Nuclear Inst. and Methods in Physics Research, A 866 (2017) 76–90

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Hadron detection with a dual-readout fiber calorimeter

S. Lee [n], A. Cardini [c], M. Cascella [d], S. Choi [e], G. Ciapetti [h,i,1], R. Ferrari [f], S. Franchino [j], M. Fraternali [f,g], G. Gaudio [f], S. Ha [e], J. Hauptman [k], H. Kim [n], A. Lanza [f], F. Li [k], M. Livan [f,g], E. Meoni [l,m], J. Park [n], F. Scuri [b], A. Sill [a], R. Wigmans [a,*]

[a] Texas Tech University, Lubbock (TX), USA
[b] INFN Sezione di Pisa, Italy
[c] INFN Sezione di Cagliari, Monserrato (CA), Italy
[d] University College, London, UK
[e] Korea University, Seoul, Republic of Korea
[f] INFN Sezione di Pavia, Italy
[g] Dipartimento di Fisica, Università di Pavia, Italy
[h] Dipartimento di Fisica, Università di Roma "La Sapienza", Italy
[i] INFN Sezione di Roma, Italy
[j] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Germany
[k] Iowa State University, Ames (IA), USA
[l] Dipartimento di Fisica, Università della Calabria, Italy
[m] INFN Cosenza, Italy
[n] Kyungpook National University, Daegu, Republic of Korea

ARTICLE INFO

Keywords:
Dual-readout calorimetry
Čerenkov light
Optical fibers

ABSTRACT

In this paper, we describe measurements of the response functions of a fiber-based dual-readout calorimeter for pions, protons and multiparticle "jets" with energies in the range from 20 to 180 GeV. The calorimeter uses lead as absorber material and has a total mass of 1350 kg. It is complemented by leakage counters made of scintillating plastic, with a total mass of 500 kg. The effects of these leakage counters on the calorimeter performance are studied as well. In a separate section, we investigate and compare different methods to measure the energy resolution of a calorimeter. Using only the signals provided by the calorimeter, we demonstrate that our dual-readout calorimeter, calibrated with electrons, is able to reconstruct the energy of proton and pion beam particles to within a few percent at all energies. The fractional widths of the signal distributions for these particles (σ/E) scale with the beam energy as $30\%/\sqrt{E}$, without any additional contributing terms.

1. Introduction

The performance of hadron calorimeters is typically strongly dominated, and negatively affected, by the effects of fluctuations in the electromagnetic (em) shower fraction, f_{em}. One approach to eliminate the effects of such fluctuations is to *measure* f_{em} for each event. It turns out that the Čerenkov mechanism provides unique opportunities in this respect. Calorimeters that use Čerenkov light as signal source are, for all practical purposes, only responding to the em fraction of hadronic showers [1]. By comparing the relative strengths of the signals representing the visible deposited energy and the Čerenkov light produced in the shower absorption process, the em shower fraction can be determined and the total shower energy can be reconstructed using the known e/h value(s) of the calorimeter.[2] This is the essence of what has become known as *dual-readout* calorimetry. We are studying the properties of particle detectors of this type in the context of CERN's RD52 project [2].

In the dual-readout calorimeter discussed in this paper, signals are generated in scintillating fibers, which measure the deposited energy,

---

[*] Corresponding author. Fax: +1 806 742 1182.
E-mail address: wigmans@ttu.edu (R. Wigmans).

[1] Deceased.

[2] The ratio e/h represents the ratio of the average calorimeter signals per unit deposited energy from the em and non-em components of hadron showers. A calorimeter with $e/h = 1$ is said to be *compensating*, but in practice almost all calorimeters have $e/h > 1$.

http://dx.doi.org/10.1016/j.nima.2017.05.025
Received 24 March 2017; Received in revised form 17 May 2017; Accepted 18 May 2017
Available online 16 June 2017
0168-9002/© 2017 Elsevier B.V. All rights reserved.

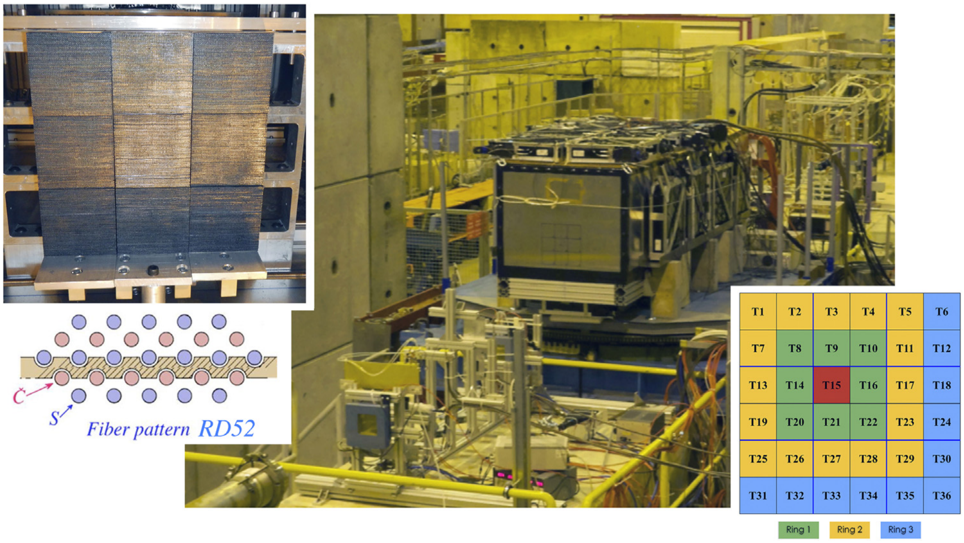

Fig. 1. Experimental setup in the H8 beam of the SPS at CERN. The calorimeter is installed inside a light tight box, surrounded on 4 sides by 20 modular leakage counters. The entire setup is installed on a movable table, which allows the impact point and the incident angle of the beam particles to be chosen as needed. The beam particles arrive through the vacuum pipe visible in the bottom left corner, and pass through several beam defining elements upstream of the calorimeter. The left inset shows a picture of the front face of the calorimeter, which consists of a 3×3 matrix of modules, and the arrangement of the scintillating and Čerenkov fibers in the lead absorber. The right inset shows the tower structure, one central tower surrounded by two complete rings and one incomplete one.

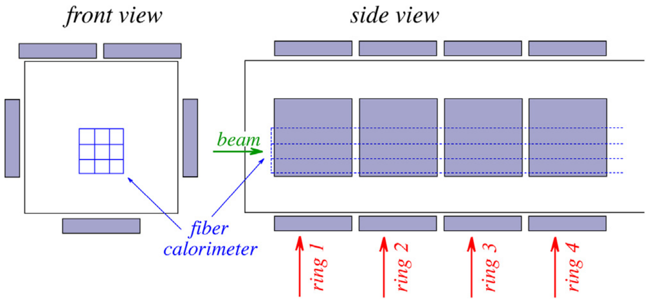

Fig. 2. Location of the leakage counters with respect to the fiber calorimeter. The front view shows that five counters form a "ring" around the calorimeter, the side view shows that there are four such "rings", located at different depths.

and in clear plastic fibers, which measure the relativistic shower particles, by means of the Čerenkov light generated by these. A large number of such fibers are embedded in a metal 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 such a detector [3,4] and on its capability to identify the particles developing showers in it [5].

In this paper, we describe experiments in which the hadronic performance of this calorimeter was measured. Hadron showers require a very large volume to fully develop. The 1350 kg fiducial volume of the calorimeter used for our purpose absorbed in practice, on average, only ~90% of the shower, depending on the energy of the showering particle. Therefore, fluctuations in (side) leakage formed a dominating contribution to the energy resolution. In order to get a handle on this contribution, the calorimeter was surrounded by a (rather crude) system of leakage counters. In our measurements, we also tried to distinguish between showers initiated by pions and by protons, using the calorimeter information. Our experimental program concentrated on two issues:

1. To what extent can the very crude system of leakage counters that we had installed around the calorimeter measure these event-to-event fluctuations and improve the measured energy resolution?
2. Can we separate pions and protons in the CERN SPS H8 beam, and measure the dual-readout calorimeter performance separately for these particles?

We also studied the performance for multi-particle "jets", produced in high-multiplicity interactions by the beam hadrons in an upstream target. In modern particle physics experiments, the detection of jets is very important. The multiparticle events we used for our studies are, of course, not the same as the QCD jets that originate from a fragmenting quark or gluon. Yet, for the purpose of calorimetry they are very useful, since they represent a collection of particles that enter the calorimeter simultaneously. The composition of this collection is unknown, but the total energy is known. In the absence of a jet test beam, this is a reasonable alternative.

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 Section 4, we investigate and compare different methods to measure the energy resolution of this calorimeter. Conclusions from these studies are presented in Section 5.

2. Equipment and measurements

2.1. Detectors and beam line

For these particular studies, which were carried out in October 2015, we used secondary or tertiary beams derived from the 400 GeV proton beam delivered by the CERN Super Proton Synchrotron. These particle beams were steered through the H8 line into the RD52 fiber calorimeter. Fig. 1 shows the experimental setup.

The fiber calorimeter used for the studies described in this paper is modular, and uses lead as the absorber material. Each of the nine modules is 2.5 m long ($10\ \lambda_{\rm int}$), has a cross section of 9.2×9.2 cm^2 and a fiducial mass of 150 kg. Each module consists of four towers ($4.6 \times 4.6 \times 250$ cm^3), and each tower contains 1024 plastic optical fibers (diameter 1.0 mm, equal numbers of scintillating and clear plastic fibers).[3] Each tower produces two signals, a scintillation signal and a

---

[3] The scintillating fibers are of the SCSF-78 type, produced by Kuraray, the Čerenkov light is generated in PMMA-based SK40 fibers, produced by Mitsubishi.