EM Calorimeter in BESIII Experiment

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Abstract. BESIII EM Calorimeter (EMC) is based on CsI crystals, working at upgraded Beijing Electron Positron Collider (BEPC), called BEPCII. The overall BEPCII and BESIII design and current status are briefly described. The design and construction of EMC and its performance are presented. EMC works very well and its performances reach the design expectations, it plays an important role in detector operation and in the BESIII trigger. There are some special features in the EMC construction and reconstruction: the crystals are assembled without support wall to reduce dead area; the time information of the EM clusters can help to suppress the machine background; the detector noise is smaller than similar detectors; the energy reconstruction with TOF signals helps to improve the energy resolution, especially for low energy showers. Several physics papers mainly based on EMC information have been published.

1. Introduction
Beijing Electron Positron Collider (BEPC) has been approved for major upgrade, called BEPCII, at the end of 2003. The original machine has been upgraded to a two rings machine, with up to 93 bunches in each ring and mini-β achieved by super-conducting quadruples, to increase its luminosity by a factor of about 100, to $10^{32} cm^{-2}s^{-1}$. The electrons and positrons collider with a cross-angle of $2 \times 11$ mill radians. Beijing Spectroscopy (BESIII)[1] is the detector to do experiment at BEPCII, it is completely built as a new detector. The project started at the beginning of 2004, and the machine and detector had been completed in the summer of 2008, and first collision event at center of mass system of 3.68 GeV was observed on July 20, 2008. After almost one year of commissioning run, the project passed the Chinese Government review at July 2009.

Until now the machine reached the maximum luminosity of $3 \times 10^{32} cm^{-2}s^{-1}$, 30% of the designed luminosity to be reached after a few years from commissioning. Most of BESIII systems work well. So far, BESIII has collected 100 M hadronic events at $\psi(2S)$, 220 M at $J/\psi$ and about 610 $pb^{-1}$ so far at $\psi(3770)$.

BESIII consists of the Main Drift Chamber (MDC), Time of Flight (TOF), CsI EM calorimeter, Muon chambers made of Resistive Plate Chamber. The center magnetic field is 1.0 tesla provided by a super-conducting magnet.

MDC has 43 sense wire layers, using He based working gas. The achieved momentum resolution is 11 MeV/c for Bhabha electrons at $J/\psi$ energy of 3.1 GeV, equivalent to a momentum resolution better than 0.6% for charged tracks of 1 GeV. The dE/dx resolution of Bhabha electrons reached 4.9%, better than designed.

For Bhabha events, the time resolution of TOF is about 80 ps for barrel counters combined hits in both layers and about 136 ps for endcap counters. The endcap TOF suffers from material...
at the endcap region. For di-muons events, the time resolution reaches 95 ps.

BESIII, as an international collaboration, consists of about 300 members, from 43 institutes from China, Japan, Korea, Pakistan, United States, German, Russia, Italy and Netherland.

2. Construction of EMC

BESIII EMC is based on CsI(Tl) crystals, with a designed energy resolution of 2.5% and a position resolution of 6 mm for 1 GeV showers. The EMC consists barrel and endcap parts as shown in Fig. 1. In the barrel, there are 120 sectors in phi direction, each consists of 44 crystals in z direction. The number of barrel crystals is 5280 in total. The crystals are 28 cm long, and typical size of the crystal is 5.2 cm by 5.2 cm in the front surface. The crystals are nearly projective but arranged that they are tilted by 1.5° in φ direction and 1 – 3° in θ direction to avoid photons go through gaps between crystals. In the endcap, the crystals with similar dimensions as in those in the barrel are arranged in 6 rings in radial direction, there are total of 960 crystals in two endcaps.

![Figure 1. one quarter of cross-section of BESIII EM Calorimeter.](image)

Two photodiodes are attached to the back face of every crystal, each is readout by an pre-amplifier. The readout units is housed in an Al box. The crystals are held by 4 screws drilled into the crystal, then mounted to the support structure. there are fibers emitting light from LED to each crystal for monitoring purpose. During the assembling, one unit, consists two φ sectors with 88 crystals, firstly assembled in a jig structure, after carefully adjusting the crystal positions and testing the readout using LED, these two sectors are mounted on a fixture, so the crystals are fixed in relative stable positions and can be moved together. The 60 such units are assembled into a barrel structure. The total weight of the barrel crystal structure is about 54 tons, inserted in the stainless steel structure of detector magnet and mounted. The endcaps crystals used similar structure to hold the crystals from the back. Fig.2 shows how the assembled crystal unit looks, Fig.3 shows the detailed assembling parts and how they were assembled together.

The crystals were produced by 3 companies, Sanit-Gobain in France, Shanghai Institute of Ceramics and Beijing Hamamatsu in China, the crystals delivered to IHEP were tested to check their dimensions, the light yield and the radiation resistivity. The light yield of crystals is required to be more than 35% of the light from a standard small crystal, the average light
of all accepted crystals is about 58% of the standard crystal, more than 35% in the design. There is a demand of the light uniformity along the length of the crystal to be less than 7%, the actual average number of this quantity for all the crystals is about 4%. The crystals are tested for their radiation resistivity, by measuring its accompanied small sample in each crystal production batch for its radiation property. The samples were subject to radiation dose up to 1000 rads in a gamma source. The requirement is that the light reduction after 100 rads should be less than 9% and less than 20% after 1000 rads. If a sample did not meet those requirements, all the crystals produced with this sample in a batch will be shipped back to the company to be replaced. 482 crystals are replaced for the reasons of bad radiation hardness, unqualified dimensions etc.

The photon sensors are Hamamatsu S2744-08 (1cm × 2cm) photodiodes, there are two diodes attached to the back surface of one crystal, each diode is readout by one preamplifier. The diodes and preamplifiers are housed in an Al cover mounted on an Al plate frame, which is screwed onto the crystals, as shown in Fig. 2 and Fig. 3.

Each photodiode is tested for its dark current, capacitance and quantum efficiency. All the preamplifiers were tested for their gains. The two preamplifiers on the same crystal are selected to have the gain difference less than 3%, to improve the overall energy measurement accuracy.

The signals from the preamplifier was sent to the main amplifier 18 meters away, the shaping time of the amplifier is 1 micro second. Then the signals are digitized in a Q module. The digitization of the signals is realized by three 20.8 Mhz 10 bit ADCs to cover a dynamic range of 15 bits. And the signal peaking time is also read out with 6 bits accuracy. The electronics are carefully designed, including careful shielding and grounding. The noise of the electronics is required to be less than 1100 electrons, equivalent to shower energy of 220 keV, the average noise of 384 channels tested in electronics lab is 973 electrons.

The detailed information about BESIII EMC electronics can be referred to the talk by Mr. Jinfan Chang at this conference.

3. Operation experience
In order to ensure the safety of the crystals from the radiation dose from the machine. The radiation dose is carefully monitored by dose probes mounted inside the detector. After
the BESIII moved into the beam line, the machine operation was carefully planned. At BEPCII/BESIII, the detector dose from machine comes from beams circulated in the ring as well as from the beam injection from Linac to the ring, the later caused more dose if the injection was not well tuned. To avoid sudden dose accumulation to damage the crystals, at the very beginning of BEPCII/BESIII commissioning, the beam injection from Linac used 1 Hz rate compared to the normal 50 Hz Linac operation. After the machine dose is under control, then the machine injection shifted to 5 Hz operation, then to 25 or 50 Hz operation.

There are two kinds of radiation monitor probes, one is pin diode and another is RadFET, the formal can withstand more dose and used to monitor the machine radiation dose online, and the later is more stable and used to estimate the real integrated dose in the crystals. There are 12 pin diodes probes mounted on the beam pipe structure, 6 at east side and 6 at west side, 60 degree apart in phi direction. The RadFET probes are distributed at a radius similar to where the crystals are, in the barrel 10 probes are positioned along the Z direction, at one phi angle. There are 4 rows of probes at phi of 0, 90, 180 and 270 degrees, so there are 40 probes in barrel. at the endcap, each side placed 4 probes along the radius direction at one phi, and probes are placed in phi direction of 0, 90, 180 and 270 degrees, so there are 32 probes in total in the endcaps. The relative doses at pin diodes and at the RadFET were calibrated before the detector was moved in the beam line by IHEP radiation office. When machine is in operation, if some dose from pin diodes exceeds certain level, there will be a warning and the machine people have to take action to reduce the doses on the detector.

There is a LED system to monitor the light output from LED, to check the system during the EMC assembling and in data taking, by reading the LED light from each crystals. Actually this system helped to find out some problems, such as loose gluing of photodiode to the crystal, broken cables, noisy channels because of bad grounding, etc during the assembling. During data taking, the system serves to find out bad channels and monitor the performance of the EMC, including the gain reduction by radiation in each crystal. The details are in the talk given by Jian Fang at this conference.

Up till now, the average drop of the light of all the crystals are less than 3%, but for a small fraction of the crystals, mostly at the endcaps, the light reduction reaches about 10% for some crystals. These light reduction is consistent to the gain reduction calculated from the EMC calibration using Bhabha events. For the worst case, the gains reduction for a small number of crystals reaches about 15%, whether it is due to radiation dose, or some other factors such as reduced light coupling between crystal and the photodiode, should be further investigated.

4. EMC in the trigger

EMC plays important roll in the BESIII trigger. In the barrel, $4 \times 4$ crystals form an trigger cell, in the endcaps, neighboring 15 crystals form a trigger cell. The threshold for trigger cell is set to about 70-80 MeV, a cluster finding scheme is carried out to form a cluster using nearby crystals above the threshold. By analyzing the data, it is confirmed that the trigger is fully efficient for clusters with energy lager than 200 MeV. There are several trigger conditions from EMC, they are the number of clusters, the total energy of the EMC energy and the energy balance in EMC. For the condition of total energy, there are two thresholds, one is Etotl which is set to about 200 MEV, and is 100% efficient at 400 MeV from the trigger study. Another is Etotm which is set to about 700 MeV, and is 100% efficient at 1000 MeV, which is mainly used for triggering neutral events. At the global level, there is a neutral trigger, which requires Etotm and number of clusters to be large than 1. There are several triggers for events containing charge tracks, besides conditions from MDC and TOF, for EMC, there is requirement of one or more clusters, or requirement of Etotl. At earlier runs at J/ψ and ψ(2S), there was an trigger condition that demand 2 or more tracks and 2 or more TOF hits. But at ψ(3770) runs, the total trigger rate became too higher because of higher beam currents and higher energy compared
with the conditions at two earlier beam energies at $J/\psi$ and $\psi(2S)$. Careful studies shown that dropping this global trigger will not result in the loss of good events with an addition trigger for back-back events, so this global trigger condition is no longer used at $\psi(3770)$ data taking. Now all the global triggers require some signals from EMC, either having one cluster at barrel or endcaps or satisfying $E_{\text{tot}}$ condition, except the barrel back to back trigger, which requires back to back tracks and back to back TOF hits, the rate of this trigger is relatively small, so no information from EMC is needed. From this change in the trigger, it shows how powerful the EMC is in its ability to reduce the background in the trigger.

Special data were taken to study the trigger efficiency, the results show that for most of the good events, including Bhabha, hadronic events, barrel di-muons, BESIII trigger is 100% efficient, only for endcap di-muons events, the trigger efficiency is about 95%.

5. EMC calibration and monitoring
After data were taken, major effects were spent to calibrate the detector and monitor the performance of various detector components. In BESIII, Bhabha events are used to calibrate the gain of each crystal, radiative Bhabha, di-photons events and $\pi^0$ are used for energy scale and understand the energy response and the resolution for showers at lower energies. To ensure the consistent of Monte-carlo (MC) and data, the detector material were carefully accounted for and put into the MC. At the beginning, the agreement at the endcaps was not good, it then found out that the material from the cables at the endcaps were not correctly put into the data base, after the correct material was added, the agreement between MC and data became quite good. Talks given by Liu Chunxiu and Bian Jianming at this conference provide details about the EMC calibration and improvement of reconstruction.

Fig. 4 shows the average energy deposited in EMC of Bhabha events at c.m. energy of 3.68 GeV, as a function of shower Z position in EMC in the data as well as in the MC. Fig. 5 shows the energy resolution in EMC of same events as a function of shower Z position in EMC in the data as well as in the MC.

![Figure 4](image1.png)

**Figure 4.** The Comparison of average energy deposited in EMC crystals along Z direction as a function of shower position between data and MC for Bhabha events.

![Figure 5](image2.png)

**Figure 5.** The Comparison of energy resolution in EMC crystals along Z direction as a function of shower position between data and MC for Bhabha events.

Fig. 6 shows the position resolution of Bhabha events at c.m. energy of 3.68 GeV, the corresponding shower position resolution is 4.4 mm. Fig. 7 shows the energy resolution as a function of shower energy, it can be seen that the energy resolution at 1 GeV is about 2.5%.

To prevent causing problem in EMC electronics, the EMC electronics is powered all the time when the machine is in operation, even at the dedicated synchrotron runs. So it is handy to
monitor the EMC conditions and make luminosity measurement easier.

6. EMC Performance

The EMC works fine now after about two years in the beam line. The noise level at the collision point in data taking is similar to that tested at the lab. From the data analyzed, the average noise for all the channels is at a level of 200 MeV as shown in Fig. 8, better than most of other detectors in the world with similar complexity based on CsI(Tl) crystals. Because mechanically it is very difficult to make repair for EMC, and if one crystal is lost, the energy at the area this crystal covers will be degraded, it is critical to keep all the channels working at all times. There is no single crystal lost so far. The number of crystal which has only one photodiode plus preamplifier working was two at the beginning of the data taking in July 2008, now the number of such crystal has increased to about 10, but the effect to the performance is minimum.

After the calibration and correctly input of the detector material, the agreement of Bhabha energy distribution along phi and Z between data and MC is very good. And the energy resolution as a function of shower energy is as expected, and at 1 GeV the energy resolution is about 2.5% as designed.

It worths pointed out that the shower time information is very useful in the rejection of the background in EMC. The time is distributed in a relative narrow window for physics events and the distribution is flat for background in the data taking window, which is much larger than the time window in which the real events occurs. For the physics data, after selecting real showers by a chosen time window cut, the background is reduced by a large factor. Also, the combined reconstruction of shower energies by adding associated TOF energy deposits can improve the shower reconstruction efficiency and the energy resolution is also improved, especially for low energy showers, as shown in Fig.9. In the figure, the solid dots are for shower reconstructed without TOF, and the circles are with the TOF in the reconstruction.

There are large sample of $\chi_{cJ}$ decays, the radiative photons in the $\psi(2S)$ to $\chi_{cJ}$ decays can be used to study the performance of EMC. The energy distributions of radiative gammas in EMC and TOF agree very well between data and MC. The difference between data and MC in reconstructed energy scale is less than 0.5 % and the difference in energy resolution is less than 5%, by study of the real data. By using TOF in the energy reconstruction, the low energy gamma reconstruction efficiency is improved by more than 7%, the improvement in low energy $\pi^0$ reconstruction efficiency is about 12%. These are significant in the physics analyzes.

On the whole, BESIII EMC performs very well from data analyzed, and it plays crucial roll
Figure 8. The equivalent noise of each channel as a function of channel number for all channels.

Figure 9. The comparison of shower reconstruction efficiency with or without using TOF hits, the dots are for the case without TOF in the reconstruction, the circles are with TOF.

in physics analyzes.

7. EMC in BESIII Physics Analyzes

At BESIII, EMC is well understood, so several papers are published mainly using EMC information, which are the BESIII first publications.

One paper published [2] is the BF measurement of \( \psi(2S) \to \gamma \pi^0 \eta \) and \( \gamma \eta \eta \) through \( \chi_{cJ} \) states. The \( \chi_0 \) and \( \chi_2 \) peak are very clear and almost background free, and they can be nicely fitted. Fig. 10 is the recoiled gamma spectrum for \( \psi(2S) \to \gamma \pi^0 \pi^0 \), Fig. 11 is the recoiled gamma spectrum for \( \psi(2S) \to \gamma \eta \eta \). The fit used the MC generated gamma spectrum for \( \chi_0 \) and \( \chi_2 \).

Figure 10. The radiative photon energy spectrum of selected \( \chi_{cJ} \to \pi^0 \pi^0 \) events. Dots with error bars are data. The solid curve is the fit. The dotted curve is the \( \chi_{cJ} \) signals. The dashed curve is the background polynomial.

Figure 11. The radiative photon energy spectrum of selected \( \chi_{cJ} \to \eta \eta \) events. Dots with error bars are data. The solid curve is the fit. The dotted curve is the \( \chi_{cJ} \) signals. The dashed curve is the background polynomial.

The results are in the Table 1 and 2. Compared with PDG and CLEOc, the results are consistent with each other and the BESIII results have smaller errors.
Another paper published[3] is the results of inclusive $\psi(2S)$ decays to $hc$. Because of the much better EMC properties compared with these of BESII, BESIII has able to see the $hc$ signal clearly with inclusive $\psi(2S)$ decays, with the tag on the radiative photon of $hc \rightarrow \gamma \eta_c$ as well as without the tag. Fig. 12 shows the $\pi^0$ recoil mass spectrum with the tag, fits are indicated by solid lines, background by dashed lines, the smaller plot is the one with background subtraction. The data is fitted by treating the signal as a Breit-Wigner convoluted with a detector Gaussian resolution plus background, which is represented by the $\pi^0$ recoil mass spectrum in the sideband of the E1 photon, and the background normalization is allowed to float. In the fit, the mass and width of $hc$ are allowed to float. The fitted results are: mass of $hc$ is $3525.40 \pm 0.13$ MeV, width of $hc$ is $0.73 \pm 0.45$ MeV, with statistical errors only. The signal has a significance of 18.6 $\sigma$ with number of signal events of 3679 $\pm$ 319. Fig. 13 is the inclusive $\pi^0$ recoil mass spectrum in $\psi(2S)$ decays, the signal corresponding to $hc$ is obvious. When fitting the spectrum, the mass and width of $hc$ are fixed to the values obtained from E1-tagged analysis. Fits are indicated by solid lines, background by dashed lines. The background is parameterized by a 4th-order Chebychev polynomial, and all of its parameters are allowed to float. The signal has a significance of 9.5 $\sigma$, with a fitted number of signal events of 10353 $\pm$ 1097. From the above two fits, the $BF(\psi(2S) \rightarrow \pi^0hc)$ and $BF(hc \rightarrow \gamma \eta_c)$ and the two separate BFs can be obtained. The systematic errors are mainly due to the background shape in the fit, the energy scale, the number of $\pi^0$ in the events, the total number of $\psi(2S)$ events. The final results are in the Table 3.

The results of separate BFs of $BF(\psi(2S) \rightarrow \pi^0hc)$ and $BF(hc \rightarrow \gamma \eta_c)$ are the first measurements, can be compared with predictions.
Figure 12. The $\pi^0$ recoil mass spectrum and the fit for E1-tagged analysis of $\psi(2S) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c$. The inset is the background subtracted spectrum.

Figure 13. The $\pi^0$ recoil mass spectrum and the fit for the inclusive analysis of $\psi(2S) \rightarrow \pi^0 h_c$. The inset is the background subtracted spectrum.

References
[1] M. Ablikim, et al. (BESIII Collaboration), "Design and construction of the BESIII detector", arXiv:0911.4960, accepted by Nucl. Instrum. Meth. A.
[2] M. Ablikim, et al. (BESIII Collaboration), Phys. Rev. D81, 052005 (2010).
[3] M. Ablikim, et al. (BESIII Collaboration), Phys. Rev. Lett. 104, 132002 (2010).