OPTICS AND FIELD ERROR COMPENSATION IN THE FNAL PERMANENT MAGNET 8.9 GEV/C PROTON TRANSFER LINE

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Abstract

Protons are transported 760 m from the Booster extraction point to injection into the Fermilab Main Injector. Apart from two, comparatively short, specialized optical matching sections the transfer lattice is described by 90^o betatron phase advance arc cells and missing-dipole dispersion suppressing cells. This repetative structure, combined with the small average bend per cell makes it feasible to construct this section exclusively from low-field permanent dipoles and gradient magnets. The permanent magnet section is nearly devoid of powered correctors: trajectory control and momentum error compensation is accomplished instead by moving select gradient magnets transversely. Permanent magnets are being used in the transfer line primarily to acquire the manufacturing and operational experience necessary to ensure success of the future FNAL Recycler Ring.

1 INTRODUCTION

Protons extracted from the Booster are transported 756 m for injection into the FMI. The 8 GeV transport line is comprised of three major sections: a matching section between the Booster and the main body of the beamline, which also incorporates the descent from the Booster to Main Injector elevation; a long section of periodic FODO cells; and a final section to match the optics between the beamline's FODO section and the FMI.

As originally designed, the 8 GeV line was to be constructed exclusively from magnets recycled from Main Ring and the present Booster to Main Ring transfer line. This remains true for the optical matching sections at each end of the line. However, in the long arc of repetitive FODO structure all electromagnets (B2 dipoles and 3Q52 quadrupoles) have been eliminated and replaced with permanent magnet dipoles, gradient magnets, and quadrupoles. The design of the permanent magnets used in the 8 GeV line are described extensively elsewhere in these proceedings [1-4].

In addition, unlike its electromagnetic predecessor which had trim correctors assigned to every quadrupole location, trajectory control through the permanent magnet arc will be accomplished largely by gradient magnet movements.

2 PERMANENT MAGNET OPTICS

The transfer line's permanent magnet section extends for 644 m and is constructed from 65 gradient, 45 dipole, and 9 permanent quadrupoles. The relevant magnet parameters are summarized below in Table 1. The available aperture at each magnet is 92.075 x 47.625 mm, corresponding to the interior dimensions of a squashed 3" beampipe.

The long arc section of permanent magnets produces a total bend of 103.45^o, with each dipole and gradient magnet bending the trajectory by 1.10^o. The first 8 dipoles have reverse bends relative to the remaining magnets in the series, which serves to keep the beam well clear of the existing Anti-Proton complex.

Magnet	#	L (m)	B (kG)	B' (kG/m)
Gradient	65	3.9751	1.4327	4.6562
Dipole	45	2.4638	2.3116	0
Quadrupole	9	0.5080	0	29.1470

Table 1 : Parameters of the permanent magnets used in the 8 GeV line FODO section.

The permanent magnet section is constructed from just three different types of cells. These cells were designed with the intent to replicate as closely as was reasonable the optics and trajectory defined by the earlier electromagnet design. These cells are depicted in Figure 1 below.

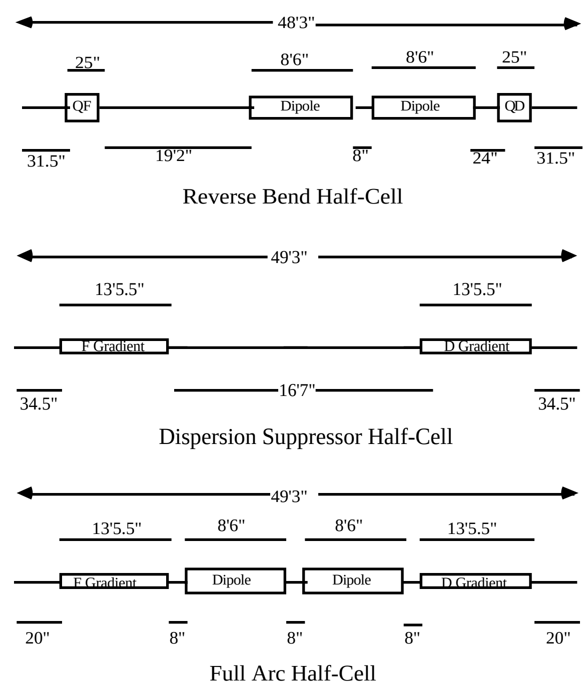


Figure 1 : Physical layout of the 3 permanent magnet cell types in the 8 GeV transfer line (not to scale).

Lattice functions for the entire 8 GeV line from Booster to Main Injector are shown below in Figure 2. The 'reverse bend' section extends from quad Q810 to 814, and the regular long arc runs from 814 through to the first Injector-end powered matching quad at 847.

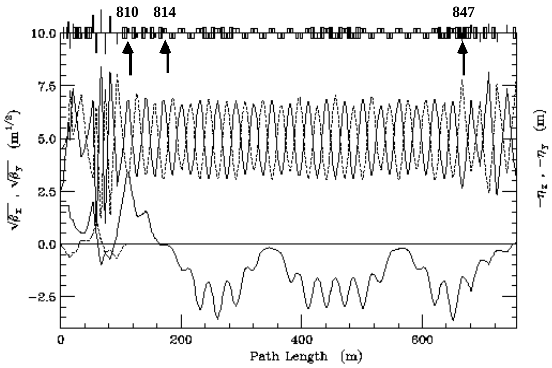


Figure 2 : Lattice functions of the proton 8 GeV line from the Booster to Main Injector.

The 'reverse-bend' section is constructed from two cells, each characterized by 4 permanent dipoles, 4 permanent quadrupoles, and 84^{o} of betatron phase advance per cell. These cells represent a compromise betweeen following as closely as possible the trajectory through the tunnel defined by the earlier electromagnet solution and achieving a smooth optical match to the subsequent long arc of FODO cells.

The regular lattice section is constructed from two types of cells -- regular cells with 4 permanent dipoles plus 4 gradient magnets per cell and missing-dipole dispersion suppressing cells with 4 gradient magnets per cell. Both types of cells have ~90^{o} of phase advance but are not perfectly matched optically. This mismatch is the consequence of intentionally creating additional space in the lattice to accommodate the possible insertion of further diagnostics in the future. As a result dispersion neither reaches precisely zero anywhere, nor is it optimally minimized through the arc. However, horizontal dispersion becomes as small as 0.12 m and does not exceed 3.71 mm, which is acceptable. With a maximum β = 47 m and $\delta p/p$ = 0.2% the transverse beam size is less than ±16 mm for a 40π mm-mr (95% normalized) emittance, which is compatible with the 48 mm (V) x 92 mm (H) aperture of the beampipe. With each dipole and gradient magnet producing 1.10^{o} of bend, the sagitta is only 5.9 mm and 9.5 mm respectively. Again, this is compatible with the available aperture.

3 FIELD ERROR PROPAGATION & COMPENSATION

Every cell boundary in the 8 GeV line has a BPM associated with it and every electric quadrupole in the line also has a recycled Main Ring correction dipole nearby. Additional correctors are located at the entrance and exit of the long arc to provide beam position and angle adjustment.

The main body of the permanent magnet section is nearly devoid of trims, and these are situated with an eye to centering the beam on downstream multiwires rather than for global trajectory control. Instead, as will also be the case in the Recycler Ring, any necessary trajectory corrections will be performed by moving gradient magnets.

The gradient magnets are designed, and installed, with the ability to 'float' transversely on the beampipe by as much as ±1". With this feature the available beam aperture is always determined solely by the beampipe dimensions and is independent of the transverse position of the magnet. The dipole kick due to horizontal translation by an amount δ is:

$$\Delta\theta = \frac{\int B_1 \cdot ds}{B\rho} \bullet \delta = 614 \cdot {}^{\mu r}\!/_{cm}$$

A 1 cm magnet displacement therefore translates into a kick ~0.85% of the nominal bend. This is comparable to the strength obtainable from a Main Ring trim ($\Delta\theta$ = 580 μr @ 5A). Fairly modest magnet moves therefore provide significant steering capability. The effect of dipole field errors on the trajectory through the long arc, and the consequent gradient magnet movements required for correction, have been investigated in simulations. Random field error compensation must be addressed by any beamline but, unlike the case with electromagnet transfer lines, systematic dipole field errors (or, equivalently, a systematic beam momentum offset) becomes an important issue for permanent magnet lines.

3.1 Simulation Approximations

Rather than using the true lattice configuration, trajectory error simulations were performed with a lattice constructed from 7 regular plus 12 dispersion suppressor cells to mimic the repetitive optics of the long arc. While results from the simulations should not be sensitive to this approximation, trajectory correction is simplified by being amenable to solution via the canned algorithms intrinsic to MAD [5].

The optics of this approximate lattice are shown in Figure 3. In all following discussions of simulations the beam is assumed to be described by 40π mm-mr emittance (95% normalized) with a momentum spread of $\delta p/p$ = 0.2%.

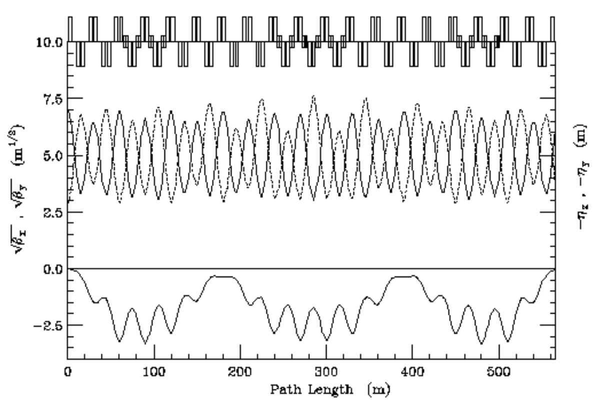


Figure 3 : Lattice functions of the 'approximate' repetitive FODO lattice employed in simulations of error propagation and correction.

3.2 Systematic Field / Momentum Errors

A systematic 1% dipole field error (much larger than any realistic error source imagined) was assigned to each of the 28 dipoles, 38 F-gradient, and 38 D-gradient magnets in the approximate lattice. Figure 4 shows the resulting horizontal beam trajectory and envelope. The solid bars intruding from the top and bottom of the graph indicate the available beampipe aperture. Position and angle of the incoming beam have been optimized to minimize the transverse excursions. The resulting rms displacement of the orbit is $\Delta x(rms) = 18.5$ mm and, with maximum displacements of $\Delta x(max) = 31.0$ mm, the beam scrapes at all high dispersion locations.

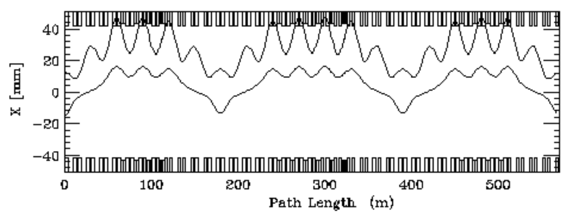


Figure 4 : Horizontal beam trajectory and envelope for a 1% systematic field (or momentum) error.

Figure 5 shows the beam trajectory and envelope after correction. Moving just the F-gradient magnets, 8 by 10 mm, 12 by 7.5 mm, and 18 by 5 mm, the excursion of the beam is dramatically reduced to $\Delta x(rms) = 1.7$ mm and $\Delta x(max) = 3.2$ mm.

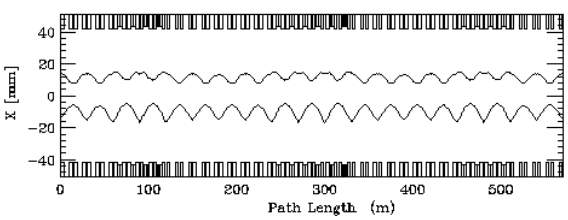


Figure 5 : Horizontal beam trajectory and envelope after moving magnets to correct for the 1% systematic error.

3.3 Random Field Errors

Random field errors can be treated analogously to the systematic errors. Uniformly distributed, random dipole errors in the range ±0.25% were assigned to all 104 magnets in the approximate lattice. The beam trajectory resulting from 20 random generator seeds was calculated. The worst case trajectory, which had an orbit wobble characterized by $\Delta x(rms) = 3.7$ mm and $\Delta x(max) = 13.0$ mm, is illustrated in Figure 6 below.

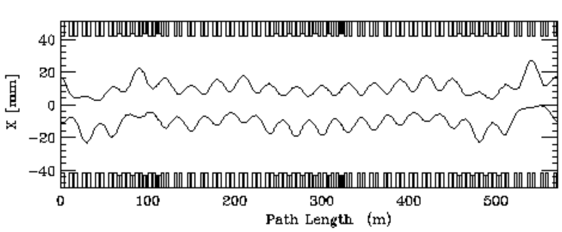
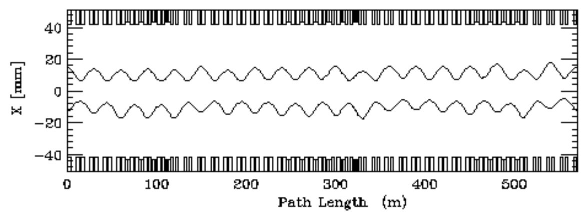


Figure 6 : Horizontal beam trajectory and envelope for the 'worst case' random 0.25% field errors.

It can be seen from Figure 6 that no correction of the orbit is strictly necessary -- there is ample aperture for lossless beam transmission. However, with small adjustments to just 12 of the F-gradient magnets, moving 4 by 1.25 mm, 6 by 1.00 mm, and 2 by 0.5 mm, the trajectory deviation can be reduced to the level achieved for the 1% systematic error case. Figure 7 shows this corrected trajectory, where orbit excursions have now been dropped to $\Delta x(rms) = 1.2$ mm and $\Delta x(max) = 3.0$ mm.



.Figure 7 : Trajectory and envelope after compensation for the 0.25% random field errors.

4 DISCUSSION

There are additional sources of error intrinsic to the permanent magnets that have not been addressed here. The two most important of these are probably the field strength variation with temperature and the systematic plus random bend center errors. To a large extent however the adverse effects of these flaws can be eliminated by sorting the magnets prior to installation.

What has been demonstrated by the simulation results presented here is that very large momentum offsets from nominal and/or large field errors can be corrected through fairly modest movements of gradient magnets, without the necessity of separate correction elements.

REFERENCES

[1] 'Permanent Dipole Magnets for the 8 GeV Transfer Line at FNAL', H.D. Glass et al, these proceedings -- 2P.12.

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[5] 'The MAD Program', H. Grote, F.C. Iselin, CERN/SL/90-13(AP).

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