THE SENSITIVITY OF THE PEP
BEAM TRANSPORT LINE
TO PERTURBATIONS*

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Abstract

The sensitivity of a beam-transport line to vari-
ous perturbations determines the extent to which one
can simplify component design and relax tolerances.
For the PEP injection lines we have studied the ef-
fects of various fabrication errors, magnet misalign-
ments, 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 per-
missible. This allows relatively loose tolerances in
magnet fabrication. Transverse misalignment of a quad-
rupole 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 be-
cause an integral number of optical wavelengths and a
short wavelength were used for the design. Analysis
shows that beam broadening from multiple coulomb scat-
tering is insignificant for pressures of less than
1/10 torr.

Introduction

The sensitivity of a beam-transport line to vari-
ous 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 inter-
spersed 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 disper-
sion function has a maximum value of 30 mm/percent at
quadrupoles Q2, Q4, Q12, and Q14. The limiting aper-
tures are ± 10 mm vertically (defined at the bend mag-
nets), and ± 25 mm horizontally (defined at the quadru-
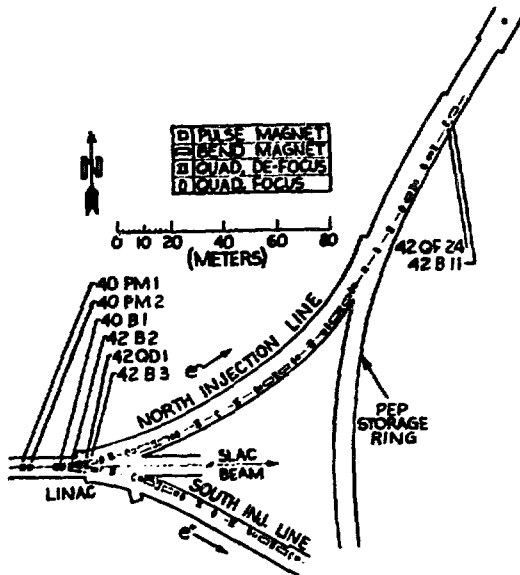poles). The range of operation is from 4 to 15 GeV/c
in beam momentum.

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 mag-
netic configuration 5000 rays were traced. These were
distributed uniformly over a specified transverse and
momentum phase space. At the end of the line, the sur-
viving 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 sur-
viving beam of the same order of magnitude occurs when
the strength of the sextupole distortion reaches approx-
imately 5 percent of the quadrupole field strength at a
radius of 25 mm. Factors of 2 in beam loss and in in-
creased 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 approxi-
mately the same rate. For positive sextupole perturba-
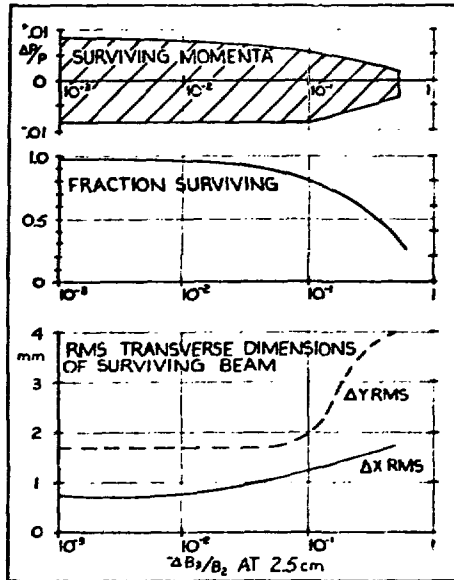tions, the situation is just reversed.

Fig. 2. The effects of sextupole errors in the quad-
rupoles.

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
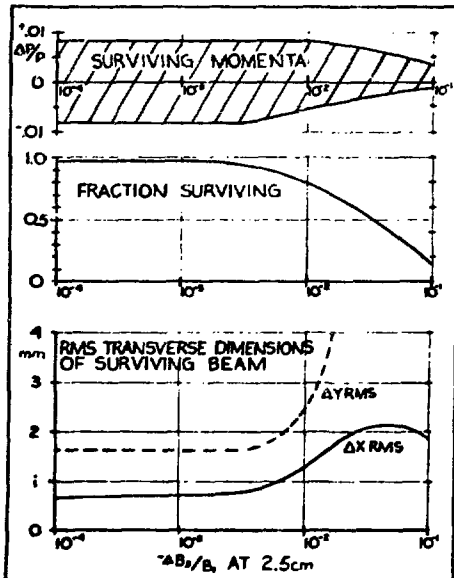effect in beam loss and in beam widening only about

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

0.6 percent strength of the sextupole component, at a
25 mm radius, relative to that of the dipole is requir-
ed. 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.

From these perturbations studies, the field uni-
formity specification was set at ± 0.3 percent at the
edge of the beam in the dipole magnets and a ± 1 per-
cent 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 per-
iodic lattice having a phase shift of 90 degrees/cell.
Because of this, the alignment tolerances of the quad-
rupoles 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 mag-
net 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 must
of the quadrupole magnets are connected electrically in
series in groups of eight (one wavelength). Each quad-
rupole is equipped with a partial shorting shunt that
may be remotely activated to reduce its energizing cur-
rent to one-half. This enables us to check the align-
ment 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 injec-
tion lines, the effect of a perturbing field at one
point in the lattice is cancelled completely by an
identical perturbation located at a pi space shift down-
stream. 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 expec-
ted in a pencil electron beam drifting a distance L is
given approximately by:

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

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 in-
jection 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.