MI-NOTE: #0163

MI-10 Injection Layout

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Introduction

The injection of protons from Booster takes place in the MI-10 straight section via the permanent magnet 8 GeV line. It is assumed that correctors will be located in the beamline to make position and angle changes at the injection Lambertson. The following layout is the current design used in the MAD lattice and does not include diagnostic equipment such as multiwires. A beam with a 40 π-mm-mr 95% normalized emittance has been assumed for this design. For emittances smaller than this the available aperture increases like $\sqrt{40/\epsilon}$.

MI-10 Layout

The injection scheme uses a horizontal bending Lambertson and vertical kickers. The injected beam approaches the Main Injector at a horizontal angle of approximately 35 mr in order for the last 8 GeV line quad to clear the MI beampipe. The beam trajectory at the entrance to the Lambertson is approximately 30 mm above the Main Injector centerline. The general straight section layout is shown in the Figure 1.

The Lambertson, assumed to be the current Main Ring A0 Lambertson, is shown just upstream of Q101 and removes the 35 mr horizontal injection angle. Quad Q101 is a recycled Main Ring 84 inch quad which is rotated 90 degrees and does not contain a MI beampipe/BPM. A large aperture BPM

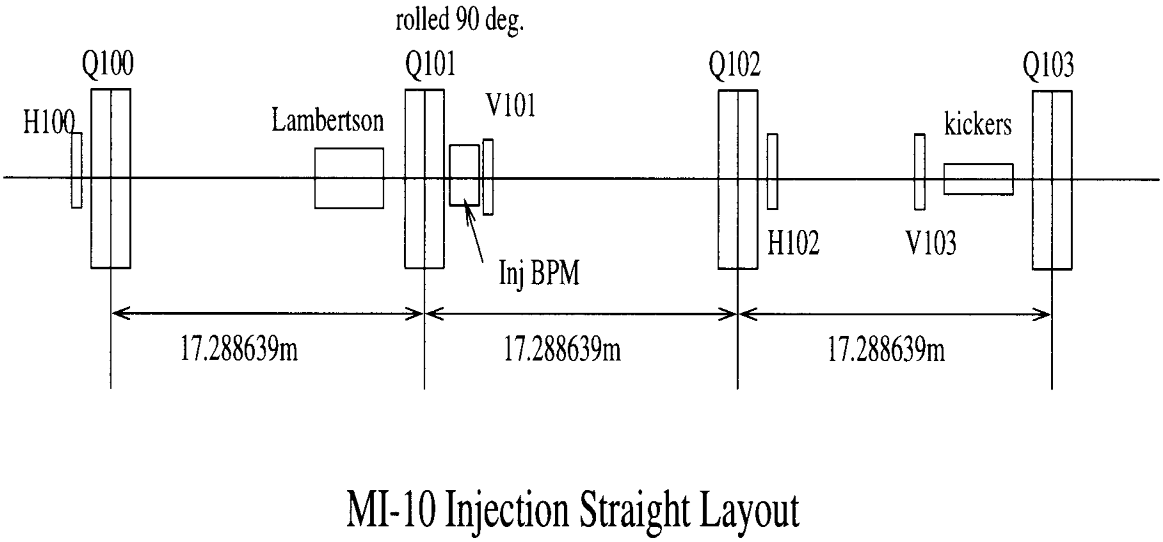


Figure 1: Layout of physical devices in the MI-10 Straight Section

is installed downstream of the quad between the quad vertical corrector. Three injection kickers are located just upstream of Q103. These remove the vertical angle of the injected beam with respect to the circulating MI beam. It should be noted that the MI dipole correctors at 101 thru 103 are not installed in their nominal upstream mini-straight positions.

Kickers

The initial specification of the 8 GeV injection kickers, when the location of the kicker was uncertain (whether up or downstream of Q103) called for a nominal kick angle of 1.05 mr. This was to be achieved by using 3 kickers, each with a nominal integrated field of 0.103 kG-m at 60 kV on the PFL, to give 350 μr/kicker. This value of voltage gave little injection tuning room so the length of the kicker ferrite was increased such that the nominal operating voltage was reduced to 48 kV.

The present kicker contains 26 ferrite cells each 1.25 inches to give a total ferrite length of 32.5 inches. Including the end field, of 4.5 inches, the magnetic length of the kicker is assumed to be 37 inches or 0.9398 meters.

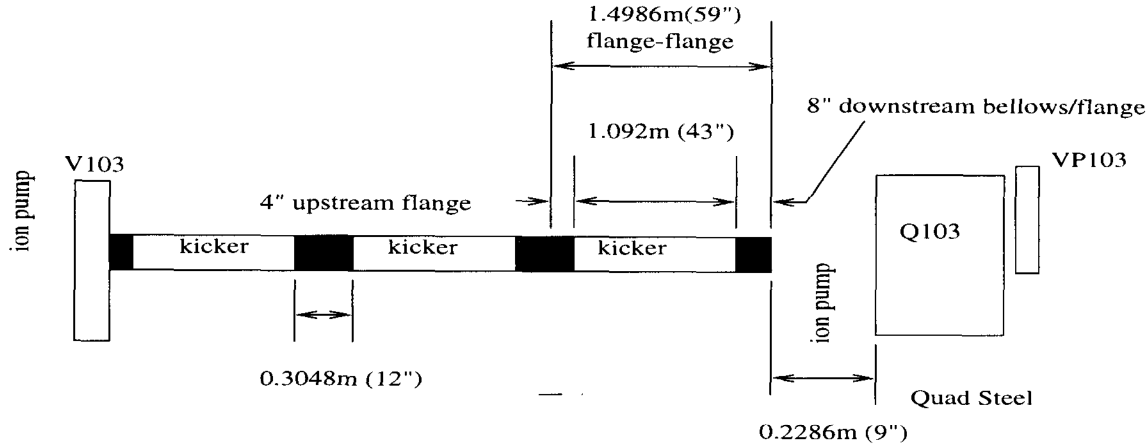
The physical parameters of the kickers used in the lattice are listed in Table 2. Limiting the maximum PFL operational voltage to 60 kV will give an upper limit on the maximum separation of the injected and circulating beam at the Lambertson. The maximum separation can be estimated by $\Delta y_{max} = \theta_{max}\sqrt{\beta_{lam}}\sqrt{\beta_{kick}}sin(\psi_{kick-lam})$. The phase advance between the Lambertson and kickers is nearly 90 degrees. For typical values of lattice parameters Δy_{max} is approximately 64 mm or ±32 mm. At an operational voltage of 48 kV, which gives 343.6μr/kicker, the Δy at the lambertson is about 50 mm.

Table 1: 8 GeV Injection Kicker parameters used in Lattice

Property	Value
$L_{magnetic}$	0.9398 m (32.5"ferrite+4.5"end= 37")
$L_{kickerhousing}$	1.0922 m (43")
$L_{flange-flange}$	1.397 m (55")
B_{max}	405.4 Gauss
BL_{max}	0.127 kG-m @ 60 kV
BL_{nom}	0.102 kG-m @ 48 kV
θ_{max}	427.8 μr / kicker
θ_{nom}	343.6 μr / kicker
$W_{beamtube}$	4.25 to 4.375 inches
$H_{beamtube}$	2.25 to 2.375 inches

To minimize the required kicker amplitude for a given separation at the Lambertsons, the kickers must be as close to the quad 103 as possible. A 9 inch slot has been provided between the kicker flange and quad steel for insertion of an ion pump/pumpout device. An additional ion pump may be inserted upstream of the vertical corrector V103. The physical layout of the kickers in the lattice is shown in Figure 2.

Approximately 17 inches were left between the kicker case and the quad steel for ion pump and transition. The space between kickers was set at 12 inches. This 12 inches is assumed to be made up of 4 inchs between case and flange on the upstream end and 8 inchs on the downstream end of each kicker. The vertical corrector V103 is just upstream of the kickers as close as possible with a second ion pump upstream of the corrector. Quad Q103 is assumed to have the special length MI beampipe with BPM inserted.



Kicker Layout

Figure 2: Layout of MI-10 injection kickers

Lambertson

The current injection design assumes a Lambertson with the properties of the current A0 injection Lambertson. These are listed in Table 1. The impact of several parameters on the location of the Lambertson should be pointed out. Any increase in the septum thickness will increase the kicker strength (for a constant beam-steel separation). Any decrease in the field strength will lead to a longer magnet which means a lower septum elevation. The height of the field region, 44mm, is the minimum vertical aperture in the 8 Gev line *and* Main Injector. If a *new* Lambertson is built, the height of the field region should be increased to about 52mm. The additional 16 inches between the magnetic length and flange length is the extension of the field free region of the Lambertson to clamp the fringe field. The flange-to-flange insert is assumed to be 106 inches.

The location (distance from the Q101 steel) and the vertical alignment (both position and angle) of the Lambertson is dictated by the injected beam elevation and trajectory, the circulating beam trajectory, the available vertical aperture through the injection straight (particularly Q101).

A positive pitch of the injected beam at the entrance to Q101 is required for closure, so the Lambertson should be as close to the quad as possible to minimize the elevation difference between the upstream end of the Lambertson and the center of the quad, therefore the vertical corrector has been moved downstream of the quad. The current solution has a special wide aperture BPM located just downstream of the quad with the vertical corrector downstream of the BPM. The layout of the injection Lambertson, BPM, Q101, and corrector V101 is shown in Figure 3.

Table 2: 8 GeV Injection Lambertson parameters used in Lattice

Property	Value
$L_{magnetic}$	2.286 m
$L_{flange-flange}$	2.6924 m
$W_{fieldregion}$	120 mm
$H_{fieldregion}$	44 mm
Opening angle	66 degrees
Septum Thickness	3 mm
B	0.46 T
BL	1.05 T-m
I_{typ}	920 A
θ	35.5 mr

The elevation of the injected beam trajectory is determined by the available physical aperture of the rotated 84 inch quad at Q101 just downstream of the Lambertson. *Note:* The good field aperture of the 84" quad extends out to the physical aperture. The physical vertical aperture of the beampipe through the rotated quad is ±60 mm, which is centered on the MI centerline. The maximum elevation of the injected beam above the MI centerline,y^{inj}_{quad}, can be estimated by $A_{quad} - \sigma_{beam} - \delta_{steel}$. Assuming a beam 95% envelope, σ_{beam}, of ± 16mm; the available quad aperture above the MI centerline, A_{quad}, of 60mm; and a separation between the beam edge and steel,δ_{steel}, of 5mm, the maximum elevation through the quad,y^{inj}_{quad}, is 39mm. To obtain closure, requires a positive angle, y', of the injection trajectory at the entrance to Q101 on the order of 1 to 2 mr which means the trajectory through the Lambertson, y^{inj}_{lam}, must be below that of y^{inj}_{quad} by about $y'(ds)$, where ds is the distance between the upstream edge of the Lambertson and the quad. This

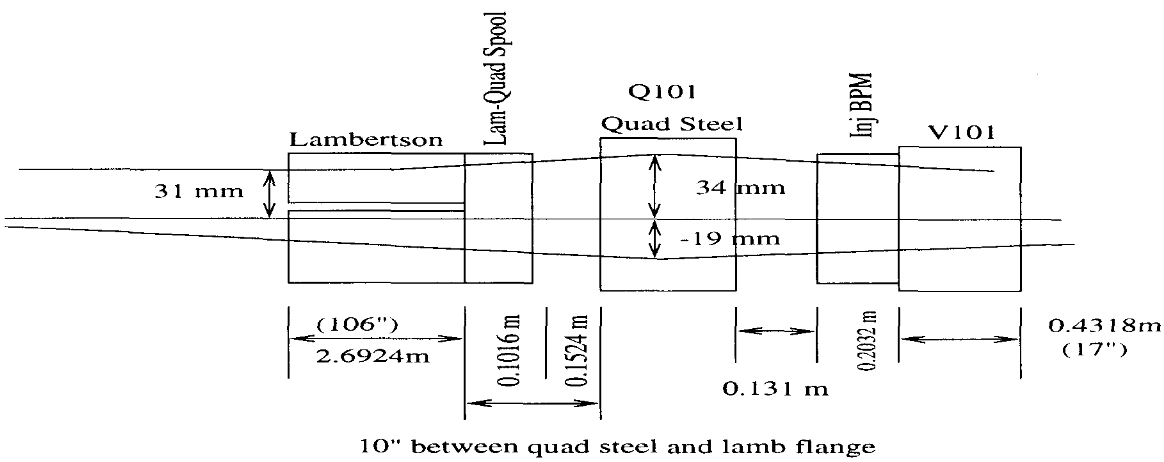


Figure 3: Layout of the injection Lambertson at Q101

angle,y', may be produced by either placing the beamline at this angle upstream of the Lambertson and installing the Lambertson at a 1 to 2 mr pitch or by rolling the Lambertson by $tan^{-1}(1.5/35)$ or 2.5 degrees to generate the required pitch. Rolling the Lambertson allows for the installation of a level beamline and produces a smaller elevation difference between the upstream end of the Lambertson and the quad, so this is the preferred method.

The vertical location of the Lambertson septum is constrained by the circulating beam closed orbit, the vertical aperture of the field region of the Lambertson, septum thickness, and the vertical aperture in the downstream quad. Several options for locating the Lambertson septum were investigated. The lattice program MAD was utilized to calculate the injection and closed orbits as well as corrector strengths, Lambertson orientation, kicker strengths, required horizontal and vertical injection position and angle for closure, and apertures.

Figure 4 shows a cartoon of two options for locating the Lambertson septum. Both options are viable and use the same longitudinal geometry of the Lambertson, quad, and kickers. Beam envelopes for the injected and circulating beam (both at 8.9 GeV/c and 150 GeV/c) are shown superimposed

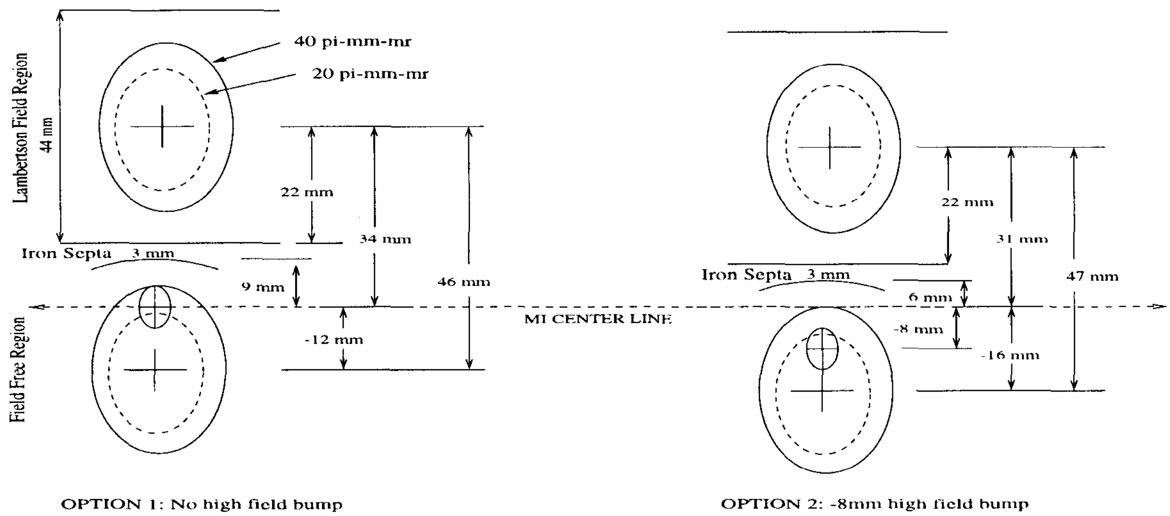


Figure 4: Options for vertical location of injection Lambertson septum. Phase space ellipse are based upon a vertical beta of 60 meters. Horizontal beam size is not to scale.

on an existing A0 Main Ring injection Lambertson cross section relative to the Main Injector centerline. A constant β_y of 60 meters throughout the Lambertson and quad was assumed as well as a normalized emittance of 40 π (horizontal dimensions are not to scale). In addition, a 20 π beam envelope is shown for comparison. It should be noted that the aperture of the field region of the existing Lambertson is 44 mm and the envelope of a 40π beam is 32 mm leaving *only* ± 6 mm between the 95% beam envelope and the Lambertson steel for injection tuning.

The first option places the septum at approximately 9 mm above the closed orbit of the Main Injector so that the edge of the beam on the unperturbed high field orbit remains approximately 5 mm from the edge of the septum. The closed orbit at 8.9 GeV/c must be displaced below the septum. The magnitude of the closed orbit distortion required at the Lambertson can be estimated by $y^{co}_{lam} \approx -\sigma_{beam} - \delta_{steel} + y_{off}$ where σ_{beam} is the beam half size, δ_{steel} is the distance between the beam edge and steel, and y_{off} is the elevation of the septum. This position offset must be generated by a kick at 641 and removed by the corrector just upstream of the kickers. To keep a minimum of 5 mm between the edge of the beam and the septum, a closed orbit bump of approximately 12 mm is needed. Centering the injected beam in the field free region, places the injected beam trajectory at 34 mm above the Main Injector center line. This produces a 46 mm separation between the injected and circulating beam which is easily removed by the kickers running at their nominal voltage on the PFL. Figure 5 shows the injected and circulating beam trajectory and beam envelope from the upstream face of the Lambertson to beyond the injection kickers at 103. The Lambertson septum and quad apertures (for the standard MI beam pipe) are also shown. This figure shows the tight aperture through this region, especially at Q101 and Q102. There is not a lot of vertical aperture left in Q101 for adjusting the vertical injection trajectory. The aperture of the star chamber is shown at Q102 as a possible option for increasing the vertical aperture through this quad. A 5 inch beampipe is assumed between Q101 and Q102 and a transition between the star and the MI beampipe would be installed downstream of the quad. This beampipe/Q102 configuration is considered in option 2 as well. Figure 6 shows the injection and high field orbit through the straight section. The Lambertson septum is also shown on this figure shown for reference. Note the high field orbit remains on the MI centerline while the injection orbit is displaced -12 mm at the Lambertson (-14mm at Q101).

The second option attempts to increase the available vertical tuning aperture through Q101 since it is not wise to install two adjacent devices with the same limiting aperture. The available vertical aperture in Q101 for tuning is increased by lowering the septum by about 3 mm to give more room between the injected beam and the top of the Q101 beampipe. This option lowers the injection trajectory by about 3 mm which opens up the aperture between the beam and the top of Q101 beampipe. The Lambertson roll, for option 2, to produce the required pitch at Q101 is only 2 degrees and the elevation at the entrance to the Lambertson is flat at 31 mm. Figure 7 shows the injected and circulating beam trajectory and beam envelope from the upstream face of the Lambertson to beyond the injection kickers at 103 for option 2. The Lambertson septum and quad apertures (for the standard MI beam pipe) are also shown. Since the septum is closer to the MI center line, the injection closed orbit bump has to be increased. In addition, this solution also requires the high field orbit to be bumped down a minimum of 4 mm at the Lambertson.

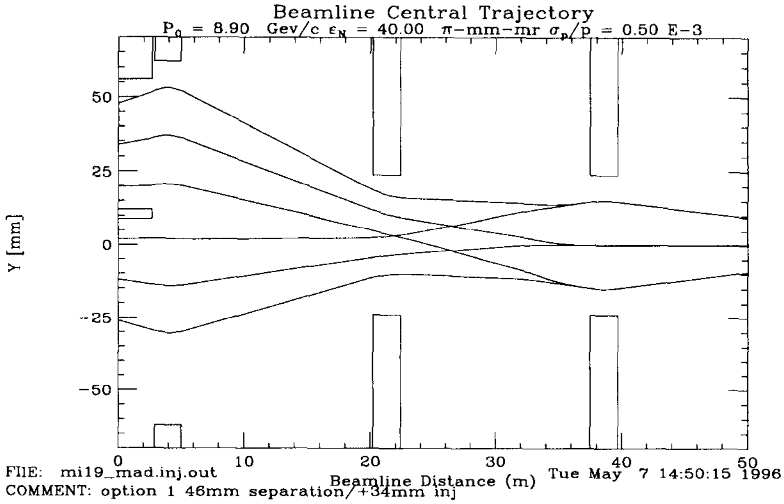


Figure 5: Option 1: Injection and circulating beam envelopes for 40π beam starting at the face of the Lambertson. Apertures shown are from the Lambertson septum, Q101, Q102, and Q103. The kickers can be seen just upstream of Q103. The vertical aperture of the star chamber in Q102 is also shown.

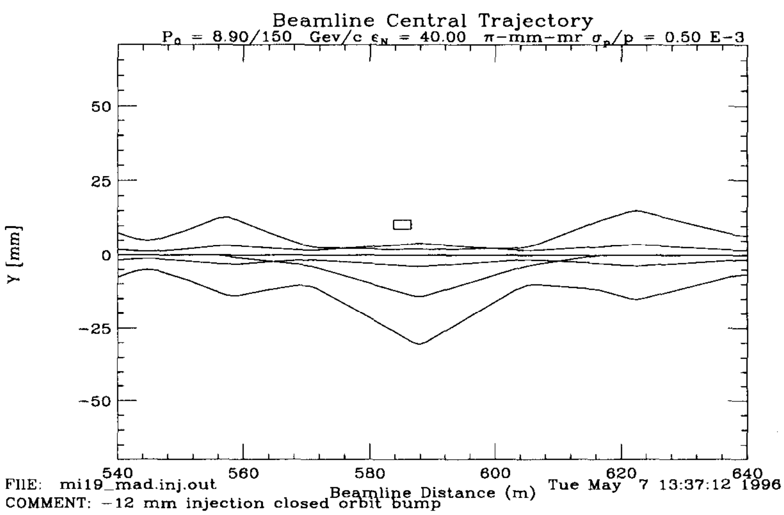


Figure 6: Option 1: Beam envelopes for an unperturbed high field orbit and injection closed orbit through the injectrion straight section. The injection bump is between 641 and 103.

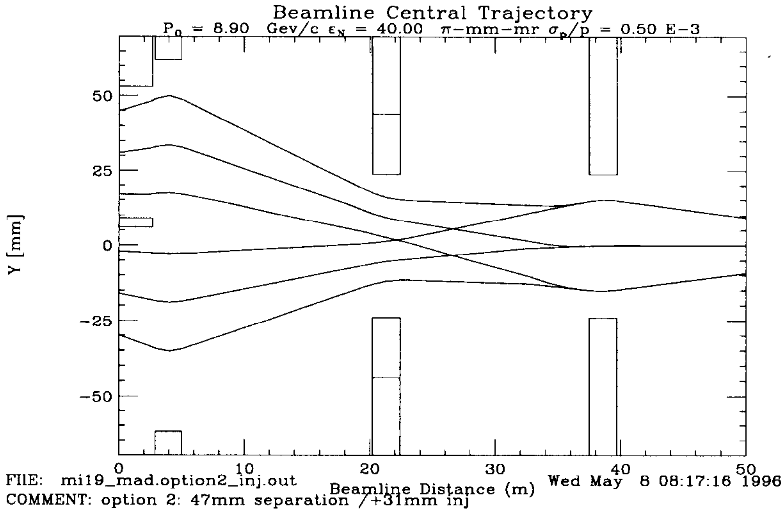


Figure 7: Option 2: Injection and circulating beam envelopes for 40π beam starting at the face of the Lambertson. Apertures shown are for the Lambertson septum, Q101, Q102, and Q103. The kickers can be seen just upstream of Q103. The vertical aperture of the star chamber in Q102 is also shown.

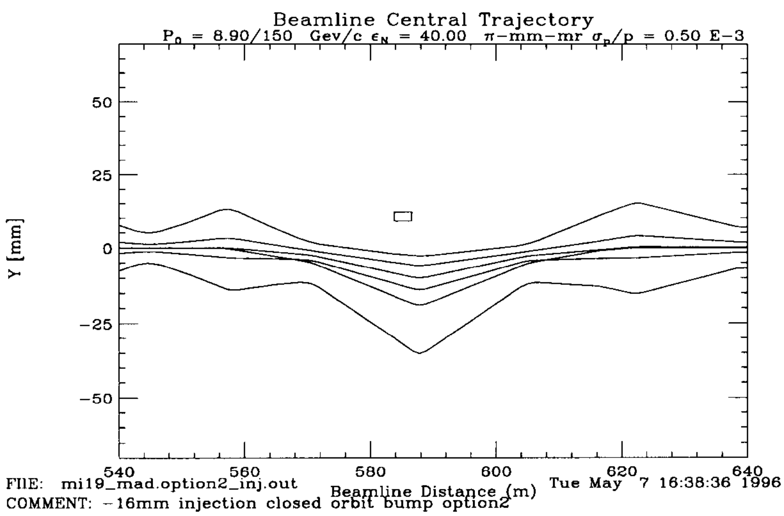


Figure 8: Option 2: Beam envelopes for an unperturbed high field orbit and injection closed orbit through the injection straight section. The injection bump is between 641 and 103.

The strength of the vertical correctors is designed to be 0.03 T-m at 10 Amps. This corresponds to about 60 μr which produces a Lambertson bump of only 2.5 mm at 150 GeV/c. This is clearly not enough to produce the desired bump. In order to displace the high field closed orbit downward, the quads on either side on the Lambertson are aligned as to produce the desired orbit. Although a 4 mm bump is required to maintain a 5 mm δ_{steel}, this option utilizes an -8mm bump thus increasing the separation between the high field circulating beam and the Lambertson septum. Table 3 lists the quad alignment offsets required for the -8 mm high field orbit bump as will as the values for the closed orbit through this region. None of the closed orbit values present any aperture problems.

Table 3: Quad alignments and high field closed orbit positions for Option 2.

Device	Δy [mm]	y_{co} [mm]
Q641	-1.698	0.0
D6412		-2.05
Q100		-2.5
ILAM		-8.2
Q101	0.48	-9.9
Q102		-2.9
Q103	-2.034	0.0

Table 4: Corrector strengths and closed orbit positions for 8 Gev circulating beam in Option 2.

Location	θ [μr]	y_{co} [mm]
V641	-200.0	0.0
D6412		-4.0
Q100		-5.0
ILAM		-16.0
Q101		-19.3
V101	43.0	-18.5
Q102		-9.3
V103	-191.0	-.9
VP103		0.0

Table 4 lists the required corrector strengths to produce a -16 mm bump at the entrance of the Lambertson. In addition, closed orbit positions for 8.9 GeV/c circulating beam are given at several positions through this region. Figure 8 shows the closed orbit both at 150 GeV/v and 8.9 GeV/c in relation to the Lambertson septum.

Magnet cross sections showing the injected and circulating beam for option 2 are shown in Figure 9.

Summary

The initial layout of the MI-10 injection straight section has been outlined. The location, orientation, and strength of the injection devices have been specified. The elevation of the beamline into the Lambertson has been lowered from a nominal of 40 mm above the MI center line, as reported in the Main Injector TDH, to something on the order of 30 to 35 mm. This change in elevation needs to be addressed as to where this difference will be incorporated into the beamline design. Two basic options were presented for the orientation of the Lambertson septa. The favored option in terms of aperture and injection tuning is that of **option 2** which incorporates the vertical displacement of the high field beam using quad alignment thus opening up the available vertical aperture through Q101. Further details with respect to beam pipe dimensions (through out the straight section) , vacuum connections, Z/N transitions, and other diagnostic equipment need to be specified. At the time these are finalized a subsequent MI note will be issued detailing these. This solution must additionally be merged with the 8 GeV beamline design to assure the correct knobs for position and angle control at the Lambertsons and kickers.