

Report to the Fermilab Director
Concerning 132 Nanosecond Operation During Run 2
June 6, 2002

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1. Introduction

1a. Ground Rules

The ground rules for our considerations of 132 nsec operation during Run 2 are

- A. We assume $2-4 \text{ fb}^{-1}$ will be delivered to each of CDF and DØ, and this will require replacement of silicon.
- B. We assume the instantaneous luminosity can reliably exceed $2 \times 10^{32} / \text{cm}^2 / \text{sec}$ at each detector, with head-on collisions spaced by 396 nsec (i.e., 36 bunch operation). We assume this level of accelerator achievement will require that something be done to allow the detectors to continue to take data effectively.
- C. We do not address any issues related to BTeV and 132 nsec bunch spacing.

For the CDF and DØ detectors, we consider the combinations of bunch spacing and initial luminosity as shown in the following table:

132 nsec and 8×10^{31}	396 nsec and 8×10^{31}
132 nsec and 2×10^{32}	396 nsec and 2×10^{32}
132 nsec and 5×10^{32}	396 nsec and 5×10^{32}

For the Tevatron, we assume the parameters given in the following table characterize 396 nsec and 132 nsec operation.

	396 nsec	132 nsec
Luminosity	2×10^{32}	???
Number of Bunches Protons/Antiprotons	36x36	140x103
Protons/bunch	2.7×10^{11}	2.7×10^{11}
Antiprotons/bunch	3×10^{10}	$> 0.94 \times 10^{10}$
Minimum Bunch Separation	396 nsec	132 nsec
Transverse emittances Protons/Antiprotons	20/15 π mm-mrad	20/15 π mm-mrad
Bunch Length	36 cm	36 cm
Half Crossing Angle	Zero	140-177 μ rad

We are not considering Run 2A vs Run 2B in this report. Rather we focus on the narrower issue of operating with 132 nsec bunch spacing. Finally, we have tried to present the information in a way that will facilitate informed decisions for guiding the evolution of the Tevatron collider. The team preparing this report was directed to neither make recommendations nor draw conclusions, and we hope the information has been presented without allowing our own conclusions to bias it too much.

1b. People Contributing

A team was formed in March 2002 by Mike Witherell, the Fermilab Director. David Finley was the team leader, and the team members were Nigel Lockyer, Mike Martens, Hugh Montgomery, Tanaji Sen and John Womersley. The charge to the team was to gather information on the proposed 132 nsec operation, present the advantages and disadvantages, include the detectors and the accelerator, and to present it in a way that will assist the Director in making a decision.

In addition to the team members, several other people contributed information to this report. For the accelerator information these include Mike Church, Bill Foster, Bruce Hanna, Steve Holmes, Ioanis Kourbanis, Paul Lebrun, John Marriner, Shekhar Mishra, Nikolai Mokhov, John Reid, Vladimir Shiltsev, Jean Slaughter, and Jim Walton; for CDF, Brian Winer, Richard Hughes, Rob Roser and Jeff Spalding; and for DØ, Liang Han, Michael Hildreth, Alexander Khanov, Flera Rizatdinova, and Elizaveta Shabalina.

2. Requirements

2a. Detector requirements and constraints

General Considerations

The CDF and DØ Run 2B upgrades are designed to operate at 5×10^{32} with 132 nsec bunch spacing. The biggest impact of running at high luminosities with 396 nsec rather than 132 nsec spacing is an increased number of minbias events on top of each collision of interest. The numbers of events per crossing are Poisson distributed and are shown for a variety of luminosities in the figures below. We see that for 396 nsec spacing, the mean number of minbias events per crossing at 5×10^{32} luminosity is of order 13.

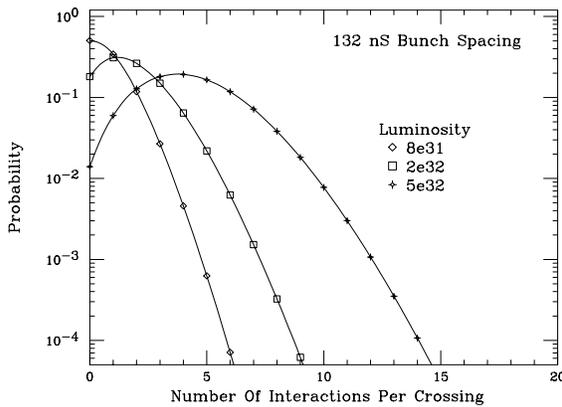


Figure 1. Number of Interactions per bunch crossing for $L = 8 \times 10^{31}$, 2×10^{32} , and $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-2}$, with 132 nsec operation.

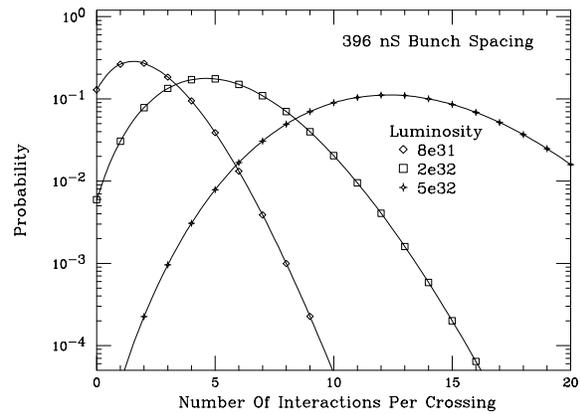


Figure 2. Number of Interactions per bunch crossing for $L = 8 \times 10^{31}$, 2×10^{32} , and $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-2}$, with 396 nsec operation.

These figures assume a total inelastic proton-antiproton cross section of 44mb. From these distributions, we see that the number of interactions per crossing is almost identical for $2 \times 10^{32} / 396 \text{ nsec}$ and $5 \times 10^{32} / 132 \text{ nsec}$ (see Figure 3 below). Since the number of interactions per crossing is the governing factor for the detectors, this implies that the detector upgrades as designed should be able to run up to about 2×10^{32} at 396 nsec without serious problems.

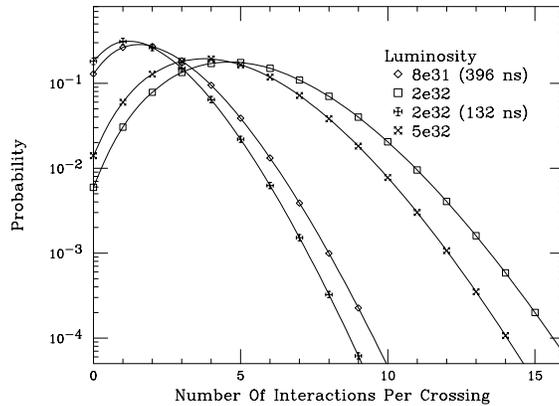


Figure 3. Extracts from the above figures comparing the number of interactions per crossing for $8 \times 10^{31}/396$ nsec with $2 \times 10^{32}/132$ nsec, and $2 \times 10^{32}/396$ nsec with $5 \times 10^{32}/132$ nsec.

The question, then, is then how quickly does the detector performance deteriorate as the luminosity is raised beyond 2×10^{32} with 396 nsec bunch spacing.

Important note about minimum bias simulations in DØ

In simulating high-luminosity running, we have to overlay minimum bias collisions onto the event of interest. The number of overlaid events obviously depends on the assumed total cross section, which should be stated. Also, when quoting a certain number of overlaid events it is important to understand whether diffractive events are included in this total. Since diffractive collisions produce few tracks at large angles they tend to have less effect than hard QCD collisions. At least for DØ, the simulation results have also proved rather sensitive to the event generator used. Their earlier studies used very-low- p_T dijet events generated with ISAJET as a minimum bias model. This was known to overestimate the track multiplicity, but was felt to be conservative. In an effort to be more accurate, the latest studies (since roughly December 2001) use a PYTHIA simulation tuned to CDF data. It is hoped that this better reflects reality but it does result in significantly lower occupancies and trigger rates and so some of the “conservatism” is gone. While nature may indeed be kind in this way, we cannot be sure until we better understand the real Run 2 detector performance.

Note: The D0 studies presented on pages 7-10 use the PYTHIA minbias model and the quoted number of overlaid events includes diffractive collisions. In contrast, CDF on pages 11-12 considers only hard collisions. A mean of 7.5 events for D0 corresponds roughly to 5 hard collisions (as used by CDF) while a mean of 15 events corresponds to 10 hard collisions.

Simulations of Track Trigger in DØ

In DØ the first system to suffer as the luminosity is ramped up is the fiber tracker, because it has the coarsest detector segmentation and therefore the highest occupancy. Fiber tracker occupancies are shown in Figures 4 and 5 for unaccompanied $Z \rightarrow jj$ events

and for a $WH \rightarrow \mu\nu bb$ events with 15 overlaid events. (Both these final states are two jets so they can be compared.)

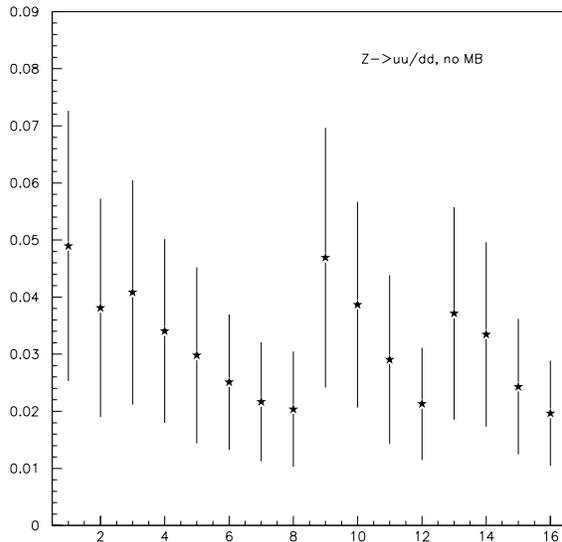


Figure 4. Fiber tracker occupancy by layer, $Z \rightarrow jj$ event with no additional minbias events.

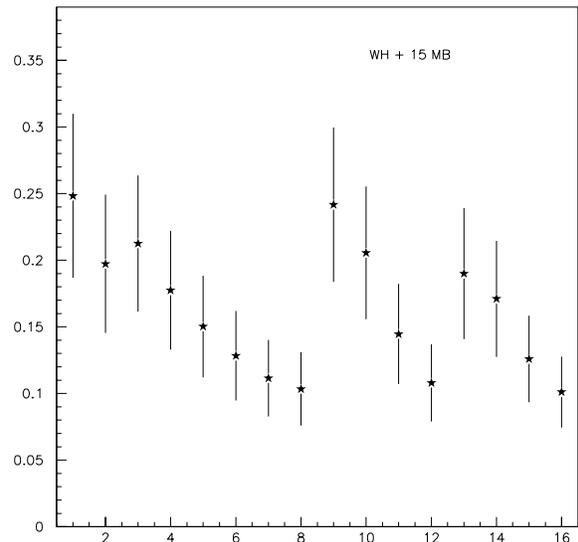


Figure 5. Fiber tracker occupancy by layer, $WH \rightarrow jj$ event with 15 additional minbias events.

In these figures, Layers 1-8 are axial layers and Layers 9-16 are the corresponding stereo layers. In the detector, layer 1 and layer 9 are at approximately the same radius, as are layer 2 and layer 10, etc. See note on page 6 about the number of minbias events.

We see that the innermost layer occupancies increase from roughly 5% to 25% in this case ($\sim 1.3\%$ per additional minbias event). The impact on track finding will be discussed below; here we will explore what happens to the fiber track trigger, which is an essential part of the first level muon trigger.

As the occupancy increases, the L1 high p_T track trigger rate becomes dominated by fake tracks. Moreover, the fake track rate is not a linear function of the number of minbias events per crossing. The older ISAJET based simulations suggested a very rapid degradation in performance with essentially every crossing giving a fake trigger once 15 events were overlaid. The newer PYTHIA simulations tend towards a much more optimistic view, as shown in Fig. 6. With the Run 2B singlet fiber trigger upgrade implemented, the fake rate remains at the few percent level. A few percent is what is required in coincidence with the muon system to allow a single muon trigger with a threshold of 10 GeV to operate at Level 1 (assuming the rates in the muon system itself remain under control).

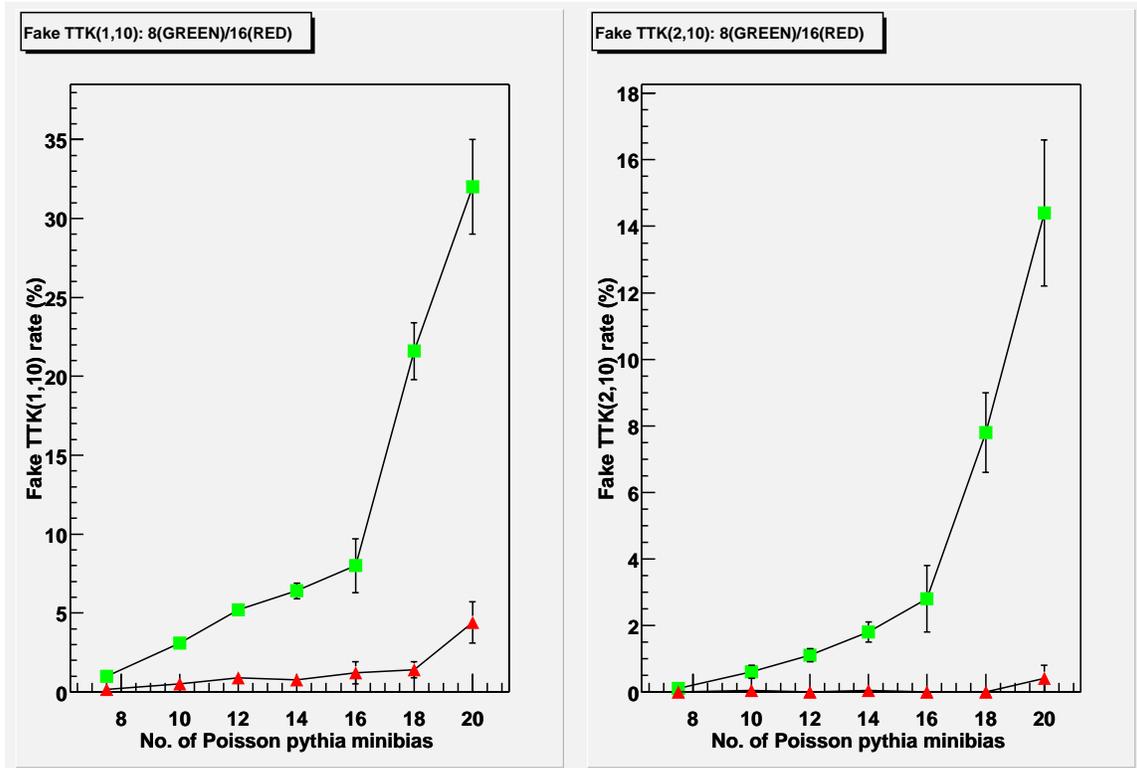


Figure 6. Fraction of crossings with a fake track trigger as a function of the mean number of minimum bias collisions per crossing. The left hand plot shows the rate for a single 10 GeV track and the right hand plot for two 10 GeV tracks. Green (upper) symbols are the present doublet fiber trigger and the red (lower) symbols show the proposed singlet fiber trigger (part of the Run 2B upgrade plan). See note on page 6 about the number of minbias events.

Simulations of Track Finding in DØ

DØ has carried out a full GEANT simulation and pattern recognition study of the proposed Run 2B silicon tracker. The track finding efficiency and fake rate have been compared for various numbers of minimum bias collisions per crossing. The primary events are either $Z \rightarrow uu/dd$ events or $WH \rightarrow \mu\nu bb$ events, and the tracks of interest are those in the jets. Tracks are found “globally”, i.e. using the fiber tracker and silicon together, using a histogramming technique. The efficiency and fake track rate are evaluated for all tracks with $p_T > 0.5$ GeV and $|\eta| < 2.0$, and shown in Fig 7 and 8.

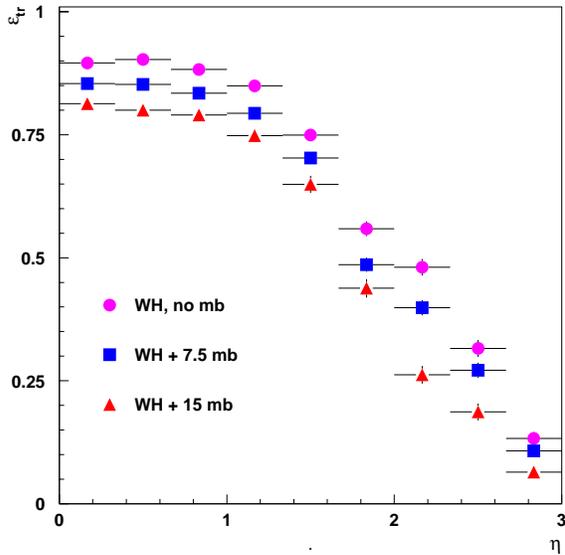


Figure 7. Track finding efficiency as a function of η for Higgs events with various numbers of overlaid minbias events.

See note on page 6 about the number of minbias events.

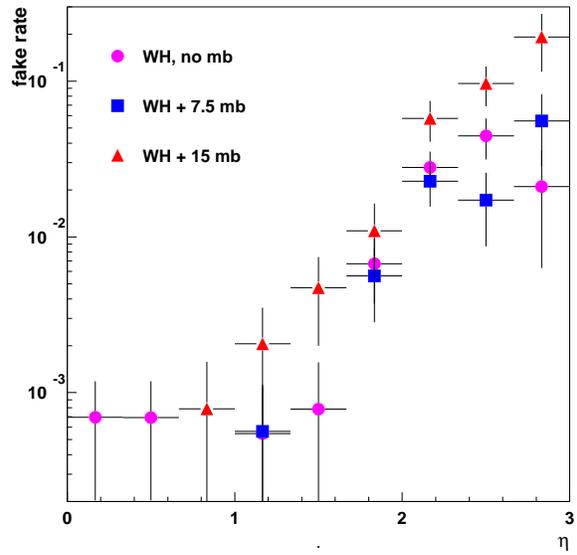


Figure 8. Fake track rate as a function of η for Higgs events with various numbers of overlaid minbias events.

The average efficiencies and fake rates are listed in the following table:

	Efficiency for tracks in jets	Fake track rate	Efficiency for muon track
Z + 0 minbias	$85.9 \pm 0.4\%$	$< 0.1\%$	
WH + 7.5 minbias (see note)	$81.5 \pm 0.5\%$	$< 0.1\%$	91.6%
Z + 15 minbias	$75.0 \pm 0.6\%$	$< 0.1\%$	
WH + 15 minbias	$75.0 \pm 0.7\%$	$0.2 \pm 0.1\%$	84.5%

We see that the tracking efficiency in jets degrades by roughly 5% in going from 7.5 overlaid minbias events to 15. The efficiency for the isolated muon track falls by a similar amount.

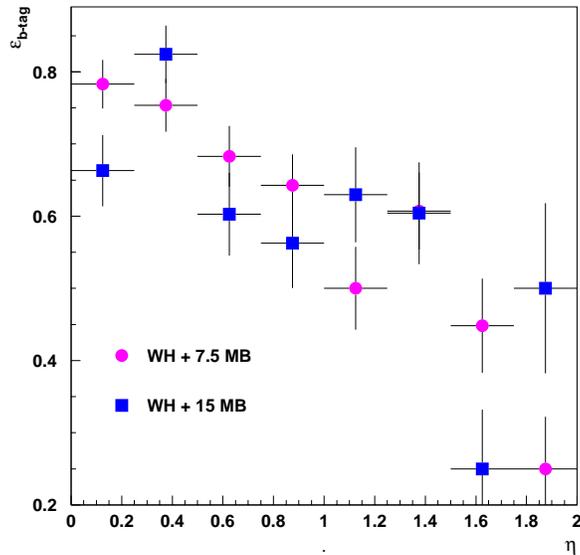


Figure 9. b-tagging efficiency as a function of pseudorapidity for WH events. See note on page 6 about the number of minbias events.

Figure 9 shows the b-tagging efficiency for the same samples. The results are summarized in the table below:

	Tagging efficiency per jet	Efficiency for one or more tag per event	Efficiency for two or more tags per event
Z + 0 minbias	1.3 ± 0.3% (fake rate)	3.0 ± 0.5%	<0.1%
WH + 7.5 minbias (see note)	64.6 ± 1.7%	75.8 ± 1.9%	28.6 ± 2.0%
Z + 15 minbias	1.3 ± 0.3% (fake rate)	3.6 ± 0.6%	0.1 ± 0.1%
WH + 15 minbias	63.0 ± 2.2%	74.3 ± 2.5%	26.0 ± 0.5%

These results indicate a 9% loss in double b-tagging efficiency in going from 7.5 to 15 minbias events, though the change is not statistically very significant. In addition, we expect a roughly 8% loss in the high- p_T lepton efficiency for the $WH \rightarrow l\nu b\bar{b}$ signal, and perhaps a 10-15% loss in event acceptance associated with the longer interaction region at 396 nsec.

Simulations of Track Trigger in CDF

The CDF detector performance degrades as a function of interactions per crossing primarily in the Level 1 tracking trigger fake rate performance. The tracking trigger couples into the lepton triggers and the large impact parameter track triggers, increasing the fakes in those triggers in almost direct proportion. Although offline tracking is

degraded, there are more handles available to reduce the fakes and the impact is consequently much less precipitous.

The CDF COT (central outer tracker) detector also plans to go to CF_4 (a fast gas) to increase the drift velocity. This is necessary to keep the maximum electron drift time less than the crossing period and hence to minimize the cross over from neighboring crossings. (This expensive gas will not be needed if the "264 nsec Concept" noted below in the Accelerator section is implemented.)

The CDF Level 1 track trigger (XFT), which is crucial for ~80% of all Run 2B triggers for high p_T physics, suffers from a rapid increase in fakes once the number of overlapping minbias events exceeds 5-6 interactions per crossing. CDF has applied the full Level 1 track trigger hardware simulation to a sample of $t\bar{t}$ Monte Carlo events. The Monte Carlo has not been adjusted to reflect the factor of two increased occupancy observed in the COT in Run 2A. Minbias events are overlapped and the fake rate is determined. It is found that the fake rate increases substantially as a function of the number of interactions per crossing. The results are shown in Figure 10. The impact of an increased number of fakes affects directly the number of fake single electron and muon triggers, which combine to use 25% of the trigger bandwidth in Run 2B.

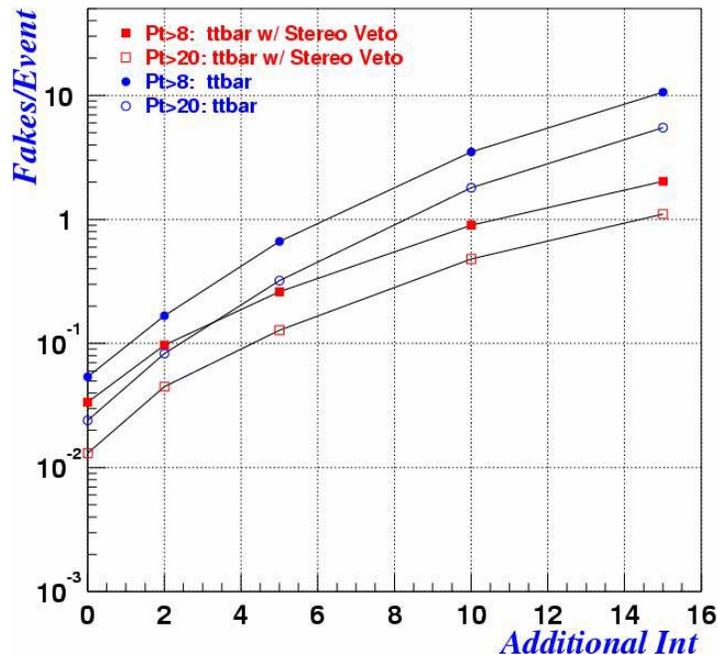


Figure 10. The average number of fake tracks per event in $t\bar{t}$ Monte Carlo as a function of the number of additional interactions per crossing. The curves are shown for XFT tracks with $P_T > 8$ GeV/c and $P_T > 20$ GeV/c. Also shown is the reduction of fake rate provided by requiring the presence of a segment in the outer stereo layer of the COT. The fake rate at large number of interaction ($N > 8$) is almost entirely driven by the soft additional interactions, not the hard scatter (in this case $t\bar{t}$).

See note on page 6 about the number of minbias events.

Additional problems arise because the azimuthal resolution of the Level 1 track trigger (XFT) degrades. The XFT is used to extrapolate into the silicon detector in order to link to a track in the silicon. The design rms extrapolation resolution from the XFT into the silicon is about 8 mrad. At 15 interactions per crossing this number has jumped to 22 mrad, which would result in many fake displaced tracks, and consequently more fake large impact parameter tracks are found. This trigger is the foundation of nearly 50% of the trigger bandwidth at Level 2. For example, most of the Higgs triggers require at least one displaced track. The XFT performance is shown in Figure 11.

The majority of fakes from the XFT are at high transverse momentum, above 20 GeV/c. The trigger has been designed to reject low momentum fakes by requiring a match in angle at the outer two superlayers. This works well. However, several low momentum crossing tracks combine to fake a high momentum track. The fake rate is also strongly dependent on the number of hits per superlayer used. Presently the XFT uses 10/12 possible hits. The fakes are known to rise rapidly if the majority logic requirement is less than ten. The COT efficiency determines how many wires are used per superlayer in the trigger and this number is set by the chamber gain and preamplifier thresholds. The gain must be kept to a minimum in order to reduce aging, which in turn competes with the need for more hits per superlayer.

The transverse momentum resolution and the phi resolution versus number of interactions show a similar trend in Figure 11. There is a break in slope at about 5-6 interactions per crossing. The design resolution is roughly 2%. At 15 interactions per crossing, the resolution degrades to 7%. The reduced momentum resolution impacts the ability to make a tight separation between the steeply falling background at lower momentum and the signal, which is at higher momentum.

In summary, the XFT will degrade in three ways with the increased number of interactions per crossing. The number of high momentum fakes found increases due to crossing low momentum tracks, the projection accuracy of the XFT track into the SVT increases the number of fake displaced tracks and increases the processing time of the SVT due to wider "roads", and finally the reduced momentum resolution mitigates our ability to clearly separate the low momentum backgrounds from the high momentum signal.

Other considerations

We find that the CPU time needed for track reconstruction (which usually dominates the offline processing time) increases faster than linearly as the number of overlaid events increases. This means additional computing resources would be needed to keep the offline analysis up to pace for the same acquired integrated luminosity: this could cost an extra \$0.5-1.0M per experiment per year.

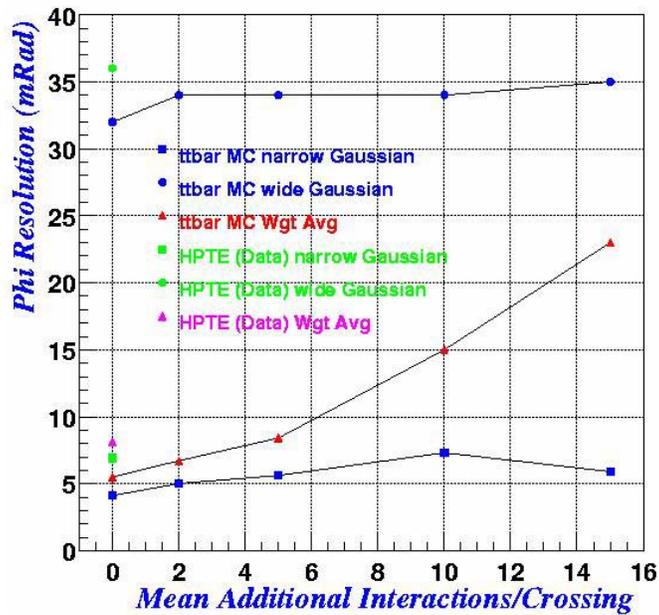
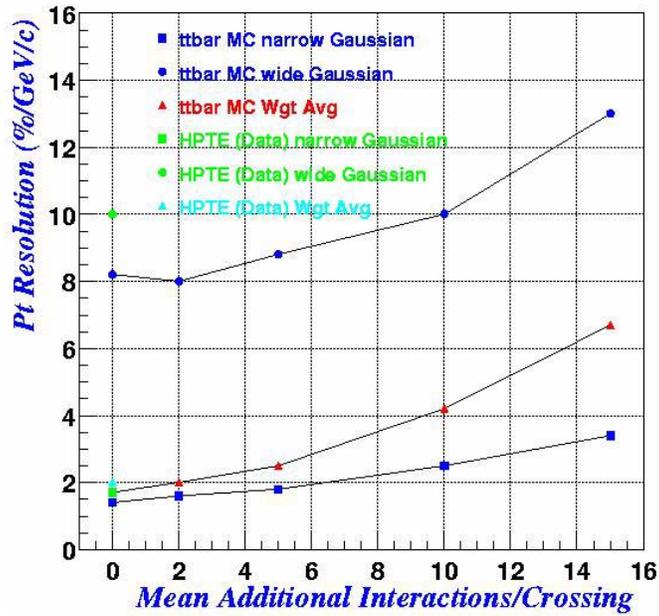


Figure 11. The transverse momentum and azimuthal resolutions of the XFT. The XFT resolution is fit to narrow and wide Gaussians. As more minbias events are overlapped, the weighted mean of the areas of the narrow and wide Gaussians indicate a much greater fraction in the wide Gaussian, and therefore a reduction in the overall resolution. The actual widths of the Gaussians are not strong functions of the number of interactions per crossing. The points from Run 2 data indicate the resolution is slightly worse in reality than in the Monte Carlo simulation.

See note on page 6 about the number of minbias events.

2b. Accelerator Requirements and Challenges

Successful operation with 132 nsec bunch spacing will require that several accelerator physics and operational challenges are dealt with properly. For clarity, they are presented below as “Major Challenges” and “Secondary Challenges”, but all have to be met to operate successfully.

Major Challenges with 132 nsec

A. Beam-beam interactions

During injection, ramp, squeeze and luminosity store, the beam-beam interactions will affect the beam quality, specifically of the antiprotons, for the worse. Long range interactions will be important at all stages while at collisions synchro-betatron resonances driven by the beams colliding at an angle will be an additional factor.

Long range interactions induce orbit changes in the antiproton bunches and also have nonlinear effects. With 396 nsec operation and proton beam intensities achieved to date of 6×10^{12} , antiproton lifetimes vary between 1-7 hours depending on the bunch. These lifetimes are sensitive to the beam separation. This sensitivity will be exacerbated when proton beam intensities reach 3.8×10^{13} ($=140 \times 2.7 \times 10^{11}$) and antiproton lifetimes are likely to be worse at injection.

The orbit changes induced by the long range interactions differ from bunch to bunch so each antiproton bunch will be on a slightly different orbit. These orbit variations enhance the variations due to feed-down of nonlinear multipoles including persistent current multipoles. Thus there will be a greater spread in basic beam parameters such as tunes, chromaticities and coupling over the antiproton beam. Additional spread in beam parameters will be introduced by 1) variation in proton bunch intensities and 2) the fact that the crossing points are at different locations for different antiproton bunches.

An important lesson from 396 nsec operation is that significant losses result when the minimum beam separation becomes too small. During the squeeze, beam separations change, especially near the transition from the injection to the collision helix. Losses around 30% were observed at this stage of the squeeze when the minimum separation was just under 2σ until April 2002. A change in the helices to increase the minimum separation to 3σ and using a shorter time to transition from the injection helix to the collision helix reduced the losses at this stage to under 5%. It is possible that the minimum beam separation with 140×10^3 bunches is smaller than at present. The constraints on the Tevatron optics may not allow these separations to be increased by much (primarily due to physical aperture restrictions and separator voltages). In that situation, sharp beam losses may again be observed during the squeeze.

After the beams are brought into collision, the long range interactions will again affect operation. Orbit variations from bunch to bunch imply that not every bunch will be centered at the two interaction points (B0 and D0). Variations in bunch luminosities will be greater and there may be a reduction in beam lifetimes due to these offsets at the IPs.

Besides the lifetime another measure of beam stability is the dynamic aperture. This quantity, often quoted in units of the rms beam size σ , indicates the stable area in transverse phase space. Outside this area particles are lost quickly. In the Tevatron nonlinear effects due to the long range collisions reduce the dynamic aperture of the antiprotons to a value smaller than the physical aperture. Tracking calculations [1] show that with 396 nsec operation and full proton bunch intensities of 270×10^9 , the dynamic aperture of antiprotons in the center of a train is about 5σ after 20 seconds. With four times the number of proton bunches, the dynamic aperture may be significantly smaller than this value. The calculations in Reference 1 assume a near perfect machine - no misalignments, no magnetic errors in the arc magnets, and no power supply ripple; but the errors in the IR quads (as measured ~10 years ago) are included. Once all these real effects are included we'd expect the dynamic aperture would likely drop by another 50%. Thus if the calculated ideal dynamic aperture is say 2.5σ (< 3), the real DA may be close to 1.2σ which implies about 60% of the beam would be lost.

It is likely that some form of compensation will be required to mitigate the effects of these interactions. It is not obvious that compressing the tune footprint will be crucial since calculations suggest the long range interactions have a small contribution to the tune spread but almost completely dominate the dynamic aperture. If compression of the tune footprint is crucial one technique to provide it could be given by a fully developed and operational set of Tevatron Electron Lenses (TEL) [2]. These lenses could be designed to adjust the centers and shapes of the tune distribution of each bunch of antiprotons.

Figure 12 shows a comparison of the tune footprints for 396 nsec spacing from all the beam-beam interactions with that from only the long range interactions. The head-on interactions contribute about 0.02 out of the total tune spread of 0.025. Table 1 shows the dynamic aperture of bunch 6 in units of rms beam size for different cases calculated after 10^5 turns. (Bunch 6 was chosen because it is representative of all bunches in a train of 12 except for the two bunches at either end of the train.) Case II shows that the head-on interactions have an insignificant contribution to the dynamic aperture – it is almost the same as that without these interactions. Cases III and IV show that the dynamic aperture with all beam-beam interactions is the same as that with only the long range interactions.

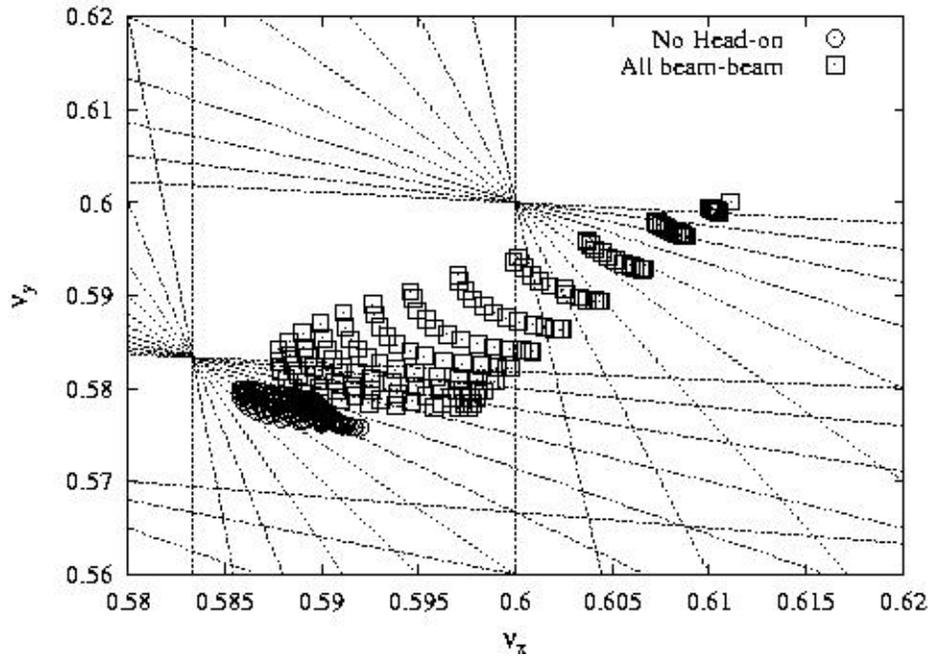


Figure12: Tune footprint with all beam-beam interactions (squares) compared with the footprint with only the long range interactions (circles) [taken from Reference [1]].

Case	(DA_{av}, DA_{min}) [6D, after 2.0 secs]
I. Single antiproton bunch (with machine errors)	(12.9, 11.0)
II. Head-on interactions and machine errors	(12.5, 11.0)
III. Only long range interactions and machine errors	(7.7, 6.0)
IV. All beam-beam interactions and machine errors	(7.7, 6.0)

Table 1: Average and minimum dynamic aperture (DA) in units of the rms beam size σ for various configurations of nonlinear interactions experienced by antiproton bunch 6 [taken from Reference [1]].

Nonetheless it is important to limit the size of the tune footprint so that the beam does not cross resonances of lower than 12th order. Consider the situation in which the luminosity is limited by the antiproton production rate, proton intensity is limited by only the tune spread of the antiprotons, and the dynamic aperture of antiprotons is sufficiently large. In this situation, footprint compression with the TEL could be crucial for increasing the luminosity by increasing the proton intensity. It is worth mentioning that an alternative strategy of compensating the long range interactions with an electromagnetic wire is under investigation at CERN for possible use in the LHC [3]. It would be useful to examine whether a similar compensation strategy would work in the Tevatron. Such compensation may be required at all stages of the Tevatron cycle.

For 132 nsec spacing, large crossing angles at B0 and D0 will be necessary to separate the beams at the parasitic collisions nearest to the IPs, and total angles of order 300 μ rad will be necessary. Crossing angles of this magnitude will reduce the luminosity by about a factor of two due to the smaller overlap between the beams (the so-called “hourglass effect”). Also, the number of interactions per crossing will be reduced by the same factor. And, the tune footprint from the beam-beam interactions at B0 and D0 will also shrink by about the same factor of two. However beams colliding at an angle will also drive synchro-betatron resonances. Although these resonances may decrease the luminosity lifetime, there is no observation of crossing angle driven synchro-betatron resonances at any hadron collider. A small synchrotron tune and a large bunch length – both true for proton and antiproton bunches in the Tevatron – are mitigating factors. But machine studies are necessary to determine the severity of synchro-betatron driven effects.

B. Crossing angles and orbit offsets in the IR quadrupoles

Even without the beam-beam interactions, the crossing angle may create complications. The beams attain their largest size within the IR quadrupoles and it is conceivable that these magnets will pose an aperture restriction when the beam orbit is offset from the central axis. As a result of the off-axis excursions, the transverse beam position at the IPs and hence the luminosity will be more sensitive to changes/fluctuations in the power supplies of these magnets, especially at higher frequencies. The nonlinear fields in these magnets as experienced by the beams will also be larger – these may limit the dynamic aperture. In short, operation with crossing angles will be more sensitive to the optics and field quality of these magnets than with the present head-on operation.

C. Background losses, collimation system

In Run 2A, with the present collimation system, proton halo background losses are observed to be directly proportional to the proton beam current. Therefore Run 2B should expect to see losses about four times higher than in Run 2A due to the increased number of protons. At present, the losses at CDF are sensitive to the collimator settings while those at DØ are not. It is believed that CDF may effectively act as a collimator for DØ.

The collimation system in use now was designed in 1999 by Nikolai Mokhov and Alexander Drozhdin, and it is based on a successful prototype installed during Run I. The collimation system is designed so that particles which are diffusing to larger amplitudes are scattered by the primary tungsten targets and are intercepted by the secondary collimators in 5 to 100 turns. Particles lost more rapidly, for example due to single large angle scattering due to poor vacuum, may not be intercepted by the collimators. Of the nine collimators installed only four secondary collimators are found to be effective in reducing losses in Run 2A. The locations chosen were not optimum and this may help explain why the collimation system is not completely effective now. The efficiency of

the collimation system is not sensitive to the bunch structure since it intercepts only particles diffusing relatively slowly in the transverse planes. In principle, no redesign would be necessary for 132 nsec spacing once the collimation works well at 396 nsec spacing.

D. Removing protons and decelerating antiprotons at the end of a store

Once the Recycler Ring begins to function in its recycling mode, at the end of a luminosity store antiprotons in the Tevatron will be decelerated and transferred to the Main Injector and then to the Recycler. Before this can be done, protons must be removed by scraping them away in the Tevatron at the end of a store. The obvious challenge will be to do this in a way that deposits the energy from the scraped protons gently enough so as to not quench any superconducting magnets. Possible ideas to do this successfully include increasing the proton emittance before scraping to reduce the peak energy deposited and to carefully control the speed of the collimators. (A larger proton emittance would of course reduce the effectiveness of the helical separation of the closed orbits and likely change the long range beam-beam force on the antiprotons and this will almost certainly have to be accommodated.)

Decelerating beam from maximum energy in the Tevatron without quenching the magnets will also be a challenge, because the margin protecting the magnets from quenching is smallest at the maximum magnetic field. More experience is needed with this process. Up to now, the highest energy at which particles have been decelerated without magnets quenching is 800 GeV. The recycling efficiency will be affected by the longitudinal and transverse emittances of the antiprotons, which grow during a store. One known limit on the recycling efficiency is the fraction of the beam inside a maximum longitudinal emittance which can be transmitted by the Tevatron and the Main Injector, and finally transferred to the Recycler Ring. One estimate of this limitation is 3 eV-sec (provided by Mike Church).

According to our ground rules, both proton removal and antiproton deceleration are assumed to be techniques proven during Run 2A. There are two special challenges attendant to 132 nsec operation which derive directly from the fact that there would be about a factor of four (140/36) more protons in the Tevatron compared to 396 nsec operation. First, while the protons are being removed, any beam-beam compensation active on the antiprotons must be undone in tandem over a range larger than for 396 nsec. Second, during proton removal a smaller fraction of the protons in the Tevatron will cause a quench and the subsequent total loss of the antiprotons.

Also, any losses at CDF and DØ associated with proton removal will be four times higher for 132 nsec operation than for 396 nsec operation.

Secondary Challenges with 132 nsec

There are several other challenges to be met, which at this time appear to be secondary to those given above and we list them here. However our perception of what is important may change as we gain more experience during Run 2A.

A. Injection of 140 proton bunches

At present protons are injected one bunch at a time from the Main Injector. In order to minimize the shot set up time and avoid proton losses and emittance growth during the entire filling process, it is necessary to inject multiple bunches from the Main Injector. This requires that beam loading compensation in the Main Injector be operational. At present a maximum of twelve bunches can be accepted from the Booster for coalescing into a single bunch. Higher beam currents cause excessive ringing in the RF and spoil the coalesced beam quality. For 132 nsec operation, the beam loading compensation must control beam currents about four times larger than at present, so that four bunches can be injected at a time into the Tevatron. This would keep the injection time of protons the same as at present.

B. Instabilities with higher beam currents

It is conceivable that coupled bunch instabilities will be important with higher beam currents. There was some evidence of these instabilities during Fixed Target operation when the total proton beam current was less than that anticipated for 132 nsec operation. The highest reliable beam current during Fixed Target operation was 2.5×10^{13} , and 132 nsec operation calls for $140 \times 2.7 \times 10^{11} = 3.8 \times 10^{13}$.

Fixed Target operation is sensitive to the instantaneous extracted beam intensity and feedback loops are used to keep this rate constant. Because of these automated feedback loops, which take a fraction of a second to establish themselves during a given spill of dozens of seconds, Fixed Target operation is less sensitive to variations of transverse or longitudinal emittance changes and dynamics. The primary difficulty with high intensity during Fixed Target running is the reliable establishment of the feedback loops during a given spill.

The Tevatron as a collider, however is much more sensitive to these effects because the beams remain in the Tevatron for hours. If longitudinal instabilities are important, then the longitudinal feedback system will need to be re-designed since the present system does not have the bandwidth to cope with a smaller bunch spacing. There are currently only a longitudinal dipole mode 0 and longitudinal quadrupole mode 0 damper in the Tevatron. It is not clear they are completely effective at 2×10^{11} / bunch. Longitudinal and transverse bunch by bunch dampers are being designed and built for 396 nsec spacing. We expect a system appropriate for 132 nsec spacing will also be required.

C. New regime of beam dynamics effects

The shorter bunch spacing may introduce several new beam dynamics effects which have not been observed in the Tevatron.

Among them is the possibility of creating electron clouds by ionization of the residual gas. The electrons initially created by the interaction of the beam particles and the gas molecules are attracted by successive bunches of intense protons, gain energy and may release low energy secondary electrons when they strike the stainless steel beam pipe. (The few electrons that scatter off protons are ignored in this discussion.) Possible consequences of this cloud are a heat load to the cryogenics and beam instabilities. This phenomenon is expected to be important in the future LHC where the electrons are initiated by synchrotron radiation from the protons. It has been observed both at PEP-II and KEKB. It has not been calculated for the Tevatron.

Another possibility is that wakes induced by the protons may be seen by antiprotons leading to a beam-beam induced instability. A similar phenomenon was observed at LEP where the threshold of the transverse mode coupling instability was lowered when both electrons and positrons were present. We expect that transient beam loading compensation will be required on the Tevatron RF cavities for 132 nsec operation.

We emphasize that it is uncertain that the phenomena mentioned above will be observed in Run 2B but we need to recognize that new challenges may have to be faced, some of which we haven't even thought of yet.

Instrumentation Requirements with 132 nsec

An important part of the switch to 132 nsec bunch spacing will be the upgrade to the instrumentation to handle the shorter bunch spacing and more than 100 bunches in each beam. Each piece of instrumentation will need to be reviewed in detail to determine the amount of work needed.

However, before any detailed work can proceed certain critical operations decisions need to be made. For instance: Do we need to routinely report bunch by bunch information for every one of the more than 100 bunches or is reporting and average for all of the bunches sufficient? Given such decisions, then a list of requirements can be made, and then a comprehensive estimate of resources can be made.

We only did a quick survey of the needs for the Main Injector and the Tevatron. The other accelerators need to be included in a proper survey, of course. Nevertheless, we have found that many of the components of the instrumentation show that a considerable amount of work must be done on all levels from the basic technology used (of flying wire phototube response time for instance), to the electronics (to handle the shorter bunch spacing), to the software to handle more bunches, to the presentation of the information in a way that is useful to the people using it, and the eventual incorporation of the measured data into the automated control of the beams as appropriate.

Below is a list of some of the major kinds of instrumentation along with brief sketches of the work needed to upgrade to 132 nsec. More detailed engineering estimates can be done if and when people become available, of course.

Main Injector Fast Bunch Integrator. This system measures individual bunch intensities. It needs upgrading for the 132 nsec bunch spacing to measure the intensities after coalescing.

Main Injector RF Cavities. For 396 nsec bunch spacing, the Main Injector uses 53 MHz RF cavities to accelerate and to recapture the bunch after coalescing. Coalescing at 132 nsec bunch spacing requires two cavities at 7.5 MHz, one cavity at 15MHz, and one cavity at the 3rd harmonic. The parts for all of these have been ordered, and the Technical Division has taken on the responsibility for making these cavities.

Main Injector Transient Beam Loading. A high intensity beam bunch couples through the RF cavities to change the net RF field applied to the beam. Compensation for this effect is required for 396 nsec operation, and additional work will be needed for 132 nsec operation.

Main Injector Low Level RF work. This system provides corrections for the high power RF cavities required by the presence of beam. The ongoing implementation of the 2.5 MHz system for 396 nsec operation will allow for the efficient accommodation of the 7.5 MHz system when the need arises for 132 nsec operation.

Main Injector Beam Position Monitors. This system is used to measure the transverse centroids of the charge distribution of the beam. The present system is designed to operate at 53 MHz (~18.83 nsec bunch spacing) and to provide a single number characterizing all the bunches. Both 2.5 MHz and 7.5 MHz systems are needed, and information on individual bunches is also needed. These changes are needed because the Main Injector project planned to tune everything with 53 MHz and run at all other frequencies blind; but running blind has been found to be unacceptable since diagnosing problems is difficult or impossible.

Main Injector Transverse Damper. This system is used to minimize transverse emittance growth of beams circulating in the Main Injector. This system is needed for 396 nsec operation. Operation at 132 nsec will require changes to the system to handle the higher beam current as well as multibatch operation.

Main Injector and Tevatron Flying Wires. This system measures transverse beam sizes by passing a wire across the beam and observing the secondaries (losses) produced by the interaction of the beams with the wire. In the Tevatron, these no longer work as a bunch by bunch diagnostic, and they were not implemented as a bunch by bunch diagnostic in the Main Injector. A major upgrade is needed now for the timing hardware and display software even for 396 nsec operation.

Tevatron Sampled Bunch Display, Tevatron Fast Bunch Integrator. Both of these systems measure individual bunch intensities, and the Sampled Bunch Display also measures the bunch lengths which are used to calculate longitudinal emittances. These systems need faster integrators to handle the shorter bunch spacing, but some of the upgraded software will already handle more bunches. For the Fast Bunch Integrator, measurements can be sequenced, with very little loss in readout bandwidth.

Tevatron Ion Profile Monitor. This system measures transverse beam sizes by observing the ions produced by the interaction of the beams with the residual gas in the beam pipe. These may not be useful at 132 nsec bunch spacing because the spread in ion drift times may be longer than 132 nsec, and this physics issue needs to be investigated. If the physics supports implementation, this system would need new electronics for the shorter bunch spacing and upgraded software.

Tevatron Beam Position Monitors. Presently these monitors are useful for proton only stores with uncoalesced beam (which has the 53 MHz component required by the present electronics). Work is needed on the electronics to improve accuracy for coalesced beam. With 396 nsec operations there are a handful of monitors located at proton antiproton bunch crossings and these are unusable for reliable measurements with the present hardware. With 132 nsec there will be even more monitors located at proton antiproton crossing points.

Tevatron Beam Line Tuner. This system is used to minimize emittance growth when transferring the beams to the Tevatron. This does not work for 396 nsec operation and needs to be made operational. In additions, it will need an upgrade for 132 nsec operation.

Tevatron Dampers. This system is used to minimize emittance growth of beams circulating in the Tevatron. It is not clear if the present design will be useful but work has been progressing on longitudinal and transverse dampers.

Tevatron Synchrotron Light Monitor. This system measures transverse beam sizes by using the synchrotron light emitted by the proton and antiprotons beams. Unlike the other beam size measuring systems, this system does not require additional disturbances to the beams and it produces its information faster than any of the other profile systems. This is still a work in progress for Run 2A. It may be able to handle the shorter bunch spacing by interleaving measurements. The software needs to be upgraded.

Tevatron Collimators. Still to be done for 396 nsec operation is the complete and proper implementation of the beam physics design for collimation. Given the complete and proper implementation for 396 nsec operation, 132 nsec operation is not expected to require additional modifications.

Luminosity Leveling Approach

With 396 nsec operation, something like luminosity leveling would likely be required once luminosities begin to exceed 2×10^{32} reliably. Theoretical studies [4] show that luminosity leveling with 396 nsec bunch spacing can reduce the interactions per crossing at the beginning of a store by a factor of two, and still achieve about 85% of the integrated luminosity one obtains without luminosity leveling. This particular percentage refers to the weekly integrated luminosity calculated for a particular model which includes an assumed stacking rate, recycling efficiency, and shot set up time.

The luminosity can be leveled by using magnetic or electric fields. The magnetic field method would use the low beta quads. They would not fully squeeze at the beginning of a store, and proceed to their fully squeezed values several hours into the store. This is the method usually contemplated for luminosity leveling. However, the electric field method would use the separators to create a crossing angle or an offset (or both).

We note that a crossing angle used for luminosity leveling can give a shorter luminous region around the interaction points at CDF and DØ. On the other hand, using the low beta quads to partially squeeze necessarily results in a longer luminous region. How much of benefit or detriment these differences are to the detectors should be more carefully quantified.

264 nsec Concept

Also, it is worth noting that if 132 nsec spacing is found to be unworkable, and the 396 nsec spacing is unacceptable even with luminosity leveling, an intermediate spacing of 264 nsec may be considered.

No beam physics details of this scenario have been worked out, but it is envisioned to have several advantages compared to the 132 nsec option.

- a. The closest parasitic interactions will be around 39.6 m from the IPs or about 9 m from the separators. This distance may be large enough that the crossing angle, if required, can be reduced substantially from that required for 132 nsec spacing so that the drop in luminosity will be significantly smaller.
- b. With half the number of proton bunches, the unwanted effects of the long range interactions will be reduced.
- c. Lower proton beam currents will also reduce the problem of instabilities.

3. Advantages and Disadvantages of Meeting Requirements

3a. Detector Advantages and Disadvantages

From the detector viewpoint there are few advantages in running at 396 nsec that can outweigh the problems with higher occupancies and trigger rates described in the earlier sections. The major reason the detector collaborations might choose to “learn to live with” higher luminosities at 396 nsec in preference to switching to 132 nsec would be in order to maximize the accumulated integrated luminosity. One consequence of a switch to a 132 nsec bunch spacing is that the Tevatron must introduce a crossing angle at the B0 and D0 collision points in order to minimize long range beam-beam interactions as the bunches approach and exit the collision regions. The crossing angle will reduce the instantaneous luminosity by up to a factor of two. Furthermore, increased backgrounds are possible because of greater excursions of the beam orbit at the low beta quads. (Given present operational conditions, this is a concern, especially at CDF). A slight mitigation of the reduction in luminosity comes from the fact that the luminous region is shorter, and hence more events are contained within the silicon detector active region than with a longer luminous region provided by head-on collisions. The shorter region may give an effective 10-15% improvement.

Since the b-tagging efficiency is reduced because of lower tracking efficiency, there will be a balance between getting a higher delivered luminosity but with lower offline efficiency, or alternatively having a lower delivered luminosity that can be reconstructed more efficiently. As an example consider the event yield for W+Higgs events based on the simulations shown earlier. Assuming the trigger continues to work well, the expected factor of two higher luminosity at 396 nsec would be partially offset by an 8% drop in charged lepton efficiency, a 9% loss in double b-tagging efficiency, and a 10-15% loss in event acceptance from the longer interaction region. In this case one still comes out ahead, but given the uncertainties on all these numbers, this is not a very robust conclusion.

It is sometimes assumed that the Run 2B upgrades could be less ambitious if the 396 → 132 nsec transition did not occur, and so there could be large cost savings. This is almost certainly a fallacy. Roughly three quarters of the cost of the upgrades is in the new silicon detectors. Replacement of the silicon is motivated by radiation damage not by instantaneous luminosity considerations. If we want to accumulate 10 or 15 fb⁻¹, the silicon has to be replaced, and the cost and scope of the new detector is unaffected by the bunch crossing time. Replacement is needed after something like 2 to 4 fb⁻¹, the expected duration of Run 2A. In the case of DØ, the other Run 2B upgrades address problems in triggering at high luminosity, and these problems would be made harder rather than easier if the number of collisions per crossing were higher. There is one component of the DØ upgrade that would not be needed, namely the new fiber track trigger pickoff chip that is

explicitly required for 132 nsec operation. It might also be possible to re-optimize the DØ Level 1 calorimeter trigger upgrade, since digital filtering of the signals for 132 nsec operation would no longer be required.

3b. Accelerator Advantages and Disadvantages

132 nsec Approach

It is hard to imagine that any aspect of accelerator operations will be easier with more bunches than the present 36 bunch operation.

Nevertheless, there are advantages for the Tevatron with 132 nsec operation. One is that the antiproton proton collisions will remain in the weak strong regime where the Tevatron collider has always been operated. This is because the total number of antiprotons remains the same for 396 nsec or 132 nsec operation; for 132 nsec operation they will be distributed in a larger number of bunches. Also, the head-on beam-beam tune shift is less with a crossing angle (as is the luminosity). Finally, the luminous region is shorter with a crossing angle, and thus more interactions fit within the silicon detectors.

The clear and possibly overwhelming disadvantage of 132 nsec operation is the fact that the long range beam-beam interactions will pose the severest beam physics conditions ever encountered by the Tevatron as a collider. Beam-beam compensation in some form may become crucial.

As with any new mode of operation, specific solutions may also be required for some effects which the Tevatron has not needed to face up to so far. For example, resonance compensation or a local correction of the field quality of the IR quadrupoles may be needed as the beams pass through these quads off center. The severity of synchro-betatron resonances caused by beams colliding at an angle is unknown.

With about four times the number of protons in the ring, the effective quench margin for the superconducting magnets will be reduced. That is, a smaller fractional loss of protons will quench the Tevatron.

Luminosity Leveling Approach

An apparent advantage of luminosity leveling is that it appears that no new hardware is required to implement it. This is true whether it is implemented by dynamically changing the strengths of the low beta quads or the strengths of the separators. Another advantage is it can be developed during machine development sessions during Run 2A.

A disadvantage of luminosity leveling is the loss of at least 15% of integrated luminosity compared to operation with no leveling.

Another disadvantage of luminosity leveling is the apparent lack of people to work with the beam specialists to write the new software, which needs to be used to operationally perform the required changes in the strengths of either the magnets or the separators.

There may be some additional operational complications which could turn out to pose an unacceptable disadvantage. For example, background losses may be different at each new setting. Collimators may have to be repositioned, and other changes in the machine may be necessary. These re-optimizations will reduce the effective store time. One suggestion for avoiding these reoptimizations would be to reduce β^* (or the settings of the separators) in slow continuous steps from the start of the store.

Another advantage of luminosity leveling is the possibility of the extension of the Run 2A configuration of the Tevatron collider complex (not just the Tevatron, but its injectors as well).

264 nsec Concept

Again we re-assert that it is hard to imagine that any aspect of operations will be easier with more bunches than the present 36 bunch operation. Nevertheless, 264 nsec operation offers the possibility of operation without the large crossing angle required by 132 nsec operation, and perhaps head-on collisions could be achieved as well.

One technical disadvantage identified so far of the 264 nsec option is that the RF cavities needed for coalescing bunches in the Main Injector will need to have different frequencies than those planned for 132 nsec operation. In addition the instrumentation would likely still have to be upgraded beyond its 396 nsec capability.

4. Risks Associated with Meeting Requirements

4a. Detector Risks

The major risk in any decision made now from the detector point of view is our reliance on simulations. The trigger and detector performance needs to be better benchmarked as a function of luminosity (and number of interactions per crossing). The trigger rates need to be measured at high luminosities and used as input to the extrapolations. We have seen large variations in predicted trigger rates depending upon the simulation used — variations large enough to encompass the range between “working” and “not working.”

The gains for switching to 132 nsec crossing period for the experiments may not become clear until the detector performance at 396 nsec has begun to degrade substantially. That will not be for several years.

4b. Accelerator Risks

There will be a cost in integrated luminosity associated with any major change in the way the accelerator complex is operated, such as those described below. There is always a risk that the investment of integrated luminosity accumulated during the machine development and commissioning periods will not be recovered during subsequent higher performance operations.

Risks for 132 nsec Operation

We list here several major risks:

Integrated Luminosity. The main risk for 132 nsec operation is: The additional long range beam-beam force may preclude delivery of integrated luminosity competitive with standard 396 nsec operation. This risk still exists even if the total number of antiprotons is increased.

Losses at CDF and DØ. It is expected that the loss rates at CDF and DØ associated with the protons will be larger by 140/36 (the ratio of the number of bunches required for 132 nsec and 396 nsec operation). In particular, the losses associated with proton removal will be about four times higher.

More Protons Require More Care. In addition to pushing the long range beam-beam interaction and losses at CDF and DØ, increasing the total protons in the Tevatron lead to other operational problems which will need to be controlled. There will be more protons that need to be removed to support recycling of antiprotons. The larger proton current may lead to instabilities which will require mitigation. The larger number of proton bunches may cause new effects, such as the electron cloud instability.

Finding the Resources for Instrumentation. The accelerators will not be controllable if sufficient resources (people mostly) are not identified and made available to make the required instrumentation work.

We list here two minimal risks:

Kickers and RF Cavities. Finishing the kickers and RF cavities required for 132 nsec operation poses no risk as long as sufficient priority is given to the effort. Installing them also poses minimal risk for operation.

Separators. Finishing the separators required for 132 nsec operation pose minimal risk as long as sufficient priority is given to their completion. However, the present plan requires relocating some of the separators and a power supply in a way that precludes head-on collisions at CDF and DØ. Leaving the present separator system in place, of course, preserves the capability for head-on collisions. Installing the new separators and one new power supply at the new location specified in the present plan can provide the capability for the large crossing angle required by 132 nsec operation. This path would pose minimal risk to operation.

Risks for Luminosity Leveling Operation

The primary risk for luminosity leveling the fact that the beam time required to set up and commission the operation, and to implement it on each store is not known.

Risks for 264 nsec Operation

No beam physics calculations have been done, and thus it may not work - even on paper. It will very likely be worse than 396 nsec operation, but better than 132 nsec since the large crossing angle is presumably not required.

5. Summary

5a. Summary for Detectors

1. Running with 396 nsec between crossings up to about 2×10^{32} ought to be acceptable for CDF and DØ with the presently scoped Run 2B upgrades.
2. Running at luminosities higher than about 2×10^{32} with 396 nsec between crossings will degrade the CDF and DØ track trigger performance.
3. We can't pinpoint a drop-dead luminosity beyond which things simply will not work. Partly this is because of simulation uncertainties. Run 2 trigger performance data at high luminosities would be a great help.
4. Offline track reconstruction and b-tagging efficiency also suffers at high luminosity.
5. Staying with 396 nsec rather than going to 132 nsec is unlikely to result in a major reduction in cost or scope of the Run 2B detector upgrades.
6. Switching to 132 nsec operation would increase the backgrounds associated with protons at CDF and DØ by a factor of order 4 (140/36).

5b. Summary for Accelerators

1. We assume the accelerator complex for Run 2A actually will get to the point where the instantaneous luminosity can be such that head-on collisions with 396 nsec bunch spacing is unacceptable for efficient operation of the detectors due to the large number of interactions per crossing.
2. Operation at 132 nsec requires a crossing angle which will reduce the number of interactions per crossing by a factor of about two, reduce the instantaneous luminosity by the same factor, and give a shorter luminous region with a larger fraction of events inside the silicon (about a 15% effect).
3. We haven't documented a clear accelerator physics showstopper for 132 nsec operation. However, an additional factor of about four in protons (140/36) compared to 396 nsec operation will certainly exacerbate long range beam-beam interactions, detector backgrounds, possible instabilities, and removal of protons for recycling.
4. With any major operational change in the accelerator complex, machine development and commissioning time will be required during which the integrated luminosity will likely be reduced.
5. We have identified many shortcomings in the instrumentation for the Main Injector and Tevatron even for the present 396 nsec operations, and several of these will require additional upgrading for 132 nsec operation.
6. Completing the assembly of the kickers, RF cavities and separators needed for 132 nsec operation poses no technical risk. However, the present plan for

installation of the separators precludes head-on collisions, and this risk can easily be eliminated as noted in the text.

7. Luminosity leveling is an attractive option which could be considered to extend the operation with head-on collisions in a manner which may allow the detectors to continue to take data effectively.

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