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Noise, Pile-up, Linearity, and Rate Capability of a Hadronic Calorimeter

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Abstract:

Pulse shaping, signal filtering, and signal processing are not the exclusive domain of cryogenic liquid calorimeters. In the latter case, these features are requirements of the calorimeter electronics because of the long drift time relative to SSC's bunch crossing time. In a fiber calorimeter with photomultiplier (PM) readout, pulse shaping at the PM's output has advantages too although they are have nothing to do with speeding up the calorimeter response. In fact shaping is already used unknowingly in conventional ADC systems when one does pedestal subtraction. We review pile-up noise and pulse shaping for fiber calorimeters and make a comparison between pile-up noise, thermal noise and their sum for a cryogenic liquid and a fiber hadronic calorimeter. We show that the fiber hadron can have at least a factor 3 less pile-up noise than the cryogenic hadron calorimeter if "adaptive filtering" works, otherwise it might be a factor 10 less.

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NOISE, PILE-UP, LINEARITY, AND RATE CAPABILITY OF A HADRONIC CALORIMETER

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1. Introduction.

Pulse shaping, signal filtering, and signal processing are not the exclusive domain of cryogenic liquid calorimeters. In the latter case, these features are requirements of the calorimeter electronics because of the long drift time t_d relative to SSC's bunch crossing time. In a fiber calorimeter with photomultiplier (PM) readout, pulse shaping at the PM's output has advantages too although they are have nothing to do with speeding up the calorimeter response. In fact shaping is already used unknowingly in conventional ADC systems when one does pedestal subtraction. This will be explained in Sec. 2. In Sec. 3 we review pile-up noise and in Sec. 4 we present pulse shaping for fiber calorimeters and make a comparison between pile-up noise, thermal noise and their sum for a cryogenic liquid and a fiber hadronic calorimeter. We show that the fiber hadron calorimeter can have at least a factor 3 less pile-up noise than the cryogenic hadron calorimeter if "adaptive filtering" works, otherwise it might be a factor 10 less.

2. Conventional Photomultiplier Signal Processing.

Consider a gated ADC with a gate width of $T = 32\,\mathrm{ns}$. Digitization and pedestal subtraction can be represented by a weight function $w(t)$, see for example Ref. 1. Consider the solid curve in Fig. 1. It is assumed that $w(t) = 1$ for $0 < t < T$ corresponding to an open ADC gate and that $w(t) = -1$ for $T < t < 2T$ corresponding to a closed ADC gate. The calorimeter signal of interest is assumed to be timed within the ADC gate and thus with the first lobe of $w(t)$ in Fig. 1. The energy E of the calorimeter cell is obtained by digitization of the PM signal $s(t)$ and pedestal subtraction. It is given by

$$E(t) = \int_{-\infty}^{+\infty} w(\tau)\, s(t-\tau)\, d\tau \tag{2.1}$$

One may take t to be just after $w(t)$ has returned to zero. The integral corresponds to a convolution of $w(t)$ and $s(t)$. If $s(t)$ has underlaying noise or pile-up, it does not contribute to E because the weight function is chosen to satisfy

$$\int_{-\infty}^{+\infty} w(t)\, dt = 0 \tag{2.2}$$

Now assume that there is a cable between the PM output and the ADC input. In (2.1) the $w(t)$ and $s(t)$ are both at the input of the ADC and the cable slewing will have affected the shape of the PM signal. Or equivalently, one may propagate the weight function $w(t)$ up the cable to the output of the PM. The shape of $w_{\mathrm{PM}}(t)$ at the PM will likewise be different from the solid curve in Fig. 1 by slewing effects. Especially high frequency components in the Fourier analysis will be affected, leading to rounding of the square corners of $w(t)$. We show the result of a calculation of this latter effect for an 80 m RG58 cable in Fig. 1 (dashed curve). Excessive rounding of the corners of $w(t)$ is clearly visible. The curve was normalized to -1 at its minimum value. [We should clearly not

use such long and lossy cables in GEM: the ADC's should be located as near to the calorimeter as possible.]

The shape of $w_{\mathrm{PM}}(t)$ is similar to the pulse shaping foreseen for the cryogenic calorimeter, see for example Ref. 1, p. 273 and Ref. 2, p. 5.

3. Pile-up Noise.

It is shown in Ref. 2, p. 6 that the variance σ_E^2 of E is given by

$$\sigma_E^2 = \int_0^{\infty} n(E)\, E^2 dE \int_{-\infty}^{+\infty} v_{\mathrm{out}}^2(t)\, dt \tag{3.1}$$

Here $n(E)$ is the energy spectrum of the pile-up noise, $v_{\mathrm{out}}(t)$ is the pulse response of the preamp and is normalized such that its maximum amplitude is 1. The first integral in (3.1) is independent of detector technology and is given by the cell size, luminosity, and physics. The second integral in (3.1) is called the pile-up noise integral $I_{2\mathrm{p}}$. It is stated in Ref. 2 that for signals $s(t)$ whose duration t_d are short relative to the duration τ_F of the pulse response of the preamp, the pile-up noise integral becomes

$$I_{2\mathrm{p}} = \int_{-\infty}^{+\infty} w^2(t)\, dt \qquad t_d << t_F \tag{3.2}$$

Obviously, the pile-up noise can be reduced by minimizing $I_{2\mathrm{p}}$.

In Fig. 2 we reproduce Fig. 1.1.5 of Ref. 2, p. 6. The three solid curves are representative of cryogenic liquid calorimeters, the first one for a drift time $t_d = 0$ (pulse response), the next two for $t_d = 50$ and 100 ns. The dashed curve is the weight function for a fiber calorimeter (with a "short" cable between PM and ADC). All four functions in Fig. 2 have the same value $I_{2\mathrm{p}} = 64 - 66$ ns. This may be surprising considering that the ADC gate for the fiber case is only 32 ns

long, half the peaking time of the other three curves and much smaller that the $\tau_F = 100\,\mathrm{ns}$ of the third solid curve in Fig. 2. $I_{2\mathrm{p}}$ is so large for the dashed weight function because of its rectangular shape. Note that w enters squared in the calculation of $I_{2\mathrm{p}}$ in (3.2). In Fig. 1 the solid curve has $I_{2\mathrm{p}} = 64\,\mathrm{ns}$ while the dashed curve has $I_{2\mathrm{p}} = 37.3\,\mathrm{ns}$, confirming what was stated above.

Note also that the peaking time $\tau_p = 50\,\mathrm{ns}$ for the first solid curve in Fig. 2. A cryogenic liquid based hadron calorimeter is likely to have a peaking time of 200 ns or more to keep the noise for the larger hadronic tower sizes under control. The pile-up noise increases more then linear with the square-root of the tower area, see Ref. 2, p. 92, and is inversely proportional to $\sqrt{\tau_p}$. The pile-up noise integral for $\tau_p = 200\,\mathrm{ns}$ is $I_{2\mathrm{p}} = 65 \times 200/50 = 260\,\mathrm{ns}$, compared to 37.7 ns for the fiber calorimeter with the long cable. With (3.1) the fiber calorimeter gives at least a factor $\sqrt{7} = 2.6$ less pile-up noise than the cryogenic hadron calorimeter.

The presence of a lossy cable reduced to pile-up noise by a factor $37.7/64 = 0.59$. It is obvious that equal or larger reductions can be obtained with optimum shaping at the preamp (and a "short" signal cable).

4. Optimum Shaping and Thermal Noise.

The study of optimum shaping of signals is an extensive and sophisticated field of research in electrical engineering. Good articles exist on its application to HEP detectors, see for example Ref. 1 and 3.

To have pulse shaping implemented right at the PM, it is natural to reduce the gain of the PM and follow it by an electronic amplifier that has the required shaping. The fiber hadron calorimeter gives 50 photo-electrons per GeV. For a total gain of 3×10^5 we get 2.4 pC/GeV. This is enough charge to be shared between triggering electronics and ADC. That gain can be achieved by using a PM with a gain of 1000 and a shaping preamp with a gain of 300.

The PM gain is chosen large enough so that the noise from the preamp contributes negligibly to the total noise. The preamp reduces the peak currents

near the PM anode by a factor 300 and thereby reduces sagging at high rates as well. This has further advantages for PM stability and linearity at the highest energies (several TeV) and highest intensities.

The pulse response of the shaping circuit should satisfy (2.2) to avoid baseline shifts and be optimized for minimum value of I_{2p}, see (3.2) so that the pile-up noise is minimized.

It was indicated in the previous section that, with an optimized shaper, we may expect at least a factor 3 less pile-up noise in the fiber hadronic calorimeter than in the cryogenic liquid calorimeter for the same tower size. To this must be added the thermal noise.

Thermal noise is negligibly small for a fiber hadron calorimeter but not for a cryogenic liquid hadron calorimeter. In the latter case the method of "adaptive filtering" is proposed to minimize the sum of pile-up and thermal noise, see Ref. 2, p. 93. There the sum of the two is shown to be about 25% larger than the pile-up noise alone. If adaptive filtering does not work or can not be implemented in a cost effective way, the total noise can be up to four times the pile-up noise, see Ref. 2, p. 94. In this case the noise of the fiber hadron calorimeter is a factor $2.6 \times 4 \approx 10$ smaller than the cryogenic liquid hadron calorimeter.

Adaptive filtering requires pulse measurements every 16 ns for subsequent analysis. This is very demanding of the data acquisition electronics and data storage. The analysis consists of calculating an amplitude function which is a linear combination of all relevant 16 ns samples. Coefficients are chosen in such a way that the variance of the amplitude function is minimized. The coefficients depend upon the relative magnitude of the pile-up and thermal noise. Those relative magnitudes depend in turn upon the instantaneous luminosity and, for a given luminosity, upon the tower size as they change with rapidity. It seems unlikely that this method could be implemented in the trigger.

The adaptive filtering has so far only been studied by Monte Carlo simulations. It has not been demonstrated experimentally.

5. Acknowledgement

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FIGURE CAPTIONS

1. The weight function used in the description of a gated ADC with pedestal subtraction. The solid line represents the true weighting function, while the dashed line is for a weighting function transformed by an 80 m RG58 cable.

2. Examples of bipolar signal processing (solid curves) and the weight function for a gated ADC with pedestal subtraction (dashed line). The signal durations t_d are respectively 0 (pulse response), 50, and 100 ns. Figure is from Ref. 2, p. 6.

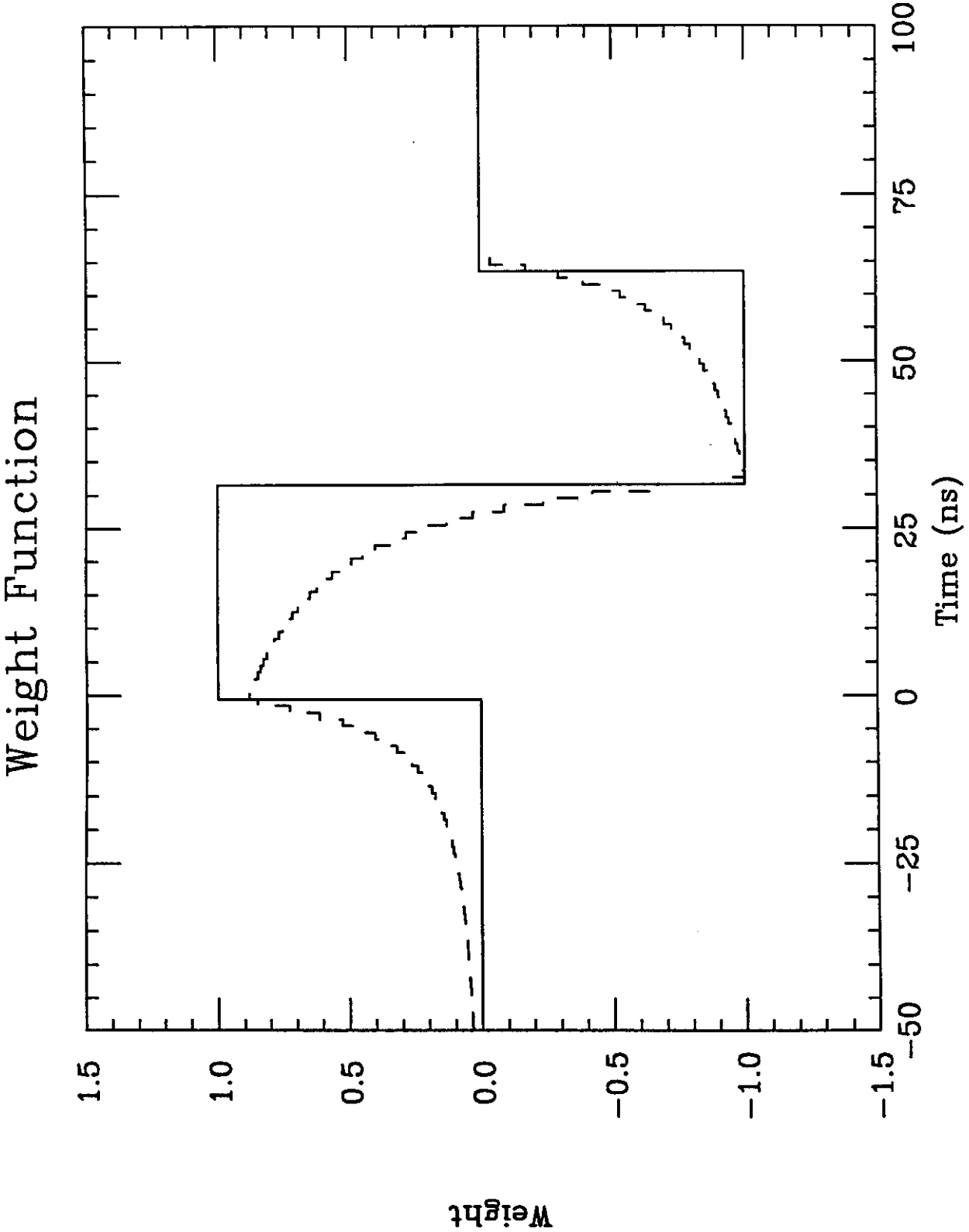
Weight Function
Weight
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−50
−25
0
25
50
75
100
Time (ns)

Fig. 1

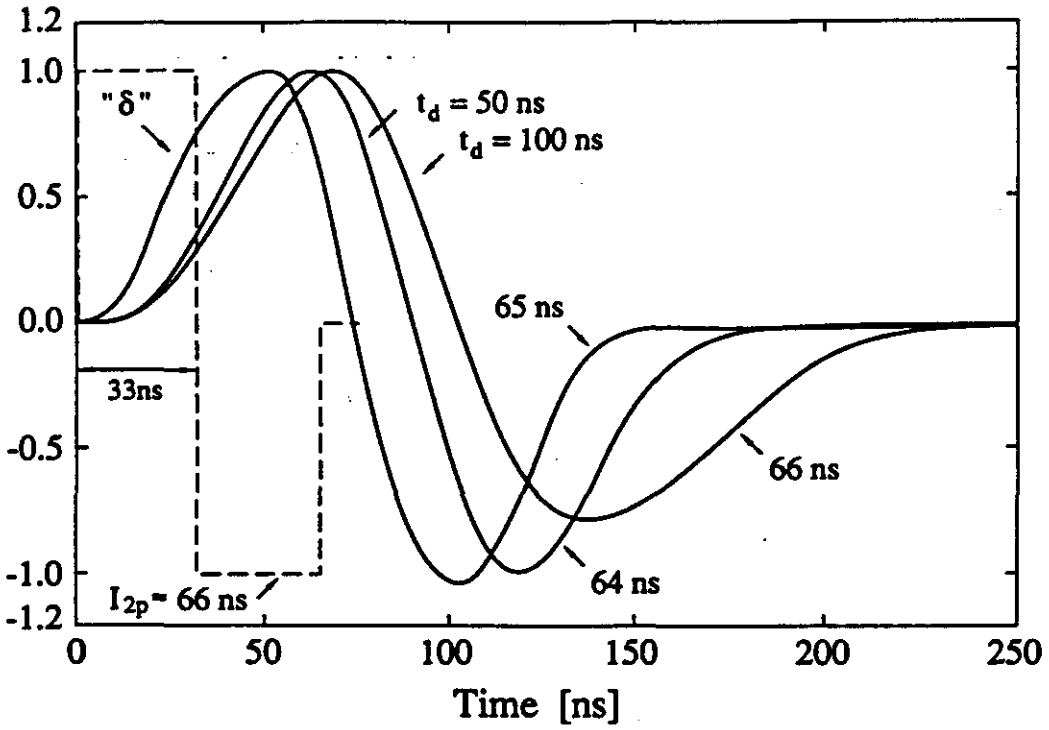
1.2
1.0
0.5
0.0
-0.5
-1.0
-1.2
"δ"
t_d = 50 ns
t_d = 100 ns
65 ns
33ns
66 ns
64 ns
I_{2p}= 66 ns
0
50
100
150
200
250
Time [ns]

Fig. 2