OPTICS MEASUREMENT OF THE FERMILAB MAIN INJECTOR 8-GEV TRANSFER LINE†

S. Assadi, F. Tecker, M.J. Yang‡, FNAL, Batavia, IL

Abstract

The new Fermilab 8-GeV transfer line for the Main Injector is now commissioned. Studies had been done to measure the optical characteristics of the beamline. In order to capture the state of the beamline as completely as possible all accelerator data, i.e. Beam Position Monitor, Multiwire Profile Monitor, magnet current, and other miscellaneous information, were read and saved. A recently developed beamline analysis program was used to collect data and to do the analysis. Orbit data was used to understand the beamline quadrupole strengths and to measure the dispersion function. The profile data was used to extract beam emittances and to estimate the initial lattice parameter of the beamline.

1. INTRODUCTION

The new 8-GeV transfer line from Booster to the Fermilab Main Injector is 764 meters long [1]. Conventional electro-magnets were used in the first section to match into a mid-section FODO lattice of permanent magnets. The final section uses conventional magnets to match the lattice into the Main Injector proper.

This write-up describes the measurements being done to document the properties of the transfer line and the beam emittances. Beam data was taken for the analysis of optics, dispersion function, and the beam emittances using the on-line beamline analysis program [2]. The data and the results of the analysis will be discussed. Both the design lattice as calculated by MAD [3] and the lattice as determined experimentally were used for the final analysis of emittances.

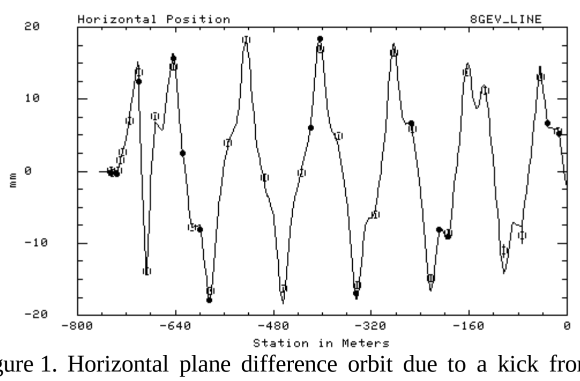

Figure 1. Horizontal plane difference orbit due to a kick from HT802 at 3 amps above nominal. The dots are data from MW profiles, the open circles are data from BPMs, and the solid line is the orbit calculation using matched quadrupole strengths. The beam is extracted from Fermilab Booster at –780 meter on the plot and at station of 0 is the injection point to the Main Injector.

2. DATA

There are 15 Multiwire Profile Monitors (MW) and over 50 Beam Position Monitors (BPM) in the 8-GeV transfer line. These multiwires are used to take data for one plane at a time. BPM data, profile data, magnet currents, the intensity monitor data, and other miscellaneous information are read through the Fermilab accelerator control system.

Reference beam data was taken with the machine at its nominal state at the beginning of each study period. The beam orbit data was taken with 1-bump kick applied at upstream of the beamline to excite position excursions. A data set consists of data with kicks at different strengths. Horizontal and vertical plane data were taken separately. An example of horizontal plane orbit is shown in Figure 1 and the vertical plane orbit is shown in Figure 2. The dispersion data was taken with beam momentum changed in steps of 0.08%. This was accomplished by changing RF frequency in the source Booster ring while keeping its magnet currents constant. All data sets taken have the MW profiles already included and no additional measurement is needed for lattice and emittance analysis.

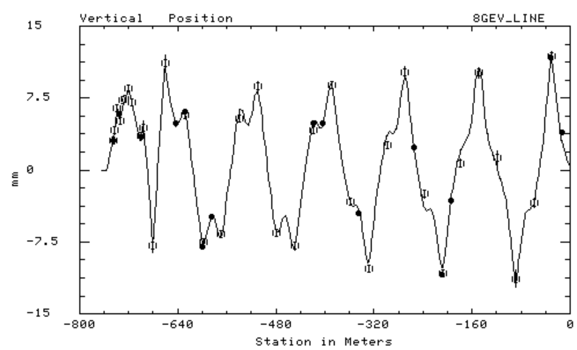

Figure 2. Vertical plane difference orbit data as caused by a kick at MPØ2. Dots are from MW profiles and open circles are from BPMs. The solid line represents the orbit calculation.

3. ANALYSIS

The goal of transfer line optics analysis is ultimately the matching of the lattice function into the down-stream machine, the Main Injector. The three types of analyses reported here were done to ensure that the optical characteristics were understood correctly.

The first step of analysis is to use 1-bump orbit data to diagnose the quadrupole magnet strengths. This analysis is independent of the beam source, the Fermilab Booster. The second is to compare the measured dispersion function with the calculation. This is used to verify that the bend strengths, the initial dispersion function, and the

† Work supported by the US Department of Energy under contract DE-AC02-76CH00300.
‡ E-mail: YANG@FNAL.GOV

quadrupole strengths used in the calculation are consistent with the reality. The last is to use the beam profile width data to extract information on the beam emittance and the σ_p/p. For a transfer line the initial lattice functions directly affect lattice calculation everywhere. In the process of fitting for emittance the initial conditions were also varied such that the RMS error from the fitting process is minimized.

Given a set of initial lattice function the lattice function can be projected down the beamline and into the Main Injector. If needed, the changes in the transfer line magnet currents can also be estimated to improve the lattice matching.

4. RESULT

4.1 Orbits and quadrupoles

The orbit data used for analysis is actually the orbit difference from the reference orbit. In this way the issue of absolute accuracy of the position data is by-passed. During this analysis the strengths of the quadruples used in the calculation can be varied to find the best fit to a given set of orbit data. It is important that the fitted quadrupole strengths can be used in calculations to reproduce all other sets of orbit data, given the corresponding corrector kick strength and polarity.

In both examples shown, i.e. Figure 1 for horizontal plane and Figure 2 for the vertical plane, the fitted quadrupole strengths were used for orbit calculation. The positions from profile monitors in general are more accurate and exert more weight than those from BPM reading, which more susceptible to calibration errors.

The first quadrupole in the 8-GeV beamline starts with Q800, followed by Q801, Q802, and so on. The vertical orbit change was induced by the 1-bump kick using the Booster extraction septum magnet MPØ2. The first available 1-bump horizontal kick is from HT802, located where Q802 is. There was no information available for diagnosing Q800 and Q802 properly.

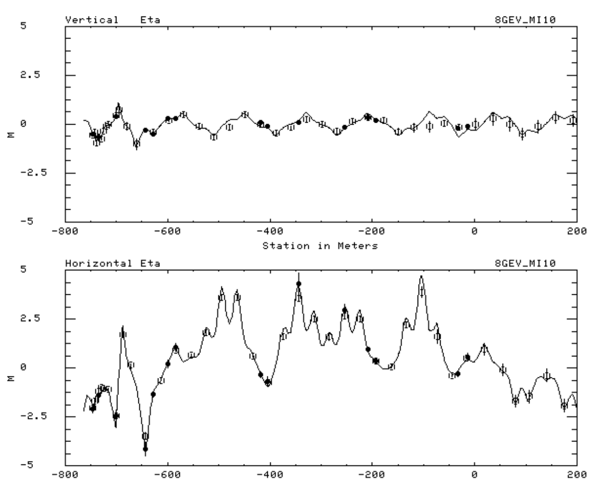

Figure 3. Measured MI 8-GeV transfer line dispersion function as compared with calculation. The horizontal plane data is at the bottom and the vertical plane at the top. Station 0.0 indicated the entrance to the Main Injector ring.

4.2 Dispersion function

The beamline dispersion function depends on the strengths of bending dipoles, the strengths of the quadrupoles, and the initial lattice function at the Booster extraction point. The horizontal and vertical plane dispersion function shown in Figure 3 were calculated using the designed dipole strengths and the quadrupole strengths as determined from the procedure above. The initial dispersion functions had to be modified in order for the calculation result to match the data. This modification is echoed in the emittance fitting procedure to be discussed next.

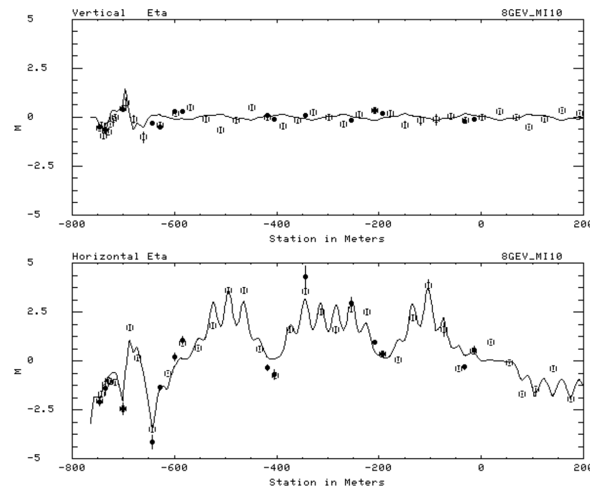

Figure 4. The dispersion function as designed for the 8-GeV transfer line is plotted against the same dispersion function data as was shown in Figure 3.

For the calculation of dispersion function there is very little differences between using the design lattice and using the lattice as determined from data. The single most significant factor is the initial dispersion used. Figure 4 plots the same dispersion function data as in Figure 3 but against the original 8-GeV transfer line design calculation. The difference is quite apparent.

4.3 Beam profile and emittance

The beta and dispersion functions at the profile monitor locations are needed to fit for the emittance. Different initial β, α, η, η' values result in different lattice function and, therefore, different fit result. The initial conditions that lead to smallest RMS error from the fitting algorithm is considered the optimized conditions.

Three scenarios were explored for the analysis of beam emittance and σ_p/p. The first is to use the design lattice and the design initial condition for calculation. The second is to use the design lattice but with a set of optimized initial conditions. The third is to use only experimentally determined quadrupole strengths and initial conditions.

Figure 5 shows the width sigma from profile data in solid green dots. The calculated sigma from the first scenario is shown in solid black line. The calculation from scenario 2 is overlaid in solid magenta. The calculation result of scenario 3 is shown separately in Figure 6.

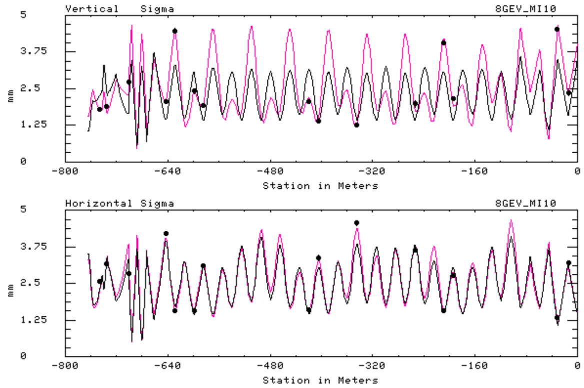

Figure 5. Plot of horizontal and vertical plane beam widths. Green dots are the data points from profile monitors. Solid lines are from calculation using design lattice and fitted emittance. The calculation using the design initial lattice function is shown in black and the calculation using optimized initial condition is shown in magenta.

4.4 Lattice function

The first horizontal BPM after injection into the Main Injector is HP102. The projected horizontal lattice functions at this location were calculated using the second and third scenario mentioned above and listed in table 1. The calculation based on the first scenario is, by design, matched with the Main Injector design lattice and will not be listed. For vertical plane the first BPM is VP101 and the projected vertical lattice function is also listed in table 2.

From table 1, the horizontal plane calculation agrees fairly well among the two scenarios even with substantial differences in the initial lattice function. The difference in the vertical plane was appreciably larger. It should be mentioned that the lattice as was designed did not reproduce the vertical plane orbit data well. This may lead to additional systematic error. In either case substantial difference exist between projected lattice function and the expected Main Injector lattice function.

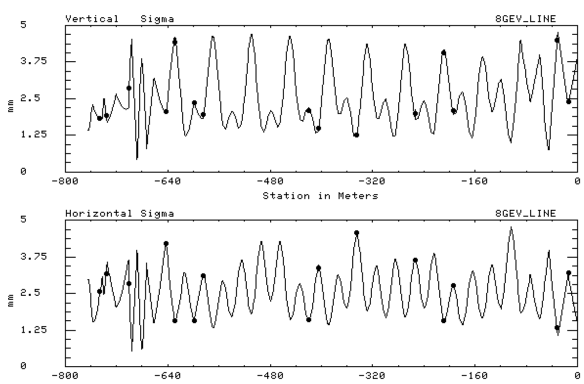

Figure 6. Same horizontal and vertical plane beam width sigma data as in Figure 5. The solid line shows the sigma as calculated using the adjusted quadrupole strength, optimized initial condition, and the fitted emittance.

The optimized initial lattice function is likely a result of the actual initial condition conbined with the unknown quadrupole errors at the beginning of the beamline. Beyond the first part of the beamline, and especially within the permanent magnet section, the quadrupole strengths are fairly well understood. From Figure 6 it is clear that the calculation fitted well with data within this part of the beamline and could still yield credible projection of the lattice function.

Table 1. Projected horizontal lattice function at the Main Injector HP102 location.

	MI/ring	MI8/design	MI8/fitted	Unit
β	54.830	63.27	60.42	M
α	2.394	2.78	2.71	
η	0.081	0.89	0.99	M
η′	-0.001	-0.046	-0.05	

Table 2. Projected vertical lattice function at the Main Injector VP101 location.

	MI/ring	MI8/design	MI8/fitted	Unit
β	57.490	74.00	69.54	M
α	2.468	3.94	3.80	
η	0.000	-0.47	-0.289	M
η′	0.000	0.044	-0.023	

5. CONCLUSION

The preliminary analysis indicates that the behavior of the MI8 beam line can be modeled quite well but not as was designed to be. The dispersion function is an indication that the bending dipoles behaved as designed. The data also showed that the permanent magnet portion of the beam line, starting from location 809 and up to 847, has worked as designed.

The horizontal plane optics appears to be quite close to the original design while the vertical plane optics may have deviated from it by some degree. The large lattice function deviations, as seen in the vertical plane, are due mostly to the initial conditions. In the case of dispersion function it was also found that the initial conditions were largely at fault.

Knowing the initial condition at the Booster extraction is very important for the proper operation of the 8-GeV transfer line. To do that the first part of the beamline needs to be well understood. More data will be taken in the future to establish the reproducibility of this analysis. The study of the Main Injector ring lattice function is also just starting and will likely take some time to mature. Adjustment will be made when the matching is verified one way or another.

6. REFERENCES

[1] The Fermilab Main Injector Technical Design Handbook.

[2] M.J. Yang, “A Beamline Analysis Program for Main Injector commissioning”, Particle Accelerator conference, 1999.

[3] Hans Groted and F.C. Iselin, *The MAD Program*, 1990, CERN SL/90-13 (AP)