

# THE OPTICAL DESIGN OF THE PEP-II INJECTION BEAMLINES\*

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## Abstract

The optical design of the PEP-II<sup>1</sup> electron and positron Injection Beamlines is described. Use of the existing high power, low emittance beams available from the SLC damping rings require that pulsed extraction of 9.0 GeV electrons and 3.1 GeV positrons for injection into the PEP-II rings occur in the early sectors of the accelerator. More than 5 kilometers of new beam transport lines have been designed and are being constructed to bring these beams to their respective rings. The optical design maximizes the tolerance to errors especially to those contributing to beam size and position jitter. Secondly, the design minimizes costs by utilizing existing components or component designs and minimizing the number required. Here we discuss important attributes including choice of lattice, specification of error tolerances, including errors in construction, alignment, field errors, power supply stability, and orbit correction.

## 1 INTRODUCTION

A key feature in the design of PEP-II is the utilization of a powerful existing source of low emittance 3.1 GeV positrons and 9.0 GeV electrons for injection into the rings. The SLAC linac, including its damping rings, positron source and other improvements made for SLC is ideal for this purpose. While two-thirds of the linac will be used for positron beam generation, the resultant beam will be pulse magnet extracted in an early sector (Sector 4 of 30) to preserve emittance, and transported 3.0 km through the Low Energy South Injection Transport line

(LESIT) in the linac housing to the Low Energy Ring (LER). The High Energy North Injection Transport line (HENIT) starts in Sector 10 where electrons are pulse magnet extracted and transported 2.36 km to the High Energy Ring (HER).

Combined the beamlines, now under construction,<sup>2</sup> consist of 62 dipoles (5 pulsed), 149 quadrupoles, 102 large power supplies (4 pulsed), 151 Beam Position Monitors (BPMs), 226 orbit corrector dipoles and 5.4 km of vacuum chamber.

## 2 OPTICS

Two concepts were foremost among the many considerations leading to the optical design. First was the need for high reliability and high tolerance to error. This influenced the choice of the lattice and placement of elements, the attention given to sensitivity to error, and the consideration of the beam stay clear and the optical needs for diagnostic instruments. Second was the need to limit the cost of construction to be as low as possible. This led to retaining use of existing components of the old PEP transport lines as much as possible and keeping the design of the two new beam lines as identical as possible to limit the number of new component designs.

### 2.1 Regions and Lattices

The two beam lines are optically almost identical and consist of four sections identified as Extraction, Bypass, Arc and Match. As shown in Figure 1, we identify the optics of these regions and the intervening subsections as Extraction Lattice (EL), Extraction to Bypass Match (EBM), Bypass Lattice (BL), Bypass to Arc Match

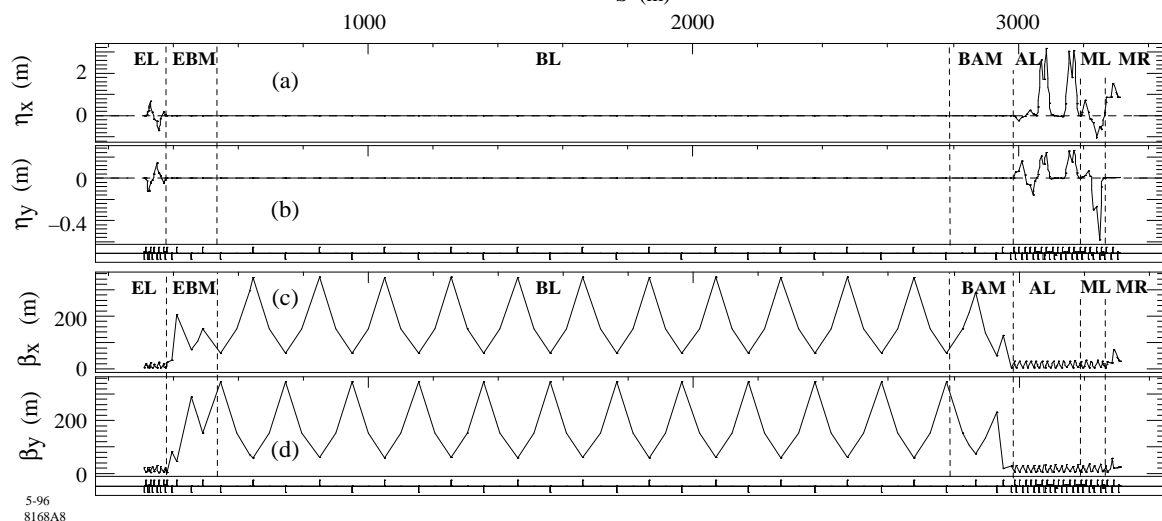


Figure 1 The beam functions of the PEP-II positron injection line. The electron line is almost identical.

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(BAM), Arc Lattice (AL), Match Lattice (ML), and Match to Ring (MR) optics.

The EL, BL, AL and ML quadrupole lattices are all evenly spaced FODO arrays of  $90^\circ$  per cell. This choice of phase advance which was already used for the old AL was extended to the others because it greatly facilitates the control of the sensitivity to power supply instabilities along with control of the dispersion and beam line geometry by allowing the placement of dipoles at points separated by the identity transfer matrix or its negative. The phase advance for the BL which has no dispersion was chosen to be  $90^\circ$  but can be modified.

Matching old and new optical systems required general methods of controlling geometry and dispersion. This was accomplished with a few simple rules applying to these lattices: 1) Two dipoles of equal bend placed  $\pi$  phase advance apart change direction and offset with no overall dispersion. 2) Two dipoles of equal opposite bends placed  $2\pi$  apart generate an offset with no change of direction or overall dispersion. 3) Four dipoles of equal strength in an evenly spaced chicane (two central opposing the two outer) straddling one or more quadrupoles generate no overall offset or direction change but do generate dispersion. 4) Four dipoles in an unevenly spaced chicane generate no direction change but do generate offset and dispersion. 5) Rolling these dipoles can decrease number of systems required.

The special matching lattices EBM, BAM, and MR where the beta (and dispersion for MR) functions are matched all consist of four unevenly spaced quadrupoles. Matching with two tandem Quarter-Wave Transformers<sup>3</sup> to handle the large difference in betas though optically elegant would require at least 6 quadrupoles and were too costly.

Starting with the BL the quadrupoles for the two beam lines are spatially and optically brought into register. Thus the quadrupoles of the two Bypasses are supported side by side on the same stand and are optically identical, both having the same focal length. This optical pairing continues even after the beams become spatially separated into their separate tunnels to the rings. Thus, except for the final four quadrupoles in the MR all other quadrupoles are functionally symmetric. The two beams are extracted at two optically different regions of the linac but are matched to the same BL, thus synchronizing all downstream optical functions of the two beams may have occurred at any point in the BL. A single "polarity reversing" quadrupole is placed at the start of the positron BL to reverse the optical function of all downstream quadrupoles. This quadrupole is placed at a point equivalent to the mid-point between two lattice quadrupoles where  $\beta_x = \beta_y$  and  $\alpha_x = -\alpha_y$ . Its strength is adjusted to reverse the sign of  $\alpha_x$  and  $\alpha_y$ , causing  $\beta_{\text{maximum}}$  of both planes to move one half a cell to match the electron beamline. From this point on all the beta functions of the two beams are matched. The AL and ML would work equally well if all quadrupoles were reversed (or the beam polarity and dipoles were reversed) but doing so would modify the dispersion and decrease the energy acceptance

### 2.3 Extraction Lattice

The design of both extraction regions provide a match to the linac lattice, remove dispersion from extraction dipoles, provide monitoring and feedback control of the extracted beam energy, position and direction. Care was taken to limit the disturbance to the linac. The lattice of each is a close continuation of the local linac lattice with a small increase of spacing to offset quadrupoles longitudinally. The spacing is 6.35 m, 6.55m, 12.7 m and 12.9 m for the linac, positron EL, linac and electron EL, respectively. Extraction for both beams is initiated by a slow (milliseconds) pulse magnet kicking the beam into a Lambertson Septum magnet, allowing the operation of PEP-II and other beams. The positron pulsed extraction has been designed to be convertible to the originally proposed system where positron and electron beams spaced in time by 60 ns are separated by a chicane of DC magnets. This conversion, for dedicated PEP-II operation at higher rate, will require no changes to the beam line geometry downstream of the first quadrupole. The energy resolution in the dispersive regions is approximately  $1 \times 10^{-3}$ , matching that needed for the energy and position feedback system and allowing the use of an adjustable collimator to limit the energy spread. The collimation design allows for an acceptance before the first quadrupole of at least 7.5% for  $e^+$  and 3.5% for  $e^-$  to allow for the loss of a klystron.

Following the EL the EBM consists of four quadrupoles providing an optical match to the bypass lines. One of these quadrupoles is used with a Wire Scanner (WS) placed  $90^\circ$  in phase advance downstream to measure the beam emittance and optical functions. The design allows for a range of beta match in each plane of  $\beta_{\text{nominal}}/2 \leq \beta \leq 2\beta_{\text{nominal}}$

### 2.3 Bypass Lattice

The BL consists of one quadrupole per sector spaced 101.6 m apart with an aperture of 50.8 mm and BPMs and orbit correctors for both planes near each. Alternating quadrupoles are powered in series by two power supplies. This spacing was increased from the proposed spacing of 50.8 m and the vacuum pipe made to be a constant diameter of 50 mm to save mechanical fabrication costs. This change caused the maximum excursion of the unshielded corrected orbit at 3 GeV to increase four-fold to 6 mm with a corresponding corrector strength an order of magnitude larger than that calculated to correct alignment errors. Study<sup>4</sup> showed that it would be cost effective to shield against this and other anomalous fields known to exist within the housing by wrapping  $\mu$ -metal around the 50 mm beam pipe over 98% of the BL.

Again, following the BL is the BAM consisting of four quadrupoles optically matching the BL to the AL. The design allows for a range of beta match in each plane of at least  $\beta_{\text{nominal}}/2 \leq \beta \leq 2\beta_{\text{nominal}}$  with the option of using a WS.

### 2.3 Arc and Match Lattice

The AL and ML have a spacing between quadrupoles of 8.5 m as did most of the original PEP transport lines.

The large dipoles of the HENIT Arc are all identical and powered by a single supply. For the LESIT this is not true following a suggestion<sup>5</sup> that saved cost and added stability. Here the first magnet of the old beamline NIT was traded with the third magnet in (LE)SIT thus causing the first and third magnets of LESIT to be identical and separated by  $\pi$  phase advance (rule 1 above) but at the same time allowing all dipoles in HENIT to be the same. The cost of additional disruption of the beamlines was offset by increased stability saving power supply costs.

Matching the geometry and beam conditions for each ring required that the dipoles of the two ML regions be quite different. Two sets of rolled dipoles were sufficient to match the plan view geometry and also bring the beam to the proper height while correcting for a vertical downward slope of  $4.4^\circ$ . However, matching the dispersion at the IPs required introducing differing chicanes of four dipoles in each line.

The MR regions consist four quadrupoles matching to the optimum parameters for injection with a range of variability of at least  $\beta_{y, \text{nominal}}/2 \leq \beta_y \leq 3\beta_{y, \text{nominal}}$ .

#### 2.4 Optics for Wire Scanners

Wire Scanners (WS) are used to measure beam size versus a varying quadrupole strength. The measurement is best in the absence of dispersion and when the beam size passes through a minimum (vertex of a parabola). This minimum occurs when the phase advance between the quadrupole and the WS becomes  $\pi/2$ . If this occurs in both planes at the nominal setting for the quadrupole then the beam size will grow in both planes for any deviation. If the nominal beam at the WS is round i.e.  $\sigma_x = \sigma_y$  and  $\beta_x = \beta_y$  and  $\alpha_x = \pm \alpha_y$  then the beam stays round and grows larger for all deviations from nominal. Such parameters occur at the mid-point between quadrupoles in a FODO array and everywhere in a drift region containing a round beam simultaneous waist. Optics suitable for WS measurements were included without adding special quadrupoles. The beam for the Bypass WS has the special features described above. In the ML for HER, a special WS optics different from that used for injection is necessary to suppress the dispersion.

#### 2.5 Tolerance to errors

The criterion for error limited the contribution of each system to  $\leq 0.1 \sigma$ , where  $\sigma$  represents the sum in quadrature of the rms of the beam size and divergence at the Injection Point (IP).

Each of the component's errors are considered from several different viewpoints with the allowed error determined by the most sensitive. These viewpoints included: Good Engineering Practice (GEP), initial setup and reproducibility, correctibility and stability. Many tolerance specifications consistent with GEP are conservative when compared with what may be tolerated. Standard care in manufacture limits variation of integrated fields to about two parts per thousand among components without increased costs. Amplitude of multipole fields is similarly controlled. This integrated field variance for

quadrupoles is conservative from the viewpoint of initial setup and correctibility (see matching sections) and for the dipoles is consistent with alignment errors and orbit corrector strength. Tolerances determined from the viewpoint of initial setup and reproducibility were usually met with power supplies satisfying the stability criteria.

Stability was divided in to two parts: fast jitter and slow drift. Changes at rates less the 0.1 Hz were considered slow drift and correctible by the feedback system. Fast jitter stems from transverse vibrations of quadrupoles or fast fluctuations of dipole fields. The tolerance for the former is limited to a few microns but can be inexpensively controlled. Costly to control are fast field fluctuations but these were greatly reduced by the optical design. Thus for quadrupoles care was taken to limit this sensitivity by limiting the unitless product,  $k\beta_{\text{max}}$ , where  $k=1/f$  and  $f$  is the focal length. For a FODO cell of  $90^\circ$  phase advance this parameter has the small value of 4.8. Care was taken that this value not exceed 12 elsewhere. For dipoles, this sensitivity was reduced by orders of magnitude by designing almost all dipoles to be paired in series according to the rules cited above. This strategy allowed the tolerance for fast jitter on the quadrupole and dipole fields to be set to a level of one part in ten thousand in keeping with GEP.

New measurements of the reused PEP Arc dipoles<sup>6</sup> show emittance growth due to higher order aberrations to be small.

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