LARGE COAXIAL GERMANIUM DETECTORS - CORRECTION FOR BALLISTIC DEFICIT AND TRAPPING LOSSES

F.S. Goulding†, D.A. Landis† and S.M. Hinshaw*

† Lawrence Berkeley Laboratory
Engineering Division
1 Cyclotron Road
Berkeley, CA 94720

* Tennelec, Inc
601 Oak Ridge Turnpike
Oak Ridge, TN 37831

Abstract

The use of a ballistic deficit corrector circuit that calculates and applies a correction on a pulse-by-pulse basis has been shown to improve the energy resolution of spectrometers using large-diameter coaxial detectors at high energies and high counting rates. The potential importance of this circuit in correcting for the loss in signal amplitude due to majority carrier trapping has also been recognized. This work has led to further approaches to improve performance.

This paper describes experimental results that demonstrate the complex nature of the problem of simultaneously correcting for both types of loss and also explains the results. Finally, the proposed design of a signal processor that should achieve good simultaneous correction for both types of loss is discussed.

I. INTRODUCTION

The amplitude observed at the output of the shaper used in a nuclear pulse amplifier is slightly dependent on the risetime of the input (detector) signal. The loss in amplitude that occurs for input signals with slow risetimes, known as the "ballistic deficit" was studied by Baldinger and Franzen [5]. Fluctuations in input signal risetime, such as those that occur due to the random location of interactions in detectors, result in fluctuations in the output signal amplitude, causing a deterioration in the energy resolution of a spectrometer. In coaxial germanium γ-ray detector spectrometers, this effect becomes very important for the large-diameter detectors now becoming rather common, for high energies, where the fractional basic energy resolution approaches 0.1%, and for high rate applications, where the short shaping times employed emphasize the ballistic deficit effect.

Another factor that degrades resolution in γ-ray spectrometers using large-diameter coaxial germanium detectors is the effect of trapping and loss of charge carriers during their transit across the detector. Many of the germanium crystals grown for use in detectors contain an electron trap of unknown origin. In large diameter n-type detectors (i.e., negative bias on the outside), the signal is largely due to electron motion toward the inner contact. Therefore, such detectors are very sensitive to the presence of electron traps that capture electrons and retain them for times much longer than the processing times used in the spectrometer. On the other hand, radiation damage produces hole traps which are very detrimental in p-type detectors (positive bias on the outside) where the signal is principally due to hole motion to the inner contact. We will collectively refer to these effects as "trapping losses". Because the release times for carriers trapped at these trapping sites is very long compared with the shaping times employed in spectrometers, trapping losses and their effects on resolution are independent of the shaping time employed. This contrasts with the ballistic deficit, which increases in inverse proportion to the shaping time.

The first approach to eliminating ballistic deficit effects was made by Radeka [6] who employed a gated-integrator fed by a pseudo-Gaussian pulse to produce a flat-topped output pulse shape that is inherently insensitive to input signal risetime fluctuations. Difficulties with the gated-integrator, such as its sensitivity to low frequency noise, have mitigated against its widespread use. Furthermore, it is obvious that a gated-integrator system is of no value in correcting for trapping losses. The time-dependent processors, described by Kandiah [7] and others, overcome ballistic deficit effects by effectively shorting out the input signal to the main shaping system until the input has reached its full amplitude. These systems have many of the drawbacks of the gated-integrator and are quite complex. Further, like the gated-integrator, they do not compensate for trapping losses.

An alternative approach was adopted by Goulding and Landis [1] whereby a measurement dependent on the input signal risetime was used to develop a correction signal that was added to the final output signal from the shaper. A suitable measurement of the risetime of the input signal is provided by observing the peaking time of the output signal and, according to Baldinger and Franzen [5], the ballistic deficit is proportional to the square of the delay in the peak. In the original paper, Goulding and Landis drew
attention to the experimental observation that this type of corrector appears also to correct for trapping losses under some circumstances. This result was explained by Simpson et al. [2]. The explanation rests on the fact that the dominant trapping of majority carriers in a coaxial detector occurs for interactions near the periphery of the detector and these events exhibit the longest collection times. Therefore, a signal dependent on the input risetime may be used to correct the main shaper output signal. In more detail, Simpson et al derive the result that the correction signal should be proportional to \((\text{peak delay})^n\) where \(2 < n < 3\). These authors demonstrated the improvement in resolution achieved for a number of detectors using this method.

At this meeting, Simpson et al [3] describe their approach in more detail and present further experimental results. Another paper [4] discusses a new technique invented by Hinshaw for correction of ballistic deficit effects. This technique is based on measuring the difference in the ballistic deficit for two shapers having different peaking times. A correction based on this difference is then added to the output signal from the slower shaping channel. It will be shown in the present paper that Hinshaw's method, which is a special case of a general class, can provide excellent correction for ballistic deficit effects. Experimental results will be presented that show that the two basic types of corrector behave quite differently in regard to ballistic deficit and trapping losses. In general, the Hinshaw method is better for ballistic deficit correction but quite ineffective for trapping loss correction, while the Goulding/Landis method is less effective for ballistic deficit correction but can provide excellent correction for trapping losses. (Note: the Simpson et al extension of the Goulding/Landis method behaves similarly.)

II. OUTLINE OF BASIC CORRECTOR METHODS

A. The "Goulding/Landis" Method

This method, like the Hinshaw method, was developed primarily as a ballistic deficit corrector. Its operation depends on two implicit assumptions:

1) That the top of the shaped output signal approximates a paraboloidal shape

2) That the basic detector pulse shapes are all the same with fluctuations only in their time scale. Coaxial germanium detector signals do not satisfy this condition well but a substantial fraction of the signals observed comes close to satisfying it.

With these conditions the relationship developed by Baldinger and Franzen can be applied:

\[
\frac{\Delta S}{S_o} = \left(\frac{\Delta T}{T_o}\right)^2
\]

where: 
- \(S_o\) = peak amplitude of the output signal for a step function input
- \(\Delta S\) = Deficit for a finite risetime input
- \(T_o\) = Peak signal time of the output signal for a step function input
- \(\Delta T\) = Delay in the peak time for a finite risetime input.

The behavior of the deficit is illustrated in Figs. 1 and 2 for both a 6th order pseudo-Gaussian shape and for a quasi-triangle shape. Figures 1A and 1B show the output pulse shapes for various linear input risetimes while Fig. 2 shows a plot of the \% amplitude deficit vs. the ratio peak delay/peak time. This figure illustrates the square law behavior for an input signal with a linear rise.
Fig. 2: A plot of the ballistic deficit vs. the ratio of the peak delay/peak time. The circles are for the 6th-order Gaussian shaper and the triangles are for the quasi-triangle.

In the Goulding/Landis corrector the peak delay is measured and a simple analog calculator computes the corrector signal $S_0 \left(\frac{\Delta T}{T_o}\right)$. This is then added to the shaper output to provide the final output signal.

B. The "Hinshaw" method

As described by Hinshaw, two processing channels are employed, one consisting of a normal shaper (e.g., quasi-triangle) and the other containing an additional RC differentiator. Because the peaking time of the output signal in the latter channel is shorter than the normal channel, the ballistic deficit is larger. Hinshaw measures this difference and adds it, suitably weighted, to the signal from the normal shaper channel to provide a corrected output.

We will consider here the behavior of a generalized version of the Hinshaw corrector in which two "normal" processing channels with different peaking times are employed. Initially we will make the same assumptions as those that were applied earlier to the Goulding/Landis corrector.

Let $T_{p1}, T_{p2}$ = peaking times in the two channels ($T_{p2} > T_{p1}$)

$\Delta A_1, \Delta A_2$ = deficits in the two channels

$T_R$ = input signal risetime

$\Delta T_{p1}, \Delta T_{p2}$ = delays in peaks in the two channels.

Then: $\frac{\Delta A}{A} = \left(\frac{\Delta T_{p2}}{T_{p2}}\right)^2$

But $\Delta T \propto T_R$

$\therefore \frac{\Delta A_1}{A} = K\left(\frac{T_R}{T_{p1}}\right)^2, \quad \frac{\Delta A_2}{A} = K\left(\frac{T_R}{T_{p2}}\right)^2$

If $\Delta m = \text{Difference in the deficits}$

$\Delta m = (A-\Delta A_2) - (A-\Delta A_1)$

$\Delta m = KA T K^2 \left(\frac{1}{T_{p1}} - \frac{1}{T_{p2}}\right)$

$\therefore \Delta A_2 = \frac{\Delta m}{R^2 - 1} \quad (2)$

where $R = \frac{T_{p2}}{T_{p1}}$

$\Delta m$ can be determined by measuring the difference in amplitudes between the two channels (the gains in the two channels are set to be equal for a pure step function input). The ratio $R$ between the two peaking times is known, so the deficit $\Delta A_2$ in the slower channel can be computed and added to the signal in this channel to provide a corrected output signal.

A little thought shows that the assumptions used in this analysis are not as restrictive as in the case of the Goulding/Landis corrector. In fact, the Hinshaw method directly measures the ballistic deficit effect at two peaking times and derives its correction based on this measurement. The square law assumption is not required, while the Goulding/Landis method depends directly on the square law relationship and departure from this relationship will result in poor correction.

A practical advantage of the Hinshaw method is that a time measurement is not needed. On the other hand, the Goulding/Landis method involves measuring a small delay in the peak time, which is quite long. Hence, this circuit is very sensitive to its adjustment while the Hinshaw method is simple and has no sensitive adjustment.
III. EXPERIMENTAL RESULTS

Early experiments showed that the two types of corrector behaved very differently depending on the particular detector being used. Where majority carrier trapping was significant the Goulding/Landis method provided much better correction for trapping losses than the Hinshaw method. The reverse was true for cases where trapping was small and ballistic deficit effects were dominant. In order to demonstrate this behavior, results were obtained for detectors where one effect or the other was dominant.

A. Ballistic Deficit Dominant

The detector used to demonstrate this case is a very large p-type coaxial detector 90 mm long and 84 mm in diameter with a central hole 8 mm in diameter. The outer contact was n⁺ lithium-diffused while the inner contact was a p⁺ boron implantation. The impurity concentration was 6 x 10⁹ acceptors/cm³ and the bias voltage of 3000 volts was just sufficient to deplete the detector. Figure 3 shows the detector pulse shapes (charge integral) calculated for interactions occurring at different radii. These shapes were representative of those observed experimentally. This detector was never exposed to radiation so no radiation damage-produced hole traps were present. Because hole collection is dominant in producing the signal in this detector we anticipate that any electron traps present in the material would have no significant effect. Figure 4a, showing the shape of the ⁶⁰Co 1.33 MeV γ-ray line measured with a Gaussian pulse shaper at 8 μs peaking time, indicates little or no evidence of trapping. The broad peak of Fig. 4b, which shows the same spectrum measured at a 2 μs peaking time, indicates the dominant role of ballistic deficit effects in this detector. Figure 4c shows the effect of the Hinshaw corrector on the spectrum while Fig. 4d shows the effect of the Goulding/Landis corrector. It is clear from this result that the Hinshaw corrector is far superior for this case although the Goulding/Landis corrector does result in a substantial correction for ballistic deficit effects. The resolution achieved using the Hinshaw corrector is remarkable for such a large detector used at short shaping times.

B. Majority Carrier Trapping Dominant

A series of measurements on various detectors resulted in the choice of the end-cap region of a segmented detector as shown in Fig. 5 to illustrate the behavior of the two correctors in a detector where trapping is dominant. Here the low field existing in the periphery of the end cap causes slow collection and, consequently, substantial trapping. These effects exaggerate the difference between the correctors and thereby more clearly illuminate the basic reasons why the Goulding/Landis method is superior.
Fig. 5: An outline drawing of the segmented n-type coaxial detector. The end-cap region is used to illustrate the behavior of the correctors for a detector where trapping losses are dominant. The coaxial portion of the detector illustrates the case where both ballistic deficit and trapping losses are important.

Figures 7a and 7b show the shapes of the 60Co 1.33 MeV γ-ray peaks observed using a quasi-triangular pulse shaper with peaking times of 8 μs and 2 μs, respectively. We see that the degradation effects in the peaks are similar despite the difference in shaping times - a characteristic of detectors where trapping effects are dominant. Figure 7c shows the improvement obtained using the Hinshaw corrector (compared with Fig. 7b at 2 μs peaking time). Figure 7d shows the much larger improvement obtained using the Goulding/Landis corrector under the same shaping conditions.

These results show quite clearly the superiority of the Goulding/Landis corrector for situations dominated by trapping losses. Note that this is a reversal of the result obtained where ballistic deficit effects were dominant.

C. Mixture of Trapping and Ballistic Deficit Effects

The coaxial portion of the detector shown in Fig. 5 represents a good example of this case. Figure 8a shows 1.33 MeV 60Co line shape measured using a quasi-triangular shaper at a peaking time of 2 μs. Figure 8b shows the effect of the Hinshaw corrector and Fig. 8c shows the effect of the Goulding/Landis corrector. While a significant improvement in resolution is achieved, neither circuit improves the performance to that which might be expected if both trapping losses and ballistic deficit effects were absent.

IV. DISCUSSION

The results presented here are confusing at first sight. The key to understanding them is to recognize the fundamentally different concepts involved in the two methods although, in a general sense, each responds to changes in the input signal risetime. The Hinshaw corrector makes a direct measurement of the change in the ballistic deficit when the shaping time changes and uses this difference to provide the correction. To first order this method works independently of the actual shape of the rise of the input pulse. As demonstrated here the result of this is that the Hinshaw corrector provides almost complete correction for ballistic deficit effects. The Goulding/Landis corrector, on the other hand, implicitly depends on the input pulse shapes being all similar with only a change in time scale from one to the next. As illustrated by Figs. 3 and 6, the pulses from a detector do not completely satisfy this condition. Therefore, it is easy to understand why this corrector is inferior to the Hinshaw corrector in cases where ballistic deficit effects dominate.

It is less easy to understand the relative behavior of the two correctors in correcting for trapping losses. We recall that the trapping losses are most serious for events occurring in the peripheral regions of coaxial detectors and that the bulk of the detector volume is near to the periphery. Therefore, many events will have the general shape shown by the slower pulses in Figs. 3 and 6 and these events will be accompanied by significant trapping losses.
Fig. 7: Shapes of the 1.33 MeV $^{60}$Co line for a detector with substantial trapping. See text for details.

Note that these shapes are characterized by a rather slow start to the rise and a rapid rise after a delay time. Such pulses cause very little ballistic deficit (since a simple delay in a signal does not cause a ballistic deficit). Therefore, for precisely those pulses that are known to suffer trapping losses, the Hinshaw method which is sensitive to ballistic deficit produces almost no correction. The Goulding/Landis method, on the other hand, is very sensitive to delay (it actually measures the peak delay and squares it) so it provides good correction for trapping losses.

The results presented here confirm the general validity of the picture presented in the previous two paragraphs. However, precisely how much correction is needed to correct for trapping losses is more difficult to decide. According to Ref. 2, the square law used by Goulding/Landis should be changed to a power law $\Delta S \propto \Delta T_p^n$ where $2 < n < 3$. The correct relationship depends on the particular detector used, on the field distribution in it and on the distribution of traps. In our work we have found that the square law works well and we have observed no benefit from using a cube law but we cannot overrule the possibility that it may be better in some cases. It is clear that correction for trapping losses can never be perfect but the improvement achieved is very significant, particularly in making it possible to employ substantial amounts of n-type material containing native electron traps. This material would otherwise be rejected.

This work has led us to consider the design of a pulse processor that combines the benefits of both types of corrector and makes possible optimum operation of detector systems over a broad range of shaping times. In most n-type
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VI. REFERENCES


Fig. 9: Block diagram of a proposed pulse processor providing both types of correction to permit optimum resolution over a broad range of shaping times.

detectors, ballistic deficit effects cause resolution degradation at short shaping times and trapping losses limit resolution at longer shaping times. The design of a proposed processor is shown in Fig. 9. It uses the Hinshaw method to correct for ballistic deficit effects. The amount of this correction is adjusted at short shaping times where ballistic deficit effects are dominant. The Goulding/Landis method is used to provide correction for trapping losses. While the channel used to develop this correction uses a short peaking time to make it sensitive to changes in input pulse rise-time, the amount of the correction is adjusted with the main processing channel set to a long peaking time where trapping losses are dominant.

Work on this approach is underway at the present time and results will be presented in a later paper.