PERFORMANCE OF A PROTOTYPE BGO CALORIMETER IN AN ELECTRON BEAM FROM 2 TO 50 GeV

J.A. Bakken¹⁾, G. Bellomi²⁾, R. Bizzarri²⁾, T. Böhringer³⁾, B. Borgia²⁾,
M. Bourquin⁴⁾, D. Boutigny⁵⁾, J.P. Burq⁶⁾, F. Carminati⁷⁾, M. Chemarin⁶⁾,
P. Denes¹⁾, C. Dionisi²⁾, H. Elmamouni⁶⁾, P. Extermann⁴⁾, S. Falciano²⁾,
F. Ferroni²⁾, G. Gratta²⁾, J.T. He^{7)*}, B. Ille⁶⁾, P. Kaaret¹⁾, P. Klok⁸⁾,
P. Lebrun⁶⁾, E. Longo²⁾, Y.S. Lu^{7)*}, J.P. Martin⁶⁾, R. Morand⁵⁾, J. Ossman⁴⁾,
D. Perret-Gallix⁵⁾, E. Perrin⁴⁾, P.A. Piroué¹⁾, N. Produit⁴⁾, S. Rosier⁵⁾,
W. Ruckstuhl⁴⁾, M. Schneegans⁵⁾, D.P. Stickland¹⁾, R.L. Sumner¹⁾,
K.L. Tung^{7)*}, E. Valente²⁾, M. Vivargent⁵⁾, R. Weill³⁾ and T. Wijnen⁸⁾,

(L3 Collaboration)

ABSTRACT

A prototype of the L3 electromagnetic calorimeter to be used at LEP and consisting of 100 tapered BGO crystals has been tested in an electron beam in the energy range of 2 to 50 GeV. The energy resolution and linearity of response have been measured, and are compared to predictions made with the GEANT Monte Carlo program.

(Submitted to Nuclear Instruments and Methods
in Physics Research)

-
- 1) Princeton University, Princeton, NJ, USA^{**}.
 - 2) Dipartimento di Fisica, Università 'La Sapienza', and INFN Sezione di Roma, Rome, Italy.
 - 3) Institut de Physique Nucléaire, Université de Lausanne, Switzerland^{***}.
 - 4) DPNC, Université de Genève, Geneva, Switzerland.
 - 5) LAPP, Annecy-le-Vieux, France.
 - 6) Institut de Physique Nucléaire, IN2P3, Lyon, France.
 - 7) CERN, Geneva, Switzerland.
 - 8) University of Nijmegen and NIKHEF, Nijmegen, The Netherlands.
- * On leave of absence from the Institute of High-Energy Physics, Academia Sinica, Beijing, China.
** Work supported in part by the US Department of Energy.
*** Supported in part by Fonds National Suisse pour la Recherche Scientifique.

1. INTRODUCTION

The L3 electromagnetic calorimeter to be used at LEP is planned to consist of 12,000 tapered BGO crystals housed in a cellular carbon-fibre composite array. We have previously reported [1] on the characteristics of an electromagnetic shower counter composed of BGO crystals, but have since performed tests on the first realistic prototype of the final detector. In particular, these tests were performed on a matrix of tapered (rather than parallelepipedal) crystals in a carbon-fibre composite structure, each crystal being equipped with essentially the final acquisition and readout electronics.

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, with small dimensional changes introduced column-by-column so that the crystal axes are radial with respect to the interaction point. The matrix itself was housed in a temperature-regulated aluminium box mounted on the arm of a rotating platform, thereby permitting azimuthal and polar movement of the matrix in the beam line (see fig. 2).

The matrix was tested in the X3 beam line of the CERN Super Proton Synchrotron (SPS) during the summer of 1985. Electrons were transported at 2 to 50 GeV/c and identified by a series of scintillators, including a small ($1 \times 1 \text{ cm}^2$) air guide scintillation counter close to the matrix, and two threshold Čerenkov counters, as shown in fig.3. Tracking information as well as the deviation from the nominal beam momentum ($\Delta p/p$) was provided by a set of wire chambers surrounding the final bending magnets. The temporal sequence of particles was recorded by latching a free running clock each time a particle passed through a particular scintillator. Any scintillator pattern could be used to define a trigger. We also routinely

interspersed random triggers both in and out of the beam burst in order to obtain ADC pedestal measurements.

2. FEATURES OF THE TEST MATRIX

Each crystal was housed in an individual carbon-fibre composite cell. For each of the half-matrices of the test matrix, the locating surface (the centre plane of the matrix) consisted of a 1 mm stainless-steel sheet, upon which the cells were built to form a matrix. Crystals were loaded into the matrix, seating on the front shell, and were fixed into position by clamps at the rear of the cell. Since the dimensions of the cell were slightly larger than those of the crystal, and as the crystal is under compression, the weight of the crystal was supported by tension in the cell walls so that none of the lateral faces of a crystal rested on a cell wall (see fig. 4). The space between crystals thus consisted of the crystal wrapping, the 200 μm carbon-fibre wall and a 100 μm distributed lateral air gap to allow for variations in the crystal size. In addition, an optical fibre (for the calibration monitoring system) was attached to each crystal, and almost every crystal had a temperature sensor on its upstream or downstream face.

One half-matrix consisted of crystals wrapped in 12 μm aluminized Mylar and having approximately 3 cm^2 of active photodiode area. The crystals of the other half-matrix were wrapped in 160 μm reflective foil^{*)} as well as the aluminized Mylar, and had 2 cm^2 of photodiode area. The increase in the amount of light collected by the crystals that had 3 cm^2 of photodiode rather than 2 cm^2 , was compensated by the loss in light arising from the unequal reflectivities of the two different wrappings. The light output of the two half-matrices was therefore roughly equal: about 900

*) Reflective foil obtained from the Harshaw Chemical Company.

electrons liberated in the photodiodes for every MeV of energy deposited in a crystal.

We obtained the results presented herein using the half matrix with 2 cm^2 of active photodiode surface (Hamamatsu S1790-01). The signals were acquired by a wide-range resettable integrator with sample-and-hold. Each channel was controlled by its own microcomputer (Motorola MC1468705G2), which performs a successive-approximation digitization of the signals. These microcomputers were formed into token-passing rings, and read out by a hierarchical VME/68K-based system, and finally written on tape by a VAX-11/750. The signal from each crystal was also converted into a current, with a gain inversely proportional to the calibration constant, by a multiplying DAC under microcomputer control. These currents were summed into quadrants of 25 crystals and separately digitized as a test of the L3 electromagnetic trigger. More extensive tests are planned, but preliminary results show good agreement between the trigger energy sum and the measured energy deposition.

3. BEHAVIOUR OF THE CRYSTALS

Each crystal in the matrix was calibrated with a narrow ($\sigma_x \approx 3 \text{ mm}$, $\sigma_y \approx 2 \text{ mm}$) 10 GeV electron beam aligned with the crystal's central axis. The position of the 10 GeV peak was then used as a gain constant (α_1 , in μV digitized per MeV deposited) for the crystal. The crystals showed rather similar gains, as can be seen in fig. 5, with the difference in gain between the brightest and the dimmest crystal being about a factor of 2.

Showers from electrons incident on the crystal axis deposit about 75% of the energy in the crystal (which we call the central crystal), about 94% in the 3×3 matrix centred about the central crystal (the sum of nine crystals, $\mathcal{E}_9$), and about 97% in the 5×5 crystal matrix centred about the central crystal ($\mathcal{E}_{25}$). The observed lateral energy deposition is shown in

fig. 6, and compared with the predictions obtained with the GEANT Monte Carlo program [2]. Owing to the large fluctuations which may occur in single-crystal energy spectra (from variations in shower development or impact point), we have chosen to use the E_{25} as the standard for linearity and resolution.

The digitized energy varies rather linearly with the incident particle energy, as shown in fig. 7. On a finer scale, though, one finds a parabolic deviation from linearity arising chiefly from the energy dependence of the fractional effects of side, front, and rear leakage, and the non-uniformity of light collection in tapered crystals. (Apparent non-linearities are, of course, further enhanced by any calibration errors, electronic non-linearities or thermal phenomena.)

The geometry of a tapered crystal causes more light to reach the photodiodes when the light is generated at the front of the crystal rather than at the rear. As the light seen by the photodiodes is the integral of the differential longitudinal energy deposition, irregularities in the light collection enter as weights into this integral, thereby distorting the linearity of the signal. We have found that an effective technique for correcting this non-uniformity is to roughen the surfaces of two of the sides of the crystal. This process greatly reduces the non-uniformity of light collection [3], as can be seen in fig. 8. As part of our crystal reception process, each crystal in the matrix was scanned with cosmic rays to measure the uniformity, then de-polished and remeasured with a source.

To quantify the effects arising from light-collection non-uniformity, we define a uniformity factor $R = [s(0) - s(L)]/s(L)$ where $s(0)$ is the amount of light collected from a point source of light at the front of the crystal (the small end) and $s(L)$ is the amount of light collected from an identical point source at the rear of the crystal. Studies made with cosmic rays indicate that the signal varies linearly with position, $s(x) \approx$

$s(L)\{1+R[1-(x/L)]\}$ for most crystals. Since the longitudinal depth of the shower maximum varies nearly linearly with $\ln(E)$, a positive uniformity factor introduces a negative second-order non-linearity in the energy response, as the light output at the front of the crystal is enhanced. Precisely the same mechanism influences the resolution as, again, the fluctuations become unequally weighted. Figures 9 and 10 show the Monte Carlo estimates for the magnitudes of these effects.

The procedure to obtain the energy of a shower is then straightforward: If we denote by $s^i(E)$ the signal (in raw ADC units) for the i^{th} crystal at energy E , then the Γ_{25}^j for the 5×5 matrix centred on j^{th} crystal is

$$\Gamma_{25}^j(E) = \sum \alpha_i s^i(E) ,$$

where α_i is the gain constant (as described above) of the i^{th} crystal, and the summation runs over the crystals in the 5×5 matrix. To this value of Γ_{25}^j , a correction for light-collection non-uniformity is then applied. As the bulk of the energy is deposited in the central crystal, it is sufficient to apply a correction based on the uniformity of the central crystal only. Using GEANT, we have found that in this energy region the uniformity correction is very well represented by a quadratic function $\gamma = a + bE + cE^2$, where the coefficients a , b , and c are linear functions of R . Hence the Γ_{25}^j , now corrected for light-collection effects, is given by

$$\Gamma_{25}^j(E) = \gamma^j(E, R) \sum \alpha_i s^i(E) .$$

4. LINEARITY AND ENERGY RESOLUTION

Linearity variations from crystal to crystal critically influence the resolution of the overall detector. We should, however, distinguish

between those non-linearities that are identical from crystal to crystal and those that are not. For example, the finite size of the crystal implies that no shower is ever wholly contained, and since the shower profile depends on energy, this leakage loss is energy dependent. Although this is a non-linearity, it is the same for all crystals of the same size. This influences the absolute energy scale (the true energy of a particle may be miscalculated) but not the resolution (as the same miscalculation is made for each crystal).

The non-linearity arising from the non-uniformity of light collection varies for each crystal, so that not only is the absolute energy scale affected, but since the miscalculation is different for each crystal, the spectrum obtained by adding the contributions of all of the crystals is broadened by the dispersion in the position of the various peaks. For this reason we choose to define the linearity of a set of crystals as the r.m.s. dispersion in the peak positions of the different Γ_{25} rather than, for example, the average χ^2 for a straight line fit to the energy values for each crystal. The r.m.s. deviation formed from $\Gamma_{25}(E)/E$ for each of the six central crystals in the half-matrix for which a 25-crystal sum may be performed is shown as a function of energy in fig. 11.

The energy resolution obtained with the test matrix is shown in fig. 12. The resolution values, given in table 1, are the averages of the resolutions of the various Γ_{25} 's, and *not the overall test-matrix resolution* (this minimizes any intercalibration or non-linearity effects). Owing to the slightly non-Gaussian shape of the spectra, the resolution is quoted as the FWHM/2.36. In addition to the intrinsic BGO resolution, the measured resolution also contains the effects of electronic noise, beam momentum uncertainty, and any calibration or linearity errors, as well as light-collection non-uniformity effects. As seen in fig. 12, the measured resolution is in good agreement with the Monte Carlo predictions that have

been corrected for the contributions from the measured electronic noise and our estimate of the uncertainty in the measurement of $\Delta p/p$.

The resolution values presented were derived from data taken with a beam spot smaller than the front face of a crystal, and centred on the crystal axis. As the beam moves off axis, the presence of material between the crystals (the carbon-fibre walls, the crystal wrapping, and the distributed air gap) contributes increasingly to a degradation in the resolution. We have estimated the maximum deterioration in the resolution that could be experienced because of these effects by taking data with the beam spot centred on the boundary of two crystals. The results, and the comparison with those from GEANT, are shown in fig. 13.

5. CONCLUSIONS

Our tests with a realistic prototype detector have given excellent energy resolution and linearity. At energies ≥ 6 GeV, the measured energy resolution (including here the error in the determination of the beam momentum, as well as electronic noise) is better than 1% for a sum of 25 crystals. We have also seen the importance of correcting for crystal-to-crystal variations in light collection. These variations affect the energy scale for each crystal, thus degrading the overall detector performance by their quadrature contribution to the average resolution. The dispersion in the energy scales of the different crystals, though, appears to be dominated by the uncertainties in the values of the light-collection uniformity factor, and should improve once these values are better known. These effects, as well as the measured resolution and linearity, are in good agreement with predictions made by the GEANT Monte Carlo program.

The intrinsic high resolution and excellent linearity of BGO, coupled with the ability to correct for crystal-to-crystal variations, gives us

confidence in the feasibility of a large BGO electromagnetic calorimeter with 1% resolution at high energy.

Acknowledgements

We would like to acknowledge our colleagues in L3 for their support throughout these tests. We are also grateful to the technical staffs of the various institutes for the construction and maintenance of the hardware we used, and to the CERN SPS Group for the operation at the X3 beam.

REFERENCES

- [1] J.A. Bakken et al., Nucl. Instrum. Methods 228 (1985) 294.
 - [2] R. Brun et al., CERN DD/EE/84-1 (1984) and DD/85-1 (1985).
 - [3] The collection of light in tapered crystals has been thoroughly studied, and more details may be found in Proc. Int. Workshop on Bismuth Germanate, Princeton University 1982, ed. C. Newman-Holmes.
- The construction of L3, L3 Internal Report (April 1985).

Table 1. Energy resolution for Γ_{25} . The column labelled Data consists of the observed energy resolution without any corrections for electronic noise (not optimized for these high-energy tests) or the uncertainty in $\Delta p/p$. The columns labelled GEANT, Noise, and $\Delta p/p$ contain, respectively, the Monte Carlo predictions for the resolution of a 25 crystal matrix (neglecting the effects of noise or $\Delta p/p$), the measured electronic noise, and our estimate of the uncertainty in the measurement of $\Delta p/p$. The final column represents the total Monte-Carlo resolution: the quadrature sum of the three preceding columns.

E (GeV)	Data ($\Gamma/2.36$)/E (%)	GEANT ($\Gamma/2.36$)/E (%)	Noise ($\Gamma/2.36$)/E (%)	$\Delta p/p$ ($\Gamma/2.36$)/E (%)	Total MC (%)
2	1.523 ± 0.063	0.768 ± 0.013	1.177 ± 0.039	0.64 ± 0.10	1.544 ± 0.108
6	0.952 ± 0.010	0.528 ± 0.011	0.443 ± 0.020	0.33 ± 0.08	0.764 ± 0.083
10	0.690 ± 0.005	0.443 ± 0.008	0.307 ± 0.014	0.30 ± 0.05	0.617 ± 0.053
20	0.599 ± 0.002	0.404 ± 0.007	0.275 ± 0.004	0.30 ± 0.05	0.573 ± 0.051
30	0.611 ± 0.004	0.403 ± 0.009	0.175 ± 0.003	0.30 ± 0.05	0.538 ± 0.051
40	0.511 ± 0.002	0.410 ± 0.011	0.103 ± 0.001	0.30 ± 0.05	0.518 ± 0.051
50	0.617 ± 0.006	0.442 ± 0.013	0.096 ± 0.001	0.30 ± 0.05	0.543 ± 0.052

Figure captions

- Fig. 1 : Schematic view of the 100-crystal test matrix.
- Fig. 2 : View of the matrix as mounted on the rotating platform.
- Fig. 3 : Layout of the X3 beam line. The inset shows the triggering scintillators S3 and S4 and the veto counters, A. Č1 and Č2 are 8 and 5 m threshold Čerenkov counters.
- Fig. 4 : Cross-sectional view of a crystal in its cell.
- Fig. 5 : Distribution of the calibration constants (relative to the average) for the 50-crystal half-matrix.
- Fig. 6 : Lateral energy deposition in the tapered crystals. The circles represent the ratio of the energy deposited in the central crystal to that deposited in the E_{25} , and the triangles are the ratio E_{25}/E_9 . The beam spot used in GEANT was derived from the data.
- Fig. 7 : Mean value of the digitized energy of all the E_{25} as a function of energy.
- Fig. 8 : Light collection in a tapered crystal [3].
- Fig. 9 : GEANT Monte Carlo predictions for the variation of E_{25}/E as a function of light-collection uniformity.
- Fig. 10 : GEANT Monte Carlo predictions for the variation of the resolution, $(\Gamma/2.36)/E$, as a function of light-collection uniformity.
- Fig. 11 : The r.m.s. dispersion of all E_{25} as a function of energy after light-collection corrections have been applied.
- Fig. 12 : Observed average energy resolution, $(\Gamma/2.36)/E$, as a function of energy. The open circles are a quadrature sum of the Monte Carlo resolution, measured electronic noise, and the uncertainty of $\Delta p/p$.

Fig. 13 : Influence of walls on the energy resolution. The beam was centred on the wall between two crystals, and the spot sizes were $\sigma_x = 15.7$ mm, $\sigma_y = 11.9$ mm at 2 GeV; $\sigma_x = 12.0$ mm, $\sigma_y = 10.9$ mm at 10 GeV; $\sigma_x = 10.2$ mm, $\sigma_y = 0.5$ mm at 30 GeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Calibration constants (relative to the average)

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13