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Simulation study of real-time monitor for BEPC-II luminosity

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A fast and real time luminosity monitor system will be used in the BEPC-II (Beijing Electron Positron Collider, China). Photons generated in radiative Bhabha scattering at the interaction point are transformed into charged particles, and then the luminosity of each bunch pair is measured through collecting the Cherenkov light produced by charged particles in fused silica. The whole process happening in the detector is simulated. The physics acceptance and detection threshold with the monitor accuracy of 1% are set based on the simulation spectra of photoelectron yield calibrated by e^- beam data.

luminosity, BEPC-II, Cherenkov detector, radiative Bhabha

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1 Introduction

In the BEPC-II (Beijing Electron Positron Collider, China) upgrade project, the one-beam pipe configuration of BEPC-I will be changed to the configuration of two-beam pipes for electron and positron respectively. The luminosity will be increased up to about 10^{33} cm^{-2} s^{-1}. The e^- and e^+ beams cross each other with a finite angle of 22 mrad. A fast bunch by bunch luminosity monitor will be very beneficial in the operation of the BEPC-II.

Due to space constraint in the IP (interaction point) area, the most appropriate interaction for the luminosity measurement here is the radiative Bhabha process, 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 to PEP II and Belle experiments [1,2]. At BEPC-II, a total of 93 pairs of e^- and e^+ bunches will collide with each other at the IP. The time interval of adjacent bunch is 8 ns. Through measuring the relative luminosity of each bunch pair, the status of each bunch pair will be clearly shown to the beam operator and modifications can be made to keep the bunches in the best status. The total luminosity of 93 pairs of e^- and e^+ bunches could also be measured if a proper calibration is done. This system is designed for both of these purposes.

2 Single bremsstrahlung radiations of e^- and e^+ collision

The luminosity monitor detects the photon from the radiative Bhabha scattering, $e^+ + e^- \rightarrow e^+ + e^- + \gamma$. Its approximate energy-differential cross section for the radiation to a single-beam side is expressed as

$$\mathrm{d}\sigma = C \ln\left(\frac{E_{\mathrm{CM}}^2}{m_{\mathrm{e}}^2}\right)\frac{\mathrm{d}E_\gamma}{E_\gamma},\ C=3.0\ \mathrm{mb}, \tag{1}$$

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where E_γ, E_{CM}, and m_e are the energy of the emitted photon, the total energy of the whole center-of-mass system, and the mass of the electron, respectively [2]. The photon is emitted with a bremsstrahlung-like spectrum, approximately $1/E_\gamma$, where E_γ is the photon energy, and a narrow opening angle ~ $1/\gamma$, the inverse of the relativistic Lorentz factor of positron (electron). The BBBREM-Monte Carlo simulation program [3] of this process, without constraint on scattering angles, is used. The minimum energy cut of the photons is set to be 50 MeV. Using these photons as incident particles, we apply GEANT4 [4] to simulate the whole luminosity system, which includes the geometry, the development of the shower, the propagation of the Cherenkov light in fused silica and light guide, and the number of the photoelectrons finally collected in the cathode of photomultiplier tube (PMT).

3 Configuration of the detector

Figure 1 shows an illustration of the layout. The arrowhead in Figure 1 means the direction of the incident photons (that is, the direction of positron entering the IP).

Along the flight direction of photons emitted by positron, a 3-mm thick copper window is made in the beam pipe to let photons be out of it. The detector is located in a small clearance between two beam pipes whose length and width are about 18.0 cm and 5.90 cm respectively. A block of high quality fused silica is used as the radiator. Due to the constraint of the space, the width, height and length of the fused silica are chosen to be 4.00, 4.50 and 6.58 cm respectively. A lead converter plate is placed just in front of the radiator. This converter is used to convert the photons from single bremsstrahlung radiations to charged particles. According to our early simulation [5], the lead converter is chosen to be 3.5 radiation lengths with which the maximum number of secondary e^+e^- entering the fused silica can be reached and also can absorb the synchrotron radiation. The high quality fused silica has been shown to be very tolerant against radiation. Cherenkov detector is less sensitive than ionization detectors to synchrotron radiation and has very low energy electron backgrounds from the lost beam particles. The block of the fused silica is wrapped with aluminum foil. At the side other than the converter, the block of the fused silica is cut into two output windows with a proper angle as shown in Figure 1 for collecting the Cherenkov light produced by the secondary electrons and positrons from the showers. The angle is 35° also due to the constraint of the space. Two trapezoid light guides with inner walls deposited optically with aluminum film help guide Cherenkov light to the cathode of two photomultiplier tubes. Two HAMAMATSU R7400U-06 tubes are used in this system, for their fast rise time and good UV response. The main parameters of PMT R7400U-06 are listed in Table 1.

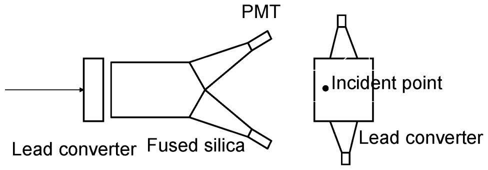

Figure 1 Layout of the luminosity monitor.

4 Estimation of average number of photoelectrons produced in photo-cathode of PMT

All parts of the luminosity system are placed according to the design. GEANT4 is used to simulate the Cherenkov light collection. One hundred thousand BBBREM events are generated. Photons from these events are used as input of the simulation. The number of the photoelectrons from the photocathode can be calculated using the quantum efficiency provided by the PMT manufacturer. Figure 2 shows the spectra of the photoelectron yields collected. Here No. 1 and No. 2 mean two PMTs respectively. We choose the signal from the first PMT to measure luminosity, and take the detector's geometry and physics response properties of the copper window, converter and detector system into account. Figure 2 shows that with the point-like bunch collision, 71096 events which have at least one photoelectron produced on the cathode of PMT are recorded from 100000 photon events generated by BBBREM. The physics acceptance is 0.711.

5 Simulation studies of the measuring accuracy of the system

5.1 Effects from the uncertainty of bunch collisions

The size of the bunch, the collision point and the impingement angle are fluctuated. The design parameters of the beam are shown in Table 2.

Using these parameters, we apply BBBREM program to generate 100000 BBBREM events (case 1). Another 100000 BBBREM events with the point-like bunch, the fixed collision point and the impingement angle are also generated (case 2). Figure 3 displays the positional distribution of the incident photons on the lead converter for both sets of bunch parameter. The circle in the figure means the radius of the collimate aperture of 3 mm in front of the lead

Table 1 Main parameters of PMT R7400U-06

PMT	R7400-U6
Effective photocathode diameter (mm)	8
Spectral response range (nm)	160–650
Rise time (ns)	0.78
Transit time (ns)	5.4
Gain	7×10^5

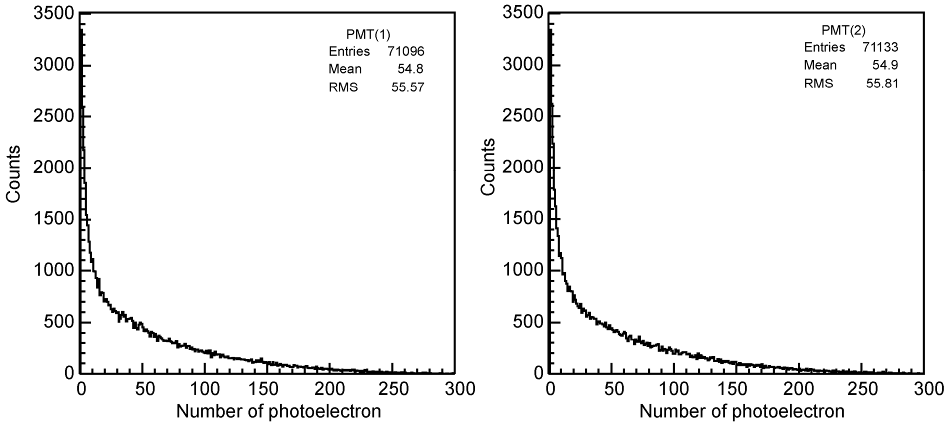

Figure 2 Spectra of the photoelectron yields (point-like bunch and events of less than one photonelectron excluded).

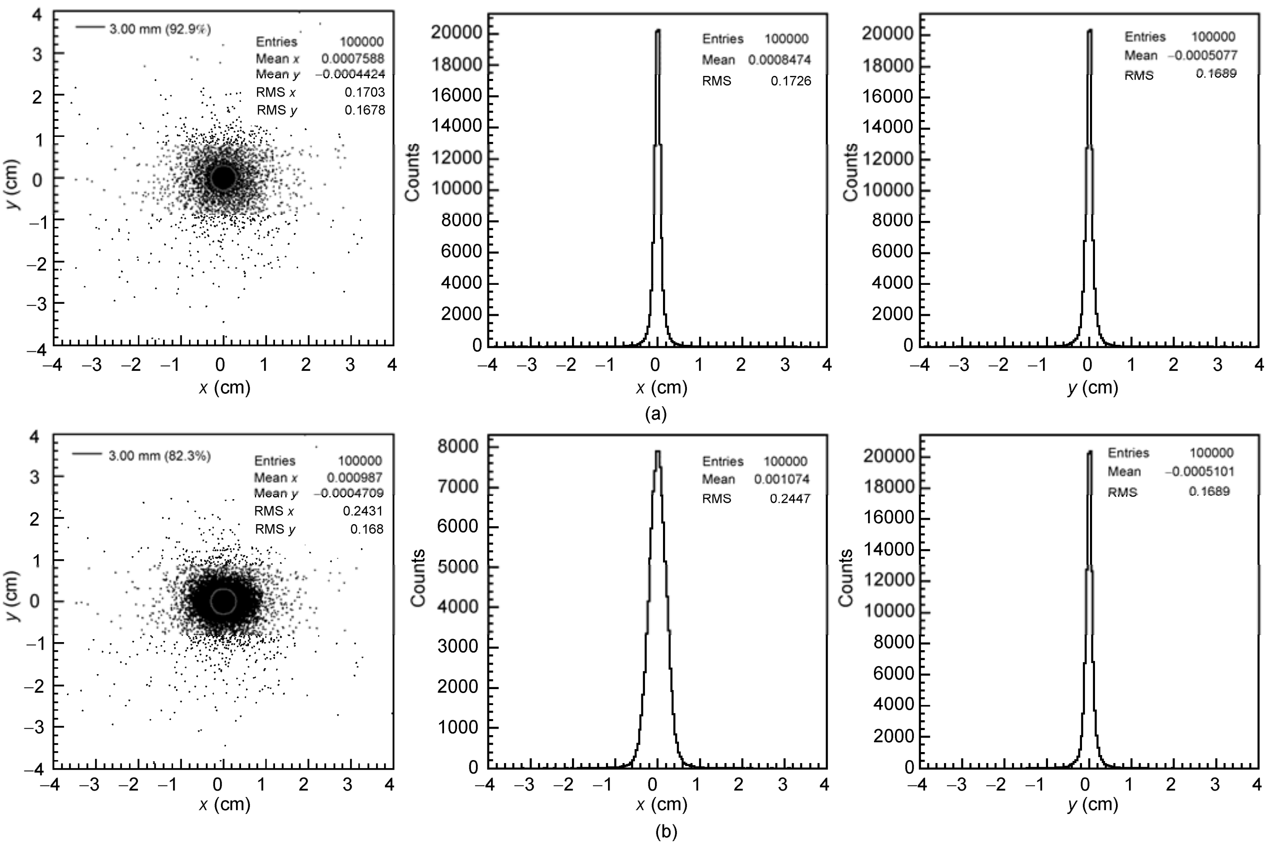

Figure 3 The hit distribution of the incident photons on the lead converter. (a) Case 2; (b) case 1.

Table 2 The parameters of the bunch

σ_x	0.4 mm
σ_y	6 μm
Length of the bunch	1.5 cm
Impingement angle	11±0.4 mrad

converter. From Figure 3, the photons that can pass the collimate aperture are 92.9% and 82.3% respectively. The bunch collision uncertainties will reduce the signal counts by a factor of 82.3/92.9. The physics acceptance will be 0.630.

5.2 Effect from the backgrounds

The influence of the background is also simulated. The background mostly comes from four parts: the synchrotron radiation (SR), the beam-gas inelastic bremsstrahlung, the beam-gas elastic Coulomb scattering and the Touschek effect. SR has large radiation power but low photon energy. The order of the critical energy of SR is about kilo-electron volt. This SR can be easily absorbed by the copper window and lead converter and has little influence on the detector whose Cherenkov threshold velocity (β_t=0.6859) is much higher than that of the secondary electron produced by SR in the fused silica. The background particles from the beam-gas and the Touschek effect are used as incident particles. Tracing the background particles with their momentum, if they or their secondary particles hit the fused silica, then we read out the number of photoelectrons in the cathode of PMTs and see if the number is over the threshold we set. If it is above the threshold, a false counting is added, otherwise, there will not be any effect on the measurement. A total number of 218937 electron background events and 217953 positron background events provided by Jin et al. [6,7] are used in the simulation. Figure 4 gives the distribution of the photoelectrons generated from the background electrons and positrons.

From Figure 4, positrons which the detector is facing contribute most of the background counts. The counting rate of the background in full luminosity can be acquired through the normalization.

5.3 Effect from the lost counting probability

From the equation given before, the relation between the total cross section and the energy cut can be calculated. The cross section of zero degree single bremsstrahlung radiations is about 160.120 mb with the minimum energy of the photons set to be 50 MeV, and the photon rate is 1.61×10^8/s under the target luminosity $L=10^{33}$ cm^{-2} s^{-1} in BEPC-II without any hardware cuts. The physics acceptance is 0.630. It means that at the target luminosity, if the detector threshold is set to be one photoelectron, the detector system should suffer a high rate of 1.01×10^8/s or 1.09×10^6/s per bunch pair. There are in total 1.25×10^6 collisions per second. The average γ events per bunch crossing which produce more than one photoelectron in the detector are 0.873 and the loss counting probability (*LCP*) is

$$P(n\geqslant 2)=\sum_{n=2}^{\infty}\frac{(0.873)^n e^{-0.873}}{n!}$$
$$=1-(e^{-0.873}+0.873\ e^{-0.873}) = 0.218,$$

following the Poisson distribution. The rate is too high for the detector to monitor the luminosity properly. The photoelectron threshold (*PE-th*) must be increased from one photoelectron to a proper value to allow the *LCP* to be less than 0.01, the required accuracy. From this point of view, the average γ events per bunch crossing must be reduced to 0.148. Therefore the corresponding event rate should be 1.85×10^5/s per bunch. On the other hand, the statistical accuracy (*SA*) is required to be less than 1%, which depends on the time interval of data updating. Balancing the error contribution from *LCP* and the *SA*, the *PE-th* should be taken properly. Table 3 shows the physics acceptance (*PA*), the event rate per bunch pair (*R*), the *LCP*, the SA with 5 s time interval of data updating and the rate of the background (*BR*) under a given PE-th. From Table 3, the proper threshold should be 106 photoelectrons with the *LCP* and *SA* required less than 1%.

6 Calibration of the yield of photoelectrons

There are no photons produced in radiative Bhabha scatter-

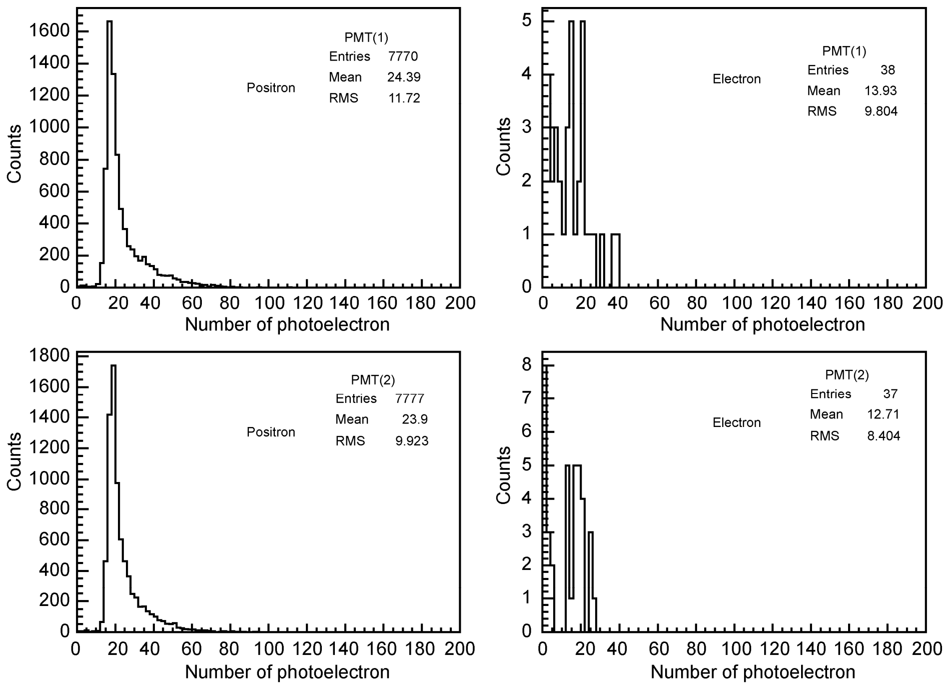

Figure 4 Distribution of the photoelectron generated from positron (left) and electron (right).

Table 3 Relation between *PE-th* and the *PA*, *R*, *LCP*, *SA* (in 5 s), *BR*

PE-th	*PA*	*R* (bunch s^{-1})	*LCP*	*SA* (in 5 s)	*BR* (Hz)
1	0.630	1.09×10^{6}	0.218	0.428×10^{-3}	7.17×10^{5}
20	0.405	0.702×10^{6}	0.109	0.534×10^{-3}	3.51×10^{5}
40	0.298	0.517×10^{6}	6.51×10^{-2}	0.622×10^{-3}	7.30×10^{4}
60	0.219	0.379×10^{6}	3.76×10^{-2}	0.726×10^{-3}	1.47×10^{4}
80	0.162	0.280×10^{6}	2.16×10^{-2}	0.845×10^{-3}	2.20×10^{3}
100	0.118	0.204×10^{6}	1.20×10^{-2}	0.989×10^{-3}	367
106	0.107	0.186×10^{6}	0.998×10^{-2}	1.04×10^{-3}	275
120	8.51×10^{-2}	0.147×10^{6}	0.642×10^{-2}	1.17×10^{-3}	0
140	6.06×10^{-2}	0.105×10^{6}	0.333×10^{-2}	1.38×10^{-3}	0

Table 4 Comparison of the simulation and e^- beam test

Energy (MeV)	Number of photoelectron		Calibration factor
	simulation	e^- beam test	
400	60.8±38.1	28.8±17.5	0.474±0.413
500	83.1±46.2	33.5±20.7	0.403±0.335
600	97.1±53.0	38.0±20.2	0.391±0.298

ing available for calibration. For checking the simulation code of Cherenkov photon transportation and collection, the same code is used to simulate the Cherenkov photon induced by the secondary e^+e^- produced in the electron beam injected into the converter [8]. The result is listed in Table 4.

From Table 4, an average calibration factor of 0.423±0.203 is obtained.

7 Conclusions

Starting with the photon-spectrum emitted in glancing collision of e^-+e^+ at IP, ending with the photon-electron numbers produced on the cathode of PMT, the physical acceptances of the luminosity system with various photon-electron thresholds have been evaluated by using GENAT4 package. With the LCP and SA required to be less than 1%, the proper threshold should be 45.0 photoelectrons after calibration.

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