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STUDY OF THE ENERGY CALIBRATION OF A HIGH RESOLUTION E.M. CALORIMETER

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Abstract : A calibration study was performed on a prototype of the L3 BGO electromagnetic calorimeter. The accuracy and stability reached is a small fraction of the typical detector resolution.

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1. Introduction

The accuracy and reliability of the energy calibration is a basic requirement for an electromagnetic calorimeter, especially when a large number of individual cells is involved and high resolution is expected.

The L3 experiment at LEP will use an electromagnetic calorimeter made of approximately 12000 BGO crystals, whose resolution was studied in a realistic prototype [1] and reported to be $\leq 1\%$ for electron energies greater than 4 GeV.

This article describes in full detail the method developed in a series of tests aimed at defining the calibration method and studying its dependence upon instrumental effects and its stability with time. Several algorithms were developed and compared and two of them were retained because of their complementarity.

The method described in this article was finally adopted to calibrate the 8000 crystals of the L3 barrel calorimeter at the X3 beam of the CERN SPS.

2. The experimental set-up

2.1 The BGO test matrix

The test matrix, shown in fig. 1, is composed of 100 BGO crystals in two mirror-symmetric half-matrices (each consisting of 5 columns of 10 crystals) joined at the median plane. The crystals are 24 cm long, $2 \times 2 \text{ cm}^2$ in the front and $3 \times 3 \text{ cm}^2$ at the rear. Crystals are wrapped with 2 layers of $6 \mu\text{m}$ aluminized mylar and inserted in a holding structure of carbon-fibre composite whose walls are $200 \mu\text{m}$ thick. In addition to wrapping material and cell walls, the space between two crystals also includes an air gap (up to $100 \mu\text{m}$) to allow for variations in crystal size. Each crystal is viewed by two photodiodes glued on the back side, with a total active surface of 3 cm^2 (Hamamatsu S2662).

The matrix was housed in a temperature-regulated box and was equipped with a grid of temperature sensors to record residual variations. The matrix was mounted on a rotating support, thereby permitting azimuthal and polar movements to align each crystal with the beam line.

For each crystal, the light collection efficiency and the gain of the readout chain are monitored by means of xenon light pulses of known intensity distributed by an optical fiber network. The light flashes are generated by a commercial xenon flash lamp whose driving circuit has been tuned to produce a pulse similar in shape and length to the pulse produced by the BGO scintillation. From the lamp, the light is transported by a primary optical fiber bundle to a mixer and from there to each individual crystal by a secondary fiber bundle. In order to match the spectrum of the BGO scintillation

light, the ultraviolet and infrared components are suppressed by appropriate filters. The intensity of the light flashes is measured on a pulse-to-pulse basis by a set of photomultipliers whose gains are monitored by americium pulsers. The stability of this system was observed during 16 days of continuous operation. The R.M.S. deviation was found to be 0.3%, well in agreement with the specifications for the full BGO detector.

2.2 The Readout Electronics

The readout electronics has been designed specifically for the synchronous trigger environment at LEP, and for the very wide dynamic range of signals expected. A partial schematic is shown in fig. 2. Each of the 12000 crystals will be equipped with its own microcomputer-controlled ADC. The output of the preamplifier is split into three channels, an analog output for the trigger, a high energy integrator, and a low energy integrator. Each integrator is followed by a sample/hold amplifier. The low energy channel has an effective gain of 32 compared to the high energy channel. The integrators are reset 1 μ s before the beam crossing, the sample/hold is switched to hold after a 5 μ s delay. The integration time for the pedestal (integrator input offset current) is 6 μ s, for the signal it is 5 μ s. This synchronous mode is of course not possible in the X3 test beam. Instead, after the reset, a beam gate is opened for 10 μ s. If a trigger occurs during this gate, the signal is the same as in the synchronous case at LEP, but the integration time for the pedestal is variable, from 6 to 16 μ s. These times are recorded for each event, so that an offline pedestal correction can be made. After the analog signals are stored by the sample/holds the integrators are reset in preparation for the next cycle. If there was no trigger, the cycle repeats. The total cycle time is 20 μ s, which gives an efficiency of 50% for asynchronous triggers.

Each sample/hold output is followed by two slow amplifier stages, each with a gain of 4. The microcomputer then has a choice of six signals to digitize, which represent six overlapping ADC ranges. The chosen signal is digitized with 12 bit resolution, using a successive approximation method. Note that successive ranges overlap by at least 25% of their range. The algorithm is to choose the most sensitive range which is less than full scale. This gives the maximum digitizing resolution.

2.3 The beam spectrometer

The test matrix was exposed to electrons transported by the X3 beam line specially designed for the L3 experiment. Tertiary particles are produced by the H3 beam of CERN SPS, momentum selected and then transported to the test area with a second deflecting magnet. Although the beam is not achromatic at the experimental equipment, the displacement dispersion to the first order is zero.

The last stage of the beam line consists of a focusing spectrometer equipped with two Cherenkov threshold counters for particle identification. The beam momentum of

the transport system can be varied between 2 and 50 GeV/c and the momentum bite is adjusted with the horizontal slit of the collimator having a sensitivity of 3 mm/%. Two delay lines proportional chambers [2] placed upstream of the bending magnet B2 and three others placed downstream of the last focusing quadrupole Q4 measure the horizontal position of the beam particles. The knowledge of the beam trajectory before and after the bending magnet allows the determination of the momentum ($\Delta p/p$) of each incoming particle. The momentum resolution is then given by the accuracy of the position measurements (about 0.4 mm) and by the multiple scattering suffered by the particle in the beam spectrometer. This resolution has been estimated by using TURTLE [3], a Monte Carlo program tracking charged particles in a beam line, where multiple scattering has been introduced. We obtain the results shown in table 1 for the beam resolution.

A dedicated study [4] on the excitation curve and of the field stability of bending magnets was performed by our group in order to measure the absolute momentum, the reproducibility of the field after switch off-on operations, and field fluctuations due to noise in the rectifier circuits or to thermal drifts of the stabilizing system. All these effects were measured and any uncertainty from any cause was found to be at least smaller than the expected calorimeter resolution. In addition, the absolute value of the bending power of B2 has been measured by the flip coil method.

Table 1. Beam Resolution

Energy (GeV)	Resolution (%)
2.	0.88
4.	0.68
10.	0.33
50.	0.19

2.4 Trigger, data acquisition procedures and monitor.

Several triggers are defined using the various counters shown in fig. 3. The coincidence of counters S1 and S2 is used to define the basic beam. The A counters are used to veto the beam halo. Counter S5 (1x1 cm² with air light guide) defines a narrow collimated beam. Counter SH (16x16 cm², read by two phototubes, in front of the matrix) is used to flag events when particles come during the 5 μ s sample time after

the trigger. The Cherenkov counters are used to discriminate electrons from pions at intermediate energies (4 to 20 GeV).

Additional triggers are also set up, enabling the collection of pedestals, both during and out of the burst time, Xe lamp calibration events and test pulses.

The BGO signal of each channel, acquired (as described in section 2.2) by a wide-range resettable integrator with sample-and-hold, is controlled by its own microcomputer (Motorola MC1468705G2). Sixty microcomputers are organized into one token-passing ring, and read out by a hierarchical VME/68K-based system. Digitized data are finally written on tape by a VAX11/750.

The entire procedure of individual crystal calibrations is completely automated. A computer program running on the data-acquisition computer performs all the requested operations:

- it directs the positioning of the motorized table supporting the matrix, to align a given crystal on the beam line,
- it activates the trigger, starting the data-acquisition,
- it counts the number of collected events and, when a preset number is reached, it disables the trigger and
- finally, it directs the alignment of the next crystal, according to a predetermined sequence.

The same program also insures on-line monitoring of the events on a sampling basis. It converts the coded pulse height in μVolt , calculates the raw energy deposition in the crystals around the beam line, and computes preliminary calibration constants. The result of such calculations is continuously presented on a video monitor enabling an overall check of the data taking.

3. Data reduction

In order to compute the calibration constants, the digitized data have to be converted into pulse height in Volt. To do that, each amplifier of the readout system must be calibrated, and the raw data have to be corrected for pedestal and temperature effects. Each step of this data reduction must be completed with an accuracy matching the high resolution of the calorimeter.

3.1 Read-out electronics calibration

The read-out electronics described in section 2.2 requires the calibration of 12 gain constants for each ADC, the slope and offset for each of the 6 ranges. Fortunately, most of these depend only on resistor ratios, and have been measured on the bench, during manufacture, with an accuracy of 0.1 %.

The ratio between the high and low channel gains is sensitive to the relative time constants for the two integrators, and therefore is sensitive to the precise shape of the pulse from the preamplifier. This ratio must be measured in the test beam, using scintillation light from the BGO crystal as the signal source, in order to achieve the required accuracy. A special measurement mode, in which two ranges are digitized for the same event, rather than only the selected range, allows the in situ measurement of the relative gains and offsets for all ranges. Fig. 4 shows the ratio of the signal from ranges 3 and 4 (the transition from low to high integrator channel), for a typical crystal, after calibration. The R.M.S. deviation is 0.15 %, mostly due to binning effects (the ADC output is up to 1000 on range 4, up to 2000 on range 3).

3.2 Pedestal Evaluation

The pedestals for the high and low channels are independent, since they depend on the input offsets of the two integrators. The pedestal for ranges 1 and 4 must be measured. The pedestals for the other ranges can be deduced from these, using the relative offsets measured previously.

A problem arises from the variation in pedestal integration time, mentioned above. Fig. 5 shows a plot of the high energy pedestal (range 4) versus the time from reset to trigger, for a particular crystal. These pedestal events are taken at several discrete delay times. This time dependence must be corrected in the calibration data. A straight line fit allows one to compute the offset, P_0 and the slope, S .

$$P(t) = P_0 + S \cdot t$$

The uncertainties in the pedestal due to this simple linear fit are less than the electronics noise, therefore a more complicated function is not required.

The knowledge of (P_0, S) for the low and high energy channels, and of the integration time for each event, allows for pedestal correction on an event-by-event basis.

A careful study of pedestal variation during the time shows a good stability of the electronics.

3.3 Temperature correction

As the light yield in BGO is temperature dependent, the variation of the BGO response with temperature was studied. For this purpose we have used a special set of runs where the matrix was exposed to a 10 GeV electron beam while the temperature of the crystals was decreasing slowly from 25°C to 21°C.

The energy deposited in 9 crystals centered on a crystal equipped with a thermal sensor has been plotted as a function of temperature (see fig. 6). Fitting a straight line to the data we have deduced the following relative signal variation per degree:

$$\frac{1}{V} \frac{\Delta V}{\Delta T} (T = 23^\circ\text{C}) \simeq -1.55\%/^\circ\text{C}$$

Even with thermal regulation the large temperature coefficient forces us to apply a correction to each event in the analysis of the calibration, in order to obtain the equivalent signal corresponding to an arbitrary reference temperature (say 20°C).

4. The calibration method

Let us define the calibration constant for a given crystal as the ratio between the energy deposited in the crystal and the electronic signal encoded by the readout system. This ratio would be a "true" constant only under the hypotheses that the crystal response were a) linear with the deposited energy, b) uniform in the light collection, c) temperature independent. We will assume for a while that these three conditions are fulfilled.

When we hit a crystal with an electron of known energy, we need to know the actual fraction of energy deposited inside the crystal or, equivalently, the total energy leakage (side, front and rear leakage). The average value of the total leakage has to be determined by Monte Carlo simulation of the electromagnetic shower, whereas the side leakage can be determined also from the data themselves by iterations. The side leakage depends crucially on the position of the electron impact point and this variation, when not taken into account, would influence on the order of a few percent the determination of the calibration constant even with a beam spot of few square millimeters. On top of the average leakage, event-by-event fluctuations contribute to the fluctuation of the calibration constant determination.

A way to measure the side leakage event by event is to look at signals in the neighbouring crystals, in a square submatrix of, say, (3x3-1) or (5x5-1). The energy deposited in the central crystal is then estimated by subtracting the measured side leakage from the measured beam energy. In this way the uncertainty is moved to the leakage outside

this submatrix and on the side walls, so that the Monte Carlo predictions and the fluctuations refer to a smaller fraction of the total energy of the beam electrons (typically a few percent). Moreover, the fluctuations due to the impact point position are corrected to the first order event by event. They are important only for electrons impinging very close to the carbon walls. As a drawback, this method requires a knowledge of the calibration constants of the neighbouring crystals. However, as the energy deposited outside of the central crystal is of the order of 25% of the total, an uncertainty of 1% on the calibration constants of the peripheral of the central crystals will produce an uncertainty of 0.25% on the calibration constant. The procedure should then converge quickly after few iterations.

Before explaining the details of the procedure, let us introduce some symbols:

p_b electron momentum as measured by the beam spectrometer.

A_i signal in Volt read on the channel i .

E_1^{MC} average fraction of energy deposited in the central crystal for a given beam shape, as predicted by MC.

E_9^{MC} same as above but for a 3x3 matrix .

E_{25}^{MC} same as above but for a 5x5 matrix .

C_i generic calibration constant for the crystal i

$\Sigma_1 = C_i A_i$ measured energy deposited in the central crystal.

$\Sigma_8 = \Sigma_8 C_i A_i$ measured energy deposited in the frame of a 3x3 matrix around the central crystal.

$\Sigma_{24} = \Sigma_{24} C_i A_i$ measured energy deposited in the frame of a 5x5 matrix around the central crystal.

We can then define three different calibration constants as:

$$C_i^1 = E_1^{MC} < \frac{A_i}{p_b} >^{-1}$$

$$C_i^9 = < \frac{E_9^{MC} \cdot p_b - \Sigma_8}{A_i} >$$

$$C_i^{25} = < \frac{E_{25}^{MC} \cdot p_b - \Sigma_{24}}{A_i} >$$

A complete calibration procedure involves at least three steps:

- 1) Calculation of C_i^1 : no other information needed.
- 2) Calculation of C_i^9 and C_i^{25} using C_j^1 to compute Σ 's.

3) Calculation of C_i^9 and C_i^{25} using $C_j^{9,25}$ to compute Σ 's.

The data collected during the 1986 calibration period are mainly divided in two classes: "fast scan", with samples of nearly 1000 events triggered by S5 scintillator counter, and "high statistics", with samples of more than 10000 events, without S5 in the trigger. Fast scans are intended to simulate the real conditions of the barrel calibration. High-statistics samples can be reduced to the fast scan samples by a software 'S5 equivalent' trigger, in order to study the short-term stability of the calibration.

As the beam profile was not the same at all energies, as shown by some typical plots (fig. 7), a knowledge of the impact point distribution is relevant for the comparison of calibration constants coming from different runs.

As we are working mainly with average values of $1/A_i$ to determine the C_i , we ought to be sure not to include in the sample spurious high and low values of A_i . High values mainly come from two particle events not flagged by a delayed SH count. In fig. 8 we show the Σ_1 distribution for unflagged events: the surviving double hits are clearly seen and are then cut by requiring $\Sigma_1 < p_b$. Low values of Σ_1 correspond to empty triggers, and are cut by requiring $\Sigma_1 > \frac{3}{8}p_b$. Both cuts were carefully studied so as not to reject any good electron event, although preliminary values of C_i are used at this level. The presence of surviving spurious events and the possible losses of good events can be controlled in an automatized fashion by comparing the calculated mean values with a peak finding algorithm, such as the one discussed later in this paper.

As we said, the energy deposited in each of the 25 crystals around the impact point should be determined by MC simulation, integrating over the beam shape. This shape is taken from the measured distribution of deposited energies in the crystals. This is shown in table 2 for the 10 GeV case as it appears for a high-statistics run after the second step of iteration in the calibration constants of the crystals involved (note the beam asymmetry). The only external assumption is the fraction of beam energy deposited in the matrix, $\Sigma_{25}/<p_b>$, which is taken from GEANT[5] to be 97.2 %.

Table 2. Fractional energy deposited in each of the 25 crystals at 10 GeV

0.08	0.20	0.27	0.20	0.07
0.20	1.14	2.71	0.97	0.18
0.35	3.73	75.6	3.16	0.30
0.23	1.34	4.03	1.22	0.22
0.10	0.26	0.37	0.25	0.09

From the table one can evaluate $\Sigma_1 = 0.756 <p_b>$ and $\Sigma_9 = 0.938 <p_b>$. This

table is also needed to correct for possible missing crystals.

The dependence of the C_i 's on the impact point was studied subdividing the area delimited by the sintillator S5 in 25 cells $2 \times 2 \text{ mm}^2$ each. A high-statistics run at 10 GeV with the beam centered on one of the crystals was used. The resulting values of C^1 are shown in table 3.

Table 3. $C^1(x, y)$ in $10^{-2} \text{ MeV/mVolt}$

3081	3013	2992	3022	3091
3026	2986	2986	3003	3068
3027	2989	2981	3008	3057
3042	3002	3002	3021	3081
3089	3046	3050	3063	3094

The variations for C^1 are as large as 3.8%, being of the order of few percent even for a more stringent impact point selection such as $5 \times 5 \text{ mm}^2$. The corresponding variations for C^9 or C^{25} are always below the percent level. It must be noted that, in principle, any variations in the energy deposited, due to the impact point location, can be corrected by a Monte Carlo estimation. However we have not applied this kind of correction to the computation of C^1 , which is used only as a first approximation for the computation of C^9 and C^{25} .

The method discussed so far is based on the mean value of the energy distributions. Although the mean value is certainly the most precise estimator as it makes use of all statistics available, it could however be sensitive to the tails of the distribution and therefore to position of the cuts applied in the data selection step. The peak of the distribution is of course free from the effects of these cuts, but its determination depends on a reduced sample of events and its statistical accuracy is correspondingly reduced (it also depends on the choice of the analytical representation of the measured distribution). Hence, we will use the mean value to define the calibration constants, and the difference between the peak location and the mean value to monitor the consistency of the data selection.

Several peak-finding algorithms (Chebyshev, B-spline etc.) have been tried. We describe here one of them, based on the Fourier expansion: if $H(t)$ is the histogram of the pulse height distribution, its Fourier expansion can be approximated by:

$$f(t) = \frac{C_0}{2} + \sum_{n=1}^m (S_n \sin n\omega t + C_n \cos n\omega t)$$

with:

$$S_n = \frac{2}{T} \int_T H(t) \sin n\omega t dt$$

$$C_n = \frac{2}{T} \int_T H(t) \cos n\omega t dt$$

$$\omega = \frac{2\pi}{T}$$

Where the period T is equal to the width of the histogram.

By experience, we found that setting $m = 7$ produces a reasonably smooth and accurate fit to the data. An example of this Fourier expansion of a pulse height distribution is given in fig. 9.

In practice, to avoid any bias from the bin choice, the event distribution is stored in 5 histograms with different binning. A Fourier expansion is performed on each histogram and the solution corresponding to the minimum χ^2 is retained.

5. Results

5.1 Distribution of calibration constants

Fig. 10 shows the distribution of the calibration constants calculated with a set of 10 GeV runs after few iterations. The number of iterations required to obtain stable results depends on the quality of the C^1 calibration constants used as input in the iterative process. Typically 2 or 3 steps are enough. Most of the constants are grouped around 25 MeV/mV with an R.M.S. deviation of 3.88 MeV/mV. The spread of the distribution is essentially due to the light-yield dispersion of the crystals.

5.2 Precision of the calibration constants determination

After the last iteration of the calibration process, the energy deposited in each block of 9 crystals can be calculated using the same events as those used for the determination of the calibration constants themselves. If the detector is perfectly calibrated each block should give the same response. In fact we get the distribution shown in fig. 11 which exhibits a dispersion of 0.15% (14 MeV) around the mean value. We should stress that this distribution includes crystals located near the matrix border, for which a Monte Carlo correction has been applied in order to compensate for the missing crystals in the sum of 9. The dispersion of the distribution restricted to 9 crystal matrices is less than 0.1% .

5.3 Statistical dependence of the calibration

The study of the dependence of the calibration constants upon the number of collected events is crucial, as it serves to put upper limit on the contribution of some systematic effects in the calibration process and it allows finding the optimal statistics necessary for a fast and accurate calibration .

For this investigation, the calibration constants C^1 and C^{25} of a crystal have been calculated for four different sample sizes. The result is shown in fig. 12 where the black dots represent the R.M.S. deviation of the constant C^1 and the open circles the R.M.S. deviation of the constant C^{25} versus $1/\sqrt{n}$.

If the error on the calibration constant of this crystal were only due to statistical effects, the extrapolation to an infinite number of events should bring the dispersion to zero. The goodness of the constrained linear fit performed on the two sets of points shows (fig. 12) that the contribution of any systematic effect to the R.M.S. deviation of the calibration constants is negligible indeed ($< 0.1\%$).

We also deduce from this study that 1000 events per calibration points are enough to keep the statistical error below the 10^{-3} level for C^1 , C^9 and C^{25} .

5.4 Stability of the constants

We want to give a figure representing the stability of the calibration constants taking into account all the effects affecting the precision and reproducibility of their determination with the described method.

The main source of fluctuations are: statistics, whose behaviour has been described in 5.3, temperature unfolding explained in 3.4 and different systematic errors such as fluctuations of the beam position, corrections for incomplete information (dead channels), exact position of separation wall and crystals located at the border.

As far as temperature is concerned, we recall that since only a fraction of the crystals can be calibrated in temperature (in the final set-up no possibility will exist for such a measurement), we correct all the measurements using a fixed value of $-1.55\%/^{\circ}\text{C}$ (the nominal temperature coefficient). This introduces therefore an uncertainty in the correction which affects the calibration constants determination.

Our goal here is to evaluate the fluctuation of the calibration constant C^9 determined at a fixed energy (10 GeV). We therefore consider those crystals which have been calibrated more than once.

We present the results for two different samples of crystals: the cluster of 9 crystals, where most of the measurements were performed (a total of 47 data sets), and the sample of all the crystals having been calibrated more than once (37 crystals, 121 entries). The R.M.S. deviations of the two samples come out to be .24 and .35 % respectively.

The first figure corresponds to the situation in which all the known systematic errors are minimized, namely, all the crystals needed for the calibration are alive and far from the median plane and borders.

We stress the fact that the data were collected over a period of time of a hundred days, thereby proving the absence of any time-dependent effect on this time scale at the level indicated by the spread of the distribution of calibration constants.

The goodness of the choice of the temperature coefficient can be now checked. Fig. 13 shows the variation of the R.M.S. deviation of the largest sample as a function of dC^1/dT . A clear minimum is in fact seen at the value actually used to correct the data.

5.5 Comparison of the 'mean value' and 'peak position' methods

Fig. 14a shows the correlation plot between the set of constants determined by the method of the "mean value" and the one coming from the "peak-finding". Fig. 14b shows the ratio of the results of the two methods done crystal by crystal, after a correction for the expected difference between the peak and the mean of these distributions. The R.M.S. deviation of the distribution is of the order of half a percent (twice the lowest possible value expected on the basis of statistical considerations only). This figure is an estimate of the sensitivity of the "peak-finding" method as an indicator for possible faults in the other method during the automatic production of the calibration constants.

5.6 Energy resolution

The mean energy resolution of the BGO calorimeter was determined in the following way.

A beam of $1 \times 1 \text{ cm}^2$ was used to perform the measurement. The results are shown in fig. 15 (and reported in column 2 of table 4), where the energy resolution ($\Gamma/2.36$ in percent) obtained for each Σ_{25} performed around a crystal is represented by a different symbol. The solid line is the MC prediction derived from the combination of the intrinsic resolution [5], electronic noise and beam momentum resolution. Table (4) summarizes the results. The figures for electronic noise were estimated by taking the value of $\sigma(\Sigma_{25})$ in the pedestal runs at the corresponding energy.

These figures agree well with previously published results [1].

Table 4. Energy resolution $\left(\frac{\Gamma/2.36}{E}(\%) \right)$

E	Data	Simulated value	GEANT	Noise	Beam
2	1.45±.07	1.48±.10	0.93	0.75	0.88
4	1.01±.07	0.99±.10	0.60	0.38	0.68
10	0.75±.07	0.59±.10	0.44	0.20	0.33
50	0.57±.07	0.52±.10	0.48	0.06	0.19

6. Conclusions

A complete study of the procedures for calibrating the L3- High-Resolution EM calorimeter was undertaken with a realistic prototype composed of 100 BGO crystals.

Besides statistics, additional contribution to the final uncertainty on these constants come from the temperature unfolding procedure, the pedestal subtraction, beam position and distribution on the crystal and from incomplete information (dead channels). We reached the goal of controlling systematic effects down to 0.1 % so that the accuracy required was eventually limited by the statistics contribution only.

We also established an intrinsic reproducibility of the calibration at the level of 0.35 % over a period of 3 months, correcting only for temperature variations.

This work showed that a homogeneous calorimeter read by solid-state photodetectors can be calibrated within a fraction than 1 %. Therefore this method was adopted to perform the complete calibration of the L3 calorimeter with the required accuracy.

Figure Caption

- Fig.1* : View of the matrix, housed in a temperature regulated box, mounted on a rotating support.
- Fig.2* : Schematic of readout electronics.
- Fig.3* : Schematic view of the X3 beam line, upstream of the BGO matrix.
- Fig4* : Ratio between high and low energy channel, the first reading (V_1) correspond to range number 3 and the second one (V_2) to range number 4.
- Fig5* : Pedestal in mV versus integration time in μs .
- Fig6* : Signal in MeV measured in BGO versus temperature. From a straight line fit, one can deduce a temperature dependence equal to $-1.55\%/^{\circ}C$
- Fig.7* : Beam profiles at 10 GeV and 50 GeV, in x and y coordinates.
- Fig.8* : Pulse height distribution in central crystal after SH cut. Also shown are the software cuts applied in the event selection.
- Fig9* : Example of the Fourier expansion method used to fit (dashed line) a typical signal distribution (solid line).
- Fig10* : Distribution of calibration constants.
- Fig11* : Peak location after the last iteration of the calibration process.
- Fig.12* : R.M.S. on the determination of C^1 (black dots) and C^{25} (open circles) plotted as a function of the inverse of square root of the number of events used in the determination.
- Fig.13* : R.M.S. of the calibration constants of the crystals calibrated more than once at 10 GeV as a function of the temperature coefficient used for the correction. Temperature varied between 21 and 25 degrees.
- Fig14* : Comparison between the two calibration methods (peak finding and mean value).
- a- Scatter plot: Mean value method versus peak method.
 - b- Ratio of the calibration constants calculated by the two methods.

Fig.15 : Energy resolution, defined as F.W.H.M. divided by 2.36, as a function of beam energy. The solid line represents the MonteCarlo prediction, including beam momentum uncertainty and electronic noise.

References

- [1] J.A. Bakken et al., Nucl. Inst. and Meth. A254 (1987) 535.
- [2] A. Manarin and G. Vismara, LEP/BI-TA/Note 85-3 (1985).
- [3] K.L. Brown and C. Iselin, CERN 74-2, (1974)
- [4] G. Gratta, L3 Internal Note, October 1986; G. Gratta and D. Luckey, L3 Internal Note, December 1986.
- [5] R. Brun et al., CERN DD/EE/84-1 (1984).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5 Integration time in μsec

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 14b

Figure 15