C0 IR R&D SUMMARY

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CONTENTS

1. INTRODUCTION

It has been proposed that at some point in the future a third detector will be installed in the Tevatron, at the C0 straight section, forming the foundation of a dedicated bottom-quark physics program at the collider. BTeV has devised a phased plan for development of a C0 detector. In this scheme the IR collision optics would be continually upgraded and refined through a series of developmental stages, culminating ultimately in a true low β^* (~0.35 m) IP, comparable to the two existing IP's.

2. CO – IR DESIGN RESTRICTIONS

A Memorandum of Understanding, reached between Fermilab & BteV [(1)] outlines the boundary conditions for developing a C0 IR design. Phase One of this BTeV R&D project calls for design of a medium β^* IR insert which realizes the following objectives:

" 1. specification of the magnets to be used (magnets will be chosen from existing magnets);
2. specification of separators (number & positions - design will be unchanged);
3. specification of the correction scheme (steering corrections & any higher order corrections that might be required), and;
4. longitudinal layout of insertion. (... The intent is to design an insertion that is sufficiently flexible that it can work in a variety of scenarios...).... "

The Memorandum outlines a second phase of developmental goals, calling for a series of insertion upgrade designs (including new magnets), resulting eventually in an IR insert with $\beta^* \approx .35$ cm.
The BTeV & Tevatron groups added additional constraints to the MOU list:

5. magnets must not encroach upon the detector space 45' both sides of the IP;
6. the synch light monitor will be located at B48;
7. $\eta^* = \eta'^* = 0$ at B0 & D0, as in the Run II lattice;
8. dispersion < 8 m in the arcs;
9. β - wave < ± 2 % in the arcs;
10. operating scenarios should cover 3 IP's at collision, any 2 IP's, and any single IP, and;
11. tunes are to remain fixed at (20.585, 20.575), as in the Run I & II lattices.

The first 6 items reflect physical constraints on the insert design, while 7 –11 are optical constraints, primarily insisting that adding a C0 IR must not disrupt standard Tevatron operations.

3. SEARCH FOR a C0 IR DESIGN USING EXISTING MAGNETS [(2)]

The first step in this R&D program calls for design and installation of an intermediate - β^* (< 5 m) collision region fairly early in Run II. There are no new magnets available for this stage and so it is a considerably more formidable challenge than starting with a blank sheet of paper to design the final low – β insert.

The maximum gradients of the available spare magnets are roughly 60% that of the B0 & D0 triplet quads (17.155 T/m/kA *cf* 29.018 T/m/kA); the only exceptions being the high-field 55" quads removed from the Q1 positions at B0 & D0 for Run II. The spares inventory includes neither the high-gradient quads from the original Tevatron low-beta inserts nor any spares for the current IR triplets. The paucity of free space further exacerbates design problems.

The restriction that nothing encroaches upon the 45' of space reserved for the BTeV detector each side of the IP pushes the first low-beta magnets nearly twice as far away from the IP than the corresponding final focus quads at B0 & D0. With these constraints a doublet approach to a low solution at C0 is the only possible option - there simply is not sufficient room to accommodate a triplet plus the necessary separators.

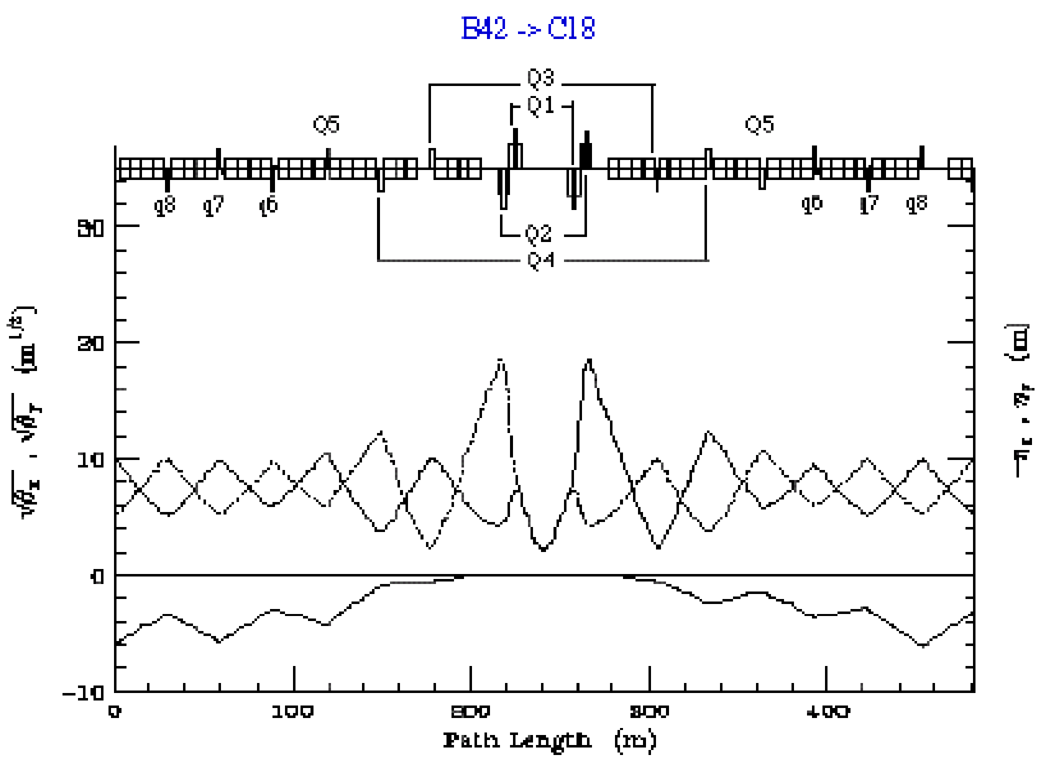
The principal argument for using triplets at B0 & D0 is to keep β_{max} as small as possible, which is most efficiently accomplished by triplet focusing. A doublet design does have advantages over a triplet principally in that it occupies less space and requires lower gradients. However, the one glaring disadvantage is that β_{max} is ~ 3 – 4 times larger for a given β^* than it would become in a triplet. Consequently, the minimum operational β^* might well be determined by the aperture of the low-beta quadrupoles rather than the maximum attainable magnet gradients.

3.1. MEDIUM - β^* INSERT

There is 116.5' of space between the C0 IP and the first arc dipole. The BTeV detector occupies 45' of this space and three separators plus their ancillary hardware fills up another 33.5'. This leaves just 38' of room for the doublet focusing elements. The earliest attempts to design a medium - β^* insert relied on individually-powering and/or replacing the standard 66" arc quadrupoles to match the IP optics into the standard arc values. Outlines of two such attempts (2 out of many similar models) are described in the following sections. It is possible (on paper) to achieve $\beta^* < 1$ m and also create $\eta^* = \eta^{*\prime} = 0$ across the C0 IP, as in the Run II design for B0 & D0.

3.1.1. $\beta^* = 1.35$ m

Lattice functions and magnets of the C0 straight after being modified for a low - β^* IR appiar below.



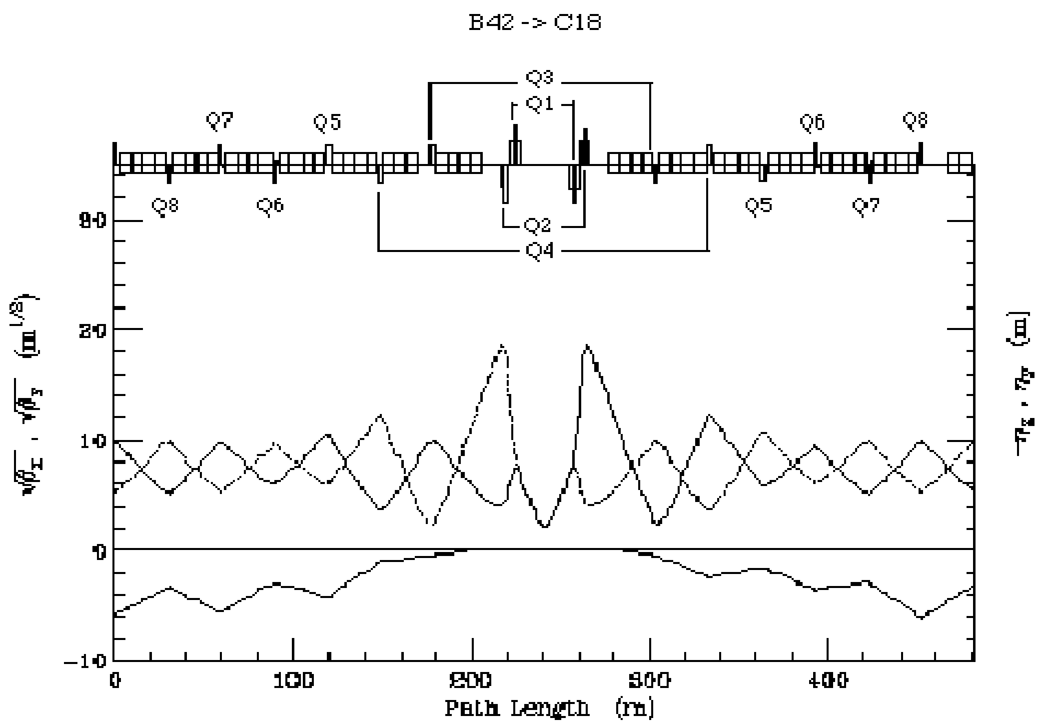
Quad Composition :

- Q1 : 82" + 55" + 82" quads
- Q2 : 66" + 55" + 66" quads
- Q3 : 90"
- Q4 : 99"
- Q5 : 82"
- q6 : 32"
- q7 : 32"
- q8 : 25"

At the minimum β* of 1.35 m the maximum amplitude in the doublet is β_{max} = 1089 m, which is comparable to the values at B0 & D0 with a β* of 0.35 m. The limit here is the maximum field of the qt8 trims, although the Q4 quads are also rapidly approaching their limits at this point.

3.1.2. $\beta^* \leq$ 1.00 m

Lower values of β* than the 1.35 m achieved in the preceding section can be reached either by extending the previous design farther into the arcs with qt9 (or beyond) trim quads or by powering more main arc magnets independently. One example of lattice functions and quad circuits obtained with the latter approach is illustrated below.



Quad Composition :

- Q1 : 99" + 55" + 66" quads
- Q2 : 66" + 55" + 66" quads
- Q3 : 90"
- Q4 : 99"
- Q5 : 82"
- Q6 : 66"
- Q7 : 66"
- Q8 : 66"

This model is very similar to that of the preceding design from B47 C13, with only minor changes made to the Q1 quad composition. The big design differences occur from B43 → B46 and from C14 → C17. Rather than using 25" and 32" 'trim' quads at these locations, the main arc magnets here are also powered independently.

The magnets in this design are capable of creating a beta as small as $\beta^* = 0.60$ m, while maintaining $\eta^* = \eta^{*\prime} = 0$ across the IP. This results in a maximum β in the doublet of about 2.5 kilometers, which is clearly not a solution the Tevatron can support. A β^* of ~ 1 m is about the smallest value compatible with keeping β_{max} comparable to the values at CDF & D0.

3.1.3. Design Defects and Fatal Flaws

Both of the models described so far assumed space for 3 separators each side of the IP, the same as there are at B0 & D0. However, with a doublet final focus rather than a triplet, 3 is not the optimum number. The optimum number of separators is therefore 4, with 3 in the plane of smaller β . Ufortunately, it is not possible to generate sufficient space to accommodate 4 separators.

A severe problem with this approach to insert design is that magnets can probably only be powered independently in the arcs at the expense of losing the spool packages and, therefore, the valuable correction elements they contain.

The following is a minimal list of additional hardware that must appear for operation:

1 S-Spool :	6'
1 Power Feed :	3'
2 BPMs :	2'
1 TAB :	2'

Total :	13'

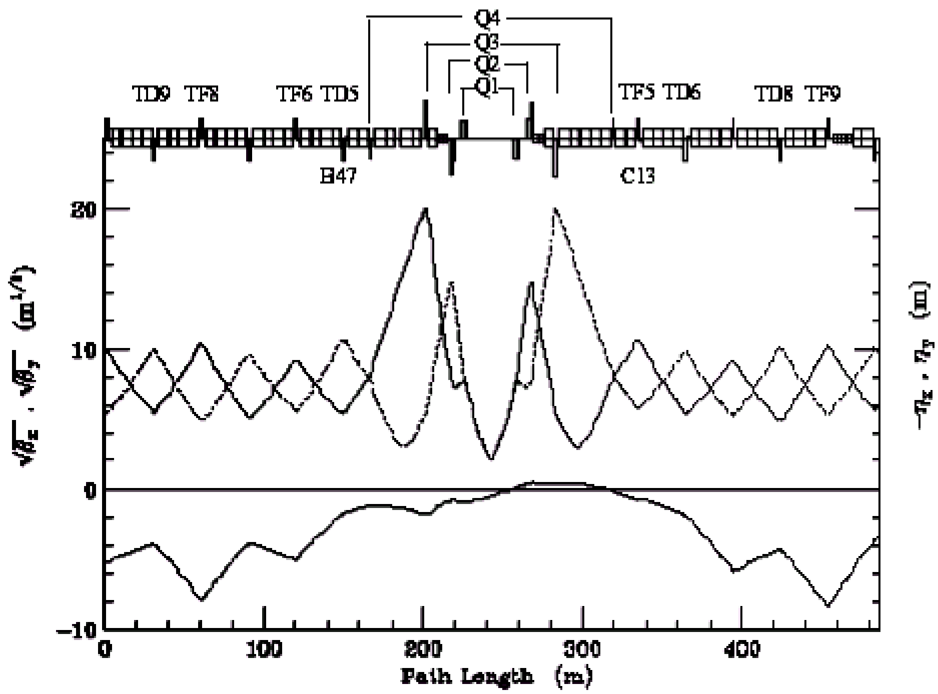
Only 20'6" of 'free' space remains for separators. There is really only room for one separator, which is clearly unacceptable!

The powering of individual arc quads leads to the loss of all the correction elements residing in the spool packages. Even if this problem could be surmounted, it does not appear that an adequate number of separators can co-exist with a doublet final focus created solely from existing magnets. This points towards two equally senseless solutions: (i) either a low-beta can be formed, but without colliding beams, or; (ii) the beams can be made to collide, but not at low beta.

3.2. QUARTER-WAVE TRANSFORMER

The principle of the λ /4-transformer matching technique is illustrated in the accompanying picture. Q4 quadrupoles are located a quarter of a Tevatron cell away from the B47 & C13 quads.

The doublet Q1 and Q2 'quadrupoles' are constructed from 2 magnets each (Q1: 66'' + 66''; Q2 : 99''+55'') . Two separators are installed between the Q2 quads and 1st dipole at the B49 & C11 locations. After considerable experimentation, the site of the Q3 quads was chosen to minimize gradients in the Q1, Q2, & Q3 magnets, minimize β_{max}, and to produce $\sqrt{\beta_x} \approx \sqrt{\beta_y}$ at the midpoints of the horizontal and vertical separators.



An attractive feature of this particular approach is that by matching α, β directly into the middle of a regular Tevatron cell no secondary peaks are formed, as might otherwise occur when fitting from a non-FODO to FODO lattice. This simple trick alone, though, does nothing to address dispersion matching – that problem is largely left to the trim quads. Trim quads at B43, B44, B46, B47 and C13, C14, C16, C18 are powered independently for extra fine α, β matching.

The 7 dipoles between the Q2 quadrupole & B47 on the upstream end, and the 8 dipoles between Q2 & C13 downstream, are moved to make space for the Q3 & Q4 magnets. Upstream dipole positions are adjusted to re-close the orbit, while retaining sufficient space for the synch light monitor.

3.2.1. 37.0 T·m/m Trim Quads

In this preliminary (optimistic) exploration of an IR design using the quarter-wave matching technique the strengths of the 8 trim quads are unconstrained. It is possible to then reach $\beta^* < 5$m at C0, and also to create $\eta^* = \eta'^* = 0$ dispersion-free IR's at all 3 interaction points in the Tevatron.

Addition of a low - β at C0 raises the machine tunes by a half-integer from their Run II values of ~20.5, right onto the integer resonance at 21.0. The ideal way to re-adjust the tunes is to leave the long B0 → D0 arc phases unchanged from their Run II values, while adding or subtracting roughly a half-integer through the short B0 → C0 → D0 section. Leaving the long arc undisturbed has obvious attractions -- separators, collimators, correction schemes, whatever, would continue to function just as before. Changing the short section by 1/2 is also beneficial -- making head-on collisions at C0 possible when all 3 IPs are at collision. This otherwise does not appear possible, and a C0 crossing angle becomes unavoidable. The second choice for tune re-adjustment is to change the long arc tune by 1/2. This ensures that at least the separators can still be made to work. The drawback to both these approaches is that, with the B & C sector tune strings powered differently than the D, E, F, & A quads, for any β^* the IR gradients are different at B0 & D0.

Attempts to implement both of these options to re-adjust the tunes were made. Neither worked. The tune quad strings have insufficient strength to change the tunes by ±1/2 while simultaneously maintaining an optical match to the B0 & D0 IP's. Furthermore, even with tune re-adjustment distributed over all 6 sextants, it is still not possible to re-establish the Run I & II tunes. A new operating point was therefore established, with the model tunes set between the 4/5 & 5/6 resonances, at (20.8167, 20.8167). This is the same fractional tune as RHIC.

The addition of a 3rd IR results in the phase advance from place-to-place in the ring becoming completely different from the Run II design. This has profound implications for machine operations. In essence, the Tevatron becomes a completely new machine.

At the new operating point, the preliminary lattice design shows some promise of being able to fulfill most of the optical restrictions listed in Section 2. A solution for a β^* of 5 m was presented, but with fairly straightforward magnet substitutions at the Q4 locations it appears that a $\beta^* \leq 2$ m might be reached. Complete solutions for all the desired operating scenarios listed in Section 2 have not been attempted, but no serious obstacles are readily apparent.

Unfortunately, this design must be rejected. This C0 insert can not be built solely from existing magnet spares. The trim quad gradients are much higher than can be physically realized by the existing spool quads. These strengths could only be attained by building new spool pieces – probably of the Bartelson type installed at B0 & D0 IR's.

3.2.2. 7.0 T·m/m Trim Quads

The latest incarnation of the C0 IR design is essentially identical in layout to the one described in section 3.2.1; the major exception being that the high gradient Bartelson-like spools in the model are replaced with regular tune quad spools. The single, most significant result of switching to these much weaker trim quads is that dispersion can neither be controlled across the C0 IR nor matched to the regular arc dispersion. The large dispersion wave thus generated has a significant impact on the matching abilities at the B0 & D0 IR's as well.

With Bartelson-like trim quad spools it is possible to satisfy most of the optics restrictions imposed on the IR design. These magnets do not currently exist though & would require a serious commitment of time and money to construct. With the much weaker regular quad spools for matching, a partial optical and partial separator solution has been patched together for a C0 IR insert. It meets none of the 10 original design constraints however, other than it is constructed solely from existing magnets.

With the completely disrupted betatron phase distribution around the ring that results from adding a 3rd IR, the existing separators are no longer in optimum locations. Creating acceptable collision helices becomes very difficult and requires many additional new separators.

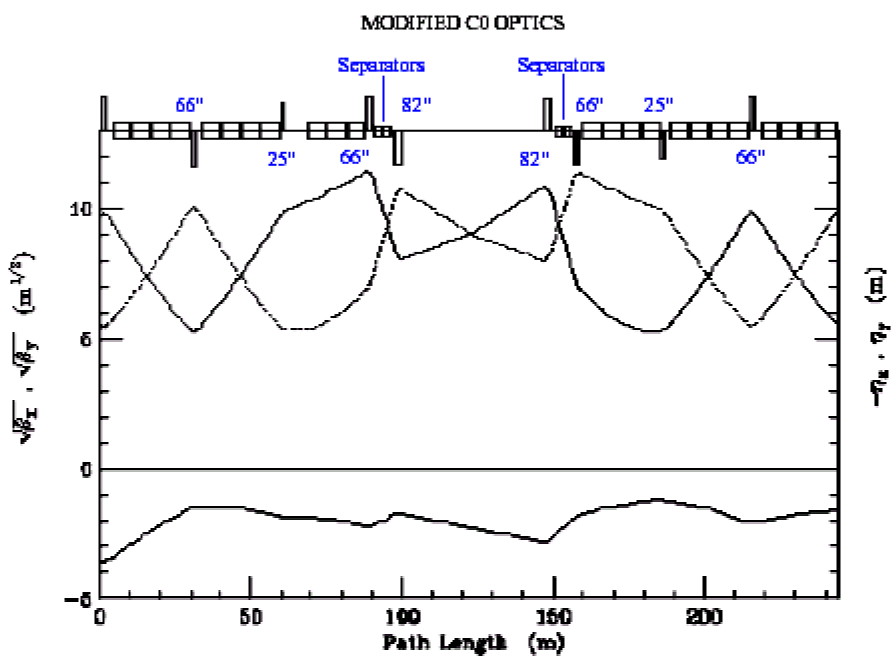
3.3. HIGH – β^* C0 IR

With the failure to find a viable medium–β^* solution, this section explores possibilities for creating colliding beams at C0 with high –β^* optics.

3.3.1. Modified Collins Insert

The standard Collins insert can be altered to accommodate 2 separators up and downstream of the IP, while maintaining an optical match to the arc lattice functions. The 32", 82" and 99" inner quads of the standard insert are replaced with 25", 66" and 82" quads, respectively. The inner 82" quads move in towards the C0 interaction point sufficiently to insert 2 separators between the 66" and 82" quads. These replacement magnets continue to run on the main bus.

Layout of the modified C0 region and optical functions appear on the following picture. In this new configuration β^* at C0 grows from the standard Collins value of ~72 m up to ~ 82 m, while at the separators $\beta_x \sim \beta_y \sim$ 90 –105 m.



It is <u>not</u> possible to create collisions at all 3 detectors, with or without a crossing angle at C0. The separators added at B49 & C11 are of limited value. Due to the uniformly large value of β across the insert, the phase difference between the separators and the C0 midpoint is ~$2\pi\cdot(0.05)$. This is woefully inadequate for any significant position control at the IP. To produce x = y = 0 at the interaction point requires ~22 MV/m/separator – nearly 6x what is physically realizable. With a maximum kick of only ~10 µr /separator available at 1 TeV, there is very little in the way of crossing-angle control either.

This is an illustration of creating collisions at C0, while separating the beams elsewhere in the ring. In this example (chosen rather arbitrarily), B0 & D0 have β^* = 35 cm.

The average beam separation here is 7.2 sigma around the ring, with half-crossing angles of $\alpha_x = -\alpha_y = 21$ μr at C0; for a total half-crossing angle of 30 μr. The beams are separated adequately through most of the machine, but fall together badly through B – sector.

3.3.2. Standard Collins Straight

In the middle of the regular C0 straight section $\beta_x \approx \beta_y \approx$ 71 m and $\alpha_x \approx - \alpha_y \approx \pm$ 0.47. Between the 99" & 82" innermost quads at the ends of the straight (where $\sqrt{\beta_x} \approx \sqrt{\beta_y}$) there is insufficient room for separators.

The observations in the preceding section regarding phase advances from place-to-place in the ring apply equally to the unaltered C0 Collins insert. With the same operating example as considered in section 3.3.1 (β^* = 35 cm @ B0 & D0), the beams can again be brought into collision at C0 using just the B17 & C49 horizontal and B11 & C17 vertical separators.

The orbits have similar characteristics to those found with the modified Collins insert and separators at B49 & C11. The average beam separation is 5.8 sigma around the ring, which is somewhat less than before. Again, though, the beams are fairly well separated through much of the machine, but fall together badly through B – sector. At C0 there are half-crossing angles of $\alpha_x \approx - \alpha_y \approx 21$ μr, for a total half-crossing angle of 30 μr.

Since collisions can not occur at all 3 IP's simultaneously, colliding beams at C0 must be created during some kind of dedicated Tevatron operation. While it is possible to install separators at C0 after modifying the Collins insert, it is certainly not obvious that the effort is worthwhile. In the example described, C0 collisions can be created with or without new C0 separators. The B49 & C11 separators did improve beam separation somewhat through the arcs but, in either case, separation was very poor in B-sector. Definitive conclusions regarding C0 modifications will only become possible after realistic operational scenarios have been studied.

3.4. CONCLUSIONS

No successful design was found for a C0 medium – β* IR insert that could be constructed solely from existing magnets. Failure of the attempts reported were a result of 2 factors: (a) insufficient space exists for installation of the required components, and; (b) the optical impact on the Tevatron would completely disrupt normal machine operations.

If a positive side to this study exists, it is that several stumbling blocks were identified that will have to be addressed eventually by any low – β* design. The 2 most important are the following:

- **The BTeV detector reduces the available free space by ~20' each side of the IP compared to B0 & D0. So, a final focus modeled on the B0 & D0 high-gradient triplets plus separators would not fit in the C0 straight. Furthermore, it is very unlikely that a triplet would fit even if constructed using higher gradient (LHC) magnets. There are two options as to how to proceed:**
  - **(i) The final focus is constructed as a high-gradient doublet. This creates sufficient space to install the optimum number of 4 separators. However, the β* attainable for collisions is then severely limited by the available aperture in the quadrupoles. The studies reported here showed that with a doublet, a $\beta^* \approx 1$ m results in $\beta_{max} \approx 1500$ m. This is not a problem that goes away with higher gradients!**
  - **(ii) The final focus is a high-gradient triplet, producing collisions at $\beta^* \leq 35$ cm. Installing the 3 separators requires creating new space into the arcs. In this scenario the inventory of new IR magnets therefore also includes high-field dipoles.**

- **A 3rd IR in the Tevatron adds roughly a half-integer of tune to the machine. If re-tuning is distributed over the entire ring, none of the correction elements, separators, collimators, etc., are in the appropriate locations any longer. Every aspect of machine operations must then be reevaluated. This study emphasized that the optimum choice for tune re-adjustment is to confine it to the short arc, adding or subtracting ~ 90^0 between B11 & B49 and again between C11 & C49. This has minimal impact on normal operations and appears to be the only way to create head-on collisions at all 3 IP's simultaneously. However, this is not possible with the current weak tune quad strings and some number of additional strong tune quads required.**

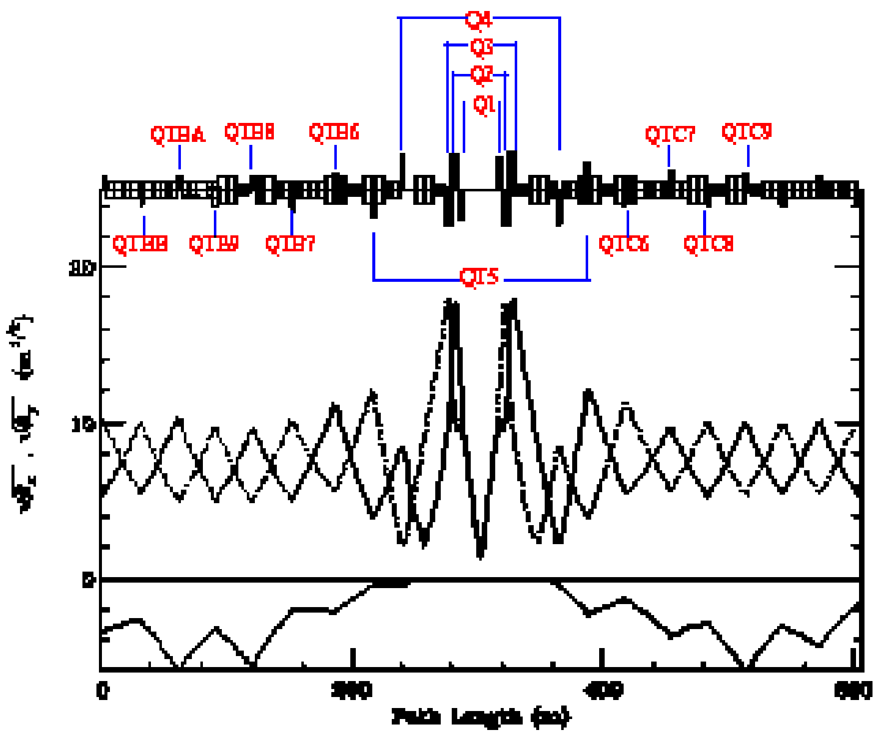
4. C0 LOW – β OPTICS DESIGN USING HIGH – FIELD MAGNETS [3]

In subsequent sections two variations of an interaction region design are presented. The first of these, which incorporates stronger dipoles, fulfills all the ideal design criteria . 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 also optically transparent to the machine, useful collisions can only occur at B0 & D0, or just C0, but not all three.

4.1. C0 IR WITH HIGH GRADIENT QUADRUPOLES AND HIGH FILD DIPOLES

4.1.1 Physical Design

Layout of the C0 region and optical functions appear on the following picture.



Both the series and independent IR quad circuits are illustrated below. The new magnets required fall into 3 gradient ranges. There are LHC-like magnets operating in the vicinity of 180 T/m. This is substantially less than the >220 T/m LHC design, but the gradients are limited in this application by the Tevatron 4.2K cryogenics. High-field 140 T/m quadrupoles, modeled like existing magnets installed at the other 2 IR's, are also used. And there are high gradient (≥ 60 T/m) correction spools which, again, are comparable to those at CDF & D0.

Quad	Location	Gradient Range (T/m)	Magnetic Length (Inch)	Inner Coil Aperture (Inch)
Q1	B49a C11a	185	93	3.0
Q2	B49b C11b	185	160	3.0
Q3	B49c C11c	185	93	3.0
Q4	B48 C12	185	66	3.0
Q5 QT5	B47 C13	140 60	55.19 25	3.0 3.0
QT6 QT7	B46 C14 B45 C15	60 140	25 23.9	3.0
QT8 QT9 QTA QTB	B44 C16 B43 C17 B42 – B41 –	60	25	3.0

A total of 30 standard Tevatron dipoles are replaced by 20 high-field dipoles. This has two substantial benefits. 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, sufficient space is created between B43 & B44 [C16 & C17] to install 4 separators, and another 4 between B46 & B47 [C13 & C14].

4.1.2. Optics and Beam Separation

There are 3 separators each side of the IP, immediately outboard of the triplets, for controlling beam position at the IP. New arc separators are necessary both for angle control at the IP and for matching the incoming to outgoing helix. Without these the 3 IR's can not operate independently.

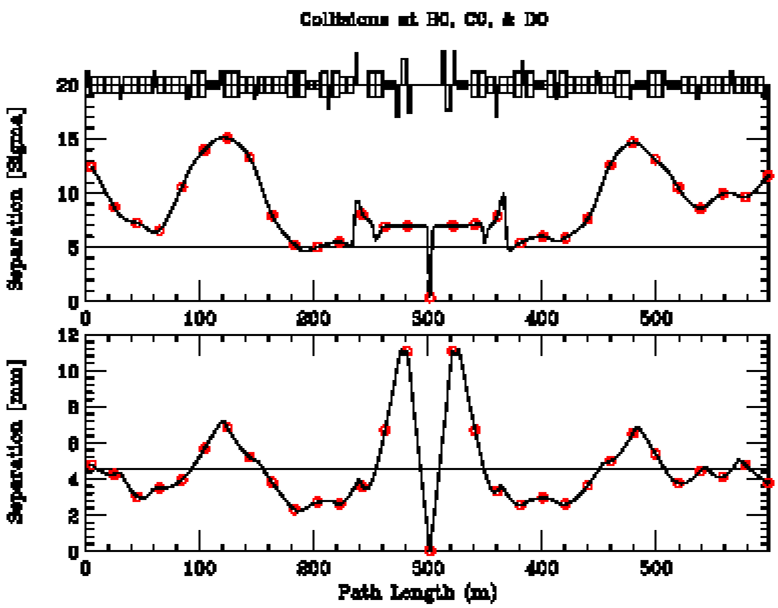
In the design discussed here, every stage of the squeeze from $\beta^* = 4.00 \rightarrow 0.50$ m at C0 can match exactly to any step in the Injection $\rightarrow \beta^* = 0.35$ m squeeze at B0 & D0 :

(1) β^* = 4.00 @ C0 – (βx^*, βy^*) = (1.61, 1.74) @ B0 & D0
(2) β^* = 4.00 @ C0 – β^* = 0.35 @ B0 & D0
(3) β^* = 0.50 @ C0 – (βx^*, βy^*) = (1.61, 1.74) @ B0 & D0
(4) β^* = 0.50 @ C0 – β^* = 0.35 @ B0 & D0

It is important that the new insertion has the optical versatility to match between all the conceivable combinations of β^* at the 3 IR's. While it is imagined that all 3 IR's will operate at low $-\beta$ simultaneously, it is unlikely that they will be squeezed in tandem. It is well known that between each step of the B0 & D0 low $-\beta$ 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.

New arc separators in this model have been situated to optimize beam separation, consistent with this one, specific, Run IIb 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 and outgoing helices across the C0 insert**. (It is also possible to have collisions at just B0 & D0, or just C0, of course.)

Shown below is the beam separation from B38 $\rightarrow$ C21. At the IP, β^* = 0.50 m and there are halfcrossing 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 acceptable but, as anticipated, is poorest each side of the IP – hovering near 5σ outboard of the 6^{th} secondary crossing points around B46 & C14.



The large crossing angles (275 μrad total half - angle) are necessary to keep the beams adequately separated through the natural minima of the Run IIb helix. However, the impact on luminosity is at least no worse here than the crossing angle effect at B0 & D0.

4.2. C0 IR WITH STANDARD TEVATRON DIPOLES

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

Having only standard Tevatron arc dipoles available for modelling has significant consequence. It is not possible to add more separators in the arcs. Collisions at C0 can not be created without disrupting the nominal Run IIb helix outside of the insertion region**, so controlled, useful collisions can only be created at B0 & D0, or just C0, but not all three simultaneously. Furthermore, without new arc separators the 2 IP collision options – B0 & C0 or D0 & C0 – are also excluded**.

The free space available for a detector shrinks markedly – by roughly 5.5 m relative to the previous design – to just 10.2 m each side of the IP.

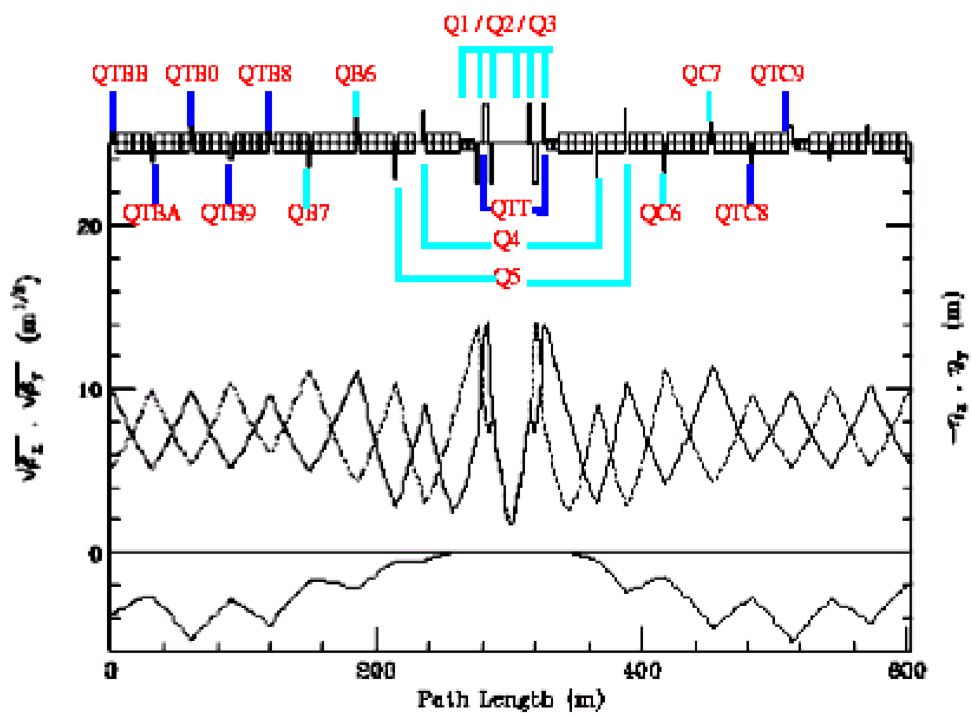
With the triplet quads closer to the IP in this version of the insert, a **β^* as small as 40 cm** can be reached before βmax becomes excessive. In all other respects the optical properties of this version of the IR are almost indistinguishable from those discussed in the preceding section.

4.3. C0 IR WITH HIGH GRADIENT QUADRUPOLES AND STANDARD TEVATRON DIPOLES (Final Design) [(4)]

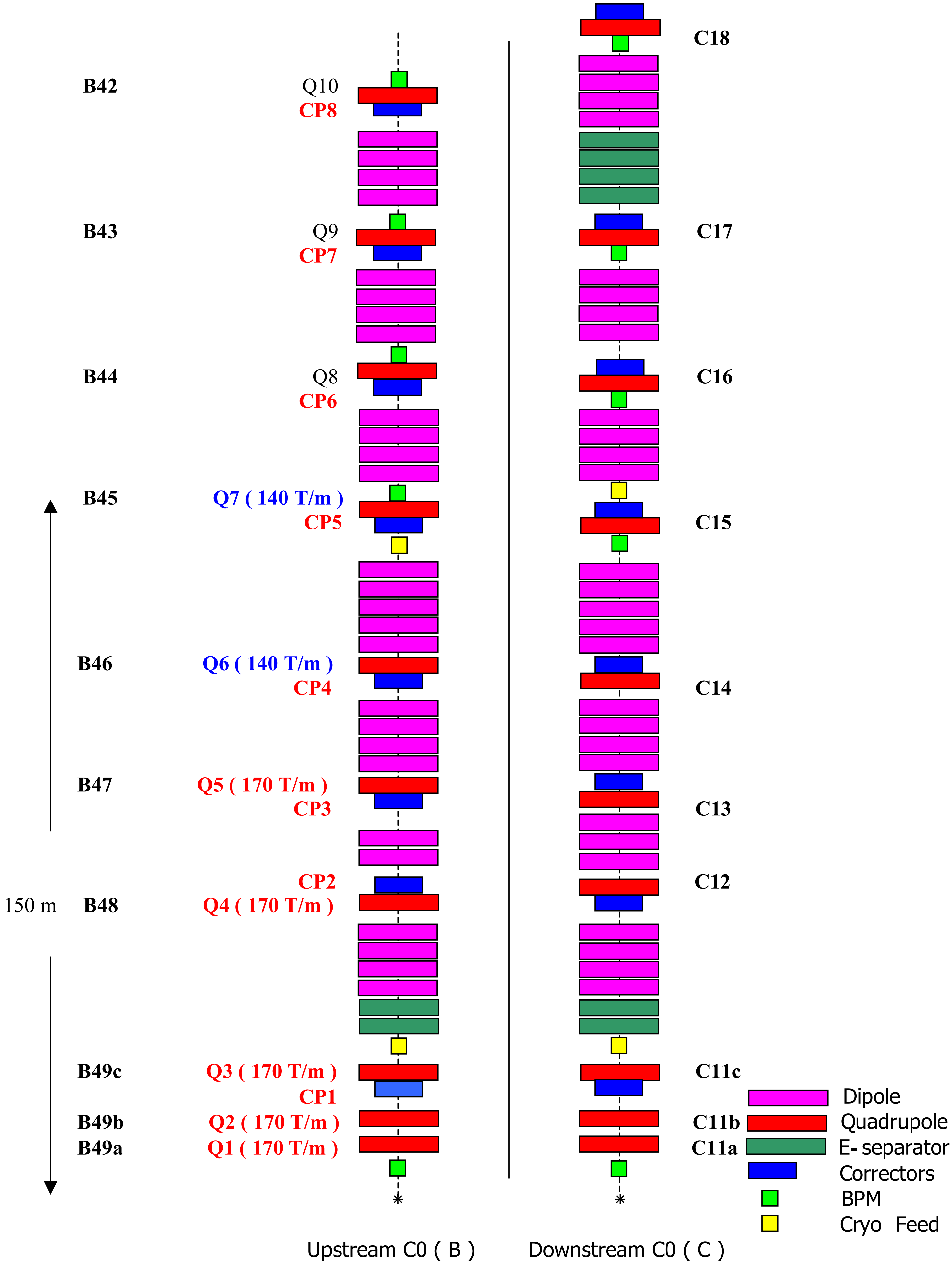
In this design with **±12 m for detector space**, a β^* of 0.5 m can be achieved using 170 T/m magnets in the final focus triplets. A total half-crossing angle of 240 μr is necessary to keep the beams separated by 5σ at the 2nd parasitic crossing. There are 2 possible Tevatron collision scenarios: B0 & D0, but not C0, and; C0, but not B0 or D0.

4.3.1. Physical Design

Layout of the C0 region and optical functions appear on the following picture.



Both the series and independent IR quad circuits are illustrated below. The magnets required fall into 3 gradient ranges. There are LHC-like magnets operating at or below 170 T/m. The high-field 140 T/m Q1 quadrupoles removed from CDF & D0 for Run II are also used. And there are strong (≤ 40 T/m) correction spools for the final optical match into the arcs.


B42
Q10
CP8
C18
B43
Q9
CP7
C17
B44
Q8
CP6
C16
B45
Q7 (140 T/m)
CP5
C15
B46
Q6 (140 T/m)
CP4
C14
B47
Q5 (170 T/m)
CP3
C13
C12
CP2
150 m
B48
Q4 (170 T/m)
B49c
Q3 (170 T/m)
CP1
C11c
B49b
Q2 (170 T/m)
C11b
B49a
Q1 (170 T/m)
C11a
Dipole
Quadrupole
E- separator
Correctors
BPM
Cryo Feed
Upstream C0 (B)
Downstream C0 (C)

Composition of the quadrupole circuits is shown below :

Quad Location	Gradient Range (T/m)	Magnetic Length (Inch)	Slot Length (Inch)	Inner Coil Aperture (Inch)	
Q1 B49a C11a	**170**	**96.5**	**138.6**	**2.75**	**New quads, powered in series**
Q2 B49b C11b	**170**	**173.5**	**215.6**	**2.75**	**New quads, powered in series**
QTT B49 C11 (in spool)	**40**	**8.0**	**17.5**	**2.75 – 3.0**	**Analogous to the TSM/TSN correctors at the B0&D0**
Q3 B49c C11c	**170**	**96.5**	**138.6**	**2.75**	**New quads, powered in series**
Q4 B48 C12	**170**	**75.0 (78)**	**117.1**	**2.75**	**New quads, powered in series**
Q5 B47 C13	**170**	**54.0**	**96.1**	**2.75**	**New quads, powered in series**
Q6 B46 C14 **Q7** B45 C15	**140**	**55.19**	**72.83**	**3.0**	**Existing B0&D0 quads, independently - powered**
QT8 B44 C16 **QT9** B43 C17 **QT0** B42 – **QTB** B40 – (in spools)	**40**	**25.0**		**2.75 – 3.0**	**Analogous to the TSM/TSN correctors at the B0&D0**

A special correction package is installed between the Q2 & Q3 magnets. This contains both vertical & horizontal BPM's, dipole correctors, plus a very short, strong (~ 40 T/m) trim quad. The dipole correctors are ideally situated for beam control at the IP; $\beta x = \beta y > 60\% \ \beta max$, and the betatron phase advance to the IP is almost exactly 90^0 in both planes. Unlike the triplets at CDF & D0, the final focus magnets here are powered in series, and independent variation of the small QT quad's gradient is sufficient to complete the match to the appropriate IP optics.

Non-standard separations appear between some of the insertion's inner arc quadrupoles. Between B48 & B47 [C12 & C13] quadrupoles space is reduced by 1 dipole, whereas between B46 & B45 [C14 & C15] separation increases by 1 dipole slot length. Extensive simulations have shown this configuration contributes markedly to the robustness of the IR's tuning range.

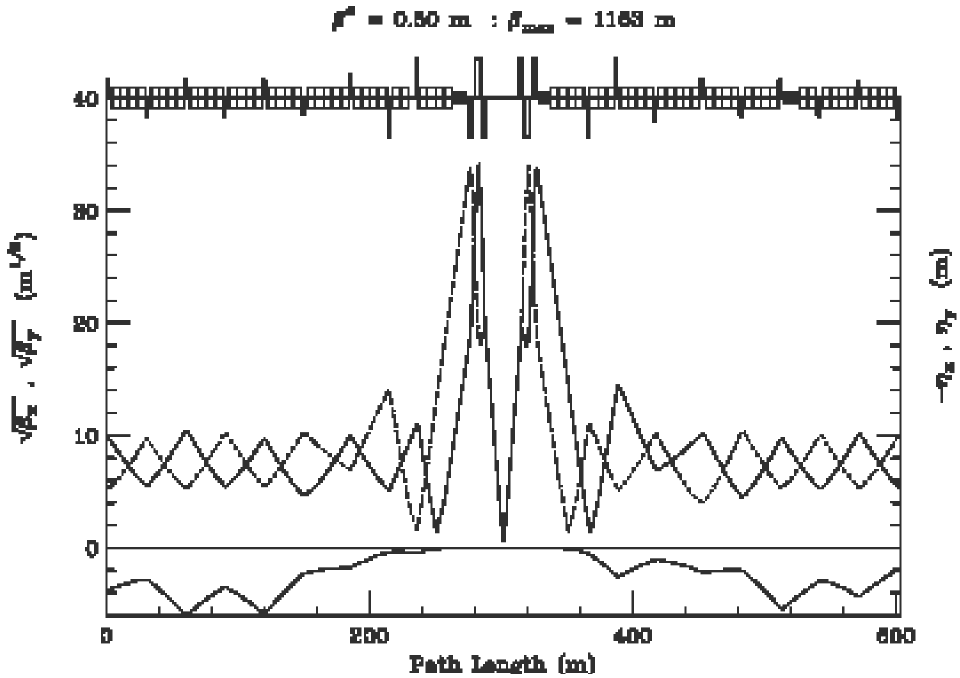
Trim quads are allocated in a lop-sided configuration, with 2 more installed in the upstream end of the insert. In B - sector it is possible to extend insert elements a good distance back into the arc before interfering with Run IIb operations. Not so in C – sector. The 4 vertical separators at C17 are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

New Correction Packages ("spools") composition appear on the following table :

Spool	**Location**		**Spool Slot Length, (inch)**	**Equipment**	
CP1	B49	C11	56.175	- **QTT** - VBPM,HBPM - VCORR, HCORR	**new trim quad** 2 BPM 2 dipole correctors
CP2 **CP3** **CP4**	B48 B47 B46	C12 C13 C14	56.175	- H(V)BPM - H(V)CORR - TS - Power Feed & Main Bus Transport	1 BPM 1 dipole corrector 1 sextupole trim
CP5	B45	C15	44.175	- VCORR - TS - Power Feed	1 dipole corrector 1 sextupole trim
CP6 **CP7** **CP8** **CP9**	B44 B43 B42 B40	C16 C17 - -	71.969	- **QT8** - **QT9** - **QT0** - **QTB** + - TS - H(V)CORR	**new trim quad** **new trim quad** **new trim quad** **new trim quad** 1 sextupole trim 1 dipole corrector
CP10	B38	-	66.1	- QT - TS - H(V)CORR - **TX**	standard trim quad 1 sextupole trim 1 dipole corrector **1 unspecified corrector**

4.3.2. Optics, Beam Separation and Collisions

Tevatron Collider experience suggests that the smallest realistic β* attainable is limited by the goodfield aperture and, therefore, βmax in the low.β triplets, rather than by any gradient limitations of the IR quads. In the current model the Q1 magnets at C0 are roughly 15' farther from the IP than the corresponding ones at B0 & D0. As a result, βmax is considerably larger at C0 for any given value of β*. With β* = 50 cm, βmax has already grown to 1163m, which is comparable to the βmax for β* = 35 cm at the other IP's.



Every stage of the squeeze from β* = 2.60 → 0.50 m at C0 can match exactly to any step in the B0 & D0 Injection → β* = 0.35 m squeeze :

(1) β*=2.60 @ C0 : (βx*, βy*)=(1.61,1.74) @ B0/D0
(2) β*=2.60 @ C0 : β* = 0.35 @ B0 & D0
(3) β*=0.50 @ C0 : (βx*, βy*)=(1.61,1.74) @ B0/D0

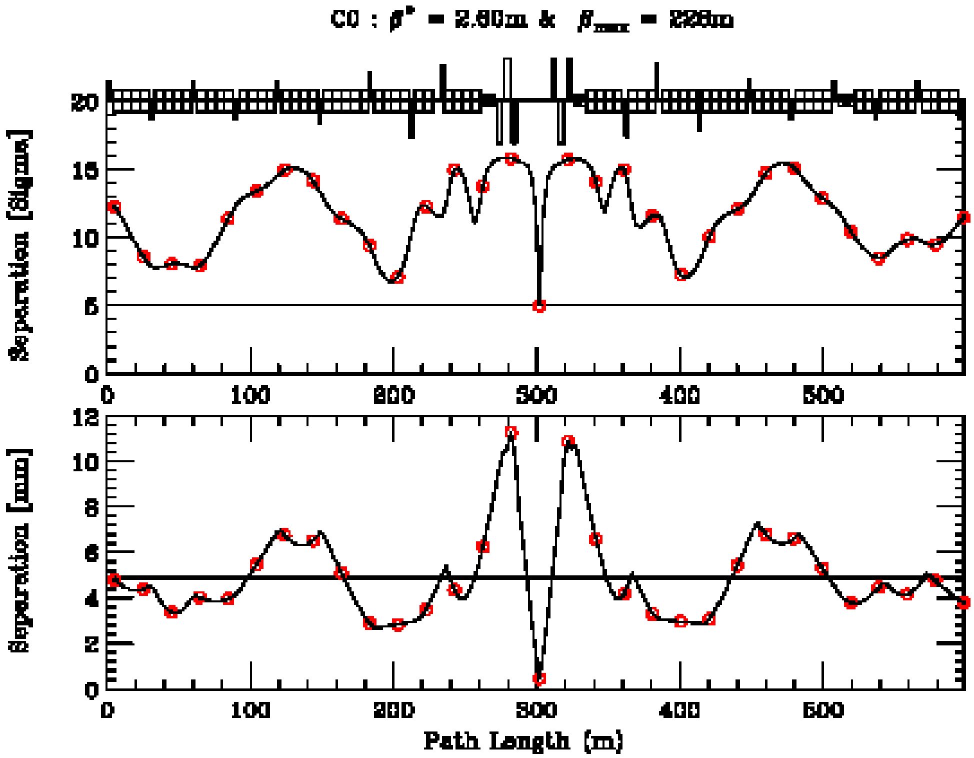
To reduce the number of interactions per crossing at the IP's, it is planned in Run IIb to reduce bunch spacing in the Tevatron from 396 → 132 nsec. With the first parasitic crossings then occurring just 19.86 m from the IP's, though, it is realized that crossing angles must be introduced to obtain separated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

Collider operation with crossing angles has at least 2 major consequences. First, luminosity is reduced due to the decreased overlap of the beams at the IP. A compromise must therefore be reached between minimizing the beam-beam tune shift from the first parasitic crossings (large θ1/2) and minimizing the luminosity reduction (small θ1/2). The second impact of crossing angles is to produce separated beams 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 βmax in the triplets is then ~1100 m. It is generally suspected (though not verified) that the minimum β* attainable is limited by the adverse impact on the beam by high-order multipoles in the low-β quadrupoles.

The favored RunIIb helix solution has the half-crossing angles at B0 & D0 of(x'*,y'*) = (+170, -170) µrad, giving 5σ of separation at the 1st crossing for β* = 35 cm, and 20π emittance (95% normalized) beams.

B0 & D0 Collisions – not C0

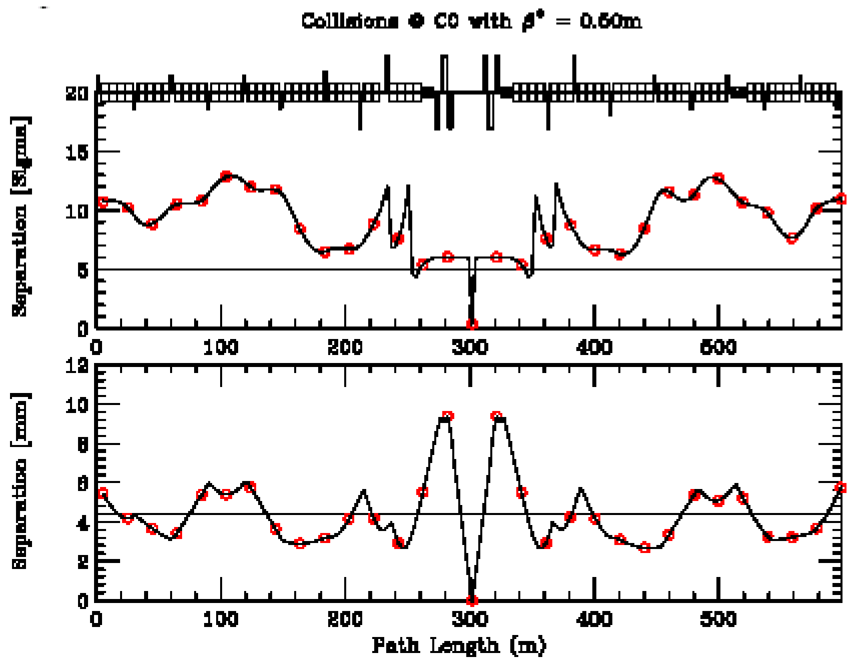
With collisions at just B0 & D0, the optics at C0 remain at the injection value of $\beta^* = 2.60$ m, and the B49 & C11 separators are turned off. The resulting matched helix from B38 → C21 is shown below. Beam separation is $\geq 5\sigma$ everywhere, but is poorest at the IP. It is this feature of the model that determines β^* at injection. For $\beta^* > 2.60$ m ($\beta_{max} < 228$ m) beam separation drops below 5σ. This trait can be used to create C0 collisions, at some level. The circles indicate the potential collision points at 7 half-bucket intervals.

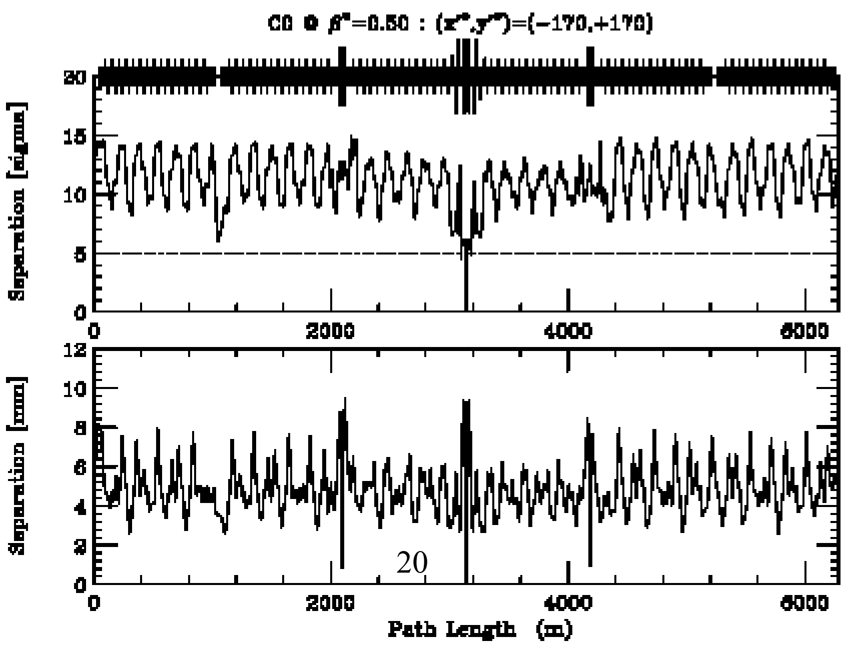


Low - β^* C0 Collisions – Not B0 or D0

For collisions at C0 the optics at B0 & D0 remain 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.

The following figures illustrate the beam separation across the insert from B38 → C21, and the separation all around the ring. With this separator solution the closest approach through the insert is at the 2nd parasitic crossing, where separation is about 5σ. Elsewhere in the ring, separation drops close to 7σ in the vicinity of A0, but otherwise the average separation is $10 \rightarrow 13\sigma$. Oscillations in the helix could be further smoothed using a larger subset of separators.

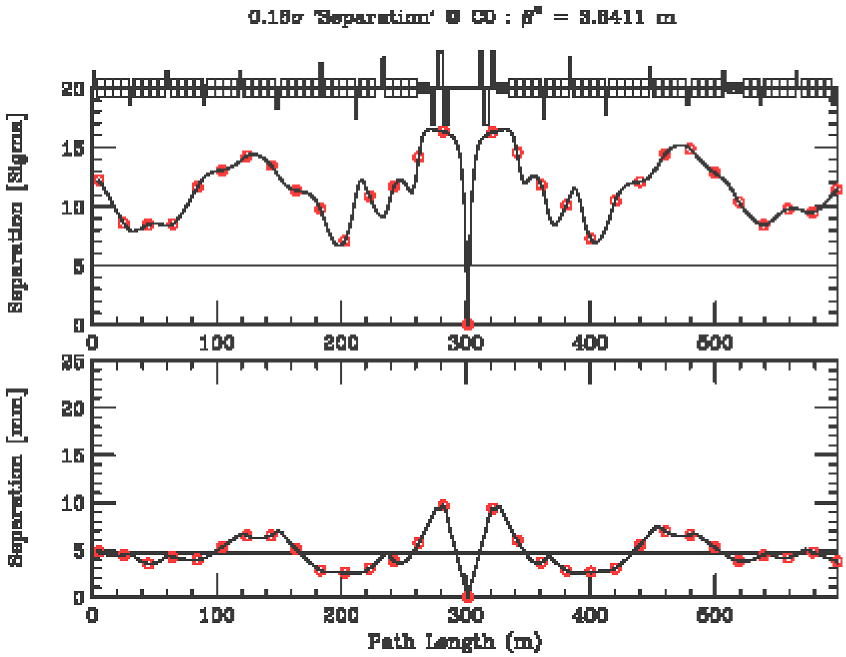




High - β^* C0 Collisions plus B0 & D0 Collisions

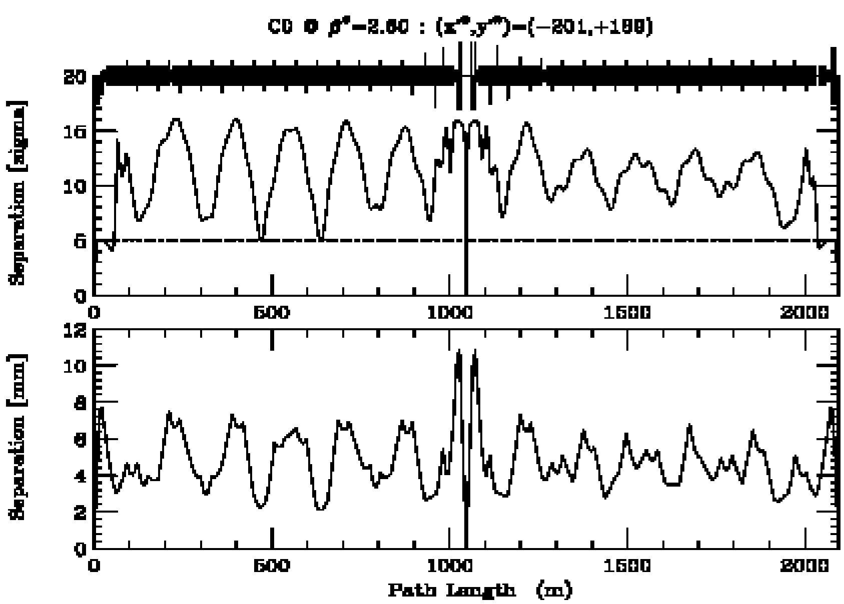
There are just 5 sets of separators in each plane between B0 & D0, including the new B49 & C11 modules. With the B0 & D0 crossing angles fixed at (x'*, y'*) = (+170, -170) µrad it is not possible to control beam position & angle at the C0 IP while simultaneously maintaining adequate beam separation through the arcs. However, if the desire for complete beam control at C0 is relinquished, collisions *can* be created, but at a reduced luminosity.

With the B49 & C11 separators off, simply raising β^* at C0 brings the beams into collision. Figure below illustrates beam separation through the C0 insertion when β. is raised from the 2.60 m injection value to 3.64 m. At the IP $(x^*, y^*) = (-6.31, +6.31)$ µm, with half-crossing angles of $(x'^*, y'^*) = (-179, +168)$ µrad. The beam centers are slightly offset at the IP; 'separated' by 17.8 µm, or a mere 0.16σ for 20π emittance beams.



This approach for creating parasitic C0 collisions would result in a C0 luminosity ≈ 1/5 the value at B0 & D0, and ≈ 1/4 the nominal C0 luminosity with a β^* of 0.50 m.

By very slightly adjusting the gradients (<<1%) of just 1 additional separator in each plane of the short B0→C0→D0 section, collisions can be created at C0 without impacting B0 & D0 collisions or noticeably altering beam separation through the arc.



At C0 β* remains at the injection value of 2.60 m and the total half-crossing angle becomes 275.9 μrad, giving ≈ 16σ separation at the 1st parasitic crossing. The beams are not offset at the IP. At C0, therefore, luminosity is ≈ ¼ that at B0 & D0, and ≈ 1/3 the nominal C0 luminosity with β* = 0.50 m.

Very modest gains can be realized by lowering β*. However, the limiting factor with this approach is the fairly alarming rate at which beam separation increases in the triplets.

4.4. SUMMARY

By adding an integer of betatron phase advance locally at C0, a low – β* insert can be designed that is optically transparent to the rest of the Tevatron, with no impact on nominal Run IIb machine operating parameters.

Two possible conceptual optical designs for a stand-alone C0 IR insert were presented. Both design variations require :

- **The final-focus triplets plus Q4 & Q5 magnets are LHC-like designs, operating at gradients up to 170 ÷180 T/m.**
- **Strong quadrupole correctors (40 ÷ 60 T/m) are needed for the final optical match into the arcs. These magnets are analogous to the TSM/TSN – series correctors at the B0 & D0 IR's.**

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 paid is a substantial reduction in free space available for the detector.

New separator modules are installed at the B49 & C11 locations. These are ideally situated for position control at the IP during C0 – only collisions. And it was also shown that these separators could be useful in creating B0, D0, *plus* C0 collisions, albeit at reduced luminosity.

Chromatic compensation is an important concern that went unaddressed in the current report. The addition of the new low-β insert has a huge impact on chromaticity, changing the machine's natural chromaticities by ($\Delta\nu_x$, $\Delta\nu_y$) = (–19.75, –19.70). If the C0 insertion is to be truly transparent to the rest of the Tevatron, the next iteration on the IR design must devise a local sextupole correction scheme for chromatic compensation.

5. C0 IR MAGNETS DESIGN AND PRODUCTION

5.1. C0 IR Equipment

The concideration of the C0 IR equipment is based on the optics design given in the preceding section 4.3. with use of LHC – like final focus quadrupoles (170 T/m field gradient), strong (40 T/m) trim quadrupolis and standard Tevatron dipoles.

The list of basic C0 IR equipment is shown in the following table.

The new low - β^* IR construction will require total readjustment of about 150 m of the Tevatron tunnel on both sides from IP. Three standard correction packages (" spools") should be replaced by new nonstandard spools even in regular Tevatron structure. The use of LHC – like quads in B47&B48, C12&C13 will be conflicting with Tevatron tunnel floor because of rather big size of cryostat.

Equipment	Number	Spare	Total	Comments
170 T/m Gradient Quads with Cryostats :				
- 173.5" Magnetic Length	2	1	**3**	LHC-like Quads Redesign, Production
- 96.5" Magnetic Length	4	2	**6**	
- 75" Magnetic Length	2	1	**3**	
- 54" Magnetic Length	2	1	**3**	
Total :	10	5	**15**	
140 T/m Gradient Quads with Cryostats :	4	2	**6**	Exist
New Spools (nonstandard) :				
- 56.175" Slot Length	8	-	**8**	Design, Production
- 71.969" Slot Length	5	-	**5**	
- 44.175" Slot Length	2	-	**2**	
Total :			**15**	
40 T/m Trim Quads :				
- 8" Magnetic Length	2	1	**3**	Design, Production
- 25" Magnetic Length	5	2	**7**	
Total :	7	3	**10**	
Correctors :				
- Dipole (V,H)	17	2	**19**	Exist
- Sextupole	13	2	**15**	
Beam Position Monitors	10	-	**10**	Exist
Electrostatic Separators :				
- Horizontal	2	-	2	Exist
- Vertical	2	-	2	
Total :	4	-	**4**	

5.1.1. High Gradient Quadrupoles

Five quadrupoles (Q1,Q2,Q3,Q4,Q5) have the gradient strength 170 T/m.These ara new quadrupoles wich will be modified from LHC design. These quadrupoles have 4 different magnetic lengths from 54" up to 174" and this fact will make design considerably expensive, because it will be necessary to fabricate at least 1 spare element for each magnetic length and increase substantialy the overall cost of the production.

Generally speaking, the LHC – like quadrupoles do not appear to be the optimum design for this application. If the old Tevatron 140 T/m technology could be resurrected there would be significant benefits. The table of comparision " old 140 T/m quadrupoles " and LHC – like quads is given below. What the 140 T/m quadrupoles lack in gradient is more than compensated for by the decrease in longitudinal overhead. If all the 170 T/m magnets were replaced by 140 T/m version :

- the detector spase would **increase** ;
- powering requirements would **decrease** by 5000 A/magnet ;
- aperture would **increase** ,
- there would be **zero** conflict with the tunnel floor.

Parameters	C0 IR Design with HG Quads	LHC Final Focus Quads	Tevatron Final Focus Quads
Nominal Gradient (T/m)	170	210	140
Bore Tube Diameter (mm)	70 - 75	60	68.6
Inner Coil Diameter (mm)	75 - 80	70	76.2
Yoke Outer Diameter (mm)	260 – 270	400	267
Magnetic Length (cm)	245, 440	550, 637	335, 589
Cryostat Outer Dimention (cm)	45 ÷ 46	~ 70 (dia.)	45.72
Field Quality (in 10^{-4} units)	< 10 at R= 25 mm	< 0.5 at R = 10 mm	< 4 at R = 25 mm
Operation Temperature (K)	4.6	1.9	4.6
Nominal Current (A)	5000 ?	10000	5000

There are a couple of questions that still need to be answered :

- Is the energy deposition in the triplet from collisions in the IR sustainable? The magnet cooling arrangement at 4.5 degrees K is very different than at LHC where superfluid helium at 1.9 degrees K is used. One issue is whether the quads can achieve their required gradients with enough of a safety factor with this cooling strategy. Radiation studies are needed
- Is the aperture of the LHC quadrupoles adequate? The Tevatron lattice have an equivalent 75mm physical aperture. The LHC quads have a 70mm aperture. However, the main issue is thought to be the dynamic aperture which may be larger for the LHC quads since the multipole content is very low. This issue has to be resolved with tracking codes with realistic multipole moments for the magnets.We need the tracking studies to get the ansver

Redesing and production LHC – like quadrupoles may be done by FNAL TD. Preliminary estimates have shown that desing, materials procurement and delivery, production and testing may require about 4 yeares.

5.1.2. Correction packages (spools)

It will be necessary to redesign and produce 15 spool bodies.There are 4 different types of spools with different composition of equipment (see p.17). The spooles have 3 different length and all these lengths are nonstandard for Tevatron. They are shorter then Tevatron standards. Two types of spooles contain new trim quadrupoles and some standard Tevatron elements. Two another types of spooles contain only standard Tevatron equipment but should be shorter because of space limitation. All spooles may be desing and produce by FNAL TD or by some other producer.

5.1.3. Trim Quadrupoles.

Trim quadrupoles in this optics design have field gradient 40 T/m and two values of magnetic lengths - 8" and 25" (see p.16). The quadrupole with 8" magnetic length may be removed from optics design by adding additional independent power converters with current ~ 500 A to the serial power supply for all final focus quadrupoles Q1,Q2 and Q3. The other trim quadrupoles have identical magnetic lengths - 25".

If the old Tevatron technology for 60 T/m trim quadrupoles (B0&D0 IR's) production could be resurrected in FNAL TD there would be significant benefits for C0 IR trim quadrupoles production. In opposite case, it will be necessary to find producer for these magnets. Some analysis was curried out to find quadrupole among the magnets used now or been in use on accelerators in different HEP institutions which may be easily modified for our needs. The main parameters of the magnets and SC cables are shown in the following tables.

	What we need	FNAL Trim Quad ☺ !	HERA Arc Quad ☺ ?	RHIC Trim Quad ☺ !	RHIC Arc Quad ☺ !	RHIC IR Quad	LHC MQXT Prototype ☺ ?	LHC MQR	LEP IR Quads I	LEP IR Quads II	UNK Arc Quad ☺ !	TESLA (Nb_3Sn) ☺ !?
Nominal Gradient (T/m)	40	60	90	29	71	48	120	160	36	60	96	60
Bore Tube Diameter (mm)	70 - 75	68.6	63	73	73	123	43 (50)	50	120	120	70	78
Inner Coil Diameter (mm)	75 - 80	76.2	75	80	80	130	56	56	180	160	80	90
Yoke Outer Diameter (mm)	190 - 200	190.5	312	267	267	350	170	266	340	340	239	242
Magnetic Length (cm)	63.5 (20.3)	60.96	187.4	75	111	144	72	340	200	200	300	52
Overall Length (cm)	130.8 (44.4)	76.2			135		80	360				63
Field Quality (in 10^{-4} units)	< 10 at R= 25	< 5 (16) at R= 25	< 5 at R = 25	~ 3 at R= 25	< 4 at R= 25	< 1 at R= 40	0.15 at R= 10		~ 20 at R= 50	~ 50 at R= 59	< 2 at R=35	< 10 at R= 30
Operation Temperature (K)	4.6	4.5	4.5	4.6	4.6	4.6	2.0	4.5	4.2	4.2	4.6	2.0
Nominal Current (A)		1000	6000	100	5000	5000	1600	4000	2000	2000	4000	100
Producer		FNAL TD	Alsthom France, KWU Germany	Everson Electric USA	Northrop Grumman USA	BNL (SMD) USA	ACICA Spain		Alsthom France	Tesla Engineeri ng, UK	IHEP Russia	

	FNAL	HERA Arc	RHIC Trim	RHIC Arc	RHIC IR	LHC MQXT Prototype	LHC MQR	LEP I	LEP II	UNK Arc	TESLA
Collar	Yes Al	Yes SSCL**	No	No	No	No Al SR	Yes SSCL	No Al SR	No Al SR	Yes SSCL	No
Yoke	Yes LCI***	Yes LCI***	Yes	Yes LCI	Yes LCI	Yes LCS	Yes LCI	No	No	Yes LCI	Yes LCI
Superconductor	NbTi	NbTi	NbTi	NbTi	NbTi	NbTi	NbTi	NbTi	NbTi	NbTi	Nb_3Sn
Number of turns per coil	13	11, 16	200	16	27	6	36				1007
Number of layers per coil	1	2	1	1	1	10	2		1	2	2
Cable width (mm)	9.93	9.5			11.6	2.3	8.8		2.95	8.5	
Mid thickness (mm)	1.75				1.16	1.35	0.84		1.5	1.46	
Keystone angle (degree)		2.05					0.91			2.18	
Copper to superconductor ratio	1.5		3	2.5	1.8	1.9	1.75		1.6	2.3	
Number of strands		23		30	36		36			19	
Strand diameter (mm)	1.09x1.7	0.84	0.51	0.33	0.65		0.48			0.85	
Filament diameter (μm)		18	10	10	6	46(15)	6		46	6	
Twist pitch of cable (mm)							66		50	62	
Critical current density (A/mm²)							2800		2700	2300	

* - SR - Shrinking Ring
** - SSCL - Stainless Steel Collar Lamination
*** - Low Carbon Iron

There is no one magnet which fits exactly to our needs. The most useful candidates for modification are the following magnets :

- arc quadrupole at HERA;
- arc and trim quadrupoles at RHIC;
- arc quadrupole designed for UNK (IHEP,Protvino);
- quadrupole designed for future TESLA linear collider.

HERA Quadrupole

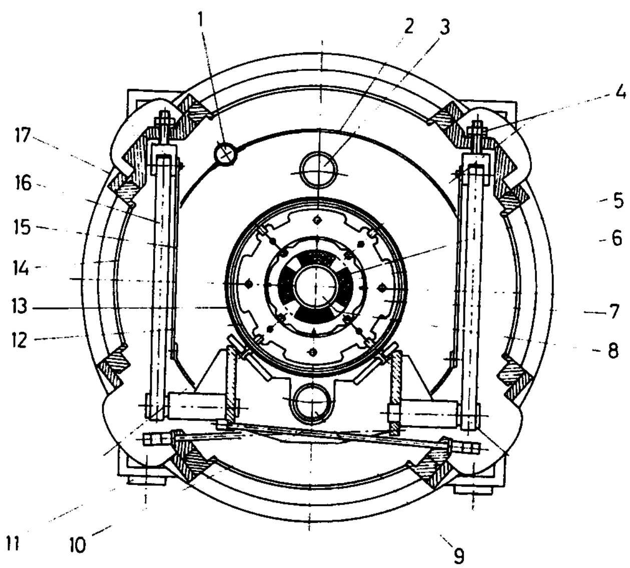
The two - layer coil with 75 mm inner coil diameter, clamped with laminated stainless steel collars is surrounded by a laminated iron yoke. A stainless steel support tube (**<u>63 mm bore tube diameter</u>**) serves to precisely align the quadrupole coil and the correction dipole. This is principal element of magnet design and so small diameter of bore tube make <u>very difficult modification</u> of this quadrupole for our needs.

Necessary modifications :

- the decrease in yoke diameter from 312 mm down to 190 - 200 mm;
- the decrease of field gradient from 90 T/m down to 40 T/m (may be done by removing one coil layer);
- the increase of bore tube diameter from 63 mm up to 70 - 75 mm.

These modifications will definitely require field and multipole coefficients calculations and optimization. Cross section of magnet is shown in the following picture :

1 – shield cooling tube
2 – radiation shield
3 – two phase helium
4 – adjastment
5 – coil
6 – collars
7 – yoke
8 – beam tube
9 – helium tube
10 – glass fiber rod
11 – external supprt
12 – cold support tube
13 – helium container
14 – vacuum container



15 – support of shield
16 – glass fiber tape
17 – reinforcing ring

RHIC Quadrupoles

There are two types of quadrupoles at RHIC which may be modified for use as a trim quads in C0 IR .The design of both magnets was made without collars.

- **arc quadrupole**

The single layer coil is spased from the cold iron by a 5 mm thick plastic (RX – 630) insulator which incorporates the pole spacers. The iron yoke are compressed and keyed. Thus the iron serves the purposes of both return yoke and mechanical constraint. The necessary prestress is applied with the iron yoke.

Necessary modifications :

- the decrease in yoke diameter from 267 mm down to 190 - 200 mm;

- the decrease of field gradient from 71 T/m down to 40 T/m ;

These modifications will require field and multipole coefficients calculations and optimization.

- **trim quadrupole**

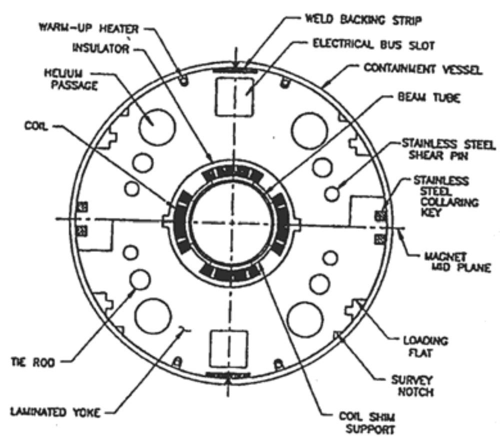
This magnet consist of racetrack layer wound coils mounted on iron poletips. The projection was added to the iron yoke so that the coil fits in a slot between this projection and the poletip. A thin non-ferrous spring is inserted between the poletip and the coil to hold it against the support projection. There is no real prestress in this design.A small tab is placed over the ends of the ends of the coils so that they can not move radially but the ends are unsupported against the Lorentz forces.

Necessary modifications :

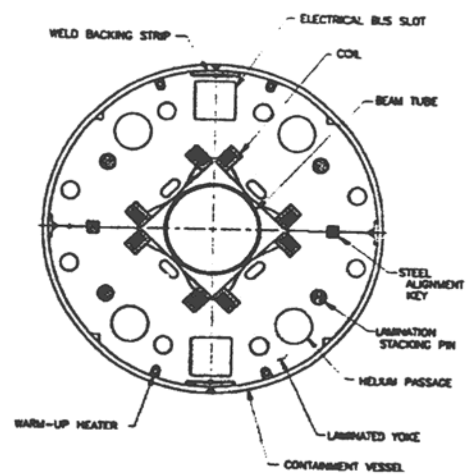
- the decrease in yoke diameter from 267 mm down to 190 - 200 mm;
- the incriase of field gradient from 29 T/m up to 40 T/m (may be done by increasing number of layers in the coil windings).

These modifications will require field and multipole coefficients calculations and optimization.

Cross sections of magnets are shown in the following picture :



Cross section of the arc quadrupole



Cross section of the trim quadrupole

UNK Quadrupole

Major element of the design are a two - layer coil with 80 mm bore and cold iron yoke.

The quadrupole coil consists of four two – layer blocks. Inner and outer layers of each block are made of one – piece SC cable without any interlayer joint. To provide the required bore field quality, the inner layer of each block has two spacers. The quadrupoles coils are collared with stainless steel collar laminations. The collars are fixed by means of pins and holes in the collars and the keys put into the grooves. The iron yoke is assembled around the collared coil. The position of the collared coil inside the yoke is fixed by four lugs. The current carrying element is a flat Rutherford – type transposed cable.

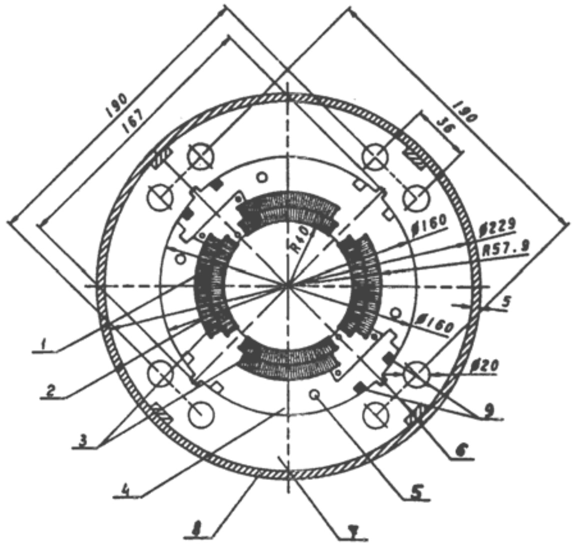
Necessary modifications :

- the decrease in yoke diameter down to 200 mm;
- the decrease of field gradient down to 40 T/m (may be done by removing of the one coil layer).

These modifications will require field and multipole coefficients calculations and optimization.

Cross section of magnet are shown in the following picture :

1 - outer layer
2 – inner layer
3 – interturn spacer
4 - collars
5 - pin
6 – rectilinear edge
7 – magnetic shield
8 – helium vessel shell
9 - key



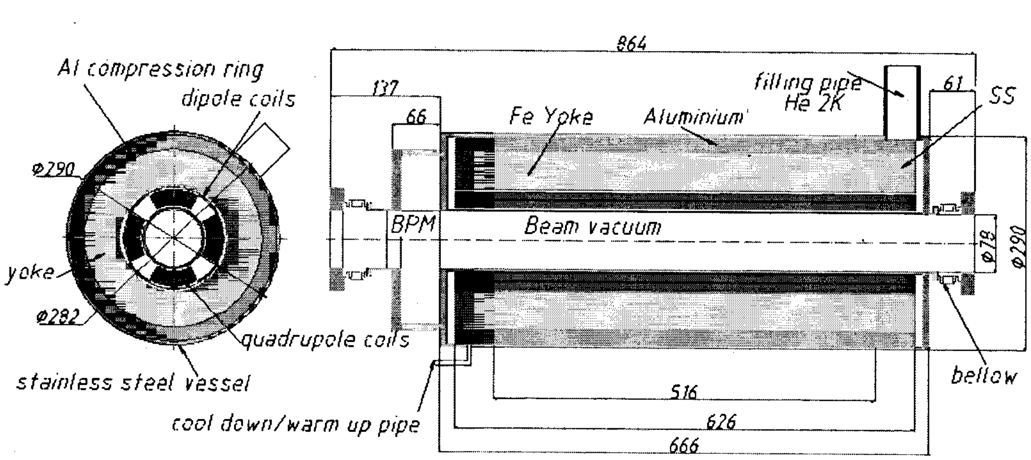
TESLA Quadrupole

Major element of the design are a two - layer coil with 78 mm bore and cold iron yoke. The superconducting coils are of the cos2θ type, wound in double layers from a flat ribbon made from electrically insulated superconducting wires (**Nb_3Sn**). The coils has a large inductance (~ 3.2 H). The coil package is surrounded by a yoke made from 5 mm thick carbon steel laminations. At the coil ends carbon steel is replaced by stainless steel. The laminations are held together by rods, and shrink cylinder made from aluminum is placed around the yoke in order to apply the necessary force on the coils.

Necessary modifications :

- the decrease in yoke diameter from 290 mm down to 200 mm;
- the decrease of field gradient from 60 T/m down to 40 T/m .

These modifications will require field and multipole coefficients calculations and optimization. Cross section of magnet are shown in the following picture :



References

1. Memorandum of Understanding, E897, BTeV R&D Project, November, 1998.
2. " Search for a CO IR Design Using Existing Magnets" J.A. Johnstone. FERMILAB-TM-2116, June 2000
3. "Conceptual Designs for IR Optics at C0" J.A. Johnstone. FERMILAB-TM-2122, August 2000
4. " C0 Low- β Optics" J.A. Johnstone. FERMILAB-TM-2139, January 2001