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Abstract

We report on the construction and test results of a 8×8 module electromagnetic BGO calorimeter with both longitudinally non-segmented modules and modules with longitudinal segmentation for improved electron/hadron discrimination and two shower separation. The data have been taken mainly at the CERN PS accelerator at electron and pion momenta ranging from 0.5 – 6 GeV/c. The crystals are read out via large area silicon PIN photodiodes coupled to specially developed low-noise preamplifiers and pulse-processor modules with automatic gain range selection. We discuss the energy and position resolution as well as the performance for particle identification and two shower separation.

1 Introduction

The next generation of high energy collider and fixed target experiments will set strong requirements for electromagnetic and hadronic calorimetry. Precise energy measurements will be an important task of such detectors. Good electromagnetic energy resolution is particularly important for ‘standard’ particle reconstruction, such as $\pi^0 \rightarrow \gamma\gamma$ or $\eta \rightarrow \gamma\gamma$, but also for one of the most promising channels for detecting the Higgs particle decay $H^0 \rightarrow \gamma\gamma$, if the Higgs mass is in the range $m_W \leq m_H \leq 2m_W$. The combinatorial background in the $\gamma\gamma$ invariant mass spectra is enormous in all these cases. The signal-to-background ratio, which is at low transverse momenta the limiting factor in particle identification, is entirely dominated by the calorimeter energy resolution. At large values of $p_\perp$ the position resolution and two-particle separation power have to be considered as well. Furthermore, if operated at high energy hadron colliders where there are large jet-production cross sections, or in the high multiplicity environment of ultrarelativistic heavy-ion reactions, the detectors must cope with a very high density of incident particles. This sets strong demands on the granularity of the detector and on the separation power for electromagnetic and hadronic showers.

The best calorimeter energy resolution known is achieved by homogeneous electromagnetic (EM) calorimeters using inorganic scintillators, such as NaI(Tl), CsI(Tl), BaF₂, or Bi₄(GeO₄)₃ (BGO). Table 1 lists properties of these materials relevant for EM-calorimeters. Among these, BGO offers the highest density and allows construction of a very compact detector. The relatively high light output and green spectral response permits replacing the standard photomultiplier read-out by a photodiode read-out. This became possible with the availability of large area low noise PIN silicon photodiodes. Examples of major detectors in operation employing some thousands of scintillator modules with photodiode read-out are L3 at CERN [1] and CLEO-II at CESR [2].

Our investigations of high resolution EM-calorimeters were motivated within the context of the WA80/93 experiment at CERN. A major goal of this experiment is a measurement of high precision π^0 and η spectra in ultrarelativistic heavy-ion collisions and thereby the search for excess thermal direct photon production. Direct photons are considered to be a clean signal of the formation of a quark-gluon plasma and their production rate provides a unique probe for the initial temperature of the reaction zone. In order to extract the yield of direct photons one must subtract the yield of photons originating from hadronic decays, principally those of the $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ decay. The accuracy of a direct photon measurement is thus directly related to the precision achieved in the reconstruction of π^0 and η mesons, and is thereby linked to the energy and position resolution. Another source of systematic errors are hadrons ($\pi^\pm, n, p, \dots$) which may mimic photon signals if they interact in the detector material. The photon identification and hadron rejection performance are therefore further crucial parameters of interest.

In this article we present results obtained with a test detector consisting of an 8×8 matrix of both longitudinally segmented and non-segmented BGO modules. The cross section of the crystals is $2.5 \times 2.5 \text{ cm}^2$ and their total length is 25 cm, corresponding to a length in radiation lengths of about $22 X_0$. Each crystal is viewed by two large area silicon PIN photodiodes. Both a charge sensitive preamplifier and a pulse-processor were developed specifically for our needs. The system produces more than 20 bits of effective resolution when used with standard 12 bit ADCs and was designed to cover the dynamic range from below 50 MeV to more than 50 GeV with an electronic resolution of better than 0.1 % [3]. After describing the laboratory tests performed to measure the quality of the individual modules, we shall discuss the experimental setup and the results obtained from beam measurements carried out at CERN. Here, the assembled detector was exposed to electrons and pions in the momentum range from 0.5 to 6 GeV/c using the T7-south beamline of the PS and also using the X1 beamline at the SPS for a short test at higher energies up to 40 GeV/c. We study in detail the energy and position resolution and the electron/pion discrimination by inspecting the lateral and longitudinal shape of the showers. The improvement arising from the use of a longitudinally sampled calorimeter are discussed, and the experimental data are compared to Monte-Carlo simulations.

2 Tests and Preparation of BGO Crystals

Three different sizes of crystals with parallelepiped geometry were used. The lateral dimensions were $2.5 \times 2.5 \text{ cm}^2$ in all cases. The length was chosen to be 25 cm for the non-segmented and 7 cm (front) + 18 cm (back) for the segmented modules. The total length of more than $22 X_0$ ensures that energy leakage of electromagnetic showers at the back of the calorimeter is sufficiently small not to deteriorate the energy resolution even up to an energy of 50 GeV

	BGO	NaI(Tl)	CsI(Tl)	BaF ₂
Radiation Length X_0 (cm)	1.12	2.59	1.86	2.05
Molière Radius (cm)	2.3	4.4	3.8	3.4
Interaction Length (cm)	21.9	41.4	36.4	29.9
Wavelength of max. emission (nm)	480	410	560	210/310
Light output rel. to NaI(Tl) (%)	11	100	45	16/5
Decay time at room temperature (ns)	300	220	~1000	0.6/620
Afterglow at 3 ms (%)	0.005	0.5 – 5	0.5 – 5	< 0.003
Hygroscopic	No	Yes	No	No

Table 1: Comparison of properties of different scintillators.

Figure 1: Typical light transmission curves of 7 cm and 25 cm long BGO crystals. The symbols indicate the reference values for minimal transmissions as requested from the manufacturer.

for photons and electrons. The lateral size was chosen according to the Molière radius, so that for central incidence EM-showers deposit approximately 75 % of their energy in a single module. Smaller lateral dimensions would lead to very little improvement of the spatial resolution and two-shower separation but would increase the complexity and cost considerably.

After delivery from the manufacturer [4] the crystals were visually inspected for mechanical defects, bubbles, and size tolerances. The light transmission was measured at wavelengths between 300 and 700 nm across their full length as well as at several points along the transverse direction to test the optical quality. Typical results obtained for 7 cm and 25 cm long crystals are shown in figure 1. The transmission values were found to be well above 70 % in the region from 400–700 nm and to drop rapidly to zero below approximately 330 nm. Since losses due to reflections at the two surfaces result in an intensity loss of more than 23 % (assuming a refraction index of $n = 2.1$ at 480 nm) the transparency closely approaches its theoretical limit. The largest differences between the two types of crystals are observed in the range of 300–400 nm. Here, the light attenuation length becomes comparable to the lengths of the crystals. For example, the transmission values at 350 nm suggest a light attenuation length of approximately 55 cm at this wavelength. The transmission not only plays an important role for the energy resolution in large crystals, but also is considered a measure of the radiation hardness (see e.g. Ref. [5, 6]).

Optimal performance of the crystals for energy measurements was ensured by checking the amount of scintillation light and the light collection properties to the read-out surface. These properties were tested by illuminating the crystals at various points along the crystal length by 662 keV γ -quanta emitted from a ^{137}Cs source and viewing the scintillation light by a Philips XP2972 photomultiplier. Five different types of wrapping materials were tested; a) ordinary white paper, b) aluminized mylar-foil, c) Teflon paper [7], d) Teflon tape [8], and e) reflective paint [9]. The highest light output was obtained by wrapping the crystals in teflon paper. Ordinary white paper resulted in about 80 %, and aluminized mylar foil in about 86 %, as much light collected relative to the teflon paper. Results obtained with the teflon tape were found to depend on the number of layers used; a single layer of 0.03 μm only marginally exceeded the results of the mylar-foil, while 5 layers gave almost the same results as the teflon paper. Painting the crystals with white reflective paint resulted in a light output somewhat lower than the teflon paper, but thickness variations were not easy to control and the surface itself was found to be of intolerable roughness.

The variations of the uniformity of the light output along the crystal were in all cases less than 3 %, with a tendency to observe more light from the end away from the read-out surface. Unlike results obtained with tapered crystals of similar dimensions [10], no further modifications were thus required to homogenize the light collection. Since teflon tape is fairly easy to handle and results in less inactive material between adjacent modules than does teflon paper, the segmented modules were wrapped with 5 layers of this tape plus one layer of aluminized mylar foil resulting in a total thickness of 21 μm between two modules. The unsegmented modules were wrapped with a single layer of teflon paper plus one layer of aluminized mylar foil for a total thickness of 270 μm between the modules. The amount of observed light was increased further by another 20 % by using optical grease instead of air coupling to the phototube. Under such conditions resolutions of 22–24 % and of 16–19 % (FWHM) were observed for the 25 cm and 18 cm crystals, respectively, at the 662 keV peak. Variations of the light yield between crystals of the same type were below 5 % in general.

The resolution of the $1.5 \times 0.75 \text{ cm}^2$ large photodiodes [11] and their optimal operation parameters were determined by illuminating the diodes directly with 123 keV γ -quanta from a ^{57}Co source. Above a negative bias of 15 V and an amplifier shaping time of 3.5 μs no significant improvement of the resolution was observed. These parameters resulted in a resolution of approximately 6 % (FWHM) and were therefore used also in the later experiment.

After testing all individual components, pairs of photodiodes were mounted in a capsule and glued [12] to the crystal before wrapping. The purpose of the capsules is to fix the two photodiodes at a defined position, guide a lightfibre to the crystal surface, hold a temperature sensor, and allow mounting of the

Figure 2: Sketch of a longitudinally segmented BGO module with capsules and photodiodes.

preamplifier printed circuit board (see below). A sketch of a crystal with the capsule and photodiodes attached to it is shown in figure 2.

3 Experimental Setup

The test measurements were performed at the T7-south beamline of the CERN PS and at the X1 beamline of the CERN SPS in order to study the low and high energy response, respectively.

The T7-south beamline is an achromatic corrected beamline which delivers electrons, protons, and pions with momenta of $0.5 - 6 \text{ GeV}/c$ at intensities of up to 10^6 particles per spill within a spill length of 0.4 s . For our test the intensity was reduced by collimators to a rate of $10^2 - 10^3 \text{ s}^{-1}$. The nominal beam momentum spread was less than 0.4% (RMS). Measurements were made at momenta of $0.5, 1, 2, 4$, and $6 \text{ GeV}/c$.

The X1 beamline at the SPS allows selection of particles in the $2 - 70 \text{ GeV}/c$ range. The intensity is similar to that for the T7-south line, but the spill length of 2.2 s allowed more efficient use of the beam. The beamline was equipped with a spectrometer with a pair of multiwire proportional chambers (MWPC) each upstream and downstream of the final bending magnet to correct for

chromatic aberrations. A momentum resolution of approximately 0.4 % (RMS) can be achieved for $p \geq 10 \text{ GeV}/c$.

Electrons were discriminated from pions and heavier particles by two threshold gas Čerenkov radiation detectors. Two scintillation counters and a small halo veto counter combined with the Čerenkov signals were used to form a trigger for the experiment. A large muon paddle behind the experimental setup was used in addition at X1 to veto muon events. A delay-line multiwire proportional chamber (DWC) was positioned directly in front of the BGO test box to reconstruct the position of incoming particles with an accuracy of better than 1 mm.

3.1 The BGO Test Matrix

The BGO test calorimeter consisted of 29 non-segmented modules and of 35 longitudinally segmented modules which were arranged in two contiguous groups to form a total matrix of 8×8 modules. The 25 cm long non-segmented modules were read out from the back. The segmented modules were oriented with the 7 cm long crystal in front and the 18 cm long crystal behind and were read out from the front and back, respectively. The preamplifier boards were mounted on the photodiode capsules and connected directly to the photodiodes. The inactive material thereby placed in front of the segmented modules amounts to an effective thickness of at most $0.1 X_0$, which is of marginal influence on the energy resolution at low incident energies ($E < 500 \text{ MeV}$) and can be neglected at higher energies.

The test matrix was mounted in a frame of 4 temperature regulated copper plates which in turn were housed in a thermally isolated box. The test box was then mounted in a support structure allowing the box to be rotated about the horizontal and vertical axes, and the whole system was placed on a movable platform to allow for horizontal and vertical translations.

An electronic pulser was used to check the function and stability of the electronic read-out chain. To distribute the signal of a master pulser to all 99 preamplifiers without introducing complex external cabling to the test box, a precision linear fan-out system was integrated in a separated part of the test box.

The response to light and the read-out gain was independently monitored for each channel by a xenon flasher. The light from the Xe-lamp was homogenized by a mixer and distributed by individual fibres to the crystals. The intensity of the light flashes was monitored for each pulse by a reference photodiode.

3.2 Temperature Regulation

The scintillation efficiency and fluorescence decay time of undoped inorganic scintillators are known to be strongly temperature dependent at room temperature. The variation of the scintillation response of BGO crystals has been measured over a temperature range from $T = -47^{\circ}\text{C}$ to $+111^{\circ}\text{C}$ by the authors of Ref. [13]. Exciting the crystals by 662 keV γ -rays they found a variation of the light output, L , of $\frac{1}{L} \frac{\Delta L}{\Delta T} \simeq -2.9\%/^{\circ}\text{C}$. Bakken et al. [1], on the other hand, found a variation of $-1.55\%/^{\circ}\text{C}$ by analyzing data from 10 GeV/c electrons over a rather narrow window from 21°C to 25°C . Evidently, attempting to achieve an energy resolution with a BGO calorimeter of better than 1 % requires either precise temperature regulation to a level on the order of 0.1 K, or temperature measurements of similar precision with subsequent correction of the data. Since the temperature dependence seemed to be known rather insufficiently, we equipped the test box both with a high resolution temperature regulation system and at the same time measured the temperature at 49 different crystals during each spill-off period [14].

The temperature of the BGO crystals was regulated by ethanol of a controllable temperature flowing through pipes embedded in the 4 copper plates. Thermal stabilization was achieved by inspecting the temperature at 4 different points of the BGO matrix at intervals of 2 seconds and calculating from the actual values, and from their variations in time, a demand value for the ethanol bath. To achieve a rapid stabilization at a certain preset crystal temperature without intolerable oscillations, the three parameters for the PID (Proportional, Integral, Differential) regulation had to be carefully tuned. The actual regulation was performed by a micro-controller running a BASIC program [15]. A successive two-fold digitization of the temperatures of the 4 thermistors by an integrated 8-bit ADC allowed to achieve an effective resolution in the input value of 0.05 K.

During data taking the temperature of the crystals was regulated to a value of 18°C . The stability of the system over periods of several days was found to be better than $\delta T = \pm 0.1\text{ K}$.

3.3 Read-out Electronics

The read-out electronics were designed as a prototype series specifically for the needs of a fixed target experiment with asynchronous triggers and with a very wide dynamic range of signals expected. The goal was to have a measurement accuracy of 0.1 % over a dynamic range from less than 50 MeV to more than 50 GeV, so that the intrinsic resolution of the BGO would be the limiting factor. The instrumentation, comprising a charge-sensitive preamplifier and a pulse-processor, is described in detail in Ref. [3]. We give here only the basic features.

Figure 3: Block diagram of a pulse-processor module.

The preamplifier was designed for high detector capacitance (100 to 700 pF), low power consumption (200 mW), and low differential and integral non-linearity. The maximum linear output is approximately +10 V and corresponds to a charge of 18 pC at the input. With the two photodiodes mounted on a crystal, an input of $1.27 \cdot 10^6$ e-h pairs (0.203 pC) per GeV deposited energy was measured, so that the maximum preamplifier output corresponds to 89 GeV. With the photodiodes connected (200 pF detector capacitance), a preamplifier noise of approximately 10^3 electrons (RMS) corresponding to 0.8 MeV was measured. The preamplifier is placed on a 1×3 inch printed circuit board with surface mount components placed on both sides. This allows the preamplifier to be mounted directly on the photodiode on the crystal, thereby minimizing the noise pickup.

The pulse-processor is a shaping amplifier with integral peak-detect-and-hold (PDH) and automatic gain selection circuitry. The prototype design used commercial 12-bit ADCs and coincidence bit registers to simulate 20 bits of effective resolution. A block diagram of the pulse-processor is shown in figure 3. After passing through a pole-zero (PZ) compensation network, the preamplifier signal is split into two sub-channels each consisting of an active pulse shaping net-

work ($3.5 \mu\text{s}$) with gated baseline restoration and peak-detect-and-hold (PDH) circuit. Following each PDH circuit, which is gated by the experimental trigger, the signal is split into three paths, each with different gain. A range select logic chooses the path with the greatest gain that is not saturated and passes that output to the ADC. The actual range is decoded as a 3-bit pattern and reported to the data collection electronics. The automatic gain selection can also be overridden and manually selected via a switch located at the front panel. The six gains and their typical energy ranges are listed in Table 2. In the case of the highest gain, the lowest detectable energy is determined by the PDH threshold. This threshold was individually adjusted for each channel to a level several times the RMS electronic noise. Under laboratory conditions the electronic noise was typically between $1.2 - 1.5 \text{ MeV}$ (RMS). During the test in the electron beam, however, those modules equipped with a thermistor had an electronic noise which worsened to a value of $2 - 5 \text{ MeV}$ (RMS). Thus the thermistors, which are mounted adjacent to the photodiodes and whose signals are fed through the printed circuit board of the preamplifier, were a source of additional noise pick-up.

Range	Gain	Energies
1	512	15 MeV – 144 MeV
2	128	140 MeV – 580 MeV
3	32	560 MeV – 2.3 GeV
4	8	2.2 GeV – 9 GeV
5	2	9 GeV – 37 GeV
6	1	37 GeV – 73 GeV

Table 2: Pulse-processor gain and typical energy ranges.

4 Data Reduction

The calibration of the detector consists of two main parts. First, each channel of the read-out system must be calibrated, i.e. the raw data are corrected for the amplifier gain and offset of the automatically selected range. Next, the relative calibration constants of the BGO modules are determined by exposing each module to the electron beam. In the case of the longitudinally segmented modules, one furthermore needs to extract the relative calibration constant between the forward and backward parts. Each step of this data reduction must be completed with an accuracy exceeding the intrinsic resolution of the calorimeter. Finally, temperature effects must be taken into account. However, the thermal stability of the present setup was sufficiently high that no further correction to the data was necessary (see section 4.3).

4.1 Read-out Electronics Calibration

Before the energy calibration can be applied, the relative gains and offsets for each range of the pulse-processor modules had to be determined. This was accomplished by using pulser data. The shape of the pulser signals was matched to that of the BGO, and the events were collected in two different modes during spill-off periods. In one of these two modes the pulse height of the pulser was kept at a fixed value, while in another mode the pulser was triggered by a ramp generator. The ramp was chosen in such a way that the pulse height of the pulser varied continuously between zero and the maximum value accepted by the preamplifier and pulse-processor system. This ensured that the response of the electronics was monitored continuously over the full dynamic range. The signal of the pulser was independently fed to several ‘ordinary’ shaping amplifiers with different gains and digitized for monitoring and calibration reasons. These digitized signals will be called “reference ADC” in the following. As an example of the ramp-pulser data, we show in figure 4 the pulser signal in a reference ADC versus the signal output of a pulse-processor module into a BGO-ADC. One clearly observes six separated lines which correspond to the gain ranges 6 to 1. Assuming a linear response in the reference channels the relative gains and offsets of the pulse-processor modules are extracted by fitting straight lines to the individual branches.

An independent intercalibration between the gain ranges of each pulse-processor was determined from pulser data taken at fixed amplitude in the region of overlap between the various gain ranges. In this procedure, pulses with an amplitude corresponding to the lower limit of a given gain range were processed and digitized. The processor was then switched to the next higher gain range and the pulses were again processed and digitized. Care was taken, that the amplitude did not change during this procedure. The results gave a set of simultaneous equations for which both the channel intercept and relative gains could be determined.

Both of these methods gave the same gain factors within a fraction of a percent in most cases. For the highest gain of the pulse-processor, however, larger deviations between the two methods were found. Careful inspection of the data traced this problem back to non-linearities in the lower channels of the reference ADC, so that only the results of the second method were used in this case.

After applying these gain and offset corrections, still some mismatches in the data of a few modules were observed at points where the pulse-processor switches from one gain range to another. These gaps or bumps in the spectra were then eliminated by carefully readjusting the relative offsets and gains of the respective ranges.

Figure 4: Distribution of ramp-pulser data for the six different gain ranges of the pulse-processor. The signal observed by a reference ADC is plotted versus the signal seen by a BGO ADC for gain ranges 3–6 (not taking into account the range information of the pulse-processor). The inset shows data of gain ranges 1–4 taken with a higher gain in the reference ADC channel.

4.2 Beam Calibration

The relative energy calibration between the modules was accomplished by exposing each module of the 8×8 matrix to a 4 GeV/c electron beam aligned with the central axis of the crystals. For this intercalibration, the information extracted from the DWC was used to select only those electrons entering the center of the modules within a $10 \times 10 \text{ mm}^2$ window. This avoids analyzing events in which a large fraction of the energy is deposited in one of the adjacent modules. The size of the window was selected in view of minimizing the error arising from the available event statistics, from systematic shifts due to changes in the beam-profiles, and from uncertainties in the actual size and position of the window relative to the module center.

Figure 5: Energy deposition of the backward versus the forward modules; a) a single module, b) sum of 3×3 matrix, and c) sum of 5×5 matrix. The lines represent fits to the data, yielding the relative calibration between the forward and backward section of the calorimeter.

Within a group of modules of the same kind, i.e. non-segmented, forward, and backward modules, the electron peak positions were then aligned relative to each other by introducing a set of dimensionless intercalibration constants $C_{NS}(i)$, $C_F(i)$, and $C_B(i)$, respectively. In order to increase the accuracy of the calibration parameters further, a second iteration was performed wherein the sum of the energy deposited in a 3×3 matrix around the central module (Σ_9) was calculated and used to readjust the calibration constants of the first iteration.

The intercalibration between the forward and backward part of the segmented modules was determined by analyzing the energy deposited in each segment on an event by event basis, as shown in figure 5. Since the sum of the forward and backward energy depositions should correspond to the beam energy, one expects the events to fall on a straight line. The slope (or equivalently the intercepts with the two axes) yields the unknown intercalibration constant $C_{FB} \equiv C_F/C_B$. As before, the accuracy of the calibration was improved by calculating the sum energy, Σ_9 , or Σ_{25} . This results in narrower forward-backward correlations as is clearly demonstrated in figure 5. The negative inverse slopes extracted from Σ_9 and Σ_{25} yield values of $C_{FB} = 1.312 \pm 0.006$ which differ from each other by less than 0.1 %, but differ by approximately 2 % from the value extracted from single modules. An independent check of the

actual value of C_{FB} was performed by analyzing the energy resolution of the detector as a function of C_{FB} . This yielded a clear minimum at the expected value of C_{FB} .

After completing these intercalibrations, the relative energy depositions measured by the three different subgroups of crystals can be added. Finally, the digitized signals of the detector must be converted into absolute values of deposited energy. This is done by introducing an absolute calibration parameter C_E and identifying the peak position measured in a 5×5 array with the nominal value of the beam energy. Since side leakage effects, estimated by GEANT [16] simulations, were found to be negligible, no further correction of C_E was needed.

Summarizing the results from the calibration procedure, we may write

$$C(i) = C_E \cdot \left\{ \begin{array}{ll} C_F(i)^{-1} & : \text{segmented (forward)} \\ C_B(i)^{-1} \cdot C_{FB} & : \text{segmented (backward)} \\ C_{NS}(i)^{-1} & : \text{non - segmented} \end{array} \right\} (\text{MeV/channel})$$

to obtain the energy per crystal in units of MeV. The constants $C(i)$ were found to be in the range of 18:16:12 MeV/channel for the NS:B:F modules. The dispersion of the calibration constants is approximately 10 % for the non-segmented and below 5 % for the segmented modules, reflecting the uniformity both of the scintillation light yield and of the wrapping and read-out. The differences between the calibration constants is correlated with the length of the crystals and thus is probably mainly due to light absorption effects in the crystals.

4.2.1 Comparison of electron and pion data

Pion data, which were tagged by two gas Čerenkov counters and collected in parallel to the electron data, were used to study systematic uncertainties of the calibration.

The total length of the crystals corresponds to approximately 1.1 nuclear interaction lengths λ . Most of the pions will thus leave the crystals without nuclear interaction and be detected as a ‘minimum ionizing particle’ (MIP) with an energy loss of $dE/dx \simeq 9.1 \text{ MeV/cm}$ (assuming a pion momentum of 4 GeV/c). A typical example of the observed energy spectrum for 4 GeV pions is shown in figure 6 for a single forward module. Applying the results from the electron calibration and comparing the detected peak positions in the different crystals, the dispersion among modules of the same length was found to be approximately $1.4 \pm 0.2 \%$ (rms). Taking into account the uncertainty in the determination of the most probable energy loss of the MIP’s, we conclude that the relative calibrations of both methods are in good agreement with each other. However, the absolute values of the observed MIP peak positions were found to be systematically higher by 2 %, 4 %, and 14 % for the 25, 18, and

Figure 6: Minimum ionizing spectrum of 4 GeV/c pions measured in a forward crystal. The point of incidence is restricted to an area of $2 \times 2 \text{ cm}^2$ with respect to the center of the crystal.

Figure 7: Observed mean energy deposition of 4 GeV/c pions measured in a forward crystal as a function of the point of incidence relative to the module center. The active region of the two PIN photodiodes is indicated by the hatched areas.

7 cm long crystals as compared to the expected values from the calculated energy loss. The reason for this apparent discrepancy can be understood from the results of figure 7, where the observed mean energy deposition of 4 GeV/c charged pions is plotted as a function of their point of incidence on a 7 cm crystal. The observed structure matches directly with the active region of the two photodiodes (indicated by the hatched areas) and demonstrates the effect of charged particles passing through the 300 μ m active depth of the photodiodes. The resulting apparent surplus energy corresponds to approximately 7 MeV of energy deposited in the BGO. This is an important effect for the MIP peak, but is of no consequence for photon showers and is only of minor influence for electron showers because the total energy was in general much higher and there is also only a small probability that charged particles from the EM-shower penetrate the 22 X_0 of the BGO crystal. Taking the effective offset of the energy deposition into account yields an excellent agreement between the extrapolated electron calibration and the observed positions of the MIP peaks.

4.3 Temperature Dependence of the Light Yield

The temperature dependence of the scintillation light yield has been measured by inspecting the variation of the 20 GeV/c electron peak (measured at the CERN-SPS) while slowly raising the crystal temperature from 18°C to 31°C. The result of this measurement is shown in figure 8. Fitting a straight line to the light yield, L , as a function of the temperature, T , yields

$$\frac{1}{L} \frac{\Delta L}{\Delta T} = -(1.3 \pm 0.1)\% / ^\circ\text{C}. \quad (1)$$

The quoted error mainly reflects the systematic uncertainty of the measurement due to the time dependence of the thermal response of the BGO array. This temperature dependence is somewhat weaker than found by the L3 collaboration [1], and is significantly different from the result found in Ref. [13]. The different read-out methods applied (photomultiplier in Ref. [13], and photodiode read-out in Ref. [1] and in this experiment) might explain part of this difference. Another reason might be the different properties of the crystals themselves, such as impurities, the density of trapping centers, etc., which are believed to influence the scintillation properties of the crystal. The small but significant difference between the L3 result and the present work might also be due to the effect that the L3 result is to be considered an *effective* temperature dependence describing the response of the crystals *and* their read-out electronics, while in our case the temperature variations were experienced by the crystals alone, leading to only small changes in the temperature of the read-out electronics.

For the data which were taken with the thermal regulation system in operation, no significant improvement of the energy resolution (see section 5.1)

Figure 8: Observed electron peak position (arb. units) at an energy of 20 GeV as a function of the temperature of the BGO crystals.

was observed after correction for the temperature variations. This is as expected, since the thermal stability of the system during normal data-taking was maintained at a level of $\pm 0.1^\circ\text{C}$ which is at the same level of accuracy as the temperature read-out and well below the intrinsic resolution of the crystals. Therefore, no correction for the temperature dependence has been applied in the following.

5 Test Beam Results

5.1 Energy Resolution

The energy resolution of the BGO test matrix has been measured for electrons in the momentum range from 0.5 – 6 GeV/c. It is of interest to compare the resolution of the non-segmented and longitudinally segmented modules. A slight deterioration is expected for the latter case due to the additional inactive material in front of the segmented modules, i.e. cables, printed circuit board, capsule, and diodes, which altogether add up to an effective thickness of at most $0.1 X_0$, and because of the additional noise due to the duplication of read-out channels.

Distributions of the Σ_{25} as obtained from the non-segmented modules are

Figure 9: Pulse height distributions (Σ_{25}) of 1, 2, and 4 GeV/c electrons and minimum ionizing peak of pions.

Figure 10: Energy resolution as a function of beam energy for non-segmented modules after summation of the energies in a 5×5 matrix.

shown in figure 9 for different energies. The peaks were fitted by single Gaussian distributions in the range $\langle E \rangle - 3\sigma \leq E \leq \langle E \rangle + 3\sigma$. The results are shown in figure 10 and are listed in Table 3 and compared to the segmented modules. The energy resolution of EM-calorimeters is commonly parameterized as

$$\left(\frac{\sigma(E)}{E}\right)^2 = \left(\frac{a_0}{E(\text{GeV})}\right)^2 + \left(\frac{a}{\sqrt{E(\text{GeV})}}\right)^2 + b^2. \quad (2)$$

where a_0 is the noise term, generally negligible above an energy of a few GeV, a is the statistical term (sampling or fluctuations of all kinds), and b is the constant term discussed below.

Fitting the data of the non-segmented (segmented) modules with such a distribution and correcting for the beam spread we find the parameters listed in Table 4 when measuring the energy in GeV. Given the average number of modules contributing to a cluster, the parameter a_0 suggests an average noise level of 3.5-5 MeV per module (if assumed incoherent). This is significantly worse than the results observed under laboratory conditions, and is believed to be caused partially by the integrated circuit temperature sensors which were directly coupled to the preamplifier boards. The parameter a may be regarded as the intrinsic energy resolution of the BGO calorimeter, and its value demonstrates that effects of photon statistics become negligible above an energy of a few GeV. The constant term b is most important for the high energy behavior. It usually contains 3 contributions; (i) fluctuations due to energy leakage, (ii) non-uniformities in the detector response, e.g. scintillation light variations within a crystal, light focusing effects to the diodes, temperature variations, etc., and (iii) intercalibration errors. As discussed above, special care has been taken to reduce all of these possible sources of uncertainty. The larger value of b found for the segmented modules with almost twice the number of read-out channels suggests, that remaining intercalibration uncertainties still may influence the energy resolution. Energy losses in the read-out of the forward modules and at the stacking boundary between the forward and backward mo-

Energy (GeV)	non-segmented $\sigma(\Sigma_{25})$ (%)	segmented $\sigma(\Sigma_{25})$ (%)
0.5	6.02 ± 0.60	6.02 ± 0.78
1.0	3.12 ± 0.51	3.57 ± 0.78
2.0	1.57 ± 0.05	1.83 ± 0.07
4.0	1.02 ± 0.06	0.97 ± 0.04
6.0	0.69 ± 0.03	1.03 ± 0.03

Table 3: Energy resolution for different beam energies and configurations after subtracting the beam spread of $\sigma(p)/p \cong 0.4\%$.

	non-segmented	segmented
a_0	$(2.75 \pm 0.19) \%$	$(2.75 \pm 0.24) \%$
a	$(1.10 \pm 0.16) \%$	$(1.22 \pm 0.17) \%$
b	$(0.30 \pm 0.07) \%$	$(0.72 \pm 0.03) \%$

Table 4: Results from fits to the energy resolution according to equation 2 when measuring the energy in GeV.

Figure 11: Mean energy deposition as a function of the point of incidence relative to the module boundaries for 4 GeV/c electrons. The module boundary and centers are indicated by the dashed lines.

dules can, according to GEANT simulations, worsen the constant term b of the unsegmented modules not by more than approximately 10 %.

A short run at the CERN-SPS at electron momenta of 10 and 20 GeV/c did not show any significant improvement of the energy resolution over the results obtained at 6 GeV (see Table 3). This is partially due to the fact that these values are already closely approaching the nominal, relatively uncertain, momentum-spread of the beam-line.

Figure 11 shows the average energy deposition for 4 GeV electrons as a function of their point of incidence relative to the BGO matrix. Here, the electron position has been determined from the delay-line wire-chamber. Approaching the stacking boundary within ± 2 mm of the surface of two adjacent modules, a smoothly decreasing amount of energy is detected. Centering the beam

directly between two modules, approximately 1.7 % of the energy is unobserved, presumably due to loss in the wrapping material and stacking tolerances. Considering the position resolution of the DWC, this value may be regarded as a lower limit of the undetected energy. Maintaining an energy resolution of better than 1 % over the whole surface of the detector thus requires the application of a position dependent correction function to account for the behaviour shown in figure 11, or to use a geometry with non-normal angle of incidence.

5.2 Position Resolution

Two algorithms have been studied to determine the impact coordinates of a particle initiating an electromagnetic shower in the BGO array.

5.2.1 Method of the modified center of gravity

The most obvious method to estimate the coordinates (x_c, y_c) of an incident particle is to calculate the center of gravity of the shower

$$x_c = \frac{\sum_i w_i x_i}{\sum_i w_i} \quad (3)$$

where x_i is the coordinate of the center of the module i , and w_i is a weight factor taken as the energy E_i deposited in that module. The sum is typically carried out over 9 to 25 modules belonging to a cluster. Because of the modular structure of the calorimeter and the approximately exponential shape of the electromagnetic shower, the center of gravity does not provide a linear measure for the incident position, but rather results in a *S*-shaped curve [17] when plotting the true position (as measured by the position sensitive delay-line wire-chamber (DWC)) versus the reconstructed position. To remove this non-linear dependence, the function

$$F(x_{\text{DWC}}) = d \left[\frac{x_{\text{DWC}}}{d} + \frac{1}{2} \right] + c \cdot \sinh \left(\frac{x_{\text{DWC}} - d \left[\frac{x_{\text{DWC}}}{d} + \frac{1}{2} \right]}{\mu} \right) \quad (4)$$

was employed to fit the data. Here, the square brackets represent the Gauss bracket symbol (the largest integer number less than the argument), d is the linear transverse extension of the modules, and c and μ are the fit parameters. Consistency at the module boundaries requires

$$c = \frac{d}{2 \sinh(d/2\mu)} \quad (5)$$

leaving only one free parameter to fit the data. Application of the inverse function, finally, leads to the correction of the measured center of gravity. The

Figure 12: Difference between the incident position of 4 GeV/c electrons as measured by the DWC and as reconstructed by the BGO-matrix. The left-hand side shows the results obtained from the method of the modified center of gravity, while the right-hand side shows the same but for the method of logarithmic weights (see text for details).

Figure 13: Position resolution, σ_x , for 4 GeV/c electrons as a function of their impact coordinate along a given module for the method of the modified center of gravity. The BGO module boundaries are indicated by the vertical dashed lines.

fit parameter μ was found to decrease with increasing shower energy starting at 4.6 mm for 1 GeV and reaching 3.6 mm for 6 GeV. To determine the spatial resolution, the difference between the known (given by the DWC) and reconstructed position was calculated as shown in figure 12. The position resolution is found to depend on the incident position of the particle with the best results being obtained at the module boundaries (see figure 13). This effect is explained by the fact that the energy deposition in that region is mainly distributed over two modules only, with small variations of the incident position resulting in strong variations in the relative energy deposit.

The global resolution, as quoted in the following, was appropriately weighted so as to represent the results as obtained for a uniform hit distribution over the front face of the modules. Also, no attempt was made to correct the results for the position resolution of the DWC. Fitting a Gaussian distribution to the position differences of the $0.5 \text{ GeV} \leq E \leq 6 \text{ GeV}$ data for both directions, yields

$$\sigma_x(\text{mm}) = \frac{3.35 \pm 0.07}{\sqrt{E(\text{GeV})}} + (0.05 \pm 0.03).$$

5.2.2 Method with Logarithmic Weights

An alternative approach to account for the exponential shape of the shower profile is to use logarithmic weights of the energy depositions in equation 3. The weights were calculated with the following formula, as suggested in Ref. [18]

$$w_i = \max \left[0, \left(W_0 + \ln \frac{E_i}{E_{\text{tot}}} \right) \right] \quad , \quad W_0 \in \mathcal{R}^+ \quad (6)$$

where W_0 is a dimensionless free parameter and E_{tot} is the total energy of the shower, $E_{\text{tot}} = \sum_i E_i$. For energies in the range of 0.5 to 6 GeV the optimal value was found to vary slightly between $W_0 \cong 4.1$ to $W_0 \cong 3.7$. An example of the position resolution obtained at 4 GeV is shown in Figure 12 (r.h.s.).

The global spatial resolution obtained with the logarithmic weighting method for energies between 0.5 and 6 GeV yielded approximately the same energy dependence as the corrected linear weighting method:

$$\sigma_x(\text{mm}) = \frac{3.25 \pm 0.05}{\sqrt{E(\text{GeV})}} + (0.24 \pm 0.03).$$

The results of both methods are shown in figure 14. Although the method of position corrected linear weights does provide slightly better results when using optimized parameters, the method of logarithmic weights has the advantage that there is only a slight energy dependence in W_0 , which may be disregarded, and there is no need for position-dependent corrections. Thus the position corrected linear weight method may be best suited to small systems in which the position dependent corrections can be well determined, while the more robust logarithmic weighting method may be more suitable to large systems.

Figure 14: Position resolution as a function of the incident electron energy. The circles show the results obtained from the method of the modified center of gravity, while the squares show the results for the method of logarithmic weights.

5.3 Electron-Pion Separation

An electromagnetic calorimeter having a depth of about one nuclear interaction length already provides by itself a discrimination of hadrons from electrons or photons due to the low probability for hadronic interactions. This leads, for the same incident energy, to very different average energy depositions. Such e/π differences may be used for discrimination when the momentum of the incident particle is known, for example, from a magnetic spectrometer in front of the calorimeter. In the present analysis, however, we shall investigate the e/π separation capability of the BGO matrix alone, i.e. we analyze the discrimination power for the same *deposited* energy of different particles. The present detector provides two different alternatives for particle separation: the analysis of the lateral dispersion of the shower and the analysis of the longitudinal distribution of the shower.

The analysis of the lateral dispersion, defined as

$$D_x = \frac{\sum E_i x_i^2}{\sum E_i} - \left(\frac{\sum E_i x_i}{\sum E_i} \right)^2 = \overline{x^2} - \bar{x}^2 \quad (7)$$

has become a frequently used tool in calorimetric measurements. In general, hadronic showers are known to result in much larger dispersions than their electromagnetic counterparts. Recently, it has furthermore been pointed out

that the actual value of the dispersion depends on the point of incidence relative to the module boundaries [19]. Correcting for such a position dependence and applying a cut on the dispersion so that 10 % of the electrons are lost, $(81.5 \pm 1.3)\%$ of the pions at 1 GeV and $(97.2 \pm 0.6)\%$ at 2 GeV deposited energy were rejected. At even lower energies, the lateral dispersion analysis breaks down very rapidly, because there is only a small number of modules involved in the shower.

A measure for the depth of the shower can be extracted from the longitudinally segmented modules by calculating the ratio

$$\frac{F}{T} = \frac{\sum E_i(F)}{\sum (E_i(F) + E_i(B))} \quad (8)$$

where F and B stand for ‘forward’ and ‘backward’ modules, respectively. In general, hadronic showers will deposit more energy in the rear than in the front part of the calorimeter, while the opposite behavior is true for electromagnetic showers. Furthermore, charged hadrons leaving the calorimeter without any

Figure 15: Two dimensional distribution of the lateral dispersion and the forward/total energy ratio for electrons and pions for clusters of 1 GeV energy deposit. The one-dimensional distributions show the projections onto each axis, where the hatched areas represent the showers induced by electrons, and the open histograms represent showers induced by pions. The box in the two-dimensional figure represents the region used to select electron events.

Method	1 GeV		2 GeV	
	<i>e</i> -loss (%)	<i>h</i> -discr. (%)	<i>e</i> -loss (%)	<i>h</i> -discr. (%)
Dispersion	2.1±0.3	32.9±1.6	2.0±0.2	92.4±0.8
Forw./Total	10.1±0.7	81.5±1.3	10.0±0.3	97.2±0.6
	1.8±0.3	84.8±1.2	1.9±0.2	72.4±1.4
Combined	10.1±0.7	89.9±1.0	9.7±0.3	83.1±1.1
	2.4±0.3	87.3±1.1	2.2±0.2	98.6±0.8
Stat. indep.	9.7±0.7	98.7±0.8	9.5±0.3	99.8±1.0
	2.0±0.3	84.3±1.2	2.0±0.2	95.3±0.8
	9.6±0.7	95.6±0.9	9.6±0.3	99.0±1.0

Table 5: Electron hadron discrimination for energy depositions of 1 GeV and 2 GeV using the lateral shower information, the longitudinal information, and both combined. The statistically independent values are calculated numbers based on those obtained from the lateral and longitudinal *e/h*-discrimination separately.

nuclear interaction will result in average F/T -ratios entirely determined by the relative lengths of the forward and backward modules. The optimum length of the forward part of the segmented BGO modules was determined by performing GEANT simulations so that good e/π -discrimination is obtained especially at low energies, i.e. in the region where the analysis of the lateral shower dispersion starts to break down. Again, introducing a cut for 10 % electron loss, the pion rejection efficiency is $(89.9 \pm 1.0)\%$ at 1 GeV and $(83.1 \pm 1.1)\%$ at 2 GeV deposited energy. As expected, the analysis of the longitudinal shower dispersion is more efficient for lower energies and complements the analysis of the lateral dispersion.

Using both methods simultaneously and again allowing for 10 % electron loss increases the rejection efficiency of pions to $(98.7 \pm 0.8)\%$ for 1 GeV and to $(99.8 \pm 1.0)\%$ for 2 GeV showers. An example of such a measurement at 1 GeV energy deposition is depicted in figure 15 where the two-dimensional distribution of the lateral dispersion and the F/T -ratio is plotted together with their one-dimensional projections both for electrons and pions. Limiting the electron loss to 2 %, the rejection power of pions drops by about 10 % at 1 GeV but decreases only within the statistical uncertainty of 1 % at 2 GeV. The actual choice of cut parameters used in the data analysis will therefore be determined on the basis of the requirements of a particular experiment. Calculating the rejection efficiencies for 10% electron loss by assuming that the lateral and transverse cuts act independently, yields lower rejection powers than observed in the actual data (see Table 5). The results thus suggest that the two methods are not independent but are even anticorrelated, such that hadrons surviving the longitudinal cut will be rejected with high probability by the lateral cut and vice versa, so that both methods complement each other very efficiently.

This effect can basically be understood from the various processes of the hadronic shower development. If on one hand the first hadronic interaction takes place in the rear part of the calorimeter, the lateral shape is likely to resemble an electromagnetic shower, but the forward/total energy ratio will be significantly smaller than that of an electromagnetic shower. On another hand, if the first hadronic interaction takes place in the front part of the calorimeter, the lateral shape will be much broader but the longitudinal energy ratio will be similar to that of an electromagnetic shower. Similar findings were reported from tests of a scintillating fibre calorimeter combined with a pre-shower detector [20].

5.4 Multiparticle Detection

To investigate the detector performance for two shower separation, artificial events were generated from the test beam data by superimposing the observed energy depositions of different electron showers. Knowing the original energies and positions of these electrons, the identification performance was then studied as a function of the distance between the two showers. To avoid systematic biases due to possible position dependent effects, all superimposed showers were uniformly distributed over the surface of the detector modules.

The first and essential step in such an analysis is the detection of local maxima in the energy depositions in the modules forming a cluster. Assuming that each maximum is generated by the localized energy release of a particle, the positions of the maxima are used as a starting value for an iterative unfolding algorithm where the lateral profile of electromagnetic showers is taken into account. As the overall procedure has been described in detail in Ref. [19], we discuss here only the detector specific probability to detect two close-by showers by their isolated maxima. Considering the pear-shaped structure of electromagnetic showers, it is anticipated that the forward part of the longitudinally segmented calorimeter should provide a more efficient recognition of adjacent showers than does the backward part. This is clearly demonstrated by the results of figure 16, where the probability is shown to detect the isolated maximum of a 1 GeV electromagnetic shower adjacent to a 20 GeV shower. This is an example of a rather difficult situation, where the low energy shower tends to be easily hidden in the tail of the high energy partner. Analyzing the lateral energy profile of the forward part alone, yields a identification probability of both showers of approximately 84 % at an average shower distance of 2 module units. The same resolving power in the longitudinally integrated profile is achieved under identical conditions for a distance between the two shower centers of about 2.4 module units. Considering the quadratic increase of the surface with distance, we conclude that the longitudinally segmented calorimeter can identify such two shower events with similar probability at about 44 % higher particle density as compared to a non-segmented calorime-

Figure 16: Probability to identify a 1 GeV electromagnetic shower in the vicinity of a 20 GeV . The 1 GeV shower is taken from experimental data and the 20 GeV shower from simulated data. The detection probability is shown as a function of the distance between the two showers, for longitudinally integrated clusters (i.e. for a non-segmented calorimeter) (circles) and for the front part of the contents of the segmented calorimeter alone (squares).

ter. Similar numbers were found for the identification of a hadronic particle in close vicinity to a high energy electromagnetic shower.

6 Summary and Conclusions

A segmented BGO calorimeter with photodiode read-out has been constructed and its performance investigated in electron and pion test beams at the CERN PS and SPS accelerators. The calorimeter consisted of longitudinally segmented and non-segmented modules whose relative performance has been compared. The read-out electronics consists of a custom built preamplifier and pulse-processor with automatic gain selection which is particularly optimized for such a calorimeter and for use in large scale experiments. The temperature dependence of the BGO light yield was measured to be $\frac{1}{L} \frac{\Delta L}{\Delta T} = -1.3\%/^{\circ}\text{C}$. In order to avoid the necessity of correcting for this effect, the crystals were housed in a temperature regulated box. An energy resolution σ_E/E of better than 1% was measured for incident energies above 4 GeV. At lower energies the resolution was largely determined by the noise level of 3.5-5 MeV per chan-

nel, which was attributed to noise induced by the read-out of the temperature sensors on the preamplifier board. The measured position resolution can be parameterized by $\sigma_x \cong 3.3\text{mm}/\sqrt{E(\text{GeV})}$. The improvement of the electron/pion separation and two shower identification which is provided by the longitudinal segmentation has been discussed. The longitudinal segmentation in particular helps to reject hadron showers at low energy depositions of $\sim 1\text{ GeV}$, i.e. in the region where the lateral dispersion method breaks down. As an example, at 1 GeV shower energy deposition with 10 % electron loss, $\sim 90\%$ of hadron showers could successfully be rejected based on the longitudinal shower shape, but only $\sim 80\%$ based on the lateral shape. Used together the two methods complement each other efficiently, because hadron showers exhibiting a similar shape as electromagnetic showers in the longitudinal direction, differ greatly from electromagnetic showers in the transverse direction, and vice versa. Finally, we have shown that the longitudinal segmentation also improves the performance for two shower separation. This is particularly true for close-by showers of very different energy where the low energy shower is likely to be hidden in the tail of the high energy companion. Since the lateral extension of electromagnetic and hadronic showers is much narrower in the front part, even such asymmetric events can be detected with high probability and subsequently be unfolded into their respective particle energies and positions. The longitudinal information can provide an essential improvement of the detector performance without significant degradation of the energy resolution, particularly in high particle density environments, such as occur in high energy heavy-ion collisions.

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