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TEVATRON OPTICS WITH MAGNET MOVES FOR ROMAN POTS AT CDF

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1. Introduction

CDF would like to install high precision track detectors. There is ample room on A-sector side, but space needs to be created at B11. The favored plan is to shove the first 3 B11 dipoles inwards toward the IP by 2.274 m. This would require removal of the inert Q1 quadrupole & its spool plus an extensive number of other mechanical & cryogenic modifications[1]. The orbit distortion these modifications introduce would then be compensated by shifting the six B16 & B17 dipoles outwards by about half that amount. Space for this dipole move could be generated by replacing the 72" spool at B18 with a short 43" spool, and removing the 16.5" spacer after B17-5.

The above scheme certainly recloses the orbit, and doesn't require the detector to move. However, by moving the B16 & B17 dipoles, the B17 & B18 arc quadrupoles also get shifted downstream – B17 by 1.115 m, and B18 by 0.696 m. Longitudinal movements of arc quads by such large fractions of their magnetic lengths will clearly impact the overall machine optics.

2. Optics Implications

To first order moving N quads doesn't change the machine tunes, but a ß-wave is launched:

$$\frac{\Delta\beta}{\beta} \approx \sum_{i=1}^{N} q_i \delta_i \cdot \frac{\sin[2\pi(\nu_0 - 2\varphi_{i0})]}{\sin(2\pi\nu_0)}$$

where ν_0 is the unperturbed machine tune, δ_i is the longitudinal displacement of the i^{th} quad, $\varphi_{i0} \equiv \varphi_i - \varphi_0$ is the phase advance from the observation point to the i^{th} quadrupole, and the inverse focal length q_i of 66" arc quads is:

$$q_i = \frac{B'L}{B_0\rho} = \pm 0.039234 m^{-1}$$

The ß-wave generated by shifting just the two quads mentioned above is predicted to be:

$$\frac{\Delta\beta}{\beta} \approx \pm\sqrt{1 - 2\gamma \cdot \cos(2\pi\mu) + \gamma^2} \cdot \frac{q\delta_{B17}}{\sin(2\pi\nu_0)} \cdot \sin\left\{2\pi\left[\nu_0 - \mu/2 - \left(2\varphi_{B17,0} - \chi\right)\right]\right\}$$

where μ is the unperturbed phase advance per arc cell, γ is the ratio of the B18 to B17 displacements $\gamma \equiv \delta_{B18}/\delta_{B17}$, and the angle χ is:

$$\chi \equiv \frac{1}{2\pi} \cdot \tan^{-1}\left\{\frac{(1+\gamma)\cdot\sin(\pi\mu)}{(1-\gamma)\cdot\cos(\pi\mu)}\right\}$$

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[1] see Appendix I – Phil Martin's impact memo of 5/18/01.

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The Tevatron operates near the half-integer with fractional tunes $(\nu_x, \nu_y) = (.585, .575)$, and the arc phase advance $\mu \approx 0.19$ (68^o). As a consequence $\sin[2\pi(\nu_o - \mu/2)] \approx 0$, $\cos[2\pi(\nu_o - \mu/2)] \approx -1$, and the expression for $\Delta\beta/\beta$ in the Tevatron can be reduced to approximately:

$$\frac{\Delta\beta}{\beta} \approx \pm\sqrt{1-2\gamma\cdot\cos(2\pi\mu)+\gamma^2}\cdot\frac{q\delta_{B17}}{\sin(2\pi\nu_0)}\cdot\sin[2\pi(2\varphi_{B17,0}-\chi)] \rightarrow\approx \pm 0.08255\cdot\sin[2\pi(2\varphi_{B17,0}-\chi)]$$

which indicates that a ±8% $\Delta\beta/\beta$ variation will propagate around the ring. Furthermore, roughly the same magnitude wave is expected to appear in each plane. As illustrated in Fig.1, this is exactly what simulations confirm.

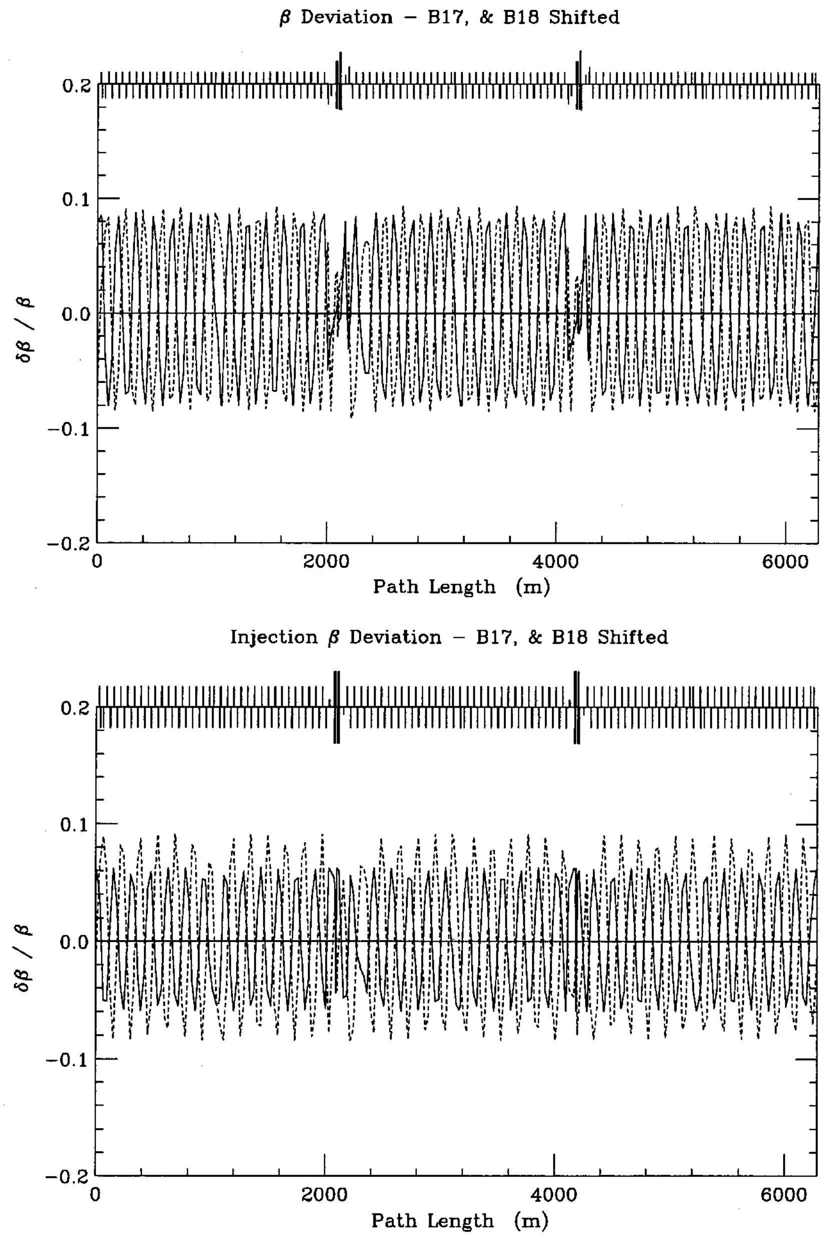

Fig. 1. $\Delta\beta/\beta$ around the ring at $\beta^* = 0.35$ m (top) and injection (bottom), generated by the B17 & B18 quad shifts.

At collision optics the ß-wave has only a small impact on ß* at the B0 & D0 IP's. Although ß* is changed by only a few percent the net impact on luminosity is not completely clear – α^* is no longer zero in this instance so the standard formulae don't readily apply. In any case, at injection an 8% beta-wave is probably unacceptable. At the injection energy of 150 GeV/c the beams already are not separated as much as desirable for Run II.

3. $\Delta\beta/\beta$ – Compensation

The most obvious & direct approach to attacking the Δß/ß problem is simply to try re-tuning the IR's. Unfortunately, a global machine solution could not be found that was consistent with the existing hardware while simultaneously adhering to the standard Tevatron operating mode of keeping corresponding gradients at B0 & D0 equal. Therefore, two distinct, alternate approaches have been explored. One possibility is to re-tune just the B0 IR gradients while leaving all other nominal Run II machine parameters unchanged. A second option is to leave all the Run II parameters unchanged while adding B0 quad trim circuits solely to cancel the ß-wave. These two methods are discussed more fully in subsequent sections.

3.1. Re-Tuning the B0 IR

By 'de-coupling' the CDF/D0 collision optics solutions & tuning CDF independently of D0 the ß-wave can be eliminated locally. In the simulation discussed here the D0 gradients were fixed at their nominal Run II values & the tune quad circuits QFA4 & QDD1 were also left unchanged. All the B0 gradients then became available to:

- re-tune to the desired $\beta^* = 0.35$m, $\alpha^* = 0$, $\eta^* = 0$, $\eta'^* = 0$ collision optics at the IP;
- match from the IP into the unperturbed Run II arc lattice functions, and;
- maintain the nominal machine tunes.

The new B0 IR gradients are listed in Table 1, and the resulting residual ß-wave is shown in Figure 2.

The principal advantage to this approach is that it does not require any new hardware or software for Tevatron operations. The C49 Tevatron ramp program already has the capability to accept different settings for B0 & D0 gradients. While this feature is currently employed only to account for the different transfer coefficients for quadrupoles at the two IR's, there is no reason it couldn't be used to implement quite different B0 & D0 IR gradient settings.

In simulations there is no difficulty imposing the 3 optical boundary conditions listed above & arriving at a unique gradient solution – after all, one is allowed to 'peek' at the consequences of quad changes anywhere in the ring during modeling. In real operations, however, the situation is probably more murky. With this technique the number of independently variable parameters increases by nearly twofold – from 15 to 28 quad gradients, with no increase whatsoever in the number of observable optical constraints. Determining the optimum B0 & D0 quad settings in practice might well be a very challenging task.

IR Quadrupoles	Nominal Run II Gradients (T/m @ 1 TeV/c)	CDF Re-Tuned for Roman Pots (T/m @ 1 TeV/c)
B0Q4	139.8367	139.6966
B0Q3	-137.9277	-137.9105
B0Q2	139.8367	139.6966
B0Q1	0	0
B0Q5	-58.63214	-53.88333
B0Q6	-108.4154	-104.6271
B0QT6	-4.60158	-5.33897
BQT7	-40.42313	-40.41926
BQT8[2]	**-8.88889**	**-8.88889**
BQT9	28.51412	31.50774
BQT0	2.96130	0.717654
AQT7	36.10513	38.17344
AQT8	0	0
AQT9	-33.02219	-33.91421
AQT0	-5.98766	-6.49850
AQTB[2]	**-8.88889**	**-8.88889**

Table 1. Re-tuned gradients at CDF to cancel locally the induced ß-wave & re-establish collision optics at the IP.

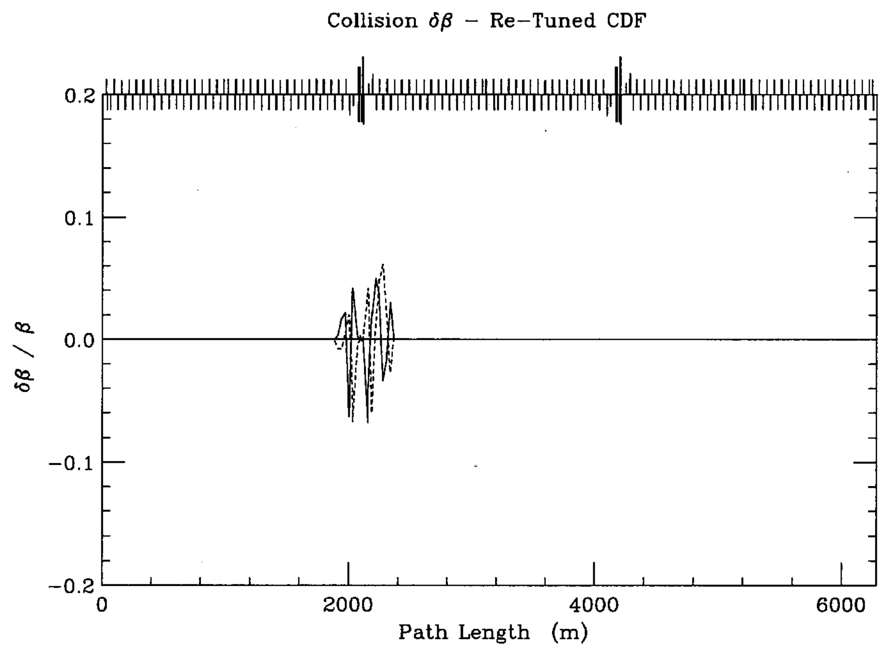

Fig. 2. Δß/ß at the collision ß* = 0.35 m after re-tuning the B0 IR gradients.

Beam separation is not a problem. After retuning CDF the beams are 'separated' at the B0 IP by an amount on the order of 2-3 microns, or $< 0.1\ \sigma$. The half-crossing angles change by $\leq 10\ \mu$rad. These small errors can be corrected during operations with additional fine-tuning of the electrostatic separators. Without any such adjustments to the separators, Fig. 3 illustrates the beam separation around the ring in mm of

[2] BQT8 & AQTB are pegged-out at their maximum gradients in both configurations.

separation & in σ's of separation ($\varepsilon_N = 20\pi$ mm-mr, 95% normalized). Figure 4 compares the change $\Delta\sigma$ with the unperturbed separator solution. In the vicinity of B17 & B18 the deviation $\Delta\sigma$ reaches > 0.5σ, but outside of the B0 interaction region $\Delta\sigma$ is zero everywhere, as is expected with this approach.

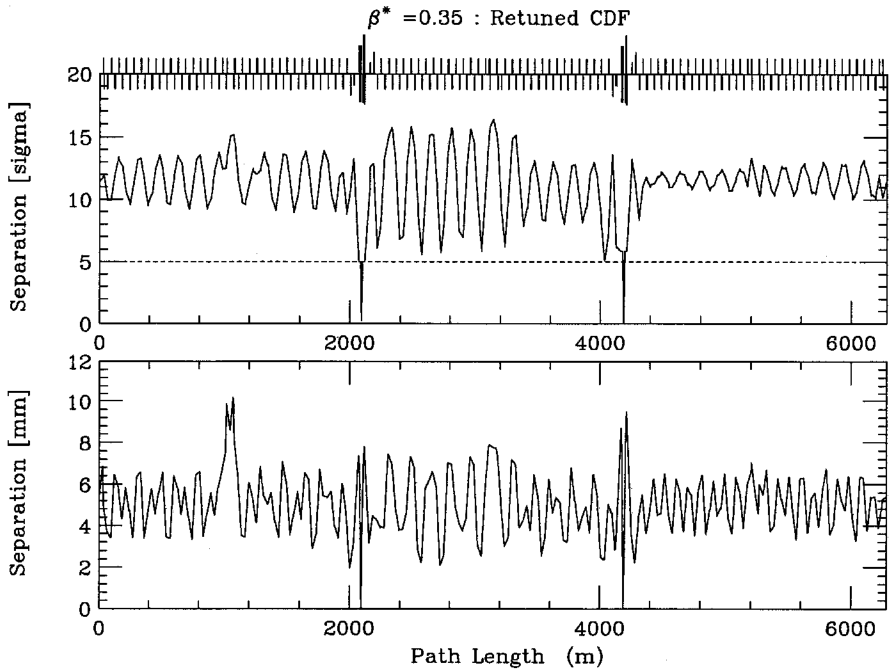

Fig. 3. Ring-wide beam separation after retuning CDF to cancel the ß-wave induced by B17 & B18 quad movements.

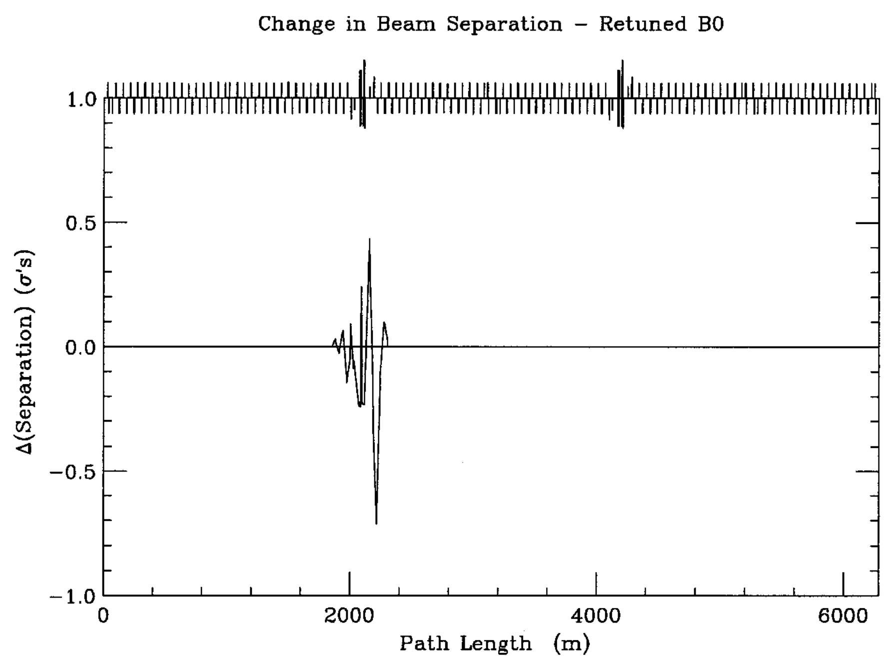

Fig.4. Deviation of beam separation from the unperturbed separator solution for the retuned CDF parameters.

3.2. Additional B0 Quad Trim Circuits

A second approach uses additional B-sector quadrupole trimming to cancel the ß-wave. In the two model variations studied here eight existing tune quad spools are split into 2 orthogonal horizontal families & 2 orthogonal vertical families distributed on the 41st–harmonic. In each plane there is 270° of phase advance between family members & 135° between families.

The family members are:

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!  41st - Harmonic Quad Circuits:

!      Horizontal #1 :
Q41HF1     : QUADRUPOLE,    L = LQUADC,     K1 = KQFA4 + KHCORR1    !    B19
Q41HD1     : QUADRUPOLE,    L = LQUADC,     K1 = KQFA4 - KHCORR1    !    B28
!      Horizontal #2 :
Q41HF2     : QUADRUPOLE,    L = LQUADC,     K1 = KQFA4 + KHCORR2    !    B24
Q41HD2     : QUADRUPOLE,    L = LQUADC,     K1 = KQFA4 - KHCORR2    !    B34

!      Vertical #1 :
Q41VF1     : QUADRUPOLE,    L = LQUADC,     K1 = KQDD1 + KVCORR1    !    B18
Q41VD1     : QUADRUPOLE,    L = LQUADC,     K1 = KQDD1 - KVCORR1    !    B27
!      Vertical #2 :
Q41VF2     : QUADRUPOLE,    L = LQUADC,     K1 = KQDD1 + KVCORR2    !    B23
Q41VD2     : QUADRUPOLE,    L = LQUADC,     K1 = KQDD1 - KVCORR2    !    B33
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In these spools KQFA4 & KQDD1 are the unperturbed F & D gradients of the ring-wide tune quad strings. These values are augmented by gradients of ±KHCORR1, ±KHCORR2, ±KVCORR1, and ±KVCORR2, as indicated.

The advantages to this particular technique are the following:

- by adding & subtracting equal gradients at locations of equal ß's, the machine tunes are guaranteed not to change to first order;
- with an odd multiple of $\pi/2$ between family members, and corrections being performed using orthogonal families of quads, the magnitudes of the correction gradients are also guaranteed to be minimized, and;
- at most, only 4 more variable gradients are added to the tuning mixture [compared with 13 in the previous approach (Sect. 3.1)].

Using 41st–harmonic families for ß correction, therefore, has a minimal impact on the nominal Run II operating parameters. The disadvantage to this approach, however, is that it requires installation of new hardware & software.

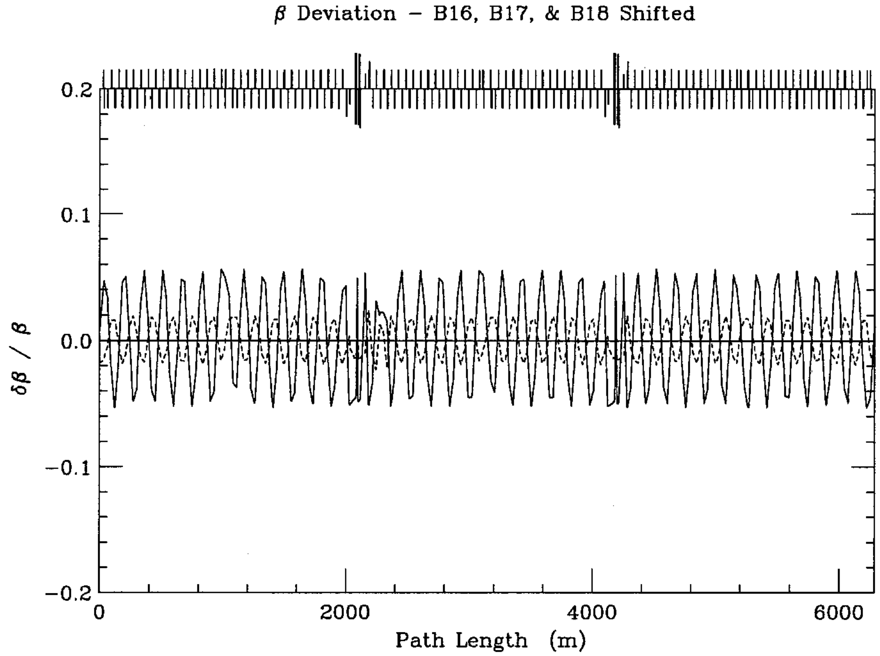
Two possible solution scenarios have been looked at:

(i) the B16 quadrupole is also shifted downstream, and;

(ii) only the B17 & B18 quadrupoles move.

3.2.1 F Quad Corrector Families + Shifted QB16:

If QB16 is also shifted downstream by approximately the same amount as the B17 quadrupole, the ß-wave is substantially reduced. As shown in Fig.5, in the collision optics configuration, Δß/ß is reduced horizontally to ≤ 5%, and vertically to ≤ 2%. In the injection lattice Δß/ß is reduced to ≤ 2% everywhere except in the immediate vicinity of B16 → B18. It's possible that this level of disturbance at injection would be tolerable.



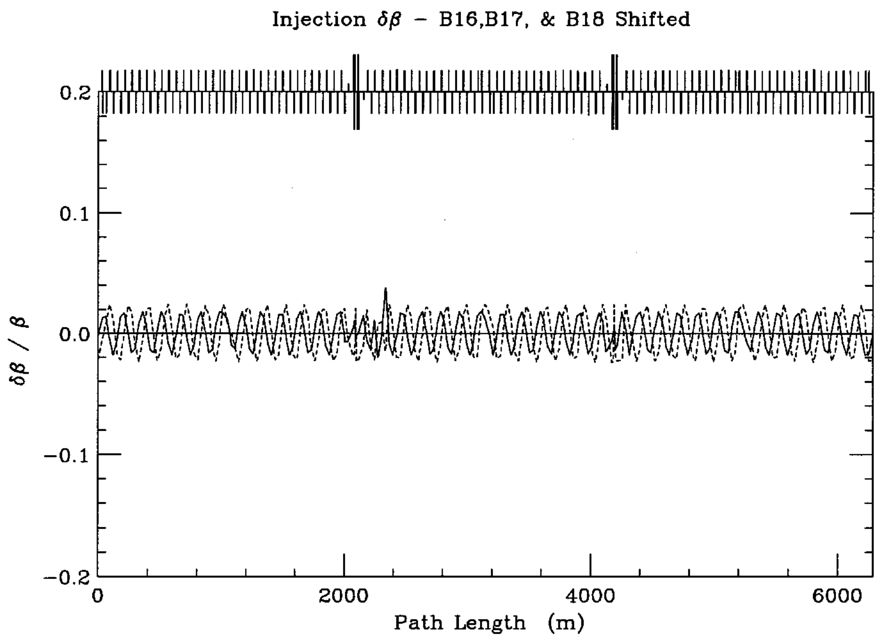


Fig. 5. Δß/ß at ß* = 0.35 m (top) and injection (bottom), after also shifting the B16 quadrupole downstream by 1.09 m.

With collision optics, and B16 also moved, only the horizontal quad harmonic families are needed to eliminate the global ß-wave. The gradients are listed below – these values are comparable to those of the normal tune quad circuits & considerably less than the ~9 T/m design fields of the tune quad spools. The corrected ß-wave is shown in Fig.6.

! B16, B17, & B18 SHIFTED - B* = 0.35:
! HORIZONTAL CORRECTORS ONLY:

BHCORR1 : =	-1.139505	! T/m
BHCORR2 : =	-0.550432	! T/m

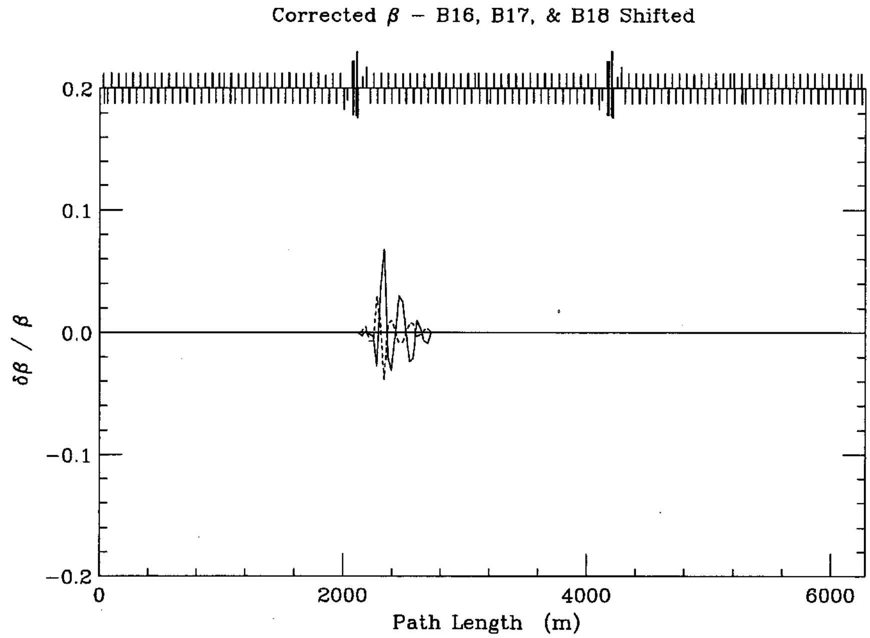


Fig.6. Residual ß-wave after moving B16 & using the horizontally focusing families of 41-st harmonic quadrupoles.

Moving the B-sector dipoles also generates a dispersion wave in the ring and this can't be eliminated with only 2 families of horizontal correction quadrupoles. Dispersion at the IP is no longer exactly zero – growing slightly to η ~ 9 mm, and also gaining a small slope. This is a relatively small effect, however, increasing beam size at the IP by about 0.22 μm (beam σ = 33.1 μm), and thereby reducing luminosity by 1.32%. In the arcs the effect of the dispersion mismatch is larger – producing a ±4.6% $\Delta\eta/\eta$–wave[3].

There are no problems with beam separation using this method. At the IP's beam separation is < 0.1σ, and the half-crossing angles differ from nominal values by, at most, only a couple of μrads. Position & angle at the IP could be corrected with modest re-tuning of the electrostatic separators. Figure 7 shows the ring-wide beam separation, and Fig. 8 shows the deviation $\Delta\sigma$ from the unperturbed separator solution – $\Delta\sigma$ is < 0.2 σ everywhere except right at B17, where it is ~ 0.3 σ.

[3] This can't be considered a large perturbation, however, in a machine where dispersion-matching was never a design issue & in the unperturbed lattice η already grows >50% beyond the 'matched' arc dispersion value.

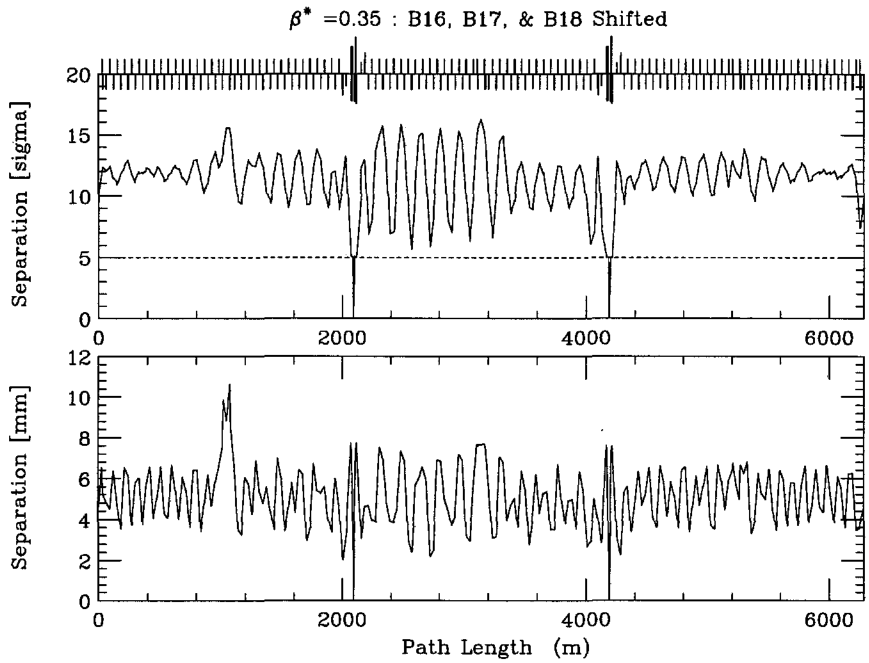


Fig.7. Beam separation after moving B16 & using the horizontally focusing families of 41-st harmonic quadrupoles.

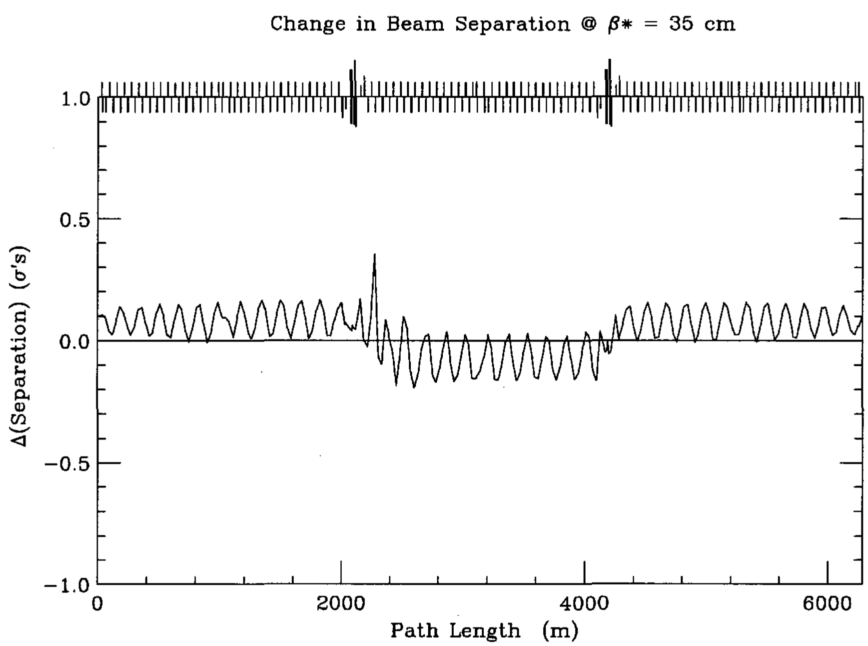


Fig.8. Deviation of beam separation from the unperturbed separator solution.

3.2.2. F + D Quad-Corrector Families:

Without moving the B16 quad, all 4 families of harmonic quadrupoles are needed to cancel the beta-wave. Gradients are listed below for injection (evaluated @ 1 TeV/c) & collision lattices. Figure 9 shows $\Delta\beta/\beta$ around the ring at collision after correction (the injection picture looks essentially identical).

! F & D CORRECTORS - B* = 0.35 :

BHCORR1 : =	-0.227940	! T/m
BHCORR2 : =	-1.523110	! T/m
BVCORR1 : =	-1.338196	! T/m
BVCORR2 : =	-0.378289	! T/m

! F & D CORRECTORS - INJECTION :

BHCORR1 : =	-0.303186	! T/m
BHCORR2 : =	-0.900478	! T/m
BVCORR1 : =	-1.167839	! T/m
BVCORR2 : =	-0.991004	! T/m

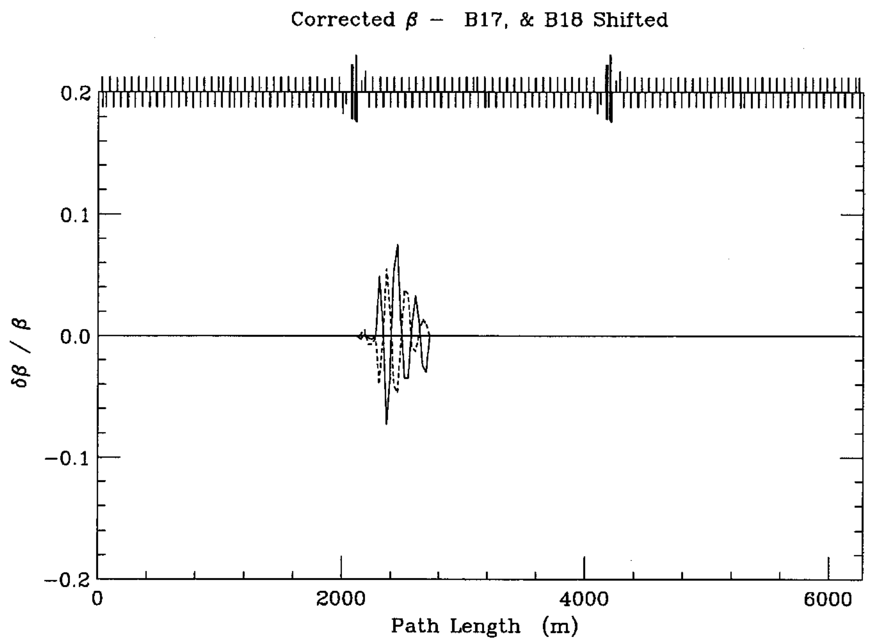


Fig. 9. Δß/ß at ß* = 0.35 m after correction using the F & D harmonic quad circuits.

Dispersion is even better behaved in this option – reaching just $\eta \sim 1$ mm at the IP, with a very gradual slope. This has a negligible impact on the luminosity, decreasing it by only ~0.02%. In the arcs the slight dispersion mismatch translates into a small ±0.22% $\Delta\eta/\eta$–wave.

Again, beam separation is not an issue here. Although the residual ß-wave after correction is not quite as small here as in the previous solution, this doesn't noticeably reduce separation. In fact, in this solution the helices wander even less than before from the unperturbed values. Figure 10 illustrates the deviation $\Delta\sigma$ from the nominal beam separation – the variation is < 0.1 σ everywhere except in the vicinity of the moved quadrupoles, where it reaches 0.2 σ.

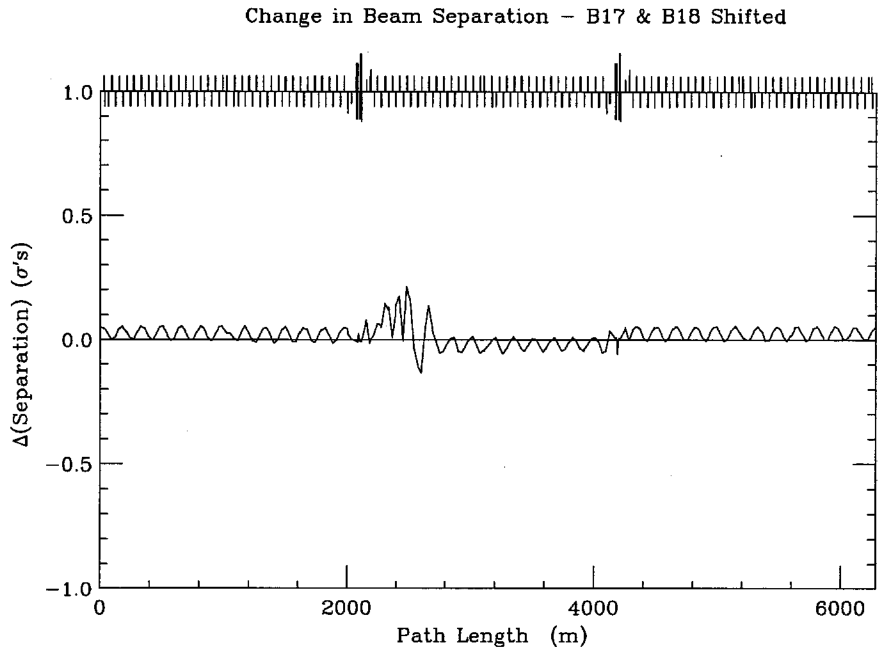


Fig.10. Deviation of beam separation from the unperturbed separator solution.

4. Summary & Conclusion

Two possible options were explored for curing the ß-wave which results from moving the B17 & B18 quadrupoles. In the first approach the CDF & D0 gradient solutions were de-coupled, allowing the IR optics at B0 to be tuned independently. This technique has the advantage that it requires no machine modifications. However, the total number of independently-controlled quad circuits in the ring nearly doubles, with no corresponding increase in optical constraints – potentially making tuning a cumbersome & unwieldy enterprise. The second method minimized the number of new independent circuits needed for beta-wave correction. Here, the Δß/ß errors were canceled using orthogonal families of 41st–harmonic quadrupoles constructed from existing arc spool pieces. The nominal Run II settings are then unaffected; but the benefits don't come free – implementation of this scheme would require both new hardware & new software. Neither of the two approaches studied had any significant adverse impact on beam separation.

The possible benefits of also moving the B16 quadrupole were investigated within the 41st–harmonic correction scheme. It was found that by shifting QB16 as well, additional Δß/ß compensation might not be needed at injection and only the horizontal 41st–harmonic circuits would be required for complete ß correction at collision. Despite this simplification of the tuning process good reasons exist for rejecting any B16 movements – not least of which is the large amount of work involved (see Appendix I). With B16 remaining in its present location two families of harmonic quads in each plane become necessary to kill the ß-wave during the squeeze from injection through to collision. However, the residual dispersion wave is more than an order of magnitude smaller here than in the option where B16 moves, and has no discernible impact on the luminosity. Furthermore, beam separation around the ring is a much closer replication of the unperturbed, nominal solution.

Both of the ΔB/B correction schemes studied — re-tuning CDF & 41st–harmonic compensation — have their advantages. Both also have disadvantages. In simulations no compelling reason was found to choose one method over the other. The expertise of the Tevatron Department is necessary to determine which approach is the most sensible & practical to implement.

APPENDIX I

Fermilab

Beams Division Headquarters

May 18, 2001

To: Mike Albrow

From: Phil Martin

Subject: Tour of B-1 on May 14

Jay Theilacker and I toured B-1 this morning so that I could see the area of the Tevatron tunnel that would be impacted by the proposed magnet moves to incorporate the Roman pots. The following is our list of comments from that tour, regarding the impact on other systems of moving the Tevatron magnets.

- The nitrogen header may need to be relocated at B11-4 in order to provide space for the bypass.
- The helium flex hose may need to be relocated at B11-4 to avoid interference with your equipment.
- In general, it appears that almost all helium flex hoses from B-11 to B-18 will need to be modified, to accommodate the 1.4" radial shift. This will entail cutting the solid pipe at one end or the other of the flex hose and adding a short piece.
- The power leads at B-12 and B-13 will require some modest work to accommodate the radial shift.
- A new spreader bar and a dogleg in the vertical riser will be needed at the B-15 feedcan to accommodate the radial shift.
- To accommodate the shift along the beamline in the B-16 to B-18 region, some of the remaining Main Ring magnets, and their stands need to be removed. The two dipoles and the quad cradle in the B-17 half-cell, together with their stands, need to be removed. Since the (vertically-oriented) cable tray is supported from these stands, the best thing will probably be to remove the dipoles, then install new trays that run more naturally between the horizontal trays at either end, flop the cables up into the new trays, and then remove the old cable tray, the quad cradle and the dipole stands.
- In the B-16 region, the amount of work depends upon whether or not the B-16 quad and spool shift downstream. If they do, then the headers need to be slightly modified in that area. That in turn requires that the first Main Ring dipole and its stand need to be removed. Since that is a massive stand, (~12 ft high) and it is trapped by the cables and cable trays, that will not be an easy task.

In addition, there will need to be some work to repair the floor where the Q1 sits, and there may be some vacuum reconfiguration necessary around B-11.

Cc: J. Theilacker D. Augustine J. Johnstone P. Bagley