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DYNAMIC RANGE COMPRESSION IN A LIQUID ARGON CALORIMETER

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ABSTRACT

The anticipated range of particle energies at the LHC, coupled with the need for precision, low noise calorimetry makes severe demands on the dynamic range of the calorimeter readout. A common approach to this problem is to use shapers with two or more gain scales. In this paper we describe our experience with a new approach in which a preamplifier with dynamic gain compression is used. An unavoidable consequence of dynamic gain adjustment is that the peaking time of the shaper output signal becomes amplitude dependent. We have carried out a test of such a readout system in the RD3 calorimeter, a liquid argon device with accordion geometry. The calibration system is used to determine both the gain of the individual channels as well as to map the shape of the waveform as a function of signal amplitude. A new procedure for waveform analysis, in which the fitted parameters describe the impulse response of the system, permits a straightforward translation of the calibration waveform to the waveform generated by a particle crossing the ionization gap. We find that the linearity and resolution of the calorimeter is equivalent to that obtained with linear preamplifiers, up to an energy of 200 GeV.

MASTER**1 Introduction**

Dynamic range is an important consideration in the design of front end electronics for calorimeters to be used in LHC detectors. The ATLAS experiment has chosen for its electro-magnetic calorimetry the technology of liquid argon with accordion geometry. In this calorimeter it is expected that high energy electrons will deposit up to 2 TeV per readout cell and that most of the physics will be performed in the range of 10 to 100 GeV. Since the expected electronic noise levels are well below 100 MeV per cell, the readout system must have a dynamic range of nearly five orders of magnitude. Also, if the readout system is linear, signals of up to 100 GeV will occupy only about 5% of the total dynamic range.

There are several approaches to the dynamic range problem. In the more traditional of these, the output signal from the preamplifier-shaper chain is split into two or more gain ranges and digitized in an ADC of appropriate precision. We have studied a different approach, namely

the dynamic compression of the signal at the preamplification stage. In this approach we use a specially designed preamplifier characterized by a response curve with two regions of different gain, joined by a smooth transition region. As the signal develops in time the compression is activated above a pre-determined level, resulting in a gain reduction. Because of the finite rise time of the preamplifier the shaper sees a signal of reduced rise time, which causes an amplitude dependence of the peaking time of its output pulse.

To evaluate the performance of such a system experimentally, we have built and tested pre-amplifiers with dynamic compression in the RD3 calorimeter. The pre-amplifiers were built with gain reduction starting at an energy of about 45 GeV. In the LHC experiment the transition would be set near 200 GeV, and, with a gain reduction of 1:4, the signals below 100 GeV would occupy about 15% of the total dynamic range. Given the effects of the compression on the shaped signal, it is necessary to sample the waveform at several points. In our case this was achieved by the use of analog switched capacitor arrays (SCA), whose output was digitized in a 14-bit ADC. A detailed knowledge of both the amplitude response and the waveform dependence on amplitude was obtained by using a precision calibration pulse injected at the preamplifier input. Using this information, data taken in an electron beam in the energy range 20 to 200 GeV were processed, and the linearity, energy resolution, and timing resolution of the system were determined. We discuss in this paper the practical aspects of implementing and analyzing data from systems with dynamic range compression of this type.

One of the important goals of this analysis is to use the calibration data to obtain information on the shape of the waveform. This is particularly important in the case of waveforms whose shape depends upon the amplitude, as this dependence can be studied in detail using the calibration system. For a large calorimetry system where the determination of the amplitude of the signal requires a knowledge of the waveform, it is important to be able to determine this waveform from the calibration signal alone, as reliance on particle data, especially for large amplitude signals, can be severely hampered by limited statistics. In order to be able to use the calibration data to calculate the waveform arising from a particle crossing the ionization gap, which we call the "signal" waveform, we have chosen to parameterize the impulse response of the system. The technique used is to make a linear expansion in terms of "basis" functions: the δ -response is expanded in a set of nonorthogonal time-dependent functions with linear coefficients, and the waveforms produced with a known current waveform (either the calibration waveform or the signal waveform) are calculated as a convolution between the current waveform and this parameterized impulse response.

2 Experimental Setup

The test of the preamplifiers were carried out in the RD3 2 meter long test module at CERN. The RD3 calorimeter is described in detail elsewhere ¹⁾ and is a prototype calorimeter for ATLAS electro-magnetic calorimeter. The calorimeter uses liquid argon as the sampling medium and lead absorber folded in the accordion geometry. It is subdivided longitudinally into 3 sections. The

first two sections are 9 radiation lengths in depth, and the third section has a depth of 6 radiation lengths. The calorimeter is segmented transversely into projective towers of $\Delta\eta \times \Delta\phi = 0.25 \times 0.25$, defined with respect to the center of projection, located at a distance of 1.2m from the front face. For this segmentation and for the energies used approximately 50% of the beam energy is deposited in a single channel in the first sampling. Thus only the first longitudinal section was equipped with preamplifiers with dynamic gain compression. The two other sections were instrumented with linear preamplifiers. The total number of instrumented channels read out by the data acquisition system correspond to a matrix of 6×6 towers from which a 5×5 matrix, centered on the beam, is used in the analysis to form the total energy sum.

Figure 1 (a) Preamplifier (upper) and shaper (lower) waveforms illustrating dynamic compression. The preamplifier is in the linear region for the 15 GeV curve. The turn-on of the dynamic compression can be seen comparing the leading edge of the 150 GeV curve with that of the 15 GeV curve. The effect of the dynamic compression is to present a pulse of faster rise time to the shaper input. The resulting output of the shaper is a pulse with reduced peaking time. (b) System noise autocorrelation as determined from the SCA data and digital oscilloscope

The preamplifiers, which operate at the temperature of liquid argon, were especially designed and built for this test. They are characterized by a gain curve with two linear regions with gain difference of approximately 3.5, joined by a smooth transition region (knee). For the present test the knee was placed at approximately 45 GeV, as can be seen in Fig. 2b. In ATLAS the knee would be set at approximately 250 GeV since it is useful to make linear trigger sums for energies below that range. The signals from the preamplifiers were shaped with dual gain shapers. Since we used different preamplifiers, the peaking time of the signal waveforms were not the same for each of the sections. In the front layer (for signals in the linear range) the 5%-100% peaking time was approximately 55 ns, whereas in the middle and back sections it was approximately 85 ns.

The dynamic compression at the preamplifier has the effect of reducing the rise time of pulses at the preamplifier output. Consequently the shaper output signals have an amplitude-dependent peaking time. The waveforms are sampled at a rate of 40 MHz, giving sequential

samples spaced by 25 ns. The waveform sampling is done asynchronously with the beam triggers and the phase, the time between the beam trigger and the SCA clock, was recorded for each event in a TDC of 50 ps/channel precision. The SCAs sample the signals continuously until a trigger occurs. After the trigger, 16 samples corresponding to a time window of 400 ns around the peak are digitized by a 14-bit ADC. All the waveform samples, together with information (pulse height and timing) from the beam counters are recorded on tape for analysis.

3 Analysis

For the channels with dynamic compression, accurate characterization of its response, gain in both regions and the break point, are necessary. This is accomplished by means of a precision calibration system. In the present studies the existing RD3 calibration system was used. In this system a network of precision resistors is used to distribute signals with sharp rise time (≈ 3 ns) followed by an exponential decay ($T_C = 270$ ns) to each individual channel. Calibration signals are also asynchronous with respect to the SCA sampling clock.

To process the electron signals we used the optimal filtering method to extract both amplitude and timing information. This technique relies on the detailed knowledge of both calorimeter waveform and the noise of the system. The electron waveforms were obtained by folding the experimentally determined impulse response from the calibration signals with the triangle current waveform from the liquid argon. The noise and the autocorrelation function for each channel was studied by examining random triggers interspersed with beam triggers.

3.1 Description of the Method

3.1.1 Calibration signal averaging

The first step in the analysis process is the determination of the average waveform from the calibration data. Calibration data were collected at a wide range of reference voltage values, which were provided by a precision 16-bit DAC. Each calibration run consists of a set of events in which a particular subset of the channels were pulsed N_p times, with $N_p = 100$ for most of the runs. In order to study a particular channel, it was necessary to scan through the run to select the events in which this particular channel was pulsed and to perform signal averaging on pulses with the same DAC setting.

The calibration pulser was a clock which was asynchronous with the sampling clock, and therefore each calibration "event" occurred at a particular time (which was measured in a TDC) with respect to the calibration clock. In order to determine the average waveform profile, samples were averaged in bins of 2.5 ns. However, it was found that with only 100 pulses to average, fluctuations introduced by the finite bin width contributed noticeably to the mean value. We therefore developed a two step process, in which the local slope of the waveform was measured for each bin, by the use of a cubic spline fit. On the second pass, the value of the signal waveform was corrected to the center of the bin, using the timing of the event relative to the sampling clock.

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as given by the TDC measurement. With this technique, the fluctuations in the mean value of the waveform in each bin was reduced by the averaging process to approximately $1/\sqrt{N_p} \approx 1/10$ of the noise level. An advantage of this method is that it also permitted the elimination of a small number of calibration events which (for unknown reasons) had obviously incorrect amplitude or timing.

3.1.2 Waveform fitting in the linear region

We first consider the problem in the low energy region, where the preamplifier response is linear and the shape of the waveform is independent of amplitude. This corresponds to data taken at a beam energy of 50 GeV. (Recall that only about half of the beam energy is deposited in the front section.)

The impulse response function $h(t)$ is parameterized as a sum of basis functions $f_n(t)$ with linear coefficients d_n :

$$h(t) = \sum_n d_n f_n(t)$$

in which $f_n(t)$ is the impulse response of an n -fold integrator with time constant τ_0 :

$$f_n(t) = \mathcal{L}^{-1} \left(\frac{1}{(1 + s\tau_0)^n} \right) = \frac{t^{n-1}}{(n-1)!} \frac{e^{-t/\tau_0}}{\tau_0^n}.$$

We calculate the calibration waveform in terms of these parameters. The calibration current, which is $i_C(t) = e^{-t/\tau_C}$, is convolved with $f_n(t)$ to produce the calibration waveform as follows:

$$g_C^{\text{lin}}(t) = \sum_{n=2}^{N_f} d_n F_n(t) \quad \text{with} \quad F_n(t) = f_n(t) * i_C(t).$$

For the waveforms used in this analysis, we have found that sufficient accuracy is obtained with $N_f = 8$. The lower limit of $n = 2$ was chosen by observing that the value of d_1 (when included in the fit) was several orders of magnitude smaller than the other d_n .

The first step in the fitting process for the linear waveforms relies on the linearity of the pulser system. For each time bin t_i , we fit the mean values of the waveform to a linear function in the DAC value. The slope of this function R_i is proportional to the amplitude of the waveform at this time value, but it is independent of any offset (i.e., any contribution to the signal for a DAC value of zero), which can be due to an offset in the DAC output voltage, but it can also vary from time bin to time bin, due to the contribution of the "clock feed-through" signal (see below). The values of the slopes are then used in a fit to determine the eight waveform parameters $\{d_n\}$ and τ_0 .

We form the χ^2 function

$$\chi^2(\{d_n\}, \tau_0) = \sum_{i=1}^{N_C} \frac{(g_C^{\text{lin}}(t_i) - R_i)^2}{\sigma^2}$$

in which R_i is the slope of the calibration waveform (with respect to the DAC value) at time t_i and σ is the fluctuation in this value. Here N_C is the number of samples on the calibration waveform.

We used samples spaced by 5 ns from the beginning of the waveform up until a point where the trailing edge of the calibration clock signal introduced a disturbance in the shaped output, which occurred at about 220 ns after the start of the pulse. Eliminating all samples after this point gave $N_C = 43$. The correlations between the points at different times, which are very strong for an individual waveform, are reduced considerably by the processes of signal averaging and fitting for the slopes, and thus a diagonal form of the weight matrix is a good statistical representation for the mean values. Since σ is the same value for all of the time values, for simplicity we can set it equal to unity when solving for the waveform parameters.

We solve for the linear parameters d_n by the usual technique. We define the vector $\vec{B}$ and the matrix $\mathcal{A}$ as

$$B_k = \sum_i R_i F_k(t_i)$$

and

$$\mathcal{A}_{nk} = \sum_i F_n(t_i) F_k(t_i)$$

The equation which results from the minimum χ^2 condition, obtained by setting the derivative of χ^2 with respect to each of the d_n equal to zero, can be written as

$$\mathcal{A} \vec{d} = \vec{B}$$

with the solution

$$\vec{d} = \mathcal{A}^{-1} \vec{B}.$$

The parameter τ_0 is then found by varying it numerically and finding the minimum value of $\chi^2_{\min}$, which is the value of χ^2 found by substituting the values for d_n found from the equation above. In this way the calibration data for all DAC values of are used simultaneously to determine the values of d_n for each readout channel.

We now use the optimal filtering formalism to determine the amplitude A and time origin τ of the calibration "events" from the measured samples S_i :

$$A = \sum_{i=1}^{N_s} a_i S_i$$

$$A\tau = \sum_{i=1}^{N_s} b_i S_i,$$

where S_i are the samples spaced by 25 ns, and $N_s=7$. The optimal filter coefficients are determined directly from the individual calibration waveform $g_C^{\text{lin}}(t)$, its derivative, and the weight matrix $\mathcal{V}_{ij}$ ³⁾. The weight matrix is the inverse of the variance-covariance matrix, which is the Toeplitz matrix formed from the autocorrelation function evaluated at multiples of the sampling interval. Thus for the case of 5 samples with spacing T :

$$\mathcal{V}^{-1} = \begin{pmatrix} R(0) & R(T) & R(2T) & R(3T) & R(4T) \\ R(T) & R(0) & R(T) & R(2T) & . \\ . & . & R(0) & . & . \\ . & . & . & R(0) & . \\ . & . & . & . & R(0) \end{pmatrix}$$

in which $R(t)$ is the autocorrelation function which is determined experimentally through the use of randomly triggered events (see Fig. 1b). In the usual optimal filtering formalism, the values of a_i are normalized, so that the units of the amplitude A are the units in which the samples S_i are measured, which are ADC counts. For each DAC value, a distribution in A gives the mean pulse height in ADC counts, and a plot of this mean *vs.* DAC value yields the response curve for the system (see Fig. 2b). A linear fit of these data gives the calibration constant for the channel (ADC value per DAC count) in the linear region.

The particle waveforms are found by using the same basis functions but convolving with the current produced by a charged particle crossing the ionization gap:

$$g_s^{\text{lin}}(t) = h(t) * i_s(t) = \sum d_n E_n(t - t_0) \quad \text{with} \quad E_n(t) = f_n(t) * i_s(t)$$

and

$$i_s(t) = (1 - \frac{t}{T_d}),$$

in which T_d is the drift time. Values of A and τ are determined as for the calibration data, solving for the optimal filter constants using $g_s^{\text{lin}}(t)$, its derivative, and the weight matrix $\mathcal{V}$. The parameter t_0 is introduced to account for a relative time shift between the calibration waveform and the signal waveform. Its value is determined by calculating the mean value of τ for a set of particle data. The optimal filtering formalism is based on a Taylor series expansion about the point $\tau=0$; in order not to compromise the accuracy of the determination of A , it is sufficient to adjust t_0 such that the mean value of τ is less than 2 ns. We divide the value of the amplitude A by the calibration constant for each channel, to measure the amplitude of the energy deposited in each channel in units of DAC counts, which are of course common to all channels. Sums of the signals over the 5×5 matrix and over the three depth segments gives the total energy in units of DAC counts. The mean value of this peak at a known value of the beam energy establishes the DAC scale in units of incident particle energy. We obtain 34.1 MeV/DAC count for this constant. From a measurement of the calibration pulse height at the input to the preamplifier for a given DAC setting, we find the relationship between the current injected into the preamplifier and the DAC value, which is 82.5 ± 1.0 nA/DAC count. The ratio of these two constants yields the signal current for a given incident particle energy of $2.4 \mu\text{A}/\text{GeV}$.

3.1.3 Waveform analysis in the nonlinear region

The techniques to fit the waveforms in the energy region where the preamplifiers become nonlinear is an extension of the method used for the linear region. We know that the shaper output waveform is a unique function of the amplitude of its input signal. Because of the finite rise time of the preamp output, a nonlinear gain produces a signal whose rise time decreases with increasing amplitude, which leads to a shaper output signal whose peaking time decreases with increasing amplitude, as is illustrated in Fig. 1a. This behavior can be modeled as a time-varying gain function $G(t)$. Our expression for the calibration waveform then becomes $G(t) * h(t) * i_C(t)$. At low amplitudes, $G(t) = 1$, so the problem reduces to the linear one described above.

We parameterize the gain function as a polynomial in t :

$$G(t) = g_0 + g_1 t + g_2 t^2 + \dots = \sum_{m=0}^{N_g} g_m t^m$$

The calibration signal then becomes

$$g_C^{nl}(t) = \sum_{m=0}^{N_g} g_m \left(\sum_{n=2}^{N_f} d_n H_{mn}(t) \right) \quad \text{with} \quad H_{mn}(t) = t^m * f_n(t) * i_C(t)$$

In the low energy region $g_0 = 1$ and $g_m = 0$ for $m \geq 1$. For this case the values of d_n and τ_0 have been determined, and these values are retained for use in the nonlinear region. Thus the fit for the values g_m for a given value of the amplitude of the calibration waveform is reduced to a linear problem. The form of the gain function obtained for three different amplitudes is shown in Fig. 2a. One sees that it has a behavior which is characteristic of dynamic gain compression. It also absorbs any behavior of the waveform not predicted by the basis functions found in the linear region, which presumably explains anomalies such as the bump in the 70 GeV curve at early times where the amplitude of the output signal is quite small. We have found that an adequate representation of the waveform at all amplitudes can be obtained using 10 parameters ($N_g = 9$) or less.

Figure 2 (a) Gain function $G(t)$ used in the fits to the non-linear waveforms. As discussed in the text, for low energies $G(t)$ becomes unity while at higher energies it decreases to describe the dynamic gain compression. (b) Response curve for the preamplifier with dynamic gain compression as determined from the calibration. The ordinate is the peak of the calibration signal and the abscissa is the voltage reference for the calibration pulser. The corresponding scale in incident particle energy is also shown.

As in the linear case, the optimal filtering formalism is used to treat the calibration data as events. From the value of $g_C^{nl}(t)$ and its derivative, we calculate the optimal filter coefficients as a function of the fitted amplitude A , and an iterative technique is used to perform the final fit for the values of A and τ . A plot of the mean value of A as a function of the DAC value yields the full response curve for the channel in question (see Fig. 2b). A polynomial fit to this curve is obtained to give the conversion between pulse height in ADC counts and deposited energy in

DAC counts. The systematic error in the method is found as a function of signal amplitude by subtracting the reconstructed amplitude in DAC counts from the actual DAC value used at each point in the calibration. This curve is shown (see Fig. 3a) for the channel centered on the beam in the front section. It contains deviations which are clearly systematic but less than 0.5% for all amplitudes. Knowing the value of g_m at each amplitude permits the calculation of the signal waveform $g_s^{nl}(t)$, in which $i_s(t)$ is substituted for $i_C(t)$ in the expression for $H_{mn}(t)$.

3.1.4 Clock feed-through correction

The calibration pulser delivers a pulse which is proportional to the calibration current, but in addition there is a small additional contribution to the waveform due to the capacitive coupling of the clock signal through the switching transistor, the so-called "clock feed-through" pulse. In the low energy (linear) region, the clock feed-through signal is automatically subtracted from the current-dependent part of the signal by fitting to the slopes of the waveform (with respect to the DAC value) at each point in time. This is of course not possible in the nonlinear case, since the effective gain of the system changes with time. In order to correct for the clock feed-through in this case, we first find and parameterize (using another set of basis functions) the waveform for the clock feed-through signal in the linear region. The values of this signal are simply the offsets at DAC=0 determined in the linear fits of the calibration data for each time bin. We then multiply this waveform by the time-dependent gain function $G(t)$ and subtract the result from the measured samples for the calibration signal. The corrected signal is then fit again, and $G(t)$ is re-determined. The maximum value of the clock feed-through signal, which occurs at a point more than half way up the signal waveform, is less than 1 GeV. Since the pulses in the nonlinear region all correspond to energy deposits of 50 GeV or more, the maximum size of this correction is no more than a few percent.

4 Results

The optimal filtering coefficients for the signal waveforms were determined from the calibration data as described above. Random triggers interspersed with beam triggers are processed in the same way as beam triggers and are used to determine the noise level for each channel. The energy and timing for each channel are reconstructed using seven samples approximately centered on the peak of the first lobe of the waveform. In the linear region where the waveform shape is constant an amplitude-independent set of coefficients is used for each channel. In the non-linear region where the coefficients are amplitude-dependent, we use an iterative technique in which the coefficients are recalculated at each step.

The present analysis employs an energy sum from a 5x5 tower matrix centered on the incident beam position. An electro-magnetic shower is fully contained in the tower since the beam particles which are detected by the beam scintillator elements populate only the central cell in array. The reconstructed timing information is also obtained for each channel within the array.

4.1 Energy Reconstruction

To obtain information of linearity and energy resolution the energy is corrected for its geometrical dependence in both η and ϕ coordinates. The corrections are made using the procedure described in Ref. 1. The data is also corrected for the leakage of energy carried by particles not stopped in the full longitudinal depth and early showering due to material in front of the active region of the calorimeter. This correction is described in Ref 4.

Figure 3 (a) Error in the reconstructed amplitude as a function of the amplitude of calibration signal. The dotted lines show that the systematic errors are within $\pm 0.5\%$. (b) Difference between the reconstructed energy and nominal beam energy. No corrections were made for the systematic deviations in (a).

During the course of the analysis it was found that both energy and timing are dependent on the position of the samples on the waveform, which is determined by the TDC measuring the sampling clock. This dependence has not been observed in previous analysis where multiple samples were used. However this is the first analysis where complete reliance upon the calibration waveform is made to determine the signal waveform. This sample-time dependence is likely to be caused by an imperfect translation between the calibration waveform to the electron waveform. Studies carried out in recent months indicate that stray capacitances and inductances in the path of the calibration signal distort the calibration waveform, especially in the rising edge, and this effect has not been taken into account in the present analysis. This observed dependence is relatively small for the energy measurement, approximately 0.5%, but the correction for this effect is important to obtain the best resolution performance. It has a considerably larger effect on the timing measurement.

The corrected energy signals for all the electrons used in the analysis 50, 100, 150, and 200 GeV are used to determine the system linearity and resolution. The linearity is shown in Fig 3b as a fractional deviation from the nominal beam energy. Previous linearity determinations for the calorimeter show discrepancies better than 0.2% for energies between 20 and 300 GeV. Our points lie within $\pm 0.3\%$. However no correction to the data for the systematic deviations shown in Fig 3a are made, and this is probably the origin of the slightly larger non-linearity.

The energy distribution for the 200 GeV electrons is shown in Fig 4a together with the

pedestal distribution whose width determines the noise. The Gaussian fit made in the range of $(-2\sigma, \infty)$ to avoid the left hand side tail is shown as an insert in the figure. The noise observed in this tower geometry is 170 MeV. The noise value is lower than previously observed, by about a factor of two. This reduction in comes from three causes: (1) longer shaping time was used in the second and third sections; (2) use of a 14-bit ADC reduces the quantization error; and (3) use of multiple sampling and optimal filtering analysis essentially redefines the shaping time. This latter effect is particularly important in the first section, which has short shaping time and consequently high thermal noise. The resulting fractional energy resolution is shown in Fig 4b as function of the electron beam momentum. The electronic noise contribution and the beam spread contribution have been subtracted in quadrature for the points in the plot. A fit assuming a functional dependence

$$\frac{\sigma E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus \frac{c}{E^2},$$

gives $a=10.2\%$ and $b=0.1\%$ for a noise figure of $c=170$ MeV.

Figure 4 (a) Energy spectrum for 200 GeV electrons. The width of the pedestal distribution shown in the inset show the noise level for a sum of 60 channels. (b) Energy resolution as function of electron energy. The dotted curve is a function $\frac{\sigma E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus \frac{c}{E^2}$. The values of $a=10.2\%$ and $b=0.1\%$ are obtained from the fit and $c=170$ MeV is found from the pedestal distributions.

4.2 Timing

Measurement of the time origin of calorimeter signals will be an important off-line tool to correctly associate the events to a particular bunch crossing. Cryogenic calorimeters are known to have excellent timing properties due to the extreme constancy of the waveform. The reconstructed timing from the channel that receives the highest energy deposit shows a resolution of 260 ps. The timing resolution of the calorimeter is actually much better than this, since this value includes the contribution from the beam scintillator elements which is estimated to be about the same

magnitude.

5 Conclusions

This work shows that the linearity, resolution, and timing measurements are not significantly compromised in a calorimeter equipped with preamplifiers using dynamic gain compression. The fitting of waveforms with amplitude-dependent peaking times has required new techniques to be developed, but there does not appear to be any fundamental difficulty in carrying out the analysis.

In the course of the analysis several lessons were learned. The most difficult hurdle was the translation of the calibration waveform to the signal waveform, especially at the level of precision required to reach the resolution of which the calorimeter is capable. An observed dependence of the reconstructed amplitude on the position of the samples leads us to believe that small perturbations introduced in the calibration waveform by small reactive impedances are large enough to invalidate the approximation of a simple exponential for the calibration current waveform. Consequently an error is made in predicting the shape of the signal waveform. In a calorimeter system which uses multiple samples and optimal filtering, particular care must be paid to the design of the calibration system, to ensure that not only the gain of each channel but also the signal waveform is determined to an accuracy consistent with the performance goals.

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