reduced to the 10% level. When the beam exited the stellarator field, the beam remained elliptical and continued to rotate, but the rotation frequency and ellipticity was less than in the stellarator region.

The first attempt at matching used a three-element match (a ring coil and two quadrupole field coils) in the short solenoid upstream of the stellarator section. The ring coil was centered at 49.3 cm with a bucking field of - 516 G and was used to adjust the beam envelope before entering the quadrupole coils. The first quadrupole was centered at 64.3 cm with a peak gradient of 57.5 G/cm and was rotated 48.2 degrees clockwise with respect to the stellarator; the second quadrupole was centered at 75.3 cm with a peak gradient of 92.2 G/cm and was rotated 1.6 degrees clockwise. A detailed description of the derivation of these orientations is given by Tiefenback [2] in this proceeding. These matching elements reduced the oscillations in major radius in the first pitch length to the 25% level and the beam more closely followed the stellarator pitch winding as can be seen in Figure 10 and corresponding plot in Figure 11.

In the end of the stellarator region and also in the following short solenoid the beam profiles with the matching elements were almost identical to the profiles without the matching element as seen in Figures 12(a) and 12(b).

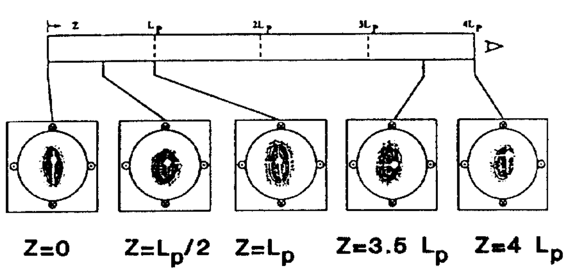

Figure 10. Three matching elements (ring, quad, quad).

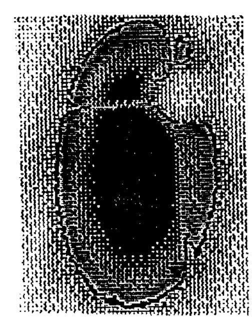

Figure 12(a). Without matching elements.

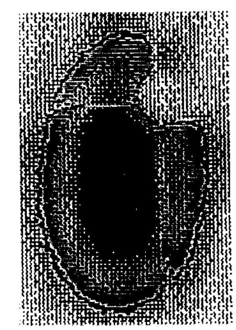

Figure 12(b). With ring and two quads.

CONCLUSION

It can be observed from Figure 9 that the use of quadrupole matching elements is not required in the first bend if the only concerns are mismatch oscillations which seemingly damp out in the 4th period of the stellarator. The issues that may require the use of a matching scheme depend on allowable emittance growth and stellarator-to-stellarator phasing. If emittance growth is observed experimentally then phase space matching can be tuned directly but if the observation of mismatch oscillations are used to achieve matching one needs to understand the damping phenomena.

REFERENCES

[1] D. Chernin, A. Mondelli, and J. Petillo, *SLIA Beamline Design Workshop*, Mission Research Corporation, Albuquerque, NM, 28 August 1989.

[2] M. Tiefenback, *Matching the Transport of Beams in a Continuously Twisted Quadrupole Channel*, Proc. of this conference.

[3] J.D. Jackson, *Classical Electrodynamics*, Wiley and Sons (1962).