Report to the Fermilab Director

Concerning 132 Nanosecond Operation During Run 2

June 6, 2002

Team 132

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.

Note: In this talk thin red lines indicate items lifted directly from the June 6, 2002 report.

Team 132: Finley and Montgomery

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Past Tevatron
Collider Complex

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Run 2B report and
D0 experience

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Team 132: Lockyer and Womersley

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CDF Co-Spokesperson

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D0 Co-spokesperson

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Team 132: Mike Martens and Tanaji Sen

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Today's operation as Collider Coordinator

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Team 132: Who Brings What?

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Recent Run 2B report and D0 experience

D0 Co-spokesperson

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Ground Rules

Requirements

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Ground Rules

1a. Ground Rules

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

1. We assume 2-4 fb^{-1} will be delivered to each of CDF and DØ, and this will require replacement of silicon.

2. We assume the instantaneous luminosity can reliably exceed 2×10^{32} /cm^2 /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.

3. We do not address any issues related to BTeV and 132 nsec bunch spacing.

Numbers

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 $8x10^{31}$	396 nsec and $8x10^{31}$
132 nsec and $2x10^{32}$	396 nsec and $2x10^{32}$
132 nsec and $5x10^{32}$	396 nsec and $5x10^{32}$

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

	396 nsec	132 nsec
Luminosity	$2x10^{32}$	? ? ?
Number of Bunches Protons/Antiprotons	36x36	140x103
Protons/bunch	$2.7x10^{11}$	$2.7x10^{11}$
Antiprotons/bunch	$3x10^{10}$	$> 0.94\ x10^{10}$
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

Numbers … with notes.

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 $8x10^{31}$	396 nsec and $8x10^{31}$
132 nsec and $2x10^{32}$	396 nsec and $2x10^{32}$
132 nsec and $5x10^{32}$	396 nsec and $5x10^{32}$

The CDF and DØ Run 2B upgrades are designed to operate at $5´ 10^{32}$ with 132 nsec bunch spacing.

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

	396 nsec	132 nsec
Luminosity	$2x10^{32}$	? ? ?
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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

B $N_{protons}$ larger by

~ 4 = 140 / 36

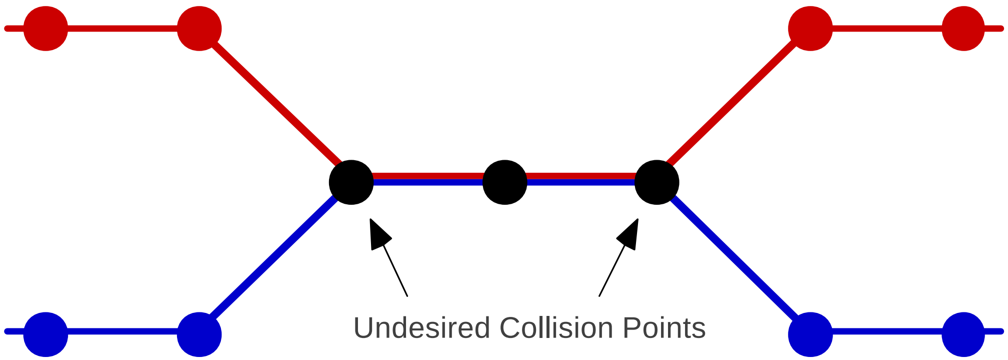
B $N_{antiprotons}$ exactly the same

36 x 3 = 103 x 0.94

Note Crossing Angle

The Need for a Crossing Angle

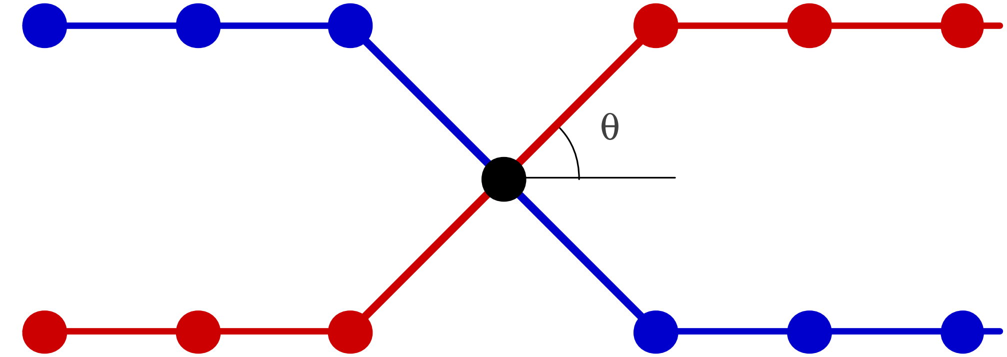
(Courtesy of John Marriner's Group 132 Talk April 13, 2000)



With Head on Collisions.

The separators are located at the first "Undesired Collision Points."

With a 7 rf bucket spacing a crossing angle is required



With Crossing Angle.

Notes on Comparing Instantaneous Luminosity for 396 nsec and 132 nsec

- The instantaneous luminosity is proportional to:
  - $N_{protons}$ (B $N_{antiprotons}$) H
  - $N_{protons}$ = number of protons per bunch
  - B = number of "bunches" … meaning …
    - number of <u>colliding bunches</u> (= number of <u>antiproton</u> bunches)
  - $N_{antiprotons}$ = number of antiprotons per bunch
  - H = Hourglass factor (always less than 1)
    - Mainly depends on (bunch length / beta function), and crossing angle
    - ~ 1 for: bunch length << beta function AND zero crossing angle

- Also assume in going to 132 nsec from 396 nsec:
  - Beam sizes held constant (transverse and longitudinal)
  - (B $N_{antiprotons}$) = Total number of antiprotons remains the same.
  - (140/36) $N_{protons}$ = Total number of protons increases by ~ 4
    - H_{132} / H_{396} ~ 1 / 2 due to crossing angle

Going from 396 nsec to 132 nsec
Factors of Four, Three and Two

- Four
  - ~4 (140/36) : Number of proton bunches for 132 nsec and 396 nsec
  - The same number of protons per bunch means …
  - Total number of protons in the Tevatron goes up by a factor of ~4
- Three
  - ~3 (103/36): Number of antiproton bunches for 132 & 396 nsec
  - The same total number of antiprotons means …
  - a. The same luminosity (if no other changes … but see below)
  - b. The number of interactions / crossing goes down by a factor of ~3
- Two
  - The instantaneous luminosity drops by a factor of ~2 due to the crossing angle

Interactions Per Crossing and an Answer

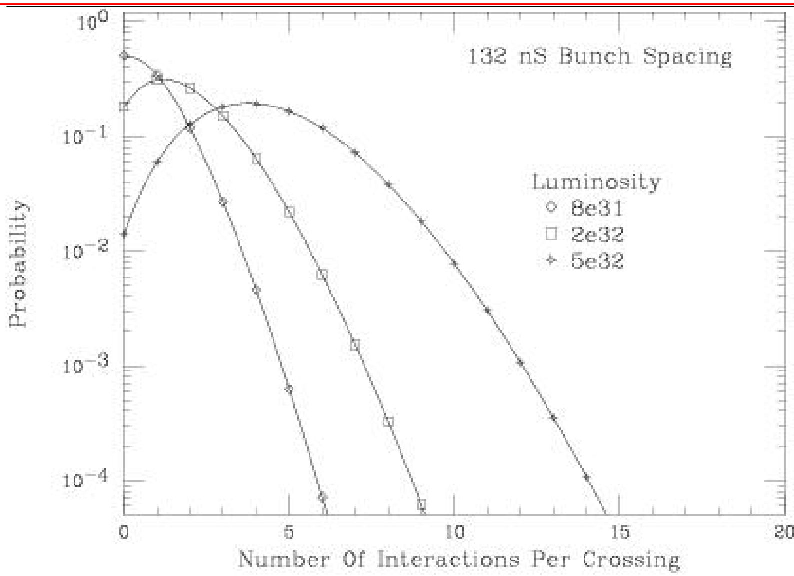


Figure 1. Number of Interactions per bunch crossing for L = 8×10^{31}, 2×10^{32}, and 5×10^{32} cm^{-2} s^{-2}, with 132 nsec operation.

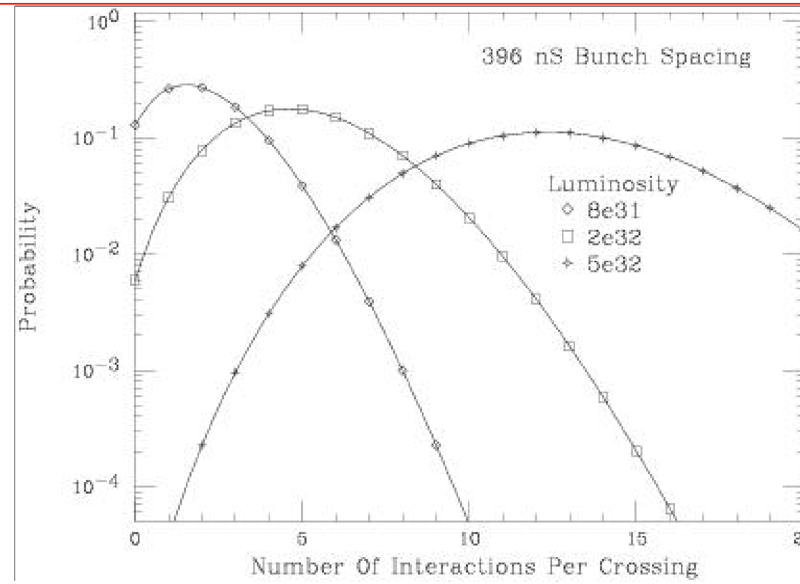


Figure 2. Number of Interactions per bunch crossing for L = 8×10^{31}, 2×10^{32}, and 5×10^{32} cm^{-2} s^{-2}, with 396 nsec operation.

From Detector Summary

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.

And Now The Question

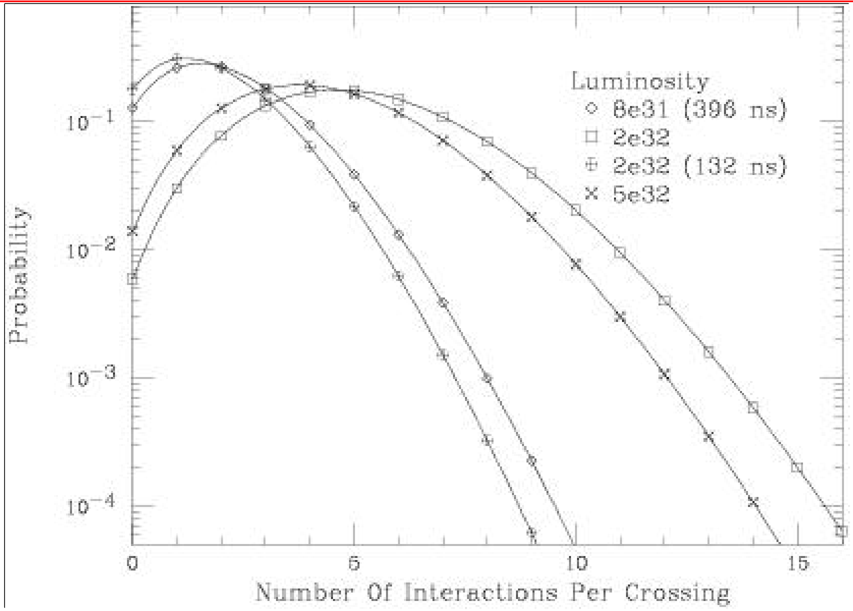


Figure 3. Extracts from the above figures comparing the number of interactions per crossing for 8×10^{31}/396 nsec with 2×10^{32}/132 nsec, and 2×10^{32}/396 nsec with 5×10^{32}/132 nsec.

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.

D0 Track Trigger

From The Detector Summary:

2. Running at luminosities higher than about 2×10^{32} with 396 nsec between crossings will degrade the CDF and DØ track trigger performance.

D0 Track Trigger:

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).

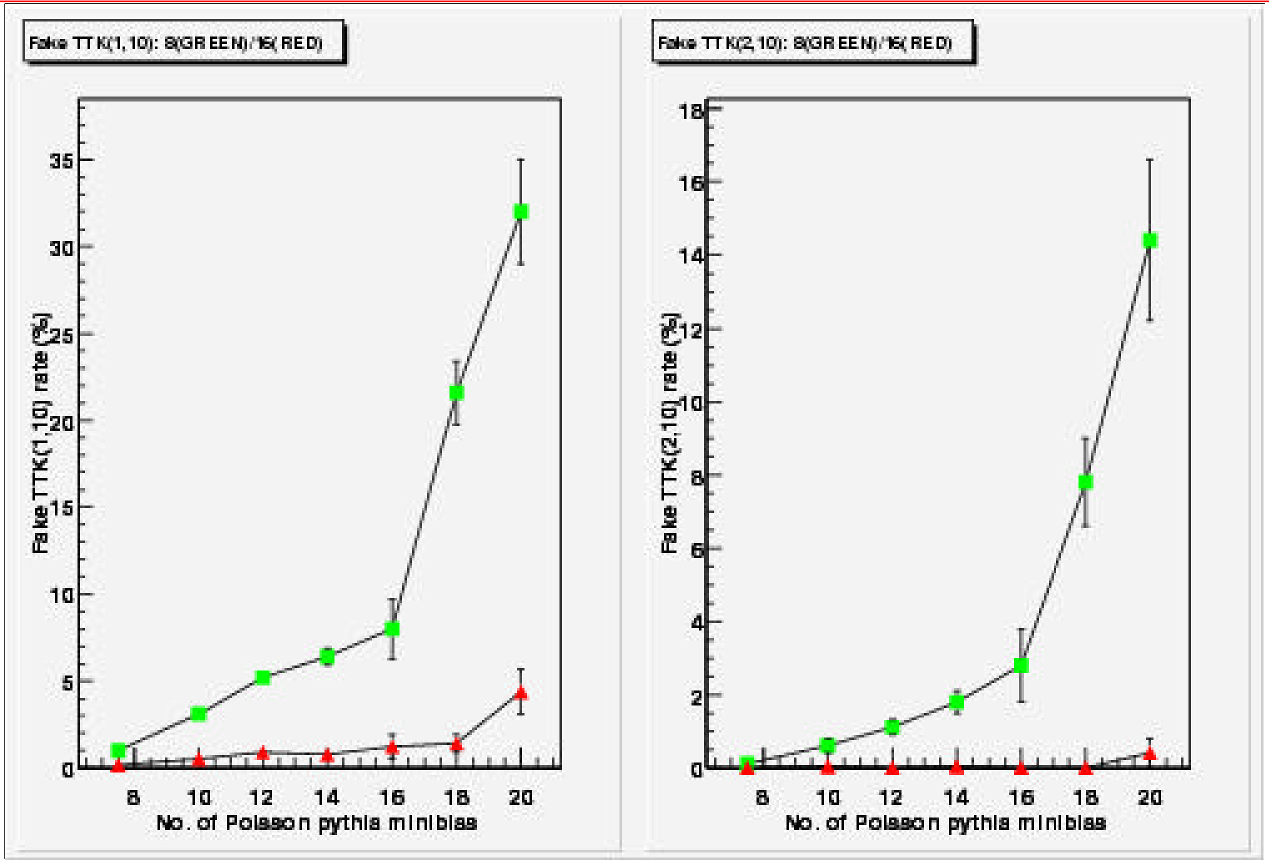


Figure 6. Fraction of crossings with a fake track trigger as a function of the mean number of minimum bias collisions per crossing. The left hand plot shows the rate for a single 10 GeV track and the right hand plot for two 10 GeV tracks. Green (upper) symbols are the present doublet fiber trigger and 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.

CDF Track Trigger

From The Detector Summary:

2. Running at luminosities higher than about 2×10^{32} with 396 nsec between crossings will degrade the CDF and DØ track trigger performance.

CDF Track Trigger:

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.

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.

CDF Track Trigger

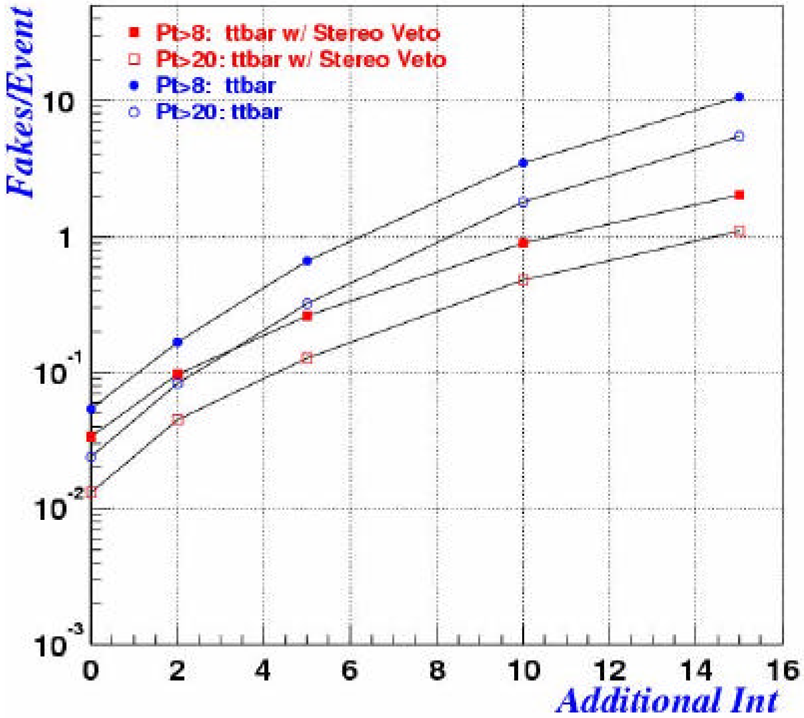


Figure 10. The average number of fake tracks per event in ttbar Monte Carlo as a function of the number of additional interactions per crossing. The curves are shown for XFT tracks with P_T>8 GeV/c and P_T >20 GeV/c. Also shown is the reduction of fake rate provided by requiring the presence of a segment 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 ttbar).

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

CDF Track Trigger

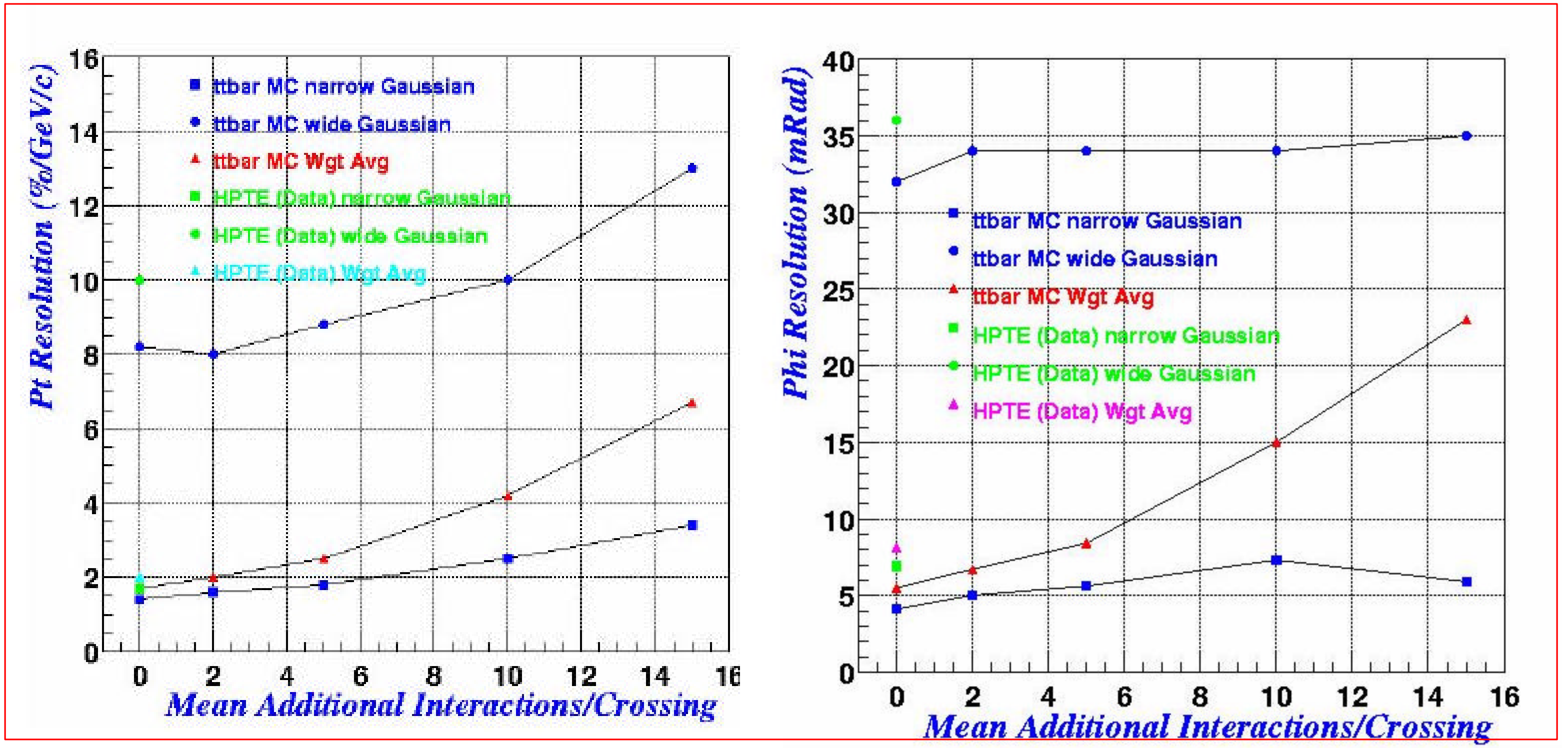


Figure 11. The transverse momentum and azimuthal resolutions of the XFT. The XFT resolution is fit to narrow and wide Gaussians. As more minbias events are overlapped, the weighted mean of the areas of the narrow and wide Gaussians indicate a much greater fraction in the wide Gaussian, and therefore 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.

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

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.

Detector 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).

The Tune Footprint Is Dominated by Head On

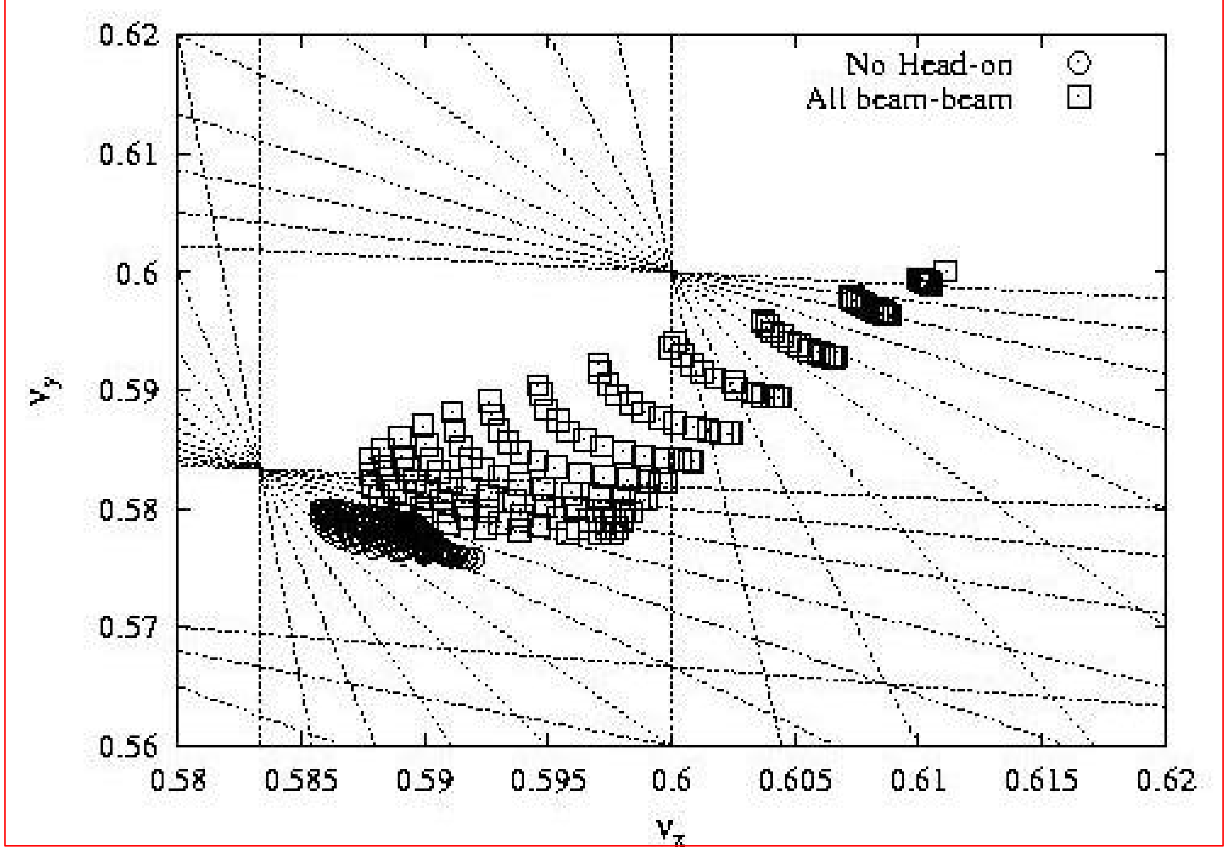


Figure12: Tune footprint with all beam-beam interactions (squares) compared with the footprint with only the long range interactions (circles) [taken from Reference [1]].

The Tune Footprint Is Dominated by Head On

These are the long range only

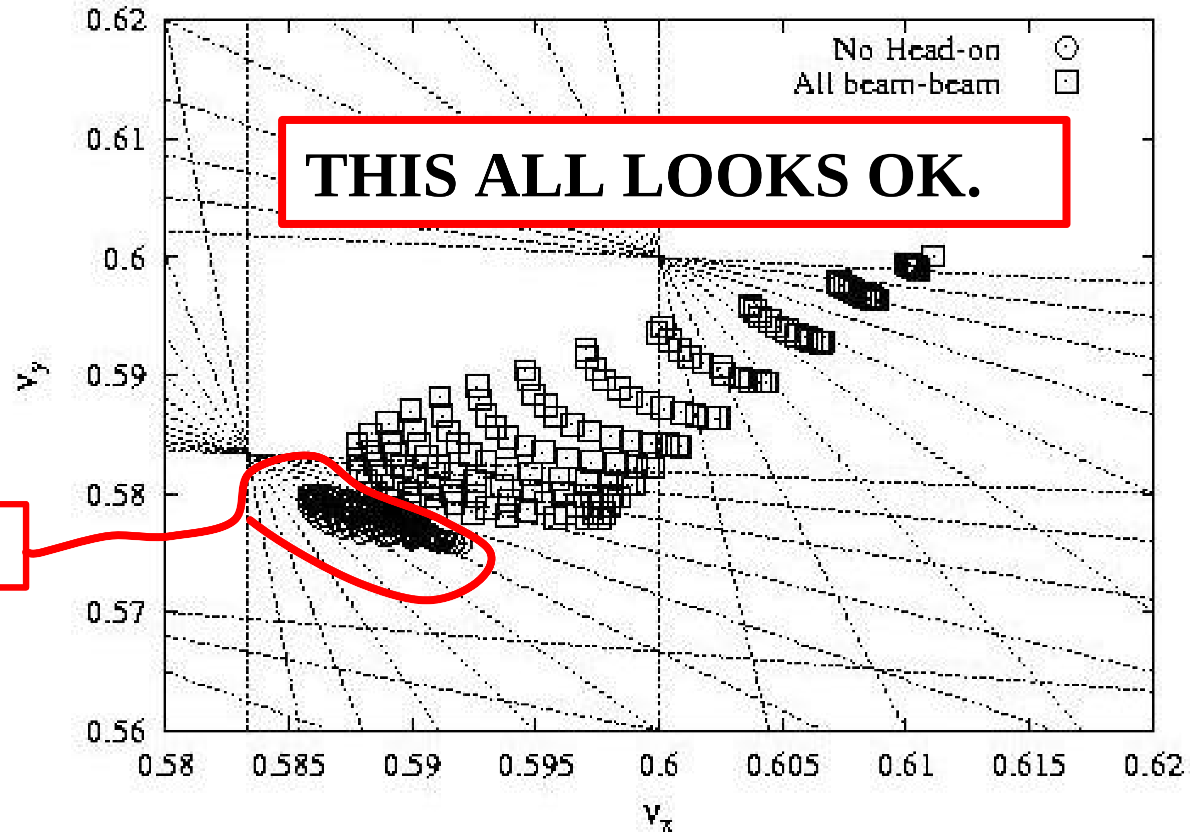


Figure12: Tune footprint with all beam-beam interactions (squares) compared with the footprint with only the long range interactions (circles) [taken from Reference [1]].

The Dynamic Aperture Is Dominated By Long Range

… the dynamic aperture … 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.

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]].

The Dynamic Aperture Is Dominated By Long Range

Note: This is for 396 nsec and the Run 2A design emittances … not 132 nsec

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)
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Table 1: Average and minimum dynamic aperture (DA) in
for various configurations of nonlinear interactions experie
[taken from Reference [1]].

THIS DOES NOT LOOK "OK" for going to 132 nsec …

but it has to be checked.

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.

Four Times As Many Protons Also …

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 $140 \times 2.7\times10^{11} = 3.8\times10^{13}$.

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.

There will be more protons that need to be removed to support recycling of antiprotons.

Recall: Recycling of antiprotons means more integrated luminosity

Accelerator Summary Item #3

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.

Instrumentation

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.

… 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.

We made a list in the report …

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.

This is true even now for 396 nsec operation.

Luminosity Leveling

Luminosity Leveling Approach

With 396 nsec operation, something like luminosity leveling would likely be required once luminosities begin to exceed $2x10^{32}$ 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.

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

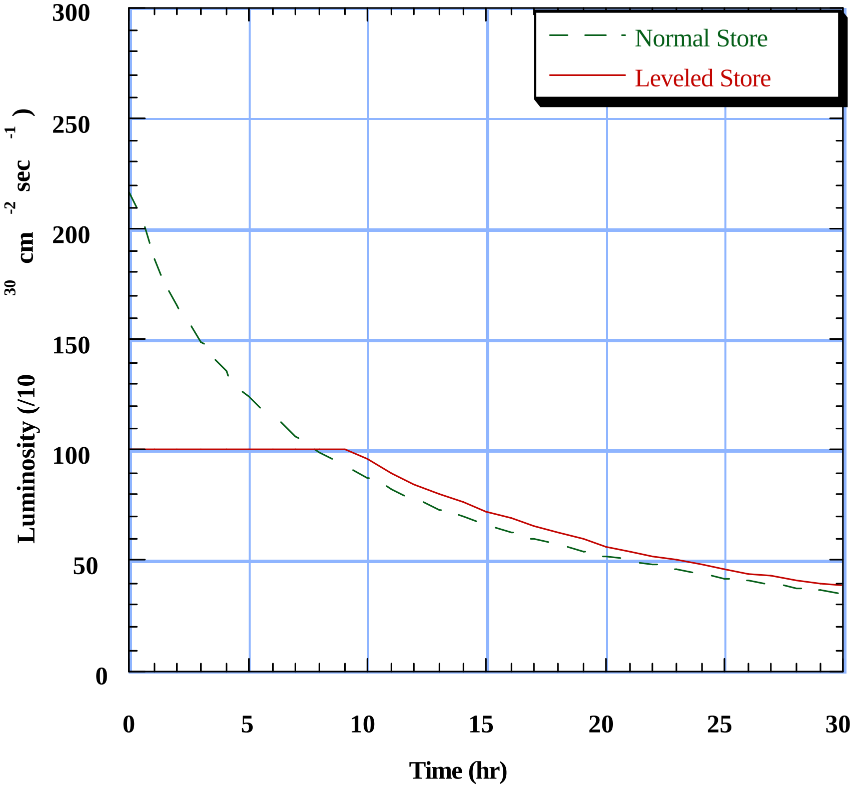
Another advantage of luminosity leveling is the possibility of the extension of the Run 2A configuration of the Tevatron collider complex (not just the Tevatron, but its injectors as well).

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.

Luminosity Leveling

(Courtesy of John Marriner’s Group 132 Talk April 13, 2000)

One can limit the peak luminosity in a store by dynamically modifying the β*. Most of the integrated luminosity is retained.



Luminosity Leveling references

[4] G. Jackson, Chapter 2 of TM-1991 (1997)
http://fnalpubs.fnal.gov/archive/1997/tm/TM-1991.html
and
J. Marriner, *Luminosity Leveling and 132 nsec Operation*
http://tdserver1.fnal.gov/Finley/Group132nsec.pdf
and
Slide 51 from J. Marriner, *Luminosity Upgrade Projects,*
DOE Annual Program Review April 1-3, 1997
http://www-bd.fnal.gov/lug/tev33/tev33_docs/jm4297

Accelerator Summary 1 to 4

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.

Accelerator Summary 5 to 7

5b. Summary for Accelerators

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.

What's New?

- What new information does Team 132 have in 2002 that Group 132 did not have two years ago?

  - Dynamic aperture calculations (for 396 nsec bunch spacing)
  - Detector simulations beyond ~ 5 Interactions per Crossing
  - Experience with 396 nsec bunch spacing (aka 36 bunch) operation

Going to 132 nsec from 396 nsec
Factors of Four, Three and Two … and Six

- Four
  - ~4 (140/36) : Number of proton bunches for 132 nsec and 396 nsec
  - The same number of protons per bunch means …
  - Total number of protons goes up by a factor of ~4
- Three
  - ~3 (103/36): Number of antiproton bunches for 132 & 396 nsec
  - The same total number of antiprotons means …
  - The same luminosity (if no other changes … but see below)
  - The number of interactions / crossing goes down by a factor of ~3

Note: These two together (1/3 x 1/ 2) give **a factor of ~ 6** fewer interactions per crossing in going from 396 nsec to 132 nsec

- Two
  - The instantaneous luminosity drops by a factor of ~2 due to the crossing angle

Comparing 396 nsec and 132 nsec Interactions per Crossing and Integrated Luminosity

- For "Standard 396 nsec bunch spacing"
  - Suppose 2 to 5 x 10^{32} cm^{-2} sec^{-1} Peak (initial) luminosity
  - Then have ~5* to ~12* Interactions per Crossing
  - Define X = Weekly Integrated Luminosity

- For "Luminosity Leveling and 396 nsec bunch spacing"
  - Assume initial luminosity cut in half and then leveled
  - Then have 2.5 x 10^{32} cm^{-2} sec^{-1} and ~6 Interactions per Crossing
  - And you get ~85% of X (after commissioning)

- For "132 nsec bunch spacing"
  - Keeping the total number of antiprotons the same and using a crossing angle <u>together</u> give one-sixth the Interactions / Crossing, <u>and</u> half the luminosity
  - Then have 1 to 2.5 x 10^{32} cm^{-2} sec^{-1} and ~0.8 to ~2 Interactions / Crossing
  - And you get ~50% of X (after installation and commissioning)

* Taken from Fig 1 or 2 of June 6, 2002 "132 nsec Report". All other interactions per crossing scaled from these.

Summary: Comparing 396 nsec and 132 nsec Interactions per Crossing and Integrated Luminosity

- For "Standard 396 nsec bunch spacing"
  - Suppose 2 to 5 x 10^{32} cm^{-2} sec^{-1} Peak (initial) luminosity
  - ~5* to ~12* Interactions per Crossing
  - Define X = Weekly Integrated Luminosity

- For "Luminosity Leveling and 396 nsec bunch spacing"
  - ~6 Interactions per Crossing
  - ~85% of X (after commissioning)

- For "132 nsec bunch spacing"
  - ~0.8 to ~2 Interactions per Crossing
  - ~50% of X (after installation and commissioning)

* Taken from Fig 1 or 2 of June 6, 2002 "132 nsec Report". All other interactions per crossing scaled from these.