A LUMINOSITY MONITOR USING THE COHERENT BEAM–BEAM INTERACTION

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Abstract

A new method of monitoring the luminosity has been developed at CESR. The method involves shaking one bunch at a specific frequency and observing the resulting oscillations of the corresponding opposing bunch. In initial tests, 1% accurate measurements have been obtained in 1 second. Measurements of different bunches in a train shows bunch to bunch differences with the optimum conditions for one bunch not coinciding with the optimum for another.

1 INTRODUCTION

In a colliding beam storage ring it is essential to be able to monitor the luminosity so as to be able to adjust machine elements (magnets, separators, etc.) to maximize the luminosity. Two methods that are used at the Cornell Electron/positron Storage Ring CESR involve measuring the vertical σ–π tune split and counting babas using the CLEO detector. The problem with the former method is that the π mode is not always cleanly visible. On the other hand, the latter method is slow since the counting rates are low—the characteristic time scale for a measurement being a minute.

With these problems in mind an alternative method has been developed[1] that uses the coherent beam–beam interaction: A given bunch of one beam is shaken vertically. This “shaker” bunch interacts with a bunch of the opposite beam (the “detected” bunch) at the interaction point (IP). The oscillations of the detected bunch are monitored and the amplitude of the oscillation is a measure of the luminosity. This Beam–Beam Interaction (BBI) luminosity monitor has proved to have several advantages: The hardware requirements are minimal and the response is fast—about a second. An added benefit is that with multiple bunches in each beam it is possible to individually monitor the luminosity of any given pair of bunches.

2 THEORY

The configuration of the BBI luminosity monitor is shown schematically in figure 1. The sinusoidal reference signal at frequency ω_s from a lock–in amplifier is used to vertically shake a given bunch of a given beam. This shaker bunch is given a kick $\Delta y'_s$ of

$$\Delta y'_s = A'_s(\text{sh}) \cdot \cos\omega_s t \, . \tag{1}$$

At the IP the shaking translates into an oscillation of the shaker bunch with amplitude $A_s(\text{ip})$ given by

$$A_s(\text{ip}) = A'_s(\text{sh}) \sqrt{\beta_y(\text{sh})\,\beta_y(\text{ip})}\, F_{sh} \, , \tag{2}$$

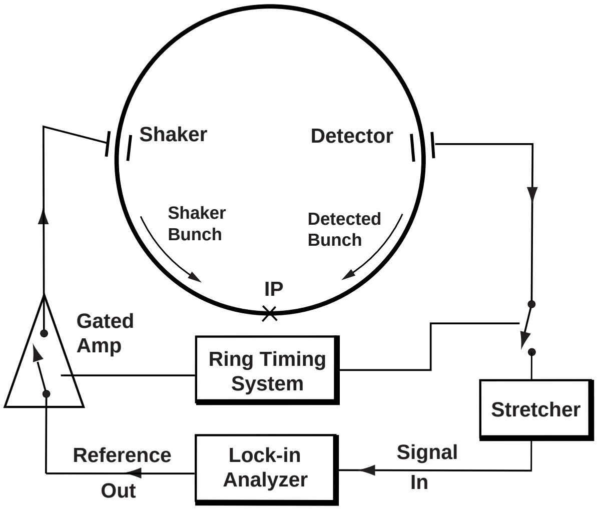

Figure 1: Schematic diagram of the BBI luminosity monitor configuration.

where F_{sh} is the transfer function from the shaker to the IP (cf. reference [1]).

At the IP the oscillations of the shaker bunch give a kick to the detected bunch. The amplitude of this kick, $A'_d(\text{ip})$, is

$$A'_d(\text{ip}) = \left| \frac{dy'}{dy} \right|_{y_{ds}} \cdot A_s(\text{ip}) \, , \tag{3}$$

where dy'/dy is the derivative of the beam-beam kick which is evaluated at y_{ds} with y_{ds} being the vertical offset between the centers of the two bunches when there is no shaking. For head-on collisions

$$\left| \frac{dy'}{dy} \right|_0 = \frac{4\pi\kappa\xi_y}{\beta_y(\text{ip})} \, , \tag{4}$$

where ξ_y is the beam–beam tune shift parameter. If we were only dealing with particles near the core of the bunches then the correction factor κ in Eq. (4) would be 1. However, since it is the centroid motion that is measured, and since particles away from the core receive less of a kick, κ is less than 1. Measurements and calculations[2] give $\kappa \approx 0.6$. ξ_y can be related to the beam sizes through the standard formula

$$\xi_y = \frac{N_p \beta_y(\text{ip}) r_e}{2\pi\gamma\sigma_y(\sigma_x + \sigma_y)} \, , \tag{5}$$

with N_p being the number of particles in a bunch, γ is the standard relativistic factor, and r_e the classical electron radius. ξ_y can also be related to the luminosity by

$$\mathcal{L} = \frac{\gamma I \xi_y}{2 e r_e \beta_y(\text{ip})} (1 + r) \, , \tag{6}$$

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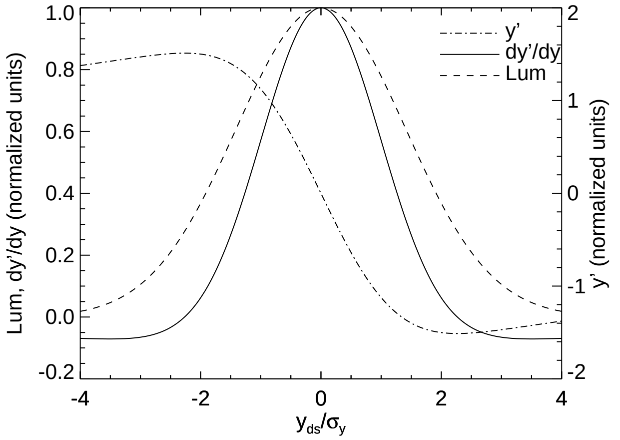

Figure 2: $\mathcal{L}$, dy'/dy, and y' as a function of y_{ds}/σ_y for $\sigma_y/\sigma_x = 0.1$. At $y_{ds} = 0$, $\mathcal{L}$ and dy'/dy are scaled to be 1.

where e is the electron charge, I the beam current, and $r \equiv \sigma_y/\sigma_x$.

Given $A'_d(\text{ip})$ the amplitude of oscillation $A_d(\text{det})$ of the detected bunch at the detector is

$$A_d(\text{det}) = A'_d(\text{ip})\sqrt{\beta_y(\text{ip})\beta_y(\text{det})}\,F_{det}\,, \tag{7}$$

where F_{det} is the transfer function from the IP to the detector. Combining Eqs. (2), (3), (4), and (7) gives

$$A_d(\text{det}) = A'_s(\text{sh})\;\;\beta_y(\text{ip})\;\left|\frac{dy'}{dy}\right|_{y_{ds}} \tag{8}$$
$$\sqrt{\beta_y(\text{sh})\beta_y(\text{det})}\,F_{sh}\,F_{det}\,.$$

For head–on collisions

$$A_d(\text{det}) = 4\pi A'_s(\text{sh})\,\kappa\xi_y\sqrt{\beta_y(\text{sh})\beta_y(\text{det})}\,F_{sh}\,F_{det}\,. \tag{9}$$

Eqs. (8) and (9) are not quite correct since the effect of the detected bunch upon the shaker bunch has been neglected. However, since this effect is small ($< 10\%$) for CESR it will be ignored.

The detector signal is stretched and held for a turn until the next signal is received. The stretched signal is measured by the lock–in amplifier (cf. figure 1). In order to prevent unwanted interference the shaker is gated so as to only kick the shaker bunch. Additionally, the signal from the BPM is gated to exclude the direct signal from the shaker bunch.

With multiple bunches in each beam the oscillations of the shaker bunch may also be transmitted to the detected bunch via intermediate bunches and the long range BBI at the parasitic crossing points. Since the long range tune shift ξ_y is an order of magnitude smaller than ξ_y at the IP this effect can be ignored.

From Eqs. (5), (6), and (9), for head–on collisions with flat beams

$$A_d(\text{det}) \propto \xi_y \propto \beta_y(\text{ip})\cdot\mathcal{L} \propto \frac{\beta_y(\text{ip})}{\sigma_x\sigma_y}\,. \tag{10}$$

Parameter	Value	Parameter	Value
ω_s	$2\pi\cdot 100\,\text{kHz}$		
$A'_s(\text{sh})$	0.5 μrad	ξ_y	0.03
$\beta_y(\text{ip})$	0.019 m	$\sigma_y(\text{ip})$	7 μm
$\beta_y(\text{sh})$	21.5 m	$\beta_y(\text{det})$	32.3 m
F_{sh}	0.79	F_{det}	0.82

Table 1: CESR BBI luminosity monitor parameters.

Thus, the BBI luminosity monitor can be use to adjust skew quadrupoles to minimize σ_y and maximize $\mathcal{L}$. However, because of the factor of $\beta_y(\text{ip})$ in Eq. (10), the BBI luminosity monitor cannot be used to adjust $\beta_y(\text{ip})$ since it is possible to increase $A_d(\text{det})$ by increasing $\beta_y(\text{ip})$ while simultaneously decreasing $\mathcal{L}$. This drawback is also inherent with the σ–π tune split since the σ–π tune split also is essentially proportional to ξ_y.

Figure 2 shows y', dy'/dy, and $\mathcal{L}$ as a function of y_{ds}/σ_y with dy'/dy and $\mathcal{L}$ being normalized to 1 at $y_{ds} = 0$. The kick y' was calculated using the standard Bassetti and Erskine complex error function formula (cf Talman[2]). For $|y_{ds}| \lesssim 2\sigma_y$, dy'/dy tracks $\mathcal{L}$ with maximum $\mathcal{L}$ coinciding with maximum dy'/dy at $y_{ds} = 0$. The BBI luminosity monitor can thus be used to adjust machine elements to obtain head–on collisions.

3 CESR BBI LUMINOSITY MONITOR

"Typical" values for the parameters of the CESR BBI luminosity monitor are given in table 1. The choice of the shaking frequency is not too critical except that it should not be near a betatron resonance frequency so that changes in the betatron frequency do not produce large changes in the signal. From Eq. (2) $A_s(\text{ip})$ is given to be

$$A_s(\text{ip}) = 0.25\,\mu\text{m}\,. \tag{11}$$

This is 4% of σ_y so the effect of the shaking on the luminosity is small. From Eq. (9) the signal at the detector is

$$A_d(\text{det}) = 1.9\,\mu\text{m}\,. \tag{12}$$

The detector electronics is described in reference [1]. "Typical" measured signal levels (without any amplification) are 200 μV with noise around 2 $\mu\text{V}/\sqrt{\text{hz}}$. This corresponds to a 1 second averaging time producing a measurement with noise–to–signal of 1%.

4 EXPERIMENTAL RESULTS

In CESR, the bunches in a beam are clustered in "trains." The bunches within a train are called "cars." The data shown was taken with 9 trains per beam and with two cars (numbered #2 and #5) per train. The spacing between the two cars was 42 nsec and the spacing between trains was either 280 or 294 nsec.

The vertical differential orbit through the IP was varied using an electrostatic bump. Figure 3 shows the monitor

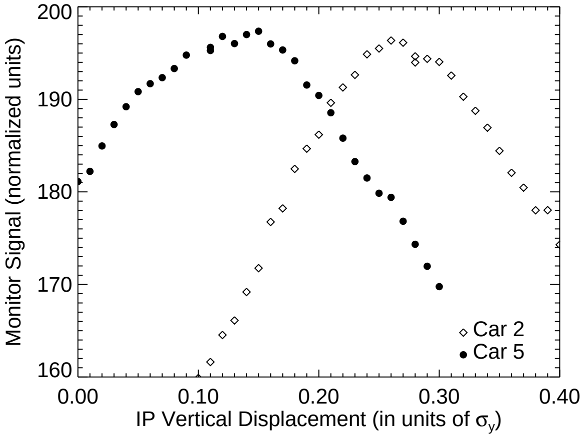

Figure 3: Monitor signals for car 2 and car 5 as a function of vertical displacement of the bunches.

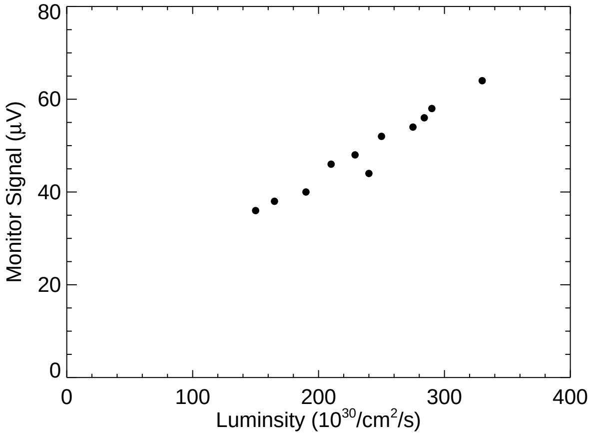

Figure 4: Car 2 monitor signal as a function of Cleo luminosity while varying y_{ds}.

signals from car 2 and car 5 of train 1 as a function of separation at the IP. The monitor signals have been normalized by the total beam current. The vertical separation is calibrated in units of the nominal σ_y (7 μm). Thus, from one end of the plot to the other, the change in y_{ds} is $0.4\sigma_y$. The fact that the peaks of the two signals do not coincide implies that the cars are not following the same vertical trajectory. This is probably due to the short range wake fields produced by the leading (#2) car.

The width of the monitor signal shown in figure 3 for car 2 or car 5 is substantially less than what one would expect from figure 2. This is not surprising since the curves in figure 2 were calculated assuming a constant beam size. However, with the beams colliding off–center, resonances will be excited through the beam–beam interaction. This will lead to beam blowup and hence greater sensitivity to y_{ds}. Indeed, a measurement of car 2 and the luminosity measured by the CLEO detector as a function of vertical displacement, as shown in figure 4, shows a linear relationship. This is appropriate for variations in σ_y (cf. Eq. (10)), but is not what would be predicted from figure 2.

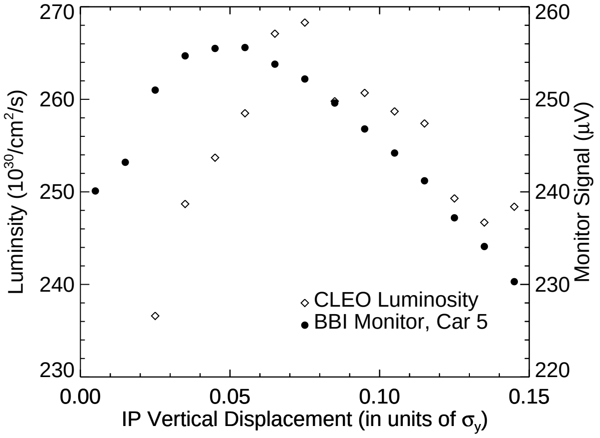

Figure 5: Monitor signal for car 5 and CLEO luminosity as a function of vertical displacement of the bunches.

Figure 5 shows the car 5 monitor signal and the CLEO luminosity as functions of the vertical displacement at the IP. Comparing with figure 3 the luminosity peak falls between the car 2 and car 5 peaks as expected. To obtain a usable signal for tuning all that is required is to simultaneously shake/detect a car 2 and a car 5 bunch to get an average signal.

5 CONCLUSION

Using the coherent beam-beam interaction to monitor the luminosity has several clear advantages: The system has a fast response time so tuning of machine elements can be done efficiently. The system is also easy to construct—the necessary shaker and detector hardware are typical of any storage ring and the external electronics is minimal. Additionally, bunch to bunch variations in the luminosity can be monitored. The one significant drawback is that it is not possible to use the BBI luminosity monitor to optimize the beta at the IP.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] For an expanded version of this paper see: D. Sagan, J. Sikora, and S. Henderson, “A Luminosity Monitor Using the Coherent Beam–Beam Interaction (Internal Report),” Cornell CBN 97–13 (1997). Available on the web from: http://www.lns.cornell.edu/

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