MI-14 Beamlines Solutions for Tev Injection, Slow Extraction, Pbar Production, and Pbar Injection

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1 Introduction

This paper describes the first consistent solution of the transfer lines through FO in answer to the first concern raised by Seimann review committee. '

> 1. *"The transfer lines from the Main Injector to the Tevatron need to be designed."*
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> "The layout presented satisfied t.he geometrical constraints, but it was not possible to match the horizontal and vertical dispersions simultaneously. (The vertical dispersion is introduced by the extraction from the Main Injector.) The short length of 210 meters may not be enough to perform all the necessary functions. If this is the case, it would be necessary to redesign the Main Injector lattice or to relocate the Main Injector with respect to the Teva tron. The latter has the potential for serious impact because the Main Injector is located close to the site boundary, and its location could affect radiation safety. Although the committee has no expertise in radiation safety or dose calculations, we know there is heightened public sensitivity about radiation safety. Satisfying this concern is important and could be time consuming."

In addition to the two Main Injector to Tevatron transfer lines, referred to by the Seimann committee, a third transport line has to pass through the FO region without inteferring with the two Tevatron Injection lines. Therefore, the design of the following three beamlines are discussed in this note:

- transport line for 150 Gev/c protons for injection into the Tevatron
- transport line for 150 Gev/c pbars for injection into the Tevatron
- a the slow spill beamline between the MI and Main Ring Fll used for:
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    - 120 Gev/c resonantly extracted protons for slow spill to Switch yard
    - 120 Gev/c protons for pbar production
    - injection of 8.9 Gev/c antiproton from the Antiproton Source.

The two Tevatron injection lines are identical in design with only minor differences. The design for the proton injection is discussed in detail. Only the differences between this and the pbar injection line will be highlighted. The section of the current Main Ring from Fll to A0 will remain intact and be used to connect the Main Injector to the Antiproton Source (Fll - Fl7) and the Switchyard (Fll-A0). This then requires only a beamline between the Main Injector and the remnant of Main Ring at Fll. It is this section of beamline that is discussed in this report.

The geometry and optical solutions of these beamlines, from the Main Injector through the Tev FO region are presented along with a description of the work remaining for the design, possible improvements to the design, and potential study suggestions. A plan view of the above beamlines is shown in Figure 1.

2 Design criteria

The following design criteria were used as guide lines in the beam line design.� The implication of each will be discussed in the following sections.

- All beamlines are to pass through Tev/MR FO without interference.
- All beamlines must transport beam with normalized transverse emittance fQ5 of 40 r-mm-mr.
- Transverse matching errors into Tev must produce an emittance growth of less than 1 7r-mm-mr.
- Transverse matching errors into the Main Injector (injection of 8.9 Gev/c pbars) must produce an emittance growth of less than 1 x-mm mr.

3 Beamline Solutions

Solutions for the main Injector to Tevatron beamlines have been previously presented.�[2,3] Neither of these solutions addressed the optics of the transport line between the Main Injector and the Main Ring remnant.� The site coordinates of all beamline elements are included in Appendix 1 and may be found in file: �

USR$DISK1:[JOHNSDNDE.BEAMLINE]MIl4VlISC.SC�

The lattice functions for the three beamlines are contained in Appendix 2,3, and 4 and in the files: 2 D Johnson, MI note #MI-0007, A 150 Gev MI-11 to Tevatron Beamline Solution.� R: Gerig, MI to Tevatron Beam Line Solution for MI-14.

3.1 Geometry

The Main Injector RF straight section MI-70 and the Tevatron RF straight section FO are parallel and separated by 10 meters. The center of the Main Injector MI-70 straight section is 12.5 meters downstream of Tev FO which makes the proton and pbar extraction straight sections symmetric about this point in the Tevatron. This horizontal geometry determines the required total bend in the transport lines.

The beamline distance between the MI-14 version of the Main Injector and the exit of the Tevatron injection lambertsons is approximately 241 me ters, an increase of 30 meters over the MI-11 design. Since the Main Injec tor extraction straight sections MI-60 and MI-80 are symmetrical about the Tevatron injection labmertsons, the geometry of the two Tevatron injection lines will be the same. The angle between the extraction straight section and the Tevatron RF straight section is 15.56 degrees (271.6 milliradians). This requires about 1360 kG-m of horizontal bend to transport the beam from the MI to the Tevatron. Excluding the horizontal injection lambertsons and c magnets used for Tevatron injection, the transport line utilizes 12 Main Ring B2 dipoles at approximately 17 kG each for the horizontal transport. As in the previous designs [2,3] most of the horizontal bending is required at the end of the transport line without interfering with the Tev tron RF (proton line) or the Fll Tevatron magnets (pbar line). A plan vi w of the proton and pbar injection layout in the Tevatron RF region is shown in Figure 2.

Both Tevatron injection lines approach the Tevatron at t e same elevation as the Tevatron itself (723.375'). The elevation of the be mline that joins the Main Ring remnant is at the Main Ring elevation (725.5'). The elevation of the Main Injector was left a free parameter in this design. The solution of the proton transport line to the Tevatron fixed the elevation of the Main Injector at 722.379'. An elevation view of the proton transport line to the Tevatron and the slow spill line is shown in Figure 3. Table 1 summarises the evolution of the Main Injector elevation and the elevations of the Main Ring, and Tevatron.

Table 1: Elevations of accelerators

�	CR rev 1	CDR rev 2	Now
MI	724.375	721.5	722.379
MR	725.5	725.5	725.5
Tev	723.375	723.375	723.375

Since the (proton) Tevatron injection line and the slow spill line share the same extraction channel, a magnetic switch is used to select bet.ween the two beamlines. This switch uses two 3 meter vertical B3 magnets on either side of the first cell quad, Q4F1, in the beamline. A plan and elevation view of this region is shown in Figures 4 and 5.

3.2 Basic Lattice

The basic lattice structure of the Main Injector straight section and cells (17 meter half-cell length) was adopted for all beamlines. This quad spacing was chosen to keep the lattice functions similar to those in the MI to accommodate 8.9 Gev/c pbars, particularly in the proton extraction straight section. The main differences between the beamlines is the adjustment of the spacing between the cell and the number of matching quads. These differences arise due to geometry and lattice matching differences.

The first three quads, Ql-Q3, closely resemble the spacing and gradient of the quads used in the MI to match from the straight section into the cells. The 8 cell quads Q4Fl - Q4D4 run in series at a gradient of approximately 200 kG/m at 150 Ger/c to produce FODO lattice with approximately 90 deg. phase advance per cell.

To match the proton transport line into the Tevatron, the last two cell quads in the string are powered individually and used (along with three additional quads) to match the lattice functions to the input of the inner quad at Tev Fll. Table 3 shows the results of this match. The lattice functions for the Tevatron injection line for protons are shown in Figures 6 and 7.

The vertical dispersion match obtained by the 12" translation in the extraction channel is consistent with the requirement that the Tevatron emit tance growth due to a vertical dispersion mismatch be less than 1 π-mm-mr.[4] A residual dispersion of 30 cm. at the end of the c-magnets is the result of the .3034 meter vertical translation. The effect of this on the emittance growth is given by $\frac{\Delta D^2_{eq}}{\beta}$ = 0.006 which corresponds to an emittance growth of $\Delta\varepsilon = 0.68$ π-mm-mr. A vertical beta increase in the extraction straight section would reduce this further. Figure 8 shows a plot of the Floquet transformation of the vertical dispersion function.

The lattice functions for the pbar transport line to the Tevatron are shown in Figures 9 and 10. The quad separations and gradients for this line differ slightly from the proton line due to the difference in the final lattice functions in the Tevatron. Table 4 shows the results of matching. The lattice functions for the MI to MR Fll beamline along with the MR lattice functions from Fll to F18 are shown in Figures 11 and 12. The slow spill beamline was matched into the inner quad at Fll. Table 5 shows the results of matching. Since this line is used for 8.9 Gev/c pbar injection into the Main Injector, the transfer line match into the MI can be inferred by Table 5. The pbar vertical emittance growth of $\Delta\varepsilon = 0.006$ can be expected.

4 Main Injector Extraction

In a previous design, [3] the Main Injector was proposed to lie in the same plane as the Tevatron, which made the use of purely horizontal transfer lines appealing because it removes the constraint of matching vertical dispersion. However, the use of horizontal extraction lambertsons in the Main Injector has several problems. The first is the requirement that the proton extraction lambertsons are also used for 120 Gev/c slow spill to Switchyard. Since the splitting stations in Switchyard are vertical, vertical extraction lambertsons (i.e. horizontal resonant extraction) were mandated. If the MI were in the same plane as the Tev, a horizontal lambertson (vertical kickers) could be used for pbar extraction. This would require a quad with a larger vertical aperture just upstream of the lambertson (i.e. a rotated 3484). However, would the reduction of the 4 inch horizontal aperture to 2 inches be acceptable?

The present design utilizes vertical lambertsons (horizontal kickers) for all injection and extraction from the Main Injector. This implies that the slow spill will use horizontal resonant extraction. This choice of lambertson orientations provides for a larger horizontal aperture than the horizontal lambertson. Also detailed calculations vertical resonant extraction hand the aperture required have not been worked out for the MI.

5 Tevatron Injection

5.1 Lambertson / Tev RF layout

The existing 8 Tevatron RF stations are to share the same 50 meter straight section as the Tevatron injection magnets (i.e..lambertsons and c-magnets). The layout of the Tevatron FO region has been previously described. [5]

- Tevatron RF must fit into upstream half of FO with proper cavity phasing to accelerate both protons and pbars.
- The Tev injection ma.gnets have to fit in the downstream 25 meters of F0 and centered 12.5 meters downstream of FO.

5.2 Lambertson and kicker orientations

Currently, the Main Ring to Tevatron injection utilizes vertical lambertsons at E0 with horizontal kickers downstream to close the horizontal orbit.

The present Main Injector to Tevatron transfer line design utilizes a pair of horizontal injection lambertsons and vertical kickers to close the (verti cal) orbit. The kickers are located in the F17 (proton) and E48 (pbar) mini straights. Table 6 summarizes the present kicker calculations and assumptions.

The model for the proton injection kicker is the current El7 kicker. This is capable of removing approximately 1" displacement at, the entrance to the lambertson. Line 20 of Table 6 shows the displacement required at the entrance of the lambertson, the exit of the lambertson, and the vertical angle through the lambertson for the kicker to close onto the Tev vertical orbit. The 3.6 mm vertical translation in the lambertson aperture does not present any problems.

The model for the pbar injection kicker is the current model for the new 36 bunch Tev injection kicker. This is capable of removing approximately 1" displacement at the entrance to the lambertson. Line 41 of Table 6 shows the displacement required at the entrance of the lambertson, the exit of the lambertson, and the vertical angle through the lambertson for the kicker to close onto the Tev vertical orbit.

6 Magnet Requirements

6.1 Dipoles

All three beamlines use 12 MR B2 magnets for their horizontal transport.� These will run at approx. 17 kG each. Only the slow spill beamline contains vertical dipoles. There are 4 3 meter B3 dipoles used at approx. 12 kG each to make the vertical translation from the Tevatron elevation to the Main Ring elevation. The slow spill line has an additional 4 horizontal B2 bends just upstream of the Fll quads. Three of these are standard B2's and one is a 0.9 meter version. These will run in series with the Main Ring remnant.

6.2 Quads

Two types of quads are used in the beamlines, with one exception discussed below. The Tevatron injection lines have 6 3Q120 quads and 8 3Q84 quads each. The slow spill line has one a.dditional quad for matching into Fll.

The quad, Q4F1, which is common to both the proton and slow spill line will require a larger aperture than the normal 3Q84 to accommodate the beams in both beamlines. With the quad centered on the proton line, the central trajectory of the slow spill line is approximately 1.75" above the quad center at the downstream end of the quad. Beacuse this has to transport also 8.9 Gev/c pbars back to the MI, the required aperture appears to be satisfied by the use of Tev I style IQ (large quad) laminations.

6.3 Extraction Lambertsons and C-magnets

The current F17 lambertson and c-magnet were used as models for the proton and pbar extraction channel magnets. The design field of 10.6 kG for the lambertson and 12.6 kG for the c-magnet were used. These would run in series. A trim coil on the lambertson would be used to control the vertical angle into the extraction channel. The 1.6" horizontal aperture of the cmagnet has an 8.9 Gev/c acceptance of about 40 π with the current 55 meter β_x. The lambertson, however, only has an 8.9 Gev/c acceptance of about 28 π with the current 58 meter β_x. These acceptance numbers assume ? 5 mm for tuning. The acceptances at 150 Gev/c are 17 times those at 8.9 Gev/c. The aperture of the lambertson used for injection of pbars will need an aperture greater than 1.6" to get a 40 π acceptance.

6.4 Tevatron Injection Lambertsons and C-magnets

Two Tevatron EO style lambertsons are used for the injection of both protons and pbars. The current EO Tevatron injection lambertson were used as the model for the present design. A field of 8.0 kG (design field of the lambertson is 9.6 kG at 1555 Amps) was used for the lambertsons. The c-magnet fields of 12 kG are consistent with those obtained in the F17 c-magnets. The c-magnet used here is about .75 meter longer than the F17 c-magnet.

7 Work Remaining

This section outlines the work remaining toward a completely integrated beamline solution. The topics are categorized according to beamline or ac celerator questions.

7.1 Main Injector and Extraction Related Work

- Determine Main Injector kicker requirements [lattice location, strength, timing, and aperture] for proton injection, pbar injection, proton ex traction, pbar extraction, abort, Tevatron proton injection (F17) and Tevatron pbar injection (E48). Include new, faster D48 kicker to de termine the requirements for the E48 kicker.
- Determine the required aperture downstream of straight section MI-60 for the injection of 8.9 Gev/c pbars and design the necessary quad(s) and/or closed orbit bumps in the Main Injector.
- Look at beam sizes in all beamlines with the longitudinal emittance added in quadrature to the transverse beam size (i.e. 8.9 Gev/c - .5 ev-set and 150 Gev/c - 4.0 ev-set).
- Determine the aperture, field, and power supply requirements for the 150 Gev/c proton extraction (8.9 Gev/c pbar injection) lambertson and c-magnet.
- Determine the placement of the slow spill extraction septa and how to inject 8.9 Gev/c pbars around it.

7.2 Tevatron Related Questions

- Investigate phase of helix through FO - is it proper to inject on to?
- Can F17 separators and the Tev (proton) injection kickers share the same straight section? If not, where can the separators be moved?
- Investigate Tevatron apertures around FO.
- Are Tevatron injection kicker apertures large enough?
- Relocation of existing devices at FO (other than Tev RF cavities).
- Investigate whether a new design for the Tevatron injection lambertsons is needed or can we use the existing EO lambertson.
- Investigate whether a new design for the Tevatron injection c-magnets is needed or can we use a c-magnet of the same design as the F17 c magnet.

7.3 Beamline Design Refinements

- Design a large aperture quad, QFl, for the 120 Gev slow spill beamline.
- Construct tuning curves.
    - sensitivity to input lattice functions
    - sensitivity to gradient errors
    - generate orthogonal knobs for lattice function control
    - Add trim magnets to beamlines for control of position and angle at lambertsons.
- Add diagnostics (BPM, BLM, SWICS) to beamline
  Match to existing AP-1, AP-3, and Accumulator
- Determine the acceptance of the AP-1, AP-3, and the Main Ring remnant for 8.9 Gev/c pbars.
- Match the end of the Fl8 to A0 beamline into the upstream end of Switchyard.

- Look at beam shapes for slow extraction in the slow spill beamline.
- Determine power supply requirements for all beamlines.
- Determine surplus magnet database for all beamlines.

7.4 Geometry Questions

- Get coordinates of beamlines to CAD system for detailed plan and elevation views of the FO region to search for interferences.

8 Possible Improvements

- Investigate MI dynamic beta [6] for the straight sections. This could be used to produce a smaller horizontal beta at the lambertson and downstream quad for 8.9 Gev/c pbar injection which could potentially reduce the necessity of a large aperture quad. This scheme has also been shown [6] reduce the dispersion mismatch into the Tevatron.
- Orient the Main Injector in the same plane as the Tevatron to have all extraction from MI in the horizontal plane. Is there enough vertical aperture for vertical resonant, extraction? This mode could eliminate the need for vertical dispersion matching between the Main Injector and the Tevatron. Does it make any sense to pursue this?
- Convert Main Ring remnant from FO to Fl? to a Main Injector style lattice (i.e. reduce half-cell length from about 30 m to 17 m) to reduce the vertical lattice functions from 100 m to around 80 m. This would increase the acceptance of this section from 30 7r to 40 x.

9 MI Studies

- Make 40 π beams in MR and inject into Tev for fixed target cycles.
- Investigate the physical aperture through Tev RF cavities by simulating the injection orbit bumps currently used at EO.
- Investigate sensitivity of horizontal splits in SY (muon bemds) to determine the feasibility of vertical resonant extraction from the MI.
- Inject 30 π protons and 22 x pbars onto helical orbits in the Tevatron.

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Table 2: Coordinates of the Main Ring and Tevatron F0

	Main Ring	Tevatron
x	30959.78263 m	30959.5394 m
y	29609.84812 m	29609.92554 m
z	220.4847 m	221.1324 m
? θ?	0.54516895 rad	0.5455988 rad

Table 3: Lattice functions at the input to the inner quad at Tev Fll used for proton injection into Tev

�	Tev functions	Beamline value
β_x	107.4	107.4

α_x	-0.895	-.09016
β_y	57.27	57.27
α_y	-0.0079	-.0078
D_x	2.864	2.864
D'_x	0.0199	0.0177
$\Delta(D^2_{eq}/\beta)_x$	�	0
D_y	0.0	0.2628
D'_y	0.0	0.0081
$\Delta(D^2_{eq}/\beta)_y$	�	.005

Table 4: Lattice functions at Tev FO (pbar direction) used for pbar injection into Tev

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�	Tev functions	Beamline value
β_x	71.79	71.79
α_x	0.451	.4536
β_y	69.07	69.08
α_y	-.0454	-.0539
D_x	2.337	2.337
D'_x	-0.012	-0.0191
$\Delta(D^2_{eq}/\beta)_x$	�	0.0
D_y	0.0	0.5548
D'_y	0.0	0.006
$\Delta(D^2_{eq}/\beta)_y$	�	0.005

Table 5: Lattice functions at input to the inner quad at MR Fll for 120 Gev/c slow spill beamline

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�	Tev functions	Beamline value
β_x	122.9	122.9
α_x	-1.257	-1.257

β_y	49.73	49.73
α_y	0.1954	0.1955�
D_x	2.98	2.913
D'_x	0.026	0.0260
$\Delta(D^2_{eq}/\beta)_x$	�	0.0
D_y	0.0	-0.1558
D'_y	0.0	0.0001
$\Delta(D^2_{eq}/\beta)_y$	�	0.0006

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[1] Main Injector Technical Review held at Fermilab, August 10-11, 1989.

[2] D. Johnson, MI note#MI-0007, A 150 Gev MI_11 to Tevatron Beamline Solution.

[3] R. Gerig, MI to Tevatron Beam Line Solution for MI_14.

[4] R. Gerig, MI note # MI-0001, A Dispersion Mismatch Criterion for the Main Injector.

[5] Conceptual Design Report of the Fermilab Upgrade: Main Injector, Project No. 92 CH-400 Technical Components and Civil Construction, revision 2, January 1990, Chapter 3.

[6] R. Gerig, MI note # MI-0002, A Dynamic Lattice Insertion for Main Injector Extraction.