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PRELIMINARY DESIGNS FOR AN IR INSERTION AT C0

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1. GENERAL CONSIDERATIONS

Given the advanced state of operational plans for late Run II (132 nsec bunch spacing) the C0 IR insert should be designed to operate such that it does not impact nominal Tevatron parameters. This implies an entirely localized insert – one which is completely transparent to the rest of the machine. This condition has several important design implications, some of which are pointed out below.

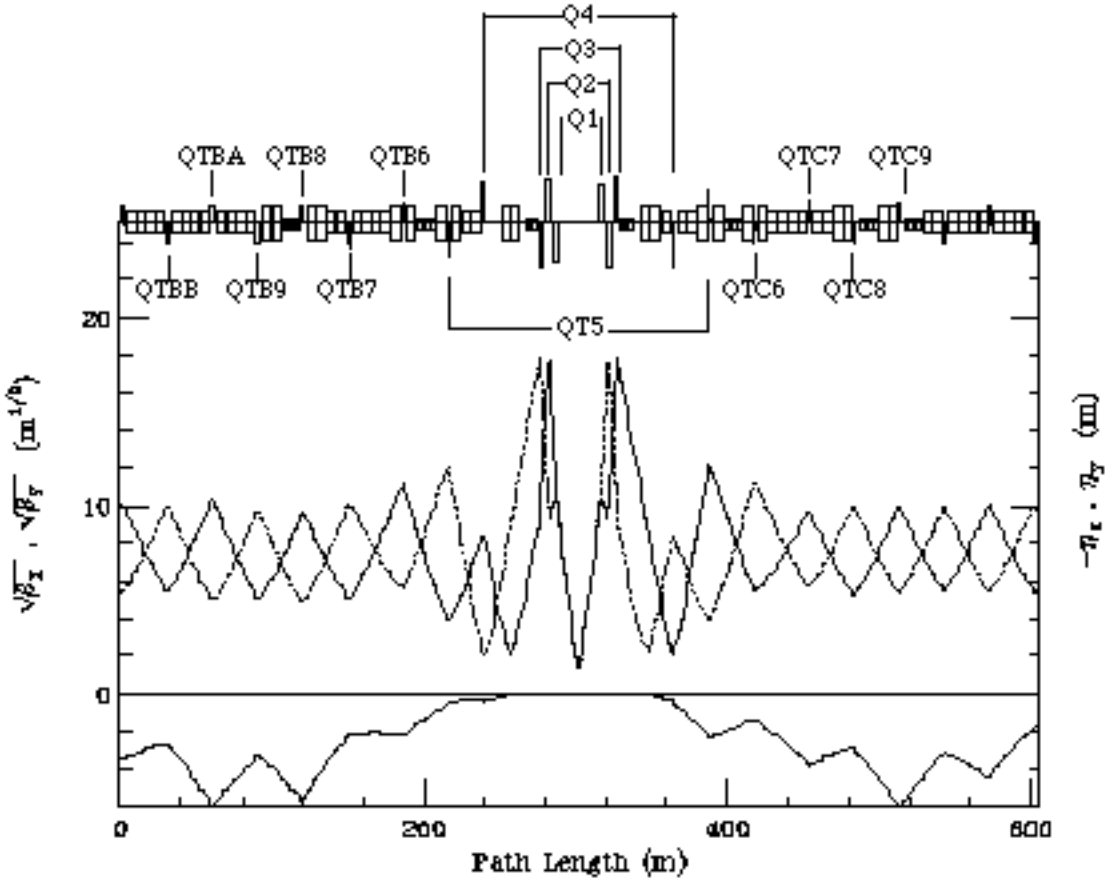
- An IR design similar to that employed at CDF & D0 is unacceptable as a C0 candidate. The addition of such a (single) low-β region to the machine raises the tune by a half-integer in each plane, moving them far from the standard operating point and right onto the 21.0 integer resonance. The nominal (fractional) operating point is most elegantly maintained by adding 2 local low-β's in each plane, thereby boosting the tunes by a full integer.

- The B0 & D0 IR's are not optically-isolated entities. Progression through the low-β squeeze involves adjusting, not only the main IR quadrupoles, but also the tune quad strings distributed around the ring. The result is that the nominal lattice functions at any point in the ring, and the phase advances across any section of the ring, are not fixed, but vary with each stage of the squeeze. A new insert must be sufficiently flexible to track these elusive matching conditions.

- Without collisions at C0 the unit transfer matrix added by the insertion ensures that the incoming & outgoing helices are automatically matched to their nominal Run II values. To maintain this match with collisions at all 3 IP's, however, requires that additional separators be added in the arcs. Space for these separators can only be generated through replacing standard Tevatron arc dipoles by new magnets with enhanced strengths.

In the following sections two design variations for an interaction region are presented. The first of these, which incorporates stronger dipoles, meets all of the ideal design criteria outlined above. The result is a truly independent 3rd Tevatron IR capable of supporting simultaneous collisions at all 3 IP's. The second, stripped-down, version includes neither stronger dipoles nor new arc separators. While this insert is still optically transparent to the machine, collisions can only occur at B0 & D0, or just C0, but not all three. The weaker dipoles also result in a significant reduction in the space available for a detector. However, as is demonstrated near the end of this report, if all the B- & C-Sector separators are freed to assist in C0 orbit control, it "might" be possible to support collisions at B0 & D0, plus C0, with the second design.

2. AN IR WITH HIGH-FIELD DIPOLES



2.1 Design

2.1.1. Quadrupoles

Both the series & the independent quad circuits of the IR are illustrated above. The required new magnets fall into 3 gradient ranges. There are LHC-like magnets operating in the vicinity of 180 T/m, which is substantially less than the >220 T/m LHC design, but limited here by the Tevatron cryogenics. High-field 140 T/m quadrupoles, modeled like existing magnets installed at the other 2 IR's, are also employed. And there are high gradient (≥ 60 T/m) correction spools which, again, are comparable to those at CDF & D0. Composition of the quadrupole circuits is described below, with indicated lengths being the magnetic lengths.

Q1	: 93"	LHC
Q2	: 160"	LHC
Q3	: 93"	LHC

Unlike the triplets at B0 & D0, the inner & outer quadrupole circuits (Q1 & Q3) of the final focus in the current model are powered separately.

Q4	[B48 / C12]	:	66"	LHC

The Q4 quads are accompanied by short spools (56") containing dipole correctors & BPM's in both planes.

Q5 & Q5T	[B47 / C13]	:	55"	140 T/m
		:	25"	60 T/m

The regular 66" arc quads plus their spools at B47 & C13 are replaced by high field 55" magnets operating at a constant 136 T/m plus a series connection of tunable strong correctors for focusing adjustments.

QTB6 & QTC6		:	25"	60 T/m
QTB7 & QTC7	[B45 / C15]	:	23.875"	140 T/m

At B45 & C15 the standard 66" quads and short spools are replaced by (existing) 32" magnets running on the main buss, plus very strong correctors like those installed at the A47, B13, C47, & D13 locations [1].

All the remaining trim quad spools, QTC8 & QTC9, and QTB8 → QTBB, are of the 25", strong, 60 T/m variety.

Some quadrupoles in the arcs have been placed with non-standard separations. Between the B48 & B47 [C12 & C13] quadrupoles the space is reduced from 4 to 3 dipoles, whereas between B46 & B45 [C14 & C15] separation is increased by 1 dipole slot length. Extensive experimentation found that this configuration contributes to extending the optical versatility of the insert.

There is a lop-sided allocation of tuning quads, with 2 more installed in the upstream end of the insert. In B-sector it is possible to extend insert elements a good distance into the arc before interfering with Run II operations. Not so in C-sector. The 4 vertical separators at C17 are integral components of Run II controls and, therefore, define the downstream boundary of the C0 insert.

2.1.2. Dipoles & Separators

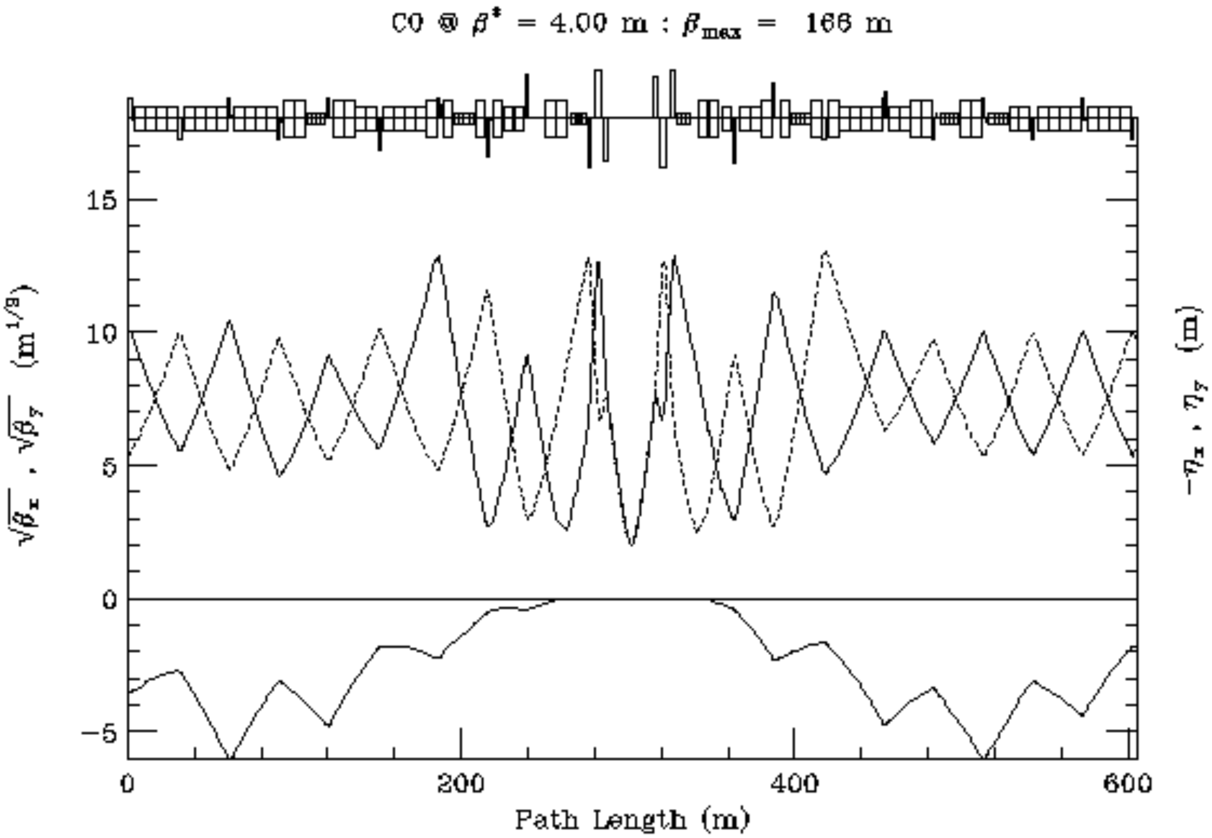
A total of 30 standard Tevatron dipoles are replaced by 20 high-field dipoles. This has two significant benefits [2]. First, additional longitudinal space for the detector is generated by installing extra strength bends in the vicinity of the IP. In the current design there is ≈13 m of free space each side of the IP. Second, by replacing 12 standard dipoles with 8 stronger ones in the B- & C-sector arcs, room is created between B43 & B44 [C16 & C17] to install 4 separators, and another 4 between B46 & B47 [C13 & C14].

[1] This configuration actually increases (by 5") the space available for power feeds.

[2] A 3rd, smaller, bonus is that the Tevatron orbit shrinks by about 11 mm — helping to alleviate the ~4 cm circumference mismatch between the Main Injector & Tevatron.

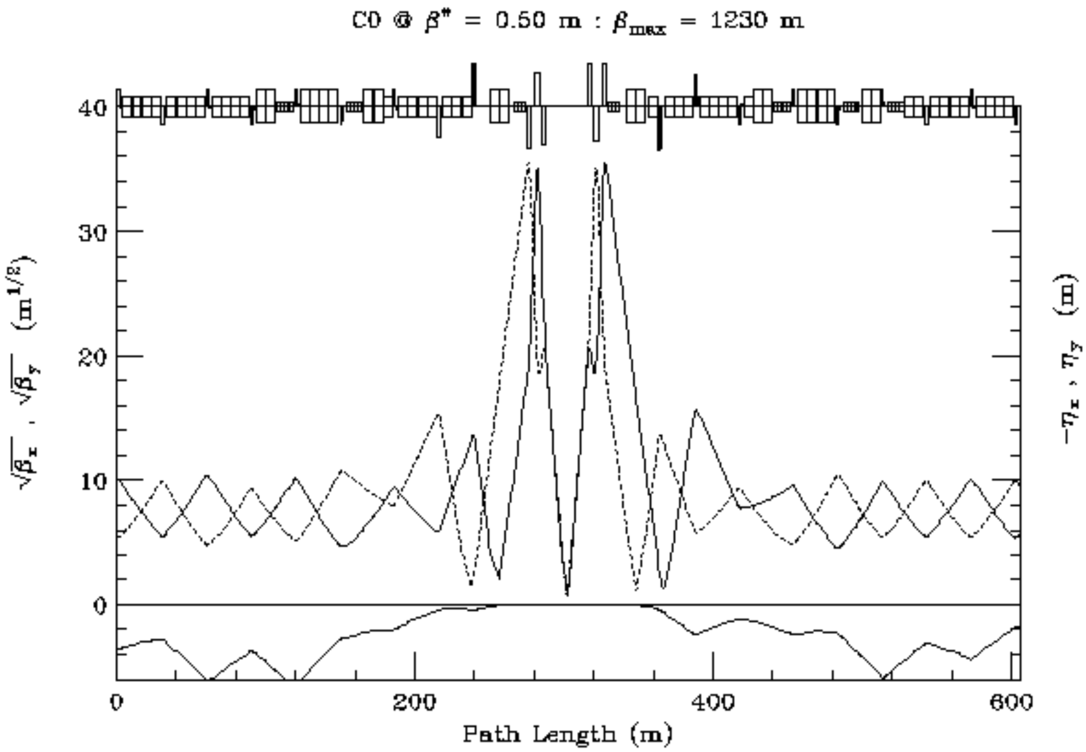
There are 3 separators each side of the IP, immediately outboard of the triplets, for controlling beam position at the IP. The new separators in the arcs are necessary for angle control at the IP and to match from the incoming to outgoing helix. Without them, the B0, C0, and D0 IR's can not operate independently.

2.2 Optics



In the injection lattice shown above a β* = 4.00 m results in a βmax of only 166 m in the triplets. This is considerably less than the >240 m of the B0 & D0 injection lattices, and not that much larger than the 120 m reached in a standard Collins insert.

It is the experience of the Tevatron that the smallest realistic β* attainable is limited by the good field aperture and βmax in the low−β triplets, rather than by gradient limitations of the IR quads. Here, because the Q1 magnets at C0 are roughly 20' farther from the IP than the corresponding ones at B0 & D0, βmax is considerably larger at C0 for any given value of β*. At β* = 50 cm, βmax has already grown to 1230 m, which, while somewhat larger (~10 %) than the βmax for a β* = 35 cm at the other IP's, can probably still qualify for use as the collision lattice.



There are 15 optical constraints that the insertion has to meet. The 6 incoming Twiss parameters are matched at the IP to $\beta_x^* = \beta_y^* \equiv \beta^*$, $\alpha_x^* = \alpha_y^* \equiv 0$, $\eta^* \equiv 0$, $\eta'^* \equiv 0$, and then matched back into the nominal arc values at the downstream end of the insert (at C17). The fractional Run II phase shifts, $\Delta\mu_x$ and $\Delta\mu_y$, are preserved across the insert. The final constraint imposed was that $\beta_{max}(x) = \beta_{max}(y)$ in the triplets on each side of the IP. While this last restriction isn't crucial, it is the best choice to minimize consumption of aperture in the low-β quads.

In the present design, every stage of the squeeze from $\beta^* = 4.00 \rightarrow 0.50$ m at C0 can match exactly to any step in the Injection $\rightarrow \beta^* = 0.35$ m squeeze at B0 & D0. The following pages give lattice functions & C0 quadrupole gradients corresponding to the extremes of this operational matrix:

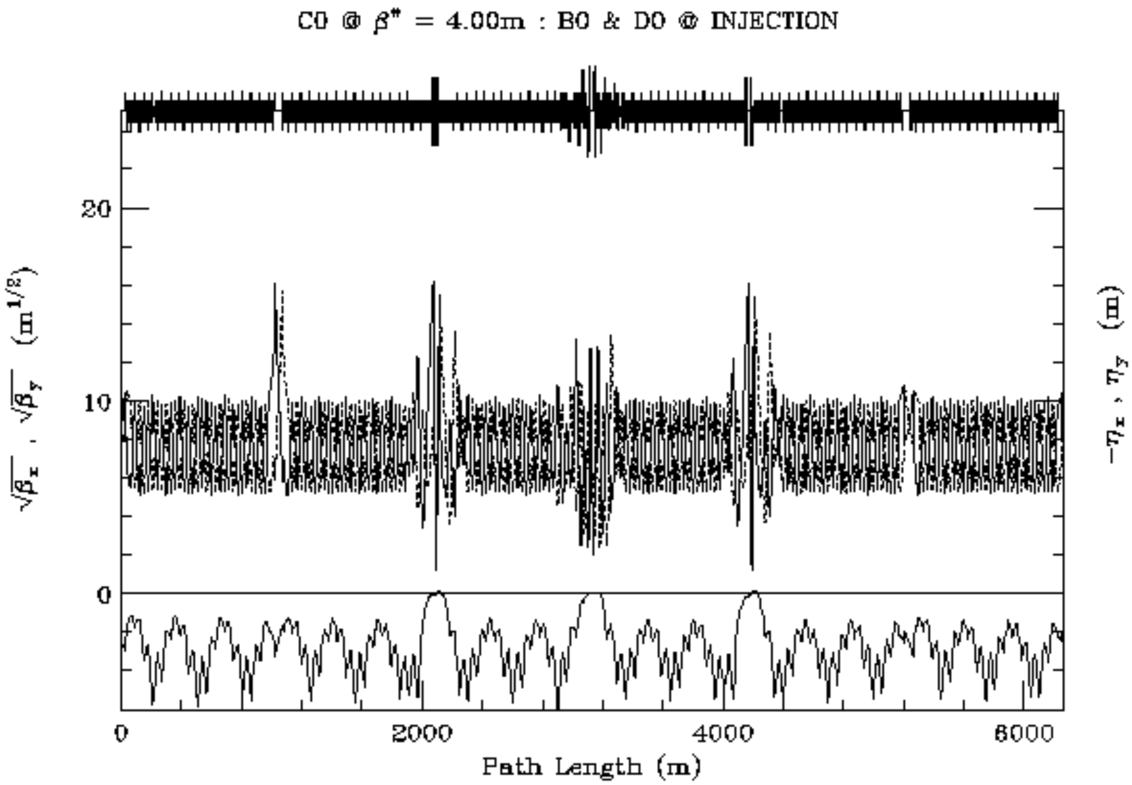
(i) $\beta^* = 4.00$ @ C0 — (β_x^*, β_y^*) = (1.61, 1.74) @ B0 & D0

(ii) $\beta^* = 4.00$ @ C0 — $\beta^* = 0.35$ @ B0 & D0

(iii) $\beta^* = 0.50$ @ C0 — (β_x^*, β_y^*) = (1.61, 1.74) @ B0 & D0

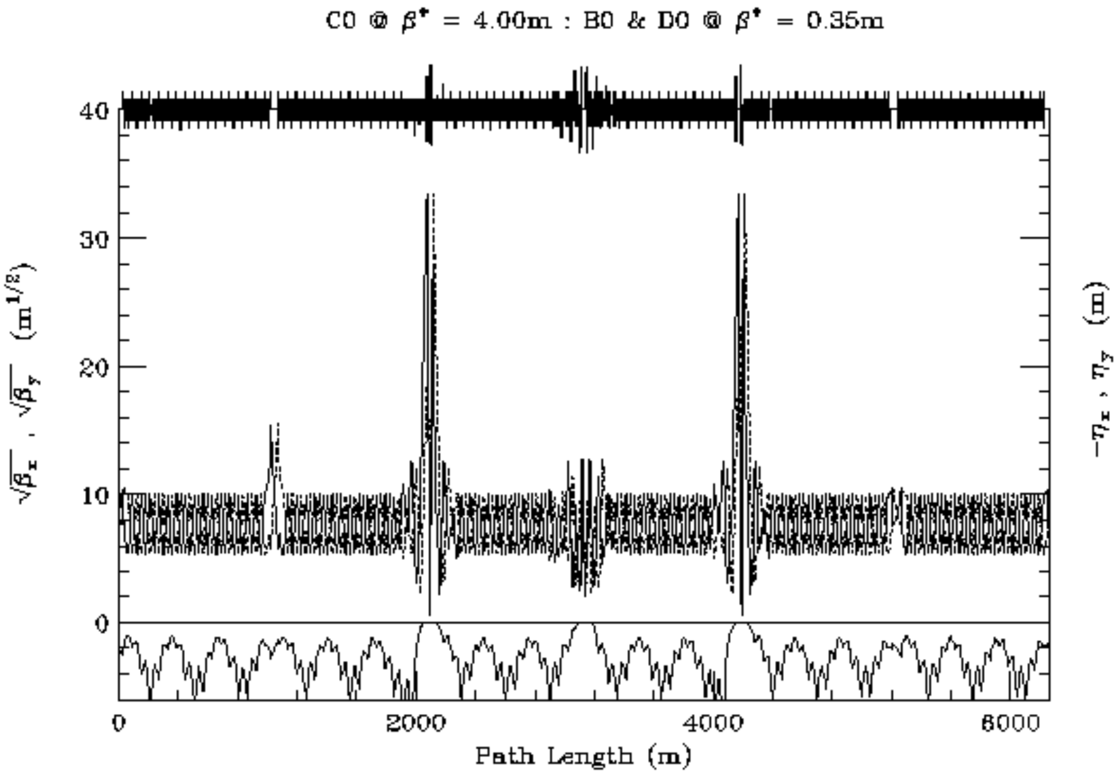
(iv) $\beta^* = 0.50$ @ C0 — $\beta^* = 0.35$ @ B0 & D0

The highlighted entries in the tables (QTC8 & QTC9) change polarity at some point during the squeezes.



1 TeV Gradients for Injection Optics @ B0, C0, & D0

Quad #	C0 @ β* = 4.00 m B0 & D0 @ (β^*_x, β^*_y) = (1.61, 1.74) up	down
Q1	-159.197	159.197
Q2	182.773	-182.773
Q3	-180.026	180.026
Q4	165.415	-165.415
QT5	-5.380	5.380
QT6	61.267	-50.421
QT7	-116.421	110.525
QT8	0.192	**22.098**
QT9	-12.545	**-16.572**
QTA	16.989	
QTB	-18.316	

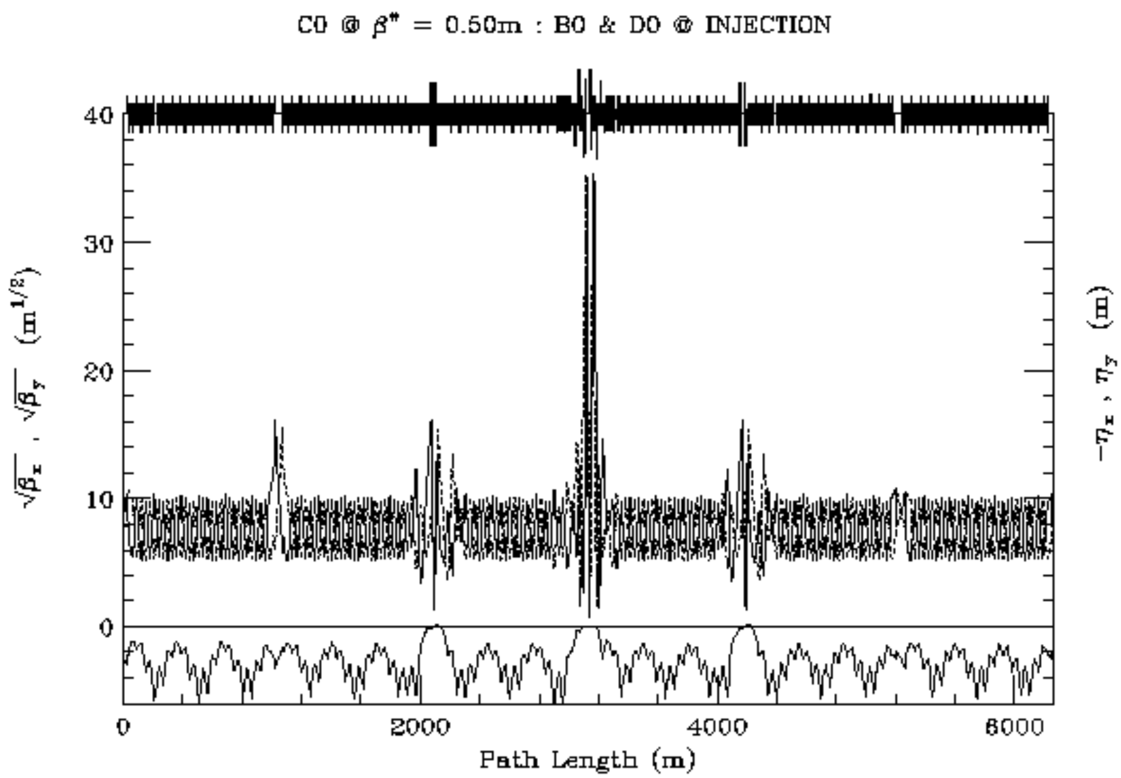


1 TeV Gradients for β* = 0.35 m at B0& D0 and β* = 4.00 m @ C0

Quad #	C0 @ β* = 4.00 m B0 & D0 @ β* = 0.35 m up	down
Q1	-158.808	158.808
Q2	182.161	-182.161
Q3	-181.170	181.170
Q4	165.529	-165.529
QT5	-1.755	1.755
QT6	54.929	-43.812
QT7	-113.596	101.506
QT8	3.083	**23.788**
QT9	-14.645	**-13.484**
QTA	15.655	
QTB	-9.758	

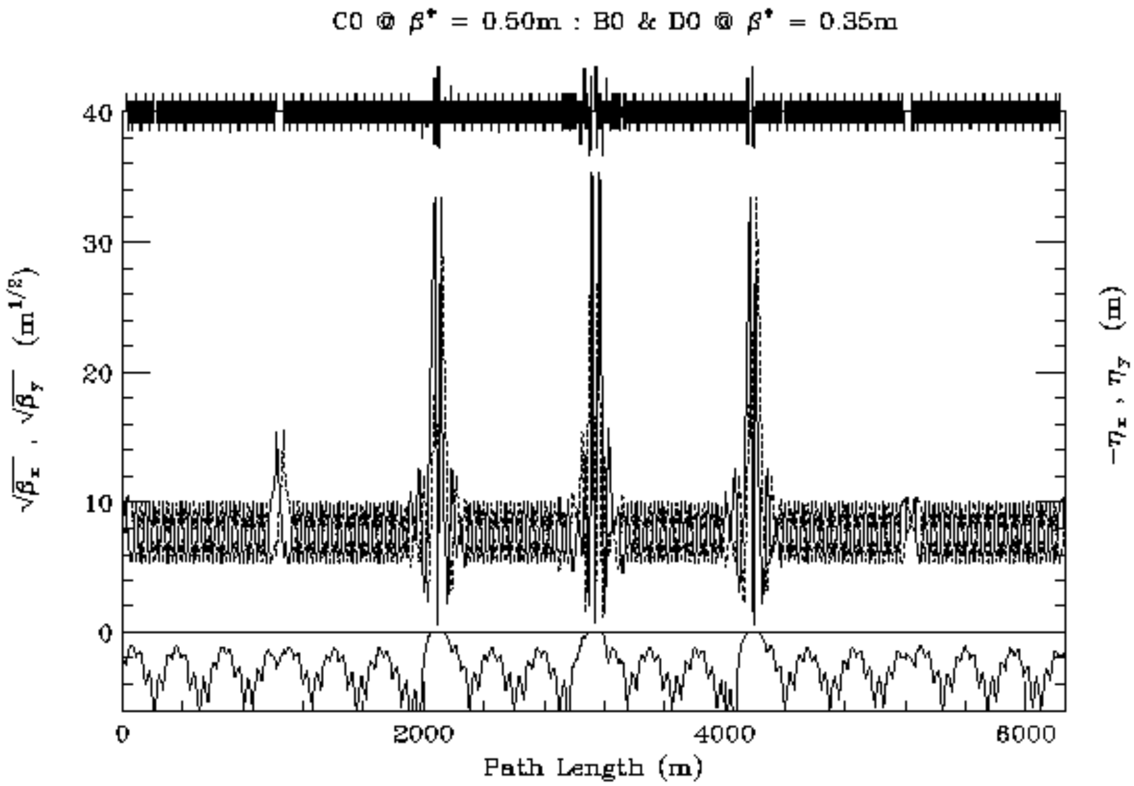
The preceding tables provided C0 quad gradients corresponding, for example, to the endpoints of an operating scenario in which β^* at C0 is fixed at 4.00 m, while β^* at B0 & D0 is squeezed from the Injection lattice values $\rightarrow \beta^* = 0.35$ m for collision. At each step of this low-β squeeze the C0 magnets are adjusted to maintain the optical match to the 'appropriate', ever-changing lattice functions & phase advances across the insert. The table below shows the extent to which the gradients vary during the B0 & D0 squeeze.

	B' [max] T / m	B' [min] T / m	$\Delta \int B' \bullet ds$ T-m / m
Q1	159.505	158.893	1.44
Q2	183.764	182.767	3.97
Q3	180.667	179.156	3.57
Q4	159.547	158.745	1.35
QT5	1.381	0.347	0.66
QTB6	63.996	58.866	3.26
QTB7	117.517	115.112	1.46
QTB8	7.761	5.048	1.72
QTB9	13.138	7.625	3.50
QTBA	15.779	13.099	1.70
QTBB	17.448	10.205	4.60
QTC6	60.315	51.426	5.64
QTC7	114.890	106.930	4.83
QTC8	9.449	8.265	0.75
QTC9	17.613	13.113	2.86



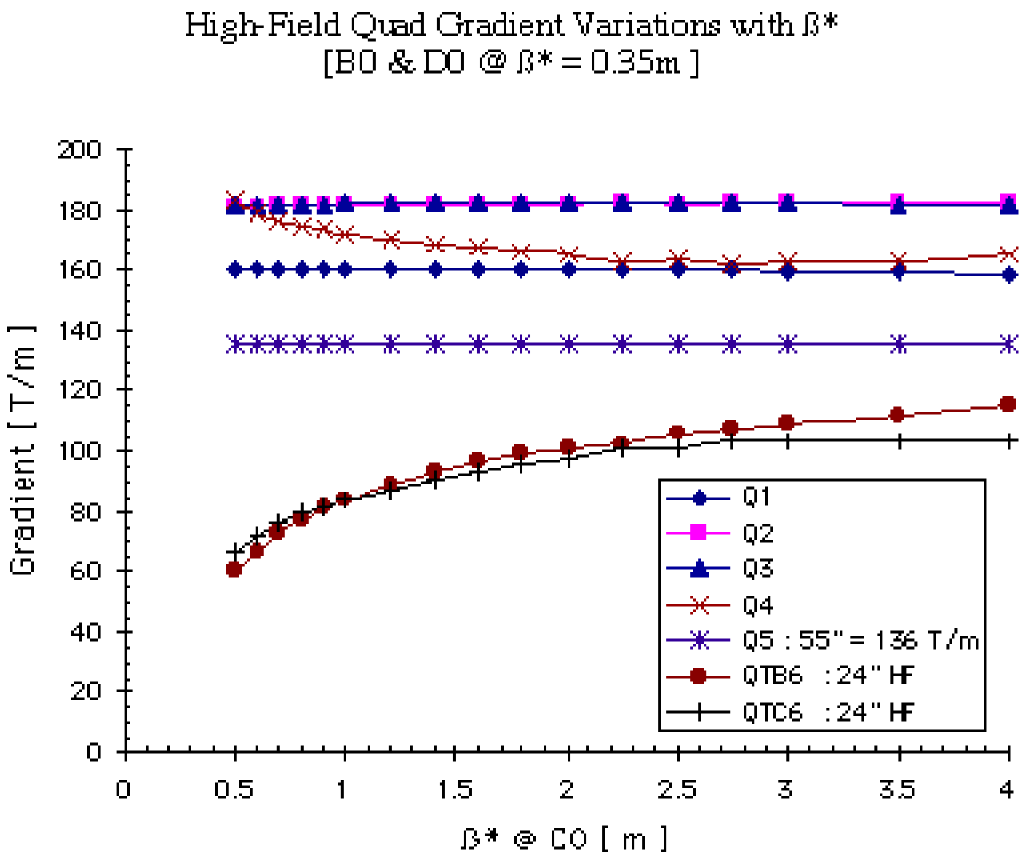
1 TeV Gradients for Collisions at C0 & Injection Optics @ B0 & D0

Quad #	C0 @ β* = 0.50 m B0 & D0 @ (β^*_x, β^*_y) = (1.61, 1.74) up	down
Q1	-159.787	159.787
Q2	179.807	-179.807
Q3	-180.416	180.416
Q4	191.400	-191.400
QT5	-52.248	52.248
QT6	2.849	-6.700
QT7	-67.307	80.573
QT8	8.930	**-20.630**
QT9	-9.832	**19.694**
QTA	-1.100	
QTB	-12.828	



1 TeV Gradients for Collisions at B0, C0 & D0

Quad #	C0 @ β* = 0.50 m B0 & D0 @ β* = 0.35 m up	 down
Q1	-160.126	160.126
Q2	180.398	-180.398
Q3	-180.909	180.909
Q4	184.500	-184.500
QT5	-45.193	45.193
QT6	-9.753	14.561
QT7	-62.911	65.942
QT8	9.292	**-9.253**
QT9	-16.317	**17.486**
QTA	-2.099	
QTB	-11.577	



With β^* fixed at 0.35 m at B0 & D0, the accompanying graph shows the variation of the high-field quad gradients through a squeeze from $\beta^* = 4.00$ m $\rightarrow \beta^* = 0.50$ m.

It is important that the insertion has the optical versatility to match between all the conceivable combinations of β^* at the 3 IR's. While it is supposed that all 3 will be at low–β simultaneously, it is unlikely that they will be squeezed in tandem. It is known that between each step of the B0 & D0 low–β squeeze a quadratic tune shift appears. By the sequential squeezing of B0 & D0, followed by C0 (or vice versa), this problem isn't compounded unnecessarily.

2.3 Beam Separation

To reduce the number of interactions per crossing at the IP's, late in Run II it is planned to reduce bunch spacing in the Tevatron from 396 → 132 nsec. With the first parasitic crossings then occurring just 19.86 m from the IP's, though, it is realized that crossing angles must be introduced to obtain separated beams at these points.

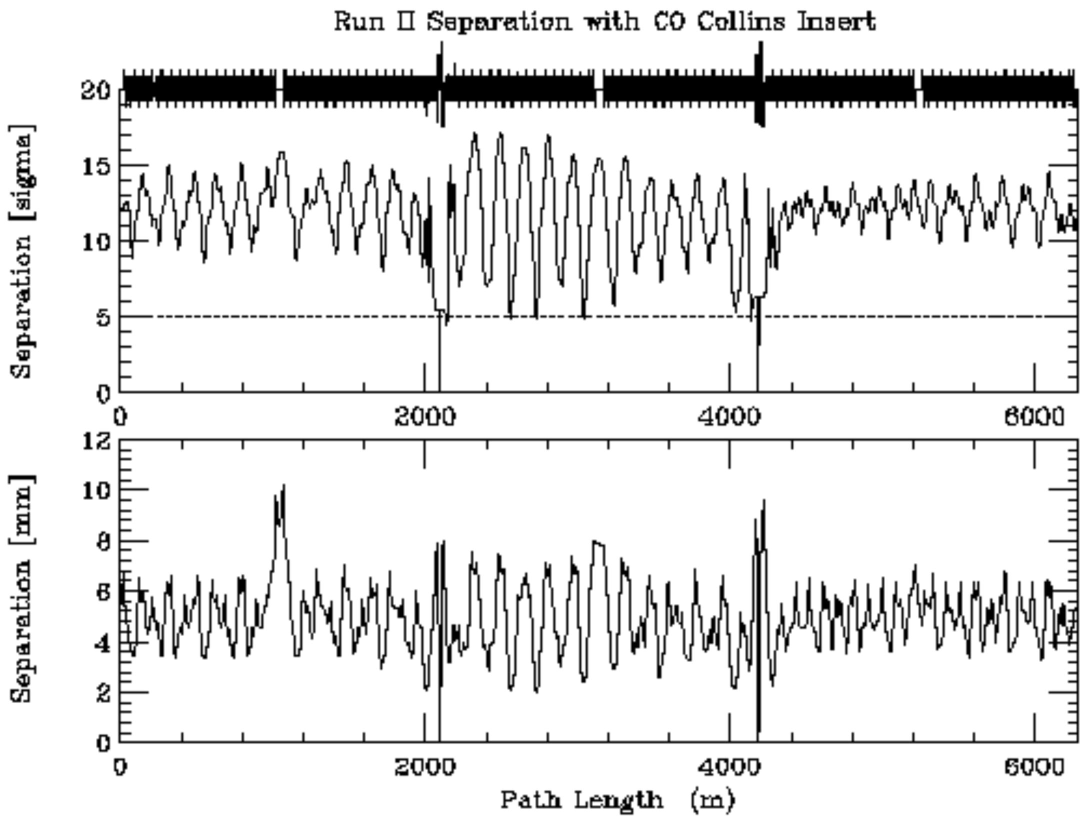
Crossing angles have 2 major consequences. First, luminosity is reduced as a result of the decreased overlap of the beams at the IP. A compromise must be reached then between minimizing the beam-beam tune shift from the first parasitic crossings (large $\theta_{1/2}$) & minimizing the luminosity reduction (small $\theta_{1/2}$). The second impact of the crossing angles is to cause the beams to be separated in the low-β final-focus quadrupoles – precisely where β already reaches its ring-wide maximum. With head-on collisions the Collider currently operates with β^* = 35 cm, and β_{max} in the triplets is then ~1100 m. It is generally thought (but not confirmed) that the minimum β^* attainable is limited by the impact on the beam of high-order multipoles in the low-β quadrupoles. The consequences of sending beams off-axis through the magnets as well is not yet fully understood – the Tevatron has never before been operated with crossing angles.

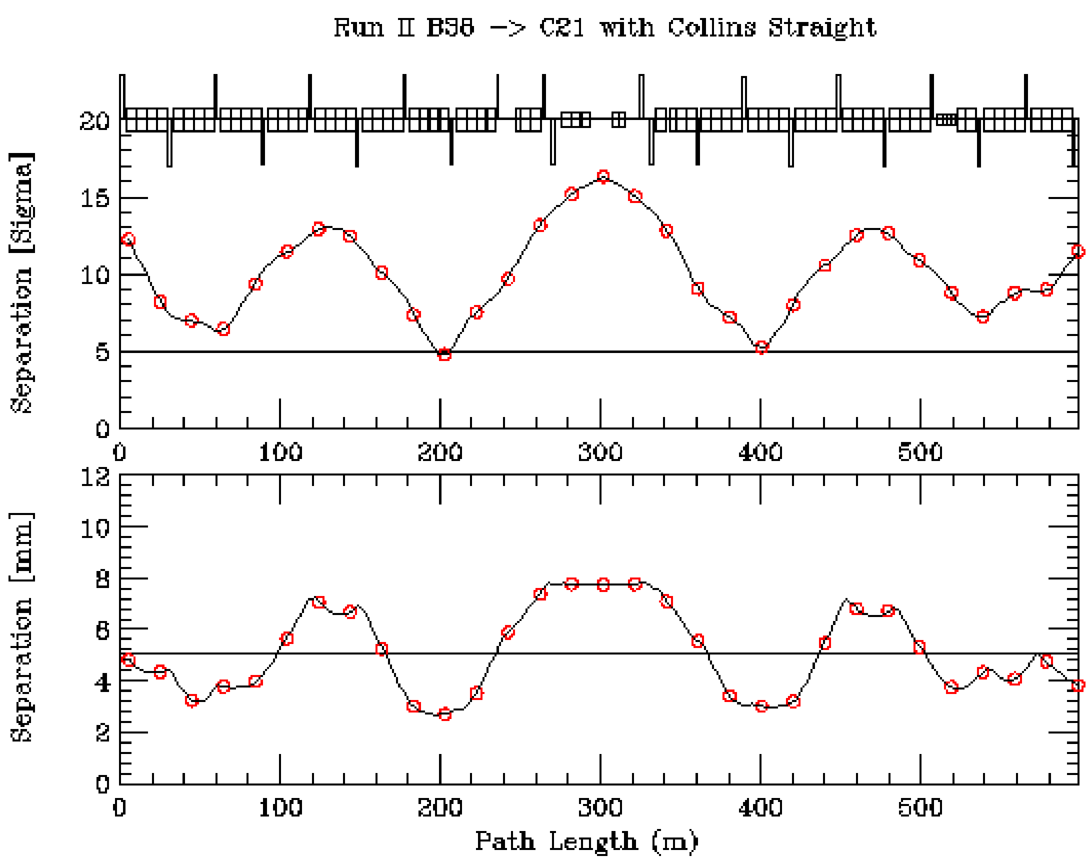
Beyond the decisions to implement shorter bunch spacing & crossing angles in late Run II few details of possible collision scenarios have been finalized. There is no 'official' helix to describe Collider operations in this era — several promising candidates exist — and the final locations of separators have not yet been established. The collision helix assumed for the purposes of this study is, therefore, only the latest *helix du jour* & might be quite different in detail from the eventual configuration. In this version [3] the half-crossing angles at B0 & D0 are (x'*, y'*) = (+170, -170) μrad, giving 5σ of separation at the 1st crossing for β^* = 35 cm, and 20π emittance (95%, normalized) beams.

It is unfortunate that this particular incarnation of the Run II helix arose concurrent with present attempts to design a new C0 IR – the helix traits through the short arc are ill-suited for supporting collisions at C0. Beam separation, with the standard Collins insert at C0 still in place, is shown in the following figures. Separation is clearly poorest in the short B0 → C0 → D0 arc, dipping to 5σ in several locations. Furthermore, the illustration of just the B38 → C21 section suggests it will be difficult for a new IR insertion to create comfortable beam separation in the vicinities of the minima at B47 & C13, while maintaining the requisite match to the nominal helix.

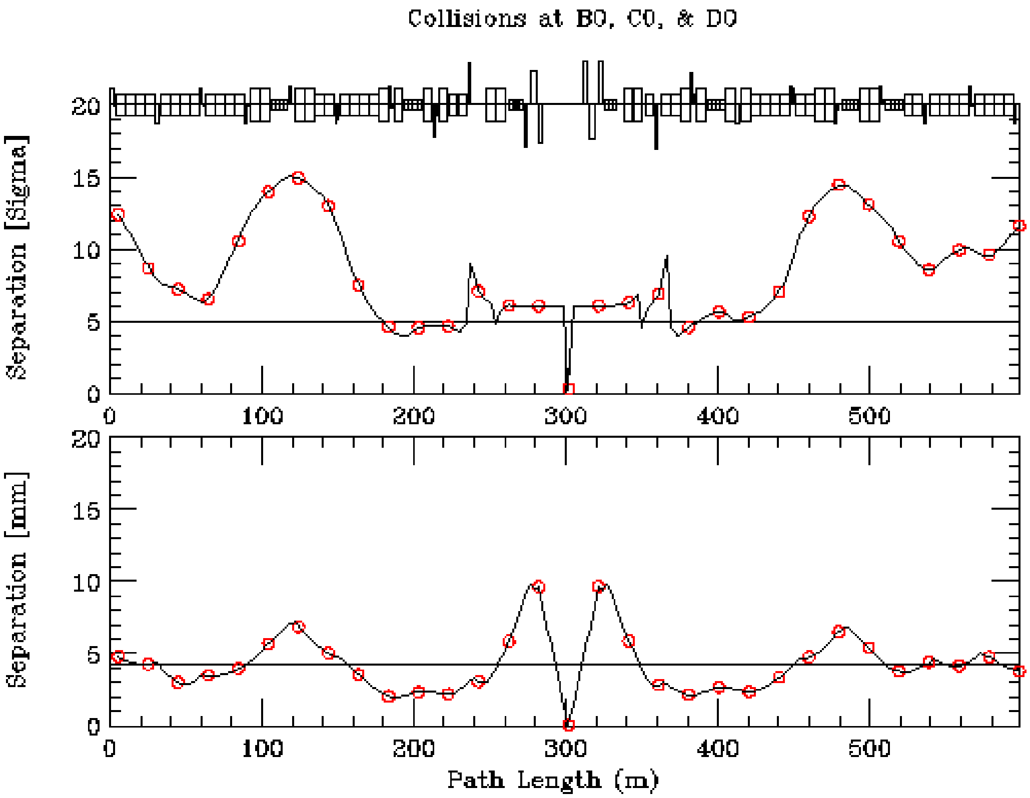
In the C0 IR design discussed here, the new arc separators have been located to optimize beam separation consistent with this one, specific, Run II helix solution. With separators at B43, B46, C13, and C16, collisions can be created at all 3 IP's while matching to the nominal incoming & outgoing helices across the C0 insert. (It is also possible to have collisions at just B0 & D0, or just C0, of course. Discussion of these less interesting scenarios is postponed, however, until the next section where, in the 2nd IR version, these become the only operational choices).

[3] " v3h15acsb4.nppn.170pnpn ", Peter Bagley, private communication.


Run II Separation with C0 Collins Insert
Separation [sigma]
Separation [mm]
Path Length (m)


Run II B38 -> C21 with Collins Straight
Separation [Sigma]
Separation [mm]
Path Length (m)

Shown below is the collision helix from B38 → C21. At the IP, $\beta^* = 0.50$ m and there are half-crossing angles of (x'*, y'*) = (-195, +195) μrad, giving 7σ separation at the first parasitic crossings. Other potential collision points are indicated, spaced at 7 half-bucket intervals. The separation is generally good but, as anticipated, is poorest each side of the IP – hovering near 5σ until outboard of the 6th secondary crossing points around B47 & C13.



The large crossing angles (275 μrad total half-angle) are necessary to keep the beams adequately separated through the natural minima of the nominal helix. However, the impact on luminosity is no worse here than the crossing angle effect at B0 & D0. A crossing angle reduces the luminosity relative to that of head-on collisions, L_0, by the factor:

$$L_\theta = \left[1 + \left(\theta_{1/2} \cdot \sigma_l \big/ \sigma_\perp\right)^2\right]^{-1/2} \cdot L_0$$

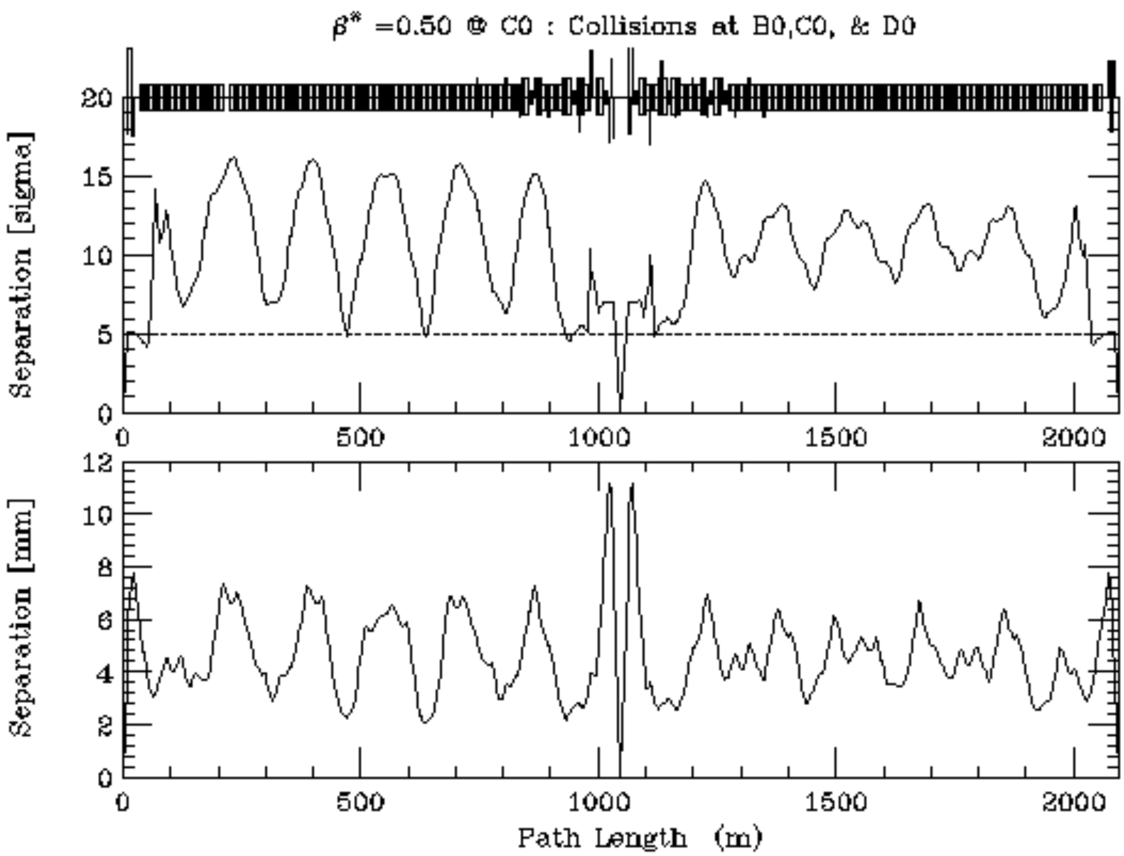
where $\theta_{1/2}$ is the total half-crossing angle, σ_l is the rms bunch length, and $\sigma_\perp$ is the rms transverse bunch size. The relevant transverse quantity is the ratio $\theta_{1/2}/\sigma_\perp$. For "N" σ of separation at the first crossing this has the value:

$$\frac{\theta_{1/2}}{\sigma_\perp} \approx \frac{N}{2\beta^*}$$

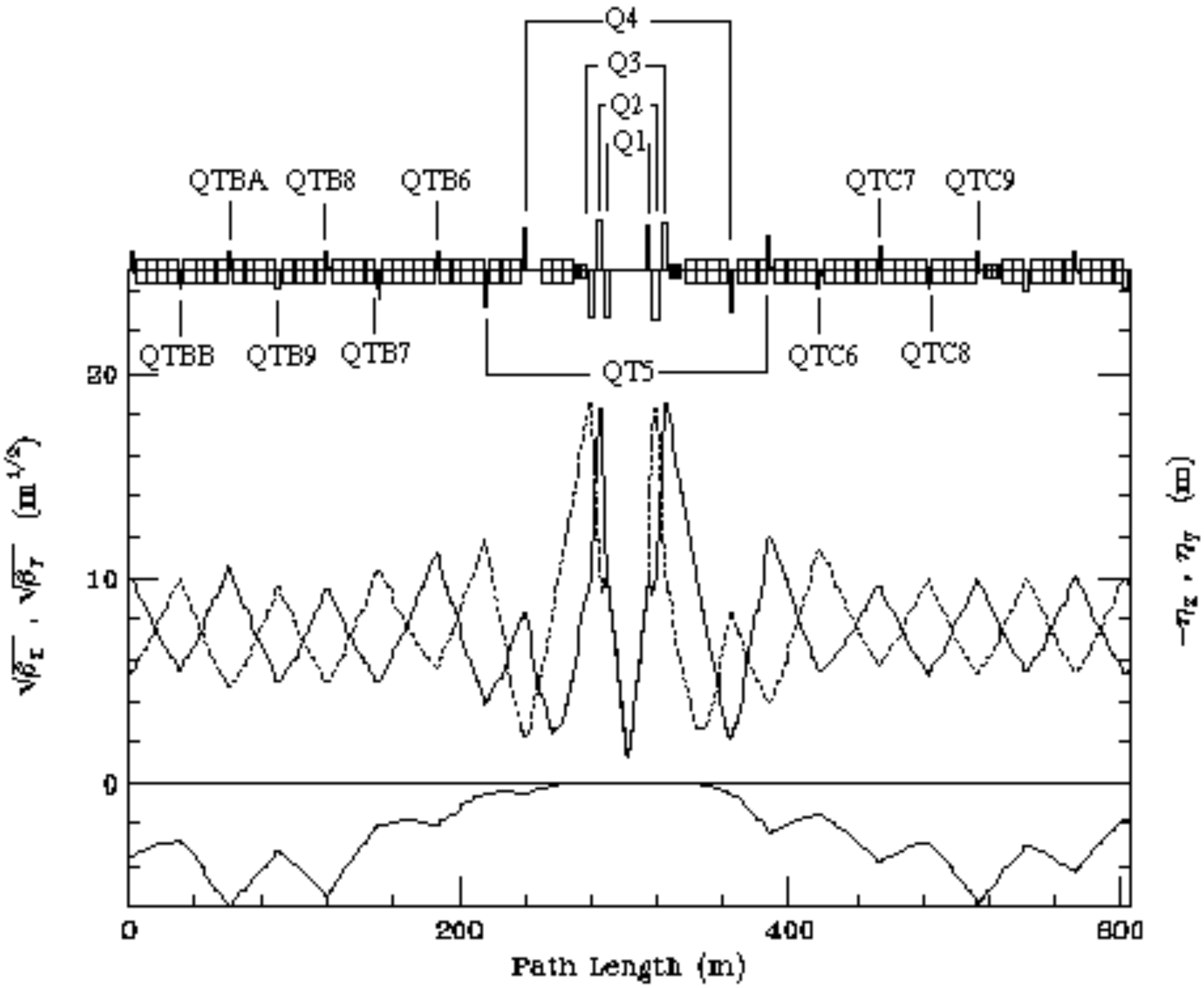
A β^* of 50 cm & 7σ separation at the 1st crossing, therefore, has an equivalent impact as 5σ separation with a $\beta^* = 35$ cm.

Separator gradients for this solution are given in the table below, followed by the beam separation through the short arc B0 → C0 → D0. The very small gradients at B49 horizontally, and C11 vertically, are a further indication that the nominal helix is not a 'natural' candidate for C0 collision scenarios. One would prefer to see large kicks at these locations to initiate separation into the arcs.

Separator Gradients (MV / m)					
Horizontal			Vertical		
			B43	4	-2.14759
B46	4	3.00372			
B49	2	-0.48634	B49	1	-2.93754
C11	1	-3.24089	C11	2	0.60083
			C13	4	3.34755
C16	4	-1.75608			



3. AN IR WITH NO NEW DIPOLES



3.1 Design

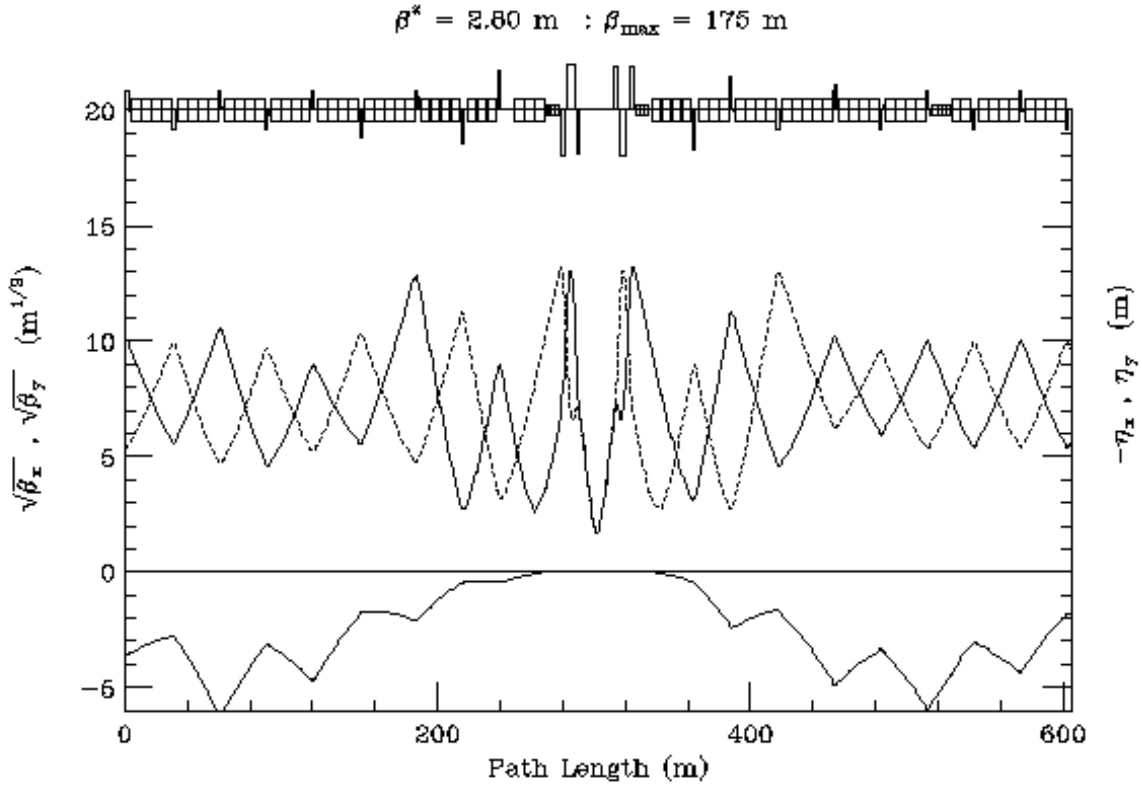
3.1.1. Quadrupoles

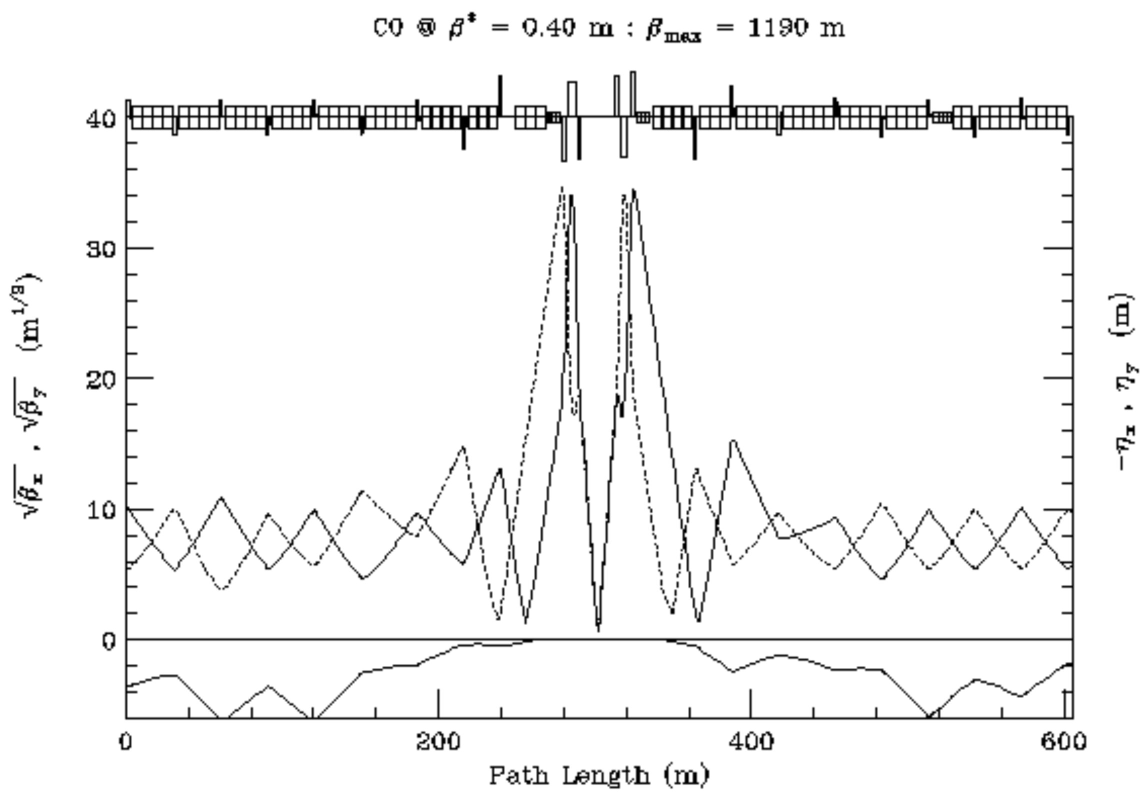
The IR quadrupole circuits, indicated above, are identical to those described in the preceding section.

3.1.2. Dipoles & Separators

Having only standard Tevatron arc dipoles available has 2 significant consequences. First, it is not possible to add more separators in the arcs. Collisions at C0 can not now be created without disrupting the nominal Run II helix outside of the insertion region. Second, the free space available for a detector shrinks markedly — by roughly $5^1/_2$ m relative to the previous design — to just $33^1/_2$ feet each side of the IP.

3.2 Optics


β* = 2.80 m : βmax = 175 m
√βx , √βy (m^1/2)
−ηx , ηy (m)
Path Length (m)
0
200
400
600
20
15
10
5
0
−5


C0 @ β* = 0.40 m : βmax = 1190 m
√βx , √βy (m^1/2)
−ηx , ηy (m)
Path Length (m)
0
200
400
600
40
30
20
10
0

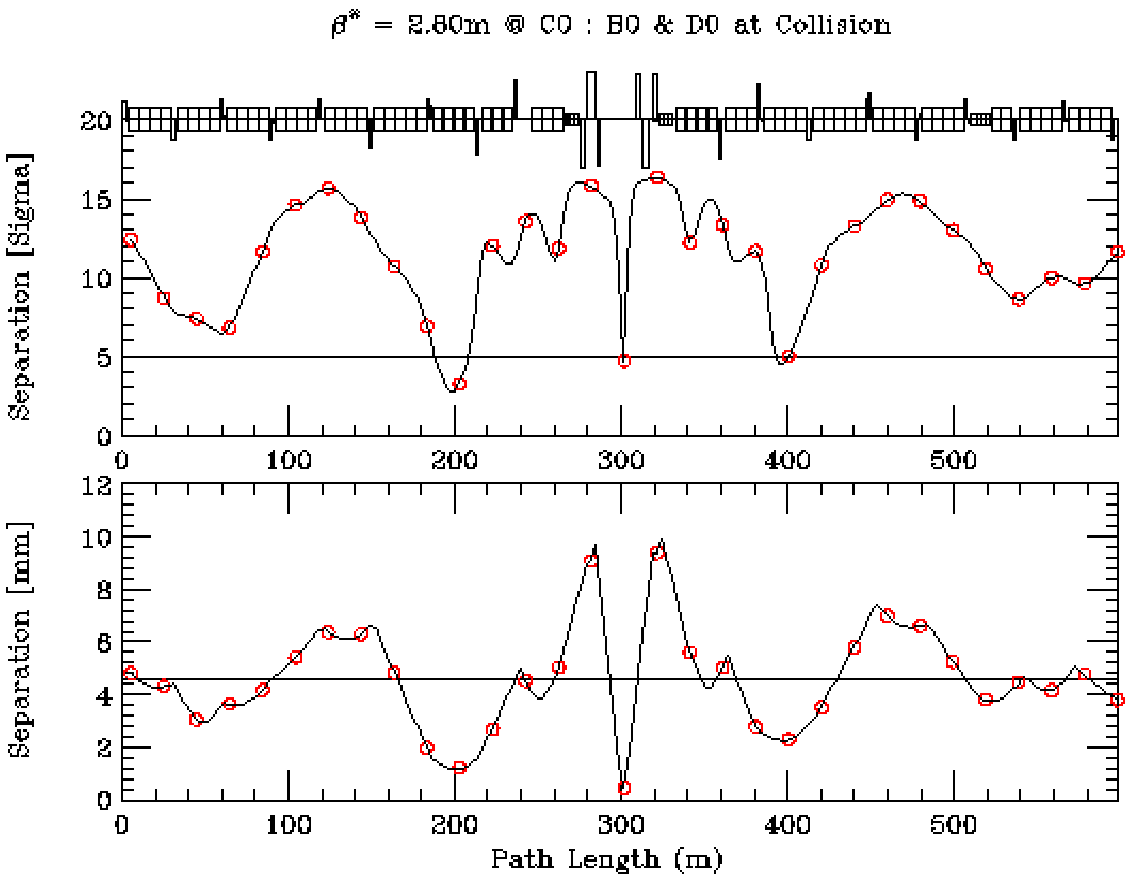
The injection & collision optics are illustrated on the previous page. At injection, $\beta^* = 2.80$ m results in a βmax of 175 m in the triplets. Again, this is much less than at B0 & D0. With the triplet quads closer to the IP in this version of the insert, a β^* as small as 40 cm can be reached before βmax becomes excessive. In all other respects the optical properties of this version of the IR are virtually indistinguishable from those discussed in the preceding section. It would be tedious therefore to present reams of nearly identical material again here.

3.3 Beam Separation

Under the restriction that C0 operations must not impact nominal Run II B0 & D0 collider parameters, and without additional separators, the Tevatron Collider can operate in 2 modes:

(i) B0 & D0 with collisions — not C0, and ;
(ii) C0 with collisions — not B0 & D0.

3.3.1 C0 Without Collisions



Without collisions at C0 the insertion optics remain at $\beta^* = 2.80$ m, and the B49 & C11 separators are turned off. The resulting matched helix from B38 $\rightarrow$ C21 is shown above. Beam separation is

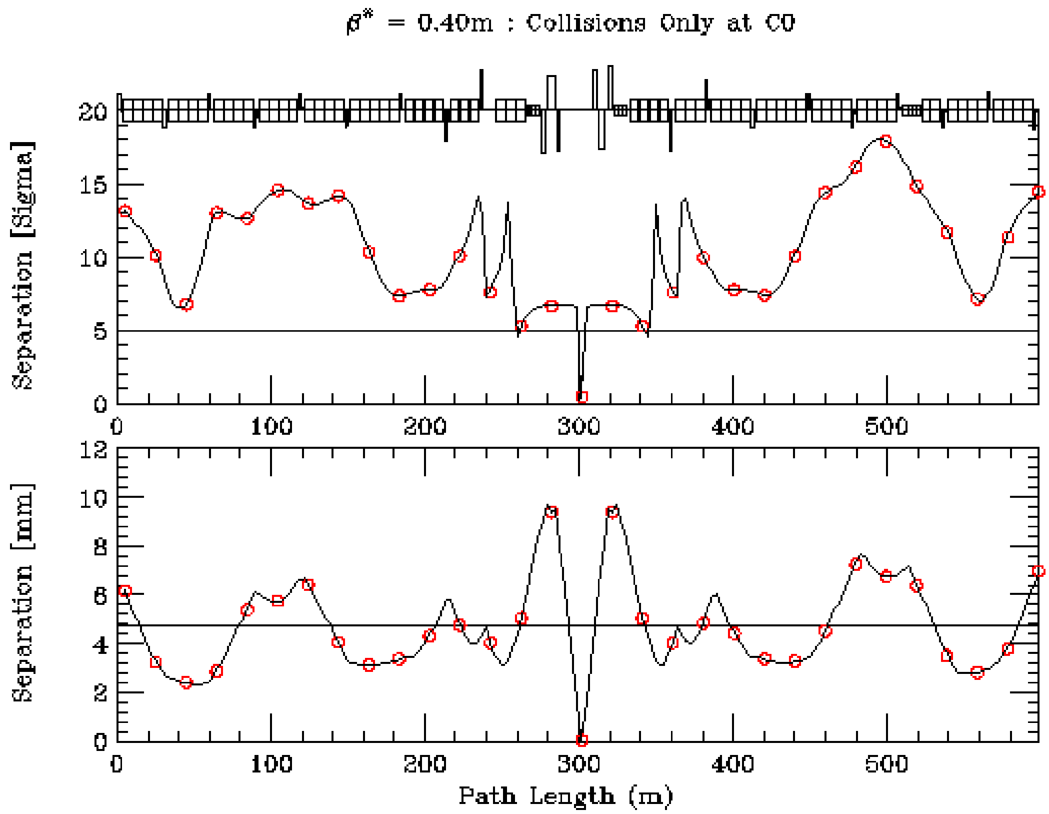
≥ 5σ everywhere except for the 5th crossing point on B-Sector side. There is nothing that can be done locally to influence this point – it is a feature of the nominal Run II helix.

3.3.1 C0 With Collisions

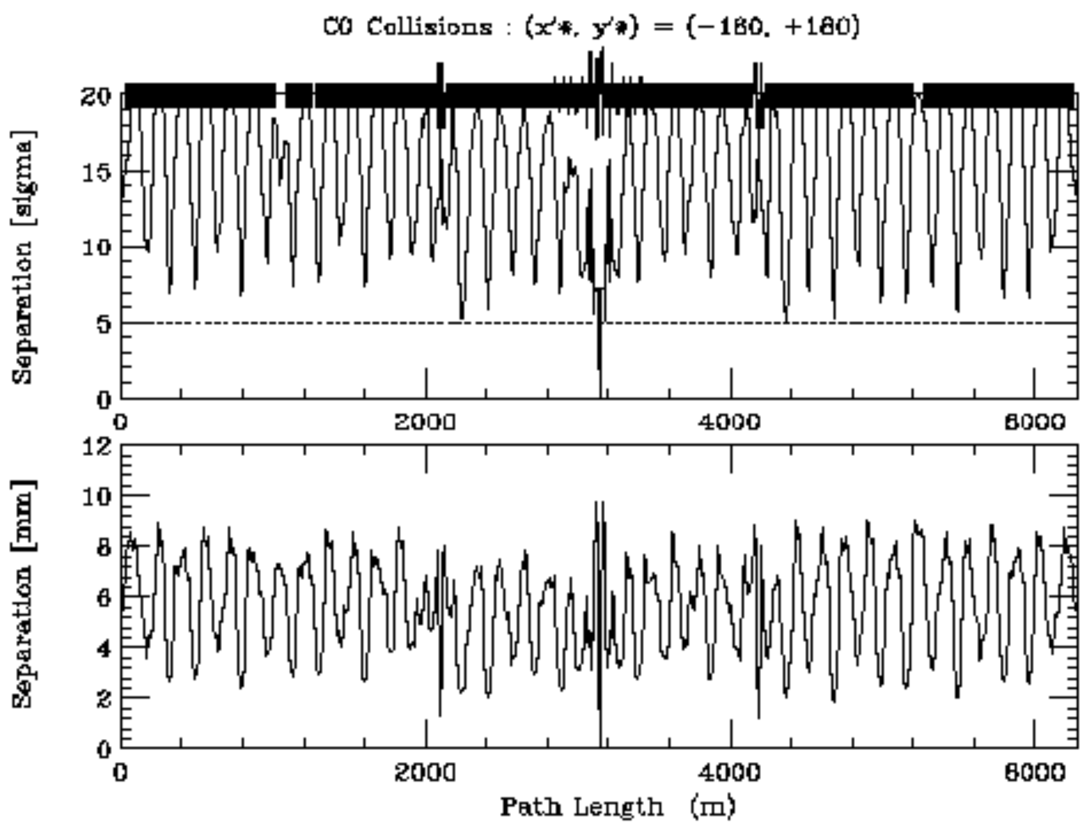
For collisions at C0 the optics at B0 & D0 are left in their Injection configuration. In this case, all the separators in the ring become available for bringing beams together at the C0 IP, while keeping them separated everywhere else. For half-crossing angles at C0 of (x'*, y'*) = (-180, +180) μrad, one possible (minimal) separator solution is listed in the table below. The selection of separators has not been optimized in any way, other than to ensure adequate beam separation around the ring. Many, many more combinations can be explored.

Separator Gradients (MV / m)					
Horizontal			Vertical		
			B11	1	-2.35261
B17	4	-0.102614			
B49	2	-4.50000	B49	1	4.50000
C11	1	4.50000	C11	2	-4.50000
			C17	4	-0.62098
C49	1	-1.35185			

On the following page appears the beam separation from B38 → C21, and the separation all around the ring. With this separator solution the closest approach through the insert is at the 3rd parasitic crossing but, nonetheless, is still ≥ 5σ everywhere. Similarly, separation in the ring drops close to 5σ in a few spots, but the average separation is 10→15σ. The use of a larger subset of separators would enable the large oscillations to be smoothed from the helix.



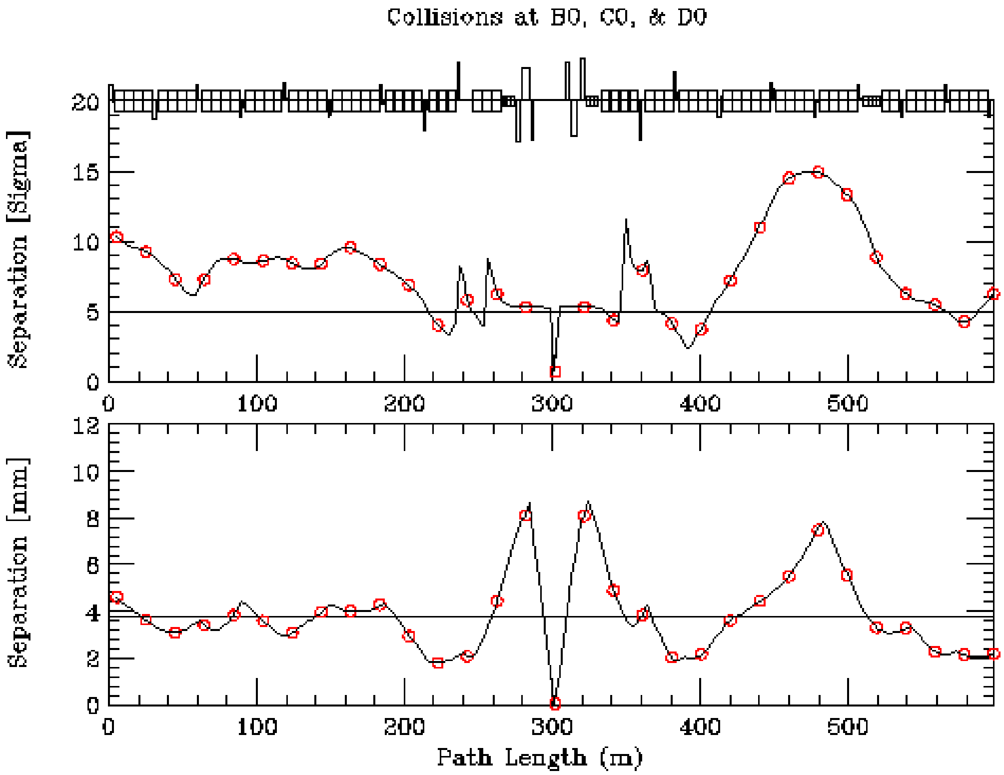
β* = 0.40m : Collisions Only at C0
Separation [Sigma]
Separation [mm]
Path Length (m)



C0 Collisions : (x'*, y'*) = (−160, +160)
Separation [sigma]
Separation [mm]
Path Length (m)

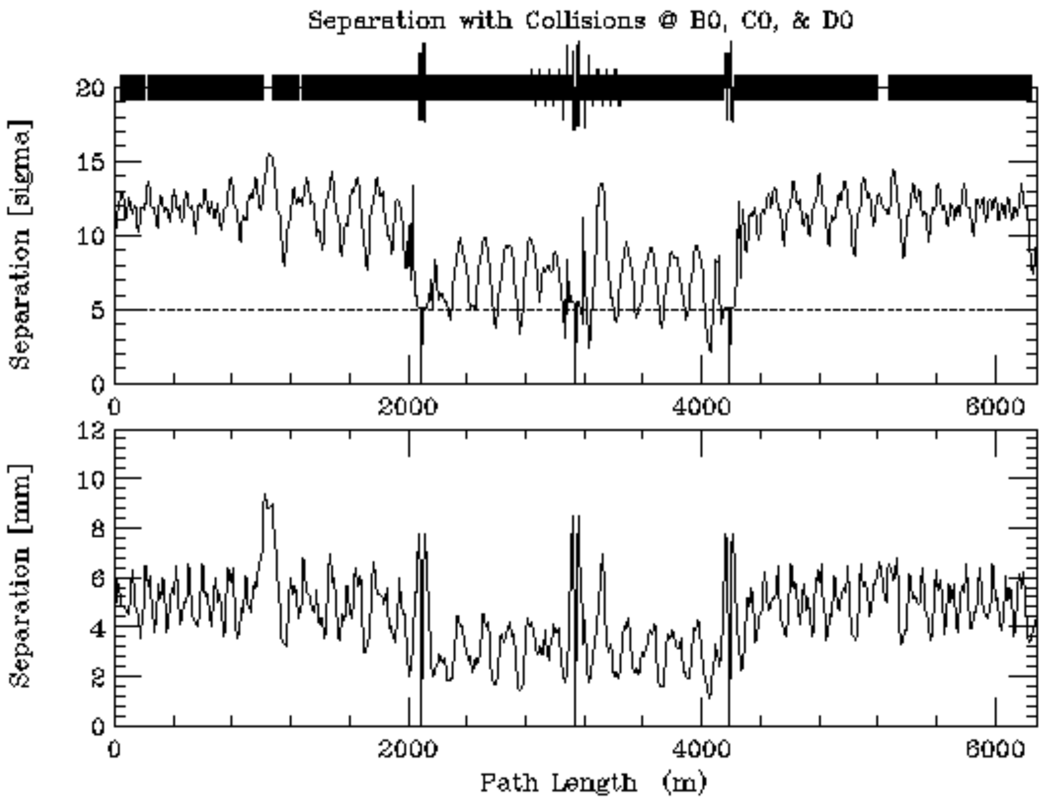
3.4 Collisions at B0, C0, & D0

In this version of the IR model, collisions can not occur at all 3 IP's consistent with the C0 insert remaining optically transparent. This brief section examines, though, whether a reasonable 'semi-local' solution exists using only the separators in the short arc. There are 5 sets of separators, including the B49 & C11 modules, in each plane between B0 and D0. With the B0 & D0 crossing angles fixed at (x'*, y'*) = (+170, -170) µrad, and (x'*, y'*) = (-180, +180) µrad at C0, only one separator solution exists with physically realizable gradients. Beam separation through the C0 insert & corresponding separator gradients for this case are shown below.



Separator Gradients (MV / m)					
Horizontal			Vertical		
B11	1	1.55253	B11	2	-2.93408
B17	4	-4.50000			
B49	2	2.55308	B49	1	-2.94817
C11	1	-2.28540	C11	2	-4.50000
			C17	4	3.57661
C49	2	-2.35765	C49	1	-2.30501

Splitting the crossing angle equally between the transverse planes optimizes beam separation into the arcs, but the solution is clearly a very marginal situation. At several crossing points through the insertion region beam separation drops below 5σ. The viability of this solution becomes even more questionable when separation in the short arc is compared with the rest of the ring (below). In going from B0 → C0 → D0 the separation is often less than 5σ, and average separation is only half that of the long arc D0 → E0 → F0 → A0 → B0.



4. SUMMARY & OBSERVATIONS

Two possible optical designs for a stand-alone C0 IR insert were presented. Both inserts are optically transparent to the rest of the machine, with no impact on Run II Tevatron operating parameters. Both design versions require high-field LHC-like quadrupoles for the final focus triplet. In the first version, with enhanced dipoles creating space for separators in the arcs, collisions can be created at all 3 IP's simultaneously. Stronger dipoles also free more than 26 m of space for the detector. At C0, β* is limited to ≥ 50 cm by βmax in the IR triplets. The second version of the IR has neither new dipoles nor new arc separators. Collider scenarios have either B0 & D0 at collision, or just C0. At C0, β* can be decreased to 40 cm, but the price is a substantial reduction in free space available for the detector.

This first pass at C0 IR designs has left a number of questions unresolved. A second iteration of the IR designs will need to address these outstanding issues:

- The LHC-like quadrupoles operate with gradients somewhat higher than the present Tevatron cryogenics can tolerate. Reducing the strengths will require that the magnets become longer. If gradients are kept ≤ 175 T/m, the magnetic lengths of the triplet quads Q1, Q2, & Q3 are estimated to grow by 5%, and Q4 by 10%, for a total of $\approx 24''$. Both IR versions discussed here can easily accommodate this change without encroaching on the detector space. In the IR with enhanced dipoles a total of $17'$ of free space currently exists between the downstream separators & Q4. The design with only standard Tevatron dipoles has $5^1/_4{}'$ between the separators & first dipole. In the model, therefore, length changes become just a technical detail.

- The addition of a new low-β has a huge impact on chromaticity, changing the natural chromaticity of the machine by $(\Delta\nu_x, \Delta\nu_y) = (-19.75, -19.70)$. If the insertion is to be truly transparent a local sextupole correction scheme must be devised for compensation.

- With all 3 IP's at collision beam separation through the C0 IR is not as large as desired. Mainly this is a result of the current Run II helix not having been optimized in any way to account for C0 interactions. A comparison of separation through the insert with B0, C0, & D0 collisions (section 2.3), with just C0 collisions (section 3.3.1), shows the large improvement in beam separation that can result with a different incoming helix. The options for alternative, global, separator solutions that optimize the collision helix for B0 & D0, plus C0, need to be explored.

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