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The small-angle performance of a dual-readout fiber calorimeter

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ABSTRACT

The performance of the RD52 dual-readout calorimeter is measured for very small angles of incidence between the 20 GeV electron beam particles and the direction of the fibers that form the active elements of this calorimeter. The calorimeter response is observed to be independent of the angle of incidence for both the scintillating and the Čerenkov fibers, whereas significant differences are found between the angular dependence of the energy resolution measured with these two types of fibers. The experimental results are on crucial points at variance with the predictions of GEANT4 Monte Carlo simulations.

1. Introduction

Sampling calorimeters based on large numbers of optical fibers embedded in a metal absorber structure offer some distinct advantages compared to other detectors of high-energy particles. Since the fibers act at the same time as the active medium in which the signals are produced and as a wave guide transporting the signals to the outside world, it is possible to construct hermetic detector structures, which is very important in modern colliding-beam experiments. Also, the very frequent shower sampling allowed by a fiber configuration strongly reduces the effects of sampling fluctuations. Such fluctuations tend to dominate the energy resolution of electromagnetic sampling calorimeters. Several particle physics experiments have taken advantage of these features, *e.g.*, CHORUS [1], KLOE [2], DELPHI [3], WA89 [4], H1 and CMS [5].

In dual-readout calorimeters, two different types of signals are produced by the showering particles. These two types of signals, which represent the total energy deposit by ionization (dE/dx) and the Čerenkov light produced by the relativistic shower products, provide complementary information, which makes it for example possible to determine the electromagnetic fraction of each hadronic shower. The fluctuations in that fraction typically dominate the hadronic energy resolution of calorimeters, and dual-readout calorimeters thus offer the possibility to eliminate the effects of these fluctuations and obtain excellent hadronic performance [6,7].

In the calorimeter discussed in this paper, signals are generated in scintillating fibers, which measure the deposited energy, and in clear plastic fibers, which measure the relativistic shower particles, by means of the Čerenkov light generated by these. A large

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number of such fibers are embedded in a copper absorber structure. This detector is longitudinally unsegmented, the fibers are oriented in *approximately* the same direction as the particles to be detected. In previous papers, we have focused on the electromagnetic performance of this detector [8] and on its capability to identify the particles developing showers in it [9]. In this paper, we investigate its performance as a function of the angle of incidence of the showering particles. This study was inspired by the results of Monte Carlo simulations, which suggested anomalous effects when electrons or photons enter the calorimeter almost parallel to the optical fibers [10]. These effects derive from the fact that the early component of em showers (*i.e.*, before the shower maximum is reached) is extremely collimated. When an electron enters this calorimeter parallel to the fibers, the signal from the early shower component strongly depends on the impact point, *i.e.*, inside a fiber or in between fibers. This effect leads to a deterioration of the em energy resolution and may also affect the calorimeter response.[1]

In Section 2, the instruments and the experimental setup in which the measurements were carried out are described, as well as the calibration and data analysis methods that were used. Experimental results are presented in Section 3. In the concluding Section 4, we discuss these results and their implications.

2. Equipment and measurements

2.1. Detectors and beam line

The measurements described in this paper were performed in the H8 beam line of the Super Proton Synchrotron at CERN. For these particular studies, we used a beam of 20 GeV electrons, which were steered into a module of the RD52 fiber calorimeter. A system of auxiliary detectors, described below, was used to select the beam particles that entered the calorimeter in a well defined, small area.

The calorimeter module used for the studies described in this paper consisted of a copper absorber matrix, 2.5 m long ($10\lambda_{\text{int}}$), with a cross-section of 9.2×9.2 cm^2. It was subdivided into four towers ($4.6 \times 4.6 \times 250$ cm^3), and each tower contained 1024 plastic optical fibers (diameter 1.0 mm, equal numbers of scintillating and clear plastic fibers).[2] Each tower produced two signals, a scintillation signal and a Čerenkov signal, which were detected by separate PMTs.[3] For this reason, this type of detector is also known as a DREAM (Dual-REAdout Method) calorimeter. The fiducial mass of the calorimeter module was ~ 120 kg, it contained 45% fibers by volume and the sampling fraction for minimum ionizing particles, both for the scintillation and for the Čerenkov sampling structure, was 4.6%. The effective radiation length and Moliere radius were both about 25 mm. Fig. 1(a) shows this module while it was under construction; details of the fiber structure, as well a front view of the finished product, are shown in Fig. 1(b), where the scintillating and Čerenkov fibers are indicated by *S* and *Č*, respectively.

The experimental setup contained also a number of auxiliary detectors, which were intended to determine the identity of individual beam particles, and to measure their trajectory. Fig. 1 (c) shows a schematic overview of the beam line, in which the positions of these auxiliary counters are indicated:

- Two small scintillation counters provided the signals that were used to trigger the data acquisition system. These Trigger Counters (T_1, T_2) were 2.5 mm thick, and the area of overlap was 4×4 cm^2. Downstream from these counters, a third scintillation counter (T_H) was installed. The latter had a hole with a radius of 10 mm in it. A (anti-)coincidence between the logic signals from these counters provided the trigger ($T_1 \cdot T_2 \cdot \overline{T_H}$).
- The trajectories of individual beam particles could be reconstructed with the information provided by two small drift chambers (DC1, DC2), which were installed upstream and downstream of the trigger counters. This system made it possible to determine the location of the impact point of the 20 GeV beam particles at the calorimeter surface with a precision of about 2 mm.
- About 80 cm upstream of the calorimeter, a preshower detector (PSD) provided signals that could be used to remove pions and muons contaminating the electron beams. This PSD consisted of a 5 mm thick lead plate, followed by a 5 mm thick plastic scintillator. Electrons started developing showers in this device, while muons and hadrons typically produced a signal characteristic of a minimum ionizing particle (mip) in the scintillator plate.
- Downstream of the calorimeter (DREAM), a tail catcher (TC) also served to identify pions and muons, since the electron showers were typically fully contained in the calorimeter. This tail catcher consisted of a simple 20×20 cm^2 scintillation counter.
- Further downstream of the calorimeter, behind an additional 8 λ_{int} worth of absorber, a 50×50 cm^2 scintillation counter (μ) served to identify muons that contaminated the particle beam.

The goal of the present studies was to measure the calorimeter performance for very small angles of incidence. For that purpose the table on which the calorimeter was installed was modified such as to allow rotation in the horizontal plane with a precision better than one milliradian.[4]

2.2. Data acquisition

Low-loss cables with a 15-mm diameter were used to transport the signals from the trigger counters to the counting room. The signal speed in these cables was measured to be 0.78*c*. The calorimeter signals, as well as the signals from the auxiliary counters that needed to be digitized (PSD, tail catcher, muon counter) were transported through RG-58 cables with (for timing purposes) appropriate lengths to the counting room.

There, the signals to be digitized were fed into charge ADCs. The signals from the wire chambers were fed into TDCs. The time information could be converted into (x, y) coordinates of the point where the beam particle traversed the chamber.

The data acquisition system used VME electronics. Two VME crates hosted all the needed readout and control boards. The signals from the calorimeter channels and the auxiliary detectors were integrated and digitized with a sensitivity of 100 fC/count, on 12-bit QDC V792 CAEN modules. The timing information of the tracking chambers was recorded with 1 ns resolution in a 16-bit 16-channel CAEN V775N TDC. Our readout scheme optimized the CPU utilization and the data taking efficiency using the bunch structure of the 42-s SPS accelerator cycle, during which period

[1] Following the convention introduced in [11], we define the calorimeter *response* in this paper as the average calorimeter signal per unit deposited energy. In this convention, a linear calorimeter thus has a constant response, and a compensating calorimeter has the same response for electrons and hadrons.

[2] The scintillating fibers were of the type SCSF-78 (polystyrene core), produced by Kuraray. Their numerical aperture was 0.55 and the cladding thickness 20 μm. The Čerenkov light was generated in PMMA based SK40 fibers, produced by Mitsubishi. Their numerical aperture was 0.50, and the thickness of the cladding 10 μm.

[3] Hamamatsu R8900, 10-stage.

[4] We thank Michael Jeckel and Ilias Efthymiopoulos for making these modifications to our equipment.