Doc Number: Beams-doc-1977
Version: 1.0
Category: Notes

MI8 Beamline Collimation Design

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9/30/2005

***Operated by the Universities Research Association under contract with the U.S. Department of Energy.**

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Abstract

In response to the need to increase the intensity of proton beams in the Main Injector while maintaining residual radiation levels which permit hands-on maintenance, a program to provide collimation in the Main Injector Ring and in the MI8 transfer line from the Booster to the Main Ring is being designed. Design requirements and an initial design concept for the MI8 collimation system will be provided in this document. This effort is part of the Proton Plan.

Topics

Introduction

In expectation of increased beam intensity requirements associated with operation of the NuMI beamline, Residual radiation around the Main Injector tunnel was examined prior to the 2004 Fermilab facility shutdown (see Residual Radiation Hints for Aperture and Alignment Issues in the Main Injector). We concluded (among other things) that a small but significant contributor to the residual radiation was losses of beam due to tails of the Booster Beam which were not accelerated but were scraped around the Main Injector at locations which had only very little less aperture than other similar lattice locations. By providing a more defined beam from the Booster, we will reduce the losses from these tails which will reduce substantially the number of hot locations in the MI Ring. Collimation in the MI8 Line can provide this improved beam to the Main Injector. Tails from the Booster Beam may contribute residual radiation at other, as yet unidentified Main Injector locations.

In addition to more general sources of beam tails, measurements of the beam motion induced by changes in the beam trajectory through the Booster Extraction Septum (MP02) suggest that non-uniformity of the fields in this bending magnet (including quadrupole and skew sextupole terms) may be sufficient to create halo from some of the extracted Booster beam (See Multipole fields in Booster extraction septum MP02). By proper placement of the collimation system, one can begin commissioning by scraping halo which would be created by this source (one selects the appropriate phase advance). Since it imposes no undesirable constraints on the collimator design, we will attempt to place collimators so that halo from this source is cleanly collimated.

The design concept for this collimator system is based on the Booster Beam Collimation system (see FERMILAB BOOSTER BEAM COLLIMATION AND SHIELDING). The difference between circulating and single pass beam collimation requires additional collimators while the improved shielding provided by the MI8 tunnel allows a more compact design. The following table compares the collimation requirement for circulating beam in the Booster and one pass beam in the MI8 transfer line.

Booster Collimators	MI8 Collimators
10 Hz at 5E12 Protons/pulse	10 Hz at 5E12 Protons/pulse (same)
2% Loss at 8 GeV plus low energy loss	1% Loss at 8 GeV (or more)
Multiturn circulating beam => collimators 1 Horizontal (radial outside) 1 Vertical (bottom)	One pass => collimators 4 Horizontal (inside, outside at two phases) 4 Vertical (top, bottom at two phases)

Tunnel not deep	Tunnel deep
Surface occupied	Surface not occupied
Air Activation not serious	Air Activation not serious
Sump Pumps in area actively carry water	Tunnel below water level -- not much sump activity
Ground Water not an issue	Ground Water not an issue

Early efforts on this collimation plan assumed that the radiation issues from sump water and the resulting surface water were determined by water levels. We have since discovered that Fermilab guidance for these issues is based on the generation of nuclides in the materials outside of the tunnel, independent of the water which is actually present. For this reason, our design iterations must focus on this limitation. A pair of collimation stations will be placed in the MI8 line approximately 90 degress apart in phase advance to capture particles of large emittance at whatever phase they may exist.

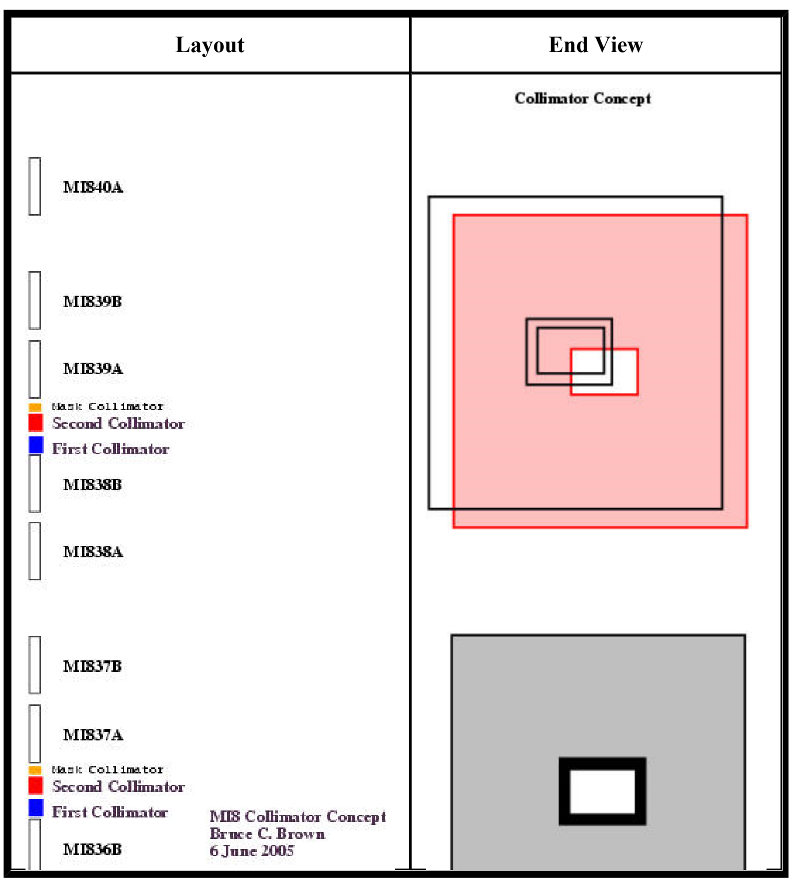
The residual radiation from activation of the collimators is a primary concern. Since marble is very difficult to activate and since it provides a good shield for the low energy gamma rays which are the primary residual radiation produced when iron is activated, we are designing a collimation system in which the shower from the hadronic interactions takes place in stainless steel and iron but beyond that region we place sufficient marble to reduce the radiation exposure for regions adjacent to the collimators (for both work in that area and for those passing through the area.

MI8 Collimation Layout

A design which provided a pair of opposing jaws (top and bottom or left and right) at one location would appear to have some advantages, at least conceptually. The demands of low maintenance (motion system well shielded) severely restrict those options. Available collimators from external beams were considered but they were not sufficiently massive and the motion and vacuum issues made this an unacceptable choice. The current design employs jaws at right angles which allow horizontal and vertical collimation at the same location. With this starting point, the Booster collimators provide an excellent reference design.

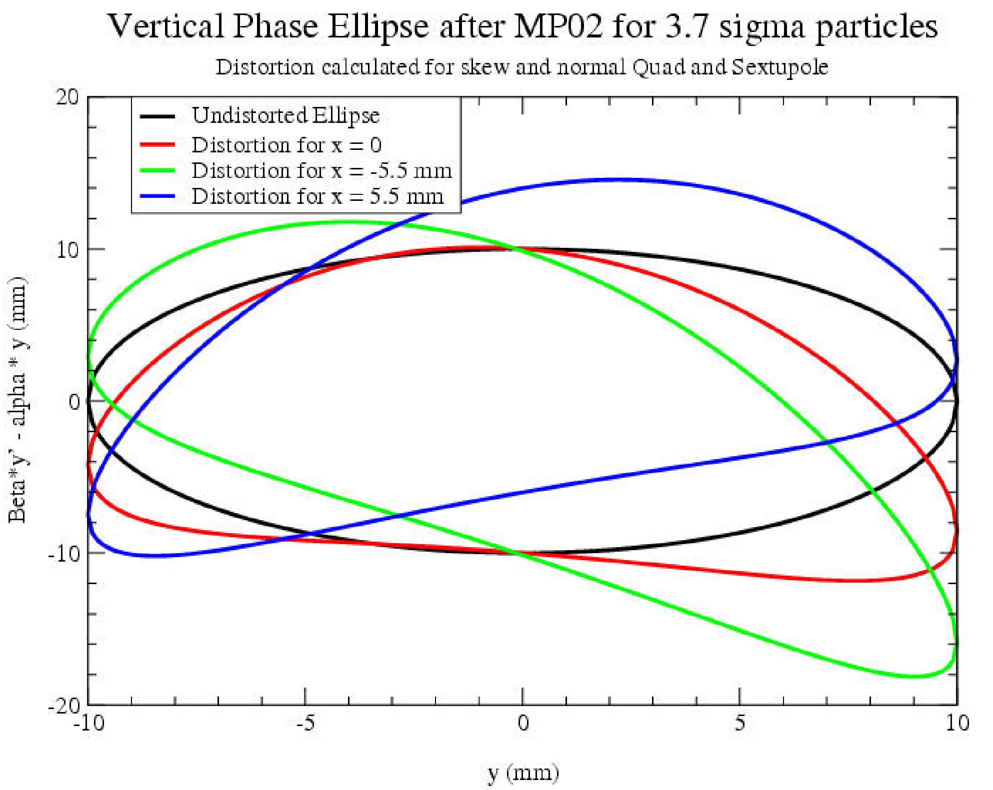
The MI8 Collimator design will intercept the beam in stainless steel vacuum boxes (part of the MI8 vacuum system) surrounded by massive steel absorbers with external marble shielding. As in the Booster collimation system, the motion system will be external to the entire collimator system. A pair of these remotely positioned collimators will be placed in 5.2 m open space in an MI8 half-cell in which the focusing is provided by gradient magnets. One collimator will provide scraping on one horizontal and one vertical edge (bottom and outside, for example) while the next will scrape the other sides (e.g. top and inside). They will be followed by a fixed collimation mask which will protect the next magnet. In order to scrape large emittance particles which happen to be at small displacement but large angle at the location of the initial collimation, a second collimator-mask set will be placed two half cells downstream (about 90 degrees phase advance). This arrangement is illustrated in the following figure.

MI8 Collimator Concept



Halo from Bend Field of MP02 Septum

Frequently one assumes that magnet field quality issues will not impact the beam quality for single pass transport. To check this assumption for a given dipole magnet, on can calculate the distortion for a phase space ellipse. In a vertical bending dipole, one expects the bend to be uniform. For a bend angle Theta, the error y' introduced by a field error dB/B is y' = (dB/B)(Theta). If we calculate this error along a vertical slice across the MP02 magnet and assume the fields from Multipole fields in Booster extraction septum MP02 (Beams-doc-1573), one can calculate the distortion of the phase ellipse for that slice of beam. The vertical aperture available for the extracted beam in MP02 is about plus/minus 10 mm. Using the design Booster lattice with Beta_v = 20 m one finds that the beam at this distance from beam center is at 3.7 sigma in the distribution so it corresponds to 0.1% of the beam intensity. The MI8 line could transport such beam without loss -- probably even with distortion. However, with the fields reported in Beams-doc-1573, one will have a substantial distortion of the extreme beam particles. The figure shows the undistorted phase ellipse (using the normalized plot (y, (beta*y' - alpha * y)) and the distortion for the central vertical slice and the vertical slices displaced by 3.7 sigma in the horizontal dimension. Similar distortions will produce halo in the horizontal phase space. Of course, the distortions from harmonic field errors will be smaller for beam particles nearer the beam center.



Since the outer portions of the Booster beam are distorted by MP02, one would wish to collimate them. If the distortion were produced at a definite phase, one could choose a location downstream with suitable phase advance to remove the distorted beam. However, with large distortions, different parts of the halo will appear at different phase advance locations. In addition, the matching section between MP02 and the higher beta FODO section of the MI8 line introduces 90 degrees of additional phase advance for the horizontal motion so that a location suitable for removing vertical halo will be different from that for horizontal halo. Some differences will remain among possible collimator locations but we do not find a clear optimum based on what we currently know about the MP02 fields. It should be noted that the direct measurement of the bend field in the central region (see Beams-doc-462) showed a smaller field error but one of the same general magnitude. Direct measurements of the skew magnetic fields with coils are not available.

MI8 Lattice -- Locations for 90 degree and 270 degree phase advance from MP02

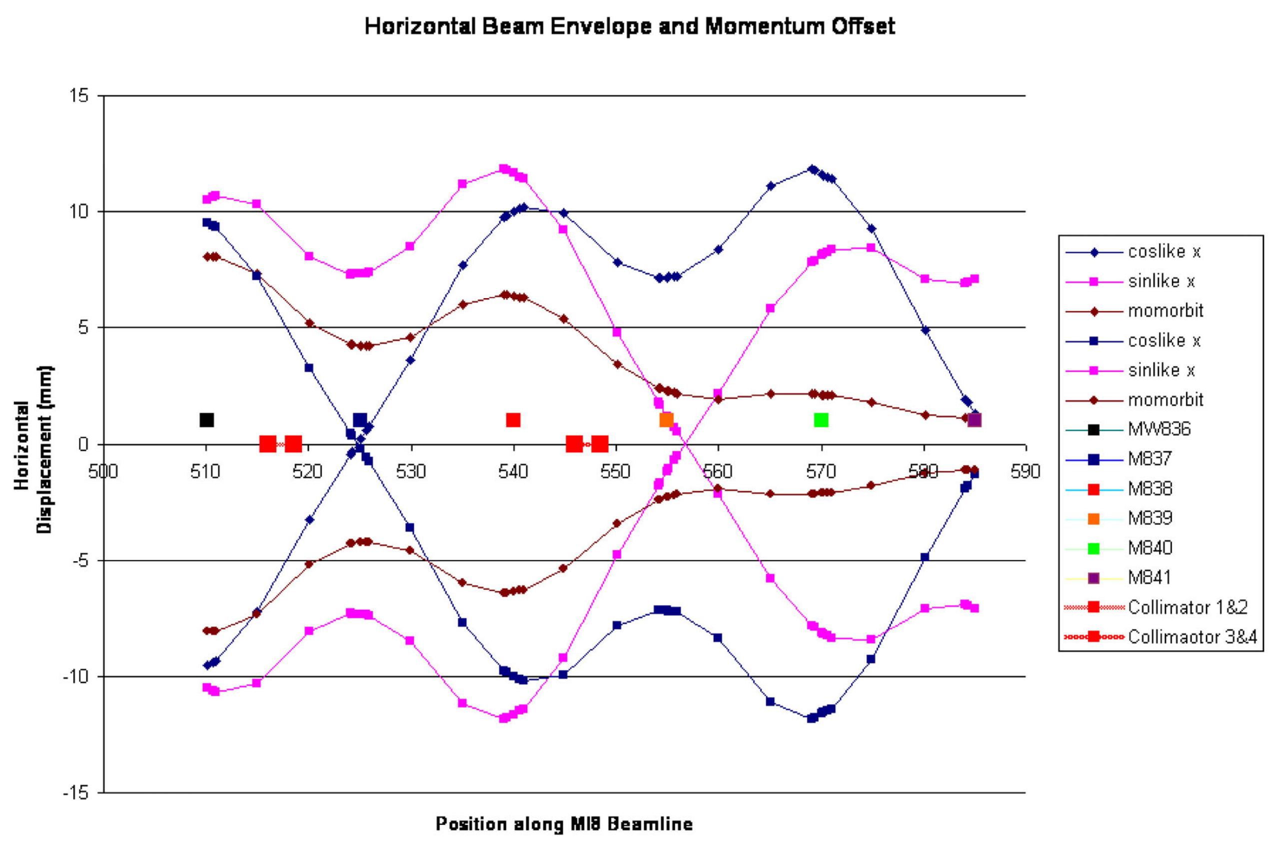
Location for Vertical Mark	Dist.	mu/2pi	Location for Horizontal Mark	Dist.	mu/2pi
MP02	5.371	0.146	MP02	5.371	0.162
H803_1	51.598	0.399	V802_3	42.013	0.420
HP806	77.089	0.855	VP805	68.451	0.747
LM809B	112.291	1.375	HT808	90.311	1.420
PDD_R (in 813 halfcell)	177.634	1.917	PDD_R (in 811 halfcell)	145.427	1.916
PGD_818A	238.843	2.397	PGD_816B	214.677	2.423
PGD_822A	299.259	2.912	PDD (1st in cell 820)	277.147	2.915

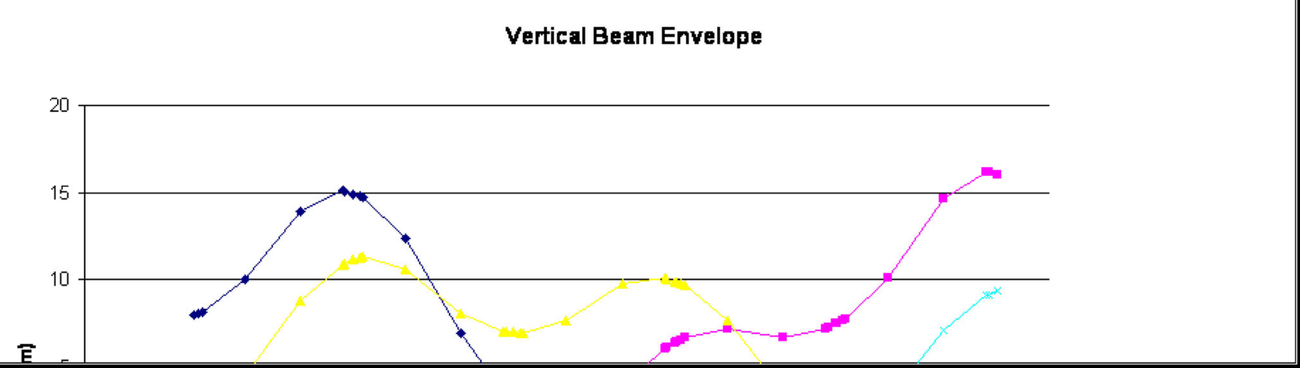
HP826	360.495	3.395	PGD_824B	334.766	3.382
PGD_830B	424.461	3.932	PGD_829A	403.964	3.934
PGD_834B	484.508	4.439	VP833	465.204	4.436
PGD_838B	544.921	4.907	PGD_837A	524.056	4.902
PGD_842B	604.963	5.371	VP841	585.660	5.392
PGD_846B	664.639	5.871	PGD_845B	649.627	5.923

Based on a representation of the MI8 Lattice in MAD, a calculation of the longitudinal profile of beam with specified emittance has been carried out using and Excel spreadsheet. In the following graphs, we examine the trajectories of particles with y = 10 mm, with x = 5.3 mm at MP02 (cosine-like) and particles with that emittance on the sine-like trajectories (each of which corresponds to the part per 1000 edge of the beam) and with dp/p = 0.003. It appears that both horizontal and vertical collimation for a range of phases in the betatron motion is provided while momentum tails will be collimated to some degree. A more detailed look at these issues will be accomplished along with the simulations of collimation at alternate locations along the MI8 line.

MI8 Beam Profile Plots

Beam Profile





Apertures and Beams Positioning Requirements

Design Properties for MI8 Collimators

Property	First Collimator	Second Collimator
Emittance	20 pi-mm-mr (h or v)	20 pi-mm-mr (h or v)
$ß_h$	35 m	32 m
$ß_v$	16 m	20 m
0.1% half-width (3.72 sigma)	13 mm	12.4 mm
0.1% half-height (3.72 sigma)	9 mm	9.8 mm
0.1% half-width (3.03 sigma)	10.65 mm	10.15 mm
0.1% half-height (3.03 sigma)	7.4 mm	8 mm
Dispersion (horizontal)	<3 m	<3 m
Momentum offset for dp/p = 0.001	<2 mm	<2 mm

Mechanical Design Overview

Simulations of the radiation using MARS were carried out using a number of configurations. The iron configuration which matched the Booster collimators was found more than adequate but since the residual radiation was the driving design feature, and the surface radiation was not critical, designs using marble to replace portions of the steel were examined. An iteration with 5" of marble shielding was found to provide very low residual radiation with a much smaller iron absorber. Less iron implies less weight and fewer demands to support and move the device. After iterations which examined dose to adjacent control cabling and nuclide production in the materials outside the tunnel walls, the following configuration was found to satisfy the design needs with about 1% loss in a collimator pair and the beam intensities shown in the table for both Booster and MI8. The driving design criteria is that the residual radiation be <100 millirem/hr on contact after 30 days of activation and 1 day of cooldown. Note that the design includes some iron where the table might suggest marble in order to provide mechanical support as needed. When further simulations are complete, additional substitution of iron for marble may be used to optimize the configuration for radiation concerns.

Material	Units	Vacuum	Stainless	Iron	Marble Side	Marble Ends (2)
Length	Inch		47	35	35	5
Inside Wall	Inch	0	2 x 2	3.5 x 3.5	20(h) x 26(w)	3.5 x 3.5
Outside Wall	Inch	2 x 2	3.5 x 3.5	20(h) x 26(w)	30(h) x 36(w)	30(h) x 36(w)
Wall Thickness	Inch		0.75	8.25(h) or 11.25(w)	5	13.25 or 16.25

Overview of Radiation Issues

The design goals of this collimator system will require the review of a number of radiation issues. We will document issues and a current understanding of their implications in this section. We will assess the radiation effects assuming a loss of 1% of the beam on each collimator pair or a total of 2% of the Booster Beam which is assumed as 5E12 protons per pulse with a repetition rate of 10 Hz.

- Prompt radiation issues can be divided into issues for single event accidents and effects of normal operation. Normal operation effects are further divided by effects for occupied and for unoccupied spaces. Since the Main Injector and MI8 line tunnels are covered by 24.5 feet of earth, there is adequate shielding for normal operation. There are no locations near this installation which are occupied but it would be adequately shielded if they were. Thermal protection will be required to prevent damage to the collimators under accident conditions. Prompt radiation issues will not impose additional single event design constraints.
- Air Activation with this collimator design should not pose any constraints on either tunnel air flow during normal operation nor any delay for access during shutdown.
- The MI8 Tunnel is below most local water and the sumps are normally dry. But the Fermilab protocol for assuring compliance with surface water rediation requirements is based on the number of radioactive nuclei created, without any assumptions about their concentration or dilution in ground water. Calculations for the collimator design are underway to assure that these requirements are met.
- The primary design effort is concerned with the residual dose at the surfaces of the devices as dictated by the need to be able to perform hands-on maintenance in the area. This collimation system has been designed to keep the radiation as measured at one foot to less than 100 millirem/hr The collimators will be set to achieve this level of activation given the transverse motion stability which can be achieved. If the motion during a given operational period is greater than anticipated, The collimators can be set to achieve less scraping of the beam which passes symmetrically through the beam line.

Since this collimation system will create a continuous radiation source, suitable documentation which reviews and documents the above points will be written and the appropriate Beams Division safety documents will be reviewed and revised as required.

Further Steps

The installation of these collimators is planned for the FY06 shutdown. Mechanical design is nearly complete and procurement and fabrication is underway. The location shown in this document will be reviewed to see if further optimization can provide a useful improvement based on loss simulations for various beamline locations using the measured lattice and the beam distortions at MP02 discussed above. The final optimization of the steel and marble for the collimator will be carried out using additional MARS studies.