# Zero-Degree Injection Line for PILAC, the Proposed Los Alamos Pion Linac*

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*Abstract*

In this paper, an optimized injection line for PILAC [1], the proposed Los Alamos Pion Linac, is presented. With the other optimized components (pion source, accelerator, and high-resolution beamline and spectrometer), the system is capable of delivering $10^9$ 920-MeV pions per second to the target.

## I. INTRODUCTION

The injection line transports beam from the pion source to the accelerator. The requirements for this line are discussed and its properties are described. Issues concerning the linear transport are touched upon, but the emphasis is on the tuning process for the nonlinear elements used for aberration correction. The beam-optics code MARYLIE [2] was used for all nonlinear optimizations and to evaluate the performance of the line. The line was optimized for 380-MeV pions (peak of pion production) but, in accordance with specifications, can transport pions of up to 530 MeV.

## II. REQUIREMENTS

### A. Geometry

The line must be as short as possible. After 20 m, half of the 380-MeV pions will have decayed. There must be sufficiently long drifts to place radiation shielding for the magnetic elements. Pion production is peaked in the forward direction, favoring a zero-degree injection system. Consequently, the line must feature a bend to subsequently separate pions from protons.

### B. Matching

The line must provide a transverse and longitudinal match between source and accelerator. Transversely, the small-size, high-divergence beam from the pion source (in TRANSPORT [3] notation described by $x = 0.45$ cm, $x' = 50$ mrad, $r_{12} = 0$, $y = 0.45$ cm, $y' = 50$ mrad, $r_{34} = 0$) must be matched to the accelerator acceptance ($x = 3.845$ cm, $x' = 6.479$ mrad, $r_{12} = -0.429$, $y = 5.631$ cm, $y' = 6.924$ mrad, $r_{34} = -0.817$). Longitudinally, an upright beam covering $\pm 45$ psec and $\pm 16$ MeV at the pion source ($s = 1.3$ cm, $\delta p/p_o = 3.32\%$) is accepted by the accelerator, provided the beam correlation is that which would be seen after traversal of an 11-m drift.

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### C. Aberration Correction

The line must have a layout conducive to placement of nonlinear elements. Because both the transverse emittance and the momentum bite of the beam transported by the line are large (22.5 $\pi$-cm-mrad and $\pm 3.32\%$, respectively), the beam will be severely degraded by both chromatic and geometric aberrations unless sextupoles and octupoles are added to cancel the most detrimental of these aberrations.

## III. PROPERTIES

The injection line has a length of 20.083 m and consists of a matching section followed by a 90° bend (Fig. 1).

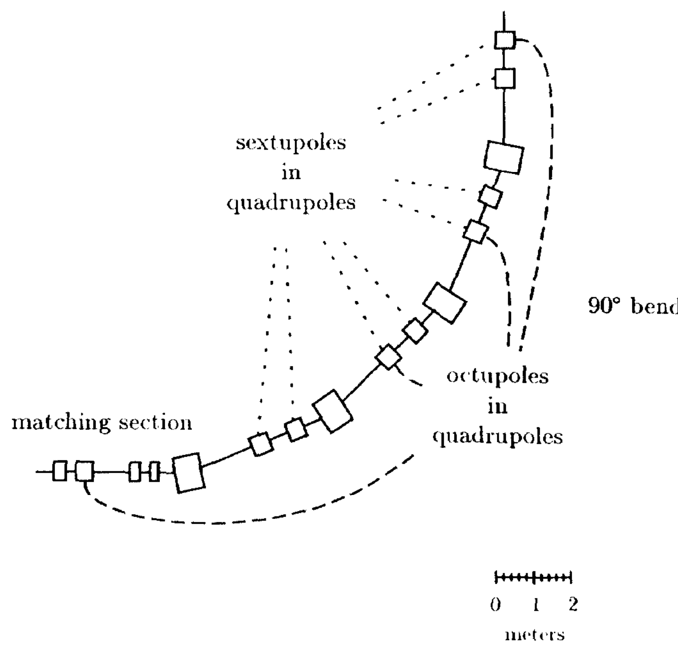


Figure 1. Layout of the PILAC zero-degree injection line.

The four-quadrupole matching section provides the proper transverse match between pion source and accelerator in the tightest possible configuration. The first doublet consists of two strong focusing elements. It represents a compromise between compactness of design (component spacing and dimensions) and pole-tip field strength. Strong focusing as close as possible to the pion source minimizes both chromatic and geometric aberrations. However, a 0.5-m drift between the pion source and the first quadrupole is needed for radiation shielding.

The 90° bend has the component layout and first-order focus of a second-order achromat [4]; its transverse transfer

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matrix is the unit matrix. Because the accelerator input beam transports well through the bend, it is possible to perform the transverse matching entirely upstream of the bend. The beam size in the bend is largely governed by dispersion. An FD lattice has a noticeably smaller dispersion than a DF lattice of the same geometry. For FD lattices, varying the dipole edge angles has an insignificant effect. Consequently, parallel-pole-face dipoles were assumed. A bend angle per dipole of 22.5° results in an equivalent drift for the line of 11.06 m for 380-MeV pions (5.10 m for 530-MeV pions). There is a 1.5-m drift between dipoles and F-quadrupoles to accomplish the separation of pions from protons.

The line features four sextupole pairs and four octupoles to correct the most detrimental chromatic and geometric aberrations. For compactness, the nonlinear elements are placed inside the quadrupoles.

## IV. TUNING OF SEXTUPOLES

Sextupoles in the dispersive section of the injection line influence second-order chromatic aberrations. Tuning of these sextupoles to produce a second-order achromat is compared with the tuning of the PILAC injection line, which produces a line with output-beam Twiss parameters $(\beta_x, \alpha_x, \beta_y, \alpha_y)$ that do not linearly depend on momentum. In either case, pairs of sextupoles are placed such that the second-order geometric aberrations caused by individual sextupoles are cancelled. However, cross-coupling of the sextupole pairs generates residual third- and higher-order aberrations.

### A. Second-Order Achromat

A second-order achromat consists of four identical cells with 90° phase advance per cell, each containing bending and focusing elements. This automatically leads to a first-order achromat with $R_{16} = 0$ and $R_{26} = 0$. Two families of sextupoles, tuned so that the horizontal and vertical chromaticities are zero, cause all second-order chromatic transfer-matrix elements to vanish except $R_{566}$, the quadratic dependence of longitudinal position on momentum. The resulting bend is called a second-order achromat.

The matched beam of the bend, when sent through the bend with sextupole families turned off, has output-beam Twiss parameters that do not linearly depend on momentum. However, there are other transverse and longitudinal chromatic aberrations, manifesting themselves, for instance, in the nonzero chromaticities. Beams other than the matched beam have a linear dependence of the output-beam Twiss parameters on momentum, which gets zeroed with the two sextupole families, whose settings are beam independent.

### B. Twiss-Parameter-Corrected Injection Line

When a matching section precedes the just-mentioned second-order achromat, the output beam exhibits the chromatic aberrations caused by the quadrupoles in the matching section. One continues to have $R_{166} = R_{266} = 0$ and $R_{516} = R_{526} = 0$, but all other previously zero second-order chromatic transfer-matrix elements are nonzero.

For an output beam intended to match to the transverse acceptance of an accelerator, the quantities that should not exhibit aberrations are the Twiss parameters. Using MARYLIE, the linear dependence of the Twiss parameters on momentum was zeroed for the line using four pairs of sextupoles. The procedure does not work for a line in which the matched beam of the bend goes through the bend.

## V. TUNING OF OCTUPOLES

Once the sextupoles are properly tuned, octupoles can be used to correct some of the third-order aberrations. Octupoles in the dispersionless sections of the injection line are used to influence third-order geometric aberrations, and octupoles in the dispersive section to influence third-order chromatic aberrations.

Because there are many nonzero third-order geometric transfer-matrix elements, an informed selection must be made. For a line accomplishing a true point-to-parallel focus, there are three Lie polynomials that, when zeroed, eliminate all third-order geometric aberrations distorting the output beam. The injection-line focus is approximately a point-to-parallel focus. There are only two independent octupole positions in the dispersionless sections of the injection line (as deduced from very large settings when using three octupoles to zero all three Lie polynomials). The third-order geometric aberrations of the injection line are caused mostly by quadrupole fringe fields, which are treated in MARYLIE in hard-edge approximation. The second quadrupole in the matching section, in which the beam is large vertically, is a major contributor to these aberrations. Thus, two octupoles were used to zero those two Lie polynomials that cause aberrations in the vertical phase space.

Two octupoles in the dispersive section of the injection line were used to zero two Lie polynomials that significantly contribute to the dependence of the horizontal particle coordinates on the cube of the momentum.

## VI. EVALUATION

To evaluate the design, a beam was transported through the injection line using MARYLIE. An input beam in MARYLIE coordinates was generated. These coordinates are $Z_1 = x$, $Z_2 = p_x/p_o \approx x'$, $Z_3 = y$, $Z_4 = p_y/p_o \approx y'$, $Z_5 = s/\beta$, and, for $\delta p/p_o \ll 1$, $Z_6 \approx -\beta\delta p/p_o$, where $p_x$ and $p_y$ are particle momenta, $p_o$ is the design momentum, and $\beta = v/c$. MARYLIE uses MKSA units. Allowed input-beam coordinates lie inside two-dimensional ellipses in $Z_1Z_2$ and $Z_3Z_4$ phase space (specified above) and inside a rectangle with $-0.0135 \leq Z_5 \leq 0.0135$ and $-0.032 \leq Z_6 \leq 0.032$ in $Z_5Z_6$ phase space. Probabilities were determined assuming a Gaussian distribution in $Z_1$ and $Z_3$ (like the pion-producing proton beam, with $Z_1 = 0.0045$ or $Z_3 = 0.0045$ corresponding to $2\sigma$) and a uniform distribution in $Z_2$, $Z_4$, $Z_5$, and $Z_6$. A pion was

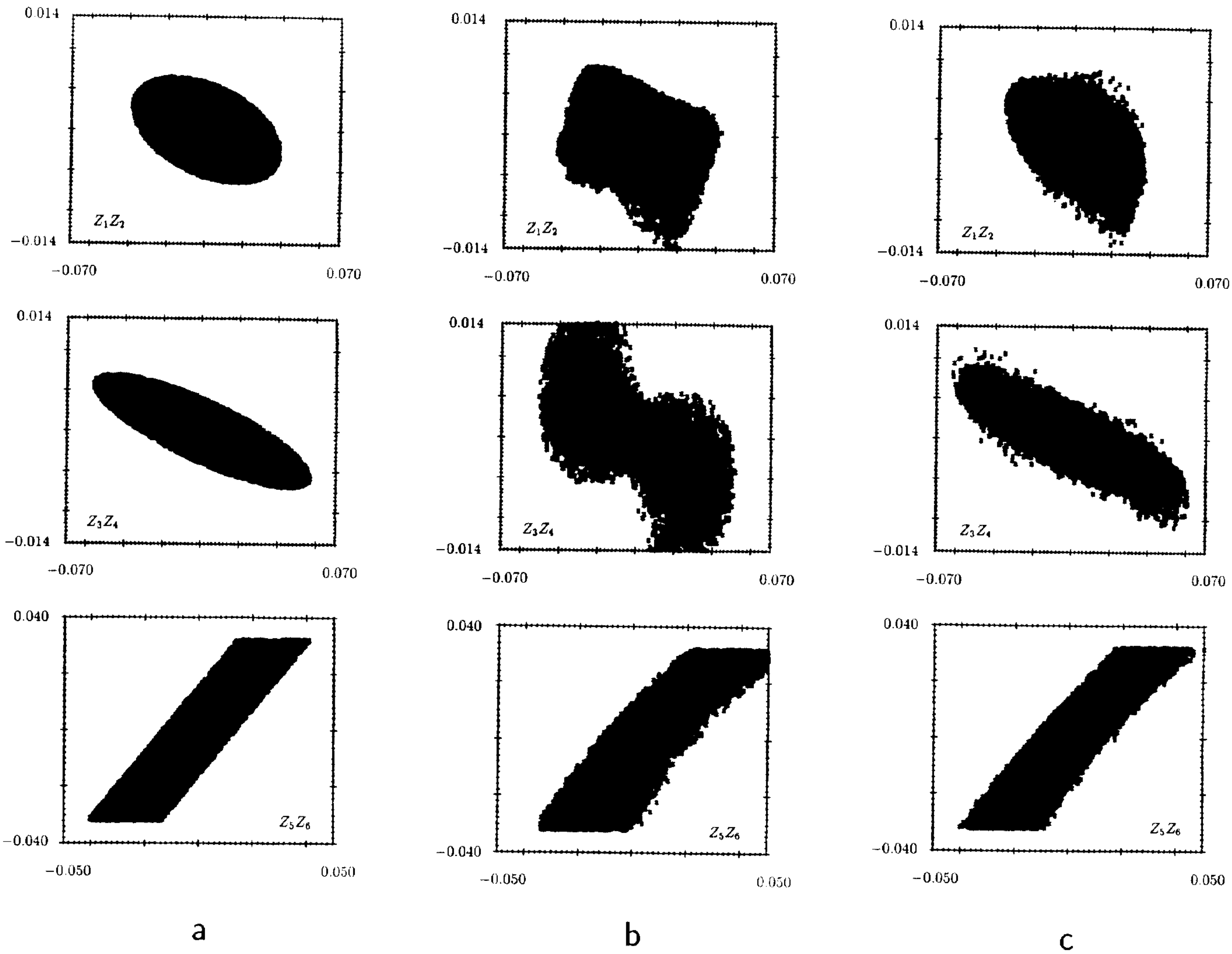


Figure 2. Transverse and longitudinal phase-space projections of the output beam for the injection line (a) in linear approximation, (b) without nonlinear elements, and (c) with nonlinear elements.

considered captured if its output-beam coordinates lie inside the two-dimensional ellipses defining the transverse acceptance of the accelerator. The longitudinal output-beam coordinates of the pion were not taken into consideration.

For the injection line as described, 82.2% of the pions lie in the transverse acceptance of the accelerator. Only 56.5% of the pions are captured when the nonlinear beamline elements are turned off. Pion decay is not folded into these numbers. Figure 2 shows the $Z_1Z_2$, $Z_3Z_4$, and $Z_5Z_6$ phase-space projections of the output beam for the injection line (a) in linear approximation, (b) without nonlinear elements, and (c) with nonlinear elements. In (b), the butterfly shape characteristic of chromatic aberrations is clearly visible horizontally but is masked vertically by the strong third-order geometric aberrations from quadrupole fringe fields.

## VII. ACKNOWLEDGMENTS

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## VIII. REFERENCES

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