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THE SENSITIVITY OF THE PEP BEAM TRANSPORT LINE TO PERTURBATIONS*

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Abstract

The sensitivity of a beam-transport line to various perturbations determines the extent to which one can simplify component design and relax tolerances. For the PEP injection lines we have studied the effects of various fabrication errors, magnet misalignments, and residual gas scattering. Using the TURTLE ray-tracing program[1], we find that magnetic-field errors corresponding to a relative sextupole strength in the dipoles of 0.5% and/or a relative sextupole or octupole strength in the quadrupoles of 5% are permissible. This allows relatively loose tolerances in magnet fabrication. Transverse misalignment of a quadrupole by a distance x causes the beam centroid to be displaced downstream by as much as 5x. This requires a quadrupole alignment accuracy of ± 0.5 mm or better. No compensation for the earth's field is necessary because an integral number of optical wavelengths and a short wavelength were used for the design. Analysis shows that beam broadening from multiple coulomb scattering is insignificant for pressures of less than 1/10 torr.

Introduction

The sensitivity of a beam-transport line to various perturbations determines the extent to which one can simplify component design and relax manufacturing and operational tolerances. For the beam-transport lines of the PEP injection system we have studied the effects of magnetic errors, magnet misalignments, and residual gas scattering on the transmission and quality of the beam. From these results we have determined the corresponding manufacturing and operational criteria.

The PEP Beam-Transport System

The PEP injection system requires two identical beam transport lines to bring the electron and positron beams from the Stanford two-mile linear accelerator to the two injection points in the PEP storage ring, as illustrated in Figure 1. Each line consists basically of a regular, strong focusing FODO lattice with interspersed bending magnets. Optically each line is three wavelengths long plus one short matching section. The bend magnets are distributed so that each wavelength is an achromatic section. There are 24 quadrupoles and 11 principal bending magnets in each line. Each line is about 225 meters long and bends the beam by 60 degrees.

The aperture of the line was designed to transmit an emittance of at least 0.6 π mm-mr and a momentum spread of ± 0.8 percent, corresponding to the maximum acceptance of the SLAC linac. The horizontal dispersion function has a maximum value of 30 mm/percent at quadrupoles Q2, Q4, Q12, and Q14. The limiting apertures are ± 10 mm vertically (defined at the bend magnets), and ± 25 mm horizontally (defined at the quadrupoles). The range of operation is from 4 to 15 GeV/c in beam momentum.

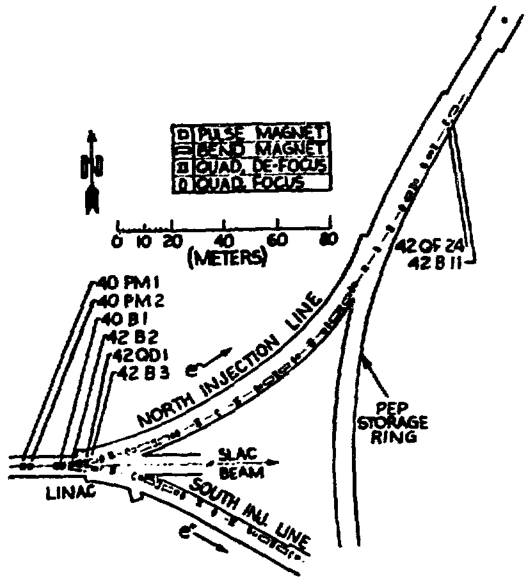

Fig. 1. A general layout of the SLAC-PEP injection system.

The Effects of Magnetic Errors

The effects of magnetic errors was investigated using the TURTLE ray-tracing program[1]. In each magnetic configuration 5000 rays were traced. These were distributed uniformly over a specified transverse and momentum phase space. At the end of the line, the surviving particles were analyzed with respect to the beam's size, angular spread, and momentum distribution. The results for a matched incident beam of 0.3 π mm-mr in each plane and ± 0.8 percent momentum spread are shown in Figure 2 as a function of the strength of a negative sextupole error in each of the quadrupoles.

A beam loss of 10 percent and widening of the surviving beam of the same order of magnitude occurs when the strength of the sextupole distortion reaches approximately 5 percent of the quadrupole field strength at a radius of 25 mm. Factors of 2 in beam loss and in increased beam width occur when the sextupole strength is about 10 or 20 percent of the quadrupole strength. There is a small difference in the degradation with respect to the sign of the sextupole component; the transport line is slightly more tolerant of positive than of negative sextupole components.

The beam loss occurs predominately at the first high-dispersion point in the line. The loss occurs only at the positive edge of the momentum spectrum up to a negative sextupole strength of 10 percent. Above 10 percent both edges of the spectrum are lost at approximately the same rate. For positive sextupole perturbations, the situation is just reversed.

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0.6 percent strength of the sextupole component, at a 25 mm radius, relative to that of the dipole is required. A factor of two effect occurs when the sextupole strength is increased to 1.2 percent of the dipole strength in each of the bend magnets.

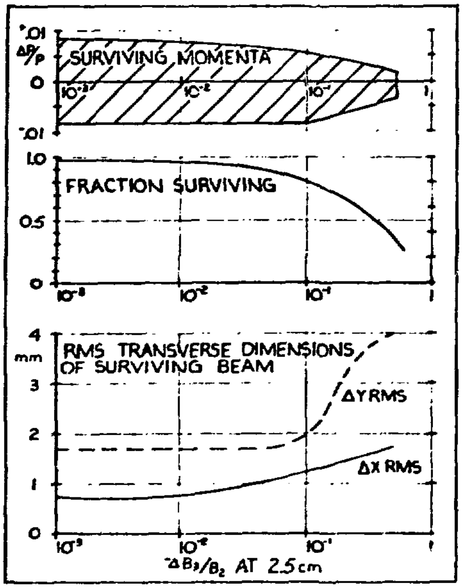

Fig. 2. The effects of sextupole errors in the quadrupoles.

Figure 3 shows the beam loss and widening of the surviving beam caused by positive sextupole errors in each of the bend magnets. To produce a 10 percent effect in beam loss and in beam widening only about

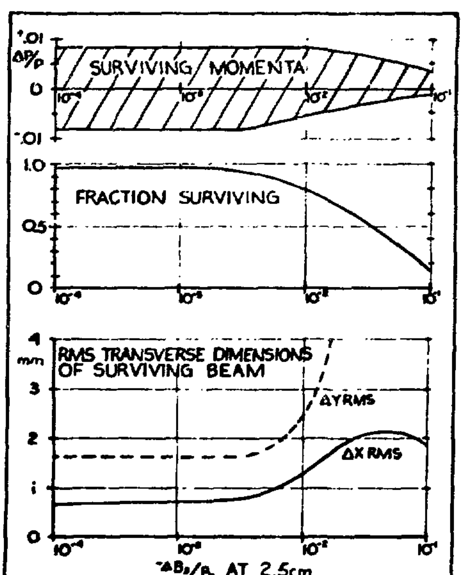

Fig. 3. The effects of sextupole errors in the bend magnets.

From these perturbations studies, the field uniformity specification was set at ± 0.3 percent at the edge of the beam in the dipole magnets and a ± 1 percent error was allowed in the full aperture field of the quadrupoles. As a result relative loose tolerances could be allowed in the manufacture of the magnets.

The Effects of Magnet Misalignments

If a quadrupole magnet is misaligned by a distance of x relative to the centroid of a beam passing through it, then the centroid of that beam can be displaced by a distance of about 5x somewhere downstream in a periodic lattice having a phase shift of 90 degrees/cell. Because of this, the alignment tolerances of the quadrupoles in the PEP injection lines was set at ± 0.5 mm maximum. The design objective was to hold this to ± 0.2 mm if possible. The alignment of quadrupole magnet relative to a beam traversing it can be measured by varying the quadrupole strength and observing the beam deflection at a favorable observation point downstream, e.g., at a 90-degree phase shift downstream from the perturbed quadrupole. In the PEP injection lines most of the quadrupole magnets are connected electrically in series in groups of eight (one wavelength). Each quadrupole is equipped with a partial shorting shunt that may be remotely activated to reduce its energizing current to one-half. This enables us to check the alignment of each quadrupole relative to the centroid of the beam passing through it.

The Effect of the Earth's Field

The effect of the earth's magnetic field on a beam trajectory in a periodic FODO lattice is negligible if the distance and angle of bend within a pi phase shift is small. In a regular lattice, such as the PEP injection lines, the effect of a perturbing field at one point in the lattice is cancelled completely by an identical perturbation located at a pi spase shift downstream. Since the PEP beam transport line is three wavelengths long, the compensation of the effects of the earth's field is almost complete. Because of the curvature of the transport lines, the values of the effective horizontal component of the earth's field at points pi phase shift apart are not exactly identical, but nevertheless the cancellation is adequate. The net deflection at the end of the injection lines caused by the earth's field is about 0.1 mm. As a comparison, if the beam were just drifting, the net deflection would be about 10 cm at 4 GeV/c.

The Effect of Gas Scattering

Multiple scattering of the beam by the residual gas in the beam transport system tends to broaden the beam in a known way. Again, the periodic array reduces the magnitude of the broadening by a significant amount. The rms transverse multiple scattering broadening expected in a pencil electron beam drifting a distance L is given approximately by:

$$\Delta x = 15L^{3/2}/p(3L_R)^{1/2}$$

where p is the momentum of the beam in MeV/c, and L_R is the radiation length of the scattering medium. For a distance corresponding to the length of the PEP injection lines, filled with air at a pressure of 0.01 torr, a 4 GeV pencil beam would grow to about ± 1.5 mm rms width. However, when the strong focusing effects or the PEP quadrupoles are taken into account, the broadening is reduced to only 0.13 mm with the same gas conditions. Qualitative considerations show, and the TURTLE calculations confirm, that the dependence of the broadening on the total drift distance L and on the inter-quadrupole spacing L_Q is $L^{1/2}L_Q$ rather than $L^{3/2}$, as in the simple (non-focussed) drift situation. Since the dependence on the pressure p of the residual gas is $\sqrt{p}$, a pressure of 0.1 torr would produce a widening of about 0.4 mm, which would be acceptable for the PEP injection beam whose transverse dimensions can be ± 3 mm at 4 GeV.

References

1. D.C. Carey, K.L. Brown, Ch. Iselin, TURTLE A Computer Program for Simulating Charged Particle Beam Transport Systems, including Decay Calculations, FERMILAB Report NAL-64, December 1971, and CERN 74-2, February 1974.