Experiments with Separated Beams in Run I at the Tevatron Collider

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Abstract

During the Tevatron collider Run I, a great deal of effort was spent understanding the luminosity at the two colliding detectors. In collaboration with the Tevatron operations group, the DZero experiment recorded data while the colliding beams were intentionally separated by several beam widths in the horizontal and vertical planes. The resulting luminosity profiles contain a great deal of information about the lattice and beam size parameters at the low-beta focus, which can be extracted by fitting in a variety of ways. This paper will review details of these separated beam measurements and present results on Tevatron lattice parameter and luminosity determination.

1 INTRODUCTION

At the start of Tevatron Collider Run 1b there was difficulty diagnosing the state of the machine. The luminosities at two collider detectors did not agree, with the DZero monitor indicating about 25% higher luminosity, and the CDF longitudinal event profile being asymmetric. Following the discovery and correction of a rolled low-beta quadrupole at CDF, the machine performance improved dramatically and luminosity measurements became more consistent, but with DZero showing a 10% deficit relative to CDF. With the search for the top quark in full swing, this difference generated some interest among DZero experimenters to explore whether there might be problems at their collision region.

As the peak luminosity climbed, both luminometers revealed shortcomings. Improved bunch-by-bunch devices were installed at both experiments, and additional scrutiny was given to the luminosity calculations. Ultimately the experiments agreed to about 3%, with that difference now resolved[1] by further work to understand efficiencies and acceptance of the system[2] used to measure the rate of interactions in the DZero collision region. However, the *accelerator-calculated* luminosity (using measured bunch intensities, emittances, and assumed lattice parameters) predicts the detectors should observe about 30% greater luminosity than is seen (assuming a world average total cross section[3]). Precision cross section measurements drive the need for a well determined luminosity, and a suitably precise calculated value (if achievable) would provide a useful cross check to the rate method.

The beams were first separated at DZero to study halo backgrounds and shielding effectiveness: it was observed that interactions still occurred some distance from the crossing point, where the beam widths are large and overlap. This luminosity z-distribution was asymmetric, which set the stage for a series of separated beam tests[4] completed on 4 stores over the course of Run 1b.

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2 EXPERIMENTAL METHOD

All scans were performed at the end of a store at relatively low luminosity, about $5 \cdot 10^{30}\ cm^{-2}\ s^{-1}$. The scan sequence was to first separate the beams to an extreme position (e.g., $200\ \mu m$) in the horizontal (x) plane, whence DZero data were taken for about 10 minutes, yielding 10K to 45K events; then the separation was changed to a smaller value and data taken again. After completing 2 or 3 data points, the beam separation was brought through zero to repeat the procedure for the same set of separations, but with opposite sign. The same scan procedure was then administered in the vertical (y) plane (with no x separation), and at least one zero-separation point was recorded. The first scan was in x only; in the final test a scan along a diagonal was made in addition to the x and y scans. Three tests occurred during normal $\beta^* = 35\ cm$ operations and one during a week of Tevatron running with $\beta^* = 25\ cm$.

The DZero Level-0 apparatus[2] is constructed of two segmented arrays of fast scintillation counters – situated near the beam pipe on either side of the collision region – and utilizes precise timing for longitudinal collision point "vertex" z-position finding. There are two readout modes: 1) a FASTZ mode (for triggering DZero) which uses a subset of the available counters, has less precise resolution ($\sigma \sim 8\,cm$), and is sensitive to vertices within $100\,cm$ of the detector center; 2) a SLOWZ mode which individually analyzes and records pulse height and time from each counter and provides vertex position resolution of $4\ cm$ for vertices out to $150\ cm$, flags multiple interactions and rejects halo particles. Initially the DZero online luminosity monitor was based upon a FASTZ ratemeter which averaged over all 6 colliding bunches. The improved monitor devices utilized SLOWZ signal scalers and a precise clock to evaluate a 1-minute rate per bunch, and was commissioned in late Run 1b (only the fourth scan has both FASTZ and SLOWZ luminosity measurements, though all runs have both conditions flagged in the recorded data). Data taking was initiated by a loose coincidence of the two Level-0 arrays, or by a prescaled clock signal (to monitor the exposure duration).

The Level-0 data were histogrammed into vertex z-distributions with bin size equal to the digitizer resolution, $0.75\ cm$. A typical distribution is shown in Figure 1, which shows single- (SI) and multiple-interaction (MI) profiles for a $100\ \mu m$ separation (the MI shape depends strongly on the SI shape). Most of these distributions display asymmetries in the relative peak height, and z-position minima clearly offset from zero in both x and y planes. Some normalization corrections are then applied, to make *luminosity* distributions which can be compared and analyzed: 1) the FASTZ luminosities are corrected (using recorded SLOWZ data) for z-acceptance to $150\ cm$; 2) the number of recorded events is scaled to account for trigger prescale and exposure duration, then must be adjusted upward slightly to account for multiple interactions (hence, to first order one must know the luminosity!); 3) all distributions and measured luminosities are corrected up for the measured luminosity decay, about 1% per 10 minute data point.

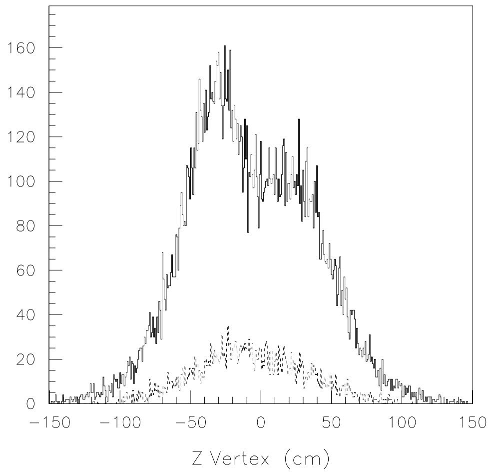

Figure 1: Longitudinal Luminosity Profile for beams separated horizontally by $100\ \mu m$. Solid lines are Single Interaction, and dashed lines are Multiple Interaction events.

3 ANALYSIS AND RESULTS

The accelerator-calculated luminosities are evaluated in the framework of an ideal Tevatron, where luminosity $\mathcal{L}$ is described by a linear model, uncoupled in x and y, characterized by 24 parameters (e.g., see [4]). Making the standard assumption of Gaussian transverse and longitudinal bunch shapes, the luminosity distribution $d\mathcal{L}/dz$ can be written

$$\frac{d\mathcal{L}}{dz} = \mathcal{A}\frac{\exp\left\{-\left(\frac{\delta X^2}{2\ \sigma_x^2}\right) - \left(\frac{\delta Y^2}{2\ \sigma_y^2}\right) - \left(\frac{(Z-Z_C)^2}{2\ \sigma_z^2}\right)\right\}}{\sigma_x(z)\ \sigma_y(z)\ \sigma_z}. \quad (1)$$

$\mathcal{A}$ contains the sum over proton and antiproton bunch intensities which, along with the bunch lengths σ_{zp} and σ_{za}, are measured to about 1% [5],

$$\mathcal{A} = \sum_{i=1,6} \frac{N_{ip} N_{ia} f_{rev}}{(2\pi)^{3/2}}. \quad (2)$$

δX and δY are the bunch center to center transverse separations, and z_c is the beam crossing point (with detector center at $z = 0$), which is measured to a few cm by Beam Position Monitor (BPM) timing. Crossing angles are possible and result in z-dependent separations. Expressions for the transverse beam widths result from convolution over bunches, $\sigma_x^2 = (\sigma_{xp}^2 + \sigma_{xa}^2)$, where

$$\sigma_{xp}^2(z) = \beta_x(z)\epsilon_{xp} + \eta_x^2(z)\left(\frac{\delta P}{P}\right)^2, \quad (3)$$

with similar expressions in y. The ϵ_{ij} are emittances, which are related to the "normalized 95%" values measured using flying wires. Note that the beam widths depend only on the sum of proton and antiproton emittances. The (well known) momentum dispersion is $\frac{\delta P}{P}$ whose coefficient $\eta(z)$ is taken to be a linear function of z (nominally *zero* in y). The "beta function" at the low-beta focus is characterized by a length β^* and given by a quadratic function with minimum at z_0,

$$\beta_x(z) = \beta_x^* + \frac{(z - z_{0x})^2}{\beta_x^*}, \quad (4)$$

with a similar expression for terms in y.

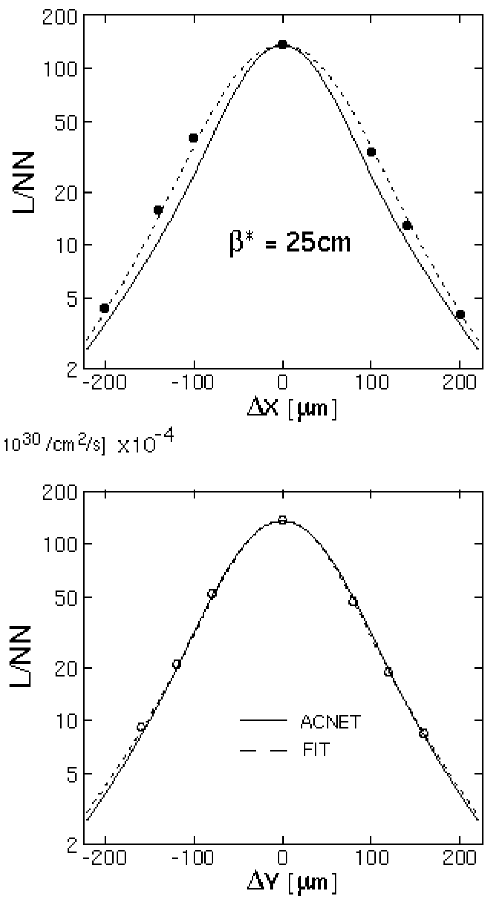

Figure 2: $\mathcal{L}/(N_p N_a)$ versus separation for X and Y scans; the overlayed model calculations use accelerator- (solid line) or fit separated beam- (dashed line) parameters and have been scaled to agree at zero separation.

We have used several approaches to extract information about the colliding beam optics. First, the behavior of lu-

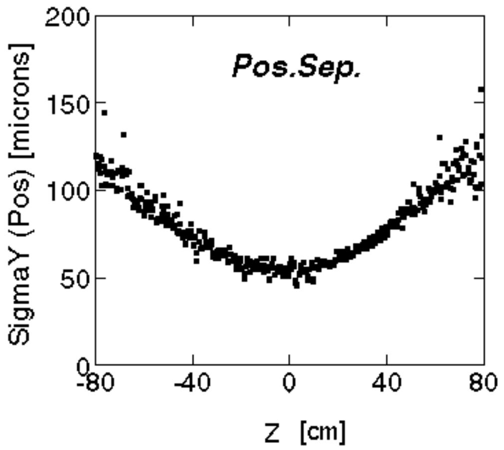

Figure 3: σ_y versus z, overlay of 3 separation ratios from scan 2 positive vertical separations.

minosity versus transverse separation *could* be fitted; however, there is no independent determination of the actual separations because BPMs are only accurate to $\sim 20\ \mu m$. Since these profiles were not all symmetric with the sign of separation, one might be concerned about the separator performance; instead we simply compared the resulting profiles and model as shown in Figure 2.

A second way is to try to fit the longitudinal luminosity profiles, $d\mathcal{L}/dz$, to extract parameters independently for the vertical and horizontal scans: there are 4 or 6 separation points in each scan, in each plane, and we find excellent consistency. The separations can be made parameters of the fit and in most cases agree with the nominal separations with about $5\ \mu m$ error. In all of the scans we find the vertical profiles to be completely consistent with expectations, but the horizontal focus is less sharp than predicted: the fits prefer a larger value for β_x^*, $25\ cm \rightarrow 35\ cm$, and $35\ cm \rightarrow 45\ cm$. It is also possible that the dispersion center is offset from the detector center. We find crossing angles (up to $50 \mu rad$) and focus offsets ($8\ cm$) from zero in both planes in most of the scans. The large number of parameters could be better determined by performing a *global* fit to all of the x and y scans for a given store.

Third, a very useful consequence of Equation (1) is that $\sigma_x^2(z)$ (and $\sigma_y^2(z)$ or $\sigma_{xy}^2(z)$) can be calculated from *the ratio of two z-distributions* recorded with different separations δX_1 and δX_2,

$$\sigma_x^2(z) = \frac{(\delta X_2)^2 - (\delta X_1)^2}{2\ \ln\left(\frac{d\mathcal{L}_1}{dz} / \frac{d\mathcal{L}_2}{dz}\right)}. \tag{5}$$

The σ_i^2 are quadratic functions of z that can be easily fit. The multiple separations of each sign again provide a consistency test which in this case validates the fundamental Gaussian profile assumption, to about $4\ \sigma$. In Figure 3 an overlay of three determinations of $\sigma_y vs.\ z$ is shown for one scan. One could improve this analysis by using a larger bin size for better statistics; it may then be possible to get widths of the individual colliding bunches. This last analysis promises to be useful in the more complex case of a coupled lattice, where a general framework has been derived that requires only measurements of $\sigma^2(z)$ along $\{x, y, diag\}$ at the focus to calculate the luminosity[6].

4 CONCLUSIONS

The separated beam technique provides a new method for fast diagnosis of the low beta focal optics, and a tool for precise measurement of machine parameters. Using separated beam scan fitted parameters gives somewhat better agreement with the measured luminosity and transverse profiles than is obtained using accelerator measured emittances and assumed lattice parameters. However the calculated luminosity is still substantially low as can be seen in Table 1. The next step will be to combine these measurements of σ^2 with the covariance matrix technique[6].

Scan	Store	β^* (cm)	Model/Meas. *Accel Params*	Model/Meas. *Fit Params*
1	5224	35	1.31	–
2	5320	35	1.34	1.19
3	5378	25	1.43	1.28
4	5628	35	1.35	1.46

Table 1: Ratios of calculated to measured luminosity for separated beam scan stores.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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