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Lessons from Monte Carlo simulations of the performance of a dual-readout fiber calorimeter

N. Akchurin [a], F. Bedeschi [b], A. Cardini [c], M. Cascella [d,e], D. De Pedis [f], R. Ferrari [g], S. Fracchia [g], S. Franchino [h], M. Fraternali [g,i], G. Gaudio [g], P. Genova [g,i], J. Hauptman [j], L. La Rotonda [k,l], S. Lee [a], M. Livan [g,i], E. Meoni [m], D. Pinci [f], A. Policicchio [k,l], J.G. Saraiva [n], F. Scuri [b], A. Sill [a], T. Venturelli [k,l], 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] *Dipartimento di Fisica, Università di Salento, Italy*
[e] *INFN Sezione di Lecce, Italy*
[f] *INFN Sezione di Roma, Italy*
[g] *INFN Sezione di Pavia, Italy*
[h] *CERN, Genève, Switzerland*
[i] *Dipartimento di Fisica, Università di Pavia, Italy*
[j] *Iowa State University, Ames (IA), USA*
[k] *Dipartimento di Fisica, Università della Calabria, Italy*
[l] *INFN Cosenza, Italy*
[m] *Tufts University, Medford (MA), USA*
[n] *LIP, Lisbon, Portugal*

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A B S T R A C T

The RD52 calorimeter uses the dual-readout principle to detect both electromagnetic and hadronic showers, as well as muons. Scintillation and Cherenkov light provide the two signals which, in combination, allow for superior hadronic performance. In this paper, we report on detailed, GEANT4 based Monte Carlo simulations of the performance of this instrument. The results of these simulations are compared in great detail to measurements that have been carried out and published by the DREAM Collaboration. This comparison makes it possible to understand subtle details of the shower development in this unusual particle detector. It also allows for predictions of the improvement in the performance that may be expected for larger detectors of this type. These studies also revealed some inadequacies in the GEANT4 simulation packages, especially for hadronic showers, but also for the Cherenkov signals from electromagnetic showers.

1. Introduction

Dual-readout calorimetry is a novel particle detection technique, which makes it possible to measure electrons, photons and hadrons with very good precision, and without the (inter-)calibration issues that complicate working with traditional calorimeter systems that consist of separate electromagnetic (em) and hadronic sections. There is a growing interest in applying this technique, both for upgrades of existing detector systems (*e.g.*, the CMS experiment at CERN's Large Hadron Collider) and for experiments at proposed future particle colliders or in space.

Generic prototypes of dual-readout calorimeters have been and are being built by the DREAM and RD52 Collaborations. Test results have been published in a number of papers [1]. The largest detector of this type had an instrumented mass of 1350 kg. This was of course more than enough to study em showers (and also muons) in all possible detail. However, high-energy hadron showers are typically only contained at the 90–95% level in an instrument of this size and, therefore, the ultimate performance for hadron detection could not (yet) be assessed properly. However, the results obtained for the incompletely contained showers are very encouraging.

* Corresponding author. Fax: +1 806 742 1182.
E-mail addresses: Richard.Wigmans@ttu.edu, wigmans@ttu.edu (R. Wigmans).

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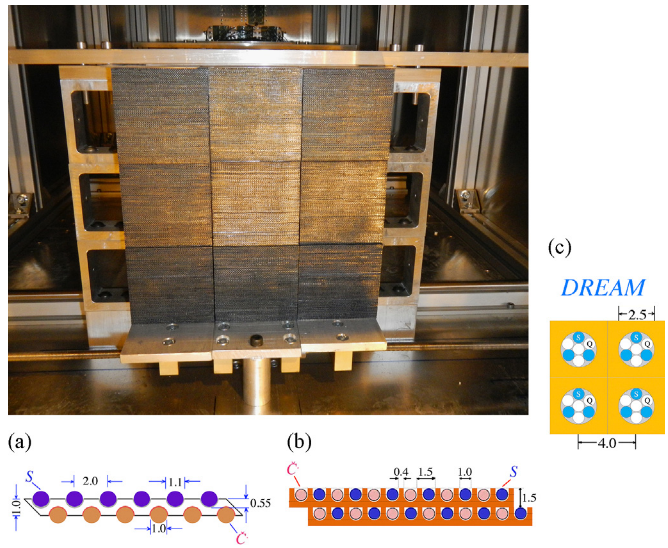

Fig. 1. Front view of the tested SuperDREAM calorimeter, and the basic structure of the lead (a) or copper (b) based modules. For comparison, the structure of the original DREAM calorimeter is shown as well (c). All dimensions are given in mm.

In this paper, we report on an extensive program of Monte Carlo studies of the performance of these unusual particle detectors. The purpose of these studies was:

1. To test the (limits of the) validity of such simulations with experimental data already obtained. In particular, we were interested in the dependence of the response and the energy resolution on parameters such as the particle's energy and its angle of incidence. The simulations also predicted certain effects that had not yet been studied experimentally, such as the anti-correlation between the two types of signals produced by the calorimeter. Verification of these predictions was also important in assessing the validity of the simulations.
2. To predict the effects on the performance for certain modifications of the detectors, for example a larger instrumented mass, an increased light yield, or a different choice of absorber medium.

These studies also made us aware of a number of subtle details of shower development and their (observable) consequences in this intricate particle detector. The paper is organized as follows. In Section 2, the structure of the simulated calorimeters and details of the simulation programs are described. Results of the simulations are given in Sections 3, 4 and 5 for muons, electrons and hadrons, respectively. The results are evaluated and discussed in Section 6.

2. Equipment and simulations

The RD52 calorimeters form the second generation of integrated em + hadronic calorimeters based on separate readout of the scintillation and Cherenkov light produced in the shower development. Two different types of optical fibers are used as the active media in this detector: scintillating fibers for the scintillation light and clear PMMA plastic fibers for the Cherenkov light. In the first generation (called DREAM), these two types of fibers were housed together in the holes of extruded copper rods (see Fig. 1c). In the RD52 (SuperDREAM) detector, each fiber is separately embedded, which leads to a substantially larger sampling frequency and correspondingly reduced sampling fluctuations. Also, the Cherenkov light is detected in clear plastic fibers, while quartz fibers were used for this purpose in DREAM.

Fig. 1 shows a picture of the front face of the RD52 calorimeter. It consists of nine modules, each module is subdivided into four towers, and each tower generates two signals, one from the scintillating fibers and one from the Cherenkov ones. In total, this detector thus produces 72 signals for each event.

These particular modules were built with lead as an absorber material. Fig. 1a shows a detail of the structure, with alternating layers of scintillating and clear fibers. We also built several modules using copper as an absorber material. The fiber arrangement in these modules, depicted in Fig. 1b, was slightly different. Each module measured 92×92 mm^2 and contained about 4000 fibers, 2000 of each type.

2.1. The simulated calorimeter structure

The simulated calorimeter structure was almost identical to the experimental ones. It consisted of nine modules, measuring 92×92 mm^2 each. The fibers were distributed according to a square grid, as shown in Fig. 2a and c. Each module contained 3721 fibers. The absorber material could be chosen. In these studies, we used either lead or copper. Small differences with the RD52 calorimeters concerned the fact that no tolerances were applied to the grooves that contain the fibers. Since the simulated modules thus do not contain any air, the sampling fraction is somewhat smaller than for the experimental ones. On the other hand, this is compensated by the fact that light produced anywhere in the 1 mm thick fibers was taken into account in the simulations. In reality, the cladding of the fibers does not contribute to the creation of scintillation light. Also, the fiber arrangement was not exactly the same as in the RD52 calorimeters. In the simulations, a perfectly square grid was used for both types of fibers, while in reality the arrangement was slightly different. Yet, the total number of fibers per module was approximately the same in all cases.

Fig. 2b shows the orientation of the entire, 2.5 m long detector, at an angle with respect to the beam particles entering the detector through its front face. The angles θ and ϕ indicate the tilt and the rotation in the horizontal plane, respectively.

All simulations described in this paper were carried out for a calorimeter with the structure described above. However, some of the experimental data with which comparisons are being made were obtained with the DREAM calorimeter, in which the fiber arrangement was quite different (see Fig. 1c). This was true for all muon data, and for the hadron data taken with a copper based calorimeter. In order to assess the possible effects of the different calorimeter structure, a subset of the simulations was also performed for a calorimeter structure that closely represented the one shown in Fig. 1c. The results of this exercise are described in the Appendix.[1] In the same spirit, we have also investigated the possible effects of air gaps inside the calorimeter structure, and the effects of changing the physics list in the simulations. The results of this work are also described in the Appendix. The figures shown in the following sections were obtained for the calorimeter structure from Fig. 2, unless explicitly stated otherwise.

2.2. The simulations

The simulations were carried out with the GEANT4 Monte Carlo package [2]. Events were generated with GEANT4.9.6 patch-02,

[1] Since experimental muon data were *only* obtained with the DREAM calorimeter, the experimental results are in this case compared with the results of these additional simulations in the text (Section 3).