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New results from the RD52 (DREAM) project

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ABSTRACT

Simultaneous detection of the Čherenkov light and scintillation light produced in hadron showers makes it possible to measure the electromagnetic shower fraction event by event and thus eliminate the detrimental effects of fluctuations in this fraction on the performance of calorimeters. In the RD52 (DREAM) project, the possibilities of this dual-readout calorimetry are investigated and optimized. In this talk, the latest results of this project will be presented. These results concern the performance of a matrix of molybdenum doped lead tungstate crystals built for this purpose, new data on the application of the polarization of Čherenkov light in this context, and the first test results of prototype modules for the new full-scale fiber calorimeter.

1. Introduction

RD52 is a *generic* detector R&D project, carried out at CERN by the DREAM Collaboration. Our goal is to investigate, and to the extent possible eliminate, the factors that prevent calorimetric measurements of the four-vectors of jets and single hadrons with the same level of precision we have grown accustomed to for electrons and photons. In most calorimeter systems serving in modern high-energy physics experiments, this precision is limited by fluctuations in the energy fraction carried by the electromagnetic shower component (f_{em}). In our detectors, such fluctuations are eliminated by simultaneous measurements of the energy deposit dE/dx and the fraction of that energy carried by relativistic charged shower particles. We have experimentally demonstrated that this makes it possible to measure f_{em} event by event [1]. We use scintillation light and Čherenkov light as signals for the stated purposes. Therefore, this method has become known as the Dual REAdout Method (DREAM). Since it is possible to eliminate fluctuations in f_{em}, this method provides in practice the same advantages as intrinsically compensating calorimeters ($e/h = 1$), but are not subjected to the limitations of the latter devices: sampling fraction, signal integration time and volume, and especially the choice of absorber material. As will be shown in this paper, this has important consequences for the precision of jet measurements.

The tri-annual Elba conference has played an important role in our reporting on the achievements in the context of this project. In 2003, we showed pictures of the original DREAM calorimeter, which was under construction at that time [2]. The first results, including the experimental proof of the DREAM principle, was presented at the 2006 conference [3]. At the same conference, we also demonstrated that it is possible to split the signals from certain high-Z crystals into scintillation and Čherenkov components, which opened the possibility to perform dual-readout calorimetry with homogeneous crystal calorimeters. At the 2009 conference, we discussed and demonstrated the different possibilities to achieve this goal [4], making use of differences in time structure, spectral and polarization characteristics, and directionality of the two signal components. At that conference, we also demonstrated the importance of detailed measurements of the time structure of the calorimeter signals, for example for measuring the contribution of neutrons to the signals. Such measurements are important to reduce another dominant source of fluctuations, namely in the nuclear binding energy losses which do not leave other measurable signals.

At this year's conference, we present some new results from our crystal program. We also show results of the first beam tests of prototype modules of the new fiber calorimeter, which is being constructed in the context of the RD52 project.

2. The RD52 crystal program

After having studied the different methods to split the signals from crystals such as BGO, BSO and $PbWO_4$ into scintillation and Čherenkov components in great detail, we have assembled two matrices of crystals (one consisting of 100 BGO crystals and one consisting of 7 Mo-doped $PbWO_4$ crystals) that were large enough to contain em showers and tested these in dual-readout mode

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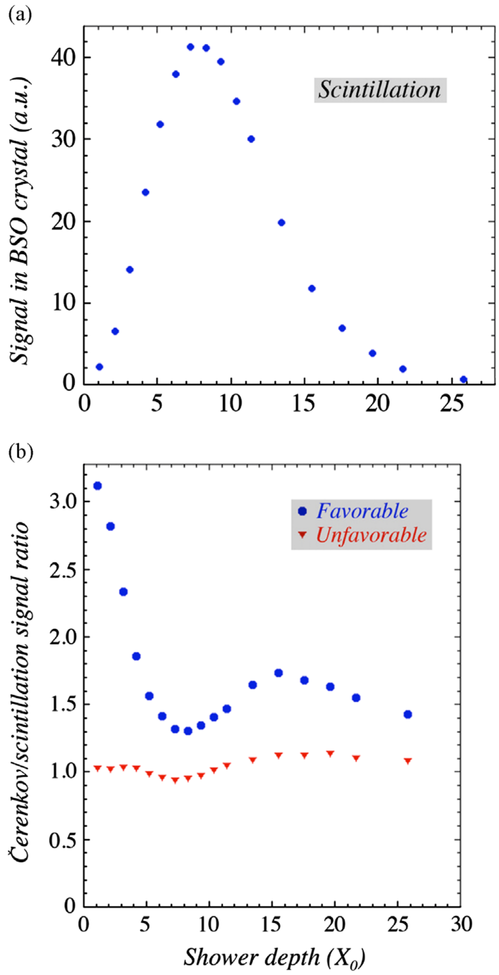

Fig. 1. The scintillation signal in the BSO crystal (a), and the ratio of the Cherenkov and scintillation signals (b) as a function of the amount of lead absorber installed in front of the crystal. The Cherenkov signal was measured for two (perpendicular) orientations of the polarization filter, one of which favored the light transmission. Results for 80 GeV electrons.

with high-energy electron beams. The results of this exercise are being presented in the poster session at this conference [5]. More details about this work can be found in Ref. [6].

Another recent result concerns a measurement of the polarization of the Čherenkov light produced in developing em showers. After we demonstrated that the radial polarization of the Čherenkov light can be used to distinguish between the scintillation and Čherenkov components of the light produced in a crystal [7], we set out to measure the effective polarization of the Čherenkov component in a developing em shower. A BSO crystal was placed at the Čherenkov angle with the beam line, such as to maximize the Čherenkov light detected at the crystal exit face. The Čherenkov component was purified by means of a UV filter, and a polarization filter was placed between the crystal and the PMT that measured the signals. On the opposite crystal end face, a yellow filter selected almost pure scintillation light. Upstream of the crystal a varying amount of lead absorber was installed, so that the crystal measured the shower characteristics at different depths.

The measurements of the scintillation signal (Fig. 1a) show indeed the typical longitudinal profile expected for 80 GeV electron showers. However, the profile for the Čherenkov signal (Fig. 1b) shows an unexpected feature. After initially decreasing very fast, the effective polarization increases again beyond the shower maximum. We have planned a number of additional beam tests to verify and understand this feature.

3. The SuperDREAM fiber calorimeter

Even though crystals offer interesting possibilities, we believe that fiber-based detectors offer the most promising applications for dual-readout calorimetry. For this reason, we have embarked on a construction program that should produce a device that is sufficiently large to contain high-energy jets at a level where shower leakage fluctuations are *not* dominating the hadronic energy resolution. As mentioned in the introduction, one advantage of the dual-readout technique over intrinsically compensating calorimeters is the fact that it allows the use of low-Z absorber material such as copper. This is especially important for obtaining excellent energy resolutions for jets.

This is illustrated in Fig. 2, which shows the response of the ZEUS calorimeter to low-energy single hadrons, relative to the response to electrons. For energies above 5 GeV, this response ratio is 1.0, since the calorimeter is compensating. The strong non-linearity observed for lower-energy hadrons is a consequence of the fact that, as the energy decreases, an increasing fraction of the hadrons do not develop showers, but rather range out, i.e. behave as muons. In comparison with mips, em showers are inefficiently sampled in calorimeters with high-Z absorber material [9]. In the ZEUS calorimeter, which used depleted uranium (^{238}U) as absorber material, the e/mip ratio was only $\sim$0.6. And since soft hadrons are typically a major component of fragmenting quarks and gluons, the jet resolution in ZEUS was significantly worse than for single hadrons. This effect could be avoided in dual-readout calorimeters that use copper as absorber material, since the e/mip value is in that case $\sim$0.9.

Yet, it turned out that the absorber structures needed for the high-frequency sampling calorimeter we want to construct are not easy to make. For that reason, the first prototype modules were using lead as absorber material, since this is easy to extrude. Fig. 3 shows a picture of the first module. The main differences with the original DREAM fiber module concern the fact that each fiber is now individually embedded in the absorber structure, whereas the fibers were bunched together in groups of 7 in the DREAM module. This difference is illustrated by the inserts in Fig. 3. Also, the number of fibers has been increased by about a factor of two. The limit in this respect is given by the fact that readout (eight PMTs for reading out the four calorimeter towers of which each module consists) has to fit within the detector envelope. For that reason, we have chosen PMTs with a very large effective photocathode area.

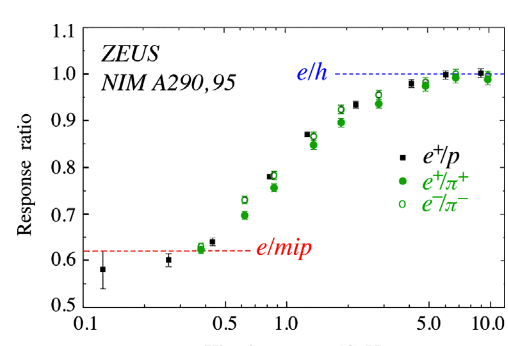

Fig. 2. The response of the (compensating) ZEUS uranium/plastic-scintillator calorimeter to low-energy hadrons [8].

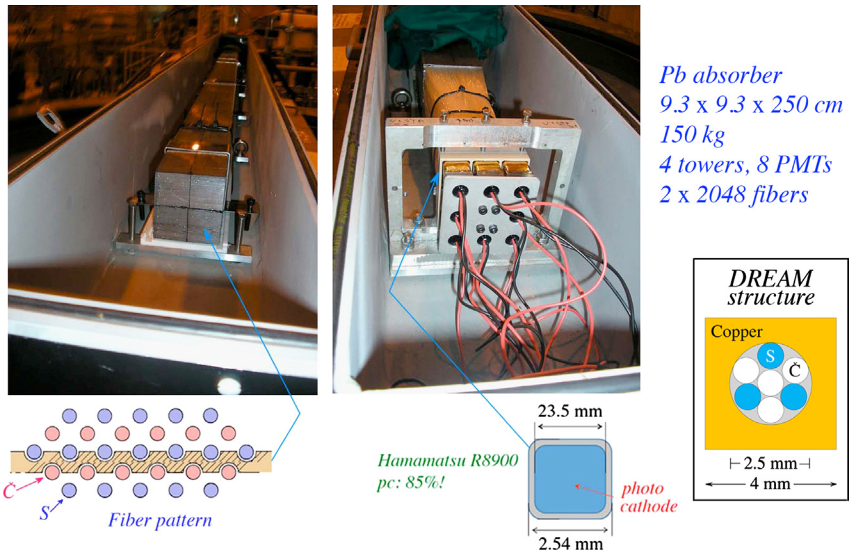

Fig. 3. Upstream (left) and downstream (right) views of the first SuperDREAM fiber module tested as CERN. See text for details.

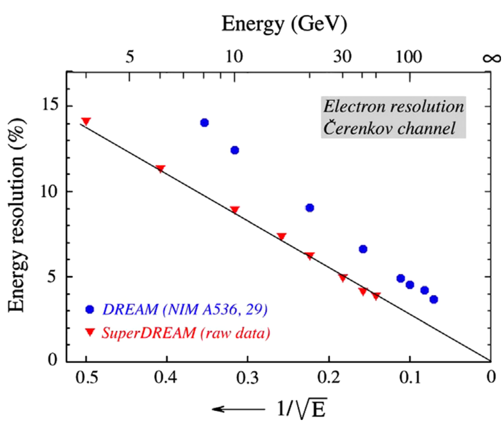

Fig. 4. Comparison of the em energy resolution in the Cherenkov channel, measured with the first SuperDREAM modules and with the original DREAM calorimeter [10].

One of the most important (and limiting) characteristics of this calorimeter is the Čherenkov light yield. In the shown lead-based module, we measured this light yield to be ~ 60 photoelectrons per GeV deposited energy, an increase by a factor 7 compared to the original DREAM module. The changes in the structure of the fiber module did indeed pay off in the form of a substantially improved em energy resolution. This is illustrated in Fig. 4, where this resolution is compared to the published values obtained with the original DREAM module [10].

The improvement is especially important at the highest energies, due to the absence of a significant deviation from $E^{-1/2}$ scaling (the so called "constant term"). Further improvements may be expected as a result of the use of copper absorber, fiber aluminization and better shower containment.

In the meantime, we have found a way to construct this type of calorimeter module using copper as absorber material as well. Fig. 5 shows the first module during its construction phase. The upper and lower pictures show the front face of the module while the Čherenkov and scintillating fibers of one tower were illuminated from the rear end, respectively. Close inspection, e.g., of the tower corners, shows that the fibers that light up are indeed not the same ones in these two pictures.

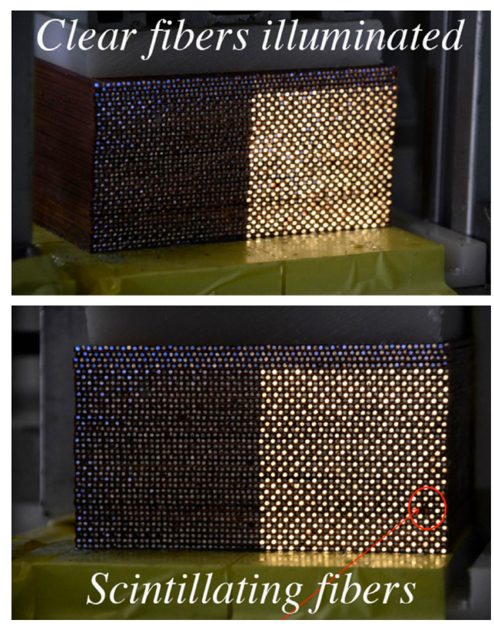

Fig. 5. Pictures of the first SuperDREAM module built with copper as absorber material.

Eventually, a substantial number of such modules will be assembled together to form a hadron calorimeter. By the end of 2012, we expect to have a detector with a mass of ≈ 2000 kg available for this purpose. However, tests with a pion beam of only *one* module (the one shown in Fig. 3) gave already encouraging results, as illustrated in Fig. 6. The calorimeter module was surrounded by a shield of scintillation counters, intended for a crude measurement of the energy leaking out of this 150 kg detector. Fig. 6a and b shows the scintillation signal distribution for 180 GeV pions sent into this module and the (anti-)correlation between these signals and those observed in the leakage shield, respectively. The virtue of the dual-readout principle is illustrated in Fig. 6c, which shows a scatter plot of the (corrected) scintillation signal versus the Čherenkov/scintillation signal ratio. As expected, the smaller this ratio, the smaller f_{em} and, therefore, the smaller the scintillation signal. After an event-by-event correction for the

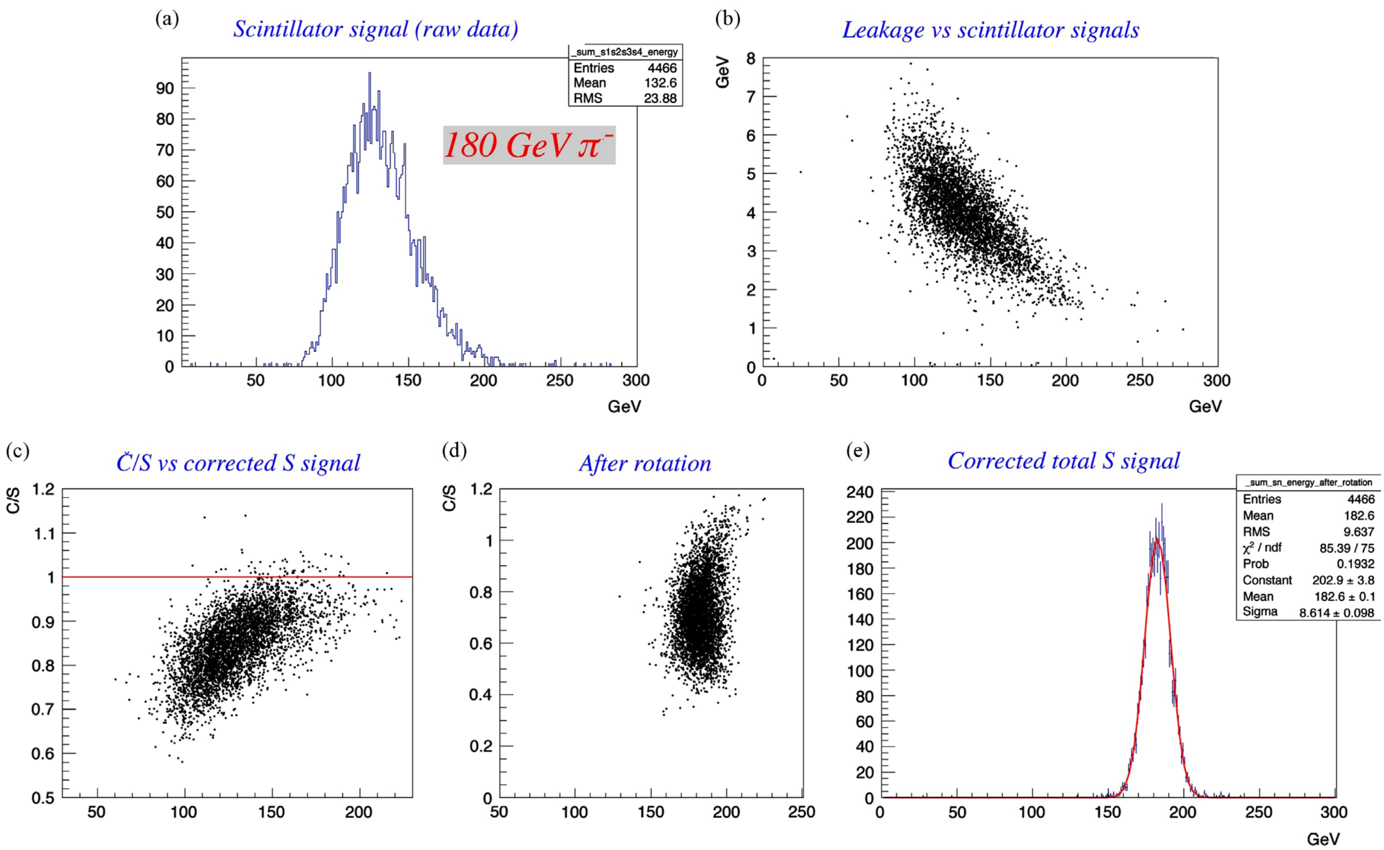

Fig. 6. First measurements of pions in a single module of the new SuperDREAM fiber calorimeter, surrounded by leakage detectors. See text for details.

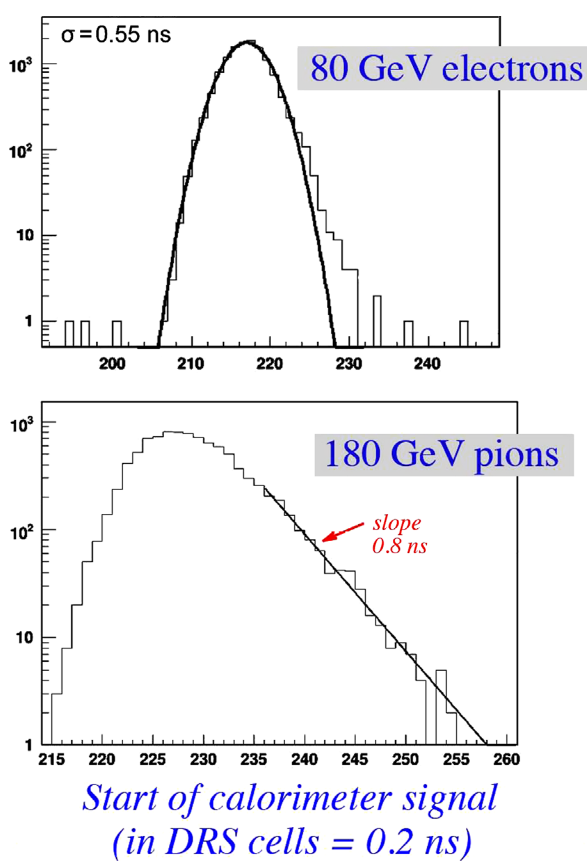

Fig. 7. Distribution of the starting times of signals from 80 GeV electrons and 180 GeV pions in the fiber calorimeter.

effect of the measured f_{em}, this scatter plot is converted into the one shown in Fig. 6d, and the projection of this scatter plot on the horizontal axis (Fig. 6e) produces a Gaussian distribution with approximately the right energy and a fractional width of less than 5%.

A crucial aspect of this type of calorimeter is its *longitudinally unsegmented* structure. However, the detailed time structure of each event makes it possible to obtain crucial information about the depth at which the light is produced. Using the fact that light travels at a speed of *c*/*n* in the fibers, while the particles producing the light travel at *c*, the starting time of the signals makes it possible to measure the depth at which the light is produced with a resolution of $\sim$20 cm, as illustrated in Fig. 7. This makes it possible to correct for small effects of light attenuation in the fibers and is an important tool for electron/photon identification in this type of calorimeter. As shown earlier [4], the time structure, measured with a Domino Ring Sampler operating at 5 GHz [11], is also an important tool for measuring the neutron contribution to the scintillation signals.

Dual-readout detectors hold the promise of high-quality calorimetry for *all* types of particles, with an instrument that can be calibrated with electrons.

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