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Results on the calibration of the L3 BGO calorimeter with cosmic rays

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During 1991 two cosmic rays runs took place for the calibration of the L3 electromagnetic calorimeter. In this paper we present the results of the first high statistics cosmic ray calibration of the calorimeter in situ, including the end caps. Results show that the accuracy on the measurement of the calibration constants that can be achieved in one month of data taking is of 1.3%.

1. Introduction

The L3 detector is one of the four LEP experiments. It consists of a central tracking chamber (TEC) surrounded by an electromagnetic calorimeter made of BGO crystals and a hadronic calorimeter consisting of uranium plates instrumented with proportional wire chambers. The outermost part of the detector consists of three layers of drift chambers for muon detection and measurement. All the subdetectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction. For more details the reader is referred to ref. [1].

Because the electromagnetic calorimeter is made of scintillating crystals, it is mandatory to monitor its stability in order to preserve its good energy resolution (~ 1.5% from 2 GeV up to 45 GeV). Therefore in situ calibration is needed. In the L3 experiment we use three different means of calibration: xenon lamps [2], Bhabha scattering [4] and cosmic rays.

The latter method can be used as a calibration tool because the energy loss of muons in BGO is known [3] and the path length through the BGO crystals can be measured using the information coming from the muon chambers of the apparatus. Knowing the specific energy loss in the BGO, one can determine a calibration constant for electrons after a set of corrections are applied to take into account the different ways in which electrons and muons lose energy inside the BGO [5,6].

In the following we will describe the 1991 cosmic ray runs and the results of the analysis. The paper is organized as follow:

- in section 2 we describe the data taking statistics;
- in section 3 we describe the data production and reduction;
- the calibration principles are illustrated in section 4;
- in section 5 we will analyze in detail the set of corrections needed to transform the muon calibration constants to the electron ones;
- the result of the calibration is presented in section 6. A sample of Bhabha events collected during 1991 is used to determine the resolution of the detector using the muon calibration;
- finally, in section 7 we will make some remarks about the measurement of the light collection efficiency using cosmic muons.

2. Data taking

The cosmic muon trigger was done using muon chambers and scintillator counters. In order to keep the DAQ scheme used during physics runs, we must simulate a beam gate to synchronize all the electronics. For this purpose we used the clock source of the BGO readout electronics; during the 5 μs after the clock pulse a gate was opened for muon chambers, scintillator counters and BGO. We look for a muon during this time. If it is found we start the BGO signal integration for 5 μs. The event was accepted requiring a track in two different octants of the muon chambers separated by at least one octant, in coincidence with the scintillator counters. The trigger rate was 3 Hz.

Data were taken in two periods: the April sample taken from 11-3-1991 until 29-4-1991, before the 1991 LEP run, and the September sample taken from 26-8-1991 until 1-10-1991, during a stop of the 1991 LEP run. During these two periods a total of about $5 \times 10^6$ triggers were collected and 708 tape cartridges were...
used to record data. The data taking time was 50% of real time because of the interference with other activities on the L3 apparatus. In a dedicated run the same statistics could be obtained in about one month.

3. Data production and reduction

Data were processed with the L3 reconstruction program REL3 modified for cosmic ray operation.

The muon momentum was measured using the curvature in the magnetic field. Its trajectory is extrapolated through the crystals of the electromagnetic calorimeter. Then a track finding algorithm based on patterns of fired crystals is used to define tracks inside the BGO. Each track is matched with the one measured by the muon chambers and the entrance and exit point in the crystals are evaluated. In order to minimize the error due to the evaluation of the track length in each crystal, only crystals traversed face to face (see Fig. 1) are used in the subsequent analysis. In fact, due to the tapered geometry of the crystals, the track length depends mainly upon the impact point coordinate along the crystal axis and two angles, while in the crossing of contiguous faces a precise measurement of the entry and exit coordinate is needed.

In addition a cut on the quality of the fit of the track is applied to the data: good hits are selected requiring a match between the track found in the BGO and the one defined by the muon chamber fit. The matching requires a pattern of the fired crystals consistent with the reconstructed muon track.

Only $\frac{1}{4}$ of the triggers have enough information in the muon chambers to reconstruct a muon matching with the BGO. The final sample contains ~0.5 good hits per trigger. This is equivalent to 2 hits per matched muon. For each hit we record the muon momentum, the crystal identifier, the coordinate along the crystal axis $t$, the track length $\Delta x$, the height $V$ of the digitized signal from the photodiodes, and the temperatures measured in the front part of the BGO, $T_f$, and in the rear part, $T_r$. The reconstruction of the whole set of data was done using about 2500 hours of CPU time on the IBM 3090 at CINECA (Bologna, Italy).

4. The calibration method

Electrons and muons lose energy in the BGO in different ways:

1) Electrons produce electromagnetic showers inside the BGO and the scintillation light is detected by the photodiodes glued on the rear face of each crystal. The collection efficiency depends on the coordinate $t$ along the crystal axis due to the tapered crystal shape. The calibration constant is defined as the ratio between the energy deposited and the signal seen by the photodiode i.e.:

$$C_e = \frac{E_{\text{dep}}}{V} = \frac{\int_0^L S(t) dt}{\int_0^L k A(t) A(t) dt}.$$  

Here $S(t)$ represents the energy loss per unit length due to the shower development, $A(t)$ is the light collection efficiency and $k$ is a constant that takes into account the quantum efficiency of the photodiode and its gain. $L$ is the crystal length. The light collection efficiency $A(t)$ was measured with a cosmic ray bench [8] before the installation into the support structure and parametrized as a third degree polynomial; $S(t)$ can be parametrized as [9]:

$$S(t) = B t^a e^{-\beta t}.$$  

$B$, $a$ and $\beta$ are functions of the incident energy $E$, and are determined by MC simulation to be:

$$B = -46.9 + 16.2 \ln(E),$$  

$$a = -2.56 + 0.571 \ln(E),$$  

$$\beta = 0.183 + 0.0271 \ln(E),$$  

where $E$ is given in MeV.

2) Muons lose their energy in BGO mainly by ionization and the muon calibration constant is defined as:

$$C_\mu = \frac{\int_0^L \frac{dE}{dx} dx}{k \left(\int_0^L \frac{dE}{dx} dx\right) A(t)} = \frac{1}{k A(t)}.$$  

where $E$ is given in MeV.
One should remember that muons traverse most of the BGO crystals almost perpendicularly to their axis (because of the face to face selection) so that the effect of the light collection efficiency is not convoluted with the energy loss. In the above formula \( l \) is the track length of the muon inside the BGO and \( r \) is the coordinate at which the crystal was crossed by the muon.

In order to determine \( C_e \) from muon constants one should apply a conversion factor that accounts for the different ways in which energy is deposited. First of all the muon signals should be corrected for the light collection efficiency and, for this reason, one has to multiply the \( C_u \) obtained for each hit by a factor \( \Lambda(t)/\int_0^l \Lambda(t) \, dt \). Then the factor \( k \) can be extracted from the \( C_u \) and replaced in the \( C_e \) expression giving:

\[
C_e = \frac{\int_0^l \Lambda(t) \, dt \int_0^l S(t) \, dt}{\Lambda(t) \int_0^l S(t) \Lambda(t) \, dt} C_u
\]

\( C_u \) is then corrected for the different parametrizations of the Landau distribution and the results agree quite well (see Fig. 2). The two fitting functions are the following:

\[
f^1 = a \exp\left( \frac{1}{2} \left( \frac{x-b}{c} \right)^2 \right), \quad x < \bar{x},
\]

\[
f^2 = a \exp\left( -\frac{1}{2} \left( \frac{x-b}{c} \right) + \exp\left( -\frac{x-b}{c} \right) \right), \quad x \geq \bar{x},
\]

(Here \( a, b, c, d, e \) are fitting parameters; in \( f^1, g \) and \( h \) are chosen in such a way that the first part of \( f^1 \) matches with the second one in the point \( x = \bar{x} \) defined as \( \bar{x} = 0.64b \)).

5. The set of the corrections

The data set that passed the quality cuts is corrected for various effects [5,7]:

Temperature: the BGO light emission is strongly temperature dependent; the light output decreases by an amount of 1.55% per °C. The crystal temperature is measured by two AD590 sensors glued on the front face and on the rear face of a subset of the crystals. For each hit we define an effective temperature as:

\[
T_{\text{eff}} = \frac{t}{L} (T_b - T_t) + T_t
\]

and the signal is then corrected accordingly. Due to the available precision in the temperature measurement we estimate an error of 1.0% on energy resolution coming from this effect. This is in fact the maximum possible error. It was estimated using Bhabha events taken during physics runs by subtraction of the predicted resolution from the experimental one.

Path length: because the calibration constants are evaluated from the peak values of the Landau distribution, a correction is needed to take into account the fact that the probability of large energy loss increases with the length of the traversed material. The most probable energy loss per unit length is given by [11]:

\[
\frac{E_p(\Delta x)}{\Delta x} = \frac{2Cm_e}{\beta^2} \left[ \ln \left( \frac{4Cm_e^2y^2\Delta x}{I^2} \right) - \beta^2 - \delta + j \right].
\]

(10)

Here \( \Delta x \) is the track length, \( C \) is a constants defined as \( C = \pi N_a(Z/A)r_e^2 \) (\( N_a \) is the Avogadro number, \( Z, A \) are the atomic weight and number respectively and \( r_e \) is the classical electron radius), \( m_e \) is the electron mass, \( \beta \) and \( \gamma \) are respectively the velocity and the Lorentz factor of the muon, \( I \) is the mean ionization potential and \( j = 1 - \Gamma + \lambda_p \), where \( \Gamma = 0.577 \) and \( \lambda_p \)
Here $X_0 = 0.046, a = 0.096, X_1 = 3.382$ and $m = 3.078$. The most probable energy loss in 1 cm of material is then:

$$E_p(1) = \frac{E_p(\Delta x)}{\Delta x} - \frac{2m_eC}{\beta^2} \ln \Delta x$$

(11)

showing the residual dependence from the logarithm of the track length.

**Muon momentum:** the energy deposition in the BGO depends weakly on the muon momentum. A correction is applied to data to take into account this effect. Correction factors are defined to be the ratio between the energy loss at the measured muon momentum and the energy loss at 10 GeV.

### 6. Results

The calibration constants for electrons were first determined using the April data only in order to exclude aging effects of the detector that could have occurred between April and September.

The fitting procedure of the peak of the Landau distribution is found to be stable if at least 200 hits are collected in the histogram. For this reason only 86% of the crystals could be calibrated.

Let $C^e_{\mu}$ be the electron calibration constants measured with cosmics muons. To evaluate the resolution that can be achieved with $C^e_{\mu}$'s a sample of Bhabha events, taken at the $Z^0$ peak in physics runs [13], was used and the energy was recalculated using this set of calibration constants. For those crystals that could not be calibrated we used the nominal calibration constant $#^1$ multiplied by the mean value of the ratio between the $C^e_{\mu}$ and those constants. In order to take into account the aging of the detector, a correction factor coming from the xenon monitor system was applied, relative to the period of the first cosmic run. The calorimeter was divided into three regions corresponding to the barrel and the two end-caps.

Fig. 3 plots the ratio between the energy measured by the calorimeter and the beam energy. The $\sigma$ of the distribution gives the resolution of the detector (see Table 1).

From columns 2 and 4 of Table 1 it can be seen that the central value of the energy reconstructed with cosmic rays calibration constants is slightly lower than the one obtained with the nominal constants, while the energy resolution of the End Cap 1 is significantly worse than the other parts of the calorimeter.

The poorer response in End Cap 1 can be explained noting that during the first period of data taking, there was a beam accident during a LEP machine development. The beam was lost in the L3 area and BGO crystals were affected by radiation. In particular the End Cap 1 had the strongest damage. Unfortunately we can only make a qualitative statement because during cosmic rays data taking no regular xenon runs were taken.

For the Barrel and End Cap 2 the resolution achieved using cosmic muons calibration is quite close to the expected value. In fact, the error on the calibration constants is the sum of various contributions: the error on the measurement of the track length, pedestal fluctuations, the BGO intrinsic resolution and Landau

<table>
<thead>
<tr>
<th>Energy resolution</th>
<th>Cosmics</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean $\sigma$</td>
<td>Mean $\sigma$</td>
<td></td>
</tr>
<tr>
<td>Barrel 1</td>
<td>0.996</td>
<td>0.019</td>
</tr>
<tr>
<td>End Cap 1</td>
<td>0.978</td>
<td>0.026</td>
</tr>
<tr>
<td>End Cap 2</td>
<td>0.965</td>
<td>0.020</td>
</tr>
</tbody>
</table>

$#^1$ Nominal calibration constants, used during normal physics runs, are obtained from Bhabha events and xenon runs [2].

[Image 0x0 to 550x750]
fluctuations. The RMS of the experimental $dE/dx$ distribution accounts for all the effects listed above and is 18% $\langle dE/dx \rangle$. With 200 hits per crystal this figure is reduced to the 1.3% level. To compare with the energy resolution given in Table 1 this number should be added in quadrature to the intrinsic resolution of the BGO (0.6%), as measured at the test beam, to the QED term (0.7%) given by the radiation of photons from Bhabha electrons and to the uncertainty in the temperature correction (1.0%) giving origin to the 1.9% expected resolution.

7. The light collection efficiency

The two sets of data (April and September) were used to compare the light collection efficiency of the crystals before and after a period of LEP operation. The light collection curve can be measured dividing the crystals into 6 parts along their axis and plotting the $dE/dx$ value for each of these parts against the crystal axis coordinate. Due to the limited statistics it was not possible to measure the light collection curve for each crystal: only average curves were obtained for each $\theta$ ring #2 of crystals using the hits of all $\phi$ crystals in a ring.

For the first time we are able to measure the distribution of the radiation damage throughout the BGO crystals of the L3 calorimeter. Its effect is seen in Figs. 4 and 5 for crystals at $\theta$ equal to 1 #3 ($\sim 90^\circ$ from the beam line) and 41 ($\sim 12^\circ$ from the beam line) respectively. In these figures the light yield collection curve is plotted as measured with cosmic rays, for the two sets of data: April and September. The September data clearly shows a global shift of the curves towards lower values, indicating that crystals lose their transparency with time (as already discovered with xenon runs).

Compared to the xenon light monitor, cosmic rays have the advantage that they allow us to measure the shift for different parts of a given crystal, so we are able to measure the shift as a function of the crystal main axis coordinate.

From Figs. 4 and 5 it is clear that crystals near the beam pipe were more damaged than the other, mainly in the front part of the crystals.

Let us define $\Delta L_{\theta} = (L_{\theta}^{\text{Sep}} - L_{\theta}^{\text{Apr}})$ (where $L_{\theta}^i$ is the mean value of the light collection efficiency for the period $i$).

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#2 Each half barrel is composed of 24 rings of crystals each of which is made of a number of crystals varying from 48 to 160 depending on $\theta$.

#3 Crystals are numbered in $\theta$ from 1 to 41
8. Summary and conclusions

The results for the first high statistics cosmic rays run are presented. Data analysis shows that the accuracy that can be achieved in the evaluation of the electron calibration constants using cosmic muons is 1.3%. The evolution of the light collection efficiency is also presented, showing that the radiation damage affects mainly crystals near the beam pipe because the induced change in the light collection curves, while for the barrel crystals an overall correction factor can be used. This study shows, for the first time, that the radiation damage is stronger in the front face of the crystals than in the rear part.

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Appendix


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