Nuclear Inst. and Methods in Physics Research, A 898 (2018) 125–132

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

Ultra-fast hadronic calorimetry

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ARTICLE INFO

Keywords:
Hadronic calorimetry
Shower time structure
Pulse shape analysis
Pileup rejection
Background rejection
MARS15

ABSTRACT

Calorimeters for particle physics experiments with integration time of a few ns will substantially improve the capability of the experiment to resolve event pileup and to reject backgrounds. In this paper the time development of hadronic showers induced by 30 and 60 GeV positive pions and 120 GeV protons is studied using Monte Carlo simulation and beam tests with a prototype of a sampling steel-scintillator hadronic calorimeter. In the beam tests, scintillator signals induced by hadronic showers in steel are sampled with a period of 0.2 ns and precisely time-aligned in order to study the average signal waveform at various locations with respect to the beam particle impact. Simulations of the same setup are performed using the MARS15 code. Both simulation and test beam results suggest that energy deposition in steel calorimeters develop over a time shorter than 2 ns providing opportunity for ultra-fast calorimetry. Simulation results for an "ideal" calorimeter consisting exclusively of bulk tungsten or copper are presented to establish the lower limit of the signal integration window.

1. Introduction

Detector systems at existing and future high energy collider experiments face increasing challenges related to event pileup and accelerator related backgrounds [1,2]. An important tool for pileup and background rejection is the timing cut for the rejection of off-time signals. For example, the beam crossing interval option of 5 ns at the High Energy LHC, or FCC-hh would reduce pile-up by a factor of five with respect to the 25 ns option, provided that the detector integration time is shorter than the beam crossing interval. The relation between the energy resolution and pileup has also been approached in a simulation study within the CLIC e^+e^- linear collider project [3].

The hadronic calorimetry is particularly challenging in this respect. Depending on the absorber material, hadronic showers may develop over several ten to several hundred ns. Part of the hadronic shower energy is spent on the nuclear binding energy in reactions releasing nucleons from the absorber nuclei. In the case of neutrons, the binding energy is recovered in neutron capture reactions, provided these occur within the volume of the calorimeter and within the signal integration time window. Otherwise the binding energy remains undetected. The energy carried by neutrinos produced in the shower is also invisible. The fluctuation of the total invisible fraction is one of the main components of the energy resolution of a calorimeter. At high event rates the late component of the hadronic shower energy deposition contributes to the background for subsequent events, complicating reconstruction.

The loss of neutral hadron energy is recovered using so called "compensating" absorber materials, like uranium. A consequence of this, however, is that the development time of the hadronic showers reaches several hundred ns [4]. On the other hand, hadronic calorimeters using steel or copper as absorber demonstrate lower levels of late energy deposition [5]. The shower time structure of steel absorbers shows advantages over the more dense tungsten [6].

Our study seeks to understand the limits on the time window for the integration of the energy deposition of hadronic showers imposed by the shower development time in the calorimeter absorber material. To reach this goal we use Monte Carlo (MC) simulations and beam tests with a prototype of a steel-scintillator calorimeter. As the thickness of hadronic calorimeters typically exceeds 1 m, an important parameter of the shower development time is the time needed for the relativistic particle to traverse the calorimeter. In this article we study the shower development in terms of the *local* time $t_{\mathrm{loc}} = t - t_0$, where t_0 is time when the particle incident on the calorimeter would have crossed the studied calorimeter layer if moving along a straight line at the speed of light. For a collider experiment, the signal integration window defined in local time implies that the readout system is capable of location dependent integration windows such that the signal integration in a given cell starts at the moment when a relativistic particle arrives at the cell from the beam interaction point along a straight line. Signal integration in local time has been used as the underlying assumption

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https://doi.org/10.1016/j.nima.2018.05.003
Received 18 December 2017; Received in revised form 2 May 2018; Accepted 2 May 2018
Available online 8 May 2018
0168-9002/

in the simulation studies for CLIC [3]. A short integration time window clearly requires a choice of the active calorimeter material with fast response. Such technologies exist, while a detailed discussion is beyond the scope of this paper.

A number of studies have previously addressed various aspects of the time development of hadronic showers [4,5,7,8]. Dedicated efforts have been made recently to measure the time structure of the hadronic showers and provide benchmarking input for the simulation tools [6]. The focus of the present study is on the local time span for the full development of the shower at a given calorimeter depth, thus addressing the question of minimum required local integration time.

Simulations were performed using the MARS15 MC shower simulation code [9,10]. The beam tests were performed at the Fermilab Test Beam Facility (FTBF) [11]. The accuracy of the measured shower time development is limited in our studies by properties of the scintillation counter used to measure energy deposition. Still, it will be shown that our setup is sufficiently sensitive to distinguish shower development times of the order of 1–2 ns. This provides key information about shower time development to verify the potential of the proposed method of signal integration.

Section 2 describes the MARS15 software used for the simulation. Section 3 describes the experimental setup, the data acquisition and the beam. Results for the test calorimeter are presented in Section 4. Section 5 presents the simulation of an "ideal" calorimeter consisting exclusively of tungsten or copper in order to establish the lower limit of the energy integration window. Conclusions are given in Section 6.

2. MARS15 simulation code

MARS15 [9,10] is a general purpose, all-particle MC simulation code. It contains established theoretical models for strong, weak and electromagnetic interactions of hadrons, heavy ions, and leptons. Most processes in the code can be treated exclusively (analogously), inclusively (with the corresponding statistical weights) or in mixed mode. The exclusive approach is used in this study. In this case the hadron–nucleus interactions are modeled with the LAQGSM event generator [12]. The LAQGSM module in MARS15 is based on the quark-gluon string model above 10 GeV and intranuclear cascade, pre equilibrium, and evaporation models at lower energies. The EGS5 code for electromagnetic shower simulation is used for energies from 1 keV to 20 MeV, with a native MARS15 module used at higher energies.

Ultimately all cascade particles transform energy to electrons through decays, inelastic, and elastic interactions with atomic electrons. Appropriate energy thresholds are applied to finish simulation in a reasonable time (see below for details). If the energy of a particle becomes lower than the threshold, particle transport is not continued and the remaining kinetic energy is assumed to be deposited in the local medium without additional delay. This is done for the majority of stable particles, nuclear recoils, heavy ions, and photons. Negative particles can be captured by the atomic nuclei of the medium. They decay while in an atomic orbit, emitting photons in the event of orbital transitions or are absorbed by the nucleus, with delay of up to 80 ns for uranium and $2.2\,\mu s$ for hydrogen. Positive particles may annihilate (positron, antinucleon) or decay (pions, kaons, etc.). Neutrons are captured in (n,γ) reactions and the photons from the capture reaction ultimately produce electrons. In all cases, electrons, protons, photons, neutrons, and neutrinos are present in the final phase of the cascade. The deposited energy in MARS15 consists of the ionization energy loss and the sub-threshold particle energies. As shown in detail below care is taken that the particle thresholds are sufficiently low to avoid bias in the results that might arise from the inclusion of non-ionization energy losses.

The electrons produced by the ionization of the medium are simulated by treating the "soft" and the "hard" collisions with atomic electrons separately. The soft electrons are simulated by sampling their angular and energy distribution, while the relatively small number of hard collisions, producing the so-called "delta-electrons", is treated by detailed simulation of the interaction kinematics [13]. The time of the energy deposition at each simulation step is calculated as the time at the end of the step.

Table 1
Studied absorber thickness, beam energies, and particle types.

Front absorber thickness	30 GeV	60 GeV	120 GeV
1.8 λ_{int}	π^+	π^+	p
3.0 λ_{int}			p

The results of the MARS15 simulation depend on the choice of threshold energies for different particles. This dependence can be studied by reducing the threshold energies. Default MARS15 threshold energies are: 1 MeV for charged hadrons and muons, 0.5 MeV for electrons and 0.1 MeV for photons and neutrons. We verified that calorimeter simulation results are stable when the threshold energies are reduced by a factor of ten.

3. Experimental setup

3.1. Test beam setup

Fig. 1 shows the top view of the experimental setup. Counter S2 is placed between two iron absorber blocks to record local shower energy deposition. The cross section of both iron blocks is 30×30 cm^2, leaving 0.9 interaction length, λ_{int}, in the direction transverse to the beam between the beam impact point in the center and the closest edge of the absorber block. The total thickness of the absorber is 60 cm, corresponding to 3.6 λ_{int} in iron. In various runs, the absorber thickness before and after the counter is subdivided into either $1.8 + 1.8\,\lambda_{int}$ (as in Fig. 1) or $3.0 + 0.6\,\lambda_{int}$ (50 cm before and 10 cm after the S2 counter). In the following, the configurations are referred to according to the thickness *in front* of the counter. The total absorber thickness is always $3.6\,\lambda_{int}$. Table 1 shows the beam energies and absorber configurations used during the studies.

The iron blocks are constructed of bricks and plates. Care was taken to avoid longitudinal joint slits in the construction along and near the beam axis. The density of the iron pieces was measured to be consistent with the density of steel, 7.7 g/cm^3, within the 2% uncertainty of the measurement.

The S2 counter is assembled with Bicron® scintillator material [14], featuring fast response time and a FEU-115M photomultiplier tube [15], with good linearity and fast response. The FWHM of the signal induced by a MIP in the S2 counter is 7.5 ns. The dimensions of the S2 counter are $2.5 \times 15 \times 1.25$ cm^3 in the horizontal direction perpendicular to the beam, vertical direction, and along the beam, respectively.

Counters S3, S4 and A1 are positioned on the beam axis to trigger the data acquisition. The beam diameter at 10% of the maximum is 1 cm. The dimensions of the counter S3 are $2.5 \times 18 \times 1.25$ cm^3, of the counter S4 $2.0 \times 6 \times 1.1$ cm^3 and of the counter A1 $25.5 \times 25.5 \times 1.0$ cm^3. The dimensions are given in the horizontal direction perpendicular to the beam, vertical direction, and along the beam, respectively. Counter A1 has a circular hole of 4 cm in diameter centered on the beam axis to veto upstream showers. The trigger logic is $S3 \times S4 \times \overline{A1}$. Trigger signals are formed using NIM discriminator and coincidence modules.

Fig. 2 shows the cross-sectional layout of the setup including the relative position of the absorber and the counter. Three different distances from the beam axis, $\rho = 0$, 5 and 10 cm, are studied to scan the dependence of the energy deposition and of the time structure on the transverse distance from the shower core.

The minimum ionizing particle (MIP) response of the S2 counter was periodically recorded using the 120 GeV proton beam with the iron absorbers moved out of the beam.