Chapter 14. Beam Transport Lines

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14.1. Introduction

The function of the injection-transfer line is to cleanly extract beam from the upstream end of the present 400 MeV transfer line, transport it, and provide the necessary matching at injection into the Proton Driver. There are several constraints on the design of this line. One of the most important is to allow normal operation of the present Booster. Thus extraction to the new line cannot disturb the existing 400-MeV lines, nor the two beam dumps. Also the extraction system must be able to operate at 15 Hz in order to select single Linac pulses, pulses not required for the Booster program.

The length of the approximately 1000-ft line is primarily dictated by allowing space for addition of a future 600 MeV Linac placed at the present Booster elevation. Since the Proton Driver will be at the Main Injector elevation, two vertical drops are required in this line--before and after a 450-ft straight section reserved for this future high-energy Linac. However, the most important considerations in the optics design and layout of the line come from the large number of fixed points and direction-specific trajectories that have been imposed on the line. Furthermore, the geometry of the line must be achieved with bends near 7 kG, or less, to keep losses from H^- magnetic stripping under 10^{-3}.

The extraction line, designed for 16 GeV protons, extracts beam using kickers and a series of septa and transports it to an intersection point with the current MI-8, (8 GeV transfer line to the Main Injector.) The layout and optics of the remainder of the MI-8 line serve to provide the basis for the remaining transport and matching required for injection into the Main Injector. Since all three straight sections are essentially identical, extraction must utilize the same optics as injection, whether optimal or not. Because of the unbroken FODO structure and absence of a long straight section, beam must be kicked off-center through ring quadrupoles and into a string of strong septum magnets in order to extract beam past downstream Proton Driver magnets. The relevant parameters describing extraction will be given along with the optics and magnets in the transfer line.

14.2. Injection Transfer Line

The injection transfer line to the Proton Driver consists of individual sections which:

a) extract and direct 400 MeV beam
b) perform an initial vertical translation to the present Booster Synchrotron level
c) perform dispersion suppression
d) support a long straight for a future energy upgrade
e) perform a second vertical translation to Main Injector elevation, and, finally
f) match and inject into the Proton Driver.

14.2.1. Extraction to the Injection Transfer Line

Extraction of the 400 MeV beam must be accomplished by integrating extraction elements into the existing operating lines. Two beamlines currently handle beam exiting the 400 MeV Linac. One line, called the transfer line, transports the central, stable portion of the Linac beam pulse down a chute (an elevation drop) to the Booster. The other, diagnostic line, diverts the remainder of the Linac beam through a spectrometer magnet and into a high-intensity beam dump. When the spectrometer is off, beam is transferred to a straight-ahead low-intensity dump. Momentum analysis and some monitoring of the beam are performed in the diagnostic line.

In order not to disrupt existing lines or move beam dumps, extracted beam needs to be directed along the existing Linac Upgrade Ramp. This is suitable without further civil construction as an enclosure for a primary beamline (see Figure 14.1). Where the enclosure ends, the beamline is directed along an open concrete pit, which will require modification to make it into a beamline enclosure.

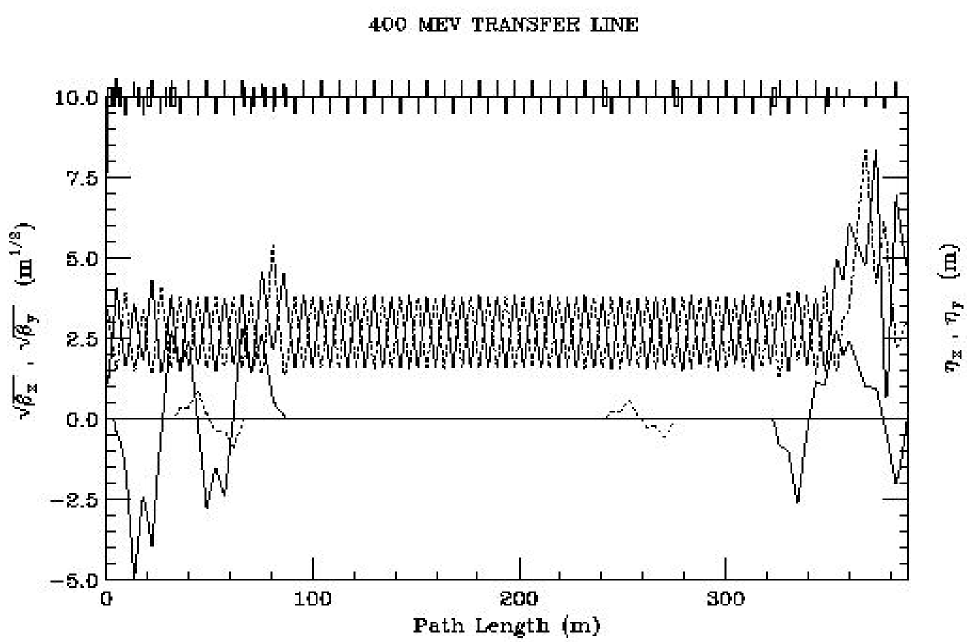

Figure 14.1. Lattice Functions for 400-MeV Injection Transfer Line

Two available drift spaces just upstream of the Linac Upgrade Ramp are potential locations for a pulsed extraction system. The drift upstream of the chopper was eliminated because of the large excursion, or dipole strength, required to clear the chopper tank (although beam could be kicked slightly across the chopper plates). The 2.1-m drift downstream of the chopper was then selected and a dipole length and strength chosen accordingly to cleanly bypass the quadrupole, QB2, in the existing transfer line.

On any 15 Hz clock cycle for which beam is to be delivered to the Proton Driver, the pulsed dipole will deflect the Linac beam horizontally from its normal trajectory and into the new line. When the dipole is not triggered, beam will pass undisturbed to the Booster or beam dump. The only drawback to placing the entire burden on a single pulsed dipole downstream of the chopper is that it has to be operated near or above 7 kG in order to steer beam properly along the Linac Upgrade Ramp. (The dipole needs to be lengthened by about a tenth of a meter to bring the field down to 7 kG.)

In current operation, the electrostatic beam chopper separates a selected (usually the central) part of the Linac beam pulse from its rising and trailing edges to send to the Booster. The edge pulses are sent down a diagnostic line through a spectrometer magnet to a high-intensity dump. The effect of this chopper on the new transfer line remains to be studied to preserve both its role and the function of the present diagnostic line.

Where the ramp straightens, it has a 45° angle relative to the Linac. (Since the bearing of the Linac is almost directly due project-south, the beam in Proton Driver injection transfer line will be headed project-southwest). The pulsed extraction dipole provides approximately 17° of the required bend. Three more dipoles add the remaining 28°. Two remaining steering dipoles are used to align the beam accurately down the ensuing vertical drop, which is immediately followed by dispersion suppression and the lengthy "linac" insert straight.

Because of the length of the line, and, in particular, the long "linac" insert, a regular 90° FODO structure was chosen for the basic optics. This also facilitates construction of achromats for the vertical drops. Since permanent magnets offer an economical opportunity for the long "linac" insert, the cell characteristics of the Linac were chosen to be compatible with permanent magnet quadrupoles whose pole tip fields were less than 2-kG. It was then observed that over half of the entire line could be implemented with permanent magnets with a length equal to that of the pulsed quadrupoles in the line (the quadrupole design in the existing transfer line), and an intervening drift of approximately 4-m. This also conveniently allows permanent magnets to replace electromagnetic quadrupoles where tuneability is not required. In addition, 4-m was found to be an optimal choice. It allows adequate space for insertion of bend elements and matches relatively smoothly to the shorter Linac FODO period. As a consequence, many quadrupoles outside of the "linac" insert can be replaced by a permanent magnet and an air core trim quadrupole when variations about the central gradient are small.

14.2.2. Vertical drops, dispersion suppression, and the linac insert

The vertical drop starts at the end of the Linac Upgrade enclosure to avoid any civil construction near the existing beam dumps. In the periodic structure imposed, a vertical achromat is achieved without modifying the cell structure or optical functions. With the magnet and drift lengths used, the length from center to center of the vertical bends is about 34 m, giving a total vertical descent of 4.1-m (13.5-ft.) This drop takes beam from the existing Linac floor elevation of 736-ft to the Booster floor elevation of 722.5-ft above sea level. The vertical bend magnet is assumed to be the kind used in the existing vertical chute. The descent to Main Injector level is less, only 9-ft, but because of the identical periodic optics, both vertical achromats are essentially identical with the exception of the vertical bend angle.

In anticipation of a possible 600 MeV Linac, conventional dispersion suppressor cells were included in the geometry of the line in order to prepare a dispersion-free Linac insert and ease future implementation. The length allows 450-ft for a linac, although there is sufficient space for a 600-ft linac, a change readily achieved by moving the second vertical drop downstream an integer number of periods. Because no changes in optics are required in this straight, the entire insert can be completely constructed out of permanent magnet quadrupoles. In addition, there are sufficient unused cells to permit a debuncher to be placed optimally in this section of the line.

14.2.3. Matching and Injection into the Proton Driver

Presently there is a length of 60 m and 15 quadrupoles in which to match optically and geometrically to the Proton Driver at injection. There is not complete freedom in this range, as a bend is located at approximately the center of this final matching section, with a stronger bend at the beginning of the section.

In addition to aiming and angling the beam properly through the injection septum, it must also be directed onto the foil to sub-millimeter accuracy through an off-center ring quadrupole. Geometrically the matching section is very constrained. Beam enters the injection septum ~205 mrad relative to the closed orbit. After traversing both the septum and the off-center ring quadrupole, the injected beam crosses the foil at a 1.2 mrad angle and a 5.2-cm offset relative to the closed orbit. The entire injection line has been completed and closed in site coordinates from the Linac to the Proton Driver foil position to a fraction of a millimeter. Until detailed injection studies can be performed, the transfer line optics are simply matched to the Proton Driver optics, with $\beta_x = 22.861$, $\alpha_x = -0.256$, $\beta_y = 9.212$, and $\alpha_x = 0.0004$. There is residual ring dispersion across the injection straight, and, although the transfer line dispersion at the foil is also approximately zero, it has not been matched exactly to the ring's residual dispersion as this may change.

It has been planned that vertical phase space painting will be controlled in the transfer line. Since we are painting in y', a kicker needs to be installed 180° in vertical phase upstream of the foil. In effect, the kicker is located in a 3.5-m straight about 34-m away from the injection point. Figure 14.1 displays the lattice functions through the entire 400 MeV injection transfer line and Table 14.1 lists the required magnets and their basic optical parameters. Designs and drawings exist for all magnets except for the injection and extraction septa and a few dipoles. However, the different dipoles can most likely be reduced to two or three different types.

Table 14.1. Magnets and their parameters for the 400-MeV injection transfer line

Description	Type	Number	Length (m)	Pole tip strength (kG)
Quadrupoles				
Extraction	perm. mag. / trim quad	7 7	0.2985	1.5 0.4
Vert. Drops	perm. mag.	2 x 9	0.2985	1.5
Mat./Disp. Sup.	Loma Linda	5	0.2985	1.0-2.0
Long straights	perm. mag.	44	0.2985	1.5
Final Match	Loma Linda	15	0.2985	0.6-2.0
Dipoles				
Extraction Dipole	new	1	1.3160	7.6
Horizontal Bend Dipoles	 Cooling Ring Steering Disp. Sup. Final Bends	 3 2 2 3	 1.3086 0.4 1.0 1.0	 3.5-4.1 3.5 3.2 4.9
Vertical Bend Dipoles	 Chute Bends	 4	 1.162	 2.2-3.3
Injection Septum	new	1	2.0	3.15

14.3. Extraction Transfer Line

The extraction transfer line extracts 16 GeV beam from the Proton Driver, transports it over about 900-m, and prepares it for injection into the Main Injector. Because of limitations in the optics and the phase advances in the Proton Driver straight section, a number of septum magnets are required to complete the extraction process. The bearing of the extraction straight was deliberately sited to be due project-east. After direction control and dispersion suppression, the line bends along an arc carefully designed to interface with the optics and direction of the existing MI8 line; thereby using existing enclosures and power and water supplies for the final transport and injection match to the Main Injector. The entire line is based on 90° FODO cells with 10-m drifts and permanent magnet quadrupoles. The Proton Driver and Main Injector are based on similar 90° FODO cells and this choice therefore provides continuity between the two rings and makes for an ideal match.

Clearly the permanent magnet version of the MI-8 line cannot support 16 GeV beam with the same optics. Therefore, the original electromagnetic design of the MI-8 line has been resurrected in order to support higher energy beam. The electromagnetic version uses B2 dipoles and 3Q52 quadrupole magnets scavenged from the old Main Ring and, therefore, new magnets are not required.

14.3.1. Extraction from the Proton Driver

The extraction system is relatively complicated. Kickers first displace beam in the FODO-based straight through four ring quadrupoles before beam has sufficient offset from the central ring trajectory to enter the field region of a septum. The first septum is not strong enough to extract beam completely and it must traverse a horizontally defocusing quadrupole and a string of four more septum magnets before finally bypassing the ring elements. A list of the extraction kicks and offsets used in the design is given in Table 14.2. Final adjustments were made to the bend angles specified to arrive at the exact distances given. Magnetic parameters given for the septa reflect field changes.

Table 14.2. Extraction separations and kick relative to central ring orbit

Magnet	Offset, x (mm)	Angle relative to extraction straight (mrad)
Upstream		
QH604	-7.211	-2.323
QH605	-28.162	-3.687
QH606	-9.327	3.824
QH607	29.109	6.043
SM607	33.475	-1.206
QH608	85.643	27.677
SM608	165.123	38.748
Downstream		
SM608	710.709	159.5

14.3.2. Upstream section of the 16 GeV extraction line

After extraction is completed, bend dipoles opposite in field to that of the septum magnets are used to reorient the direction of the upstream section of the transfer line to project-east again. Since the extraction system generates a strong dispersion wave at the beginning of the line, the dipoles in this reverse-bend section are interspersed in the FODO structure to cancel the dispersion and ease the match into the periodic arc structure.

14.3.3. Match into existing MI-8 line

A softly bending arc with a radius of curvature about 163-m merges the new extraction line with the present MI8 line before cell #814 at site coordinates 30439.2043-m easting and 30148.2215-m westing. The arc is designed with conventional dispersion suppression cells at either end and the match occurs at an approximate zero dispersion point in the MI-8 line. (The point chosen occurs just after the vertical drop in elevation from the Booster to the Main Injector level.) The lattice from the point of extraction to intersection with the MI8 line is plotted in Figure 14.2. From there the beam and optics follow the lattice given in Figure 14.3, but starting at 172.4 m in the figure. A table of the required magnets follows with the quadrupole radial aperture assumed to be 4.5 cm.

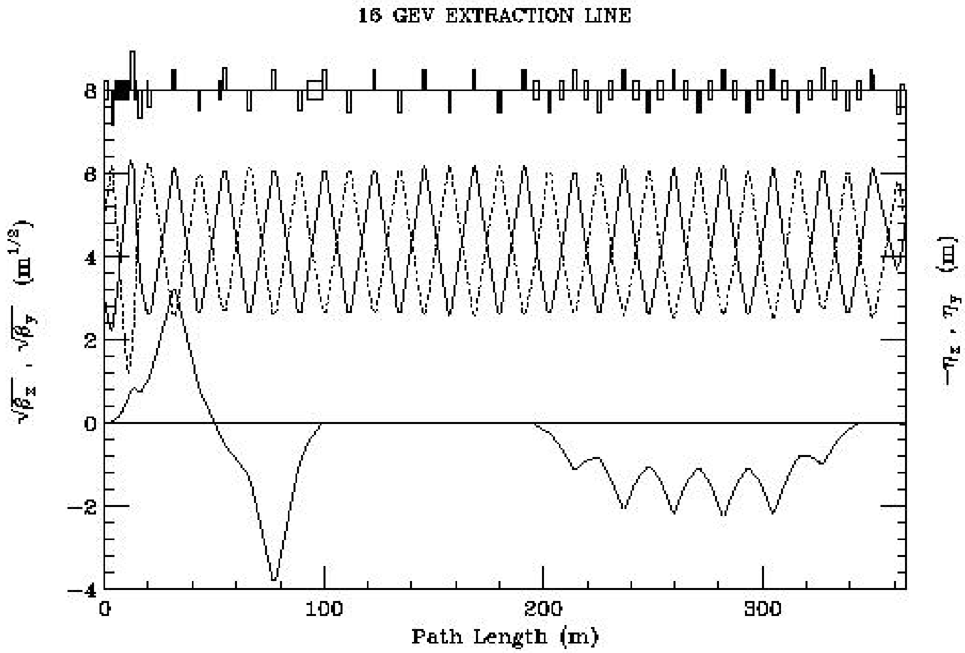

Figure 14.2. Upstream section of the extraction line

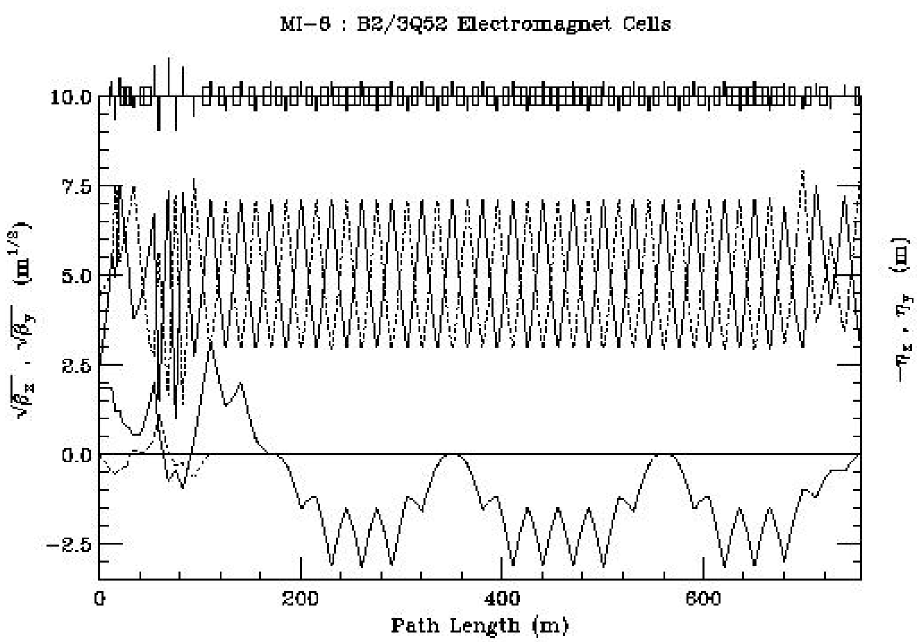

Figure 14.3. Downstream section of the extraction line located in the MI-8 enclosure

Table 14.3. Magnets in the downstream section of the extraction line

Description	Type	Number	Length (m)	Pole tip strength (kG)
Quadrupoles				
Upstream matching	electromagnetic	33	1.4	1.9-4.3
Upstream transport	perm. mag.	15	1.4	2.3
Arc	perm. mag.	14	1.4	2.3
MI8 match	perm. mag./ air-core trim	3	1.4	1.7-2.7
Dipoles				
Extraction Septa	new			
SM607		1	1.65	8
SM608		4	1.35	14
Horizontal				
Bend Dipoles	Rev. Bends	1	0.7610	1.2
		1	0.8384	1.2
		1	6.4634	1.2
	Arc	6	3.0	1.32
	Disp. Sup.	8	3.0	0.66