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# EXPERIMENTAL DEMONSTRATION OF INTERACTION REGION BEAM WAIST POSITION KNOB FOR LUMINOSITY LEVELING*

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*Abstract*

In this paper, we report the experimental implementation of the model-dependent control of the interaction region beam waist position ($s^*$ knob) at Relativistic Heavy Ion Collider (RHIC). The $s^*$ adjustment provides an alternative way of controlling the luminosity and is only known method to control the luminosity and reduce the pinch effect of the future eRHIC. In this paper, we will first demonstrate the effectiveness of the $s^*$ knob in luminosity controlling and its application in the future electron ion collider, eRHIC, followed by the detail experimental demonstration of such knob in RHIC.

## GEOMETRIC REDUCTION OF LUMINOSITY

In collider operation, it is sometimes useful to control (lower) the luminosity for one detector without affecting others. There are many methods to control the luminosity for one specific interaction point (IP), for instance, introducing offsets between two colliding beams or increasing the waist beta function of both beams at IP. It is straightforward that adjusting the location of the beta waist ($s^*$) can achieve the same goal.

The luminosity at one IP can be calculated from the following integral

$$L = N_1 N_2 f \int \rho_1 (x, y, s + s_0)\, \rho_2 (x, y, s - s_0)\, dxdydsds_0 \quad (1)$$

where $N_1$, $N_2$ ,$\rho_1$ and $\rho_2$ are the bunch intensities and 3-D normalized distribution functions of two colliding beam respectively, $f$ is the bunch repetition rate. $s = (z_1 + z_2)/2$ and $s_0 = ct = (z_1 - z_2)/2$ correspond to the collision location and time of two beam slices at $z_1$ and $z_2$. We assume both beams has Gaussian distribution in all three dimensions:

$$\rho_{1/2} = \frac{1}{(2\pi)^{\frac{3}{2}} \sigma_{x,1/2}\sigma_{y,1/2}\sigma_{s,1/2}} \times \exp\left[-\frac{x^2}{2\sigma^2_{x,1/2}(s)} - \frac{y^2}{2\sigma^2_{y,1/2}(s)} - \frac{z^2}{2\sigma^2_{z,1/2}}\right] \quad (2)$$

where subscripts 1 and 2 represents two colliding beams and $\sigma_x$, $\sigma_y$ and $\sigma_z$ are the rms beam sizes. Including hourglass effect and the shifted $s^*$, the two transverse beam sizes are function of the longitudinal position:

$$\sigma_{x/y,1/2}(s) = \sigma^*_{x/y,1/2}\left(1 + \frac{\left(s - s^*_{x/y,1/2}\right)^2}{\beta^{*2}_{x/y,1/2}}\right) \quad (3)$$

where $\sigma^{*2} = \beta^* \epsilon$, $\beta^*$ is the beta star located at beta waist position $s^*$, $\epsilon$ is the beam emittance.

The luminosity integral (Eq. 1) can be evaluated by integrate the transverse coordinates and the normalized time $s_0$, and reads:

$$L = \frac{N_1 N_2 f}{2\pi\sqrt{\sigma^2_{x,1} + \sigma^2_{x,2}}\sqrt{\sigma^2_{y,1} + \sigma^2_{y,2}}} G = L_0 G$$

where $L_0$ is the luminosity with zero length, and $G$ is the geometric factor that reflects the reduction of hourglass effect and shifted $s^*$. $G$ has the following integration form:

$$G = \int \frac{e^{-u^2} du/\sqrt{\pi}}{\sqrt{1 + \frac{(u-u^*_{x,1})^2}{t^2_{x,1}} + \frac{(u-u^*_{x,2})^2}{t^2_{x,2}}}\sqrt{1 + \frac{(u-u^*_{y,1})^2}{t^2_{y,1}} + \frac{(u-u^*_{y,2})^2}{t^2_{y,2}}}} \quad (4)$$

with

$$t^2_{x/y,1/2} = \frac{2\beta^*_{x/y,1/2}\left(\sigma^{*2}_{x/y,1} + \sigma^{*2}_{x/y,2}\right)}{\epsilon_{x/y,1/2}\left(\sigma^2_{z,1} + \sigma^2_{z,2}\right)}$$

and the scaled beta waist position $s^*$ reads,

$$u_{x/y,1/2} = \frac{\sqrt{2} s^*_{x/y,1/2}}{\sqrt{\sigma^2_{z,1} + \sigma^2_{z,2}}}$$

where $\epsilon$ is the rms emittance. In the RHIC and its future upgrade eRHIC, both beam are designed to be round with matched rms beam size at the waist position, $\sigma^{*2}_{x/y,1/2} = \sigma_r$. The expression for $t_{x/y,1/2}$ reduces to $t_{x/y,1/2} = 2\beta^*_{x/y,1/2}/\sqrt{\sigma^2_{z,1} + \sigma^2_{z,2}}$.

## USE $s^*$ AS LUMINOSITY CONTROL KNOB

We propose to control the luminosity of one collision point by moving the waist position $s^*_{x/y}$ of one of the colliding beam. Taking RHIC beam parameter as an example, we will demonstrate the effectiveness of this method. RHIC has round beam and identical design parameters for two

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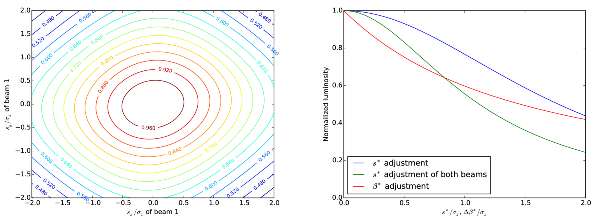


Figure 1: Top: The luminosity control contour due to the waist position adjustment of beam 1. The waist position of the other beam is intact. Bottom: The residue luminosity comparison of $s^*$ tuning of one beam and $\beta^*$ tuning of both beams, the $s^*_x = s^*_y = s^*$ and $\Delta\beta^*$ is the beta function tuning amplitude. In both figures the luminosity is normalized by original luminosity with any adjustments.

colliding beams. The parameter $t_{x/y,1/2} = \sqrt{2}\beta^*/\sigma_z$ and $u_{x/y,1/2} = s^*_{x/y,1/2}/\sigma_z$. To evaluate the integral in Eq. 4, we choose $\beta^* = \sigma_z$. It is worthwhile to note that the factor $G$ also includes the effect of the hourglass effect, therefore we evaluate the luminosity control effect by normalized the $G$ factor by $G(u_{x/y,1/2} = 0)$. Figure 1 (top) illustrates the luminosity control ability by tuning $s^*$.

It is useful to compare this method with the more straightforward $\beta^*$ adjustment for luminosity control. Figure 1 (bottom) compares the luminosity $\beta^*$ adjustment and the $s^*$ adjustment of one or both beams. The $\beta^*$ adjustment assumes the beta functions of both beams in both transverse directions have same values ($\beta_{1,H} = \beta_{1,V} = \beta_{2,H} = \beta_{2,V} = \beta^*_0 + \Delta\beta$), where $\beta^*_0 = \sigma_z$. It shows that the adjustment of $\beta^*$ of both beams is more effective when luminosity reduction is less than ~40% since the $\beta^*$ adjustment change the both beam size at interaction point directly. However, the $s^*$ adjustment for both beam is more effective for larger luminosity reductions.

## $s^*$ ADJUSTMENT EXPERIMENT IN RHIC

During the accelerator experiment session in 2014 RHIC Au-Au run, We proposed to adjust $s^*$ during RHIC accelerator experiment session to prove that the $s^*$ control knob is feasible in RHIC, in the RHIC During the experiment, RHIC has waist beta function at IP ($\beta^* = 0.7$m). We were aiming to adjust $s^*$ of one IP by $\sim \pm\beta^*$ so that the effect can be seen from both the optics measurement and the luminosity measurement through the Zero Degree Calorimeter (ZDC) coincidence rate from both detectors in RHIC, STAR (IP 6) and PHENIX (IP 8).

Taking advantage of the recent progress of achieving ~10% of beta-beat control [1], we develop a model-dependent scheme to adjust $s^*$. We start from the nominal lattice which has $s^* = 0$ m, according to the lattice model. For a preset target $s^*$ in one of the IP, we use MADX to calculate the necessary change of the interaction region (IR) quadrupoles of both IRs. The constrains include:

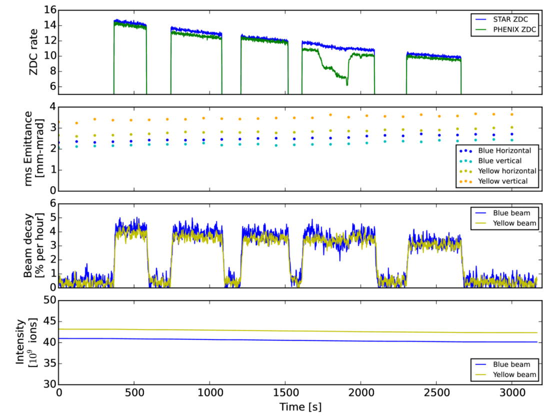


Figure 2: From top figures to the bottom: first: The ZDC rate of the STAR and PHENIX detector; second: the rms emittance of the two colliding beam in two transverse directions; third: the bunch decay rate of both beams; fourth: the bunch intensity of both beams.

- the waist beta function $\beta^*$ is unchanged in the IP with $s^*$ shifting,
- both $\beta^*$ and $s^*$ of the other IP remain intact,
- The dispersion function of both IP remain intact.

The quadrupole settings is then sent to RHIC and we take measurements to confirm the change of IR $\beta^*$ and $s^*$ by optics measurement. In the mean time the ZDC rate of both detectors will reflect the corresponding luminosity change due to the $s^*$ adjustment. Since the optics the other detector is unchanged, it's ZDC rate can serve as reference, so that the contribution to the luminosity change from other factors, such as beam intensity and emittance, can be eliminated.

In this experiment, we only attempt to adjust $s^*$ at IP8 of the blue beam only to show the feasibility in RHIC . Therefore, according to the constrains above, this adjustment will only change the luminosity of the PHENIX detector, not that of the STAR detector. Table 1 lists the $s^*$ change we planned during the experiment. The value of $s^*$ is limited by the power supply of the IR quadrupoles.

After both beam are ramped to the collision energy, blue ring optics correction is first performed to ensure the optics function in the machine is ~10% from the value predicted by the model. After the optics correction, we attempts 5 $s^*$ setting as listed in table 1. After each adjustment is made, we first fit the $s^*$ using the BPM measurement data, then put two beam at collision and observe the luminosity change. The collision is kept for ~5 minutes to accumulate reasonable statistics of the ZDC rate.

Figure 2 illustrate the overview of the 5 attempts as function of time, including the comparison of ZDC rate of the two detectors, the bunch intensities, the bunch intensity decay rates and the beam emittances. For all the $s^*$ changing attempts, no emittance or beam lifetime deterioration is ob-

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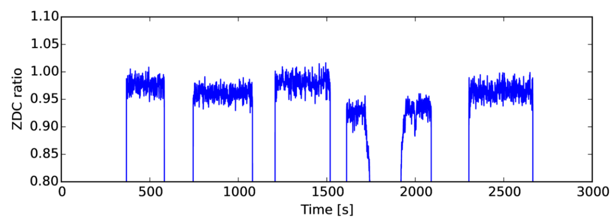


Figure 3: The ZDC rate ratio, defined as the PHENIX ZDC rate divied by the STAR ZDC rate.

Table 1: Optics Measurement and Corresponding Luminosity Reduction

| | Requested | | Measured | | |
|---|---|---|---|---|---|
| # | H. $s^*$ (cm) | V. $s^*$ (cm) | H. $\beta^*/s^*$ (cm) | V. $\beta^*/s^*$ (cm) | Luminosity Ratio |
| 1 | 0 | 0 | 79 / -4 | 73 / 2 | 0.996±0.012 |
| 2 | 0 | 45 | 77 / -3 | 71 / 46 | 0.980±0.011 |
| 3 | 0 | 0 | 69 / 2 | 71 / 5 | 1.00±0.013 |
| 4 | 0 | -45 | 68 / 5 | 73 /-34 | 0.949±0.013 |
| 5 | 35 | 0 | 71 / 30 | 74 / -5 | 0.984±0.013 |

served. There is visible ZDC rate between the STAR and the PHENIX detector when non-zero $s^*$ is set. During the attempt #4, the PHENIX ZDC rate was affected by the unexpected operation of the orbit feedback system. After we turned of the orbit feedback and re-align two beams at IP, the PHENIX ZDC rate return to where it was before the accident. The ratio of the ZDC rate between the two detector reflects the luminosity change due to the $s^*$ shifting, as shown in figure 3. Table 1 lists the measured $\beta^*$ and $s^*$ of each step and the luminosity reduction due to the $s^*$ shift. It worth to note that, the requested $\beta^*$ for all attempts are 70 cm. The measured $s^*$ change between attempts well reflects the requested values, which indicates the real optics of the machine is very close to the model, as indicated in the beta-beat figure. The luminosity reduction is about 2-5% with the rms error <1.5% due to the ZDC rate fluctuation.

We noticed the asymmetric luminosity reduction between the vertical $s^* = \pm45$cm requests, which may be explained by the presence of large vertical $s^*$ in the other ring. During the experiment, the yellow ring is untouched after ramping to the collision energy. We then measure the optics function of the yellow ring using the same fitting routine and list them in table 2. The yellow ring optics at IP 8 deviate from the model, especially in the vertical plane, because no optics correction is performed in yellow ring. We may use the yellow optics as input, together with the 1.5 m rms bunch length for both beams and 70 cm horizontal and vertical $\beta^*$ of the blue beam , to calculate the anticipated luminosity reduction using the geometric integration (Eq. 4) as in figure 4.

Table 2: Measured Optics of the Yellow Ring IP 8

| Optics | $\beta^*_H$ (cm) | $s^*_H$ (cm) | $\beta^*_V$ (cm) | $s^*_V$ (cm) |
|---|---|---|---|---|
| Values | 79 | -13 | 89 | 29 |

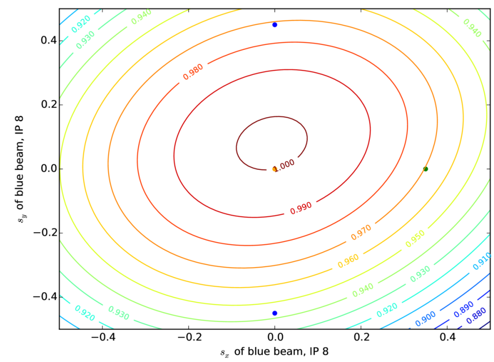


Figure 4: The luminosity reduction as function of the $s^*_H$ and $s^*_V$ of the blue beam. The requested $s^*_V$ change is marked with blue dots; the requested $s^*_H$ is marked with green dot and the origin $s^*$ is marked yellow dot.

From figure 4, the $s^*_V = \pm45$ cm requests of the blue beam are expected to yield 0.972 and 0.943 luminosity reduction from the geometric integration, when the optics measurement of the yellow beam is used as the integration parameters. This anticipation agrees well with the experiment data (0.980±0.011 and 0.949±0.013). The horizontal $s^*$ adjustment yields a larger discrepancy, 0.97 luminosity from the integration and 0.984±0.013. The larger difference may be explained by the larger beta beat in the horizontal plan of the blue beam after the optics correction. In the horizontal plane, the model dependent $s^*$ adjustment method is expected to be less accurate.

## SUMMARY

The $s^*$ adjustment is an alternative method to control the luminosity of two colliding beams. It has special advantages to the future ERL based electron ion colliders, since it can effectively control the pinch effect of the electron beam [2]. We demonstrate the feasibility of $s^*$ adjustment in RHIC. Taking advantage of the recent progress of beta beat reduction, our model dependent $s^*$ produce anticipated result, both from the optics measurement and the luminosity monitor.

## REFERENCES

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