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PERFORMANCE OF A SAMPLING CALORIMETER
WITH ALTERNATE U and Fe ABSORBERS

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ABSTRACT

A sampling hadronic calorimeter, consisting of a sandwich of scintillator plates and alternate U and Fe absorbers, has been tested in a 135 GeV energy beam. The energy resolution turns out to be significantly improved with respect to the homogeneous configurations in which only U or Fe absorbers are used.

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1. INTRODUCTION

One of the main problems to be investigated in hadron calorimetry is the correlation between energy resolution and relative response to electrons and hadrons.

In a sampling calorimeter consisting of a sandwich of inert material layers interspaced with active detectors (scintillator, liquid argon, etc.) the response to an electromagnetic shower is usually larger than to a hadronic one ($e/\pi > 1$). The resolution is therefore dominated by an "intrinsic" term, independent of the sampling thickness, due to the fluctuation of the content of the electromagnetic energy (mainly π^0 's) in the shower.

It has been shown that the resolution can be improved with appropriate weighting algorithms, using the information on the shower development [1,2]. In fact, electromagnetic showers, whose scale parameter is the radiation length X_0 , are shorter than hadronic showers, whose scale parameter is the interaction length Λ . The fraction of electromagnetic energy in a hadronic shower is thus related to its longitudinal shape.

Other authors have obtained a substantial improvement in resolution by using uranium absorbers [3]. In this case, the energy released in the neutron-induced fission processes increases the response to the hadronic showers and tends to compensate for the invisible energy released in nuclear interactions. A nearly identical response to electrons and to hadrons, together with a substantial improvement in the resolution, has been found in the energy range 5-50 GeV by using thin uranium absorbers.

In a previous paper [4] we have presented results obtained from a sampling calorimeter in the energy range 135-350 GeV using scintillator as the active detector. Its response and resolution were studied with iron and uranium absorbers of different thicknesses, and the results can be summarized as follows:

i) With iron absorbers (2.5 cm thick) the e/π ratio is about 1.1 and the resolution $\sigma/E \approx 0.6/\sqrt{E}$, after the weighting procedure, in good agreement with previous results.

ii) With uranium layers (0.5, 1.0, 1.5 cm thick) an e/π ratio between 0.8 and 0.9 was obtained (depending upon the sampling thickness), that is a significant "overcompensation" observed for the first time. For this reason weighting procedures are needed in this case as well, in order to optimize the resolution.

These results suggested that an exact compensation and therefore a better resolution could be obtained by using a mixed configuration U-Fe.

In the present work we discuss the performance of a calorimeter with alternate absorber layers of 1 cm of uranium and 2.5 cm of iron thickness. Measurements were performed on a 135 GeV energy proton beam (momentum bite $\sim 1\%$)

containing a large fraction of positrons. The calorimeter gave an almost equal average response to electrons and to hadrons ($e/\pi \approx 1$) and a substantial improvement in the energy resolution was obtained with respect to the homogeneous configurations (only U or Fe absorbers).

2. MECHANICS, CALIBRATION, MONITORING

The data discussed here have been taken with the same calorimeter as described in ref. [4]. Only the configuration of the absorber layers has been changed. Detailed descriptions of the mechanical structure, of the linear electronic chain, of the monitoring system, and of the calibration procedure may be found there and we repeat here only the most relevant features.

The calorimeter, fig. 1, is divided into two sections along its length. The upstream part, which collects most of the shower energy, comprises a total of 52 elements (absorber + scintillator) grouped in 13 modules, each viewed by one photomultiplier. This part of the calorimeter was mechanically designed in such a way as to permit easy changing of the absorbers and has been used in different configurations with Fe or U plates of various thicknesses [4]. In the present work, the absorber system consists of alternate layers of U ($60 \times 60 \times 1 \text{ cm}^3$) and Fe ($60 \times 60 \times 2.5 \text{ cm}^3$). For easy handling and for safety reasons each uranium plate was enclosed in a steel box with walls 1 mm thick. The scintillator plates (NE110 produced by Nuclear Enterprise), placed between the layers, were 0.5 cm thick. The downstream part of the calorimeter consists of 48 elements (Fe $60 \times 60 \times 2.5 \text{ cm}^3$ and scintillator $60 \times 60 \times 0.5 \text{ cm}^3$) grouped in 12 modules.

The calorimeter was equipped with low gain photomultipliers (THORN-EMI D254A), followed by Le Croy VV100BTB amplifiers (current gain ~ 40). The signals were recorded by a Le Croy FERA 4300 ADC (11 bits, 480 pC full scale).

The gain stability of the photomultipliers was monitored by a light-emitting diode (LED) system and the calibration of the modules was done by using the fact that the longitudinal energy profile of the hadronic shower must be independent of the position of the shower vertex. Denoting by A_j^i the ADC output of the j^{th} module from the sample with shower vertex in the i^{th} module, we obtain a set of equalities:

$$\alpha_1 A_1^1 = \alpha_2 A_2^2 = \alpha_3 A_3^3 = \dots$$

$$\alpha_2 A_2^1 = \alpha_3 A_3^2 = \alpha_4 A_4^3 = \dots ,$$

where α_i are the calibration constants. To convert from ADC counts to energy one should weight each output with the energy loss in the corresponding module. In the reported results the energy is expressed in ADC channels normalizing each output to that with the configuration fully equipped with 2.5 cm iron plates,

using the formula:

$$E_i = \alpha_i A_i [(dE/dx)_{abs} \Delta x_{abs} + (dE/dx)_{scint} \Delta x_{scint}]_i [(dE/dx)_{Fe} \Delta x_{Fe} + (dE/dx)_{scint} \Delta x_{scint}]^{-1} . \quad (1)$$

In this way the responses of the calorimeter in different absorber configurations are directly comparable.

3. RESULTS

Data were taken with a proton beam at 135 GeV energy. At this energy the beam contained a significant fraction of positive electrons giving rise to electromagnetic showers. The separation between the two beam components has been made by exploiting the fact that the electromagnetic showers are much shorter than those induced by hadrons. As discussed in ref. [4], the requirement that at least 97% of the total energy is deposited in the first four modules selects an electron sample with $\sim 0.5\%$ of hadron contamination and a hadron sample also with $\sim 0.5\%$ of electron contamination.

Figure 2 gives the energy distributions for hadrons and for electrons obtained after this selection. In the same figure the corresponding energy distributions obtained in ref. [4], in which the calorimeter was equipped with Fe or U layers separately^{*)}, are also given for comparison. While in the homogeneous configurations the electron and hadron peaks are displaced ($e/\pi > 1$ for Fe and $e/\pi < 1$ for U), in the mixed U-Fe configuration the calorimeter gave practically the same response for electrons and hadrons ($e/\pi \simeq 1$).

It is also interesting to compare the response of the calorimeter to electromagnetic showers in the three different configurations. It is already known that the fraction Q of energy deposited in the active material (relative to the total energy deposited in the calorimeter) for electron showers is not accounted for by the minimum ionizing particle losses ($Q_e/Q_{mip} \equiv E_{vis}/E \neq 1$). Such an effect, sometimes called "transition effect", has also been reproduced by Monte Carlo simulation for several absorber/active layer configurations [5]. In our case we were not able to measure E_{vis} in the different configurations because the calorimeter was insensitive to minimum ionizing particles. However, the ratio $R = (E_{vis})_U / (E_{vis})_{Fe}$ could be measured and it was found to be $R = 0.68$ [4]. For the present data we quote $R' = 0.83$, with $R' = (E_{vis})_{U-Fe} / (E_{vis})_{Fe}$. It seems very likely that such dependence of the electromagnetic response on the

^{*)} The two homogeneous configurations are called Fe25 (100 Fe layers 2.5 cm thick), and U10 (20 U layers 1.0 cm, 32 U layers 1.5 cm, 48 Fe layers 2.5 cm thick).

atomic number Z plays a role in the behaviour of the e/π ratio. However, we recall that in our previous measurements [4] such an effect is independent of the beam energy and of the sampling thickness, while the e/π ratio seems to be energy and sampling dependent.

In fig. 3 the scatter plot of the total energy (E_{tot}) versus the maximum energy deposited in any single counter (A_{max}) obtained for hadrons in the mixed U-Fe configuration is compared with those given in ref. [4] for Fe25 and U10 configurations. The tail of high values of A_{max} corresponds to showers in which a large fraction of the energy is concentrated in a single module and therefore having a large electromagnetic component. As can be seen from fig. 3, these events are correlated with higher values of E_{tot} in the iron case ($e/\pi > 1$) and with lower values of E_{tot} in the uranium one ($e/\pi < 1$). As expected, the scatter plot does not show any correlation in the mixed U-Fe configuration discussed here. In ref. [4] for the homogeneous configurations we have used the $E_{\text{tot}}-A_{\text{max}}$ correlation to reduce the variance of the energy distribution by means of a weighting algorithm. The energy has been corrected event by event using the formula:

$$E'_{\text{tot}} = E_{\text{tot}} - c/\sqrt{E_{\text{tot}}} \sum_i A_i^2, \quad (2)$$

where A_i are the calibrated amplitudes of the modules. The values of c selected by optimizing the resolution were found to be:

$$c \simeq 0.01 \text{ ch}^{-1/2} \text{ for the Fe25 configuration}$$

$$c \simeq -0.01 \text{ ch}^{-1/2} \text{ for the U10 configuration.}$$

This algorithm, already used by other authors [2], was also found to be the best in our case in both calorimeter configurations, but there is no obvious reason why this should be so. Indeed we have tried different types of corrections. As an example, in fig. 4, the energy for the U10 configuration at 135 GeV, corrected with the above algorithm (2), is plotted versus the energy corrected with the formula:

$$E''_{\text{tot}} = E_{\text{tot}} - b/E_{\text{tot}} \sum_i |A_i - A_{i-1}|. \quad (3)$$

It can be seen that the results of the two algorithms are strongly correlated. The correction (3) appears to reduce further the resolution σ/E but actually it introduces a non-linearity of the energy scale as was verified at different points (135, 210, 300, 350 GeV). The result is that no further improvement in resolution can be obtained beyond that achieved with the algorithm (2). Obviously in the mixed U-Fe configuration the application of weighting procedures scarcely affects the energy resolution. The results are summarized in

table 1 both for electrons and for hadrons. One can remark upon the substantial improvement obtained in the energy resolution in the U-Fe case compared to the homogeneous configurations, even after the weighting procedure has been applied. This means that weighting algorithms (at least when only information on the longitudinal shape of the shower is available) do not optimize the energy resolution as well as may be done by using an appropriate mixing of different absorbers ("hardware compensation").

4. CONCLUSIONS

We have studied the response and the resolution of a sampling hadronic calorimeter made of scintillator plates and alternate layers of uranium and iron at 135 GeV beam energy. In such a configuration the average response to electrons and hadrons is practically equal ($e/\pi = 1$) and the energy resolution is significantly better than that obtained in homogeneous configurations with only Fe or U as absorber (where $e/\pi = 1.1$ and $e/\pi = 0.8$, respectively, was found).

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Table 1

Summary of results obtained for different configurations at 135 GeV beam energy. The statistical errors are negligible. The systematic errors on E (mainly due to calibration) are estimated to be of the order of 1% for hadrons and less than 3% for electrons.

Configuration	Hadrons				Electrons			e/ π
	Unweighted		Weighted		E	σ/E	$E_{\text{vis}}/(E_{\text{vis}})_{\text{Fe}}$	
	E (ch)	σ/E (%)	E (ch)	σ/E (%)	(ch)	(%)		
Fe25	1113	5.5	1032	5.0	1235	2.4	1	1.11
U10	1044	6.0	1114	5.1	835	3.4	0.68	0.80
U-Fe	1005	4.3	998	4.3	1026	2.7	0.83	1.02

FIGURE CAPTIONS

- Fig. 1 Top view of the calorimeter and the beam counters (the downstream section, modules 14 to 25, is only partially shown).
- Fig. 2 Unweighted energy distribution for a) hadrons and b) electrons at 135 GeV beam energy. For comparison the previous results for homogeneous configurations [4] are also shown: c) hadrons and d) electrons, Fe25 configuration (100 Fe layers 2.5 cm thick); e) hadrons and f) electrons, U10 configuration (20 U layers 1.0 cm, 32 U layers 1.5 cm, 48 Fe layers 2.5 cm thick). The energy is expressed in channels normalized to the Fe25 configuration via the formula (1) given in the text.
- Fig. 3 E_{tot} unweighted versus A_{max} for hadron showers: a) U-Fe mixed configuration; b) Fe25 configuration [4]; c) U10 configuration [4].
- Fig. 4 Hadron energy E'_{tot} corrected with the algorithm (2) versus energy E''_{tot} corrected with the algorithm (3) for configuration U10 at 135 GeV. The algorithms are described in the text.

Fig. 1

ETOT (Channels)*10⁻³

Fig. 2

AMAX (Channels)*10⁻³

Fig. 3

Fig. 4