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C0 LOW–β OPTICS

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ABSTRACT

A low–β insertion has been designed for the BTeV experiment at C0. 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.

1. DESIGN CONSIDERATIONS

Given the advanced state of operational plans for Run IIb (132 nsec bunch spacing) a new C0 Interaction Region (IR) insertion should be capable of operating in a manner that does not impact nominal Run IIb Tevatron parameters. This implies creating an entirely localized insertion – one which is completely transparent to the rest of the machine. This constraint 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 would raise the tune by a half-integer in each plane, moving them far from the standard operating point and smack onto the 21.0 integer resonance. The nominal (fractional) tunes can most elegantly be retained by adding 2 low-β's locally in each plane, thereby boosting the machine 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 lattice functions at any point in the ring, and the phase advances across any section of the ring, are not fixed quantities, but vary through the squeeze sequence. The C0 insertion must be sufficiently flexible to track these elusive matching conditions.

- With collisions only at B0 & D0 the unit transfer matrix added by the C0 insert ensures that the incoming & outgoing helices are automatically matched into the established Run IIb values. To maintain this match with collisions at all 3 IP's, however, would require additional separators in the short B0 → C0 & C0 → D0 arcs. There is no space available for more separators, 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.

2. PHYSICAL LAYOUT

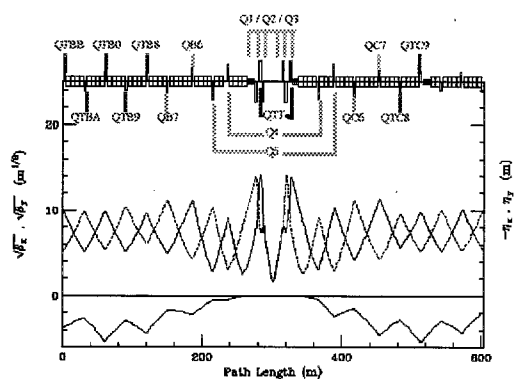

Fig.1. Power circuits of the IR quadrupoles.

Both the series & independent IR quad circuits are illustrated in Fig. 1 [1]. The magnets required fall into 3 gradient ranges. There are LHC-like magnets operating at or below 170 T/m. This is substantially less than the >220 T/m LHC design, but the gradients are limited here by the Tevatron 4.2K cryogenics. 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.

[1] The complete survey of the B38 → C21 region is attached as Appendix I.

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Composition of the quadrupole circuits is described below, with the indicated lengths being magnetic lengths.

- The triplets:

Q1	: 96.5"	170 T/m
Q2	: 173.5"	170 T/m
Q3	: 96.5"	170 T/m

A schematic layout of an IR triplet is given in Fig.2, showing the slot lengths & magnetic lengths of the elements, and spaces allocated for flanges, cryo, coil supports, whatever. 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° 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.

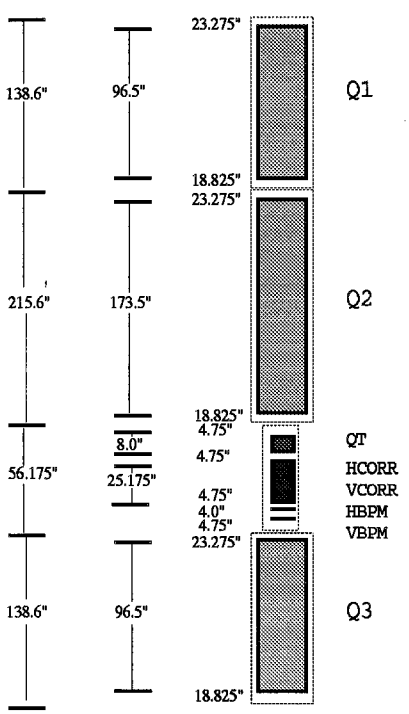


Fig.2. Details of the IR triplets.

- B48/C12 & B47/C13:

Q4	: 75"	170 T/m
Q5	: 54"	170 T/m

Apart from their magnetic lengths the Q4 & Q5 magnets are the same design as the triplet quadrupoles, having 18.825" of space at one end of the cryostat & 23.275" at the other to accommodate the necessary ancillary hardware (see Fig. 2). These quadrupoles are accompanied by new, short (56.175") spools, containing a BPM, dipole corrector, and sextupole trim. These spools also serve as the magnet power feeds & transport the main bus.

- B46 & C14:

Q6	: 55.19"	140 T/m

The regular 66" arc quads and their spools at B46 & C14 are replaced by independently-powered (existing) high–field 55" magnets plus new spools identical to those at the Q4 & Q5 locations.

- B45 & C15:

Q7	: 55.19"	140 T/m

At B45 & C15 the Tevatron 66" arc quads and their short spools are replaced by independently-powered (existing) 55" quadrupoles plus new, short (44.175") spools which provide the power feed to the magnets plus contain a dipole & sextupole corrector .

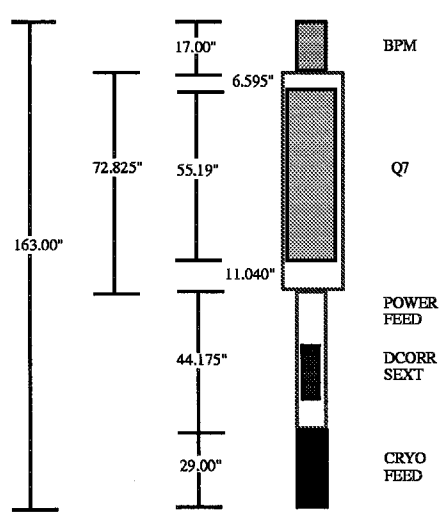


Fig.3. B45 / C15 slot layout.

- B38 → B44 & C16 → C17:

The QTBA trim quad spool (B39) is not used in this optical design, but all the remaining trim quads – QTB8 → QTBB, and QTC8 & QTC9 – are of the 25", strong, 40 T/m variety.

Non-standard separations appear between some of the insertion's inner arc quadrupoles. Between the 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.

3. OPTICS

There are 15 optical constraints the insertion satisfies. 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 IIb phase shifts, $\Delta\mu_x$ and $\Delta\mu_y$, are preserved across the insert. The final constraint imposed in the design is that $\beta_{max}(x) = \beta_{max}(y)$ in the triplets each side of the IP. While this last restriction isn't really crucial, it is the best choice, minimizing the consumption of aperture in the low-β quads.

In the injection lattice, shown in Fig.4, $\beta^* = 2.60$ m results in a βmax of 228 m in the triplets. This is slightly less than the >240 m of the B0 & D0 injection lattices and, so, is not anticipated to pose any problems for Tevatron operations. [The *maximum* β^* (*minimum* β_{max}) at injection is determined, not by gradient limitations, but by beam separation at the IP. See Sections 4.1 & 5].

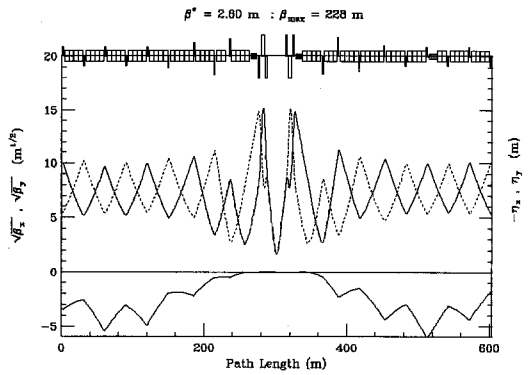


Fig.4. C0 injection optics

Tevatron Collider experience suggests that the smallest realistic β^* attainable is limited by the good-field 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 $\beta^* = 50$ cm, βmax has already grown to 1163m (Fig.5), which is comparable to the βmax for $\beta^* = 35$ cm at the other IP's.

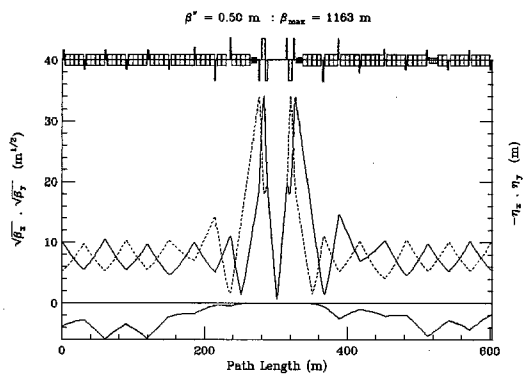


Fig.5. C0 collision optics

3.1. LOW–β^* SQUEEZES

Every stage of the squeeze from $\beta^* = 2.60 \rightarrow 0.50$ m at C0 can match exactly to any step in the B0 & D0 Injection → $\beta^* = 0.35$ m squeeze. The following pages illustrate the lattice functions & tabulate the C0 quadrupole gradients corresponding to the extremes of this operational matrix.

(1) β^*=2.60 @ C0 : (β_x^*, β_y^*)=(1.61,1.74) @ B0/D0

(2) β^*=2.60 @ C0 : β^* = 0.35 @ B0 & D0

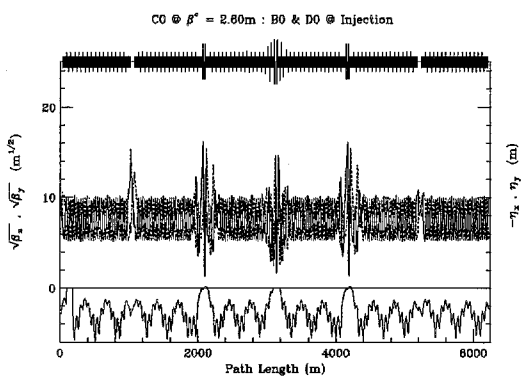
(3) β^*=0.50 @ C0 : (β_x^*, β_y^*)=(1.61,1.74) @ B0/D0

(4) β^*=0.50 @ C0 : β^* = 0.35 @ B0 & D0

(Without additional arc separators, the combination of β^* = 0.50m at C0 with β^* = 0.35m at B0 & D0 has no operational value and is included here only for the sake of completeness & academic interest).

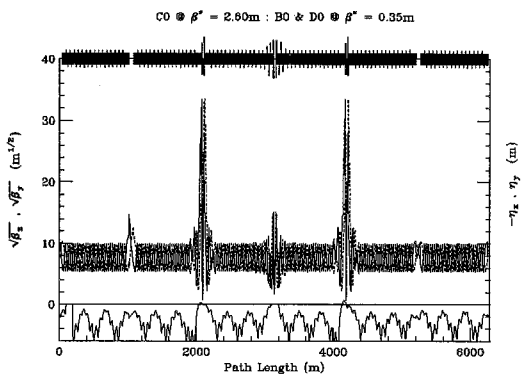
All gradients in the following tables reflect 1 TeV/c operations. Highlighted entries indicate magnets that must change polarity at some point during the transition between the various operating modes.

3.1.1. β^*=2.60 @ C0 : (βx^*, βy)=(1.6,1.7) @ B0/D0



Quad #	C0 @ β^* = 2.60 m B0 & D0 @ (β^*_x, β^*_y)=(1.61, 1.74) up	down
Q1	-167.520	167.520
Q2	167.520	-167.520
Q3	-167.520	167.520
QTT	37.696	-37.696
Q4	143.736	-143.736
Q5	-148.937	148.937
Q6	116.180	-121.899
Q7	-91.884	94.789
QT8	7.438	-24.221
QT9	10.731	-5.304
QT0	4.929	
QTA	0.0	
QTB	0.317	

3.1.2. β^*=2.60 @ C0 : β^* = 0.35 @ B0 & D0



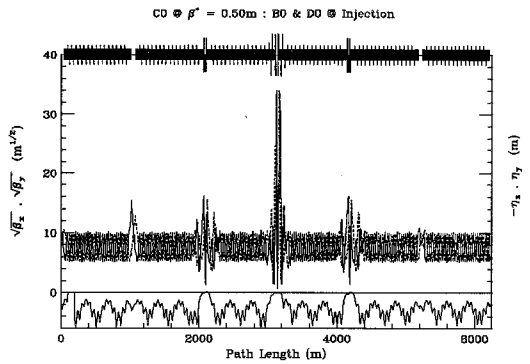
Quad #	C0 @ β^* = 2.60 m B0 & D0 @ β^* = 0.35 m up	down
Q1	-167.997	167.997
Q2	167.997	-167.997
Q3	-167.997	167.997
QTT	17.806	-17.806
Q4	140.691	-140.691
Q5	-147.714	147.714
Q6	111.184	-114.454
Q7	-90.388	90.082
QT8	11.860	-15.710
QT9	1.663	-2.752
QT0	5.168	
QTA	0.0	
QTB	1.455	

Tables 3.1.1 & 3.1.2 list the C0 quad gradients corresponding to the endpoints of an operating scenario in which β^* at C0 is fixed at 2.60 m while β^* at B0 & D0 is squeezed from the Injection values $\rightarrow$ β^* = 0.35 m for collisions. 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 following table indicates the extent to which these gradients must vary during the B0 & D0 squeeze.

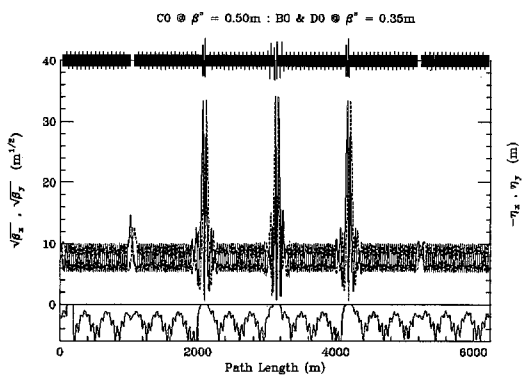
C0 Gradient Variations C0 Fixed @ $\beta^* = 2.60$ m B0 & D0 Squeeze : $(\beta^*_x, \beta^*_y)=(1.61, 1.74) \rightarrow \beta^* = 0.35$m			
	B' [max] T / m	B' [min] T / m	$\Delta \int B' \bullet ds$ T.m/m
Q1 /Q3	167.997	167.520	1.169
Q2	167.997	167.520	2.102
QTT	37.696	17.806	4.042
Q4	143.736	140.691	5.801
Q5	148.937	147.714	1.677
QB6	116.180	111.184	7.004
QC6	121.899	114.454	10.437
QB7	91.884	90.388	2.097
QC7	94.789	90.082	6.598
QTB8	11.860	7.438	2.808
QTC8	24.221	15.710	5.404
QTB9	10.731	1.663	5.758
QTC9	5.304	2.752	1.621
QTB0	5.168	4.929	0.152
QTBA	0	0	0
QTBB	1.455	0.317	0.723

3.1.3. β^*=0.50 @ C0: (βx^*, βy)=(1.6,1.7) @ B0/D0

Quad #	C0 @ $\beta^* = 0.50$ m B0 & D0 @ $(\beta^*_x, \beta^*_y)=(1.61, 1.74)$ up	down
Q1	-166.421	166.421
Q2	166.421	-166.421
Q3	-166.421	166.421
QTT	0.268	-0.268
Q4	167.764	-167.764
Q5	-166.247	16.247
Q6	95.005	-102.514
Q7	-72.795	80.691
QT8	10.020	-32.941
QT9	-0.958	19.056
QT0	-2.622	
QTA	0.0	
QTB	-6.498	



3.1.4. β^*=0.50 @ C0 : β^*=0.35 @ B0 & D0



Quad #	C0 @ $\beta^* = 0.50$ m B0 & D0 @ $\beta^* = 0.35$ m up	down
Q1	-167.257	167.257
Q2	167.257	-167.257
Q3	-167.257	167.257
QTT	6.7203	-6.7203
Q4	156.618	-156.618
Q5	-162.995	162.995
Q6	87.505	-91.247
Q7	-71.738	74.967
QT8	11.380	-22.750
QT9	-6.271	17.547
QT0	-7.268	
QTA	0.0	
QTB	0.317	