1.8 TeV Tevatron Upgrade Lattices

A. A. Garren
SSC Central Design Group*
c/o Lawrence Berkeley Laboratory
Berkeley, CA 94720

M.J. Syphers
Fermi National Accelerator Laboratory*
Batavia, IL 60510

Abstract

The present Fermilab Upgrade program calls for a future higher energy ($\geq$ 1.5 TeV) superconducting accelerator to reside in the existing Tevatron tunnel [1]. Three possible lattice designs for this accelerator are presented here. The first involves longer straight sections which permit the extraction of 1.8 TeV beams to the fixed target experimental areas or to external aborts. The second option uses stronger focusing quadrupoles to reduce the beam size throughout the accelerator. In this scheme, a large number of quadrupole circuits provide the necessary matching of the dispersion function across the long straight sections. The third option uses longer standard cells in the arcs, the cell length strategically chosen so as to minimize the dispersion wave generated by the medium- and mini-straight sections located in the arcs. The beam size is not as small as in the second option, though it is better behaved than in the present Tevatron lattice, plus it is believed that separator and low-beta schemes may be more easily implemented using this lattice design.

1 Introduction

If the Fermilab Upgrade plan were to proceed as proposed [1], [6], the removal of the 150 GeV Main Ring from the main accelerator enclosure would leave room for a higher energy superconducting accelerator in its place, directly above the present Tevatron. The purpose of this study is to investigate various improvements that may be made to the lattice design of such an accelerator.

There are at least two schools of thought concerning the layout of a new ring. The first assumes the synchrotron would operate at its maximum energy for both the colliding beams and fixed target HEP programs. The maximum energy is thus determined by the constraint that the beam must be extracted to the external experimental areas. If all of the components of the new machine were superconducting there would be no lattice problem; the dipoles and quadrupoles could be replaced by new ones with unchanged length and with strength scaled with energy. However, the kickers and septum magnets of the beam extraction system do not scale. To obtain the same separation between the circulating and extracted beams as with the Tevatron, a longer string of septum magnets will be required, so the long straight section may have to be lengthened. To do so requires stronger dipole magnets in the vicinity of the straight section than those in the remainder of the arc.

Members of the other school would argue that if higher strength magnets are necessary near the long straight sections, the new ring should be made up entirely of these devices. In this scenario, the fixed target program would operate at an energy lower than that of the collider program, dictated by the extraction energy possible with the present 50 m long straight section. The higher energy, lower intensity beams of the collider may be aborted internally, as is done in the present Tevatron with antiproton beams. Therefore, the lattice of the new machine could, in principle, be identical to that of the present Tevatron.

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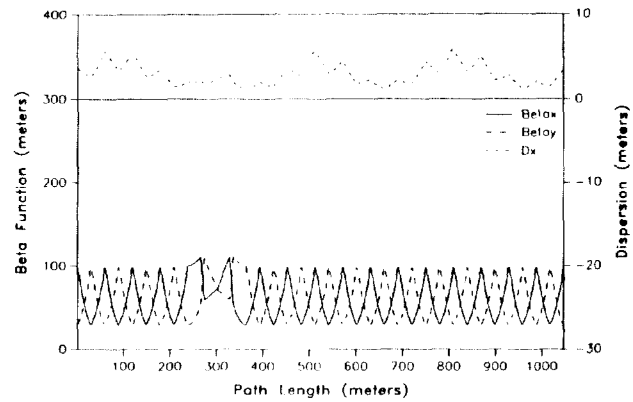

Figure 1: Tevatron normal superperiod (Sectors C, E, and F).

However, even in this scenario, there are other reasons for improving the overall lattice of the synchrotron. In particular, the strengths of electrostatic separators needed for separating the circulating proton and antiproton beams depend upon the beam size. The present Tevatron separator scheme already pushes the electrostatic technology to its limits for 1 TeV beams [4]. At these high energies, the beam size is dominated by the product of the dispersion function and the momentum spread of the coalesced bunches used for collider operation. For this reason, it may be of great practical importance to create a new lattice with a smaller dispersion function than that of the present Tevatron. The normal superperiod lattice of the present Tevatron is shown in Figure 1.

2 Lengthening the Straight Section

One of the first issues that needed to be settled was to determine the maximum energy beam that could be reasonably extracted from the Fermilab tunnel. Considering a string of septum magnets of length ℓ and field B_ℓ at the beginning of a drift space of length L, then the transverse separation at the end of the drift L will be given approximately by

$$\Delta x = L\alpha p(1 - p/2)$$

where $p = \ell/L$ and $\alpha = B_\ell L/(B\rho)$.

To lengthen the straight section by ΔL, one removes dipoles of length $\Delta L/2$ on each side, moves the inner quadrupole doublets

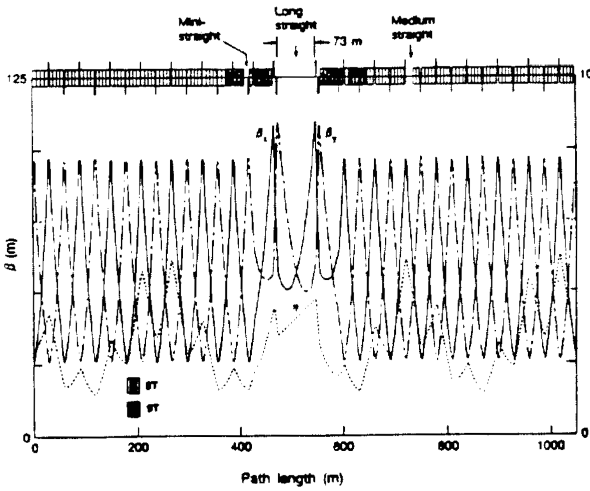

Figure 2: Normal superperiod for Upgrade lattice – Option 1

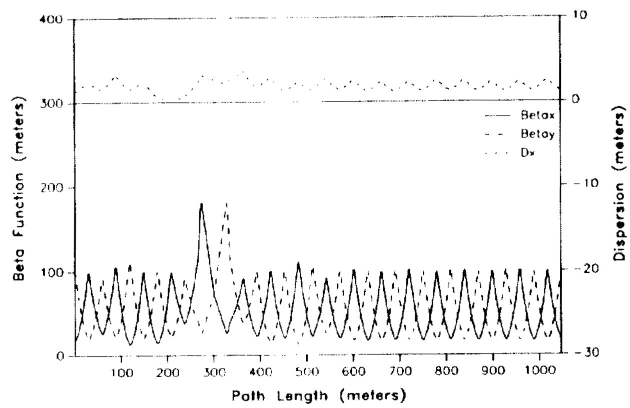

Figure 3: Normal superperiod for Upgrade lattice – Option 2

outward by the same amount, and replaces sets of dipoles beyond the doublets with stronger dipoles to preserve the total bending. As a result, n standard strength dipoles on each side will be replaced by a smaller number of stronger dipoles. For an Upgrade lattice of energy E (TeV) and field $\hat{B}$ (T) in the stronger dipoles, the length increase of the long straight section is approximately

$$\Delta L = (14.2m)(1 - 4.44E/\hat{B})n,$$

while the straight section is displaced radially inward by an amount

$$D = (.0288m)(1 - 4.44E/\hat{B})n^2.$$

It is assumed that the drift space L is 80% filled with 1.2 T septum magnets such as those used in the present Tevatron. Though the tunnel could, in principle, support a radial displacement of 1.5–2 m, a maximum radial displacement of $D = 0.5$ m is applied in order to create a continuous aisle for the transport of magnets and other equipment throughout the enclosure.

An 8.8 T magnet is assumed for the stronger dipoles. This is the highest field presently being contemplated by the Fermilab magnet program. [5] The extracted beam channel clears the present Tevatron center line by approximately .3 m at the downstream end of the A0 straight section. The outside diameter of the 8.8 T magnet design is much larger than the present Tevatron dipoles and thus .5 m is a more appropriate choice for Δx.

With these choices for Δd, Δx, $\hat{B}$, B_t, and p, the above three relationships may be solved for E, ΔL, and n. If 13 normal strength dipoles are replaced by enough strong dipoles to produce the same bending angle, the straight section length will increase by 21 m and will support the extraction of 1.8 TeV beams. The normal bending magnets throughout the remainder of each arc must then have a field of 8 T.

A lattice has been designed based upon the parameters of the preceeding discussion and has been reported elsewhere [3]. In addition to the longer straight section and strong dipoles, the mini-straight section found in each superperiod was also moved in order to make kicker magnets more effective. Figure 2 shows the resulting superperiod design. The optical matching was performed using the SYNCH program [2] and is described in [3].

3 Lowering the Dispersion Function

For the next two lattice designs it is assumed that the long straight sections will not change length. It is assumed that the accelerator will operate in collider mode at the highest energy that can be provided by the magnet program and that fixed target HEP will operate at a presumably lower energy dictated by the 50 m extraction long straight section at A0. For the purpose of consistency, an energy of 1.8 TeV was used throughout the design of these lattices, though all magnet fields may be scaled to whatever energy is actually achievable.

The Fermilab Upgrade plan calls for a large number of proton and antiproton bunches to circulate the synchrotron. To minimize the beam-beam interaction the two beams need to be separated by at least five sigma in the transverse direction using electrostatic separators. For the coalesced bunches used in the Tevatron the rms beam size, at high energy, is approximately given by $\sigma_x = D_x\sigma_p/p$, where D_x is the dispersion function and σ_p/p is the rms of the relative momentum distribution. It is therefore desirable to have small dispersion wherever possible.

As seen in Figure 1, the dispersion function is not matched to the cells in the arc, resulting in a wave of dispersion with a peak value in excess of 5 m. If the straight sections were matched in dispersion to the standard cells, the largest value of D_x in the arcs would be 4 m with the present cell phase advance of 70°. By increasing the cell phase advance to 90°, the cell dispersion is reduced to 2.6 m.

If the standard superperiod were made up only of standard cells with equal bending, matching the dispersion through the straight sections would be a relatively straightforward task of adjusting the quad strengths and locations in the vicinity of the straight section. However, each superperiod contains two regions where dipoles are missing. The so-called medium-straight contains only half the bend of a normal cell, while the mini-straight contains 3/4 of the normal bending. To match the dispersion generated by these regions to the rest of the arc while maintaining reasonable amplitude functions requires more quadrupole circuits.

Using the SYNCH program, a lattice has been developed which performs the above operations. The result is shown in Figure 3. The standard cells have 90° phase advance with 2.6 m dispersion. The maximum dispersion in the ring, which occurs in the vicinity of the long straight section, is 3.6 m. The cell quadrupoles operate at a strength of 0.05/m. To obtain the proper match of the amplitude functions across the straight sections, the first three quadrupoles on either side of the straight section have strengths less than that of the standard quad. Eight more quadrupole circuits within the arcs, with strengths within ± 10% of the standard quad, were used to perform the dispersion match. The peak amplitude of the beta wave within the arc produced by these perturbations is less than 10% of the standard cell β_{max}.

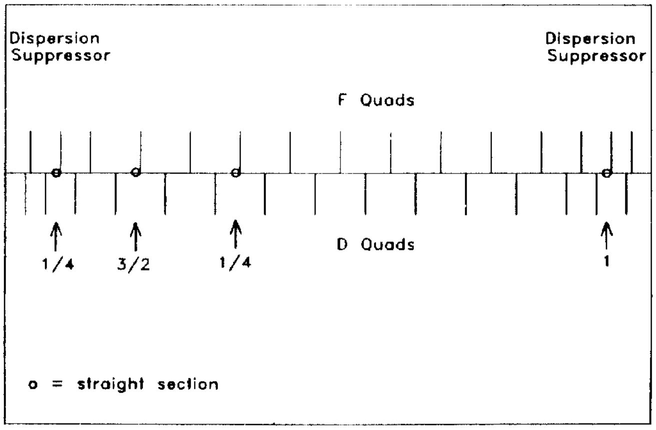

Figure 4: Schematic layout of lattice for Option 3. The circles indicate the medium (3/2), mini (1), and *micro* (1/4) straight sections.

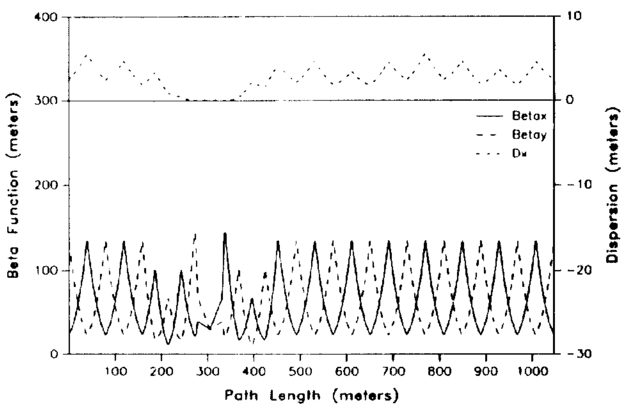

Figure 5: Normal superperiod for Upgrade lattice – Option 3

4 Increasing the Cell Length

The approach taken in the third lattice design is to minimize the dispersion mismatch generated by the mini- and medium-straight sections by changing the length of the standard cells. The cell phase advance is 90° and the cell length is chosen so that there are $4n + 2$ (n an integer) cells between these two straight sections. A longer cell length (40 m, for $n = 2$) was chosen to provide better packing of bending magnets, thus reducing the bend field. While the medium-straight of the present Tevatron has two missing dipoles whereas the mini-straight has only one missing dipole, the medium straight is divided up into three new straight sections (one medium, two *micro*'s) for the new lattice design as shown in Figure 4. This arrangement of missing dipoles restricts the dispersion wave to remain between these small straight sections. The dispersion is brought to zero within the long straight sections through the use of dispersion suppressor regions on either side.

At 1.8 TeV, this design uses eight 8.35 m, 7.8 T dipoles for each standard cell while a dispersion suppressor consists of two cells, each containing six 7.87 m dipoles of the same field strength. The quads within the arcs have strengths of 0.036/m (150 T/m, 1.44m long) and those in the dispersion suppressors have strengths of 0.052/m. The matching quads in the straight section regions have strengths of ~0.095/m (~160 T/m, ~3.6 m long). The lattice functions are shown in Figure 5.

The changes in the ring geometry create excursions of the beam trajectory with respect to the present Tevatron trajectory. The maximum radial excursion of the new design relative to the present Tevatron is about 13 in. to the outside. This brings the new ring (assuming an outside magnet diameter of 18 in.) close to, but within the tunnel wall. The long straight sections move radially inward by about 5 in. with a 0.5 mrad change in slope.

Due to the increased cell length, the maximum amplitude function and the cell dispersion function are larger than in the preceeding lattice option. However, the zero dispersion long straight sections should make low-beta insertions easier to design and tune. The dispersion function peak is still smaller than in the present Tevatron and is much more uniform throughout the arcs. It is also felt that separator schemes may be simpler in this lattice than those used in the present Tevatron, though no work has been done in this area.

5 Summary

Table 1 summarizes the lattice properties of the present Tevatron and the three options discussed above.

Table 1: Lattice Parameters

	TEV	OPT 1	OPT 2	OPT 3	
Energy	1.0	1.8	1.8	1.8	TeV
Radius	1000	1000	1000	1000	m
Str. Sec. Length	53	73	53	53	m
Cell phase adv.	68	74	90	90	deg.
cell β_{max}	98	98	99	135	m
global β_{max}	110	110	180	144	m
cell D_{max}	4.0	3.5	2.6	4.7	m
global D_{max}	5.9	5	3.6	5.6	m
D in str. sec.	2.5	3.2	2.4	0.0	m
Magnet Field	4.4	8, 9	8.0	7.8	T
Cell Quad Strength	.038	.041	.050	.036	m^{-1}
Cell Half-length	29.7	29.7	29.7	39.7	m

References

[1] The Fermilab Upgrade — An Overview, Fermilab, December, 1988.

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