RESULTS FROM VERNIER SCANS DURING THE RHIC 2008 PP RUN*

A. Drees† and T. D'Ottavio
Brookhaven National Laboratory, P.O. Box 5000, Upton NY 11973-5000, USA

Abstract

Using the vernier scan or Van der Meer scan technique, where one beam is swept stepwise across the other while measuring the collision rate as a function of beam displacement, the transverse beam profiles, the luminosity and the effective cross section of the detector in question can be measured. This report briefly recalls the vernier scan method and presents results from the 100 GeV 2008 RHIC polarized proton (pp) run.

INTRODUCTION

The RHIC Zero Degree Calorimeters (ZDC) [1] were originally designed exclusively for heavy ion operations due to their forward position behind the separating RHIC DX dipole magnets and consequent sensitivity to only forward neutrons. During pp runs the ZDCs are exposed to considerably fewer particles because of the small forward neutron cross section. Therefore, the PHENIX and STAR experiments use individual beam beam counters (BBCs) for luminosity monitoring which are of different types, shapes, locations and geometrical acceptances.

Like the ZDCs, the BBC detectors consist of two identical units on either side of the Interaction Point (IP) vertex location. Collision rates are typically measured by a coincidence of particle detection on both sides. Once charged particles and a larger geometrical acceptance are accounted for, the BBC coincidence rate in pp operation is larger than the ZDC coincidence rate by about 2 orders of magnitude. With luminosities of more than $10^{31} cm^{-2} s^{-1}$, this can lead to other problems such as detector dead-time, other saturation effects in the detectors and their electronics, and an increased probability for double-events. Since the ZDCs are common to both RHIC experiments and much less affected by such problems, they are the detector of choice for luminosity monitoring and comparison between the experiments. The considerable increase in pp luminosity in recent years now allows for the ZDCs to be used in pp operation without the concern of statistical limitations. However, they need to be calibrated every run, so vernier scans at the individual IPs have been performed. These scans also yield valuable emittance measurements. This report presents an analysis of data from 2007-8 pp run vernier scans.

THE METHOD

The vernier scan technique was invented by S. van der Meer in 1968 [2]. A scan is done by observing the counting rate R in a suitable monitor system while sweeping the two beams vertically and horizontally through each other. A Gaussian-shaped curve results with its maximum at zero displacement. The interaction rate observed by such a suitable detector, R_{det}, is defined as the total number of beam particles (Nt_{blu} and Nt_{yel}) going through each other in some area A with the cross section σ_{det}:

$$R_{det} = \frac{Nt_{blu} Nt_{yel}}{A} \sigma = \mathcal{L} \sigma_{det} \tag{1}$$

For two beams with Gaussian distribution in both, horizontal and vertical directions, the luminosity is given by [3]:

$$\mathcal{L} = \frac{k_b f_{rev} N_1 N_2}{2\pi \sqrt{(\sigma_{x1}^2 + \sigma_{x2}^2)(\sigma_{y1}^2 + \sigma_{y2}^2)}}. \tag{2}$$

with i=1,2 for blue and yellow beams respectively and N_i being the number of particles per bunch, assuming all bunches in one beam are of the same intensity and collide in that particular IP. Bunch-to-bunch variations are typically negligible. The number of actually colliding bunch pairs in RHIC, however, has a significant effect of about 5-10% depending on the fill pattern and IP. This correction is applied before cross sections are calculated. If one beam is transversely displaced by distance d, the luminosity $\mathcal{L}(d)$ is:

$$\mathcal{L}(d) = \frac{k_b f_{rev} N_1 N_2 \exp\left[-d^2/2(\sigma_{x1}^2 + \sigma_{x2}^2)\right]}{2\pi \sqrt{(\sigma_{x1}^2 + \sigma_{x2}^2)(\sigma_{y1}^2 + \sigma_{y2}^2)}} \tag{3}$$

The terms $\sqrt{\sigma_{i1}^2 + \sigma_{i2}^2}$, where $i = x, y$, in Eq.3 and Eq.2 correspond to the beam profile derived from the width of the distribution measured by the vernier scan. The result for the horizontal plane is:

$$\sigma_{Vx} = \sqrt{\sigma_{x1}^2 + \sigma_{x2}^2}. \tag{4}$$

Vernier scans measure the effective beam profile over the whole longitudinal interaction area between the two halves

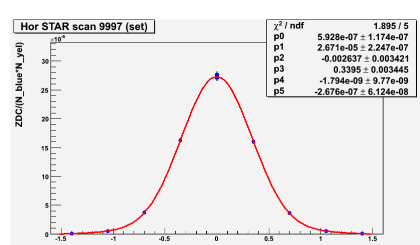

Figure 1: Vernier scan in STAR using the ZDCs in the horizontal plane.

* Work performed under Contract Number DE-AC02-98CH10886 with the auspices of the US Department of Energy.

† drees@bnl.gov

of a beam-beam detector, i.e. approximately ± 0.3 m (PHENIX BBC), ± 3.5 m (STAR BBC) and approximately ± 20 m in the case of the ZDC. The PHENIX BBC, however, is practically measuring the transverse size at the center of the IP while in the two other cases the measured transverse beam size is subject to the evolution of the beam profile along the longitudinal axis (a.k.a. the "hourglass" effect [4]). However, the collision rates from those detectors do correspond to the number of events originating from the entire effective beam area and therefore are still appropriate for luminosity monitoring. Hence, applying a Gauss-fit + constant + 1^{st} order polynomial (to account for asymmetric backgrounds) to the normalized collision rate = $R_{det}/Nt_{blu}Nt_{yel}$ as measured by the various beam-beam detectors as a function of beam displacement yields the effective beam size with and without the hourglass effect as well as the maximum achievable rate R_{max}, the optimal position and the background. Figure 1 shows an example of a typical data set and the applied Gauss fit. From this the effective cross section σ_{det} can be derived when all bunches collide in the given IP:

$$\sigma_{det} = 2\pi\ R_{max}\ \sigma_{Vx}\ \sigma_{Vy}\ k_b/(f_{rev}N_1N_2) \qquad (5)$$

where f_{rev} is the revolution frequency and k_b the number of bunches per ring. Note that in Eq. 5 R_{max} is not normalized and it is assumed that bunch to bunch variations are small and all bunches collide at the IP.

Table 1: List of vernier scans performed at STAR and PHENIX during the 2008 RHIC pp run. All scans were done at a β^* of approximately 1m and with a pattern of 109x109.

fill	IP6	IP8	beam	date	comment
9906	x	x	yellow	Feb. 9	off-center
9937	x	x	yellow	Feb. 22	
9977	x	x	yellow	Mar 2	
9983	x		yellow	Mar 4	early in store
9990	x		blue	Mar 6	early in store
9997	x	x	yellow	Mar 7	90 sec/step
9998		x	yellow	Mar 9	off-center
10000		x	blue	Mar 9	90 sec/step

DATA ANALYSIS

Table 1 lists the available vernier scans from the RHIC 2008 pp run at the STAR and PHENIX IPs respectively. Several corrections are routinely checked together with contributions to the systematic error. In more recent runs with increased luminosity and reduced β^*, two corrections had to be added (in bold):

- beam displacement in the other plane during the scan (correction)
- actual bunch-pairing in given IP, fill pattern correction (correction)
- crossing angle between the colliding beams (systematic error)
- uncertainty in the step size (systematic error)
- uncertainty in the bunch intensity (systematic error)
- **accidental coincidence rate due to high single side counts (correction)**
- **hourglass correction to the emittance and luminosity measurement due to long bunches and small β^* values (correction)**

A more detailed account of those error contributions and corrections can be found in [5]. This report focuses on the last two items in this list. The total systematic error accumulates to about 5%.

Accidental Coincidences

During the 2008 pp run the single unit rates of the ZDCs or BBCs have increased considerably compared to early runs such as the run in 2003 [5]. High single rates cause a certain number of accidental coincidences, i.e. they artificially increase the collision rate by a varying amount. This amount depends on the bunch intensity, the number of bunches and the background conditions. The correction is simple using the ZDC single rates assuming the ZDC coincidence window is larger than the bunch length, which it is. The same applies to the BBC counters:

$$R^{coinc}_{corr} = R^{coinc}_{raw} - \frac{R^{single}_{up} R^{single}_{down}}{f_{rev}k_b} \qquad (6)$$

with R_{up} and R_{down} referring to the rate detected by the individual unit on either side of the IP. For the scans listed in Tab. 1 this correction ranges from 5-9% for the ZDCs and from 9-13% for the STAR BBCs during the the 2008 run. Single rates were not available for the PHENIX BBCs. The measured R_{max} and as such the derived effective cross section for the ZDCs (or BBCs) has to be reduced by that amount.

Hourglass Correction

When the longitudinal beam size $\sigma_z \simeq \beta^*$, the reduction of the nominal luminosity $\mathcal{L}_0$ due to the geometrical (hourglass) effect for Gaussian beams becomes non-negligible and is given by a correction factor R [4]:

$$R \equiv \mathcal{L}/\mathcal{L}_0 \qquad (7)$$

The reduction factor is a function of the bunch length (or more correctly, the overlap region of the two bunches) and the value of β^*. The longer the overlap region with respect to the β^* value the more the reduction factor deviates from 1 towards 0. Figure 2 represents a measurement of the hourglass effect in the PHENIX IP by comparing the beam sizes at ± 20 m with those at ± 0.3 m. The resulting measured hourglass reduction factors range from 0.73 up to 0.83 while the calculated factors range from 0.7 up to 0.78. In the calculation and measurement the overlap region is assumed to be Gaussian. This is in fact the case

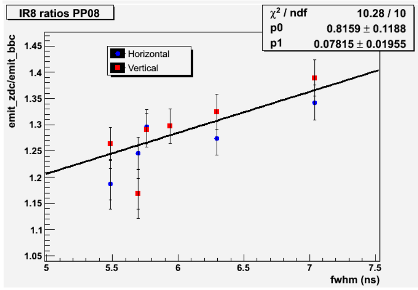

Figure 2: Ratio of emittance measured by the ZDC and the emittance measured by the BBC in PHENIX as a function of the FWHM of the overlap region of both beams. The BBC emittance is derived after a ± 30 cm vertex cut.

for RHIC 2008 data. On average the measured factors are approximately 5% larger than the calculated ones. This can be attributed to a remaining hourglass contribution within the ± 30 cm vertex area. There is no visible effect when emittances from the STAR ZDC and BBC are compared since the STAR BBC covers a ± 3.5 m area.

RESULTS

Figure 3 shows a fit to the results from the six vernier scans performed with the PHENIX ZDC while Fig. 4 shows the equivalent data from the STAR ZDC. After tak-

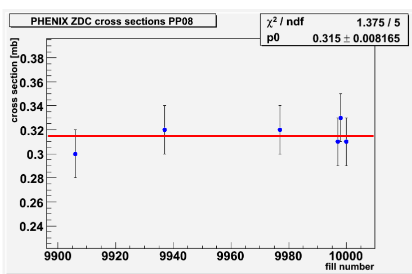

Figure 3: Measured effective PHENIX ZDC cross sections from the RHIC 2008 pp run after corrections.

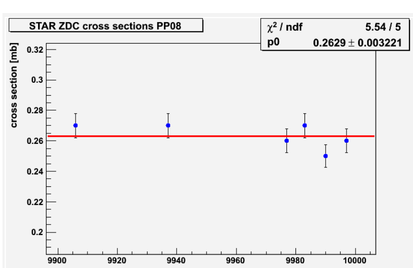

Figure 4: Measured effective STAR ZDC cross sections from the RHIC 2008 pp run after corrections.

ing into account the above mentioned corrections and systematic error contributions the analysis of the six vernier scans yields the following values for the effective ZDC cross sections:

- STAR $\sigma_{ZDC} = 0.26 \pm 0.02$ mbarn and
- PHENIX $\sigma_{ZDC} = 0.31 \pm 0.02$ mbarn.

The difference between the two IPs can be attributed to small differences between the two experiments in the readout electronics and the HV settings used to operate the ZDCs. However, once set, the effective cross section for the ZDCs is remarkably stable and reproducible regardless of the conditions under which the vernier scan was done. This, in turn, is not true for the BBC detectors, especially for the STAR type. Figure 5 shows the measured effective BBC cross sections for STAR. The dependence of the measurement on the actual luminosity is quite prominent. While the luminosity increases by a factor 2.3 over

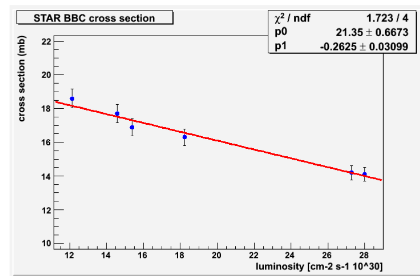

Figure 5: STAR BBC effective cross section as a function of pp luminosity .

the course of the six measurements, the effective cross section drops by 25%. No such effect is seen in the ZDCs. The BBC cross sections were corrected for accidental coincidences. The measured drop, though it contains a small amount of double events, cannot be explained by just those and is not yet understood. Double events are expected to occur at a much smaller rate. The PHENIX BBC, with a smaller geometric acceptance than the STAR BBC, also depicts some dependency on the luminosity. However, the effect is only about half the size, i.e. it drops by about 12% over the course of the same luminosity range. Electronic and/or detector saturation effects are suspected at this point. Therefore, the BBC detectors are not only not suitable if one wants to compare the two IPs in a straight forward way but they should not be used as a luminosity monitoring device for the individual IPs either once the realm of higher pp luminosities is reached.

REFERENCES

[1] A. Baltz et al., Nucl. Instr. and Methods, A417 (1998) 1

[2] S. van der Meer, ISR-PO/68-31, KEK68-64.

[3] P. Castro-Garcia, CERN SL/96-70, KEK97-01-158.

[4] M.A. Furman, PAC 91, p.422 and "Handbook of Accelerator Physics and Engineering", edited by A. Chao, M. Tigner, World Scientific, p. 248 ff. (1999).

[5] A. Drees et al., "Results from Vernier Scans at RHIC During PP Run 2001-2002", PAC 2003 proceedings.