Dual-Readout Calorimetry for High-Quality Energy Measurements

Final report
on a project in the context of the
Advanced Detector Research Program

DOE award DE-FG02-07ER41495
September 1, 2007 - Augustt 31, 2010

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December 2013

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1 Introduction and summary

This document constitutes the final report on the project "Dual-Readout Calorimetry for High-Quality Energy Measurements". This project was proposed in December 2006 in the context of the Department of Energy's *Advanced Detector Research* program.. In the course of 2007, DOE decided in favor of this proposal, it was given award number DE-FG02-07ER41495 and FY2008 funding was provided ($75,000). The same amount was provided from FY2009 funds. After that, DOE decided to continue to support this project as a separate task in the base grant of the TTU group (DE-FG02-07ER40938, which later became DE-FG02-12ER41840)

The project was carried out by a consortium of US and Italian physicists, led by Dr. Richard Wigmans (Texas tech University). This consortium built several particle detectors and tested these at the European Center for Nuclear Research (CERN) in Geneva, Switzerland. The results were published in the peer reviewed scientific literature, and presented at many scientific conferences and at universities and research laboratories all over the world.

This final report is organized as follows. In section 2, the arguments for and goals of the project are spelled out. The results are summarized in section 3, and conclusions are given in section 4. This project led to ten (10) papers in the scientific literature, which are listed in the appendix. These papers were all written by Dr. Wigmans, and support from award DE-FG02-07ER41495 is acknowledged in all of them.

2 The scientific goals

In the years preceding the proposal that formed the basis for award 07ER41495, the authors had established the merits of the *dual-readout method* (DREAM) approach to hadron calorimetry. They had demonstrated that simultaneous detection of the Čerenkov light and scintillation light produced in hadron showers makes it possible to measure the electromagnetic shower fraction ($f_{\rm em}$) event by event and thus eliminate the detrimental effects of fluctuations in this fraction, which dominate and limit the performance of all hadron calorimeters used in modern HEP experiments.

The initial measurements were performed with a sampling calorimeter which contained two active media: Scintillatng fibers, which measured dE/dx, and clear optical fibers for the detection of the Čerenkov light produced in the shower development. The results demonstrated that the DREAM method offered the same advantages as intrinsically compensating calorimeters: Linearity for hadron detection, the same response for electrons and hadrons, and a hadronic energy resolution that scales with $E^{-1/2}$. With the elimination of the contribution of fluctuations in $f_{\rm em}$, the energy resolution of this type of calorimeter was now dominated by fluctuations in the Čerenkov light yield and by sampling fluctuations[1].

In order to reduce these newly dominant sources of fluctuations as much as possible, and thus to achieve the best possible hadronic energy resolution, the idea arose to use scintillating crystals as dual-readout calorimeters. Such crystals were of course already known to provide excellent energy resolution for the detection of particles developing electromagnetic (em) showers.

[1]This statement applies to detectors that are sufficiently large to make the effects of leakage fluctuations insignificant. This was not the case in the DREAM calorimeter mentioned here.

Initial measurements with a $PbWO_4$ crystal in acosmic-ray telescope had shown that a significant fraction ($\sim 10\%$) of the light produced in this type of crystal was caused by the Čerenkov effect. The main challenge in applying such crystals as (hadron) calorimeters was to split the light produced by shower particles into a scintillation and a Čerenkov component.

The proposal mentioned several methods by which this might be accomplished. Measuring the time structure of the signals formed an important ingredient in this context. The authors proposed to investigate and optimize these methods, and to find/develop suitable crystals for this purpose. The ultimate test would be a measurement of hadron showers, in which the merits of the dual-readout method for a calorimeter based on crystals could be established. Such a test was also foreseen in the proposal.

3 Summary of the results

The efforts to separate the signals from scintillating crystals into scintillation and Čerenkov components led to four different methods by which this could be accomplished. These methods are based on a) the directionality, b) spectral differences, c) the time structure and d) the polarization of the signals. Figure 1 illustrates three of these four methods. It concerns measurements

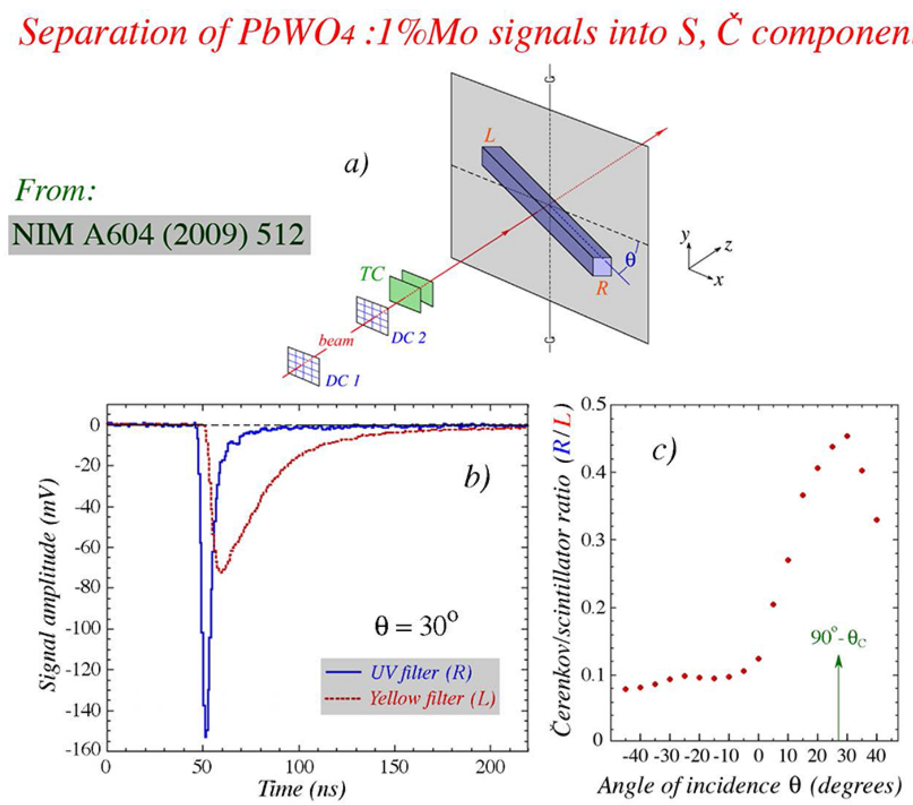

Figure 1: Unraveling of the signals from a Mo-doped PbWO4 crystal into Čerenkov and scintillation components. The experimental setup is shown in diagram a. The two sides of the crystal were equipped with a UV filter (side R) and a yellow filter (side L), respectively. The signals from 50 GeV electrons traversing the crystal are shown in diagram b, and the angular dependence of the ratio of these two signals is shown in diagram c.

on a lead tungstate crystal doped with 1% of molybdenum. The crystal was placed in a particle beam and its longitudinal axis could rotate as indicated in Figure 1a. Both ends of the crystal were equipped with optical filters, a UV filter on the R side, a yellow filter on the L side. The time structure of the signals was recorded with a digital oscilloscope, which provided a sampling capability of 5 gigasamples/s over a bandwidth of 2.5 GHz. The molybdenum doping of the crystals has two effects: It shifts the scintillation spectrum of lead tungstate to longer wavelengths and increases the decay time of the scintillation process. As a result, the combination of optical filters and time structure led to an almost perfect separation between the two components of the light signals, since the Čerenkov light is instantaneous and strongly concentrated at short wavelengths (Figure 1b),. The fact that the signals measured on side R (L) of the crystal consist almost completely of Čerenkov (scintillation) light is confirmed by the angular dependence of the the R/L signal ratio, which strongly peaks at the Čerenkov angle (Figure 1c).

The possibilities offered by the fact that the Čerenkov light is (radially) polarized, while the scintillation light is not polarized at all, are illustrated in Figure 2. In this case, the readout side of the crystal was, in addition to a colored filter, also equipped with a polarizing filter. In

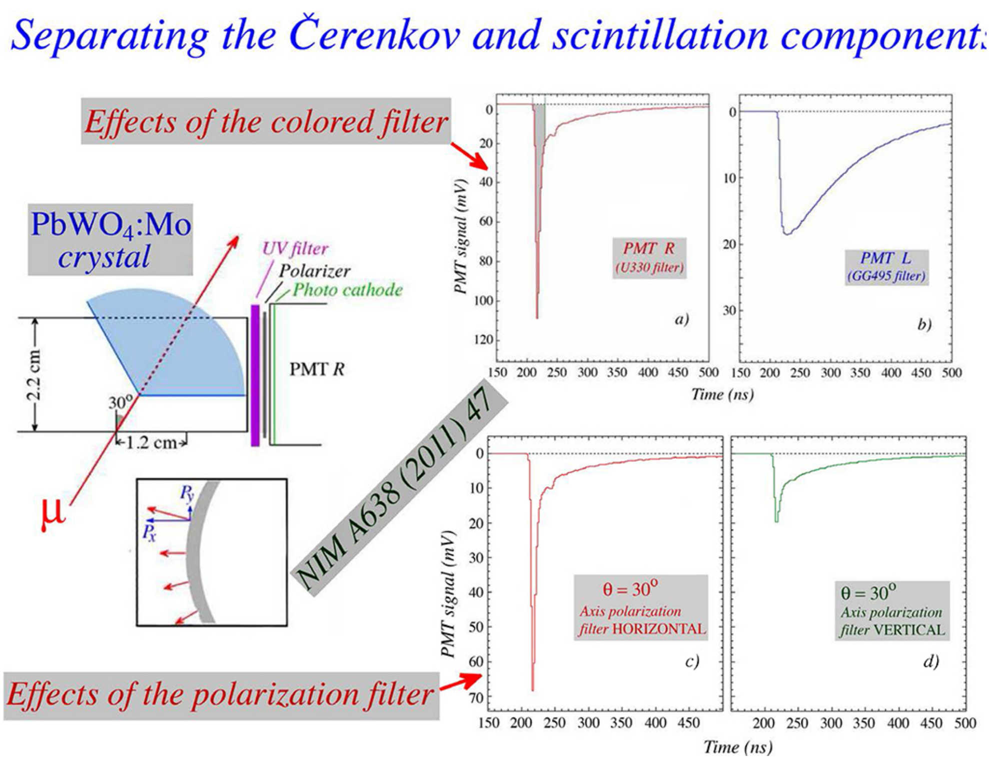

Figure 2: Emission of Čerenkov light by particles traversing the BSO crystal at an angle of 30 degrees. Shown are a top view and a view from the end face from which the Čerenkov photons exit the crystal. The Čerenkov cone is indicated by the shaded area (top left), and the polarization vectors of the detected Čerenkov photons by the arrows (bottom left). Average time structure of the signals generated by 180 GeV pions traversing this crystal. Diagrams a and b show the signals recorded when the light passes through a UV (U330) or a yellow optical transmission filter. Diagrams c and d show the time structure when a polarization filter is added on the UV side. The transmission axis of the latter filter is either oriented horizontally (c) or vertically (d). The zero of the time scale is given by the start of the time base of the oscilloscope.

this case, a UV filter of the type U330 was used, which also transmitted a small fraction of the scintillation light. This can be seen from the time structure in diagram a, which shows, apart from the prominent prompt Čerenkov peak, also a tail due to this scintillation component. The side equipped with the yellow filter (diagram b) *only* exhibits the scintillation component. Even more interesting are the effects of the polarizing filter. By rotating this filter, installed on the UV side of the crystal, over 90 degrees, the Čerenkov peak disappears almost completely, while the scintillation tail in the time structure is not affected at all (diagrams c, d). This clearly demostrates the polarized nature of the Čerenkov light.

Lead tungstate was not the only type of crystal for which the separation of the light signals into scintillation and Čerenkov components was demonstrated. The methods described above even worked for BGO crystals, which produce two orders of magnitude more scintillation light than $PbWO_4$. Figure 3b shows the typical time structure of the signals from BGO light transmitted through a UG11 UV filter. Despite the fact that scintillation photons outnumber Čerenkov ones by three orders of magnitude in the light produced in this crystal, the characteristic prompt Čerenkov peak manifests itself very clearly in the time structure of these signals. Figure 3b shows that it is even possible to extract both scintillation and Čerenkov signals from this transmitted light, by means of properly chosen gates.

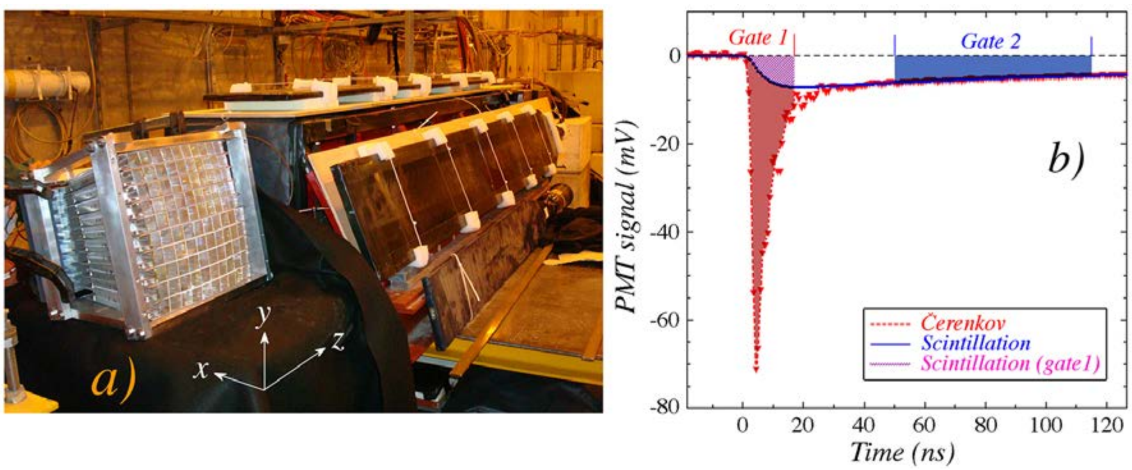

Figure 3: The calorimeter during installation in the SPS test beam, which runs from the bottom left corner to the top right corner in this picture. The 100-crystal BGO matrix is located upstream of the fiber calorimeter (a). The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter (b). These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light (gate 2) and Čerenkov light (gate 1).

This technique was used to test the applicability of the dual-readout method for hadron detection in a calorimeter consisting (partly) of crystals. We used a matrix of 100 BGO crystals, recovered from the L3 experiment at LEP, as the em section of a calorimeter system in which the original DREAM fiber calorimeter served as the hadronic section. The setup is shown in Figure 3a. This system was exposed to "jets" of particles that were produced by interactions of 200 GeV pions in a target placed upstream of the calorimeter. In this way, on average about half of the total energy was deposited in the crystal section. It turned out that the methods developed for the fiber calorimeter in stand-alone mode also worked very well for this hybrid setup.

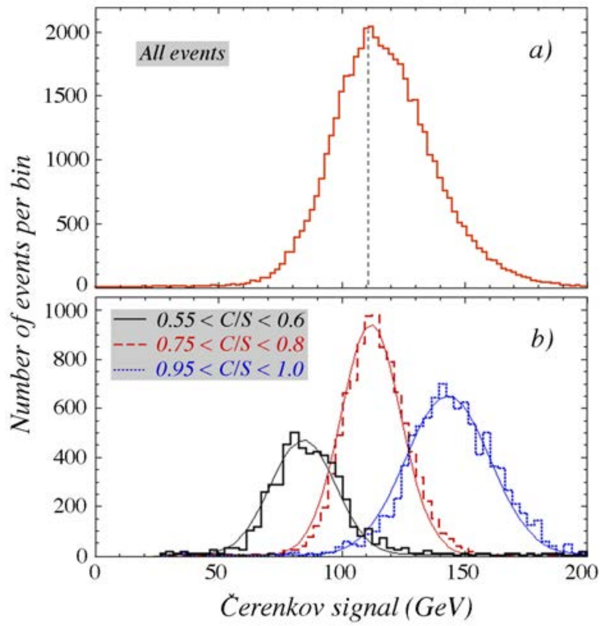

Figure 4: The Čerenkov signal distribution for 200 GeV "jet" events detected in the BGO + fiber calorimeter system (a) together with the distributions for subsets of events selected on the basis of the ratio of the total Čerenkov and scintillation signals in this detector combination (b).

This is illustrated in Figure 4, which shows in diagram a the distribution of the total (Čerenkov) signal recorded for these events, and in diagram b the signal distributions for subsets of events selected on the basis of the ratio of the total Čerenkov and scintillation signals in this detector combination. The asymmetric total signal distribution is thus a superposition of many much more Gaussian distributions with a central response value that increases with the fraction of the total energy carried by particles that develop em showers.

The time structure of the signals, which turned out to be such a powerfuk tool for separating the crystal light into Čerenkov and scintillation components, could also be used for another very important purpose, namely to determine the contribution of neutrons to the calorimeter signals. The time resolution required for this aspect is much less demanding than for the Č/S separation, since the neutrons typically contribute an exponentially decreasing signal component with a time constant of 10-20 ns. This component is the result of elastic neutron-proton scattering in the plastic fiber cores. Figure 5a shows the average time structure of te Čerenkov and scintillation signals reorded for 200 GeV multi-particle events ("jets") developing in the DREAM calorimeter. The scintillation signals exhibit a characteristic exponential tail with a time constant of $\sim$20 ns. No such tail is observed in the Čerenkov signals, which indicates that non-relativistic particles are responsible for it. Since the time structure was measured for each individual event, the relative contribution of the tail to the total scintillation signal could be determined event-by-event. It turned out that this contribution could be used in a similar way as the em shower fraction to distinguish between different types of showers. This is illustrated in Figure 5b, which shows signal distributions for three event samples with different relative neutron contributions. The

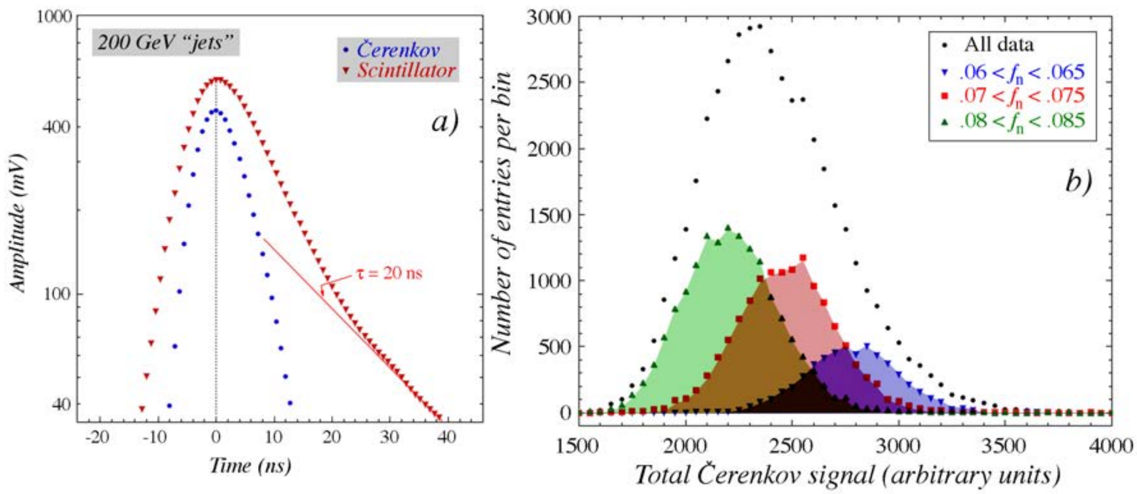

Figure 5: Average time structure of the Čerenkov and scintillation signals recorded for 200 GeV "jets" developing in the DREAM calorimeter. The scintillation signals exhibit a tail with a time constant of ~20 ns, which is absent in the Čerenkov signals (a). Distribution of the total Čerenkov signal for these "jets" and the distributions for three subsets of events selected on the basis of the fractional contribution of neutrons to the scintillation signal (b).

larger the neutron contribution, the smaller the calorimeter response. These signal distributions are also considerably more symmetric than the overall signal distribution, which is a superposition of all different subsets. Even though there is obviously a correlation between the em shower fraction and the relative contribution of neutrons to the scintillation signals, this correlation is not perfect and, therefore, the two types of data are providing complementary information for the improvement of the hadtronic energy resolution. This was demonstrated in paper 3 from the Appendix.

4 Conclusions

The goals we defined in the proposal on which award ER41495 was based were all met. We developed several methods to separate the signals from high-Z crystals into scintillation and Čerenkov components and demonstrated that a detectorr based on such crystals can indeed be used as a dual-readout calorimeter. When defining the follow-up of this project (now known as RD52 or SuperDREAM), in which we want to build a dual-readout calorimeter that is large enough to make the effects of hadronic shower leakage insignificant, it was decided to concentrate on a structure based on optical fibers, as in the original DREAM instrument. This option is not only at least an order of magnitude cheaper, but also has distinct other advantages over a crystal based instrument.

First of all, light attenuation is not a limiting issue, since we have demonstrated that attenuation lengths of the order of 10 m are achievable in the fibers we use. In crystals, light attenuation lengths for the Čerenkov component were measured to be only of the order of 10 cm, *i.e.* smaller than the nuclear interaction length which governs the fluctuations in hadronic showers. The response of a crystal calorimeter would thus be extremely dependent on the starting point and the fluctuations of the showers, and would make it impossible to achieve energy resolutions at the level of a few percent. As we demonstrated in paper 10 (appendix), this effect already dominated the resolution of electromagnetic showers, which develop on a length scale that is an order of magnitude smaller than that for hadronic showers, thus wiping out the advantage of the absence of sampling fluctuations.

A second advantage concerns the fact that the optical fibers, unlike the high-Z crystal material, produces very useful signals when traversed by the numerous MeV-type neutrons liberated in hadronic shower development. The protons in the hydrocarbon structure recoil in the elastic $n - p$ collisions and generate scintillation signals in this process. As shown in paper 3 of the Appendix, these neutron signals provide essential supplementary information, which further enhances the power of the dual-readout method (see also Figure 5).

A third advantage of the fiber structure is the flexibility it allows in terms of readout. Fibers make it possible to make a completely homogeneous absorber structure, with all the readout located beyond the detector. We have demonstrated that longitudinal readout segmentation does not provide any essential advantage, while the fiber structure allows for an arbitrarily fine lateral readout segmentation.

Crystals do provide in principle a higher light yield than the fibers in a sampling structure. However, it turns out that in order to effectively separate the Čerenkov component from the dominating scintillation component, a large fraction of the Čerenkov light has to be sacrificed, *e.g.* because of the heavy filtering that is necessary. In our studies of crystals (papers 5,9 from the Appendix), we measured the Čerenkov light yield to be at best ~ 50 photoelectrons per GeV, which is comparable to the rates measured in the RD52 fiber sampling calorimeters.

DOE is supporting the SuperDREAM (RD52) project through award 12ER41783.

Appendix

Publications based on grant DE-FG02-07ER41495

Papers in the refereed literature

1. *Effects of the Temperature Dependence of the Signals from Lead Tungstate Crystals*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A593** (2008) 530 – 538.

2. *Separation of Crystal Signals into Scintillation and Čerenkov Components*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A595** (2008) 359 – 374.

3. *Neutron Signals for Dual-Readout Calorimetry*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A598** (2009) 422 - 431.

4. *Dual-Readout Calorimetry with Crystal Calorimeters*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A598** (2009) 710 - 721.

5. *New Crystals for Dual-Readout Calorimetry*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A604** (2009) 512 - 526.

6. *Dual-Readout Calorimetry with a Full-Size BGO Electromagnetic Section*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A610** (2009) 488 - 501.

7. *Optimization of Crystals for Applications in Dual-Readout Calorimetry*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A621** (2010) 212 - 221.

8. *Polarization as a Tool for Dual-Readout Calorimetry*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A638** (2011) 47 - 54.

9. *A Comparison of BGO and BSO Crystals Used in the Dual-Readout Mode*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A640** (2011) 91 - 98.

10. *Detection of Electron Showers in Dual-Readout Calorimeters*, N. Akchurin *et al.,* Nucl. Instr. and Meth. **A686** (2012) 125 - 135.