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The DREAM project—Towards the ultimate in calorimetry

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ABSTRACT

High-precision jet spectroscopy will be increasingly important in future high-energy accelerator experiments, particularly at a linear e^+e^- collider. The dual-readout technique makes it possible to meet and exceed the requirements on calorimeter performance in experiments at such a collider. The DREAM Collaboration is exploring the limits of the possibilities offered by this technique, by systematically eliminating the limiting factors, one after the other. Powerful tools in this context are the simultaneous measurement of scintillation light and Cherenkov light generated in the shower development process, and a detailed measurement of the time structure of the signals. In this talk, the latest results of this generic detector R&D project are presented. In particular, I report on the first tests of a hybrid dual-readout calorimeter system, in which a BGO crystal matrix served as the electromagnetic section.

1. Introduction

DREAM[2] started in 2002 as a generic detector R&D project, intended to explore (and, if possible, eliminate) the obstacles that prevent calorimetric detection of hadrons and jets with a comparable level of precision as we have grown accustomed to for electrons and photons. The initial collaboration, consisting of fewer than 10 physicists, built a prototype detector based on optical fibers, which was successfully tested at the SPS in 2003 and 2004. The excellent results obtained in these tests generated a lot of interest, and the collaboration has considerably expanded since that time.

In the early tests, we concentrated on the dominating source of fluctuations, i.e. fluctuations in the electromagnetic content of hadron showers. After these initial studies, in which the effects of these fluctuations on hadronic calorimeter performance were successfully eliminated, the collaboration has focused on the remaining effects, which rose to prominence as a result: sampling fluctuations, signal quantum statistics and nuclear breakup effects.

In this context, we have also carried out (in 2006–2008) a series of successful studies of crystal calorimeters, and of methods to split the signals from these crystals into scintillation and Cherenkov components. Recently, a full-size crystal matrix consisting of 100 BGO crystals served as the em section of a hybrid calorimeter system, in which the original fiber calorimeter formed the hadronic section. Some preliminary results from these tests are shown in this contribution.

We have now reached the point where we believe that we have all the ingredients in hand to build the perfect calorimeter system, or at least a calorimeter system that meets and exceeds the performance requirements of experiments at the ILC and CLIC. Proposals to build such a calorimeter have been submitted to our funding agencies. Some aspects of such a calorimeter are discussed in this contribution.

2. The DREAM approach to ultimate calorimetry

In almost all calorimeters, fluctuations in the electromagnetic shower fraction (f_{em}) dominate the energy resolution for hadrons and jets. These fluctuations, and their energy-dependent characteristics, are also responsible for other undesirable calorimeter characteristics, such as hadronic signal non-linearity and a non-Gaussian response function. There are two possible approaches to eliminate (the effects of) these fluctuations [1]: by designing the calorimeter such that the response to em and non-em energy deposit is the same (compensation, $e/h = 1.0$), or by measuring f_{em} event by event. The DREAM project follows the latter approach. Therefore, calorimeters built according to the DREAM principles are *not* subject to the limitations imposed by the requirements for compensating calorimetry: a small sampling fraction (and the corresponding large sampling fluctuations), and the need to integrate the signals over a very large detector volume (because of the crucial signal contributions of soft neutrons).

2.1. The unique benefits of Cherenkov light

Detecting Cherenkov light generated in shower development is a crucial ingredient of DREAM calorimeters. Since Cherenkov light

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[1] On behalf of the DREAM Collaboration
[2] The name DREAM stands for Dual-REAdout Method.

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is in practice almost exclusively generated by the em shower component, a comparison between the Cherenkov signals and those from a medium based on dE/dx measurements (e.g. scintillator) generated by the *same shower* makes it possible to measure f_{em} for that shower.

The DREAM principle is illustrated in Fig. 1. The two types of signals generated by 100 GeV π^- are shown in a scatter plot, in which each event is represented by a dot. The fact that these dots do *not* cluster around the diagonal demonstrates that the two signals provide complementary information about the shower development. The two signals, Q and S, depend on the energy of the showering particle (E), on the em shower fraction (f_{em}) and on the (energy-independent) e/h value, which suppresses the response to the non-em shower component (Eqs. (1) and (2)). The dual-readout method works because the two e/h values, $(e/h)_S$ and $(e/h)_Q$, are very different: in our fiber calorimeter they were measured to be 1.3 for the copper/scintillator structure and 4.7 for the copper/Cherenkov fiber structure, respectively. Eqs. (1) and (2) thus can be solved for either of the two unknown quantities, f_{em} or E. If we divide 1 by 2, the shower energy is eliminated and the resulting Eq. (3) gives a simple, *energy-independent* relationship between the ratio of the two measured signals and the em shower fraction. A measurement of this ratio thus provides directly the value of f_{em} for each individual event.

One can also solve Eqs. (1) and (2) for the shower energy E. This results in Eq. (4), which provides a simple recipe to determine that energy for each individual event on the basis of the two measured signals and one constant (χ) characteristic for the calorimeter system.

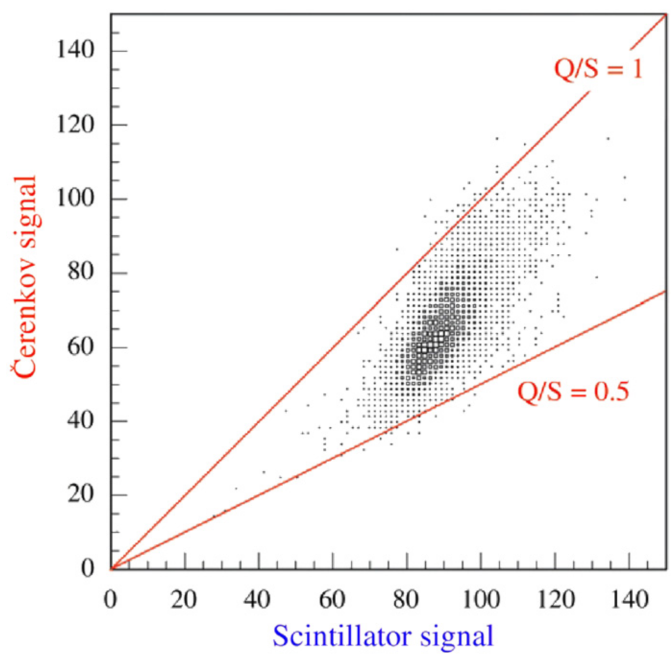
The DREAM fiber calorimeter, as well as many results obtained in beam tests of this device, have been described in detail in a number of papers [2]. The recipe described above turned out to work very well indeed. Among the results obtained by applying Eqs. (3) and (4), we mention:

- When the calorimeter was calibrated with electrons, hadronic energies determined with this recipe were within a few percent equal to their nominal values.
- Hadronic signal linearity was restored.
- Hadronic response functions became Gaussian.
- Hadronic energy resolutions improved considerably, especially at the highest energies.
- Deviations from $E^{-1/2}$ scaling in the hadronic energy resolution were eliminated.

All these results were not only observed for single hadrons, but also for multiparticle "jets", which were mimicked by means of high-multiplicity interactions in an upstream target.

2.2. Further improvements

The elimination of (the effects of) this dominant source of fluctuations meant that other types of fluctuations now dominated the detector performance. Further improvements should be obtained by concentrating on these. Three types of fluctuations dominated and limited the energy resolution of the DREAM fiber calorimeter:



$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right] \qquad (1)$$

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right] \qquad (2)$$

e.g. If $e/h = 1.3$ (S), 4.7 (Q)

$$\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})} \qquad (3)$$

$$E = \frac{S - \chi Q}{1 - \chi} \qquad (4)$$

with $$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$$

Fig. 1. Scatter plot of the Cherenkov signals for 100 GeV π^- mesons versus those generated by the scintillating fibers in the DREAM calorimeter. Each event is represented by a dot. Also shown are the equations that form the basis of the dual-readout method. The use of the symbol Q for the Cherenkov signals derives from the fact that these signals were generated by quartz fibers in the original DREAM calorimeter.

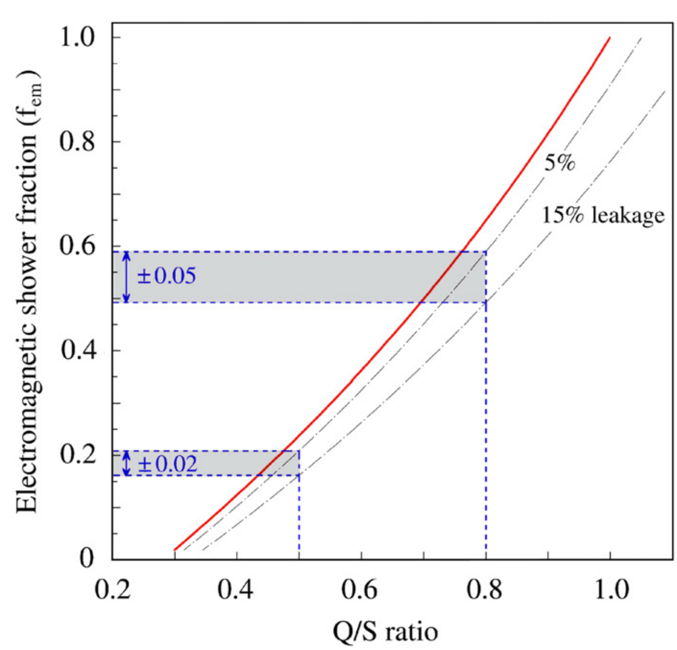


Fig. 2. The relationship between the Q/S signal ratio and the em shower fraction, f_{em} (Eq. (3)). Also shown is how a shower leakage of $10 \pm 5\%$ translates into an uncertainty in the em shower fraction.

1. Leakage fluctuations.
2. Fluctuations in the Cherenkov light yield.
3. Sampling fluctuations.

The first source could be eliminated by making the detector sufficiently large. The tested instrument had an effective radius of only 0.8 λ_{int}. Side leakage amounted, on average, to about 10% of the shower energy [3], and fluctuations in this fraction played a dominant role. This is illustrated in Fig. 2, which shows that these fluctuations lead to an uncertainty in the relationship between the measured quantity (the Q/S signal ratio) and the one needed for the DREAM recipe (the em shower fraction f_{em}).

There is absolutely no reason why the DREAM principles should be limited to fiber calorimeters. In particular, they could be applied to *homogeneous* detectors, provided that a way was found to distinguish the Cherenkov and scintillation light produced by such detectors. If successful, this approach could eliminate at once both the effects of sampling fluctuations and the effects of fluctuations in the Cherenkov light yield to the hadronic energy resolution. For this reason, the DREAM Collaboration has since 2006 carried out a variety of studies involving crystal calorimeters.

In order to distinguish the contributions from the Cherenkov and the (dominating) scintillation components to the crystal signals, we have exploited three properties:

1. The Cherenkov light is *directional*, while the scintillation light is isotropically emitted.
2. The Cherenkov light is *prompt*, whereas the scintillation processes in the crystals exhibit one or several decay constants.
3. The two types of light have *different spectra*. If these two spectra are sufficiently different, they can be separated by means of optical filters.

Fig. 3 illustrates the effects of all three methods, for measurements carried out on a $PbWO_4$ crystal doped with 1% molybdenum [4]. A beam of 50 GeV electrons was steered through the center of this crystal, which was placed on a platform that could rotate around a vertical axis (Fig. 3a). The signals generated by the beam particles were read out with PMTs from both sides. One side (labeled R) was equipped with a UV optical transmission filter, the other side (labeled L) with a yellow filter. The PMT signals were digitized with a sampling oscilloscope, which measured the amplitude of the signals every 0.8 ns. The (average) time structures of the two signals are depicted in Fig. 3b. These signals are very different. The UV signal is prompt, whereas the yellow signal exhibits an exponential decay with a time constant of 26 ns. The fact that the UV signals are caused by Cherenkov light and the yellow signals by scintillation light is further illustrated by the angular dependence of the signal ratio (integrated over the entire time structure), which is shown in Fig. 3c. This ratio is strongly dependent on the angle of incidence

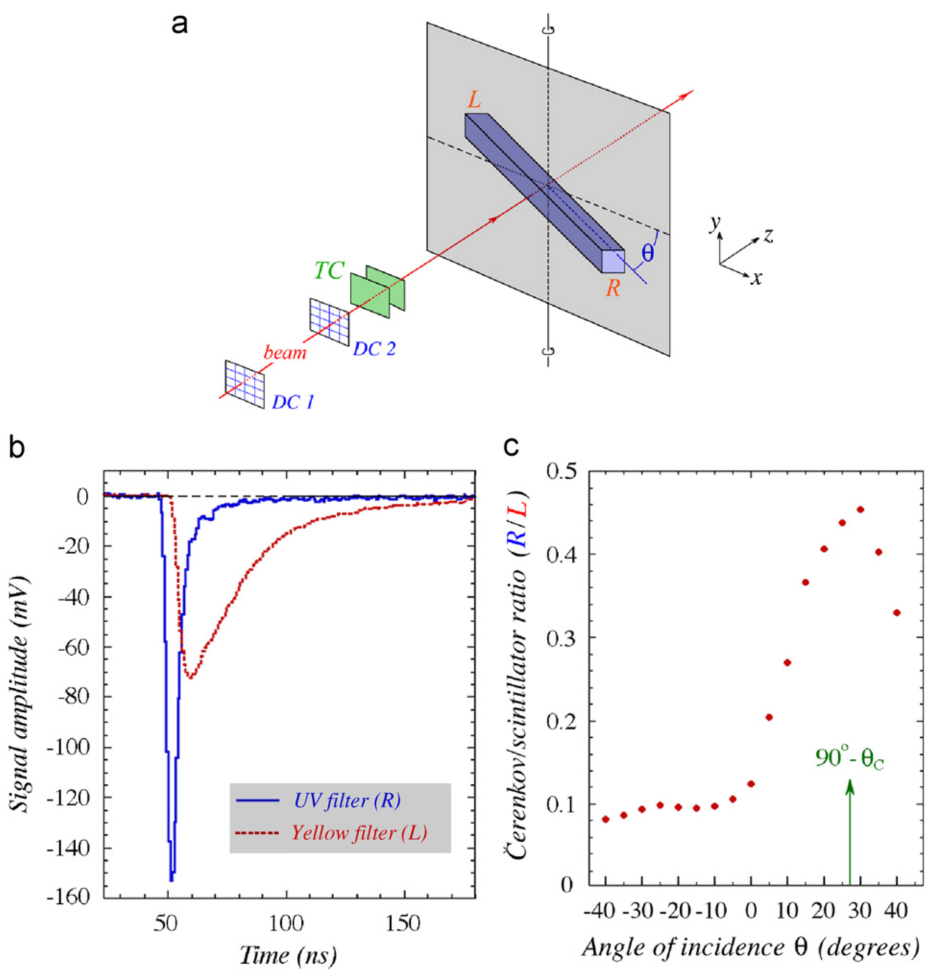


Fig. 3. Unraveling of the signals from a Mo-doped $PbWO_4$ crystal into Cherenkov and scintillation components. The experimental setup is shown in diagram a. The two sides of the crystal were equipped with a UV filter (side R) and a yellow filter (side L), respectively. The signals from 50 GeV electrons traversing the crystal are shown in diagram b, and the angular dependence of the ratio of these two signals is shown in diagram c. (For interpretation of the references to the color in this figure legend, the reader is referred to the web version of this article.)

and reaches a maximum near the expected value of $\theta = 27^{\circ}$, i.e. 90° minus the Cherenkov angle ($n = 2.2$).

We have recently tested the use of crystals as DREAM calorimeters in a series of measurements in which our fiber calorimeter was preceded by an electromagnetic section consisting of 100 BGO crystals recovered from the L3 experiment. In order to maximize the sensitivity to the performance of the crystal matrix, these measurements were carried out with high-multiplicity multi-particle "jets", which deposited on average about half of their energy in the crystal matrix. The crystal signals were split into Cherenkov and scintillation components based on their time structure [5].

Fig. 4 demonstrates that the dual-readout principle also worked well for this hybrid calorimeter system. The figure shows the total (i.e. BGO + fiber) Cherenkov signal distribution for the 200 GeV "jet" events (Fig. 4a), as well as the signal distributions for event samples selected for three bins of the Cherenkov/signal ratio (Fig. 4b). The larger this ratio, the larger the total calorimeter signal. The overall, asymmetric signal distribution is evidently a superposition of many more narrow, Gaussian distributions such as the ones shown in Fig. 4b. This result is similar to the one found for the dual-readout fiber operated in stand-alone mode.

2.3. *The last barrier*

If the dual-readout principles could be as efficiently applied in homogeneous detectors as in the original DREAM fiber calorimeter, then the contributions of signal quantum fluctuations and sampling fluctuations, which dominated and limited the hadronic energy resolution of compensating calorimeters (SPACAL, ZEUS) to (the current world record of) $\sim 30\%/\sqrt{E}$ could be reduced to insignificant levels in this type of calorimeter. The resolution of a sufficiently large detector would then become dominated by *nuclear breakup* effects. Fluctuations in the fraction of the total energy needed to release protons, neutrons and heavier nuclear fragments in the nuclear reactions initiated by the shower particles lead to fluctuations of the *visible energy*, and thus to fluctuations in the calorimeter response. It has been demonstrated previously [6] that a measurement of the total kinetic energy carried by neutrons generated in the shower development is a powerful tool for reducing the effects of these fluctuations.

We have demonstrated that the signal contributions from shower neutrons can be measured event by event from the time structure of the scintillator signals [7,8]. The neutron contribution manifests itself as a tail with a characteristic time constant (~ 20 ns in our fiber calorimeter). As illustrated in Fig. 5, this tail was absent in the Cherenkov signals and also in scintillator signals generated by em showers. The neutron fraction derived from the time structure turned out to be anti-correlated with the Cherenkov/scintilation signal ratio, and thus with the relative strength of the em shower component. However, it does provide complementary information, which leads to further improvements in the energy resolution.

3. Future plans

If the techniques described above would be fully exploited for eliminating the effects of the fluctuations that limit the performance of hadron calorimeters, then the theoretical resolution limit of $\sim 15\%/\sqrt{E}$ should be within reach. We are planning to build a detector that could indeed reach that performance level. All the knowledge accumulated during the past seven years will be incorporated in the design of this instrument. Some of the critical elements of the fiber calorimeter (section) include:

- The size. In order to limit leakage fluctuations to the level of $0.01E$, the detector radius should be at least 30 cm, and the total instrumented volume 5000 kg.
- The fiber packing, and the closely related total photocathode area, will be maximized.

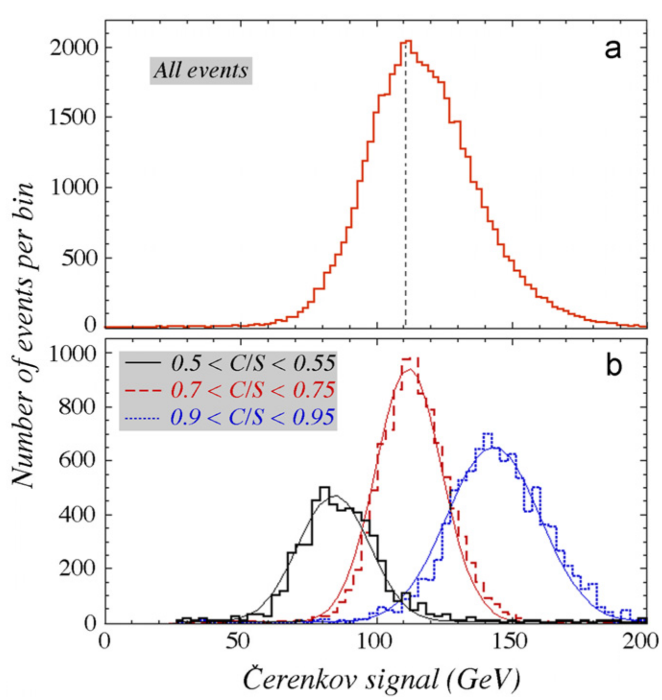


Fig. 4. The Cherenkov signal distribution for 200 GeV "jet" events detected in the BGO + fiber calorimeter system (a) together with the distributions for subsets of events selected on the basis of the ratio of the total Cherenkov and scintillation signals in this detector combination (b).

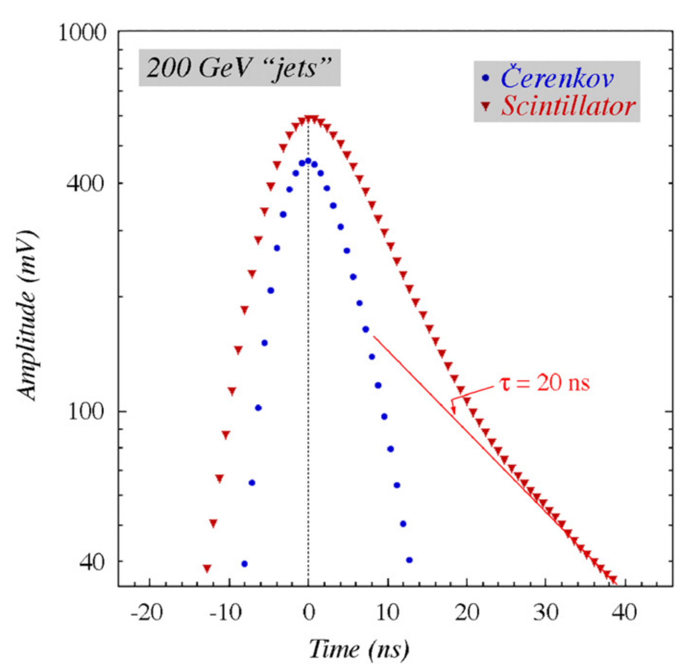


Fig. 5. The average time structure of the Cherenkov and scintillation signals recorded for 200 GeV "jets" in the fiber calorimeter.

- Fibers will be individually embedded in the absorber structure, not in groups of seven as in the existing detector.
- The numerical aperture of the Cherenkov fibers will be maximized, such as to give >100 photoelectrons/GeV.
- The upstream end of the Cherenkov fibers will be aluminized. This will make it possible to eliminate effects of light attenuation.
- The time structure will be measured for all 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. At the next Elba conference, we hope to be able to deliver on this promise.

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