Time profile analysis of photodetector signals in multi read-out calorimetry with GHz samplers

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Abstract. We present possible applications of DAQ systems based on Domino Ring Samplers (DRS) for time profile analysis of photodetector signals used for present and future multiple read-out calorimeters. The example of an 80-channel system in preparation for dual read-out calorimetry (DREAM) is described.

1. Introduction
Calorimeters are crucial components of almost every experiment in high-energy particle physics. The detection of particles that develop electromagnetic showers can be performed with high precision, but this is not true for particles that are subject to the strong interaction. This is primarily due to the following facts:

- the calorimeter typically generates a larger signal per unit deposited energy for the electromagnetic (em) shower component (primarily initiated by the process $\pi^0 \rightarrow \gamma \gamma$) than for the non-electromagnetic one (i.e. $e/h > 1$);
- the fluctuations in the energy sharing between these two components are large and non-Poissonian.

Therefore, in typical calorimeters the hadronic response function is non-Gaussian, the hadronic signals are non-linear, and the hadronic energy exhibits substantial deviations from $E^{1/2}$ scaling [1].

In order to deal with those problems, few ways have been tried, e.g. compensating calorimeters (designed to have $e/h \approx 1$), offline compensation, Particle Flow Analysis.

The DREAM (DUal REad-out Method) collaboration has recently used the Dual Read-out approach [2]. Such approach is based on the measurement of the em shower component, $f_{em}$, event by event. This is done by comparing the shower signals produced in the form of scintillation light and Cherenkov light in the same detector. In hadronic showers, Cherenkov light production is dominated by their em shower component, with $e/h \approx 5$, as shown by DREAM results. This shows that the signals from the non-em component of the hadron showers are dominated by spallation protons produced in nuclear reactions. These particles are usually not sufficiently relativistic to produce Cherenkov light. The electrons and positrons through which the energy...
of the em shower component is deposited are relativistic down to a fraction of 1 MeV and thus dominate the production of Cherenkov light in hadron showers.

On the other hand, for the production of scintillation light, the em and non-em components give more similar contributions, \( e/h \approx 1.4 \).

If \( E \) is the energy of the incident particle, the Cherenkov signal \( (Q) \) and the scintillation signal \( (S) \) are given by

\[
Q = E \left[ f_{em} + \frac{e}{h} Q^{-1}(1 - f_{em}) \right] \\
S = E \left[ f_{em} + \frac{e}{h} S^{-1}(1 - f_{em}) \right]
\]

if \( Q \) and \( S \) are calibrated with electrons.

If the \( e/h \) ratios are known, \( f_{em} \) can be calculated event by event and the incident energy can be determined. DREAM has shown that using this method, the Gaussian response, the linearity, and the energy resolution can be improved [2].

In principle there are four ways to detect Cherenkov light and separate it from scintillation light. They exploit different properties of \( S \) and \( Q \):

- Directionality: \( S \) is isotropic, \( Q \) is emitted at an angle \( \theta_c = \arccos(1/\beta n) \) with respect to the particle momentum;
- Time profile: \( Q \) is prompt, \( S \) has a characteristic time up to several hundreds ns, depending on the material;
- Wavelength spectrum: \( Q \) has a spectrum \( \lambda^2 \), \( S \) depends on the material;
- Polarization: \( Q \) is polarized, \( S \) is not polarized.

DREAM has used the first three methods using a fiber calorimeter, Lead Tungstate crystals (PbWO\(_4\)) and Bismuth Germanate (Bi\(_4\)Ge\(_3\)O\(_{12}\), or BGO) crystals. Fibers were plastic scintillating fibers (to detect scintillation light), quartz and acrylic plastic fibers (sensitive to Cherenkov light).

Lead Tungstate and BGO have different properties concerning the \( Q/S \) separation. The decay times \( \tau \) for scintillation light are 50 and 300 ns respectively. The \( \lambda_{\text{max}} \) of the scintillation light spectrum are 560 and 460 nm. The relative \( Q/S \) outputs are roughly 100:1.

DREAM has been able to measure the time structure of the signals using a digital oscilloscope, which provided 5 GSamples/s with an analog bandwidth of 2.5 GHz. The time structure could be studied event by event but for two channels only.

In this paper we propose a method to study the time structure of the signals at DAQ level, event by event and channel by channel.

The separation between Cherenkov and scintillation light is not the end of the story. The kinetic energy of the neutrons is correlated to the nuclear binding energy loss (“invisible energy”). Again, this can be inferred from the time structure of the signals.

In fact, more than 95% of the neutrons are produced in nuclear deexcitation, with average energy \( \langle E_n \rangle \approx 3 \text{ MeV} \). These neutrons lose their energy predominantly through elastic scattering. The energy loss in elastic scattering scales as \( A^{-1} \) (\( A \) is the atomic mass). Therefore free protons dominate this process.

The density of free protons in DREAM plastic fibers is \( 8 \cdot 10^{21} \text{ protons/cm}^3 \). The cross section for elastic \( n - p \) scattering goes from 2.2 b (for 3 MeV neutrons) to 12 b (for 0.1 MeV neutrons). In this range of energies, the mean free path between elastic \( n - p \) scattering events goes from 56 cm to 10 cm. The average time between subsequent \( n - p \) scattering events is about 23 ns. This is independent of \( E_n \). Therefore we expect an exponential tail in the time structure of the signals. Since neutrons lose on average 50% of their kinetic energy in elastic \( n - p \) scattering, \( E_n \) is reduced to a fraction \( e^{-1} \) in about 33 ns if we neglect other processes. If we take into account
other processes through which neutrons may lose energy (elastic scattering off C, Si, Cu nuclei, inelastic scattering) we expect an exponential tail with constant \( \tau \approx 25 \) ns.

The detection of the energy loss by neutrons may lead to an energy resolution down to \( 15\% / \sqrt{E} \) (\( E \) in GeV) [4].

2. Domino Ring Samplers
As discussed, a signal from a hadron calorimeter exhibits a time structure with three components:

- a prompt component due to Cherenkov light;
- a slower component due to scintillation light;
- another slower component due to neutron energy loss.

We propose a DAQ system to make time profile analysis of the individual channels of the DREAM detector. Analog signal sampling of the DREAM read-out for time profile analysis requires some specific characteristics:

- high frequency sampling;
- large bandwidth to avoid smoothing of the prompt Cherenkov component;
- it must cover a large time window to include the slow neutron component;
- it must be cheap and scalable to serve about one hundred channels.

A system based on the Domino Ring Sampler (DRS) chip [5], developed at the Paul Scherrer Institute (PSI), Villigen, Switzerland, for the MEG experiment, is adequate to cope with these requirements.

The main features of the DRS chip are:

- Integration of 10 analog channels in one chip;
- analog bandwidth of about 200 MHz;
- very low power consumption, about 35 mW per chip;
- the response of the sampler cells can be calibrated and the useful input voltage can be extended to 2 Volts (twice the range for commercial Flash ADCs).

In the present version II of the DRS chip, sampling frequency is set to 2.5 GHz with about 200 MHz intrinsic bandwidth. The temporal width of the sampled signal depends on the programmed number of cells (up to 1024) to be sequentially backward converted from trigger time \( t_0 \).

The sampler is made of two sections, an analog part for the signal sampling and a digital part for control and multiplexing. The analog signal is stored in a multi capacitor bank (1024 cells in DRS II) that is organized as a ring buffer, in which the single capacitors are sequentially enabled by a shift register driven by a high frequency clock internally generated, called Domino wave. An on-board PLL system locked to an external low frequency reference clock helps in reducing the sampling signal jitter down to less than 200 ps. The chip is housed in a PLCC package and mounted on a mezzanine card.

Once the external trigger has been received, the sampled signal in the ring buffer is delivered to the output stage by a multiplexer and digitized at high resolution (12 bits) at lower frequency (40 MHz). The signal conversion is done by an external ADC.
3. Test setup
A prototype of a board based on DRS II chips has been tested at the Istituto Nazionale di Fisica Nucleare, Pisa, Italy.

The test setup consists of a cosmic ray telescope, as shown in figure 1.

The analyzed PM signal is taken from the central counter 2 of a three scintillator plate telescope. The coincidence of discriminated signals of counters 1 and 3 is used to trigger cosmic ray events. The negative PM signal of counter 2 is fed into the input of a 500 MHz bandwidth, 5 Giga-samples/s digital scope.

The positive output of counter 2 PM is fed into an active signal adapter (50 Ω to differential); no limiting bandwidth is introduced by this device.

The adapted signal is fed to channel 1 of a mezzanine card, hosting a DRS chip and mounted on a motherboard with VME interface.

Stop to the Domino sampling sequence is given by the delayed trigger signal.

In this test the DRS sampling frequency was set at 2.5 GHz (the sampling frequency can be set to a value from 1 through 4 GHz) and all 1024 DRS analog cells converted and acquired (so that the time window was 400 ns).

The DRS sampled signals are acquired with a system based on Struck devices including a SYS3100 interface hosted in the PCI bus of a desktop computer and a VME Crate Controller (Master).

Data acquisition start and stop is handled by a manual switch on the trigger line; on stop the last event in the digital scope is stored and converted to a text file; the corresponding event number in the DRS acquisition chain is counted using a scaler.

The trigger rate is about 8 Hz. It corresponds to a throughput of about 300 kB/s (two Bytes/sample, with 1024 cells/channel, 9 channels/mezzanine, 2 mezzanines). The acquisition time includes DAQ processes, which are not optimized for our setup.

4. Calibration
To transform the DRS output from raw ADC counts to mV, a detailed calibration procedure has been followed.

A signal of constant pulse height is sent to all the 1024 cells and all 8 channels for the 2 mezzanine cards.

The calibration curves, which give the ADC counts as a function of the input pulse height.
in mV, are then obtained. An example is given in figure 2 for the cell no. 20, channel 0, in the second mezzanine card. These curves must be fitted or interpolated and inverted to get the transformation table from ADC counts to millivolts (in fact this has been done with a cubic spline interpolation). From the example figure above we can see that the device is linear with good approximation in the range 100 to 700 mV. For this reason, inside the board it is possible to add an offset in the range -2 V, +2 V to the input signal to have it positive and in the most efficient range. This possibility limits the effective bits to 11 for the ADC range (1 is for the sign). We can see also that the saturation is reached at 1800-1900 ADC counts.

5. Bandwidth
The DRS board has been used to check the bandwidth for the test system. This is important in general to study signal distortions.

We have performed a spectral analysis of the cosmic ray signal at the output of a photomultiplier (“input” signal) and compared with the signal as sampled by the DRS card (“output” signal).

In a preliminary test, using a square wave signal, we already have indications that our prototype readout system has a bandwidth of about 35 Mhz. The rise time $t_S$ of the generated square wave is in fact about 5 ns (from 10% to 90%; this is due to the limited bandwidth of the generator), while the rise time $t_O$ of the signal after sampling by the DRS card is about 11 ns. For a step response of the form

$$V(t) = V_0 \left(1 - e^{-t/\tau}\right)$$

(3)

where the time constant is $\tau$, the rise time is

$$t_r = t_{90\%} - t_{10\%} = \tau \cdot \log 9 \approx 2.2\tau$$

and the high cutoff frequency $f_H = \log 9 / 2\pi\tau$.

For a system composed by $n$ cascaded blocks, each having a rise time $t_i$, whose input signal has a rise time $t_S$, the output signal has a rise time equal to

$$t_O = \sqrt{t_S^2 + t_1^2 + ... + t_n^2}$$

(4)
We can therefore extract the overall rise time of our system

\[ t_r = \sqrt{t_1^2 + t_2^2 + \ldots + t_n^2} = \sqrt{t_0^2 - t_0^2} \approx 9.8 \text{ ns} \]

and the cutoff frequency \( f_H \approx 36 \text{ MHz} \). The overall bandwidth is assumed to be given by the convolution of the cables bandwidth (\( \approx 150 \text{ MHz} \)), the DRS input stage and the DRS chip intrinsic bandwidth (\( \approx 200 \text{ MHz} \)). For a more accurate evaluation of the system bandwidth, a Fourier analysis of the input and output signals have been performed.

Figure 3 shows an input signal in the time domain, as seen from a digital scope.
Figure 4 shows an output signal, sampled by the DRS card. The signal is pedestal subtracted.

The signal analysis in the frequency domain has been done using the Discrete Fourier Transform (DFT).

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig3}
\caption{PM signal in the time domain, sampled with the digital scope. Horizontal scale is in seconds.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig4}
\caption{PM signal in the time domain, sampled with the DRS. Horizontal scale is in seconds.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig5}
\caption{Magnitude of the DFT of the same event PM pulse sampled with the DRS (solid line) and the digital scope (dashed line) signals.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig6}
\caption{Ratio of the magnitudes of the DFT’s of the DRS and digital scope sampled signals. Horizontal scale is in MHz.}
\end{figure}
The magnitude of the DFT of the input signal and the magnitude of the DFT of the output signal are shown on the same plot in figure 5. We have normalized the function so that its value is 1 at \( f = 0 \). The horizontal scale is in MHz.

Finally, in figure 6 we show the ratio of the magnitudes, i.e. the magnitude of the transfer function of our system (from the photomultiplier to the DRS). We can see that we have a frequency cutoff at about 35 MHz at -3 dB. The dashed line superimposed on the plot represents the magnitude of the DFT for a low-pass filter with cutoff frequency \( f_H = 35 \text{ MHz} \) and a second order pole.

The bandwidth we have estimated is the bandwidth of the whole system, which includes cables, board amplification and other limiting devices.

The intrinsic bandwidth of the DRS is about 200 MHz, given by the input capacity of 44 pF in series with a resistor of 22 \( \Omega \).

6. Integration in the DREAM system
The DRS chip will be used in the DAQ system for the DREAM test beam at CERN during the Summer 2008. The DAQ main components are shown in figure 7.

Four mezzanine cards mounting two 10 channel DRS chips each are plugged on a 9U VME motherboard. The motherboard, named Pulsar, has been developed by a group of physicists and engineers from Fermilab and the University of Chicago [7]. A picture of a Pulsar board with mezzanine cards is shown in figure 8. The Pulsar has three big Altera APEX20K200 Field Programmable Gate Arrays (FPGA) together with fast large SRAMs. DRS configuration is made via the Pulsar VME interface, while sampled and converted data are sent to the host computer via s-link optical interface. A new design external card is used to match 50 \( \Omega \) PM signals to the differential input block for DRS and to generate DC levels for the DRS calibration cycle, acting on internal DACs. Auxiliary cards distribute reference and synchronization clock signals and the trigger signal produced by the DREAM logic; another Pulsar board generates the event number, used also by the default DREAM DAQ system in case of two parallel system acquisition.

Data acquisition with the new system is managed with two independent software packages, one used to configure the system before start of data taking, and the other used to handle the data transfer to the host computer in different run modes (calibration, pedestals, physics events). A special task take care to handle local disk occupancy moving data from the host computer.
to the DREAM central computing facility, being relatively high the amount of acquired data: event size is about 160 kB (4 mezzanines, 2 DRS chips/mezzanine, 10 channels/chip, 1024 cells/channels, 2 Bytes/cell) when all DRS cells of all 80 channels are converted. The expected acquisition rate is about 1kHz.

The 80 channels are enough to sample either all PM signals of the fiber detector (quartz and scintillating), or a 40 BGO/PbWO$_4$ crystal matrix (two-side read-out) to be installed upstream of the fiber detector, or a sizeable fraction of both detectors at the same time.

Preliminary results are expected to give first answers on the potentiality of many channel time structure analysis in signal component separation to improve energy resolution. Those results will be the reference for future developments of this DAQ system when higher bandwidth versions (IV) of the DRS chip will be available.

7. Conclusions
We propose a read-out system for the DREAM detector based on the time profile analysis of signals. The core of the system is the DRS chip. It has been successfully tested on a cosmic ray telescope. The system will be used in the DREAM test beam in Summer 2008.

Acknowledgments
We would like to thank the MAGIC group of INFN, Pisa and University of Siena for the support.

References
[1] Wigmans R 2000 *Calorimetry - Energy Measurement in Particle Physics, International Series of Monograph on Physics* vol 107 (Oxford: Oxford University Press) 537
[2] Akchurin N et al 2005 *Nucl. Instrum. Meth.* A 537
[3] Wigmans R 2007 *Nucl. Instrum. Meth.* A 572 215
[4] Wigmans R 2007 *New J. Phys.* 10 025003
[5] Ritt S 2004 *Nucl. Instrum. Meth.* A 518 407
[6] Pegna R et al 2007 *Nucl. Instrum. Meth.* A 572 382
[7] Anikeev K at al 2006 *IEEE Trans. Nucl. Sci.* 53 653