Luminosity monitoring and calibration of BLM

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Abstract: The BEPCⅡ Luminosity Monitor (BLM) monitors relative luminosity per bunch. The counting rates of gamma photons, which are proportional to the luminosities from the BLM at the center of mass system energy of the ψ(3770) resonance, are obtained with a statistical error of 0.01% and a systematic error of 4.1%. Absolute luminosities are also determined by the BESⅢ End-cap Electro-Magnetic Calorimeter (EEMC) using Bhabha events with a statistical error of 2.3% and a systematic error of 3.5%. The calibration constant between the luminosities obtained with the EEMC and the counting rates of the BLM are found to be 0.84±0.03 ($\times 10^{26}$ cm$^{-2}\cdot$count^{-1}). With the calibration constant, the counting rates of the BLM can be scaled up to absolute luminosities.

Key words: luminosity, luminosity monitor, EEMC, Bhabha scattering, cross-section

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1 Introduction

The Beijing Electron Positron Collider (BEPC) has been upgraded from BEPCⅠ to BEPCⅡ. As new technologies such as two rings and multi-bunch are employed, the target luminosity is set to around 10^{33}(cm$^{-2}\cdot$s^{-1}) @ 1.89 GeV, which is 100 times more than that of BEPCⅠ.

Luminosity (instantaneous luminosity) is a physical quantity which represents how many physical reaction events are produced per unit of time. It is an essential parameter used to rate the performance of a collider. In principle, any QED process can be used to determine luminosity. In practice, Bhabha events $e^+e^- \to e^+e^-(\gamma)$ are preferred because of their large cross section and ability to be separated from background events due to their characteristic topology. The BEPCⅡ Luminosity Monitor [1–3] (BLM) and the End-cap Electro-Magnetic Calorimeter (EEMC) both determine luminosity of the BEPCⅡ using Bhabha events.

2 Luminosity by BLM

The BLM determines luminosity by detecting the zero-angle gamma photons from the radiative Bhabha scattering $e^+e^- \to e^+e^-(\gamma)$. The luminosity L is proportional to the counting rate of the BLM $n_{\rm BLM}$ [1]:

$$n_{\rm BLM} = L\sigma_{\rm RB}(k_{\rm T},\ \Omega_{\rm D}), \tag{1}$$

where $\sigma_{\rm RB}(k_{\rm T},\ \Omega_{\rm D})$ is the radiative Bhabha integrated cross section accepted by the BLM:

$$\sigma_{\rm RB}(k_{\rm T},\ \Omega_{\rm D}) = \int_{k_{\rm T}}^{k_{\max}} {\rm d}k \int_{\Omega_{\rm D}} {\rm d}\Omega \frac{{\rm d}^2\sigma}{{\rm d}\Omega {\rm d}k}. \tag{2}$$

$\Omega_{\rm D}$ is the portion of the solid angle viewed by the BLM, and it is defined by the geometry of the inter-

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action region and of the BLM. $k_{\rm max}$ is the maximum energy the photons can have [4]:

$$k_{\rm max} = \frac{\omega}{2} - \frac{2m_0^2c^4}{\omega} \cong \frac{\omega}{2}, \qquad (3)$$

where ω is the center of mass system (CMS) energy of the colliding beams (twice the energy of the single beam in the BEPCII), m_0 is the electron rest mass and c is the speed of light. $k_{\rm T}$ is the minimum value of photon energy that can be detected by the BLM, and is dependent on the threshold of the discriminator of the BLM's front-end electronics (FEE).

The cross section of radiative Bhabha scattering is around 38 mb at the $\Psi(3770)$ CMS energy with a polar angle θ of photons less than 1 mrad and its energy more than 600 MeV [4], therefore the counting rate of the BLM is very high and the feedback of luminosity is very fast (sub-second). With this high counting rate, the BLM can determine luminosity bunch by bunch so that each bunch can be monitored and adjusted to best status. To optimize the performance of the collider, the beam orbits at the interaction point (IP) are sometimes adjusted, which affects the photon acceptance of the BLM. The counting rate is stable with minor adjustment in normal running.

Relative luminosity measurements play a fundamental role in the tuning of luminosity optimization. Every machine parameter that affects luminosity can be varied and its related luminosity simultaneously obtained. Because of the fast measurement capabilities of the BLM, scans can be systematically and extensively used for discovering the optimum value of parameters such as the vertical and horizontal overlap of beams at the IP, and the vertical and horizontal crossing angles at the IP. A detailed example of the measurement of bunch sizes with relative luminosity by varying the overlap of beams at the IP is reported in Ref. [1]. A complete scan to measure the bunch sizes takes only 20 minutes.

2.1 Bunch-by-bunch measurement of the relative luminosity

One of the most important features of the BLM is that it can measure the relative luminosity bunch by bunch. During the luminosity measurements of each bunch, problems with the collider can be found and solved to improve its performance. Below is a case study to illustrate its usage.

During 2008, luminosity did not increase in proportion to the bunch number as expected. When a single bunch pair of 5×5 mA^2 was stored, luminosity $L_{\rm sgl}$ was 2.5×10^{30} cm$^{-2}\cdot$s^{-1}, but when 93 bunch pairs of 450×450 mA^2 were stored, total luminosity was only 1.1×10^{32} cm$^{-2}\cdot$s^{-1}, which was around half of $93\times L_{\rm sgl}$. Along the bunch train, the rear bunch's luminosity was lower than that at the front, as shown in the 2008 data in Fig. 1. Experiments were then conducted as shown in Fig. 2. When 10 e$^-$ bunches were stored in the e$^-$ ring and 70 e$^+$ bunches were stored in the e$^+$ ring, the luminosity of the five rear bunches was around half of that of the five front bunches. However, when 10 e$^+$ bunches were stored in the e$^+$ ring and 70 e$^-$ bunches were stored in the e$^-$ ring, the luminosity of the five rear bunches did not decrease as much. It was also observed that in the e$^+$ ring, the bunch length increased along the train with the rear bunch's length being almost twice the size of the front bunch. It was therefore deducible that the rear luminosity decreased because the distortion of the rear e$^+$ bunches became severe when the e$^+$ bunch number increased, but not of the e$^-$ bunches. The difference between the e$^+$ ring and the e$^-$ ring was then sought. After a temporarily used screen monitor in the e$^+$ ring was removed, the rear luminosity increased to be the same as at the front, as shown in the 2009 data in Fig. 1 and the total luminosity rose from 1.32×10^{32} cm$^{-2}\cdot$s^{-1} to 2.0×10^{32} cm$^{-2}\cdot$s^{-1}, which was 50% higher [5]. It was shown that the distortion of the e$^+$ bunches was originating from the monitor screen in the e$^+$ ring.

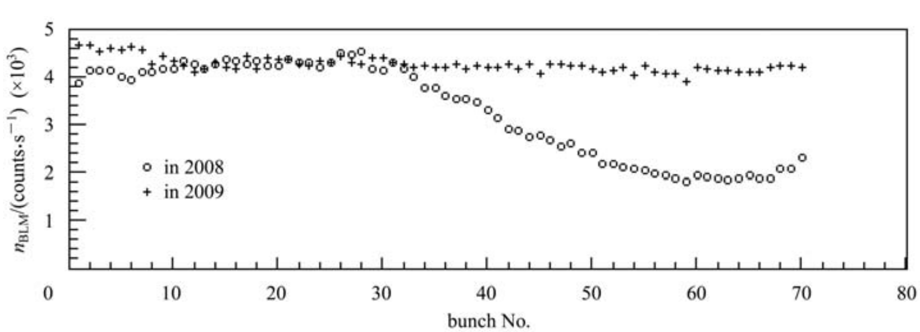

Fig. 1. The relative luminosities in 2008 and 2009.

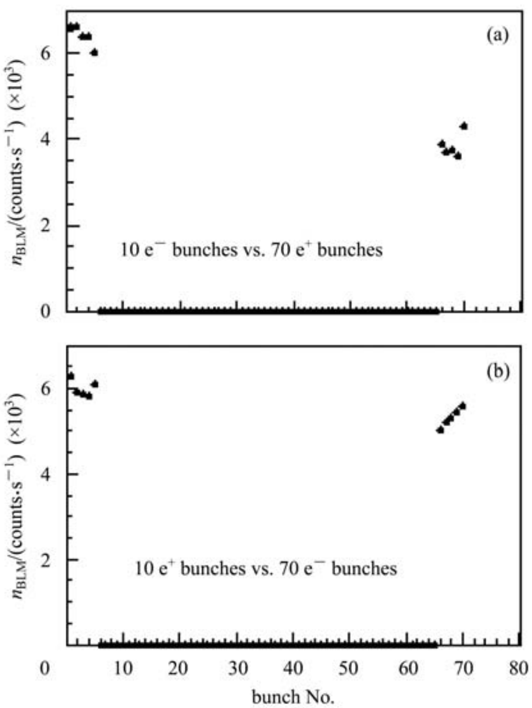

Fig. 2. (a) 10 e^- bunches stored in the e^- ring and 70 e^+ bunches stored in the e^+ ring, with the 10 front and rear bunches colliding; (b) 10 e^+ bunches stored in the e^+ ring and 70 e^- bunches stored in the e^- ring with the 10 front and rear bunches colliding.

2.2 The counting rate of the BLM and error analysis

Due to the space constraint, the small Cherenkov radiator of the BLM only samples the partial secondary e^- (e^+) shower [3], it is impossible to set k_T in expression (2) exactly without proper calibration using a photon beam, which is not available. So $\sigma_{RB}(k_T,\ \Omega_D)$ is not able to be determined with proper precision and the absolute luminosity L cannot be obtained from the Expression (1).

According to Expression (1):

$$L/n_{BLM}=1/\sigma_{RB}(k_T,\ \Omega_D)\equiv K, \tag{4}$$

K can be evaluated with n_{BLM} and L which can be obtained with the EEMC. For calibration, in order to obtain a sufficient number of Bhabha events, a one minute time interval is taken as the unit of time. The units of luminosity $L(t)$ and the counting rate $n_{BLM}(t)$ at time t are cm^{-2}·min^{-1} and counts·min^{-1} respectively, then K can be obtained with

$$K=L(t)/n_{BLM}(t). \tag{5}$$

With K (cm^{-2}·count^{-1}) obtained, n_{BLM} can be scaled to absolute luminosity.

As mentioned above, the counting rate of the BLM is very high, so the statistical error of $n_{BLM}(t)$ is less than 0.01%.

One systematic error of $n_{BLM}(t)$ arises from the minor adjustment of the beam orbits which was measured around 1.0%, the other arises from background value caused by beam gas and lost beam which is studied in Ref. [1] and it is less than 4.0%. So the total systematic error of $n_{BLM}(t)$ is 4.1%.

3 Absolute luminosity from EEMC

The EEMC determines luminosity by simultaneously detecting the final state e^+ and e^- from Bhabha scattering [6]. So with information from both e^+ and e^-, the identification is more reliable and the background is easier to subtract. It can determine absolute luminosity and is not as sensitive as the BLM to the jitter of beam orbit. However, the cross section of Bhabha events accepted by the EEMC is less than 264 nb at the CMS energy of $\Psi(3770)$, so its statistical error is bigger and its feedback is slower. It is impossible to monitor the status of beam-beam collision in real time using the EEMC.

3.1 Event selection

Below is the Bhabha event selection criteria :

(1) At least 2 showers are required in the EEMC.

(2) The largest deposit energy of shower E_{max1} is more than 1.4 GeV, the second largest deposit energy of shower E_{max2} is more than 0.8 GeV. Fig. 3 shows the distribution of E_{max1} and E_{max2} of the events of data and corresponding Monte Carlo simulation that pass the selection criteria (1)(2)(3)(4).

(3) Two tracks with maximum deposit energy in the EEMC satisfy $0.85<|\cos\theta|<0.93$, where θ is the polar angle of the shower measured by the EEMC.

(4) The angle difference of the two showers in R-φ plane is then calculated, which is defined as $|\delta\varphi|=|\varphi_1-\varphi_2|-180°$, where φ_1 and φ_2 are the azimuthal angles of the two showers measured by the EEMC in degree. Fig. 4 shows the $\delta\varphi$ distribution of all the events that pass previous selection criteria. The minor peak centered at $\delta\varphi$=0 corresponds to $e^+e^-\rightarrow\gamma\gamma(\gamma)$ and the two high peaks are of Bhabha. The standard deviation of the central minor peak is around 1.8° by Gaussian fitting. To remove $e^+e^-\rightarrow\gamma\gamma(\gamma)$ from our sample, $|\delta\varphi|>6°$ is required. There is still some background in the real data sample, which contributes a flat part in the $\delta\varphi$ plot. To subtract this kind of event, the events with $6°<|\delta\varphi|<43°$ are regarded as signals $N^{sgn}(t)$ and those with $43°<|\delta\varphi|<80°$ are treated

as background $N^{\rm bg}(t)$, and the latter is directly subtracted from the former.

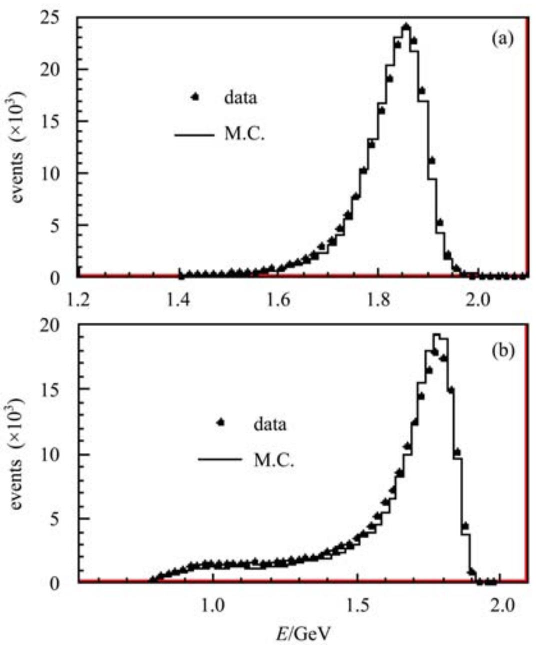

Fig. 3. (a) The distribution of $E_{\rm max1}$ of real data and the Monte Carlo simulation; (b) The distribution of $E_{\rm max2}$ of real data and the Monte Carlo simulation.

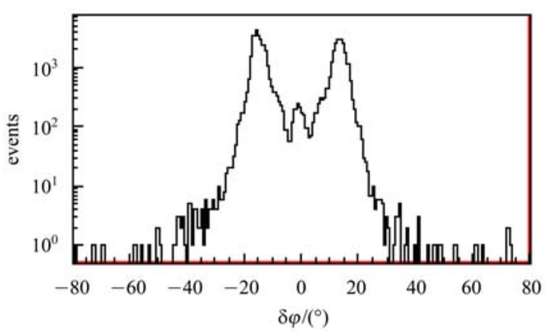

Fig. 4. $\delta\varphi$ distribution of real data sample.

3.2 Luminosity calculation and error analysis

Luminosity is calculated as

$$L(t)=\frac{N_{\rm Bhabha}(t)}{\varepsilon_{\rm trg}\cdot A\cdot\sigma}=\frac{(N^{\rm sgn}(t)-N^{\rm bg}(t))_{\rm data}}{\varepsilon_{\rm trg}\cdot(N^{\rm sgn}-N^{\rm bg})_{\rm M.C.}/N^{\rm tot}_{\rm M.C.}\cdot\sigma}, \quad (6)$$

where $N^{\rm sgn}(t)$, $N^{\rm bg}(t)$ are the number of events over one minute from t in the signal and background regions respectively. $N_{\rm Bhabha}(t)=N^{\rm sgn}(t)-N^{\rm bg}(t)$ is pure Bhabha events. $\varepsilon_{\rm trg}$ is the trigger efficiency. $N^{\rm tot}_{\rm M.C.}$ is the total Monte Carlo event number generated using Bhwide [7, 8] with $15^\circ<\theta<165^\circ$ in polar angle and full 2π in azimuthal angle and σ is the corresponding integrated cross section to order α^3 which covers the same angle. $A=(N^{\rm sgn}-N^{\rm bg})_{\rm M.C.}/N^{\rm tot}_{\rm M.C.}$ is the acceptance of Bhabha events selected from the corresponding Monte Carlo sample with the selection criteria described in Chapter 2.2.

The statistical error of $L(t)$ in Expression (6) is around 2.3%. The systematic error of $L(t)$ arises from the selection of the cuts, the possible background contribution and the uncertainty in calculation of the cross section.

By varying the cut criteria, the systematic errors caused by it can be measured and are listed in Table 1.

Since the $\delta\varphi$ cut for $e^+e^-\to\gamma\gamma(\gamma)$ rejection is more than 3σ, the background contribution is less than 0.03%. The uncertainty in theoretical calculation of the cross section is around 0.2% as given by Bhwide. The precision of Bhwide is 1.5% [7, 8].

The trigger efficiency of the Bhabha events is 0.999 with the relative error of 0.1% [9].

Adding all the above sources of systematic errors, the total relative error in luminosity is 3.5%.

Table 1. The systematic error in luminosity.

error sources	error(%)	note
$\cos\theta<0.93$	2.9	varying from 0.91 to 0.95
$\cos\theta>0.85$	0.9	varying from 0.83 to 0.87
$E_{\rm max1}>1.4$	0.9	varying from 1.3 to 1.7
$E_{\rm max2}>0.8$	0.5	varying from 0.6 to 1.2
$\lvert\delta\varphi\rvert<43^\circ$	0.0	varying from 39° to 47°
$\lvert\delta\varphi\rvert>6^\circ$	0.0	
σ	0.2	
Bhwide	1.5	
trigger efficiency	0.1	
total error	3.5	

4 The calibration of the BLM using the Bhabha events from EEMC

According to Expressions (5) and (6),

$$K=L(t)/n_{\rm BLM}(t), \quad (7)$$

where $L(t)$ is calculated with Expression (6), correspondingly $n_{\rm BLM}(t)$ is the total counts of all bunches over one minute from t. Fig. 5 (a) shows the trend graph of $L(t)$ and $n_{\rm BLM}(t)$ of 2010.2.19 according to which the ratio between $L(t)$ and $n_{\rm BLM}(t)$ is stable during the 14 runs. In Fig. 5 (b) the calibration constant K can be fitted to be 0.90±0.04 ($\times10^{26}$ cm$^{-2}\cdot$count^{-1}) with the relative error of 4.5%. Likewise K is obtained throughout every day during 2010.2.1–2010.3.7 at $\Psi(3770)$. As shown in Fig. 6 (a), the constant K is stable during 2010.2.1–2010.3.7 and, in Fig. 6 (b), the constant K can be fitted to be 0.84±0.03 ($\times10^{26}$ cm$^{-2}\cdot$count^{-1}) with the relative error of 3.6%.

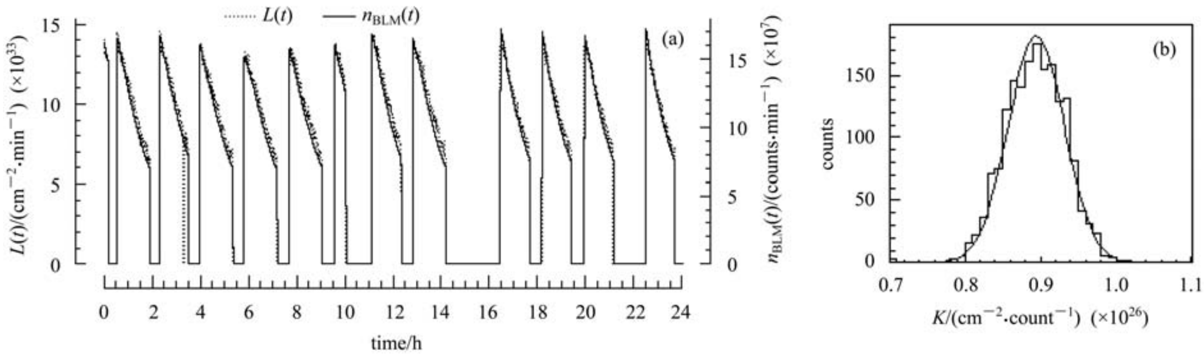

Fig. 5. (a) The trend graph of $L(t)$ and $n_{\mathrm{BLM}}(t)$ in 2010.2.19; (b) The distribution of K in 2010.2.19.

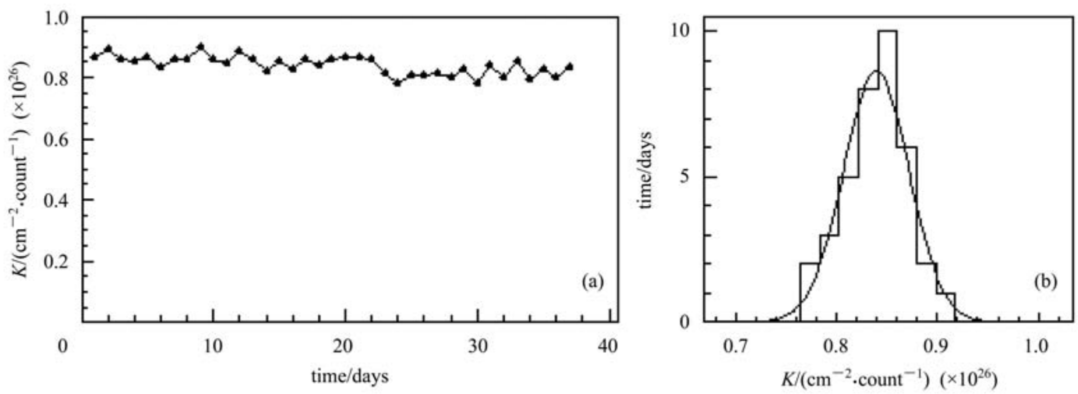

Fig. 6. (a) The trend graph of K during 2010.2.1–2010.3.7; (b) The distribution of K during 2010.2.1–2010.3.7.

As mentioned in chapter 2.2, $\sigma_{\mathrm{RB}}(k_{\mathrm{T}},\ \Omega_{\mathrm{D}})$ is dependent on k_{T} and Ω_{D}, so when the beam energies change or the geometry of the interaction region changes, the calibration constant K must be renewed.

5 Conclusions

The EEMC and the BLM are complementary in determining the luminosity of the BEPCⅡ. The EEMC can determine absolute luminosity and the BLM can monitor the relative luminosity bunch by bunch. It becomes a powerful monitor unit to optimize the BEPCII running parameters.

In this paper, $n_{\mathrm{BLM}}(t)$, the counting rate of the BLM is obtained with the statistical error of 0.01% and the systematic error of 4.1%. The offline luminosity $L(t)$ is also evaluated with Bhabha events detected by the EEMC with the statistical error of 2.3% and the systematic error of 3.5%. $n_{\mathrm{BLM}}(t)$ of the BLM is calibrated using the $L(t)$ from the EEMC and the calibration constant is obtained to be K=0.84±0.03 ($\times10^{26}$ cm$^{-2}\cdot$count^{-1}), so the counting rate of the BLM can be scaled up to absolute luminosity.

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