132 NSEC BUNCH SPACING IN THE TEVATRON PROTON-ANTIPROTON COLLIDER

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I. INTRODUCTION

The Tevatron proton-antiproton collider currently operates at a center-of-mass energy of 1.8 TeV, delivering a luminosity greater than $1.5 \times 10^{31} \text{cm}^{-2}\text{sec}^{-1}$. This is achieved with six proton and six antiproton bunches colliding at two locations, B0 (CDF) and D0. An electrostatic separator system causes the two beams to pass with approximately 5σ separation at the ten other possible collision points around the accelerator. In this configuration each experimental detector, with a sensitivity to about 45 mb of the total $p\text{-}\bar{p}$ cross section, witnesses 2.4 interactions per crossing.

The Fermilab Main Injector is projected to support a Tevatron luminosity in excess of $5 \times 10^{31} \text{cm}^{-2}\text{sec}^{-1}$. Hardware currently under construction will allow operation with 36 proton and 36 antiproton bunches when the Main Injector comes on-line in late 1998. A representative set of collider parameters for the first Main Injector-based collider run (Run II) is given in Table I. Improvements to the antiproton accumulation rate, to low beta systems, and/or reduction of the rms bunch lengths to 15 cm or less hold the promise of raising collider luminosity above 10×10^{31} $\text{cm}^{-2}\text{sec}^{-1}$. Continued operation with 36 bunches would, however, result in 3-4 interactions per crossing at this higher luminosity. Reducing the number of interactions per crossing below 1 will require circulating more bunches as indicated in the right-most column of the table.

This paper summarizes a preliminary conceptual design for a Tevatron collider configuration in which bunches are spaced at 132 nsec. Increasing the number of bunches is not expected to raise the luminosity--the sole motivation is to reduce the number of interactions per crossing by about a factor of three. Multibunch schemes with 72, 108, 96, and 120 proton and antiproton bunches have been studied.

Implementation of any of these multi-bunch scenarios will require new hardware. The introduction of a crossing angle will result in reduced luminosity and the bunch length must be shortened considerably compared to present operations to minimize this impact. This means that a new rf system, operating at 159 MHz, will be required. Other new hardware probably includes 1)upgraded low beta optics; 2)upgraded abort kicker; 3) new coalescing cavities operating at three times the frequency (7.5 MHz) of those currently operational in the Main Ring and also planned for the Main Injector, and; 4) a new 7.5 MHz rf system in the Antiproton Accumulator.

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II. DESIGN AND PERFORMANCE ISSUES

The proton-antiproton luminosity in the Tevatron is given by the expression:

$$L = \frac{3\gamma f N_p (B N_{\bar{p}})}{\beta^* (\varepsilon_{Np} + \varepsilon_{N\bar{p}})} H\left(\frac{\beta^*}{\sigma_l}\right)\left(1 + \frac{2\alpha^2\sigma_l^2}{\sigma_p^2 + \sigma_{\bar{p}}^2}\right)^{-1/2} \qquad (1)$$

where γ is the relativistic factor, f is the revolution frequency, B is the number of bunches in each beam, N_p ($N_{\bar{p}}$) is the number of protons (antiprotons) in a bunch, ε_p ($\varepsilon_{\bar{p}}$) is the 95% normalized transverse beam emittance, σ_l is the rms bunch length, β* is the beta function at the interaction point, σ_p ($\sigma_{\bar{p}}$) is the rms transverse beam size at the interaction point, and α is the crossing half-angle. The form factor $H(\beta^*/\sigma_l)$ approaches 1 asymptotically as $\beta^*/\sigma_l \rightarrow 0$, clearly indicating that bunch length should be kept as small as is reasonable compared to β* to minimize the luminosity reduction. A 14 cm bunch length is chosen to minimize the impact of the 190 μrad crossing angle.

A major limiting factor in the Tevatron proton-antiproton collider is the beam-beam tune shift. In the present collider mode, with six proton and antiproton bunches, there are twelve potential collision points around the ring. Through the use of electrostatic separators the beams are made to collide with zero crossing angle at the interaction points, but separated by 5σ (center to center) at the other ten (parasitic) crossings. This basic configuration must be continued as the number of number of bunches increases to 36 and beyond.

The separator nearest to the interaction region is beyond the position of the first parasitic crossing for 132 nsec spacing. It does not appear to be possible to avoid these first parasitic collisions unless a crossing angle is introduced to separate the beams within the low β quadrupoles. An interesting alternative technique for avoiding a crossing angle through the use of rf resonant magnets has been envisioned [1], but, at least with existing technology, a substantial crossing angle seems to be inescapable.

The existence of a crossing angle dictates that the orbits be separated within the low β quadrupoles. The necessary aperture in the low β quadrupoles and, conceivably, changes to the low β optics which minimize this separation need to be considered. Also, although long range beam-beam effects are not significant in the current operating mode, once the number of bunches approach 100 such effects can no longer be ignored.

Table I: Collider Parameters for Run II and options for reduced bunch length or bunch spacing

	Collider Run II: 36 bunches 53 MHz 396 nsec	Option I: 36 bunches 159 MHz 396 nsec new low β	Option II: 108 bunches 159 MHz 132 nsec new low β	
Beam Energy	1000	1000	1000	GeV
Circumference	6283.0	6283.0	6283.0	meters
Protons/bunch	$3.3x10^{11}$	$3.3x10^{11}$	$2.7x10^{11}$	
Antiprotons/bunch	$3.6x10^{10}$	$3.6x10^{10}$	$1.2x10^{10}$	
Bunches	36	36	108	
Total Antiprotons	$1.3x10^{12}$	$1.3x10^{12}$	$1.3x10^{12}$	
Proton emittance (95%, norm)	30π	30π	25π	mm-mr
Antiproton emittance (95%, norm)	20π	20π	20π	mm-mr
β^*	0.35	0.25	0.25	meters
Longitudinal Emittance (95%)	3	3	2	eV-sec
rf Frequency	53	159	159	MHz
rf Voltage	1	15	15	MV
Bunch length (rms)	0.43	0.17	0.14	meters
Bunch Length Form Factor	0.70	0.86	0.89	
Crossing Half-angle	0	0	0.19	mr
Crossing Angle Form Factor	1.00	1.00	0.77	
Typical Luminosity	$8.3x10^{31}$	$14.2x10^{31}$	$10.4x10^{31}$	$cm^{-2}s^{-1}$
Integrated Luminosity	16.72	28.67	20.99	pb^{-1}/wk
Bunch Spacing	396	396	132	nsec
Interactions/crossing (@45 mb)	2.17	3.73	0.91	
Antiproton tune shift (2 crossings)	0.016	0.016	0.016	
Proton tune shift (2 crossings)	0.003	0.003	0.001	
Average helix separation (d/σ)	5	5	6.5	
Long Range tune spread (antiproton)	0.008	0.008	0.008	

The length of the luminous region is modified appreciably with the introduction of a crossing angle and shorter bunches. Figure 1 shows the distribution dL/dz that will be seen by an experimental detector for various crossing angles and a 14 cm bunch length. The result is a luminous region of ≈8cm length (rms)--a factor of four shorter than those currently experienced and a desirable experimental feature.

A. Multibunch Loading

The first collider run of the Main Injector era will operate with 36 bunches of protons and antiprotons. A workable configuration calls for three batches of protons and antiprotons containing twelve bunches each, with the batches spaced symmetrically around the ring. For 132 nsec it would be most natural to continue with a threefold symmetric scheme. There are two possible three-fold symmetric loading schemes, resulting in either 72 or 108 bunches colliding. In 72x72 operation two batches of twelve bunches each would be spaced 396 nsec apart, followed by a 3.7 μsec abort gap. This sequence would be repeated twice more around the ring. The abort gap of 3.7 μsec is larger than that for 36x36 operation, and the abort at A0 could be used. The 108x108 scenario calls for three batches of twelve bunches spaced by 396 nsec followed by a gap of 1.8 μsec.

Single gap configurations are also possible. However, these have the disadvantage of not allowing utilization of existing aborts, and of providing unequal luminosity at B0 and D0.

B. RF System

A 14 cm bunch length is required to minimize luminosity loss due to the 190 μrad crossing angle selected for this study. The total voltage required to produce a 14 cm bunch length, with a beam longitudinal emittance of 2 eV-sec, is 15 MV at 159 MHz or 11 MV at 212 MHz. The 159 MHz system is evaluated here. A total of 12 proton and 12 antiproton cavities would be required. Power requirements are estimated at 935 kW for each system, based on providing 1.25 MV per cavity.

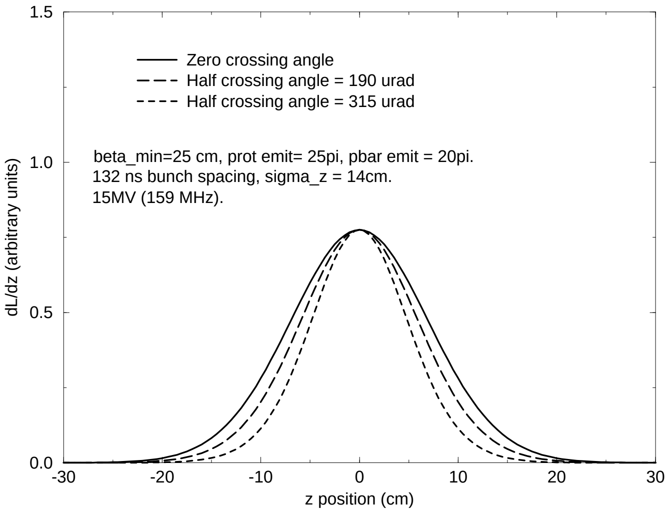

Figure 1: dL/dz for three crossing angles and the Tevatron parameters contained in the rightmost column of Table 1.

C. Interaction Region Optics

Six pairs of high gradient (140 T/m) low β quadrupoles are powered in each Tevatron interaction region. In the present mode of operation dispersion at the IP is zero, but with a non-zero slope, resulting in dispersion reaching its maximum value within the low β triplet - precisely where the beam already reaches its ring-wide maximum from β_{max} (≥1 km). An alternative match to the lattice which gives both η and η′≡0 throughout the straight section has been found [2] that uses the current IR physical configuration of magnets and gradients compatible with the existing quadrupoles. Extending to β*=0.25m requires a maximum gradient in one of the low β quadrupoles of ≈185 T/m. This lies beyond the capabilities of the present system and would require an upgrade to quadrupoles similar to those proposed for the CERN LHC [3].

The dispersion-free solution significantly reduces beam-size in the low-beta quads--particularly at injection. This optics configuration is particularly desirable for 132 nsec bunch spacing since the beams must be separated through the IR triplet and the momentum spread in the beam will be large due to the short bunch length.

D. Electrostatic Separators & IP Crossing Angle

A crossing half-angle of 190 µrad, giving 3σ separation at the first parasitic crossing, has been chosen. Assuming the current physical location of electrostatic separators, an average of 6.5σ separation is maintained at all other parasitic crossings. In general the electric fields are comparable to, or less than, those currently in use.

The primary dynamical consequence of a non-zero crossing angle is thought to be the excitation of synchro-betatron resonances. These resonances were a serious problem at the e^+e^- collider DORIS [4]. The excitation of such resonances in the Tevatron has not been studied in detail, but it is expected that they will be less important than in the DORIS experience because of the relatively low synchrotron frequency. Note, however, that the proposed parameters and crossing angle for the Tevatron Collider are rather similar to those proposed for the LHC.

E. Long Range Beam-Beam Effects

The large number of parasitic beam-beam crossings can lead to significant orbit and tune shifts. If the bunches are not uniformly populated and regularly spaced each bunch will have a different orbit and a different tune. In the Tevatron the bunches can not be regularly spaced because of the requirement for an abort gap. A bunch loading scheme that leads to 72 bunches colliding with a 132 nsec spacing has been considered. This configuration was chosen because it was thought to be as irregular as any that might be used. The maximum orbit shift is about 20 µm, 2/3 of the rms transverse beam size at the interaction point. The bunch-to-bunch range of tune shifts is shown in Table II. The range of tune shifts is less than, but comparable to, the maximum working space of 0.025. The range of linear coupling and the range of chromaticities are neither overwhelming nor small.

Table II. Range of tune shifts for the 72 antiproton bunches

Tune plane	Tune shift
Minimum $\Delta\nu_x$	-.0008
Maximum $\Delta\nu_x$	.0026
Minimum $\Delta\nu_y$	-.0118
Maximum $\Delta\nu_y$	-.0017

III. SUMMARY

A number of scenarios for operation of the Tevatron collider with 132 nsec bunch spacing have been analyzed. Collider parameters are summarized for 108 bunch operation in Table I. The 132 nsec spacing, coupled with a 190 µr crossing angle, produces a luminosity approximately 20% low as compared to bunches spaced at 396 nsec colliding head-on. This results primarily from the crossing angle form factor. Other factors, such as reduced proton bunch intensity due to coalescing of fewer bunches, tend to be ameliorated by the resultant lower longitudinal and transverse emittances.

Luminosity in all scenarios will continue to be limited by antiproton availability. Schemes for increasing the antiproton availability, and hence the luminosity, by an additional factor of ten are currently under study at Fermilab.

IV. REFERENCES

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