PSR INJECTION-LINE UPGRADE*

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Abstract

We describe the new injection line to be implemented for the Los Alamos Proton Storage Ring (PSR) in the change from a two-step injection process to direct H^- injection. While obeying all geometrical constraints imposed by the existing structures, the new line has properties not found in the present injection line. In particular, it features decoupled transverse phase spaces downstream of the skew bend and a high degree of tunability of the beam at the injection foil. A comprehensive set of error studies has dictated the imposed component tolerances and has indicated the expected performance of the system.

1 INTRODUCTION

We are converting to direct H^- injection to reduce the beam losses in PSR and thus allow an increase in beam current from 75 μA to 100 μA, through improved quality of the injected beam and injection painting [1,2].

To make direct H^- injection possible, the injection line must be rerouted to bypass the ring dipole through which the beam is presently injected. This seemingly minor change in geometry, coupled with stringent requirements on the beam at the foil, necessitates changes throughout the line, while the existing tunnel walls place severe restrictions on the layout.

2 PRESENT INJECTION LINE

Figure 1 shows a sketch of the present injection line.

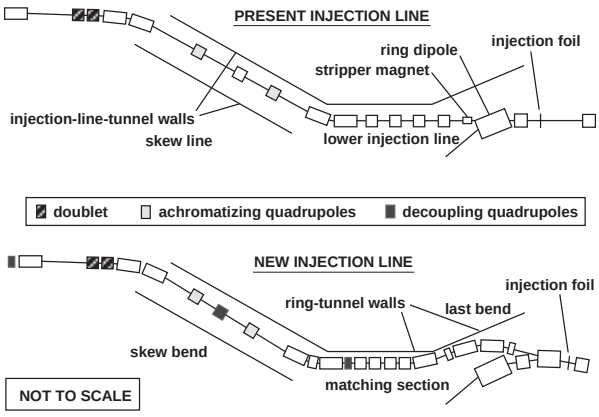

Figure 1. Top view of present and new injection line.

The present injection line consists of a skew line to take the beam from the transverse coordinates of the upstream transport line to those of the ring injection section, and a lower injection line to transport the beam through a stripper magnet, where H^- are converted to H^0, and through a hole in the side of one of the ring dipoles to the injection foil in the ring, where H^0 are converted to H^+.

The skew line contains an S-shaped bend in a 24.36° plane. In beamline order, a 1.5° kicker magnet deflects the beam into the injection line, a doublet provides needed focusing, and an FDF triplet, between two 6.75° dipoles and two −7.5° dipoles, makes the bend achromatic while providing focusing in both transverse planes. The D quadrupole resides at the dispersion crossover, thus decoupling achromaticity from vertical focusing. The skew bend causes downstream transverse linear coupling, leading to an apparent transverse-emittance growth of a magnitude that depends on the input beam and on the focus of the line.

The four quadrupoles in the lower injection line prepare the beam for the stripper magnet, where the vertical beam size must be small because of the narrow gap and the horizontal beam size must be small to minimize the additional horizontal-emittance growth caused by the stripping process. Because of these constraints the injected beam is not matched to the stored-beam parameters.

3 NEW INJECTION LINE

The new injection line consists of a skew bend, matching section and last bend, as sketched in Figure 1.

3.1 Layout

The bend in a skew plane is retained because it is not practical to replace it by separate horizontal and vertical bends. In order to gain space for the matching section, the bend angles of the 6.75° dipoles are increased to 7.5° and a −1.5° dipole is added between the −7.5° dipoles. The 26.86° roll angle of the skew bend is determined by the layout of the last bend.

The matching section is as close to a ring-tunnel wall as possible and is more compact than desirable. It is not possible to push the skew line upstream to gain more space, because it would obstruct access to the injection-line tunnel, as well as get too close to the floor.

The layout of the last bend is essentially fixed by the requirement of dipoles at or below the field-stripping limit of 3.8 kG, with small bend angles, and the presence of the existing PSR elements and ring-tunnel walls.

3.2 Expected Input Beams

The accelerator-output-beam transverse profiles are Gaussian with longer-than-Gaussian tails. These profiles are described well by the sum of two Gaussian distributions. Typically, the "wide-peak beam" (about

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70% of the total beam) and the "narrow-peak beam" (the remaining 30% of the beam) have transverse rms emittances of about 0.08 π-cm-mrad and 0.02 π-cm-mrad, respectively.

The momentum distribution is skewed, with a long low-momentum tail. The momentum deviation of the beam does not exceed about ±0.5%.

3.3 Nominal Beam at Injection Foil

The stored-beam Twiss parameters at the injection foil are $\beta_x = 2.675$ m, $\alpha_x = 0.6180$, $\beta_y = 11.093$ m and $\alpha_y = -1.3894$, with $D_x = 1.456$ m and $D_x' = -0.166$.

We will inject a zero-dispersion beam. For a dispersion-matched injected beam of the assumed momentum distribution, the foil must practically cover all horizontal coordinates to cover the same fraction of the beam as for the zero-dispersion injected beam, resulting in over twice the number of foil traversals.

To establish nominal injected-beam parameters and a preliminary injection point (injected-beam centroid location) at the foil, we chose among the upright injected-beam ellipses based on foil-edge location (as far from the stored-beam axis as possible, to minimize the number of foil traversals) and number of large-emittance stored-beam particles created. For transverse rms emittances of 0.08 π-cm-mrad, the nominal ellipses have rms parameters of $x = 0.10$ cm, $x' = 0.80$ mrad, $y = 0.16$ cm, $y' = 0.50$ mrad.

Through repeated ACCSIM runs, we found the desired injection point, $x_0 = 0.721$ cm, $x_0' = -1.960$ mrad, $y_0 = 2.250$ cm, $y_0' = 3.100$ mrad. For this injection point, the 2-rms injected-beam ellipses touch stored-beam ellipses with emittances of $\varepsilon_x = 3.2$ π-cm-mrad and $\varepsilon_y = 6.3$ π-cm-mrad. Figure 2 shows the transverse phase space at the injection foil. Shown are the 2-rms injected-beam ellipses and the stored-beam ellipses being filled. The foil edges are shown at −2.5 rms of the injected beam.

Horizontally, the foil edge is close to the axis, and there is no advantage in a closed-orbit bump. We will have a vertical closed-orbit bump for injection painting and to minimize the number of foil traversals [1,2].

3.4 Handling of Non-Nominal Injection-Line Input Beams

The injection line was designed with a particular input beam. For all accelerator output beams that have been documented to date, it is possible to restore the nominal injection-line input-beam Twiss parameters with the four quadrupoles immediately upstream of the skew bend. In case the non-nominal input beams are allowed to go through the line, the matching section can then restore the nominal Twiss parameters at the foil.

3.5 Issues Concerning Skew Bend

In order to explain the beam-optics properties of the skew bend, we need to distinguish between transfer-matrix elements in the upright coordinate system (R_{ij}) and in the skew coordinate system (S_{ij}).

The skew bend must again be achromatic, to avoid dispersion-related emittance growth and beam-centroid motion with beam-energy shifts. With two quadrupoles one can set $S_{16} = S_{26} = 0$ downstream of the bend, which automatically results in $R_{16} = R_{26} = R_{36} = R_{46} = 0$.

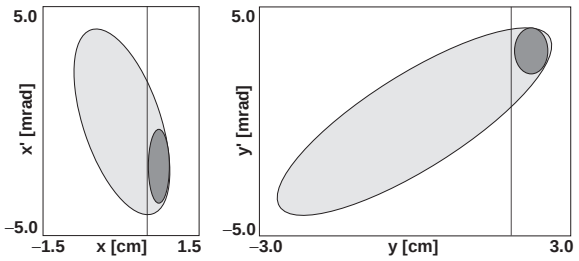

Fig. 2. Horizontal (left) and vertical (right) phase space at injection foil. Shown are the 2-rms injected-beam ellipses (dark shade), the stored-beam ellipses (light shade) and the foil edges (vertical lines).

In order to avoid the transverse linear coupling usually caused by beamlines in a skew plane, the skew bend is tuned so that $S_{11} = S_{33}$, $S_{12} = S_{34}$, $S_{21} = S_{43}$, and thus also $S_{22} = S_{44}$, resulting in a decoupled R matrix ($R_{13} = R_{14} = R_{23} = R_{24} = 0$, $R_{31} = R_{32} = R_{41} = R_{42} = 0$) with two identical diagonal blocks ($R_{11} = R_{33}$, $R_{12} = R_{34}$, $R_{21} = R_{43}$, and $R_{22} = R_{44}$). There is no downstream apparent transverse-emittance growth, regardless of input beam.

The proposed skew-bend design is quite similar to the present configuration (see Figure 1). The doublet provides needed focusing, the two F quadrupoles of the FDF triplet make the bend achromatic, and the D quadrupole at the dispersion crossover provides additional vertical focusing. This latter magnet and two new quadrupoles at zero-dispersion locations, one upstream of the 1.5° kicker magnet and one downstream of the last skew-bend dipole, decouple the line. Tuning for achromaticity and decoupling are independent.

The degree of coupling will be checked with a vertical steerer upstream, and two BPMs downstream, of the skew bend. We should be able to detect coupling that leads to 1% emittance growth.

For each near-nominal setting of the doublet, the skew bend can be made achromatic and decoupled. By measuring the rms beam sizes at strategic points in the line, we will be able to distinguish between the nominal and near-nominal tunes.

3.6 Issues Concerning Matching Section

The matching section has four quadrupoles, which is the minimum required to adjust four beam parameters at the injection foil. The matching-section quadrupoles are in a dispersionless part of the line so that adjusting the focus at the foil does not affect the dispersion at the foil.

The matching section can produce the nominal beam parameters at the foil with the nominal and all expected non-nominal input beams. It can also produce beams that differ in size by ±25% from nominal in either or both planes. These are beams with reasonable foil-edge locations and maximum stored-beam emittances that we will want to check out in trying to establish the optimal tune for the actual input-beam transverse and longitudinal distribution.

3.7 Issues Concerning Last Bend

The last bend contains four dipoles to guide the beam around the ring dipole, and two quadrupoles to make the bend achromatic.

Horizontally, the last bend points at the nominal injection point ($x_0 = 0.721$ cm, $x_0' = -1.960$ mrad), vertically, it is aligned for on-axis injection ($y_0 = 0$ cm, $y_0' = 0$ mrad). The last bend will have two dual-axis steerers. To get to the nominal injection point, no horizontal steering is required, but the steerers have to achieve $\Delta y = 2.250$ cm, $\Delta y' = 3.100$ mrad at the foil, with deflections of about 2.2 mrad and 1.4 mrad, respectively. For on-axis injection, no vertical steering is required, but the steerers have to achieve $\Delta x = -0.721$ cm, $\Delta x' = 1.960$ mrad at the foil, with deflections of about −1.4 mrad and 3.5 mrad, respectively. Horizontal on-axis injection can also be achieved by lowering the currents of the first and third dipole, by about 2.0% and 3.7%, respectively.

3.8 Particle Losses

The apertures will clear at least 6.6 rms of the nominal beam with transverse rms emittances of 0.08 π-cm-mrad and a full momentum spread of ±0.5%. In the skew line and in the matching section, there is no allowance for steering errors, which we attempt to minimize. The aperture of the last bend has an allowance for vertical steering to the injection point and horizontal on-axis injection. Scraping losses in the line thus are expected to be minimal.

Particle losses from field stripping were computed from the relevant formulas [3]. They should be around $1.6 \cdot 10^{-5}$ from all injection-line dipoles and below $2 \cdot 10^{-11}$ from the quadrupoles of the matching section.

3.9 Component Tolerances

A comprehensive study of the relative sensitivity of the line to alignment and field errors of all magnets resulted in tolerances that are readily achievable. To limit steering by individual magnets to 0.3 mrad, we specify dipole rolls below 0.1°, transverse alignment of the skew-bend and last-bend quadrupoles to 0.5 mm and of the stronger matching-section quadrupoles to 0.25 mm, and dipole longitudinal alignment to 1.0 mm. To keep apparent transverse-emittance growth due to individual magnets below 3%, quadrupole rolls should be below 0.1°. The 1.5° kicker magnet is regulated to ±0.2%, causing beam-centroid shifts at the foil to the 0.28-rms injected-beam ellipse, horizontally, and the 0.12-rms injected-beam ellipse, vertically. For an equivalent effect from all other dipoles, the skew-line dipoles will be regulated to ±0.01% and the last-bend dipoles to ±0.002%. To control fluctuations in the injected-beam parameters, the quadrupole power supplies need to be regulated to about 0.1%, with the last matching-section quadrupole requiring 0.01% regulation.

4 PERFORMANCE OF SYSTEM

Beam losses in the injection line should be minimal, even in the presence of the expected magnet errors and imperfections. The performance of the injection line will be judged against the factor-of-nine reduction in foil traversals (to about 35) and factor-of five reduction in ring losses (to about 0.1%) computed for the nominal injected beam.

We simulated beam transport through injection lines with errors and beam injection into the ring. The input beam was Gaussian-distributed, transversely, with rms emittances of 0.08 π-cm-mrad and had a skewed momentum distribution. The central energy was chosen to minimize ring losses. The lowest-energy particle had about −0.537%, the highest-energy particle about 0.330% momentum deviation. The assumed injection-line errors were those that can not be corrected, namely random roll errors, dipole power-supply fluctuations and quadrupole set-point errors to twice the tolerances. Also included were random normal and skew sextupoles to $4 \cdot 10^{-4}$ and normal and skew octupoles to $2 \cdot 10^{-4}$ of the dipole field, and random normal and skew sextupoles and normal and skew octupoles to $2 \cdot 10^{-3}$ of the quadrupole field, at the pole radius. These limits correspond to twice the maximum measured values of the mapped magnets.

The study showed that, for injection lines with errors, the nominal ring losses can be preserved as long as more beam is allowed to miss the foil and go to the H^0 dump. The approach should be to always keep the nominal foil-edge locations and injection point, in which case the number of foil traversals, the nuclear-scattering losses and the scraping losses all remain essentially unchanged.

For tuning the line, the injected-beam rms parameters will be determined, to better than 20% accuracy, with an emittance station near the foil. For the range of beams to be then expected, the nominal ring losses can likewise be preserved by allowing more beam to miss the foil.

REFERENCES

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