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A LARGE-AREA MODULAR ELECTROMAGNETIC SHOWER DETECTOR FOR THE
CERN INTERSECTING STORAGE RINGS

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SUMMARY

We describe the design and performances of a large-area (13 m^2) shower detector built for an experiment at the CERN ISR to detect electrons and gamma rays with energies up to 4 GeV. The main characteristics of the detector are: a) linearity of the energy response from 0.5 to 4 GeV; b) good energy, time, and space resolutions; c) modularity of the mechanical assembly; d) low cost of construction.

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1. INTRODUCTION

We have built a large-area shower detector for an experiment¹⁾ as the Split-Field Magnet (SFM) spectrometer of the CERN Intersecting Storage Rings (ISR). The physics aim of this experiment was to study p-p collisions with final states characterized by the presence of: a) electrons produced at large angles, and b) high transverse energy release.

The shower detector was used to provide:

i) at the trigger level

- a minimum energy release selection which, together with the requirement of Čerenkov light emission in two atmospheric pressure Čerenkov counters, allowed electrons to be selected with good efficiency and high rejection of pion background;
- a threshold energy selection which, without any other requirement, allowed triggering on high transverse energy release;

ii) at the off-line analysis level

- an adequate energy measurement both for gamma rays and electrons in the energy range (up to 4 GeV) of interest for the physics programme of the experiment;
- a further rejection against non-showering charged particles when comparing the energy measurement with the momentum evaluation given by the magnetic spectrometer.

2. DESIGN CONSIDERATIONS

The main parameters that we have taken into account in designing the detector were:

- a) the thickness of the radiator necessary to obtain an 80% shower containment at 4 GeV electron energy; from standard calculations²⁾, 8 radiations lengths, i.e. 4.5 cm of lead, are sufficient.

- b) the total sensitive area ($\sim 13 \text{ m}^2$) to be covered by the electromagnetic shower detector; this was determined by the aperture of the SFM magnet and by the minimum distance from the interaction point at which the detector could be placed;
- c) the optimum dimensions of each element of the detector, in order to keep the probability of two particles hitting the same element below 10%;
- d) the need to calibrate the energy response of the detector in an electron beam of known momentum before the installation at the ISR and, eventually, during shut-down periods; this condition implied the subdivision of the detector into self-supporting and mechanically independent modules which could easily be assembled into telescopes of different sizes;
- e) the cost per single module to be kept as low as possible, in view of the large number of elements (32) to be built.

3. DESCRIPTION OF THE BASIC MODULE

The basic module, shown in Fig. 1, has a sensitive surface of $200 \times 20 \text{ cm}^2$ and consists of a 1 cm thick lead plate followed by 10 layers of 1 cm thick scintillator interleaved with 9 lead plates each 0.4 cm thick. The light produced in the scintillator is collected at both ends through simple plexiglas light-guides by two 4-inch Philips 58 AVP photomultipliers. The thickness of the scintillator was chosen to be 1 cm since this thickness already implies an average of 200 reflections for the light propagating over a length of 2 m.

The scintillator is polymethyl methacrylate doped with naphthalene (1%), butyl-PBD (1%), and POPOP (0.01%) (POLIPOP)*). Although the light yield from POLIPOP is a factor of 5 less than from NE110 scintillator, results from a test on two equal prototype counters, shown in Fig. 2, prove that there is no considerable loss in energy resolution due to photostatistics. On the other hand, the use of POLIPOP was recommended by a factor of 5 saving in cost. In Table 1 the

*) POLIVAR, Pomezia, Italy.

cost of one module is expressed in terms of its major items (the electronics are not included); notice that the scintillator cost is more than 50% of the total.

Each scintillator plate, wrapped with aluminized mylar and protected by a light-tight plastic foil^{*)}, was assembled, together with alternate layers of lead, on a light mechanical support. The lead-scintillator stack was then tightly bound to the support by means of evenly spaced 0.4 mm thick metallic strips. This allowed the simultaneous machining and gluing of all plates to the light-guides.

Each light-guide, shown in the insert of Fig. 1, consists of a rectangular randomizer block which in turn is glued onto a cylinder which guides the light to the photomultiplier.

The dimensions of the randomizer, required to achieve a light-collection uniformity of $\pm 3\%$ across the counter, were determined by means of a simulation program (GUIDE 7)³⁾.

The construction of the module was completed by fixing to each end of the main frame an additional support to hold the photomultiplier, its magnetic shielding and basis.

In this way, each module, weighting 300 kg, could be easily handled for calibration and installed on the telescope main support.

4. CHARACTERISTICS OF A MODULE

The single module response to electrons and pions has been studied in detail in a CERN Proton Synchrotron (PS) test beam for momenta up to 4 GeV/c with the set-up shown in Fig. 3. Figure 4 shows the electronics associated with the sandwich module and the five quantities, three pulse heights and two time differences, digitized and recorded for each triggering particle.

*) Acella, Peyer & Co, Zürich, Switzerland.

4.1 Energy response

Figure 5 shows the peak value of the pulse-height distribution of a single photomultiplier anode signal (PM1, PM2) and of the passive sum of the two PM dynodes (DS) for electrons of energy up to 4 GeV hitting the centre of the counter. The response was linear with energy within 5%.

The corresponding energy resolution at the centre of the counter, as given by the DS signal, is shown in Fig. 6a.

The best fit to the experimental points is given by the following formula:

$$\sigma(E)/E = 0.025 \pm 0.15/(E)^{\frac{1}{2}} .$$

This value compares well with the design expectation based on the semiempirical formula⁴⁾:

$$\sigma(E)/E = 0.05 \frac{\Delta E^{\frac{1}{2}} (\text{MeV})}{(E)^{\frac{1}{2}} (\text{GeV})} ,$$

where ΔE is the mean energy loss per sampling step, ~ 9 MeV in our case.

The r.m.s. energy resolution does not depend on the hit position along the counter (see Fig. 6b).

4.2 π/e discrimination

The π/e discrimination has been measured for different energies of the incident particles. Figure 7a shows the typical pulse-height spectra for pions and electrons of 1 GeV/c momentum. Notice that the equivalent energy of the pion, independent of its momentum, is ~ 120 MeV.

The corresponding integral spectra are shown in Fig. 7b: with an electron detection efficiency of 90% the acceptance for pions is 2.8%.

The results on π/e discrimination at various energies are summarized in Fig. 8, where the pion acceptance is shown as a function of energy for fixed values of the electron efficiency.

4.3 Time and space resolution

The time difference between the beam signal and each of the two PMs signals (corrected for time-slewing effects) is shown in Fig. 9 for electrons of 1 GeV/c momentum.

The sum of these two times gives a time-of-flight (TOF) measurement which is independent of the impact position along the counter. The corresponding resolution is shown in Fig. 10a as a function of the electron energy: the r.m.s. resolution turns out to be ~ 0.32 nsec, fairly independent of energy. The time resolution was also found to be independent of the hit position along the counter (see Fig. 10b).

The difference of the time measurements relative to the two PMs gives the hit position along the counter, as shown in Fig. 11. The corresponding longitudinal position resolution for different electron energies is shown in Fig. 12a: above 2 GeV the r.m.s. resolution is ≤ 2 cm, while below this energy it is slightly worse. This position resolution figure is found to be constant along the counter (see Fig. 12b).

4.4 Dynamic range

The operational dynamic range of the detector was determined by:

- i) the value of the equivalent electron energy released by charged pions passing through the counter (it was used to monitor the stability of the detector during data taking);
- ii) the value of the maximum measurable electron energy;
- iii) the value of the trigger energy cut-off.

The first two conditions already implied a linearity range of 40. Moreover, the light attenuation along the counter, shown in Fig. 13, gave another factor of 4 to 5 to the single photomultiplier anode signal variation.

The best solution found for confronting these rather severe requirements, both from the point of view of the PMs linearity range and of the analog-to-digital converters (ADCs) sensitivity, was the use of the electronic chain shown in Fig. 4.

The single PM anode signals cover a low-energy range (from below the pion peak up to the 1 GeV electron peak) over the full counter length, while the passive sum of the 14th dynodes from the two PMs covers the high energy range up to 4 GeV at the extremities of the counter (see Fig. 13).

4.5 Stability

The gain stability of commercial 58 AVP photomultipliers (PM) as a function of the particle rate was studied with measurements in the laboratory. The PM was illuminated by a light-emitting diode driven by a nanosecond pulse-generator of variable frequency, and the anode response was recorded with an ADC. The gain stability test consisted of a series of short measurements at fixed frequency.

The frequency was increased starting from 100 Hz up to 10^5 Hz and then decreased back to 100 Hz. Gain variations were observed still at relatively low frequencies of $\lesssim 10^4$ Hz corresponding to a d.c. anode current of the order of 1 μ A. In Fig. 14a the behaviour of two typical PMs, one "stable", the other "unstable", is shown: the full line guides the eye through the successive measurements. Decreasing the frequency (dashed line in the figure) the gain did not recover to the previously measured values. A time of the order of $\frac{1}{2}$ hour was needed to recover the original gain at 100 Hz. This effect is particularly dangerous at the ISR, where beam losses can cause large changes of the instantaneous rate in the counters.

The result of the measurement was that, in order to achieve the necessary PM gain stability over the required dynamic range and for a particle rate of $\sim 10^4$ /sec (as expected in the ISR experiment), the PM current had to be kept low. This was incompatible with the gain needed to match the sensitivity of commercially available ADCs and discriminators. Therefore, fast linear amplifiers^{*)} with a gain factor of 10 were added on both PM1, PM2 signals and on the DS signal. Figure 14b shows the behaviour of the same PMs of Fig. 14a working in this condition of lower gain. The gain stability is better than 2% for all PMs up to frequencies of 0.5×10^5 Hz.

*) LSR 612A

5. CALIBRATION OF THE 32 MODULES

Results from the detailed study of a prototype module have shown that its response, as measured by the ADCs, could be expressed as a function of energy and position in the following form:

$$\psi_i(x, E) = f_i(x) \cdot g_i(E) ,$$

where i runs from 1 to 3 for PM1, PM2, and DS, respectively. This factorization was not imposed *à priori* but derived from the analysis. The position dependence was first fitted at fixed energy to the sum of two exponentials; $g_i(E)$ was then determined by simultaneously fitting the data for all energies. The energy behaviour was found to be linear

$$g_i(E) = a_i + b_i \cdot E ,$$

where $b_{i\text{th}}$ represents the over-all gain of the electronic chain associated to the $i\text{th}$ signal.

On the basis of these considerations we established a standard calibration procedure which allowed the above-mentioned parameters for the 32 modules to be determined with adequate precision. In particular, for each module we measured:

- i) the PM1, PM2 and DS energy dependence (from 0.5 GeV up to 4 GeV) at the centre of the counter and at both ends;
- ii) the equivalent energy of charged pions;
- iii) the PM1, PM2 and DS attenuation curves for 1 GeV/c electrons and pions.

The reproducibility of the counter characteristics is shown in Figs. 15a,b for the light attenuation and the energy measurement resolution, respectively.

6. MONITORING AND PERFORMANCE AT THE ISR

In the already mentioned¹⁾ ISR experiment, the 32 modules were vertically assembled into four telescopes of 10, 6, 6, and 10 modules, respectively. Each telescope was equipped with two scintillator counters (15 cm wide) to be used for the detection of penetrating particles. These counters were mounted on the back of each telescope at half height and matched its full horizontal width.

The electronics associated with each module (described in Fig. 4) were placed in the experimental area close to the PMs. The five signals of each module arrived at the counting room through 70 m of RG213 50 Ω cables. The presence of two shapers close to the PMs turned out to be necessary in order to reach the time resolution figures obtained in the PS test runs. Furthermore, in order to apply an energy cut at the trigger level, the two anode signals were resistively split into three parts: 30% of the signals were used for the ADC's; 60% and 10% were used for the electron and high-energy release triggers, respectively.

During data taking, the stability of the over-all electronic chain was monitored by triggering on penetrating particles crossing the central part of the counters. The peak value of the pulse-height distributions for each PM signal and for the DS signal were compared with the corresponding values obtained during the PS calibration runs.

On the other hand, the possible variations of the optical properties of the modules, due to their exposure to high radiation in the ISR tunnel, could be studied off-line after reconstruction of charged particle tracks in the SFM spectrometer.

The attenuation curves measured in the calibration runs (see, for example, Fig. 13) were found to be well reproduced within $\pm 5\%$.

To illustrate the performance of the shower detector, we show in Fig. 16 the π^0 mass spectrum obtained by requiring two neutral energy clusters in two adjacent sandwich telescopes. The mass resolution found ($\sim 13.1\%$) agrees well with the expectations. Figure 17 shows a comparison between the electron energy as measured by the shower detector, and the momentum of the reconstructed electron track as given by the SFM spectrometer. Notice the small pion contamination left after the Čerenkov selection.

The space resolution for electrons obtained by plotting the difference between the vertical coordinate of the hit point determined by geometrical reconstruction and the vertical coordinate derived from the time difference of the two PMs signals

is shown in Fig. 18a. Its r.m.s. value (3.4 cm) compares well with the space resolution found in the test runs (≤ 3 cm), once the accuracy in the track extrapolation and the multiple scattering is taken into account.

Figure 18b finally shows the TOF resolution relative to identified electrons of 1 GeV mean energy. In the experiment, the start signal -- given by hodoscopes of scintillation counters specially dedicated to the TOF measurement of charged particles -- had a r.m.s. resolution of 0.3 nsec. The r.m.s. time difference between the sandwich and the TOF counters, 0.42 nsec in Fig. 18b, is therefore consistent with the intrinsic time resolution of the sandwich as measured in the test beam.

7. CONCLUSIONS

We have built an electromagnetic shower detector of the lead-scintillator sandwich type, whose characteristics are summarized in table 2. It is a good example of economic design of a large-area electromagnetic shower detector for medium energies (0.5 + 4.0 GeV) having the following qualifying characteristics: i) energy resolution close to the theoretically best expectation; ii) high resolution in time and adequate resolution in space; iii) good π/e separation.

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Table 1

Detail of the cost of one module (excluding electronics)

Item	Cost in 1978 Swiss francs
Scintillator (POLIPOP)	1,800
Lead plates (machined)	590
Plexiglas light-guides	520
Wrapping materials (Mylar, Acella)	190
Mechanics	320
TOTAL	3,420

Table 2

Sensitive area	13 m ²
Thickness	8.2 radiation lengths
Sampling	4 mm of lead
Energy resolution	$a + b \sqrt{E(\text{GeV})}$ with $\langle a \rangle = 0.03$ $\langle b \rangle = 0.14$
2 γ invariant mass resolution	$\leq 13\%$ (1 σ) for $E_\gamma > 800$ MeV
Linearity	Better than 5% (up to 4 GeV of electron energy and pion rates of 10 ⁴ sec ⁻¹)
Uniformity	Better than 3% over the full surface
Energy deposit of 1 GeV electrons	~ 8 times a minimum ionizing particle
π/e discrimination at 1 GeV	$\leq 3\%$ of π for 90% electron efficiency
Space resolution (along the counter)	$\Delta x \leq 2$ cm (1 σ) for $E \geq 2$ GeV
Time resolution	$\Delta t < 0.32$ nsec (1 σ) for $E \geq 1$ GeV

Figure Captions

- Fig. 1 : Front and side views of the basic module showing the supporting structure. The insert show the assembly of the lead-scintillator sandwich and of one light-guide. (All dimensions are in millimetres).
- Fig. 2 : Comparison of two lead-scintillator prototypes sandwiches with equal sampling but different scintillator ($\circ$ = POLIPOP, + = NE110).
a) Pulse-height response as a function of the electron beam momentum.
b) Energy resolution as a function of the electron beam momentum.
- Fig. 3 : Layout of the experimental set-up used for the tests at the CERN PS;
 C_1, C_2 = Čerenkov counters, T_1, T_2, T_3 = beam-defining counters,
PT = punch-through counter, SW = sandwich counter mounted on a movable chariot.
- Fig. 4 : Scheme of the linear electronics associated with one module.
- Fig. 5 : Peak value of the pulse-height distribution of a single photomultiplier anode signal (PM1) and of the passive sum of the two PMs 14th dynodes (DS), as a function of the electron energy when the counter is hit at its central position ($x = 100$ cm).
- Fig. 6 : Showing the energy resolution given by the DS signal:
a) as a function of the electron energy in the central position of the counter;
b) as a function of the position along the counter for 1 GeV electrons.
- Fig. 7 : a) Typical DS pulse-height spectra for pions (shaded area) and electrons of 1 GeV/c momentum, hitting the counter at its centre.
Notice that the pion peak data (ADC values < 20 channels) have been plotted with a bin width of two channels instead of five channels.

b) Integral electron spectrum of Fig. 7a compared with the tail of the pion integral spectrum (expanded scale), showing how the π/e discrimination was calculated.

Fig. 8 : Pion contamination as a function of energy for fixed values of the electron detection efficiency.

Fig. 9 : Typical time-of-flight distribution of the anode signals PM1 and PM2 for 1 GeV electrons in the centre of the counter.

Fig. 10 : Time-of-flight resolution for electrons obtained by averaging the time information of both PMs:

- a) as a function of the electron energy at the centre of the counter;
- b) as a function of position for 1 GeV electrons.

Fig. 11 : Showing the linear relation between the beam impact point along the counter and the time difference of the two PMs.

Fig. 12 : Space resolution for electrons, obtained by the time difference of the two PMs:

- a) as a function of the electron energy at the centre of the counter;
- b) as a function of position for 1 GeV electrons.

Fig. 13 : Showing how the dynamic range of the ADCs was covered by the three analogic signals; the curves refer to PM1 and PM2 signals for 1 GeV electrons and to the DS signal for 1 GeV and 4 GeV electrons.

Fig. 14 : Typical behaviour of two 58AVP photomultipliers' gain as a function of the rate:

- a) high-tension working values;
- b) low-tension working values and a linear amplifier addition to the electronic chain.

- Fig. 15 : Statistics obtained from the calibration data of the 32 modules for
- a) the measured attenuation length;
 - b) the energy resolution for 1 GeV electrons.
- Fig. 16 : The invariant mass spectrum of pairs of gammas detected in the sandwich telescopes.
- Fig. 17 : Comparison between the electron energy measured by the shower detector and the momentum of the electron track given by the SFM spectrometer. Two atmospheric pressure gas Čerenkov counters, placed between the intersection region and the shower detectors, were used to select the electron candidates.
- Fig. 18 : a) Space resolution obtained as difference between the impact point of the electron reconstructed track and the position evaluated by the two PMs time difference.
- b) Time-of-flight resolution obtained at the ISR for identified electrons.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

a)

b)

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18