Energy calibration of the EMC with Bhabha events at BESIII

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Abstract. In this report we present the calibration of energy in the electromagnetic calorimeter using Bhabha events collected with BESIII detector. Since Bhabha events have advantage of high statistics and known kinematics, absolute counter-by-counter calibrations have been performed by matrix conversion method. We have achieved the energy resolution of 2.3% at the beam energy 1.843GeV.

1. Introduction

The BESIII detector[1] is working at the interaction point of the BEPCII $e^+e^-$ collider[2]. The Electro-Magnetic Calorimeter (EMC) plays an important role in the BESIII detector, whose primary function is to measure precisely energies and positions of electrons and photons. Detecting direct photons and photons from decays of $\pi^0$, $\eta$, $\rho$, etc. produced in $\psi'$, $\psi''$, $\tau$ and D decays is essential for BESIII physics. In radiative decay processes, such as $J/\psi \rightarrow \gamma \pi\pi$, $J/\psi \rightarrow \gamma KK$, $J/\psi \rightarrow \gamma \eta \eta$, direct photons must be precisely measured and separated from photons from $\pi^0$, $\eta$ decays. Also the EMC plays an important role in electron identification.

The desired photon energy detection range for BESIII is from ~20MeV to the full beam energy of 2.3GeV for studying the $e^+e^- \rightarrow \gamma\gamma$ process. Accurately measuring photon energies and their hit coordinates is crucial for reconstructing physics processes and for new discoveries. In order to get exact energy, two steps of calibration are required. First, the energy of each counter is calibrated and then the calibration of shower energy after clustering is performed. So several channels are used such as cosmic-ray, Bhabha, radiative Bhabha, gamma-gamma, $\pi^0\gamma\gamma\rightarrow - + e e 0$ and so on, are used. Each channel has different usage and purpose. For counter-by-counter calibration, Bhabha channels are very useful due to high statistics and known kinematics. The calibration of shower energy is considered in details in the report[3] at this conference.

In this report, we describe the crystal counter energy calibration with Bhabha events to achieve good performance to match physics requirements.

2. CsI(Tl) crystal calorimeter

The BESIII EMC is composed of one barrel and two end cap sections. The entire calorimeter have 6240 CsI(Tl) crystals. The length of the crystals is 28 cm or 15.1 $X_0$. All crystals are arranged as 56 rings (44 rings in the barrel and 2×6 rings in the end caps). Each crystal covers an angle of about $3^\circ$ in both polar and azimuth directions.
The 5280 barrel crystals are divided into 44 rings. A barrel ring has 120 crystals. All crystals point to the interaction region with a small tilt of $1.5^\circ$ in the $\phi$ directions and $1.5^\circ$ to $3^\circ$ in the $\theta$ directions (i.e., $\pm 5$ cm from IP in the beam direction), in order to avoid photons from the interaction point escaping through cracks between crystals.

The each end cap has 6 rings. The number of crystals in 6 rings is 96, 96, 80, 80, 64, 64. Each of the 6 rings are split into two half circles and can be opened for accessing the drift chamber. The end caps with inner radius of 50cm are placed at $z = \pm 138$ cm from the collision point.

In order to minimize the dead areas and gaps between the crystals, the crystals are suspended from the support girder. In Ref.1, the details about the calorimeter construction are described.

3. Energy calibration

From the digitized signal of $i$-th counter ($ADC_i$), the energy deposit ($E_i$) is obtained by the following formula:

$$E_i = \frac{ADC_i - PED_i}{e_i} \times c_i,$$

where $ADC_i$ is the ADC value, $PED_i$ is the pedestal value, $e_i$ is the gain of the electronics chain and $c_i$ is the energy conversion constant. The values of $ADC_i$ and $PED_i$ are experimentally measured. The pedestal and electronics gain constants are obtained from online. The digitized signal read out from the offline raw data is subtracted pedestal and calibrated by electronics, i.e. $(ADC_i - PED_i)/e_i$. The energy conversion constant $c_i$ that relates the incident photon energy to the input charge of the preamplifier is the most difficult calibration constant to obtain.

Before installation into the container, every CsI(Tl) crystal was tested in the lab. The scintillation light obtained with $^{137}$Cs source read out by a PMT was measured. Cosmic ray tests in which the crystals were read out by photodiodes and preamplifiers were performed. The energy conversion constant database established by these tests is used in the BESIII EMC crystal calibrations as initial values. These constants, however, can only be used to determine the relative performance of the crystals. So the initial $c_i$ was obtained using the cosmic rays data without magnetic field which are taken during the BESIII detector joint debugging. It ensured the quick start of the calorimeter with good performance at the initial stage.

But the light output can be changed in each counter under the container due to several reasons: the pressure of structure, the geometry of calorimeter, radiation damage and so on. To achieve more accurate $c_i$, counter-by-counter calibration is executed using Bhabha events.

3.1. Cosmic ray calibration

During the BESIII detector joint debugging, the cosmic ray data without magnetic field are taken. We select the events with the back-to-back condition and only two crystals with the energy larger than 10MeV. The cosmic ray data is mainly $\mu$ lepton in BESIII detector, and its momentum is basically larger than 1GeV, so we may suppose that the deposited energy is proportional to the depth through CsI crystal. We check the ADC (MeV) distribution for each crystal. First each crystal was calibrated by the relative light yield, the calibration constant is $C_i^{LY} = LY_{\text{average}}/LY_i$, where $LY_{\text{average}}$ is the average of the relative light yield, $LY_i$ is the relative light yield of the $i$-th crystal. Then the comparison with the MC was made, the Monte Carlo constant is $C_i^{MC} = E_i^{\text{average}(MC)}/E_i^{\text{average}(data)}$. Finally the cosmic ray calibration constant for each crystal is $C_i^{\text{cosmic}} = C_i^{LY} \times C_i^{MC}$.

Fig.1 shows the performance of Bhabha events at a center-of-mass energy of 3.686GeV in Oct 2008, i.e. in the early stage of BESIII running. The triangle dots are the results after the cosmic
calibration. The square dots are the results of the first Bhabha calibration. We can see that the cosmic calibration is very rough, but as the input of Bhabha calibration it ensured the initial digi-calibration successfully accomplished.

Fig.1 (a) and (b) are the energy peak and resolution versus ThetaID of crystal counter, respectively.

3.2. Bhabha Calibration

3.2.1. Bhabha Events

We use the online Bhabha events or offline PreSelected Bhabha events. The criteria conditions of Bhabha sample are in the following:

\[
1 \text{GeV} < E_{\text{sh1}} < 4 \text{GeV}, \quad 0.4 \text{GeV} < E_{\text{sh2}} < 4 \text{GeV},
\]

\[
|\theta_1 - \theta_2| < 3^\circ, \quad -25^\circ < \phi_1 - \phi_2 < -4^\circ \parallel 2^\circ < \phi_1 - \phi_2 < 20^\circ, \quad \text{Mdc\_hit} > 20.
\]

Event selection is very important for Bhabha calibration. Because the light yield and uniformity change with time through the radiation damage, and the status of every crystal is different, we select the shower with the energy in the range of energy Peak(i\_x\_tal) ± 1\(\sigma\)(i\_\(\theta\)) for every crystal.

3.2.2. Method

We wish to find the parameters \( (g_i) \) that minimize the discrepancy between the expected shower energy and the measured one. The \( \chi^2 \) is given by

\[
\chi^2 = \sum_{k=1}^{N} \frac{E_{\text{exp}}^k - \sum_{i=1}^{5\times5} g_i E_i}{\sigma(\theta, \phi)},
\]  \hspace{1cm} (2)

\[
E_{\text{exp}}^k = E_e(\theta, \phi) f(E_e, \theta, \phi). \]  \hspace{1cm} (3)

Where \( E_{\text{exp}}^k \) is the expected shower energy, \( E_i \) is the measured energy in i-th counter and is summed to shower range up to 5×5 around maximum energy counter and \( g_i \) is weight value for each counter, i.e., Bhabha calibration constant which represent the energy response in i-th counter. The expected shower energy \( E_{\text{exp}}^k \) is written by Eq.(3). \( E_e(\theta, \phi) \) is the e\(^k\) kinematics energy determined from incident direction but is not real deposited energy due to passive material and energy leakage. So those effects are supplemented by the function \( f(E_e, \theta, \phi) \) which is the energy leakage from MC.
By minimizing the $\chi^2$ defined in Eq.(2), matrix equation is extracted.

\[
\sum_j g_j Q_{ij} = R_i, \quad (4)
\]

\[
Q_{ij} = \sum_{k=1}^{N} \frac{E_{ik} E_{jk}}{\sigma_{k}^2}, \quad (5)
\]

\[
R_i = \sum_{k=1}^{N} \frac{E_{ik} E_{\text{exp}}}{\sigma_{k}^2}, \quad (6)
\]

Where $Q$ is matrix with order 6240. Matrix $Q$ is sparse because Bhabha event hit specific region in which counters have correction. All $g_i$ are decided simultaneously by inverting matrix equation. Matrix conversion is main part in Bhabha calibration and the difficulty result from the inverse of matrix $Q$. Sparse matrix package (SLAP) [4] is used to invert matrix equation. Bhabha calibration procedure is shown in Fig.2.

If there is no difference between counter in energy response, the value of all $g_i$ is unity. Bhabha calibration constant $g_i$ distribution is shown in fig.3. Finally original energy conversion constant ($c_i$) is corrected by Bhabha calibration constant ($g_i$) i.e., $c_i \times g_i \rightarrow c_i$.

After Bhabha calibration we check the calibration constants via checking the performances of E5x5cms energy peak and resolution versus theta-index, E5x5cms energy peak and resolution versus phi-index in barrel, and E5x5cms energy versus ixtal profile and so on. Those checks are shown in Fig.4.
Fig. 3 Bhabha calibration constant in second calibration version.

Fig. 4 (a) and (b) are the E5x5cms energy peak and resolution versus theta-index, respectively (c) and (d) are the E5x5cms energy peak and resolution versus phi-index in barrel, respectively (e) is the E5x5cms energy versus ixtal profile.
3.2.3. EMC Performance after Bhabha calibration

After Bhabha calibration EMC performance are shown in Fig.5. In the center-of-mass system, energy resolutions for electrons (from $e^+e^- \rightarrow e^+e^-$) are $\sim 2.3\%$ in barrel and $\sim 4.1\%$ in end cap, for photons (from $e^+e^- \rightarrow \gamma\gamma$) $\sim 2.7\%$ in barrel and $\sim 4.2\%$ in end cap. Data and MC also consist very well.

![Fig.5](image)

Fig.5 (a) and (b) are e5x5 energy distribution of Bhabha events and digamma events at the center-of-mass energy 3.686GeV, respectively. (c) and (d) are the energy resolution versus the thetaID of Bhabha events and digamma events, respectively.

4. Conclusion

The BESIII CsI(Tl) calorimeter has been working quite well for two years. All the 6240 CsI(Tl) counters are alive. The single crystal energy calibration is very good. Data and MC consist very well after the calibration with Bhabha. The energy resolution for $e^+e^- \rightarrow e^+e^-$ is $\sim 2.3\%$ at the center-of-mass energy 3.686GeV. Current Bhabha calibration method shows the stable and reliable picture and EMC all crystal counters are monitored by Bhabha calibration.

References

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