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THE EHS LEAD-GLASS CALORIMETERS AND THEIR LASER BASED MONITORING SYSTEM

CERN¹-Heidelberg²-Padova³-Paris⁴-Rome⁵-Serpukhov⁶-Trieste⁷ Collaboration

B. Powell

CERN, European Organization for Nuclear Research, Geneva, Switzerland

R. Heller, N. Ibold, K.R. Schubert, J. Stiewe and M. Vysocansky
University of Heidelberg, Heidelberg, Germany

M. Mazzucato, P. Rossi, L. Ventura and G. Zumerle
University of Padova and INFN, Padova, Italy

M. Boratav, J. Duboc, J. Passeneau and M.C. Touboul
University of Paris, Paris, France

P. Bagnaia, C. Dionisi, D. Zanello and L. Zanello
University of Roma and INFN, Roma, Italy

V.M. Bujanov, Y.V. Fisjak, A.G. Kholodenko, E.P. Kistenev and B.F. Poljakov
Institute for High Energy Physics, Serpukhov, USSR

E. Castelli, P. Checchia and C. Troncon
University of Trieste and INFN, Trieste, Italy

ABSTRACT

We describe the two gamma detectors built for the European Hybrid Spectrometer (EHS). Their monitoring system is presented in detail. Results from tests and the performance obtained during the first EHS experiment are given.

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1. INTRODUCTION

The CERN European Hybrid Spectrometer (EHS) was designed [1] to be operated with a rapid cycling bubble chamber as a vertex detector (fig. 1). The interest in such a hybrid spectrometer, despite its limitation to low fluxes, lies in its unique ability to handle high multiplicity events. This is due to the visualization of the vertex which is far superior to that obtained with electronic detectors. Special attention has been given to achieving high spatial and energy resolution for secondary particles and to detecting photons as well as charged particles in order to have as complete an information as possible on complex events.

In this paper we describe the photon-detection system which has been designed to detect and measure π^0 's produced in the forward hemisphere of the c.m. system at SPS energies. The performance given here corresponds to that measured during the first EHS experiment, made in 1980, which was a search for short-lived particles using a specially built bubble chamber with high optical resolution [2].

The system consists of two separate large lead-glass calorimeters placed at 14 and 39 m from the centre of the first analyzing magnet (M1). The two calorimeters have different designs because they see different kinematical regions. The IGD (Intermediate Gamma Detector) which is located in front of M2, has a central hole corresponding to the magnet aperture and sees lower energy π^0 's: this apparatus must be able to handle high multiplicities. The FGD (Forward Gamma Detector) covers the projection of the hole at the end of the spectrometer and detects fast π^0 's. It therefore needs to have a good energy resolution up to a few hundreds of GeV and to be able to separate pairs of γ 's a few centimetres apart.

The technique of using lead-glass counters as photon detectors has been known for a long time. The problem with such a large set of counters, comprising more than 1600 PM's, is to keep under control the variations in the gain of the different counters as a function of time, thus insuring uniformity of response during data taking and keeping to a minimum the time spent calibrating with an electron beam. We shall, therefore, give

particular emphasis to the description of our laser-based monitoring system, which plays a key role in this respect.

In sects 2 and 3 we describe the principles of the construction of the FGD and IGD. In sect. 4 we describe briefly the data acquisition system. Sect. 5 is devoted to the monitoring system. In sect. 6 we report on the performance of FGD, IGD and the monitoring system, with special emphasis on the energy and spatial resolution and on the stability.

2. DESCRIPTION OF THE FGD

In the FGD, in order to obtain a high spatial resolution without increasing the granularity of the lead-glass structure, the determination of the shower axis and the energy measurement are done by different parts of the detector [3]. It consists of three separate sections (fig. 2): proceeding along the beam, first comes the converter, a lead-glass wall to initiate the electromagnetic shower; second comes the position detector, a three-plane scintillator hodoscope which measures the shower profile with a granularity of 1.5 cm; third comes the absorber, a lead-glass matrix thick enough to totally absorb showers up to the highest energies available (~ 150 GeV). The energy is measured by adding together the contributions of both the converter and the absorber.

The FGD is mounted on a computer controlled movable two-coordinate platform for calibration purposes.

2.1 The converter

The converter is a wall of 28 lead-glass blocks $15 \times 15 \times 60$ cm³. These are mounted with the long axis perpendicular to the beam direction, two blocks on each level, thus covering a surface of 210 (vertical) $\times$ 120 (horizontal) cm². Each block is wrapped with aluminized mylar and viewed by an RCA 8055 PM (5" in diameter). The phototubes are used with a voltage-divider chain similar to the one described by Appel et al. [4], which ensures a linear response up to 16 mA. Grounds of signal and high-voltage are separated.

Since the blocks are mounted transversely to the beam, one must correct for attenuation effects. To minimize them, a highly transparent CORNING CEREN 32^(*) glass was adopted which has $X_0 = 3.2$ cm (total thickness of $4.7 X_0$). Fig. 3 shows the transmittance as a function of the wave length. In addition, we found that by installing 3 mm thick Schott GG400 filters (cut-off at 400 nm) between the PM's and the glass blocks the attenuation can almost be neglected (fig. 4).

2.2 The position detector

The profile of a shower which has started in the converter is obtained from the analogue signals produced in three planes of scintillator "fingers" (each 1.5 cm wide in the direction perpendicular to the beam and 1 cm thick). The horizontal and vertical planes have fingers of constant length. The third plane, which is oriented at 45° and thus has fingers of varying length, is meant to help in resolving ambiguities. The total number of counters is 375. A plexiglass light-guide with a semi-cylindrical head couples each finger to a low-cost side window PM (RCA 931A)^(**). A single light-tight box encloses all the PM's. The scintillator used is Plexipop made by Montedison^(***), with an attenuation length of ~ 1.5 m. We tested the uniformity of the attenuation in a sample of 2 m long fingers and found that the variations from counter to counter do not exceed 10%.

2.3 The absorber

The absorber consists of a 14×8 matrix of lead-glass blocks measuring $15 \times 15 \times 60$ cm³ in the central 8×8 portion and $15 \times 15 \times 40$ cm³ in the 3×8 upper and lower portions. As a reasonable compromise between transparency and short radiation length we selected CORNING CEREN 25^(*) lead-glass ($X_0 = 2.5$ cm). The wrapping of the blocks and the phototubes used are the same as for the converter.

At high energies the energy resolution is no longer dominated by the photon statistics of the Cerenkov radiation. Among other factors, an

(*) Sovirel, Paris, France.

(**) Following a scheme already adapted for a prototype installed at Fermilab.

(***) Montedison, Mestre, Venice, Italy.

important contribution comes from differences in the absorption of blue light due to fluctuations in the shower development along the block. To exploit the flat transmission region of the glass [5], a 3 mm thick Schott glass filter, type GG 420, was inserted between each block and its PM, thus providing a cut-off at 420 nm (fig. 3). Optical contact was made using Rhône-Poulenc B431 grease. A force of ~ 50 N is applied to each PM by means of springs to maintain the optical contact.

A test was made using several blocks both with and without filters at various energies. Fig. 5 shows that the improvement in resolution, which is almost zero at 10 GeV, increases with the energy and becomes $\sim 25\%$ at 50 GeV. The reduction in signal amplitude due to the filters was measured to be $\sim 30\%$.

3. DESCRIPTION OF THE IGD

The IGD was designed to measure both the position and the energy of a shower using a two-dimensional matrix of lead-glass counters [6]. This is accomplished by choosing the cross section of the individual counters small enough so that the energy leakage into adjacent counters can be used to determine the position of the shower axis. A size of $5 \times 5 \text{ cm}^2$ was chosen as a compromise between the precision of position measurement and the complexity of the detector.

Fig. 6 shows the array of 1122 counters covering a surface of $195 \times 160 \text{ cm}^2$ with a central aperture $35 \times 90 \text{ cm}^2$ matching the gap of the analysing magnet M2. The individual counters measure $5 \times 5 \times 42 \text{ cm}^3$ and are made of lead-glass F8 manufactured in USSR, with $X_0 = 2.8 \text{ cm}$. Like the FGD, the IGD is mounted on a movable two-coordinate platform so that each counter can be calibrated individually by exposing it to an electron beam.

The PM's (FEU-84) are shielded against the stray field of the magnet M2 primarily by means of a heavy iron plate. They are then shielded individually against the residual field which is of the order of 20 G. The S20 photocathodes have a diameter of 24 mm, so the geometric collection

efficiency of the light is 20%. However, tests have shown that above a few GeV the resolution is not affected [7].

Fig. 7 shows the design adopted for the counters. The cylindrical light-guide (33 mm in diameter and 20 mm thick) is made of the same lead-glass as the counters and is cemented to the lead-glass block. It is used as a mechanical support for the PM housing. This geometry allows the magnetic shields to be made more efficient by extending them beyond the photocathode.

The shielding consists of two cylinders of 0.6 mm thick "steel-50" and a 0.3 mm thick layer of Permalloy rolled inside the inner cylinder. The PM is pressed against the light guide and the optical contact is obtained with a thick Dow-Corning grease. The PM is also wrapped with Teflon to avoid current leakage through the glass.

With a strongly non-linear voltage divider chain, the response of the FEU-84 has been shown to be linear up to 20 mA for a typical operating voltage of 1600 V.

The PM's are enclosed in a single light-tight box which is air-cooled to keep the temperature stable to within 1°C.

4. ELECTRONICS AND DATA ACQUISITION

In spite of their different design the FGD and IGD use the same electronics and are treated by the on-line Data Acquisition System (CERN DAS) [8] as a single system.

The digitization of the analogue signals is done using LeCroy 2282, charge-sensitive, 12-bit ADC's, 48 channels per module, controlled by a LeCroy 2280 microprocessor in standard CAMAC crates. A 300 ns gate is used for all ADC channels.

A 12 bit precision from the ADC's is crucial in order to obtain a good spatial precision. In fact, both in IGD and in the position detector of FGD, spatial precision is obtained by using the small amplitude tails detected on either side of the main body of the shower, hence the need for a large dynamic range.

The 2280 microprocessor allows automatic pedestal subtraction and data compression. Pedestal stability was checked and found satisfactory (fluctuations of 1-2 counts), so that pedestal-free channel contents can be written onto magnetic tape. When in data compression mode, only those channels whose content, after pedestal subtraction, exceeds a previously fixed digital threshold are moved into the 2280 internal memory at the end of the conversion. This property was fully exploited during data taking and was particularly useful for IGD, reducing the number of channels by approximately an order of magnitude.

While during beam spills data were collected in data compression mode, between spills the signals from the monitoring system were recorded in normal mode (all channels), for further off-line analysis.

The HV for the PM's was distributed through computer controlled DATEP units which are described elsewhere [9].

5. THE MONITORING SYSTEM

Calibration and monitoring play a key role in operating a system with more than 1600 PM's. All lead glass blocks are calibrated in an electron beam, yielding a set of "calibration coefficients" $E(e)/N(ADC)$. During data taking these coefficients can vary and the main aim of our optical monitoring system is to measure these variations. To do this we use a single powerful light source (a laser) together with a light distribution system adjusted to give approximately equal amounts of light to each counter. One of the advantages of this method is that it allows us to equalize the counter gains at a 10-20% level before using a beam. For the finger counters of the FGD position detector this equalisation is sufficient to obtain the wanted spatial precision and it is crucial for

speeding up the beam calibration of the IGD. The laser itself is monitored for long-term variations by using a stable reference system.

We show in sect. 6 that the system allows us to calculate adequate corrections to the calibration constants two months after an electron beam calibration up to now.

5.1 Description of the monitoring system

The central light source is a type FL105 dye-laser pumped by a type K600 nitrogen ultraviolet pulsed laser^(*). Their general characteristics are listed in table 1. The main features are:

- (a) The short duration of the pulses (~ 4 ns) and the wavelength (410-460 nm with stilben-3 dye) which approximate as well as possible the Cerenkov light in the lead-glass blocks.
- (b) The large power output which allows to choose a simple, uniform light distribution system and to simulate showers of at least 50 GeV in each block.

The laser light is distributed to the different counters via a system of optical fibres which is shown schematically in fig. 8. The first element following the laser is a mixing chamber developed by LCT^(**) to destroy the speckle caused by the coherence of the laser light. This speckle would make it impossible to have a uniform distribution of the light in the optical fiber system. The complexity of the light propagation paths in the mixing chamber produces both the destruction of the coherence and a good uniformity. The intensity loss in the mixing chamber is about a factor of 20.

The distribution system is characterized by a two stage cascade. In the first stage seven long fibres are drawn from the mixing chamber, four to the IGD, two to the FGD and one is kept as a spare. Each of them ends

(*) Both lasers from LAMBDA PHYSIK, Göttingen, Germany.

(**) Laboratoire Central de Télécommunications, Paris, France.

in a distribution box where the light is distributed to the second stage consisting of shorter fibres which go to the individual counters. These fibres are grouped in "stars" containing 30 to 50 arms.

Since the main fibres have lengths of up to 75 m, low attenuation type QSF400A quartz fibres by Quartz and Silice^(*) are used. Their main characteristics are given in table 2.

The fibres used for the second stage have lengths between 2.5 and 4 m. Since attenuation is less important here we chose type SI100 glass fibres by Quartz and Silice^(*). Besides their moderate price they offer the advantage of being easy to polish. Their main characteristics are also given in table 2.

The distribution boxes which couple the two stages of the distribution chain are designed to give optimal uniformity of light to the output stars. The stars are positioned in a conical arrangement at a fixed angle α with respect to the box axis (fig. 9). There are six output stars at $\alpha = 4^\circ$ in the FGD distribution boxes and nine stars at $\alpha = 5^\circ$ in the IGD distribution boxes. In addition, a single 5 mm diameter fibre at $\alpha = 0^\circ$ connects each box to a photodiode which is used to measure the intensity of each flash as will be discussed later.

The light intensity profile as a function of α , coming from a QSF400A fibre, has been measured at ~ 20 cm from the fibre exit. Its FWHM, $2\alpha = 20^\circ$, agrees with the numerical aperture as given by the manufacturer in table 2. The shape is approximately gaussian. It has been checked that this profile is insensitive to movements of the laser beam at the input of the mixing chamber and to moderate changes of the bending radius of the fibre.

The output intensity of each SI 100 fibre is 10^{-6} to 10^{-5} of the output intensity from the primary fibre. Within this range, adjustments are possible by varying the distance of the "star" from the main fibre exit (from 6 to 20 cm). The fabrication of SI 100 fibre stars^(**) has been

(*) Quartz and Silice, Pithiviers, France.

(**) J. Laaber, Rüsselsheim, Germany.

carefully controlled and the r.m.s. variation of the output intensities in each star is typically 3 to 5%. The final spread in the counter PM's is larger because of the coupling pieces between the fibres and the lead glass blocks.

Early tests showed that the best approximation to the Cerenkov light is obtained by injecting the light at a wide angle with respect to the glass block axis. The IGD coupling pieces (fig. 7) consist of a plexi-glass cylinder cut at an angle of 45° , glued to the face opposite to the PM and painted white on all open sides. The FGD coupling pieces are prismatic, and are also painted white on all open sides. They are mounted opposite to the PM's for the absorber blocks and on one of the long sides perpendicular to the PM for the converter blocks. The hodoscope fibres enter parallel to the axis of the "fingers" on the side opposite to the PM's.

5.2 The reference system

A light intensity reference system is necessary to monitor the long-term variations of the laser light intensity, which can arise from different causes such as the ageing of the dye, a change in the primary laser beam output, instabilities in the HV settings, "breakdowns", etc.

For this purpose we have designed and installed two "absolute" light sources, but it turned out that we could also measure the absolute intensity of each laser flash by means of high stability vacuum photodiodes. This last method is particularly useful since it allows correction also of the fluctuations between successive pulses. Therefore, all our stability results are based on this method and the "absolute" sources were used only as a cross check.

The photodiodes are EMI PD1900 whose characteristics are listed in table 3. One such photodiode is used for each distribution box, to which it is connected by a large diameter multicore fibre as already mentioned. The amount of light transmitted by the fibre is kept to a value low enough to produce a peak output current from the photodiode smaller than $20 \mu\text{A}$, which ensures that the luminous flux on the diode is well below the level which would cause fatigue. The signal is then amplified and sent to an ADC channel.

As already mentioned this method allows not only long-term stability monitoring but also the correction for short-term fluctuations of the laser output. The normalized distribution of the laser signals for a "healthy" PM has a FWHM of 2% for the FGD absorber, providing an efficient tool for the debugging of the detector.

The first "absolute" reference source uses the Cerenkov light emitted by relativistic particles in a plexiglass truncated cone, with 6° aperture, 40 cm long and with the larger face glued to a 3" PM (RCA 8051). The cone shape was chosen to guarantee a high efficiency for the collection of the Cerenkov light by total internal reflection. The output signal distribution has a FWHM of 10%.

The second "absolute" source made use of the signals produced by the decay photons from a CO^{60} source in a large NaI crystal.

6. PERFORMANCE

In this section we discuss the performance of our set of counters in terms of energy resolution, spatial resolution and stability.

6.1 FGD

The FGD was, on several occasions, exposed to a 50 GeV negative beam containing $\approx 3\%$ of electrons. These were identified by a CEDAR gas Cerenkov counter. An average of 1000 showers were collected for each counter, with a beam of section $2 \times 2 \text{ cm}^2$ onto the centre of each absorber block in turn. This entire calibration only takes a few hours.

We compute the calibration constants of the absorber block hit by the beam and of the converter block in front by the method described by Appel et al. [4]. It consists in taking a linear combination of the converter and absorber block outputs for each shower and finding those coefficients which minimize the width of the distribution of this linear combination.

To reduce the systematic effects in the PM responses to the 1% level, the rate-dependence of the gains should in principle be corrected for. For

the RCA 8055 used in the FGD, this effect is completely negligible with the low beam flux (10^4 /s) used during the EHS experiment. For this reason, no selection of the PM's was made. During calibration though, relatively high fluxes ($> 10^5$ part/s) on single counters were used to speed up the operation and the PM gains did, on the average, show an increase of a few percent during the spill. Bench tests using LED flashes have shown that the time interval between two spills (≈ 8 s) is long enough for the gain of the PM to go back to the rest condition.

We took advantage of the high resolution of the system for the e^- signals (the FWHM at 50 GeV is $\approx 3\%$) to extrapolate to low flux the gain of each PM. Fig. 10 shows the signals of the e^- showers in a particular counter plotted as a function of time, time zero being the beginning of the spill. The contributions from several spills were merged together to improve the statistics, and the gain at zero flux was extrapolated using a simple linear fit.

A more reliable method was to collect samples of 100 laser flashes during the spill, while the counter was exposed to the calibration beam. Since such flashes are uniformly distributed in time and their intensity distribution is only 2% in FWHM (sect. 5.2) the extrapolation is more precise. During the experiment this procedure was, for practical reasons, only applied to a fraction of the counters. The results of the two methods, when available, agree at the 1% level. The average increase in gain during the spill with 10^5 part/s was found to be 3% and in no case exceeded 7%. The laser signal also allows one to check on the reliability of the extrapolation procedure, by comparing the amplitudes obtained with and without the beam hitting the counter (fig. 10(b)).

The average FWHM of the measured energy with 50 GeV electrons is 3.5%. The calibration runs took place with the small lexan bubble chamber LEBC installed in the beam line and with other material (plastic counters, etc.) degrading the quality of the electron beam. Earlier tests with a clean beam of the same energy had given an average FWHM of 2.7%. Samples of data at 40, 100 and 150 GeV were also collected after the end of the experiment, using an electron beam centred on a set of 16 blocks in the

m	α_m	β_m
0	7.74×10^{-2}	0
1	-9.97×10^{-3}	-1.38×10^{-1}
2	-2.82×10^{-3}	-3.28×10^{-2}
3	-8.99×10^{-4}	-1.00×10^{-2}
4	-2.93×10^{-4}	-3.24×10^{-3}
5	-9.61×10^{-5}	-1.06×10^{-3}
6	-3.16×10^{-5}	-3.48×10^{-4}
7	-1.04×10^{-5}	-1.14×10^{-4}
8	-3.41×10^{-6}	-3.75×10^{-5}

The largest error in this approximation was found to occur at $m = \pm 1$:

t (μ s)	r_Q/s	Error in Q_1 (%)	Error in $\dot{Q}_1$ (%)
0.2	0.043	0.3	2
1.0	0.096	1	10

Pulse calculations for $0 \leq t \leq 220 \mu$ s were carried out using two different initial angular distributions of ions around the wire $z_0 = 0$: i) the delta-function distribution in which the entire charge Q leaves the wire at the same angle α , ii) the Gaussian distribution specified by

$$\omega(\theta) = (2\pi\sigma^2)^{-1/2} \exp \{-(\theta-\alpha)^2/2\sigma^2\}, \quad \sigma = 30^\circ.$$

For the Gaussian distribution, the integration over θ was performed numerically using a 16-point Gauss quadrature formula for each of the angular sub-intervals $[0, \alpha_L]$, $[\pi - \alpha_L, \pi]$, $[\pi, \pi + \alpha_L]$, $[-\alpha_L, 0]$. The discretization parameter N (appendix, section A4) was set equal to 16.

Fig. 5 shows the induced charges on the three central wires, with $Q_0 + Q$ and $\hat{Q}_0 + Q$ plotted instead of Q_0 and $\hat{Q}_0$ in order to ensure zero charge at $t = 0$. Fig. 6 shows the corresponding currents, plotted with reversed sign in order to give the voltage polarity which would be observed across a finite impedance. Fig. 7 shows the right-left differences $Q_1 - Q_{-1}$, etc., plotted with the same convention.

Fig. 8 shows the induced charge and (sign-reversed) current on a cathode strip running parallel to the wires and bounded by the x interval $[-s, s]$. All

coordinates and an empirical formula for the lateral development of the shower^(*). Fig. 13(b) shows the distribution of the effective masses of all pairs of showers for a sample of events collected during our experiment. The 7 MeV standard deviation of the mass distribution is in agreement with the energy and spatial precision obtained in the calibration with the electron beam. This shows that the precision found for individual counters is preserved with good uniformity for the whole detector.

In the FGD hodoscope two showers are separated if they are distinct on at least one plane. Given the shower width of 1.3 cm (r.m.s.) and the finger size, two showers are resolved on one plane if their separation is larger than 3 cm. This allows one to see the two photons from a 300 GeV π^0 . There is, therefore, no need to analyse the shower shape to disentangle overlapping showers.

6.2 IGD

The IGD was calibrated in a 40 GeV/c negative beam with an electron content of $\sim 20\%$. A rough equalization of the PM gains was obtained using the monitoring laser.

A clean narrow electron beam was obtained using the CEDAR Cerenkov counters and small scintillators: the result was a pencil-beam of about 10 mm in diameter and with an electron yield of the order of 200/spill (for a beam intensity of 5×10^4 particles/s).

As can be seen in fig. 14, the fraction of the incident electron energy absorbed in a counter is dependent on the impact position relative to the centre of the block, except within a few millimeters around the centre. One method of calibration would be to centre a narrow electron beam on each individual counter in turn and the energy thus detected would be directly proportional to the counter sensitivity. An absolute normalization could be made later e.g. by centring the π^0 peak to its nominal value. Though used widely such a method has several drawbacks in

(*) A more detailed description of the software procedures used for the reconstruction of the showers is in preparation.

our case due to the large number of counters. For example, one would need to reduce the beam size to the millimetre range without increasing the beam intensity (to avoid rate-dependent variations of the PM gains). Since high statistics are needed to have a well defined peak position, such a method would be very time-consuming and impracticable for large sets of counters (~ 15 h of effective beam time in our case).

We have calibrated the IGD using an "in-flight" method: the detector was continuously moving across the beam with a speed such that each counter "sees" a few hundred showers. This allows the use of a wide beam and the time for the calibration of the entire detector goes down to approximately six hours of beam time. An obvious drawback of the method is the more complicated off-line analysis of the calibration data. In this case the calibration coefficients α_i are the solutions of the set of linear equations

$$\frac{\partial}{\partial \alpha_i} \left[\sum_j (\sum_i A_{ij} \alpha_i - E)^2 \right] = 0,$$

where E is the incident electron energy (assumed to be constant), A_{ij} the measured amplitude, the index i is to the counter number ($i = 1 \dots 1122$) and j is the event number. If the number of counters, n , were not too large, the straightforward approach to the solution of the equations would be the inversion of an $n \times n$ matrix. For large n (as in our case) the computer memory size becomes a critical parameter but inversion is still feasible if one makes use of the fact that most elements of the matrix are equal to zero. Other possible methods consist of dividing the detector in smaller subsets or in using more sophisticated iterative minimization procedures. These methods were used independently to compute the calibration coefficients and found to give comparable results. A few hundred showers per counter are enough to give calibration coefficients stable to within 1%.

A special treatment had to be applied to the counters situated on the edges of the detector. For these, only the showers more than 25 mm from the edges were used for the calibration and the resulting coefficients had to be corrected afterwards for a systematic bias of $\sim 2.5\%$ (computed from a similar analysis using some of the inner counters).

A2. THE SYMMETRIC CHAMBER WITH $L > s$

We summarize here some properties of the electrostatic field of a symmetric multiwire chamber whose complex potential may be represented to sufficient accuracy by (25). The physical potential is

$$V(z) = cV_0 \{ (2\pi L/s) - 2 \ln |2 \sin (\pi z/s)| \} , \quad (26)$$

and the equation ($\text{Im } \psi = \text{constant}$) of the field line which leaves the origin at angle α is

$$\arg \{ \sin (\pi z/s) \} = \alpha , \quad (27)$$

or equivalently,

$$\frac{\tanh (\pi y/s)}{\tan (\pi x/s)} = \tan \alpha . \quad (28)$$

Using (26) and (27), the equation of this field line can be written as

$$\sin (\pi z/s) = \xi^{1/2} e^{i\alpha} , \quad (29)$$

where

$$\xi = \frac{1}{4} \exp \{ (2\pi L/s) - (V/cV_0) \} .$$

To express (x,y) in terms of (V,α) for the purpose of field plotting we solve for z in equation (29) to obtain

$$\begin{aligned} x &= (s/\pi) \arcsin \{ (\xi - \eta + 1)/2 \}^{1/2} \\ y &= (s/\pi) \operatorname{arcsinh} \{ (\xi + \eta - 1)/2 \}^{1/2} , \end{aligned}$$

where

$$\eta = \{ (\xi - 1)^2 + 4\xi \sin^2 \alpha \}^{1/2} .$$

The calculation of (x,y) in terms of (V,α) for a symmetric chamber which is not necessarily subject to the restriction $L > s$ is discussed by Tomitani [6].

If an ionizing particle, moving in a straight line parallel to the y -axis, crosses the chamber at distance X from the origin (where $|X| < \frac{1}{2}s$), each electron released on the track will move towards the wire $z_0 = 0$ along a field line specified by an equation of the form (28). If the density of ionization along the track is uniform, the number of electrons approaching the origin between angles α and $\alpha + d\alpha$ will be proportional to $(\partial y/\partial \alpha) d\alpha$, where from (28),

$$\frac{\partial y}{\partial \alpha} = \frac{(s/\pi) \sin(2\pi X/s)}{\cos 2\alpha + \cos(2\pi X/s)}.$$

Very close to the wire, this angular distribution is likely to be blurred by the presence of avalanche electrons. The angle α is limited to the range $|\alpha| \leq \alpha_L$, $|\pi - \alpha| \leq \alpha_L$, where α_L is obtained by setting $x = X$ and $y = L$ in (28).

A3. SOLUTION OF THE DRIFT EQUATION $\dot{z} = \mu E$

The differential equation (13) which describes the drift motion of the ions in the chamber region can be written as

$$\dot{z} \sin(\pi \bar{z}/s) = \beta \cos(\pi \bar{z}/s) \quad (30)$$

where

$$\beta = 2\pi \mu c V_0 / s.$$

Taking the real part of (30) gives

$$\dot{x} \tan(\pi x/s) + \dot{y} \tanh(\pi y/s) = \beta,$$

or

$$\frac{d}{dt} \left[\ln \left\{ \frac{\cosh(\pi y/s)}{\cos(\pi x/s)} \right\} \right] = \frac{\pi \beta}{s}.$$

Imposing the condition $x = y = 0$ at $t = 0$ gives

$$\frac{\cosh(\pi y/s)}{\cos(\pi x/s)} = e^{\pi \beta t/s}. \quad (31)$$

Eliminating first y , then x , between (31) and (28) leads to the expressions (14) for x and y in terms of t and α .

A4. SOLUTION OF THE CONVOLUTION EQUATIONS

If we define the Fourier series

$$A(\theta) = \sum_m a_m e^{im\theta}, \quad C(\theta) = \sum_m c_m e^{im\theta}, \quad U(\theta) = \sum_m u_m e^{im\theta}, \quad (32)$$

where the summation is from $m = -\infty$ to $m = +\infty$, the system of convolution equations

$$\sum_m a_{k-m} u_m = c_k, \quad -\infty < k < \infty, \quad (2)$$

is seen to be equivalent to the relation $A(\theta)U(\theta) = C(\theta)$. Therefore, provided $A(\theta) > 0$ for all θ (for which it may be shown that a sufficient condition is $1 \leq L/s \leq s/2\rho$), the solution of (2) is

Two sets of calibration data for FGD, separated by about seven weeks, allow one to investigate the long-term stability. The ratios of the calibration coefficients for the two data sets for each counter are shown in fig. 20(a). Differences of up to 10% can be seen (mainly due to changes made to the HV settings). Fig. 20(b) shows the same quantity but where the monitoring results have been used for corrections. The r.m.s. of the distribution is 1.3%. Thus, by using, for each run period, calibration coefficients interpolated between the two sets of values, one obtains the desired 1% stability.

For practical reasons, the long-term stability and the quality of the monitoring system could be checked for only a small set of IGD counters. For this we used data from two calibration runs separated by two weeks. In the meantime, the gains of some counters were modified up to a factor of two. Nevertheless, using the same calibration coefficients for both runs and correcting them by the monitoring procedure described above, a shift of only 2% was found in the measured energy distribution. This shift was an overall shift for all counters, and can probably be explained by a deterioration of the beam.

7. SUMMARY

We have described the two lead-glass electromagnetic calorimeters, IGD and FGD, used in the CERN European Hybrid Spectrometer and we have reported on the performance obtained during the first experiment made in 1980. We have also given a detailed description of the monitoring system which uses a laser for the central light source.

The energy resolutions obtained are well described by the formulae

$$\Delta E/E = .10/E^{1/2} + .02 \text{ for FGD (FWHM),}$$

$$\Delta E/E = .15/E^{1/2} + .02 \text{ for IGD (FWHM).}$$

The spatial precision (r.m.s.) for FGD and IGD is respectively 2.5 and 3.7 mm in their respective energy ranges (~ 50 GeV and ~ 5 GeV).

The monitoring system allows the control and correction of short and long-term drifts in the gain. The system proved to be effective in speeding-up the debugging of the system and allowed us to correct the PM gains to a level of $\sim 1\%$ from one running period to another.

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TABLE CAPTIONS

- Table 1 General characteristics of the nitrogen and dye lasers used in the monitoring system.
- Table 2 Characteristics of the optical fibres used in the monitoring system.
- Table 3 Characteristics of the PD1900 photodiodes used for the monitoring of the laser output.

TABLE 1

Laser	Output power	Pulse duration (FWHM)	Repetition rate	Wave length
K 600	600 kW	~ 4 ns	1 - 200 Hz	337 nm
FL 105	60 kW	dito	dito	340 - 840 nm (depending on dye)

TABLE 2

	Material (core/cladding)	Diameters core/cladding/coating	Attenuation (at 600 nm)	Numerical aperture ($\sin \alpha$)	Opening angle 2α (FWHM)
QSF 400A	quartz/silicone	400/550/850 μ	13 db/km	0.18	20°
SI 100	glass/glass	100/150/900 μ	40 db/km	0.25	29°

TABLE 3

<p>Cathode to anode voltage: 30 V maximum 9 V typical</p> <p>Cathode current: 5 μA maximum</p> <p>Cathode current density: 25 μA/in² maximum average 500 μA/in² maximum peak</p> <p>Capacitance anode-cathode: 13 pF</p> <p>Drift stability: .5%/24 h (1 μA anode current) 1.0%/24 h (5 μA anode current)</p> <p>Temperature stability: .03%/°C (20°C - 50°C)</p>
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FIGURE CAPTIONS

- Fig. 1 General layout of EHS in its final version (as it will be by summer 1982). U, W and D indicate proportional and drift chambers, IH and FH are scintillator hodoscopes, ISIS a large ionization sampling drift chamber, M1 and M2 the spectrometer magnets, SAD and FC Cerenkov counters, TRD a transition-radiation detector, INC and FNC hadron calorimeters, IGD and FGD the gamma detectors.
- Fig. 2 General layout of the FGD.
- Fig. 3 Transmittance curves for the three types of lead-glass used in IGD (F8) and FGD (CEREN 25 and CEREN 32). The transmittance of the filters used is also shown. All curves are for 40 cm thick lead-glass and 3 mm filters.
- Fig. 4 Pulse height along the converter blocks (with and without the use of filters) as a function of the distance d between the shower and the PM.
- Fig. 5 Energy resolution in the FGD absorber blocks with and without the use of filters. The lines correspond to $\sigma(E)/\sqrt{E} = a+b/\sqrt{E}$.
- Fig. 6 General layout of the IGD.
- Fig. 7 Design of a single IGD counter showing the mounting of a PM with its individual magnetic shielding, and of an optical fibre.
- Fig. 8 Principle of the light distribution for the monitoring system.
- Fig. 9 The light distribution boxes of the monitoring system: i = input fibre, x = variable input-output distance, d = output star with 33 fibres, and a = adjustment screw.
- Fig. 10 Response of a single PM in FGD as a function of time during an accelerator spill: (a) for electrons and (b) for laser signals with ($\star$) and without ($\diamond$) the beam on the counter.

FIGURE CAPTIONS (Cont'd)

- Fig. 11 Linearity curve for the central part of the FGD.
- Fig. 12 FWHM versus energy in the FGD, with the bubble chamber in the beam line (x) and without (o).
- Fig. 13 The effective mass distributions of showers detected (a) in the IGD alone, (b) in the FGD alone, (c) in both detectors.
- Fig. 14 Ratio of the energy of an electron absorbed in the central block to the total energy, for the IGD counters. The data correspond to 5 GeV electrons; x and y are the coordinates in a plane perpendicular to the beam direction with $x = y = 0$ in the counter centre.
- Fig. 15 Measured energy distribution in the IGD for 40 GeV electrons.
- Fig. 16 Energy resolution obtained with the IGD prototypes at various energies. The straight line represents the formula $\Delta E/E = .15/\sqrt{E} \text{ (GeV)} + .02$.
- Fig. 17 Ratio of the amplitudes in two adjacent IGD counters (data taken with 5 GeV electrons) as a function of the impact coordinate.
- Fig. 18 Results of the parametrization for 5 GeV electrons (see text): (a) χ^2 distribution of the fit, (b) energy fit and (c) difference between actual and fitted coordinates. Solid lines are for the case with all detected amplitudes used, dotted lines when only six counters are used.
- Fig. 19 Spatial precision versus energy in the IGD.
- Fig. 20 Ratios of the calibration constants obtained in two calibration runs seven weeks apart for all FGD counters: (a) raw data and (b) data corrected with the monitoring signals.

FIG. 1

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FIG . 8

FIG. 9

FIG.10

FIG.11

FIG. 12

FIG. 13

Fig. 14

Fig.15

Fig. 16

Fig.17

Fig. 18

Fig. 19

second calibration coefficients
first calibration coefficients

FIG. 20