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Accelerator Instrumentation**

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Online Calculation of Tevatron Collider Luminosity using Accelerator Instrumentation

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Abstract

The luminosity of a collision region may be calculated if one understands the lattice parameters and measures the beam intensities, the transverse and longitudinal emittances, and the individual proton and antiproton beam trajectories (space and time) through the collision region. This paper explores an attempt to make this calculation using beam instrumentation during Run 1b of the Tevatron. The instrumentation used is briefly described. The calculations and their uncertainties are compared to luminosities calculated independently by the Collider Experiments (CDF and D0).

1 INTRODUCTION

The primary focus of accelerator instrumentation is on diagnostics in order to identify problems in machine operations. However this same instrumentation may be used to calculate the luminosity of the collision regions assuming that one has knowledge of the lattice. Run 1 of the Tevatron Collider Program and the availability of on-line analysis tools provided the opportunity to attempt this measurement. Some initial uncertainty regarding the calculation of luminosity by the two Collider Detectors (CDF and D0 at the B0 and D0 collision regions respectively) provided the motivation.

1.1 Assumptions

The only assumption about the beam is that both proton and antiproton bunches can be described as three dimensional gaussian distributions,

$$\rho^K(x, y, s, ct) = \frac{N^K e^{-\frac{1}{2} \left(\left(\frac{x-x^K(s)}{\sigma_x^K(s)} \right)^2 + \left(\frac{y-y^K(s)}{\sigma_y^K(s)} \right)^2 + \left(\frac{s-ct+\phi^K}{\sigma_l^K} \right)^2 \right)}}{\sqrt{(2\pi)^3 \sigma_x^K(s) \sigma_y^K(s) \sigma_l^K}},$$

where N^K is the bunch intensity, $\sigma_x^K(s)$, $\sigma_y^K(s)$, σ_l^K , are the transverse and longitudinal bunch sizes, $x^K(s)$, $y^K(s)$, are the closed horizontal and vertical orbits, ϕ^K is the cogging offset (collision offset with respect to $s=0$), and x , y , s , and ct are the independent transverse, longitudinal and time coordinates (in meters) of the bunch. The super-

script K signifies the type beam (p for proton, a for anti-proton). Since the proton crossing at $s=0$ defines $ct=0$, $\phi^p=0$. The gaussian assumption is borne out by measurements from our transverse and longitudinal profile monitors.

1.2 Luminosity

With this form of the beam distribution, the luminosity (with units = $(m^2 s)^{-1}$) may be written as

$$L = h\nu \int_{x,y,s,ct} dx dy ds (2cdt) \rho^p(x, y, s, ct) \rho^a(x, y, s, -ct),$$

with h the rf harmonic number and ν the rf frequency. Integrating over x , y , and ct gives the longitudinal luminosity profile,

$$l(s) = \frac{h\nu N^p N^a e}{\sqrt{2\pi^3 (\sigma_x^p(s)^2 + \sigma_x^a(s)^2) (\sigma_y^p(s)^2 + \sigma_y^a(s)^2) (\sigma_l^p{}^2 + \sigma_l^a{}^2)}} \left(\frac{(x^p(s)-x^a(s))^2}{\sigma_x^p(s)^2 + \sigma_x^a(s)^2} + \frac{(y^p(s)-y^a(s))^2}{\sigma_y^p(s)^2 + \sigma_y^a(s)^2} + 4 \frac{(\phi^a + s)^2}{\sigma_l^p{}^2 + \sigma_l^a{}^2} \right) \quad (1)$$

with $l(s)$ having dimensions of $(m^3 s)^{-1}$. This quantity needs to be summed over the number of colliding bunches.

The transverse beam size σ_i may be written as functions of the lattice parameters β and D (dispersion), the measured values of emittance ϵ_i (in rms and unnormalized form), and fractional momentum spread $\Delta p/p$,

$$\sigma_i(\epsilon_i, \Delta p/p, s) = \sqrt{\beta_i(s) \epsilon_i + (D_i(s) \Delta p/p)^2}. \quad (2)$$

Usually the vertical dispersion is so small that it is neglected. Since the collision point is in a drift region,

$$\beta(s) = \beta_{\min} + (s - s_{\beta_{\min}})^2 / \beta_{\min},$$

and $D(s) = D'(s - s_{D_{\min}}) + D_{\min}$ with D' the derivative of the dispersion. $\Delta p/p$ for a relativistic beam can be related to the longitudinal beam size σ_l by

$$\Delta p/p = \sqrt{2eV} \gamma_t h E_s \sin(\pi \nu \sigma_l), \quad (3)$$

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where V is the voltage of the rf, γ_t is the transition γ , and E_s is the synchronous energy.

Since the transverse beam monitors are (usually) not located within the collision region, it is necessary to know the lattice well enough to calculate the ratio of $\sqrt{\beta_{\min} / \beta_{\text{monitor}}}$ in order to use the measured bunch sizes. In addition the location of β_{\min} as well as the dispersion must be determined.

In order to minimize the beam-beam tune shift in Run 1, electrostatic separators were installed in the Tevatron. These separators give rise to separated helical orbits for the proton and antiproton beams. Another set of electrostatic separators near the collision regions are adjusted to bring the beams into collision once low beta is achieved. If this adjustment is incorrect, the trajectories of the proton and antiproton closed orbits in the collision region may not coincide and thus should be measured. In this region, the closed orbits are simply $x(s)=m_x s + b_x$, and $y(s)=m_y s + b_y$, with different slopes and offsets for proton and antiproton beams.

2 INSTRUMENTATION

The measurements described in this paper all took place at the end of Run 1B (1994-1996). The instrumentation platform in each of the following cases was a commercial Apple Macintosh® computer running National Instruments' LabVIEW® which was interfaced [1] to the Accelerator Divisions Control System ACNET via Token Ring or Ethernet. This front-end platform and software gave us a powerful data acquisition/analysis tool which allowed on-line analysis of copious amounts of data. The summary results were then available to ACNET. In addition another software interface TCPort allowed the front end to request data from any ACNET device in the accelerator. This last feature was used by the another front-end (the "Luminometer") to acquire the measured data from the other front-ends and make the luminosity calculations for each bunch and collision region. This was done by numerically integrating equation (1) over the variable "s". The update times (for 12 different collisions) was typically less than a few seconds and primarily was limited by the update times of the actual instrumentation.

The following sections provide brief details of the Instrumentation Front-Ends.

2.1 SBD - Beam Intensities and σ_1 .

The Sample Bunch Display (SBD) [2] is composed of a front-end interfaced via GPIB to a Tektronix® 620 Oscilloscope. The oscilloscope was connected to a high bandwidth (3kHz to 6GHz) wall current monitor. The front end sequenced the oscilloscope through each individual proton and antiproton bunch, calculating the intensity, centroid, and rms of the central bunch as well as any satellite bunches (up to ± 5 rf buckets away). The system of oscilloscope, cabling, and wall current monitor were

characterized *a priori* to better than 1% absolute intensity. During the a store the total summed intensity of all the bunches could be compared to a DCCT monitor, which had been calibrated to better than 1% by a current source. The two results agreed within the 1% error margin. The rms calculation precision was limited by the sampling rate of the scope (2Gsa/s), but was estimated to be accurate at the 5% level (the rms beam size varied from 2-3 ns during a store).

2.2 Flying Wires and Sync Lite - transverse σ_t .

The Flying Wire System [3] is composed of 3 Flying Wires, all controlled by the same front-end through a VME interface (for the loss monitor data) and a commercial (nuLogic®) NuBus® plug-in for the closed loop motion control. The wires are 30 micron diameter carbon filament which are "flown" through the beam at speeds of 5 m/s. The losses, primarily pions, are detected 1 m upstream (antiprotons) and downstream (protons) by two loss monitors (plastic scintillators). The loss profiles as a function of wire position are fitted to a gaussian profile with a sloping background using a non-linear Levenberg-Marquardt algorithm [4]. There are two horizontal Flying Wires, and one vertical. The two horizontal wires are used to measure both ϵ_x and $\Delta p/p$ by solving Eq. 2 for the two unknowns. Since the vertical dispersion is negligible and we ignore any coupling effects, the single vertical wire suffices for ϵ_y . During a store, the Flying Wires are flown every 30 minutes. The error in the Flying Wire measurement is 5% in emittance, ignoring the lattice uncertainties.

The Synchrotron Light Monitor (Sync Lite) [5] consists of two optical telescopes (one proton and one antiproton) which image the beam using the synchrotron light (at 400 nm) which is produced from the upstream edge of an upstream dipole (protons) and downstream edge of a downstream dipole (antiproton). Each telescope is equipped with a high-speed gated-Intensifier coupled to a CID-Tech® CID camera. The cameras are multiplexed into a single NuBus® framegrabber. The analysis sequences through each proton and antiproton bunch with a complete cycle taking less than 12 seconds. The "normal" analysis consists of a pixel by pixel gain normalization and then the projection of the two dimensional image into horizontal and vertical profiles. These profiles are fitted with a similar algorithm as mentioned above. Since there is only one horizontal profile, it is impossible to unfold ϵ_x and $\Delta p/p$. However the SBD bunch length can be used as in Eq.3 to calculate $\Delta p/p$ and thus ϵ_x can be unfolded from σ_x .

During this measurement, the Flying Wires and the Sync Lite measurements were consistent with each other at the 5% level.

2.3 CPM - ϕ and closed orbit trajectories.

A Collision Point Monitor (CPM) [6] is located at the B0 and D0 Collision regions. Each system includes the standard front end interfaced to a Tektronix® 520 Oscilloscope. The two channels of the oscilloscope are connected through a multiplexer to two pairs (horizontal and vertical) Beam Position Monitors (BPM's). These BPM pairs are located on the drift region end of the low beta quadrupoles, one pair on the upstream side, the other on the downstream side. The function of the system is to calculate straight line beam trajectories (we ignore beam-beam steering) through the collision region. We have shorted the downstream end of the Upstream plates (and shorted the upstream end of the Downstream plates) in order to force the raw proton and antiproton BPM plate signals through the same analysis path (the two plates of each BPM are fed into the two scope channels). The analysis involves a digital rectification of the BPM signals, and the calculation of proton and antiproton trajectories. Since according to Eq.1 we are only interested in the difference between the proton and antiproton orbits, the absolute systematics should tend to cancel. Unfortunately, the system suffered from proton feed-through into the antiproton signal, thus spoiling the calculation. We plan to add an active feedthrough subtraction in a future update.

In addition the proton and antiproton doublet signals are captured on a single oscilloscope trace for each BPM plate. By determining the zero crossing point for each beam and subtracting, we can calculate the cogging offset. The result of this calculation was a measurement of the offset to better than 1.5 cm (50 ps).

3 RESULTS

The program “Luminometer” was written to acquire the instrumentation data every 20 seconds. In addition it read out the luminosities calculated by the Collider detectors from their luminosity monitors. Since the CPM position data was suspect, it was (arbitrarily) assumed that we had head-on collisions, but the cogging offset ϕ was used. The Flying Wire data were combined with the Sync Lite data and the SBD bunch length to obtain the transverse beam sizes. The lattice parameters were those which were considered as the best estimates (10%). The results are shown in the Figure. This particular store was a 6 (proton) on 1 (antiproton) store. Production luminosity begins at the rise of the D0 Detector plot. This where the beam has already been taken to low beta and scraped in order to lower the detector background. (A programming error in Luminometer prevented the acquisition of CDF data).

The most striking result is that the calculation predicts higher luminosity (50% more) than the detectors observe. The error in the detector luminosity is 5%. The suspicion is that the lattice values are incorrect, although the magnitude of the error seems to be outside the suspected theoretical bounds. We are exploring systematic errors in the Flying Wires and Sync Lite. It is also possible that the

beams were not making head-on collisions, but this possibility seems remote since the beams are empirically adjusted to maximize luminosity. The “microstructure” in the calculated plots is due both to the statistical noise in the Sync Lite calculations (every 12 s), and the effect of a simplistic averaging of the current Sync Lite results with older Flying Wire results (flown only every 30 minutes). This gives rise to a step feature whenever fresh Flying Wire data became available. This will be changed in a future version which will weight the Flying Wire data as a function of elapsed time.

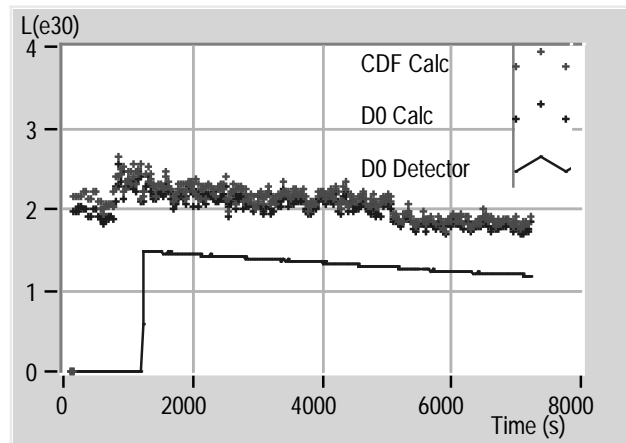


Figure: Operation of Luminometer. The upper traces are those calculated by the on-line program “Luminometer”. The lower trace is the D0 Detector Luminosity . See text for more details.

4 CONCLUSIONS

The results from the Luminometer show much work remains to be done, if we are to achieve the goal of measuring luminosity with accelerator instrumentation. We hope to improve the software algorithms (CPM) and actual hardware (Flying Wires and Sync Lite) to give us more confidence in the results. Finally we need to spend a major effort on the attempt to measure the lattice, especially to correlate beam sizes from the measuring instruments to the collision regions. We may install a test Flying Wire system in a collision region (before the detectors are installed in Run 2) in order to compare the beam size there and that measured simultaneously at the normal Flying Wire and Sync Lite locations.

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