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A HADRON CALORIMETER WITH WAVELENGTH SHIFTER READ-OUT

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ABSTRACT

We report the results of a performance test of a fine-sampling copper/scintillator calorimeter with wavelength shifter read-out. The optimization of the optical read-out system is described in some detail. The linearity and resolution of the calorimeter obtained with electrons and hadrons in the momentum range 2-10 GeV/c are discussed.

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1. INTRODUCTION

The present paper describes a series of tests of a fine-sampling copper/scintillator calorimeter at the CERN Proton Synchrotron (PS). A detailed description of the optimization of the optical read-out system is given.

The calorimeter consisted of three modules designed to be part of a large calorimeter for an experiment at the CERN Intersecting Storage Rings¹). The performance of these modules has been investigated with electron and hadron beams at different momenta up to 10 GeV/c.

2. THE SET-UP

The measurements were carried out in the d_{31} beam at the CERN PS, where the maximum rates are $\sim 10^6$ (10^5) positive (negative) particles per burst (300 ms). The maximum obtainable momentum is 10 GeV/c. The electron rate is normally below 1%; however, for the duration of the tests a lead converter was placed immediately after the target, ensuring rates of ~ 100 electrons per burst up to 7 GeV/c.

The set-up, shown schematically in fig. 1, consisted of three copper/scintillator units mounted side by side on a device permitting movement in the horizontal direction and rotation around a vertical axis. The beam definition was provided by the narrow counter C_A ($20 \times 150 \text{ mm}^2$) and the counter C_B in front of the calorimeter. The electron tagging was done by means of two Čerenkov counters. Muon definition was obtained by placing a counter C_C immediately after the calorimeter and another C_D behind an 80 cm thick iron wall.

For each event, a 46-channel finger hodoscope H provided the hit-pattern information. The total width of the hodoscope was 138 mm.

3. THE MECHANICAL DESIGN

Each of the three identical calorimeter units had the appearance of a rectangular box, the dimensions being 214 mm wide, 500 mm high, and 1336 mm deep (in the beam direction); hence the total calorimeter area facing the beam was $642 \times 500 \text{ mm}^2$.

A horizontal section through one of the calorimeter units is shown in fig. 2. The absorber volume consisted of alternating 5 mm thick copper plates and 2.5 mm thick acrylic scintillator plates; in total, 100 cells. The distance between two consecutive copper plates, 3 mm, was ensured by five brass spacers, located in holes in the scintillator plates. Four of these spacers were cylindrical (o.d. 10 mm) positioned close to the corners of the calorimeter unit, whilst the fifth spacer of each cell had the shape of a washer (o.d. 14 mm) surrounding the central rod.

The purpose of this rod was to constrain mechanically the assembly of the copper and the scintillator plates. To allow, at the same time, for location of a radioactive source intended for calibration of the unit in the final set-up, the rod was made hollow, using a stainless-steel tube (i.d. 6 mm, o.d. 10 mm).

The light-collection system, described in detail in Section 4, consisted of BBQ-doped acrylic wavelength shifter (WLS) sheets, 2 mm thick, entirely covering both side-surfaces of the absorber volume, and acrylic lamella light-guides glued to their back edges for directing the light towards the photomultiplier (PM) tubes. The aluminium I-shaped profile at the back of the calorimeter unit served as a rigid structure for the assembly, and carried the two 1.5" PHILIPS XP 2008 UP photomultiplier tubes with their magnetic shielding, designed for the final use of the calorimeter in a magnetic field up to 0.1 tesla. The outer walls of the box were made of 1 mm thick stainless-steel sheets and a 20 mm thick aluminium front plate. All corners were covered with black tape for light-tightness.

4. THE OPTICAL READ-OUT SYSTEM

The optical system for the copper/scintillator modules was determined by the requirements of the big calorimeter, of which they are a part. The large amount of scintillator needed (18 tons) called for an economic solution. Acrylic scintillator, as used by Kienzle et al.²⁾, is economically attractive but has a rather low light yield compared to the more expensive aromatic scintillators. Generally speaking, the efficiency of energy transfer to the primary scintillating agent is low for scintillators based on PMMA (polymethyl methacrylate). As shown in fig. 3,

the light yield can be improved by adding certain aromatic components, e.g. naphthalene to the material. Unfortunately, an increasing fraction of naphthalene tends to gradually spoil the excellent mechanical properties and ruggedness of acrylic. The mechanical insensitiveness is a particular advantage of acrylic glass products as compared to aromatic scintillators. After a series of tests, we selected a composition of PMMA and 10% naphthalene doped with 1% butyl-PBD as primary scintillating agent, as a reasonable compromise between light yield and mechanical strength. There is no secondary agent, such as is commonly used to shift the light towards blue, since the emission spectrum of butyl-PBD has its peak at 368 nm, matching well the absorption of the BBQ used in the wavelength shifter (fig. 4). For many applications the strong self-absorption of such a UV-emitting scintillator would be unacceptable. In our case, however, because of the small cell width the attenuation is acceptable and permits a shower to be located by comparison of the signals read out on the two sides.

Wavelength shifters have only recently come into use for calorimeters, although the general principles of fluorescent-radiation converters for collecting light from scintillators have already been described extensively many years ago³⁾. We selected BBQ as the fluorescent chemical having an emission spectrum peaked at ~ 500 nm (see fig. 4)*). The concentration of this chemical has to be optimized in two respects: the absorption efficiency for the incoming scintillator light should be high, and the self-absorption for the re-emitted light which has to travel along the WLS towards the PM should be small. Both quantities rise with increasing concentration of BBQ.

An undesired feature of WLS plates is their sensitivity to Čerenkov light. When the shower develops near the edge of a calorimeter unit, part of it will extend into the WLS. The Čerenkov light produced by these leaking particles is converted by the fluorescence mechanism and cannot be distinguished from the "useful"

*) WLS plates doped with POPOP have also been tested. POPOP has a faster fluorescence decay time and its emission spectrum is better matched to standard photocathodes. Nevertheless, the resultant light yield is essentially the same as for BBQ-doped WLS because the absorption of POPOP matches badly the emission of butyl-PBD. Further problems arise from the fact that the POPOP absorption spectrum is located in the blue, making the device sensitive to Čerenkov light produced in the WLS plates.

scintillator light. If the fraction of signal due to Čerenkov light becomes significant, the uniformity of response of the calorimeter will be badly influenced. One obvious way to reduce this effect is to make the WLS-plate thin. The limit is given by the increasing number of internal reflections required for the light to reach the end of the plate -- reducing the transmittancy due to surface imperfections. Our measurements showed a significant increase of attenuation for plates of 1 and 1.5 mm thickness, compared with samples of 2, 3, and 4 mm. A further reduction of the Čerenkov effect was obtained by doping the WLS material with an ultraviolet absorbing chemical (UVA) -- absorbing part of the Čerenkov light before it is converted by the BBQ, as illustrated in fig. 5. Any light of wavelength shorter than the wavelength corresponding to the crossing point gets absorbed by the UVA. To some extent it is desirable that the UVA cuts off also the short wavelength components of the scintillator emission spectrum which are most strongly attenuated in the scintillator. In this way the uniformity of response near the edge of the calorimeter is improved, but at the expense of light yield.

After extensive optimization tests, we adopted a composition of 80 mg/l BBQ in Plexiglas 201^{*)} containing a certain concentration of UVA. Figure 6 illustrates the uniformity obtained with two WLS plates, both doped with the same concentration of BBQ but differing in thickness and presence of UVA. The attenuation along the WLS (a combination of bulk attenuation and losses due to surface imperfections) is of course undesired, as it weights the light according to the position of its conversion. This was improved by means of a diffuse end reflector -- a white paint (Diegel 05197 HVZ) with a very good adherence to acrylic. The resulting attenuation is shown in fig. 7.

The light from the WLS is guided to the PM by means of a light-guide of the lamella type. To reduce Čerenkov light produced by particles crossing the light-guide, it is essential to make it of ultraviolet-absorbing acrylic glass or to use a UV filter in front of the photocathode. In our case the optical

*) We are indebted to Drs. Fischer and Kretz of Röhm GmbH, Darmstadt, W. Germany, for their kind assistance and the provision of numerous samples.

coupling between light-guide and PM was obtained by means of a 3 mm thick disk of elastic silicon rubber doped with a UV-absorbing chemical^{*)}. The disk acts as a UV filter with an absorption edge at ~ 390 nm.

5. MUON CALIBRATION

In order to calibrate the calorimeter with single ionizing particles, runs were made with muons traversing the vertical median plane of each unit. To avoid the central rod, the calorimeter was lifted by 50 mm for these runs. Data were taken at 2, 5, and 10 GeV/c. As an example, fig. 8 shows the pulse-height distribution at 5 GeV/c. The position of the peak, i.e. the most probable value of the pulse height, was the same at 5 and 10 GeV/c to within 0.3%. This agrees with the theoretical expectation for the most probable value (unlike the mean) to be almost independent of energy for energies above 5 GeV. The peak value at 2 GeV/c is somewhat lower than expected, probably due mostly to the poor quality of the beam at this momentum. The calibration of the PMs was done using the most probable values of the muon pulse-height distributions at 5 GeV/c. These values were also used to define a "single ionizing pulse". Henceforth, all the pulse-height distributions will be presented in terms of the equivalent number of single ionizing particles.

Having measured the calorimeter response to muons, the absolute energy scale was established on the basis of a calculation using the Landau formula for most probable energy loss in a thin absorber⁴⁾. According to this formula, the most probable energy loss of a 5 GeV/c muon traversing our calorimeter is 644.8 MeV. The error on this number, deriving from the uncertainty on the calculated average ionization potential for acrylic scintillator, is negligible (0.1%).

6. RESPONSE TO ELECTRONS

Data were taken with electrons at 2, 5, and 7 GeV/c incident on module 2. Again, the calorimeter was lifted by 50 mm so that the rod was avoided. Figure 9

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shows the measured average signal (in terms of equivalent single ionizing particles) as a function of the beam momentum. It is seen that the response is linear to within 2% in the range 2 to 7 GeV/c. The large uncertainty is mainly due to the point at 2 GeV/c; however, this should be considered with some caution, as the electron beam in this case contained a substantial contamination of lower-energy particles. Figure 10 displays one of the observed pulse-height spectra. The fully drawn curve represents a Gaussian fit to the distribution. Defining the resolution as

$$R = \frac{\sigma}{E_{\text{peak}}} ,$$

one obtains a parametrization as a function of energy of the form

$$R = \frac{0.16(\pm 0.009)}{\sqrt{E}} , \quad (E \text{ in GeV}) .$$

The resolution agrees with being the sum in quadrature of a part due to photon statistics ($\sim 8\%$) and a contribution from sampling fluctuations ($\sim 13\%$)^{*)}.

Using the conversion factor between energy and equivalent single ionizing particles computed on the basis of most probable muon energy loss, the calorimeter response has been compared with the known incident momentum (see table 1). The observed reduction of the calorimeter signal -- explicable as being due to transition effects in the copper/scintillator interfaces -- has been found to be in agreement with similar measurements by other groups⁵⁾.

7. UNIFORMITY AND POSITION RESOLUTION FOR ELECTRONS

In order to investigate the uniformity of response across the face of the calorimeter, a scan and a calibration were made with electrons at 5 GeV/c. The modules were placed at three different horizontal positions (runs A, B, C), the beam being always perpendicular to the front plate. For each run, the hodoscope

*) The sampling fluctuation part is calculated from the empirical formula:

$$R = 0.05 \left(\frac{d\varepsilon}{dx} \right)^{\frac{1}{2}} \frac{1}{\sqrt{E}} ,$$

where $d\varepsilon/dx$ is the ionization loss in MeV per sampling cell for a minimum ionizing particle.

covered a 138 mm wide section of the calorimeter. Off-line cuts have been made to ensure that only one electron per event hits the modules.

The average pulse height measured by each of the two PMs of module 2 is shown in fig. 11 as a function of the impact position of the incident electron. Each of the points corresponds to three hodoscope channels. It is apparent that, apart from the region very close to the WLS, the relationship between position and pulse height is linear. Near the WLS a rise is indicated due to conversion of the short wavelength scintillator light in the BBQ and to the Čerenkov light created by shower particles crossing the WLS plane. The dependence of pulse height on impact point can be inverted and used in an algorithm for the calculation of the horizontal impact coordinate on the basis of calorimeter read-out. The results of such an algorithm are displayed in fig. 12. For every three hodoscope channels, the distribution of calculated impact points has been fitted with a Gaussian. The error bars shown in fig. 12 are the r.m.s. widths of these Gaussians. For particles hitting the module close to the WLS, the coordinate cannot be calculated in a well-defined manner because the pulse height at the nearest phototube fluctuates from event to event between very large and very small values (the small pulse heights are due to partial leakage of the electron shower into the crack between modules). Hence, no results are shown for impact points less than 20 mm from the edge.

Figure 13 displays, event by event, the difference between the measured and the calculated impact points for all the events (after cuts) of run B. The width of this distribution gives the spatial resolution of the device (at 5 GeV/c):

$$\sigma_x = 19.5 \text{ mm} .$$

The resolution as a function of position is given by the error bars in fig. 12. It is seen to be independent of the point of impact for points more than 20 mm from the edge of the module.

8. RESPONSE TO HADRONS

Runs were made with negative pions at 5, 7, and 10 GeV/c and with protons at 5 and 10 GeV/c incident on the centre of module 2.

The calorimeter response to hadrons is summarized in figs. 14a,b,c. Figure 14a shows the position of the peak of the pulse-height distribution (in terms of equivalent number of single ionizing particles) as a function of incident pion momentum. The three points (π) are well fitted -- within 1% -- by a straight line going through 0. The two proton measurements also lie on this line, provided the difference in the available energy of a pion and a proton is taken into account. Figure 14b is an example of a measured pulse-height distribution (π^- , 5 GeV/c). The narrow peak at 1 e.p. is produced by muons in the beam and non-interacting pions. (With a total depth of 3.06 absorption lengths, 4.7% of the incident pions are expected to traverse the calorimeter without interacting.) The curve drawn on top of the pulse-height distribution is a Gaussian fit to the upper part. The r.m.s. σ given by this fit determines the resolution for pions at 5 GeV/c:

$$R = \frac{\sigma}{E_{\text{peak}}} = 0.23 .$$

Figure 14c shows the variation of the resolution with incident momentum. The best fit to the pion data is given by

$$R = \frac{0.01E + 0.45}{\sqrt{E}} , \quad (E \text{ in GeV}) .$$

Apart from the usual $E^{-1/2}$ dependence, an $E^{1/2}$ term appears, reflecting the effects of energy non-containment.

Measurements were also made with the calorimeter rotated and the beam (protons, 10 GeV/c) incident at the centre of module 2. The pulse-height distributions for these runs turn out to be almost independent of the angle of incidence for moderate angles, i.e. as long as the bulk of the proton-induced cascade stays within the calorimeter. The increase in the total amount of material traversed for angles up to 27° manifests itself in the decrease of the fraction of non-interacting protons in accordance with the formula e^{-t} (t : calorimeter thickness in absorption lengths).

The question of energy leakage has been studied by placing a second set of three copper/scintillator modules immediately upstream of the previous device. To minimize the distance between the two, the second calorimeter was mounted with its back (and the PMs) facing the beam. Care was taken that the beam did not directly hit the tubes.

Figure 15 compares the distribution of the sum of pulse heights from all the six modules (the "full containment" distribution), for incident $7 \text{ GeV/c } \pi^-$, with the pulse-height distribution measured by the upstream calorimeter only. Actually, to facilitate the comparison, only the Gaussian fitting the upper part of each distribution is displayed. It is observed that with increased containment the most probable value of the pulse height increases by $\sim 4\%$, whereas the r.m.s. width decreases by $\sim 10\%$. Hence an improvement in resolution is produced.

Figure 16 shows the ratio of the signal measured by the downstream calorimeter to the sum of the signals from both devices -- again for π^- at 7 GeV/c . The peak at ~ 0.5 is due to muons contaminating the pion beam (the number of non-interacting pions is negligible). The peak at ~ 0.8 corresponds to late interactions. It should be noted that in 80% of the events the energy leakage into the downstream calorimeter is less than 10%. On the average the signal measured by the "back" calorimeter is 9.5% of the total (incident muons have not been considered).

The above results agree very well with Monte Carlo calculations. The Monte Carlo also indicates that the average amount of energy leaking out of the sides of a calorimeter of the given size is comparable with the amount leaking out of the back.

Having estimated the magnitude of the effects due to non-containment, it is useful to compare the calorimeter response to hadrons with the response to electrons depositing the same amount of energy. The ratio of electron-to-pion signal (corrected for leakage) turns out to be ~ 1.41 , approximately independent of incident momentum. The deviation from 1 is due to nuclear effects.

A final study concerned the Čerenkov light produced by shower particles crossing the WLS. For this investigation the central module was opened and a $49.5 \times 80 \text{ cm}^2$ sheet of black paper inserted, preventing the scintillator light from reaching one

of the WLS plates. A set of measurements was then performed with a 5 GeV/c pion beam hitting at various distances from the covered plate. In all cases the amount of light measured at the "black" side of the module was at the level of a few per cent of the "normal" signal, i.e. the average pulse height of a 5 GeV/c pion hitting at the centre of the module.

9. SUMMARY

We have reported the results of a performance test of a fine-sampling copper/scintillator calorimeter with wavelength shifter read-out. The optimization of the optical read-out system to ensure minimum sensitivity to Čerenkov light for maximum useful light yield has been described in some detail. The light output of the final device is ~ 200 photoelectrons per GeV for an incident electron beam.

The linearity and resolution of the calorimeter have been studied with electrons and hadrons in the momentum range 2-10 GeV/c. In both cases the response as a function of energy is linear within 2%. The energy resolution has been determined to

$$R = \frac{0.16}{\sqrt{E}}, \quad (E \text{ in GeV})$$

for electrons, and to

$$R = 0.01\sqrt{E} + \frac{0.45}{\sqrt{E}}, \quad (E \text{ in GeV})$$

for hadrons. The first term in the hadron resolution reflects the influence of longitudinal energy leakage. The spatial resolution has been determined for incident 5 GeV/c electrons to

$$\sigma_x = 19.5 \text{ mm}.$$

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Table 1

Ratio of momentum to
calorimeter response
for incident electrons

Momentum (GeV/c)	$\frac{\text{Inc. momentum}^{\text{a)}}}{\text{Cal. response}}$
2	1.13 ± 0.08
5	1.24 ± 0.07
7	1.22 ± 0.06

a) The error on the momentum
has been assumed to be 5%.

Figure captions

- Fig. 1 : Schematic view of the set-up.
- Fig. 2 : Horizontal cross-section through a calorimeter unit.
- Fig. 3 : Light yield relative to NE 102A as a function of naphthalene content in PMMA (1% butyl-PBD, no secondary scintillating agent), measured via a BBQ-doped wavelength shifter.
- Fig. 4 : Transmission curve for BBQ. Emission spectra for butyl-PBD, POPOP, and BBQ.
- Fig. 5 : Absorption length as a function of wavelength for acrylic doped with UVA or BBQ.
- Fig. 6 : Uniformity of response across a calorimeter cell for two different wavelength shifter plates (3 mm thick, UV transparent; 2 mm thick, UV absorbing).
- Fig. 7 : Attenuation along a wavelength shifter plate.
- Fig. 8 : Pulse-height distribution for 5 GeV/c muons.
- Fig. 9 : Response to electrons as a function of incident momentum.
- Fig. 10 : Pulse-height spectrum for electrons at 5 GeV/c.
- Fig. 11 : Mean pulse height as a function of position for electrons at 5 GeV/c. The error bars indicate the FWHM of the pulse-height distributions.
- Fig. 12 : Impact position calculated from left and right pulse heights for electrons at 5 GeV/c.
- Fig. 13 : Event-by-event difference between measured and calculated impact points for electrons at 5 GeV/c (run B). The curve is a fitted Gaussian, r.m.s. width 19.5 mm.

- Fig. 14 : a) Response to hadrons as a function of incident beam momentum.
b) Pulse-height distribution for pions at 5 GeV/c.
c) Resolution at 1 GeV/c,

$$R = \frac{\sigma}{E_{\text{peak}}} \sqrt{E} ,$$

as a function of incident beam momentum.

- Fig. 15 : Comparison of the pulse-height distribution measured by all six modules (curve 2) with pulse-height distribution measured by the upstream calorimeter (curve 1) for pions at 7 GeV/c.

- Fig. 16 : Ratio of signal in downstream calorimeter to the sum of signals measured by both calorimeters for pions at 7 GeV/c.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

a)

b)

Fig. 14 a) b)

Fig. 14 c)

Fig. 15

Fig. 16