Future Helix Upgrades

J. Johnstone

- A Glimpse at the Tevatron Separators
- Areas of Projected Helix Improvement
  - – Injection
  - – Ramp & Low-β Squeeze
  - – Collisions
- Summary

Helix Generation & Manipulation

Electrostatic Separators			
Horizontal		Vertical	
Site	# of Modules	Site	# of Modules
		A17	1
A49	1	A49	2
B11	2	B11	1
B17	4		
		C17	4
C49	1	C49	2
D11	2	D11	1
D48	1		

- 22 modules total with 12 separate power supplies.
- Electrode length of 101.25" per module.
- Maximum gradients of ~40 kV/cm (100kV per plate & a 50mm gap).
  $\Rightarrow$ ~10-11 μrad kick / module at 1 TeV.

- Injection : B17 & C17 dominate in controlling orbits through the F0 Lambertson & in providing separation through the arcs.
- Collision : Separators are ganged as 3-bumps to maintain arc separation:
  B0 → C0 → D0 : B11H – B17H – C49H
  B11V – C17V – C49V
  D0 → E0 → F0 → A0 → B0 : D11H – D48H – A49H
  D11V – A17V – A49V

Improvements to the Helix

Helix improvements are being actively pursued at all stages of the Collider cycle:

- Injection : At 150 GeV beam separation is aperture limited. Expanded sub-sets of separators are continually being refined to smooth the helix, without increasing maximum beam excursions.[1]
- Acceleration Ramp & Low - β Squeeze : The full complement of separators can be employed to improve separation during the ramp and to smoothly transform from the injection to collision helix.
- Collisions : Possibilities for increasing beam-beam separation primarily at the 1st parasitic crossings each side of the IP's include additional arc separators, longer separators & the introduction of a crossing angle.

Acceleration Ramp

The rms beam extent in terms of the 95% emittance ε_{95}, and momentum spread δ_{95} is[2]:

$$\sigma(E) = \sqrt{\beta\varepsilon_{95}/6\gamma + (\eta\delta_{95}(E)/2)^2}$$

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[1] Consult the complementary AP breakout talk by Y. Alexahin.

[2] All subsequent calculations assume $\varepsilon_{95} = 20\pi$ μm (normalized), and momentum spread δ_{95} = 14.E-4 (at 150 GeV).

- The betatron component shrinks only as quickly as $E^{-0.5}$, and the synchrotron contribution decreases as $E^{-0.75}$.

- The separator kick decreases faster, as 1/E, so the injection helix solution can not scale beyond ~500 GeV, at which point the separators reach their maximum gradients[3]. From 500 GeV → flattop the beam separation steadily decreases.

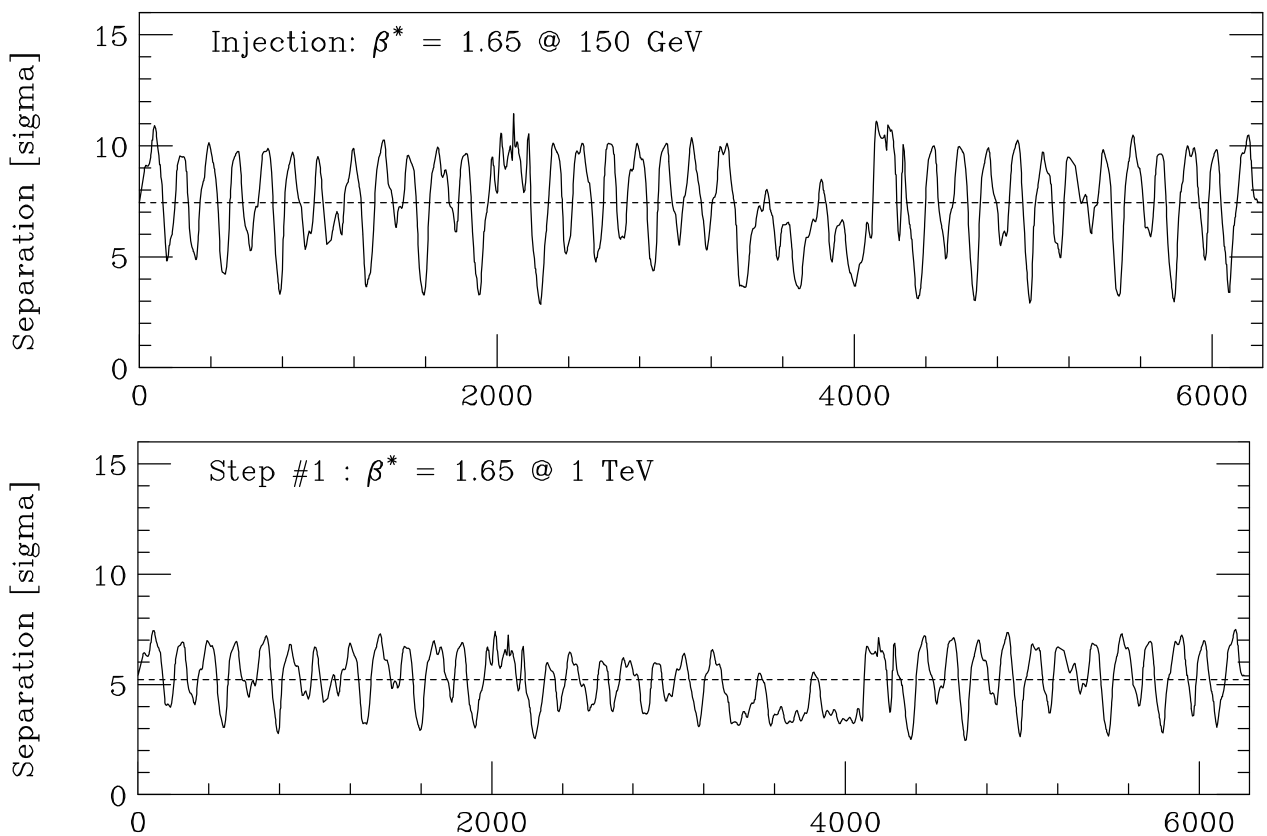

Fig.1 . The average beam separation drops by ~33% from $\langle\sigma_S\rangle = 7.5$ at 150 GeV injection to $\langle\sigma_S\rangle = 5.0$ at 1 TeV as the separators lose their punch during the second half of the ramp.

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[3] It is assumed in these calculations that 40.0 kV/cm IS the maximum attainable gradient in separator.

Low - β Squeeze

- Transition from injection to collision helices is difficult to perform smoothly. At injection the B17 (horizontal) polarity is determined by the required pbar horizontal position at the F0 Lambertson. At collision B17 must have the opposite polarity to produce the desired pbar orbit at the D0 roman pots. As the B17 voltage goes through zero there is a tendency for the beam separation to collapse horizontally.

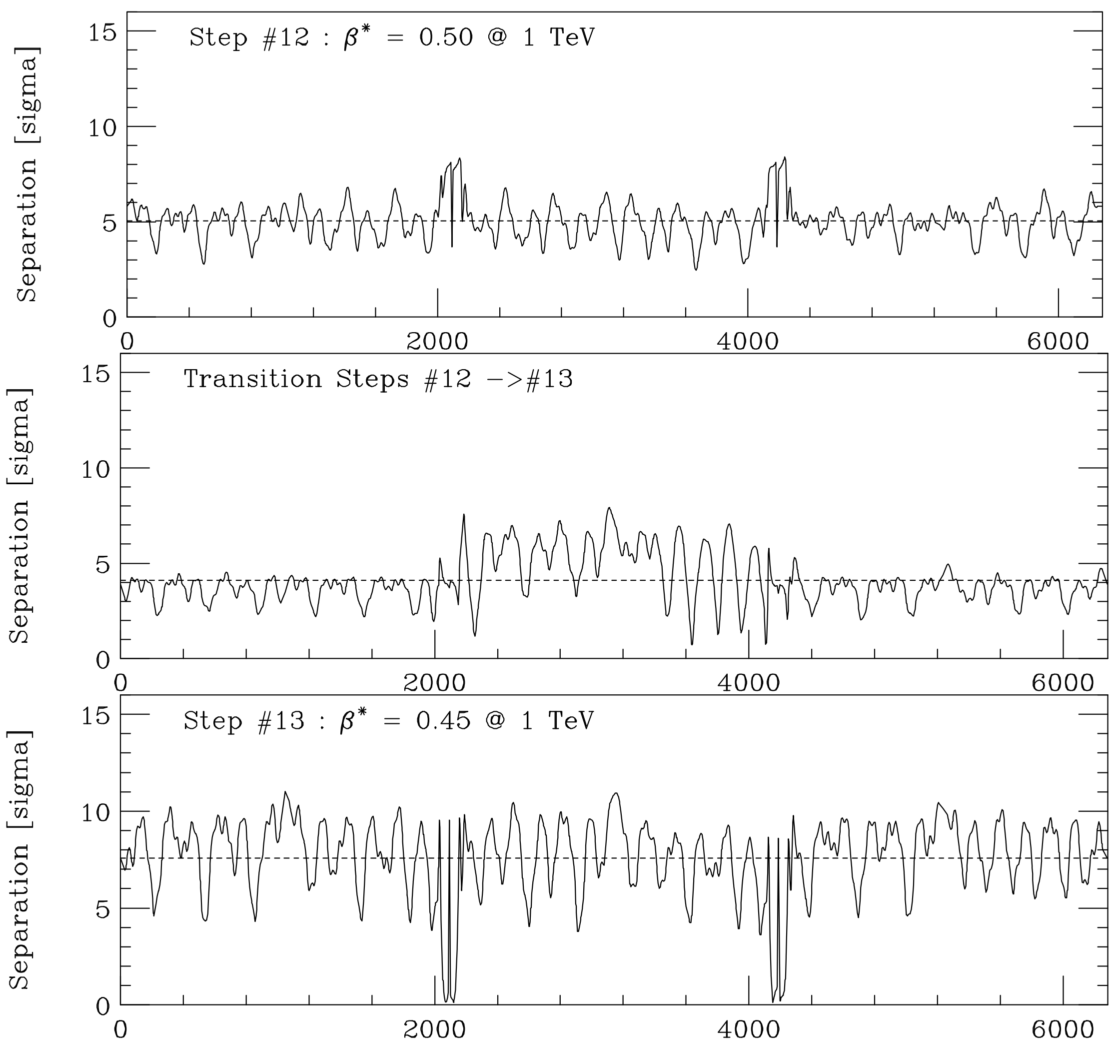

Fig. 2. Collapse of beam separation in the baseline Run II transition from injection to collision helices. Average separation is $<\sigma_S> = 3.8$, several locations have $\sigma_S \sim 1$, and at worst separation is only $\sigma_{min} = 0.68$.

- The challenge is to construct a separator solution that matches to the optimum 150 GeV helix but improves separation on the ramp. It should also transform smoothly to the collision helix.

- One preliminary candidate being explored uses all 12 separators to address both problem areas.

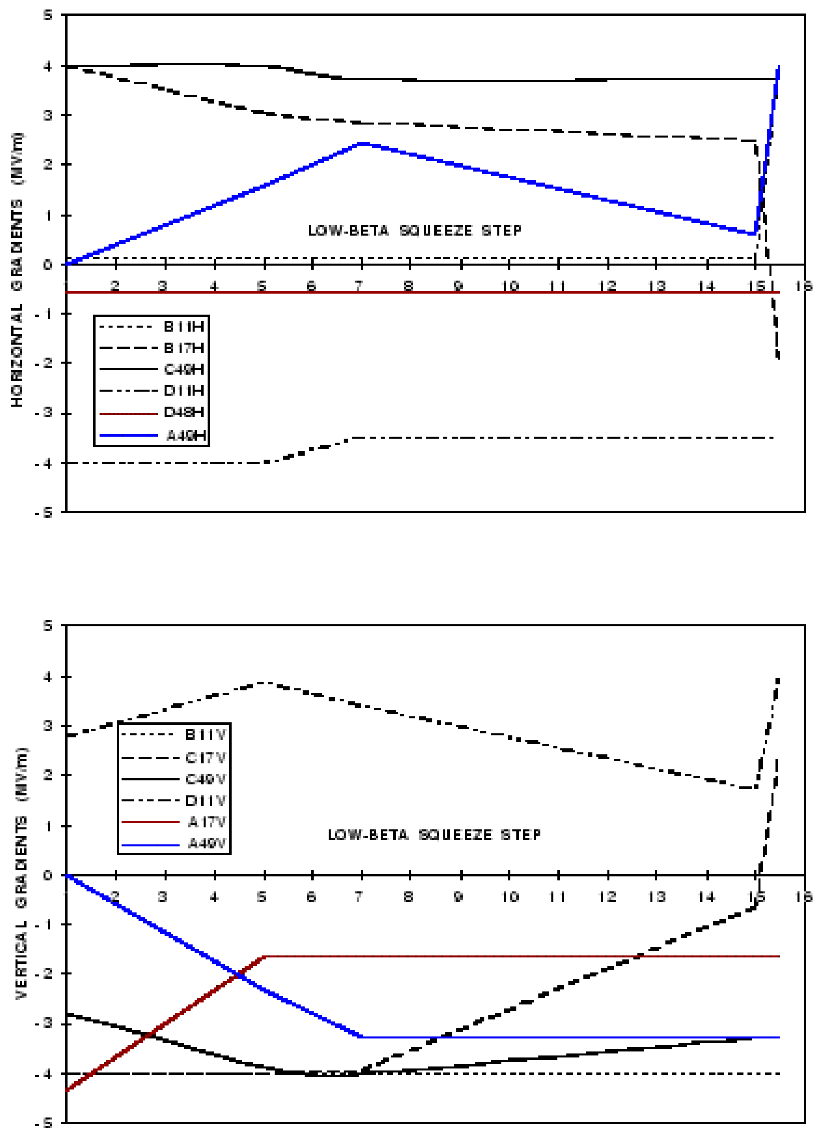

Fig. 3. Evolution of separator gradients from Step 1 @ 1 TeV through to collisions. Fitting of orbits was performed at Steps 1, 5, 7, & 15. Other values result from linear interpolation.

- At step 1, the average separation of $\langle\sigma_S\rangle = 6.6$ is an ~30% increase over the current Run II helix at flattop.

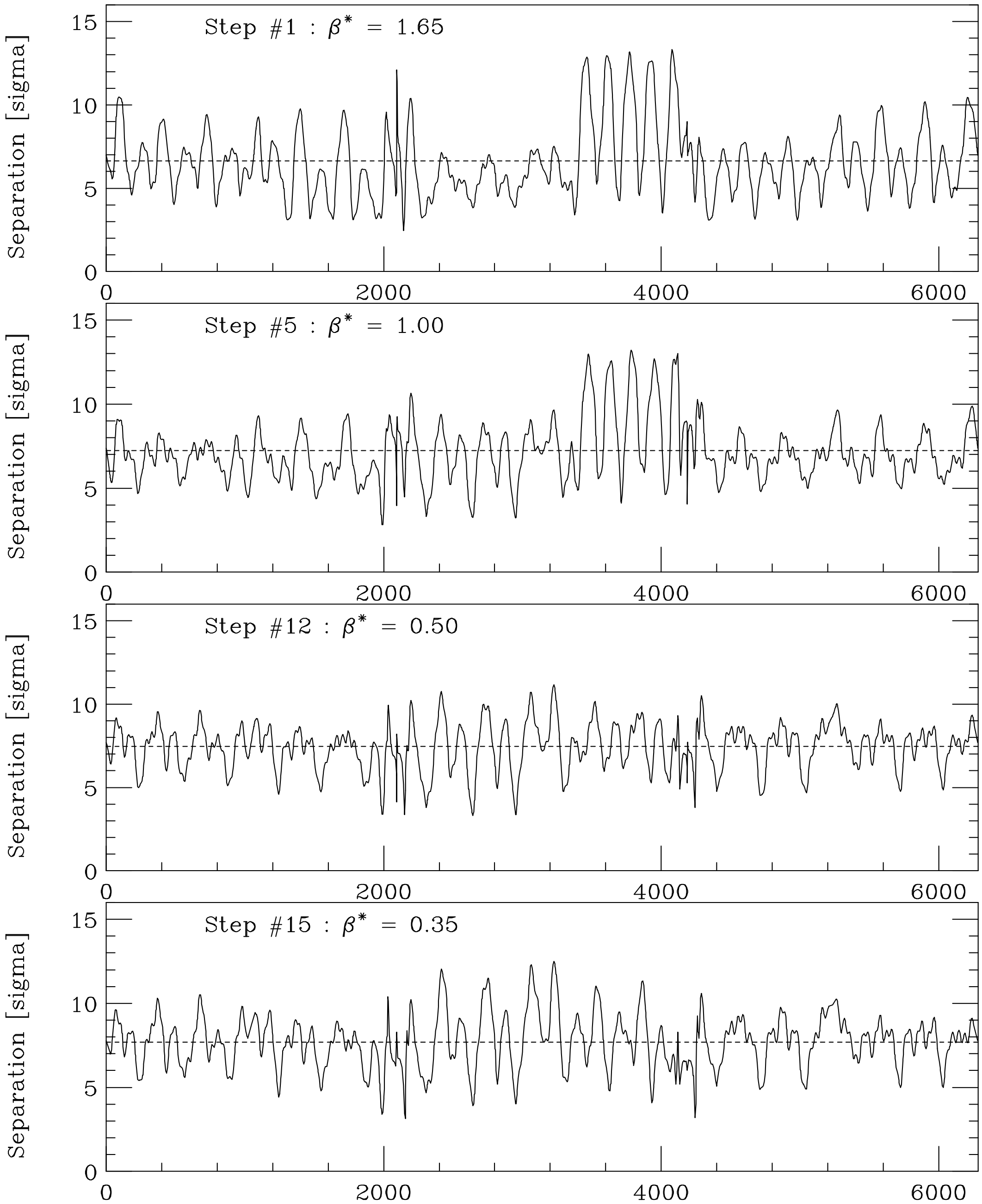

Fig. 4. Samples of the steps in the transition from injection helix (top) to collision helix at Step #15 (bottom, $\beta^* = 0.35$ but prior collisions). Average separations are, top to bottom, $\langle\sigma_S\rangle = 6.6$, 7.2, 7.4, and 7.7.

- During the separator ramp in which B17 & C17 change polarity to bring the beams into collision at β^* = 0.35m, beam separation remains well behaved throughout the arcs.

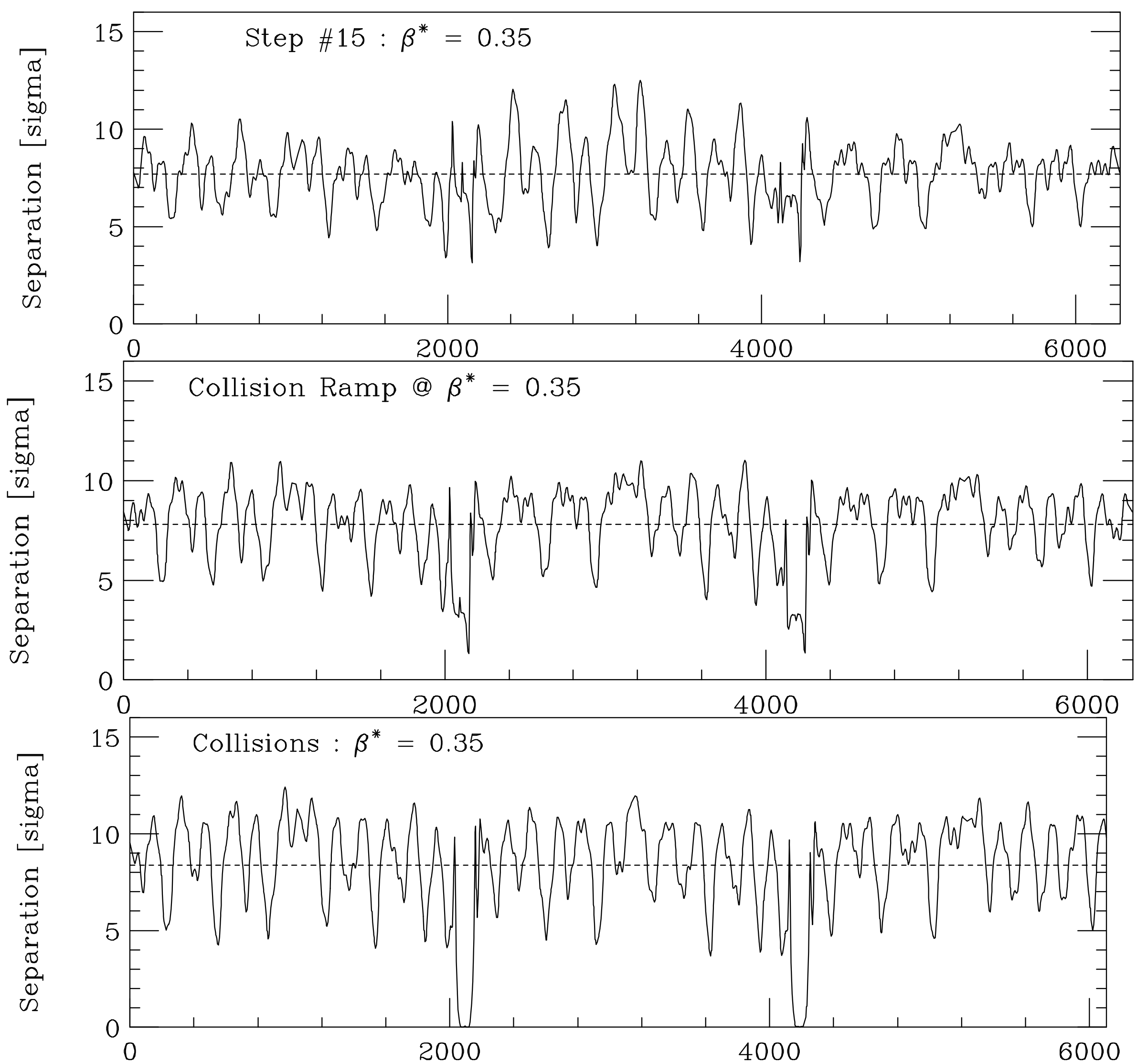

Fig. 5. Bringing the beams into collision at Step #15 (β^* = 0.35m). Separated beams (top), halfway through the final separator ramp (middle), and collisions (bottom). Average separation in the arcs steadily increases during the ramp, from $<\sigma_S>$ = 7.7 (top) up to $<\sigma_S>$ = 8.4 (bottom).

Collisions

- Beam-Beam separation is not aperture limited.
- The average ring-wide separations of $<\sigma_S> = 8.2$ and $<r_S> = 4.3$ mm are essentially equivalent to Run I. The exceptions are the first near-miss points 59m each side of the IP's. Tracking indicates these 4 points are responsible for nearly all the long range beam-beam tune shifts.

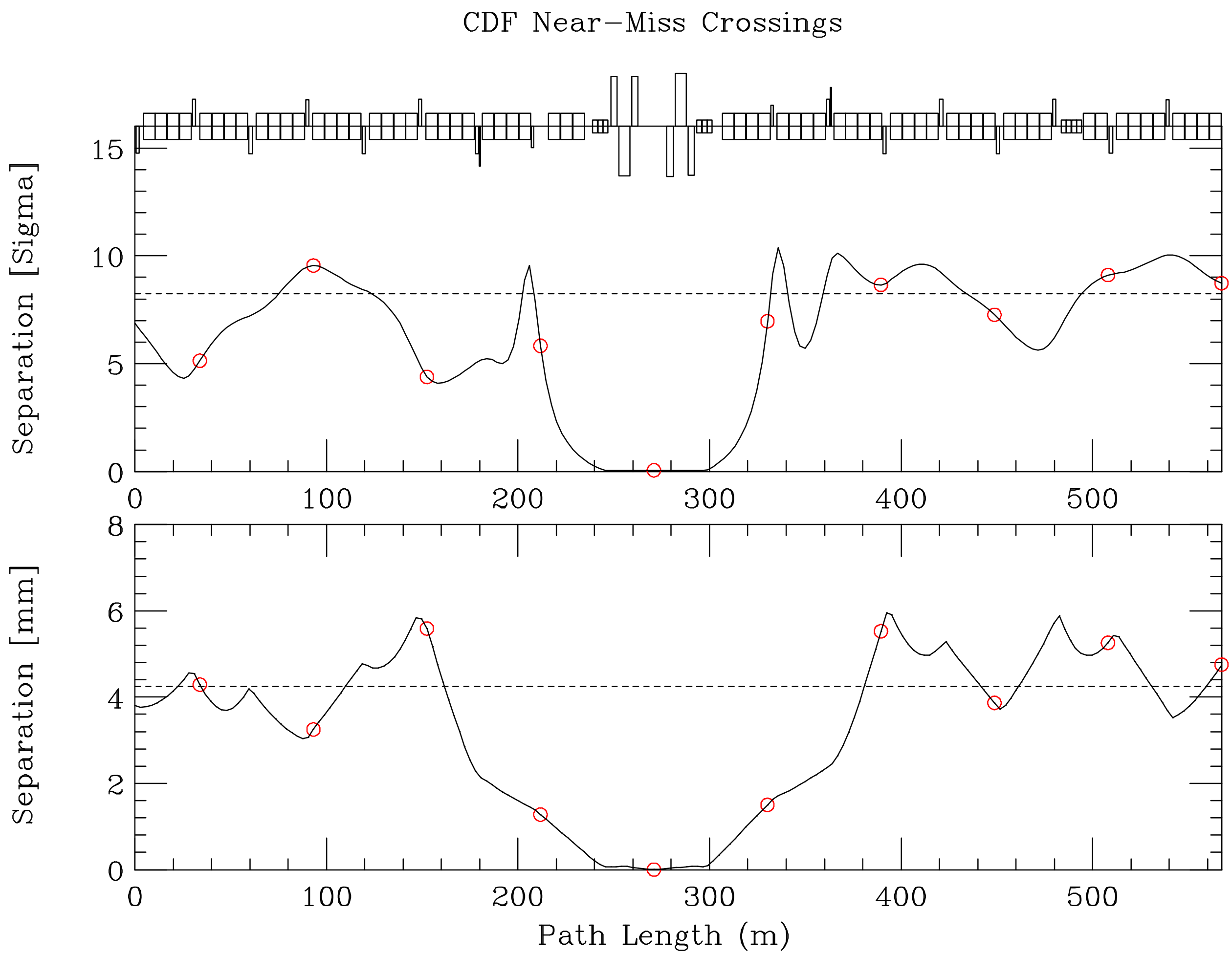

Fig. 6. Bunch separation (circles) in the vicinity of B0.

1st NM	Proton Helix							B-B Separation	
	x mm	x' mr	βx m	ηx m	y mm	y' mr	βy m	Sep'n σ	Sep'n mm
A48	0.305	-0.010	146.6	0.15	-0.558	0.017	11.63	5.92	1.27
B0 IP	0.0	0.0	0.35	0.0	0.0	0.0	0.35	0.0	0.0
B12	0.682	0.021	11.16	0.38	0.305	0.010	153.2	6.97	1.49
C48	0.273	-0.009	148.0	-0.23	0.552	-0.017	11.67	5.83	1.23
D0 IP	0.0	0.0	0.35	0.0	0.0	0.0	0.35	0.0	0.0
D12	-0.582	-0.018	11.11	0.44	0.301	0.010	151.5	5.87	1.31

Table 1. Separation of the p-pbar bunches at the first near-miss points around B0 and D0. Average separations at the 4 locations are just $<\sigma_S> = 6.15$ and $<r_S> = 1.33$ mm.

- Paths available for improved beam separation:
  – increased separator voltages;
  – crossing angles at the IP's, and;
  – additional and/or stronger separators.

- Increased Voltages: Currently separator voltages are kept to ~106 kV maximum. They are conditioned to run at 130 kV, so a modest ~10% increase should be reasonable, increasing beam separation by a uniform 10% throughout the ring.

- Crossing Angles: A crossing angle impacts predominantly just the first near-miss locations. Further away from the IP's the beam separation is quickly dominated by the arc separation bumps.

- Instantaneous luminosity can be expressed as:

$$L = \frac{f \cdot N_1 N_2}{4\pi \cdot \sigma_t^{*2}} \cdot F\left(\beta^*, \theta_{1/2}\right)$$

F contains the hour-glass effect and crossing angle information.

- Since a crossing angle shortens the luminous region, impacting luminosity, there is a strong incentive to keep the angle as small as possible. A total half-crossing angle of $\theta_{1/2} = 50\mu r$ creates an additional 22% separation at the first near-miss spots, while inflicting a fairly modest 7% reduction in luminosity:

1st NM	Proton Helix							B-B Separation	
	x mm	x' mr	βx m	ηx m	y mm	y' mr	βy m	Sep'n σ	Sep'n mm
A48	0.552	0.002	148.4	0.16	-0.629	0.008	11.61	6.77	1.67
B0 IP	0.0	-0.035	0.35	0.0	0.0	0.035	0.35	0.0	0.0
B12	0.624	0.029	11.16	0.38	0.555	-0.001	153.2	6.53	1.67
C48	0.530	0.002	147.8	-0.23	0.473	-0.025	11.66	5.19	1.42
D0 IP	0.0	-0.035	0.35	0.0	0.0	0.035	0.35	0.0	0.0
D12	-0.653	-0.009	11.12	0.44	0.548	-0.001	151.8	6.70	1.70

Table 2. Improved bunch separation at the near-miss points at B0 and D0. With $\theta_{1/2}$ = 50 μr average separations at the 4 locations are $\langle\sigma_S\rangle$ = 6.30 and $\langle r_S\rangle$ = 1.62 mm – an enhancement of 22%.

- Additional Separators: The Tevatron currently has 4 spare modules, and another 4 are under construction. As many as 6 of these will become available for installation in the arcs.

- Tevatron free space is sparse. Magnets completely fill the space between the 17 & 48 locations, the 17 & 48 straights are usually occupied, too, and the long straights are also largely spoken for.

  This does not leave a lot of flexibility in the choice of new separator locations.

Available Tevatron Straight Sections			
Site	Space (in)	# ES Modules	Comments
A0	257 349	2 3	Spaces are between each of the abort kickers & abort blocks. Suitable for horizontal separators.
A17	(309)	(2)	Requires moving some or all of the BPM's and Schottky detectors.
B48	347	3	
C0	336 420	2 3	This space will eventually be re-claimed by BTeV.
D17	275	2	
E0	397	3	

Table 3. Tevatron space that is, or can be made, available for additional separator installation without major surgery.

- One possible new configuration adds separators to the A0, B48, D17, A17 straights & relocates the D48 horizontal separator. The result is a total of 6 additional arc separators. The solution is optimized to provide the greatest gains in separation in the long arcs.
- The additional modules increase separation at the 70 crossing points by 20% on average. The impact on the 4 nearest-miss points is only ~half this amount because of their close proximity to the IP's.

- Ideally, additional separators would be used to smooth the arc helix – improving small separations while decreasing the maximum beam excursions. This is difficult to achieve satisfactorily in practice due to the paucity of available sites.

Separator Gradients (kV/cm)					
Horizontal			Vertical		
A49	1	40.000	A49	2	-40.000
B11	2	40.000	B11	1	40.000
B17	4	-19.042			
			B48	2	20.919
			C17	4	-27.906
C49	1	37.070	C49	2	40.000
D11	2	-40.000	D11	1	40.000
			D17	2	-34.381
A0U	1	5.897			
A17	1	-20.857	A17	1	-30.912

Table 4. Improved separator configuration using 6 additional arc modules.

- Longer IR Separators: The Run II IR optics are different than those of Run I, and the Q1 quadrupoles (located between the outboard end of the A4, B1, C4, D1 separators & the arc dipoles) are unnecessary.
- Removing the Q1 magnets frees ~73" of space. Replacing the accompanying P spool with a shorter H spool yields an additional ~6". The 3 separator modules each side of the IP's could be extended by 24" beyond their existing ~101 length, with a corresponding increase in kick per given voltage.
- New separators need to be installed at both B0 & D0 to be useful.

LONGER SEPARATORS AT D0 WOULD REQUIRE THE EXPERIMENT TO RELINQUISH IT'S ROMAN POTS WHICH ALREADY OCCUPY THE OLD Q1 LOCATIONS

Cumulative Improvements

	Near-Misses Gain (%)	Ring-Wide Gain (%)
10% Separator Voltage Increase	10.0	10.0
50 μrad Half-Crossing Angle	21.5	0.5
Additional Arc Modules	11.4	19.9
Increased IR Separator Lengths	19.0	19.0
Total Separation Gain	**77.2 %**	**57.7 %**

Table 5. Beam separation improvements from modest helix upgrades.

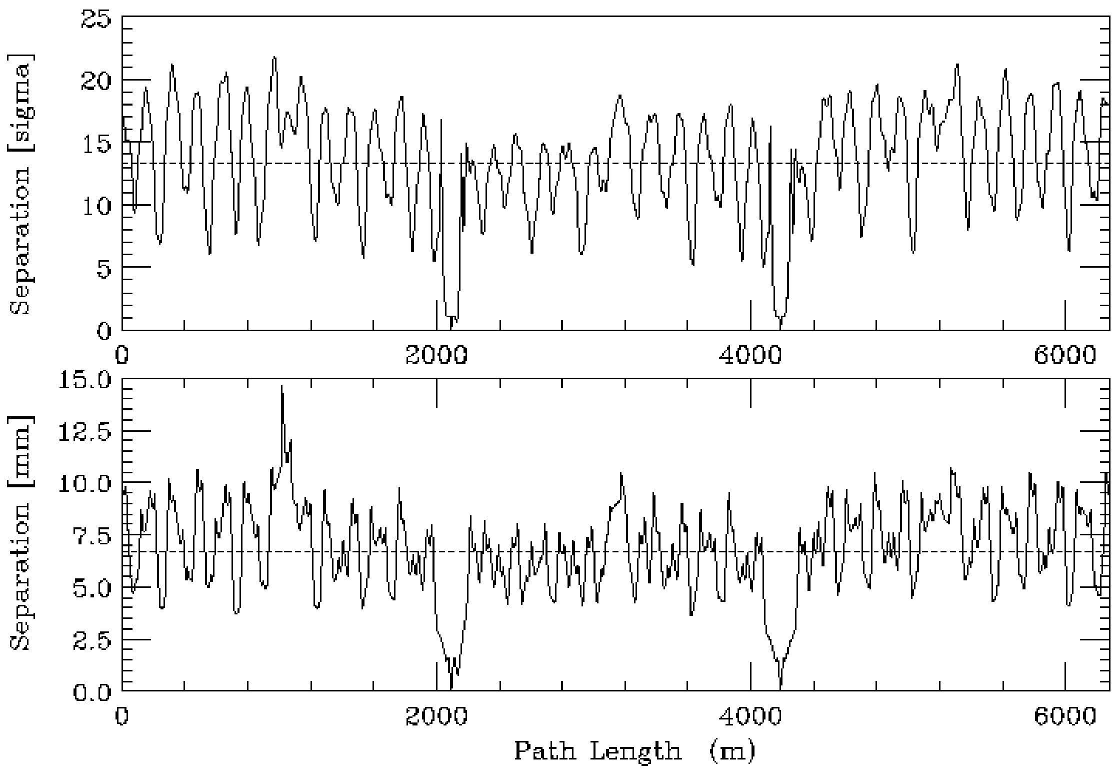

Fig. 7. Orbit separation during collisions with separator configuration upgrades. Average ring-wide values are increased to $<\sigma_S> = 13.33$ and $<r_S> = 6.66$ mm. (*c.f.* Figure 4).

Summary

- Powering changes in the use of the existing Tevatron separators are leading to improved beam separation from injection through the low-β squeeze.
  At injection these refinements imply a smoother helix that does not eat up additional aperture, while on the ramp and squeeze there is increased separation to reduce beam-beam effects.
- At collision, modifications to the separator configuration include operational changes which can be implemented & tested essentially immediately, the addition of new separators in the arcs, and the construction of longer IR separators over a period of a couple of years.

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