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A fast luminosity monitor for BEPCⅡ *

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Abstract The fast luminosity monitor counting the γ photons above a given energy threshold emitted from radiative Bhabha scattering has been operated in the BEPCⅡ to measure the relative luminosity bunch by bunch for the first time and used successfully in beam tuning of BEPCⅡ. In the relative mode the monitor is able to deliver the relative luminosities with an accuracy of 0.8 %. By steering the electron beam while observing the counting rate changes of the monitor the horizontal and vertical sizes of the bunch spots can be estimated as: $s_{\mathrm{xe^+}} = s_{\mathrm{xe^-}} = 0.356$ mm, $s_{\mathrm{ye^+}} = s_{\mathrm{ye^-}} = 0.011$ mm.

Key words luminosity monitor, radiative Bhabha, relative luminosity, background subtraction, beam spot

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1 Introduction

In the BEPCⅡ (Beijing Electron Positron Collider) upgrade project, the one ring configuration has been changed to the configuration of the two rings for electron and positron respectively. The target luminosity is set to about $10^{33}(\mathrm{cm^{-2}\cdot s^{-1}})$@1.89 GeV. A total of 93 pairs of $\mathrm{e^-}$ and $\mathrm{e^+}$ beams cross each other with a finite angle of 22 mrad at the interaction point (IP). A fast bunch by bunch luminosity monitor will be very beneficial in the operation of the BEPCⅡ. The most appropriate QED-process for the luminosity measurement here is the radiative Bhabha scattering, sometimes referred to as the single Bremsstrahlung radiation, where a hard photon is emitted in the glancing collision of an electron with a positron at the IP. This process can be used in the fast and real time luminosity measurement and has been applied in PEP Ⅱ and Belle experiments [1, 2].

Due to space constraints in the IP area of BEPCⅡ, a simple gamma photon counter has been set as Fig. 1.

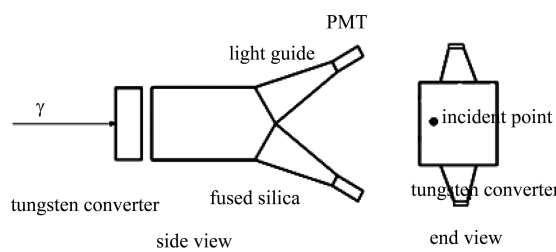

Fig. 1. The structure of luminosity monitor.

At BEPCⅡ, the time interval of the adjacent bunch is 8 ns. Through measuring the radiation photon counts over a given threshold in a period of each bunch pair crossing, the relative luminosity of each bunch pair crossing is obtained. The total absolute luminosity of 93 pairs of $\mathrm{e^-}$ and $\mathrm{e^+}$ bunches could also be measured if a proper calibration is done. This system is designed for both of these purposes. Please refer to Refs. [3, 4] for the structure of the luminosity monitor.

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2 Luminosity monitoring

2.1 Radiative Bhabha process

$$\begin{aligned} &e^+ + e^- \to e^+(\gamma) + e^- \ , \\ &e^- + e^+ \to e^-(\gamma) + e^+ \ . \end{aligned} \tag{1}$$

Eq. (1) is the radiative Bhabha whose cross sections could be calculated with the accuracies matched with experiments. They are the standard processes for luminosity measurement. In the first (second) reaction of Eq. (1) a single gamma is emitted from a e^+ (e^-) in a small cone of an order of mrad along its incident direction when a bunch pair of e^+ and e^- crosses at the IP. The two gamma photon counters are situated at $\sim$3.3 m from the IP on the east (e^+) side and the west (e^-) side. The gamma in the first reaction is counted by the east counter. The gamma in the second reaction is counted by the west counter. The counting rates of single Bremsstrahlung photons (SB) from the two gamma photon counters are independently related to the luminosity of e^+e^- collision:

$$\begin{aligned} &\left(\frac{dn}{dt}\right)^{\pm}_{\rm SB} = LA^{\pm}_{\rm SB}, \\ &A^{\pm}_{\rm SB} = \int\limits_{\Omega^{\pm}} d\Omega \int\limits_{k_{\pm \rm th}}^{k_{\max}} \left(\frac{d\sigma}{d\Omega dk}\right) dk. \end{aligned} \tag{2}$$

The (dn/dt), L and $A_{\rm SB}$ are the counting rate, the luminosity and the counter physics acceptance respectively. The plus and minus signs indicate the quantities of the counters on the east and west side respectively. $A^{\pm}_{\rm SB}$ is determined by the geometry factor $\Omega^{\pm}(k)$ and the gamma sensitive threshold $k_{\pm \rm th}$ of the counters, which depends on the gamma – e^+e^- conversion efficiency, Cherenkov photon collection efficiency, PM-gain and readout electronics threshold. It's difficult to evaluate the physics acceptance $A_{\rm SB}$ directly from the integration of Eq. (2). There is no proper gamma photon beam to calibrate the $A_{\rm SB}$ experimentally. The way to evaluate the $A_{\rm SB}$ is from the GEANT4 simulation which starts from the radiative Bhabha scattering gamma spectrum, traces the gamma interactions through the tungsten collimator and converter, traces the Cherenkov photons emitted from the converted secondary e^+ and e^- in fused silica and counts the numbers of photon electrons collected by the photo-cathode of the photo-multipliers. $A_{\rm SB}$ will be evaluated by the photon-electron numbers which correspond to the front-end electronics (FEE) thresholds.

2.2 Background subtract

From Eq. (2)

$$L_i \propto \left(\frac{dn}{dt}\right)^{i}_{\rm SB} \ , \tag{3}$$

$$\begin{aligned} &\left(\frac{dn}{dt}\right)^{i}_{\rm M} = \left(\frac{dn}{dt}\right)^{i}_{\rm SB} + \left(\frac{dn}{dt}\right)^{i}_{\rm BG}, \\ &\left(\frac{dn}{dt}\right)^{i}_{\rm BG} = \left(\frac{dn}{dt}\right)^{i}_{\rm GB} + \left(\frac{dn}{dt}\right)^{i}_{\rm loss}. \end{aligned} \tag{4}$$

As shown in Eq. (3), the relative luminosity of the ith-bunch pair is proportional to $\left(\frac{dn}{dt}\right)^{i}_{\rm SB}$ which is the counting rate of the radiative Bhabha gammas from the collision of the ith-bunch pair at IP. The measured rate $\left(\frac{dn}{dt}\right)^{i}_{\rm M}$ with the collision of the ith-bunch pair is the signal rate ("SB"-subscript) plus the background rate ("BG"-subcript) shown in Expression (4) . There are two background terms, $\left(\frac{dn}{dt}\right)^{i}_{\rm GB}$ – due to e^- beam radiation from the residual gas (GB) and $\left(\frac{dn}{dt}\right)^{i}_{\rm lost}$ – the contribution of lost positron (electron) from the beam. It's essential to subtract the background in the relative luminosity measurement. The two main sources of background shown above depend strongly on the operating status of the accelerator and should be measured properly to make the relative luminosity measurement more accurate. Two different schemes that are called Separate Beam Background Subtract (SBBS) and Missing Bunch Background Subtraction (MBBS) are adopted to determine the background during the measurement [5].

2.2.1 Separate Beam Background Subtract (SBBS)

To measure the background rates of e^+ (e^-) side counter, the e^+ (e^-) beam should keep the same orbital parameters as the collision and steer the e^- (e^+) beam completely away from the collision. In this case the counts of e^+ (e^-) side counter are the background counts only. Fig. 2(a), (b) show that the normalized counting rates of e^+ side counter $\left(\frac{dn}{dt}\right)^{+}_{\rm M}$ in collision (a) and in separate (b) change respectively with the FEE thresholds which correspond to different counter physics acceptances. The signal counting rate could be obtained by the subtraction: $\left(\frac{dn}{dt}\right)^{+}_{\rm SB} = \left(\frac{dn}{dt}\right)^{+}_{\rm M}$ (in collision) – $\left(\frac{dn}{dt}\right)^{+}_{\rm M}$ (in separation).

According to Fig. 2(a, b) the counting rate ratio of the separated beams over the colliding beams are lower than 3.5%.

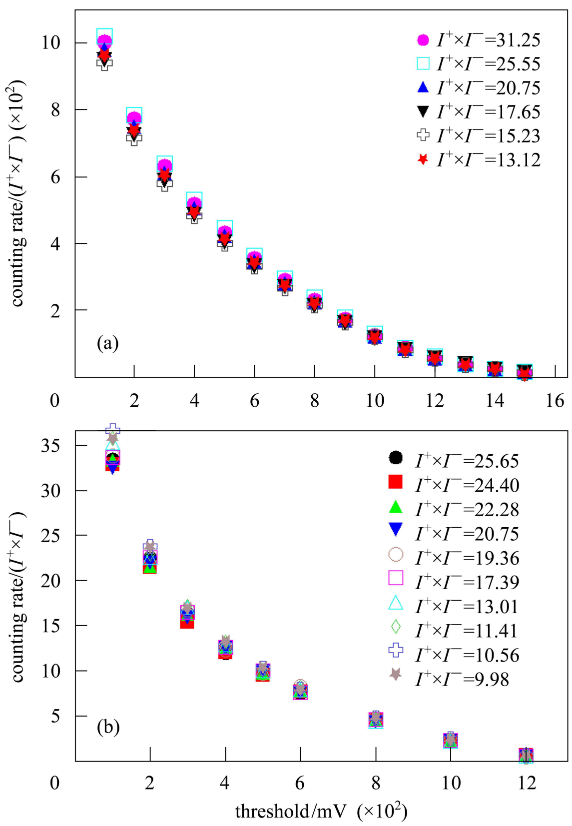


Fig. 2. (a) The counting rate with colliding beams normalized by the product of bunch currents of $e^-$and e^+ beams vs. the FEE threshold. (b) The counting rate with separated beams normalized by the product of bunch currents of e^- and e^+ beams vs. the FEE threshold.

2.2.2 Missing Bunch Background Subtraction (MBBS)

In the Missing Bunch Background Subtraction (MBBS) method, most $e^+(e^-)$ bunches have their counterpart $e^-(e^+)$ bunches, called the jth-bunch pair, and sample some given $e^+(e^-)$ bunches which have missed their counterpart $e^-(e^+)$ bunches, marked with "k". we have the following expressions:

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^j_{\mathrm{M}} = \left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^j_{\mathrm{SB}} + \left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^j_{\mathrm{GB}}, \qquad (5)$$

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^k_{\mathrm{M}} = \left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^k_{\mathrm{GB}}, \qquad (6)$$

where $\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^j_{\mathrm{M}}$ and $\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^k_{\mathrm{M}}$ are the counting rates associated with the colliding and non-colliding bunches respectively, $\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^j_{\mathrm{SB}}$ is the counting rate due to SB photons and I_j and $I_k$are the currents of the colliding and non-colliding $e^+(e^-)$ bunches. As the term $\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^k_{\mathrm{GB}}$ is proportional to the average residual gas pressure p_{IR} at the Interaction Region (IR) and to the average current of the beam viewed by the detector, it is straight-forward to derive from Eqs. (5) and (6) the relation:

$$\left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^j_{\mathrm{SB}} = \left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^j_{\mathrm{M}} - \left(\frac{\mathrm{d}n}{\mathrm{d}t}\right)^k_{\mathrm{M}} \cdot \left(\frac{I_j}{I_k}\right). \qquad (7)$$

As an advantage of the bunch-by-bunch luminosity monitor, MBBS allows real-time background subtraction. And the current of each bunch is required to be properly known which will affect the accuracy of measurement.

Figure 3 shows the normalized counts of the collision bunches (20th-bucket, left) and missed bunch (10th-bucket, right) vs. the FEE threshold in MBBS. The ratio between the counting rates with the non-colliding and colliding bunches are lower than 4%.

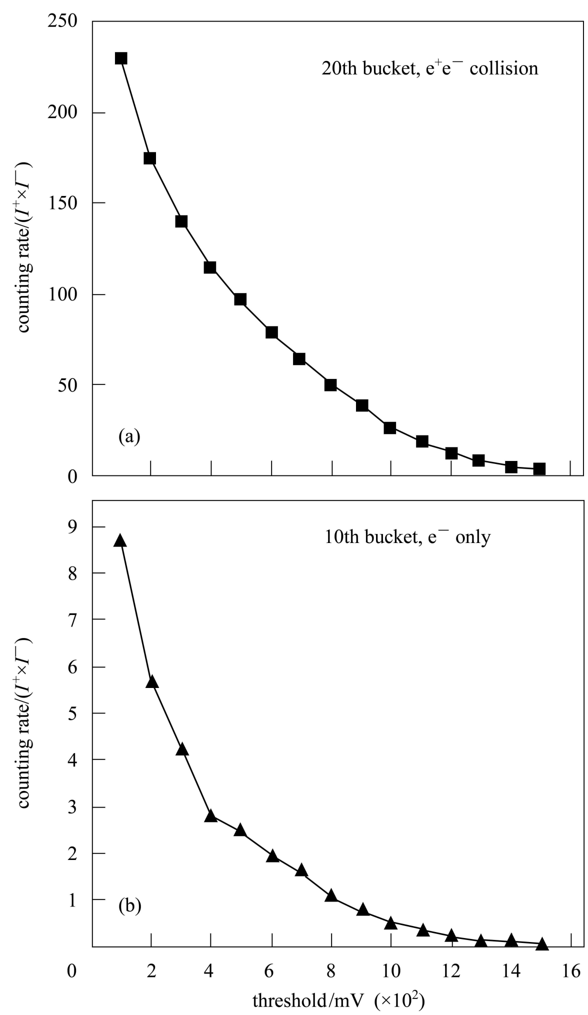


Fig. 3. The normalized counts of the collision bunches (20th-bucket,left) and missed bunch (10th-bucket,right) vs. the FEE thresholds in MBBS.

2.3 Errors of relative luminosity measurement

The luminosity monitor records the radiative Bhabha gammas bunch by bunch. The frequency of the system is up to 250 MHz, and can resolve the radiative Bhabha gammas at an interval of 4 ns. That is, the dead time of the system is 4 ns. With high luminosity there is a probability that more than one radiative Bhabha gamma could be generated in one collision (between e^+ bunch and e^- bunch). But these gammas are recorded as one radiative Bhabha gamma, which could cause a counting loss. The counting loss can be corrected according to Eq. (8).

$$n_0 = n/(1-n\cdot\tau), \tag{8}$$

where τ is the dead time of the system that is 4 ns, and n is the counting rate from the luminosity monitor. n_0 is the actual counting rate after the dead time correction. Typically when the counting rate n is 10^5s^{-1} the error due to dead time is 0.04% .

Considering the background in SBBS, the counting rate due to SB gammas n_{SB} can be evaluated as

$$n_{\text{SB}} = n_0 - n_{\text{b}} , \tag{9}$$

where n_{b} is the counting rate in case of separated beams. According to error theory, the statistical error of n_{SB} can be evaluated as

$$\sigma^2_{\text{SB}} = (\sigma^2_{\text{n}_0} + \sigma^2_{\text{n}_\text{b}}). \tag{10}$$

As shown in Table 1, the error of relative luminosity with the threshold set to 400 mV and the pair of bunches currents of 5 mA×5 mA is about 0.8%.

Table 1. The counting rates and their errors due to different thresholds in SBBS. (I^+ = 5.11 mA, I^- = 5.00 mA)

Thr./mV	100	200	300	400	500	600	800	1000	1200	1400
n	32489	24933	20306	16919	14101	11533	7545	4131	1886	811
n_0	32490	24933	20307	16919	14101	11533	7545	4131	1886	811
σ_{n_0}	180	158	143	130	119	107	87	64	43	28
n_{b}	1071	719	525	383	313	240	150	73	22	0
σ_{n_b}	33	27	23	20	18	15	12	9	5	0
n_{SB}	31419	24214	19782	16537	13789	11293	7395	4059	1864	811
σ_{SB}	177	156	141	129	117	106	86	64	43	28
$\frac{\sigma_{\text{SB}}}{n_{\text{SB}}}$	0.0056	0.0064	0.0071	0.0078	0.0085	0.0094	0.0116	0.0157	0.0232	0.0351

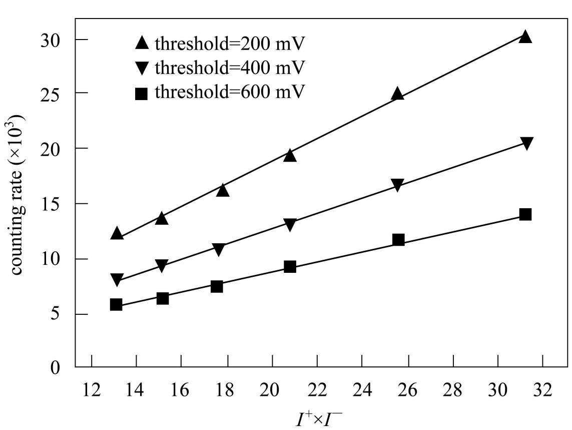


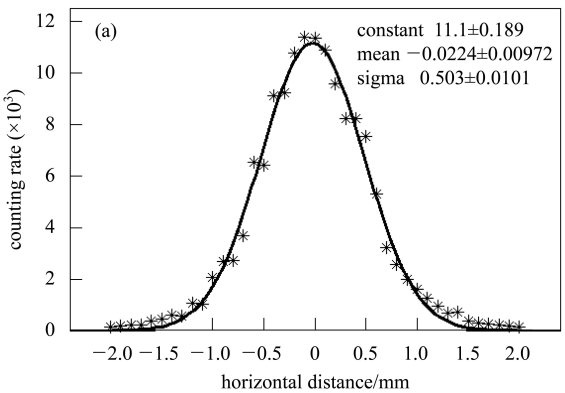
Fig. 4. The relative luminosities change with the products of I^+ and I^- under various FEE thresholds. The slope with the threshold set to 200 mV is 1030±32, the slope with the threshold set to 400 mV is 692±21, and the slope with the threshold set to 600 mV is 470±19.

Figure 4 shows the counting rates without background subtraction and counting loss correction change with the products of I^+ and I^- under various FEE thresholds. And the counting rates are linearly dependent on the product of I^+ and I^- which is proportional to luminosity. According to Expression (2), the lower the thresholds of FEE, the larger the physics acceptances are, and the steeper the linear plots in Fig. 4 are.

3 Determination of bunch sizes

By steering the electron beam while observing the counting rate changes of the luminosity monitor, the horizontal and vertical sizes of the bunch spots can be estimated as shown in Fig. 5. There are 70 e^+ bunches and 10 e^- bunches stored in the storage rings. The total e^+ current is 321.660 mA, and the total e^- current is 54.758 mA. The data of Fig. 5 is the counting rate of the fifth e^+ and e^- bunch pair. Fitted by gaussian function, the horizontal standard deviation is s_{x} = 0.503 mm, the vertical standard deviation is s_{y} = 0.015 mm.

The space distribution of e^+ and e^- bunches is



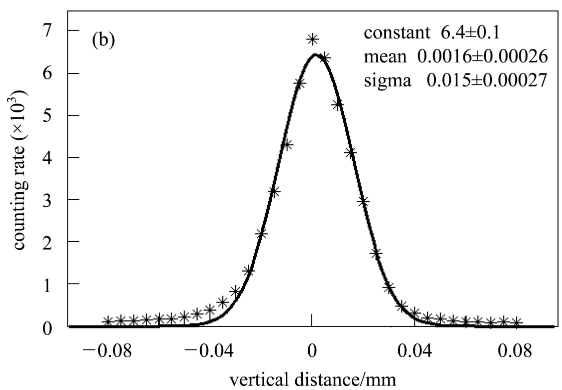


Fig. 5. (a) The average of the counting rate of the fifth bunches vs. the horizontal distance between the centers of e^+ and e^- bunch. (b) The average of the counting rate of the fifth bunches vs. the vertical distance between the centers of e^+ and e^- bunch.

roughly gaussian functions that are $A\mathrm{e}^{-(x-a)^2/2s_{\mathrm{e}^+}^2}$ and $B\mathrm{e}^{-(x-b)^2/2s_{\mathrm{e}^-}^2}$ respectively. Because the counting rate is proportional to the number of both e^+ and e^- in collision, the counting rate is proportional to the convolution of the two gaussian functions

$$A\mathrm{e}^{-(x-a)^2/2s_{\mathrm{e}^+}^2} * B\mathrm{e}^{-(x-b)^2/2s_{\mathrm{e}^-}^2} = AB\sqrt{2\pi}\frac{s_{\mathrm{e}^+}s_{\mathrm{e}^-}}{\sqrt{s_{\mathrm{e}^+}^2+s_{\mathrm{e}^-}^2}}\mathrm{e}^{-(x-c)^2/2s^2}, \tag{11}$$

where $c=a+b$, $s^2=s_{\mathrm{e}^+}^2+s_{\mathrm{e}^-}^2$. Supposing $s_{\mathrm{e}^+}=s_{\mathrm{e}^-}$ in both horizontal and vertical direction, then

$$s_{\mathrm{xe}^+}=s_{\mathrm{xe}^-}=s_{\mathrm{x}}/\sqrt{2}=0.356\ \mathrm{mm},$$

$$s_{\mathrm{ye}^+}=s_{\mathrm{ye}^-}=s_{\mathrm{y}}/\sqrt{2}=0.011\ \mathrm{mm}.$$

4 Conclusions

The BEPCⅡ luminosity monitor plays a fundamental role in the machine tune-up during the luminosity optimization. In the relative mode it is able to deliver non-calibrated measurements with the accuracy of 0.8 percent with a threshold setting of 400 mV. This capability allows real time optimization of whatever the machine parameter vs. the luminosity and makes the implementation of a luminosity feedback feasible. The horizontal and vertical sizes of the bunch spots can be estimated as: $s_{\mathrm{xe}^+}=s_{\mathrm{xe}^-}=0.356$ mm, $s_{\mathrm{ye}^+}=s_{\mathrm{ye}^-}=0.011$ mm.

References

1 Ecklund S et al. Nucl. Instrum. Methods A, 2001, **463**: 68–76
2 Hirai T. Zero-degree Luminosity Monitor for the Belle Experiment. http://www.hp.phys.titech.ac.jp/prepri/TIT-HPE-99-09.ps.gz
3 XUE Zhen et al. Nuclear Electronics & Detection Technology, 2007, **27**(1): 126–129 (in Chinese)
4 SHAN Qing et al. Journal of Univ. of Science and Technology of China, 2008, **38**(11): 1241–1245 (in Chinese)
5 Mazzitelli G et al. Nucl. Instrum. Methods A, 2002, **486**: 568–589