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TEST RESULTS OF THE AFS HADRON CALORIMETER AT THE CERN ISR

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INTRODUCTION

The AFS hadron calorimeter has been designed to permit unbiased selection and study of events characterised by large transverse energy. Half of the calorimeter is now installed at the Intersecting Storage Rings at CERN; in its final form it will cover the full azimuth over a polar region of $40^\circ < \theta < 140^\circ$ (Fig. 1).

The calorimeter is built in a modular way from 128 uranium stacks (plus 64 copper "catchers"), each of which is a fine sampling uranium/copper scintillator sandwich (Fig. 2). Uranium is used as passive absorber material to achieve optimum resolution and unbiased triggering. Fluctuations in the energy deposited by hadrons are compensated on an event-by-event basis by the energy gained from fission induced in the development of the hadronic shower. This compensation provides excellent hadron energy resolution, as well as nearly equal energy response for hadronic and electromagnetic showers.

This paper reports on the calibration of the calorimeter modules, and presents preliminary results from studies in a test beam.

URANIUM MODULE DESIGN

Each module (Fig. 2) has a cross-section of $20 \times 120 \text{ cm}^2$, which faces the intersection region. The active depth is 80 cm, providing 3.8 nuclear absorption lengths, with the read out segmented twice along the longitudinal direction. The electromagnetic (front) section is six radiation lengths deep, while the remainder forms the hadronic section. The entire assembly is held together by a central rod, 10 mm in diameter.

The scintillators, sandwiched between the metal plates, are read out using two layers, subdivided into six wavelength-shifter (WLS) plates, on each side of the module. The two WLS layers are optically decoupled, the outer viewing the front and the inner the back section. Thus the module is divided into six $20 \times 20 \text{ cm}$ towers, each of which is read out by two photomultipliers for the electromagnetic section, and two for the hadronic section (Fig. 3). These towers are optically coupled, that is light can propagate internally along the scintillator plates. (For a detailed discussion of the read out system see Ref. 1).

The attenuation length in the scintillator is $\sim 30 \text{ cm}$, and this provides a means for measuring the position of the shower. In the long direction (along the stack) this can be achieved by comparing energies in the towers above and below the one in question (which has the maximum energy). Across the stack, the light reaching each side provides a left-right ratio. In each case, the resolution is of the order of 1 cm for single electromagnetic showers at normal incidence.

CHOICE OF PASSIVE ABSORBER

Monte Carlo studies indicated that plates in the hadronic part of the calorimeter could be made 3 mm thick (instead of 2 mm, as in the electromagnetic section) without seriously affecting the energy resolution. This was confirmed in a test beam. The effect of reducing the fraction of uranium by substitution of copper (5 mm plates) in the back section was also

investigated. The test results are shown in Fig. 4. As expected, the resolution is degraded with increasing copper fraction. A copper content of 20% (in absorption length), however, results in very little degradation of resolution, but provides a more economically favourable solution. (For a complete discussion, see Ref. 2). The final composition chosen for uranium stacks is listed in Table 1; all subsequent results in this paper were obtained using such stacks.

CALIBRATION

The calibration of the read out chain is attained using the natural radioactivity of ^{238}U . The "U-noise" is integrated using a 10 μs interval and the total signal in the hadronic section obtained in this way is equivalent to the signal from a ~ 3 GeV pion (measured using the normal integration period of 120 ns). This procedure provides an equalisation of tubes to within $\sim 2\%$. The method has been checked by exposing the stacks to muons and electrons.

The front back balancing is set by comparing the energy left by muons in each part of the calorimeter with the calculated value for the probable energy loss (using Ref. 3). The subsequent ratio of energy front/back for electrons at 5 (10) GeV is 42% (36%). This agrees well with predictions from the EGS Monte Carlo program (Ref. 4). The electron test data are used to set the absolute energy scale.

PERFORMANCE TESTS

Tests were made at the CERN PS in a beam that consisted mostly of pions, with 20 K particles/burst. At 4 GeV/c there were about 5% electrons, which were identified using two Cerenkov counters. Three identical stacks were mounted side by side in a device that provided horizontal and vertical motion, and rotation around two perpendicular axes (Fig. 5).

To obtain the best resolution, the energy sum for any shower should be taken over all towers that have substantial energy deposited in them. In a multiparticle environment of the kind anticipated in R807, however, it is better to limit the sum to as few towers as possible. An algorithm

for pattern recognition must, therefore, involve a compromise between such competing requirements. Our preliminary approach has been to find the tower with the maximum energy, and to construct "masks", centred on that tower, and to use these to calculate the full energy of the showers. (Masks are defined in Fig. 5). The results reported below are presented in terms of such masks.

LINEARITY

The linearity was measured in the range 2 → 10 GeV for electrons and hadrons at normal incidence to the central stack (Fig. 6). The data were normalized to electrons at 4 GeV. The response to electrons is linear over the complete range to better than 1%. The 2 GeV hadron point is not shown because it was impossible to separate pions from muons at this energy. (In coming tests, time-of-flight methods will be used to identify the particles at low momenta). The hadrons show a fall-off of about 4% in energy at 10 GeV, consistent with expected longitudinal leakage.

The statistical errors are small $\sim 0.1 \rightarrow 0.2\%$, and the systematic point-to-point errors are estimated to be $\sim 1\%$. The latter arise from ADC pedestal variations and from inaccuracy of the beam momentum settings.

ENERGY RESOLUTION

The resolution as a function of entry angle into the stack is presented below. The electron resolution for a single tower, at normal incidence, is:

$$\frac{\sigma(E)}{E} = \frac{15.0 \pm .4\%}{\sqrt{E}}$$

This is consistent with a contribution of $\sim 11.5\%$ from sampling fluctuations and about 8% from photoelectron statistics (indicating ~ 150 photoelectrons/GeV). Including additional towers worsens the resolution because of an increase in contribution from uranium noise.

The resolution for normally incident hadrons, using a mask of 9 towers and averaging over momenta in the range 5 to 10 GeV, is:

$$\frac{\sigma(E)}{E} = \frac{35 \pm 1\%}{\sqrt{E}}$$

this is consistent with an intrinsic resolution of $\sigma(E)/E \approx 20\%/\sqrt{E}$ for an ideal uranium calorimeter, and a sampling fluctuation contribution of $\sigma(E)/E = 25\%/\sqrt{E}$.

e/ π RATIO

The ratio between the visible energies of electrons and pions of same momentum (e/π), measured over a 9 tower mask, is:

$$e/\pi = 1.15 \pm 0.02$$

(This is an average over momenta in the range 5 to 10 GeV).

POSITION RESPONSE OF THE CALORIMETER

The position response along and across the stack for 4 GeV normal incidence electrons is shown in Fig. 7. The x position is calculated using the energy in the up (u) and down (d) towers in a 3-tower mask. The y position is determined from the difference of the signals read out on the two sides of the stack. In each case, only the energy in the electromagnetic section is used. The error bars, which indicate RMS widths of the calculated distributions, correspond to a resolution of $\approx \pm 1$ cm.

RESPONSE IN THE ϕ DIRECTION

The energy response in x along the last two towers of a stack, with normally incident electrons at 4 GeV, is shown in Fig. 8. Between two towers, there is a little loss owing to a small gap between neighbouring WLS plates, but otherwise the response is flat along the stack. Only at the end of the stack, is light lost at the edge of the scintillator, and the response falls. Tests on prototype modules indicated that even this can be avoided by polishing the end of the scintillator. We found, however, that adequate polishing was difficult to achieve for large volume batches of scintillator plates.

The electron energy response and resolution as a function of angle ϕ (for particles entering tower B3 (Fig. 5) is shown in Fig. 9. The 3 and 9 tower masks give the same energy response, indicating that no energy is

leaking into side stacks. The 12 tower masks show slightly higher energy due to light transmitted up the stack. The slight decrease in energy with increase in angle is caused by the shower gradually crossing the central constraining rod. A systematic error of about 1% is predicted from pedestal variations and from the error in fitting the peak-position of the shower.

The equivalent plots for hadrons are shown in Fig. 10. The difference in energy response for masks of 3 and 9 towers indicates that the shower width is greater than the size of one stack. This is also reflected in the poorer energy resolution.

RESPONSE IN THE θ DIRECTION

As particles pass close to a WLS bar, part of the short wavelength light component which would normally be strongly absorbed in the scintillator, reaches the WLS bar. This increases the total amount of light seen by the calorimeter.

Fig. 11 shows the result of a scan in y (across the uranium stack) for normally incident electrons of 4 GeV. The two towers that provide the main contributions to the total signal are plotted separately. In the case of individual towers, the increased light near the WLS bar due to reduced absorption of high frequency scintillator light, almost exactly compensates the energy leakage. The sum over a mask of 9 towers, however, shows a clear rise.

A similar position scan for electrons incident at $\theta = 40^\circ$ is shown in Fig. 12. For individual towers, the leakage into adjacent towers now exceeds the gain from increase in scintillation light near the WLS bar. The showers for electrons of non-normal incidence are larger transversely, and thus the increase in summed energy is smaller than in Fig. 11.

As a result of their greater width, hadron showers are less severely affected by the WLS bars than electromagnetic showers. Even at close to normal incidence they show only a 10% rise in pulse height.

A first attempt has been made to correct for the non-uniformity near the edge of a tower. Events of this type can be isolated, since the

increased light on one side of the stack will lead to a change in the determination of the left-right position. To a first approximation, for those events which yield a position that is beyond the real limits of the tower in question, the energy can be corrected using an exponential of the form $[1 - \exp(a + by')]$, which y' is the distance beyond the edge of the tower. The corrected points are plotted as stars in Fig. 11. The next level of correction would take into account the gentle rise in energy across the face of the tower.

e- π DISCRIMINATION

Both the longitudinal and transverse segmentation of the calorimeter can be used to discriminate between electrons and pions. The fraction of energy deposited in the electromagnetic section of the calorimeter for electrons of 2 to 10 GeV is 64% $\rightarrow$ 34%. Requiring this fraction to be above a threshold thus provides a means of discriminating against pions. Fig. 13 shows the rejection factor obtained as a function of energy, after requiring a constant efficiency of 75% for electrons. The discrimination is obtained by imposing a cut on the front/back ratio and on the fraction of energy within the central stack of a 9 tower mask.

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TABLE 1: Composition of a Uranium Stack

Front Section:	
Uranium plates, 2 mm	10
Scintillator plates, 2.5 mm	11
Rear Section	
Uranium plates, 3 mm	76
Copper plates, 5 mm	38
alternated in the ratio 2:1	
Scintillator plates, 2.5 mm	114

REFERENCES

- Ref. 1 A hadron calorimeter with wavelength shifter read-out, Nucl. Instr. and Methods 179 (1981) 45-54.
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- Ref. 3 R.M. Sternheimer, R.F. Peirls, Phys. Rev. B., 11, 3681, (1971).
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FIGURE CAPTIONS

- Fig. 1: Schematic view of the AFS hadron calorimeter. Each large rectangular box represents a uranium module. The smaller boxes in the corners are of similar construction, but are built using just copper as the absorber. They are referred to as "copper catchers" as they record energy which leaks out through the corner regions of the uranium array.
- Fig. 2: Uranium calorimeter stack. The outside WLS bars read the front electromagnetic section, and the inside bars read the hadronic section.
- Fig. 3: Horizontal cross-section through a uranium stack.
- Fig. 4: Hadronic resolution as a function of the copper fraction expressed in absorption lengths.
- Fig. 5: Definition of coordinates used in test beam results and of "masks" used for energy summing.
- Fig. 6: Linearity for hadrons and electrons. Data are normalized at 4 GeV, and the percentage change with respect to this energy is plotted. Hadrons show some longitudinal leakage at higher energies.
- Fig. 7: Shower position determination along and across a tower for normally incident 4 GeV electrons. Direction x is calculated using the energies in towers above and below the "peak-tower". Direction y is found using left-right information.
- Fig. 8: Energy response at the end of a uranium stack for normally incident 4 GeV electrons. The very small dip between towers is representative of the good uniformity along the stack.
- Fig. 9: Energy response and resolution as a function of angle θ for 4 GeV electrons. Results include the use of "masks" of 3, 9 and 12 towers.
- Fig. 10: Energy response and resolution as a function of angle θ for 4 GeV hadrons. Results include the use of "masks" of 3, 9 and 12 towers.
- Fig. 11: A position scan in y for electrons of 4 GeV normal incidence. The two towers providing the main contributions are plotted separately. The starred points show the data corrected using left-right information to isolate events where the particle hits near a WLS bar.
- Fig. 12: A position scan in y for electrons of 4 GeV incident at $\theta = 40^\circ$. The three towers providing the main contributions are plotted separately.
- Fig. 13: Energy dependence of pion rejection for fixed electron acceptance, using longitudinal and transverse shower information.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

Mask definition.

Assume peak energy located in tower B 3

$$3 \text{ mask} = \Sigma (B2 + B3 + B4)$$

$$9 \text{ mask} = \Sigma (A2 + A3 + A4 + B2 + B3 + B4 + C2 + C3 + C4)$$

$$12 \text{ mask} = \Sigma (9 \text{ mask} + A5 + B5 + C5)$$

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

$\theta = 40^\circ$ ELECTRONS

FIGURE 12

FIGURE 13