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GAMMASPHERE - Elimination of Ballistic Deficit by Using A Quasi-Trapezoidal Pulse Shaper

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Abstract

Gammasphere uses an spherical array of very large (7.2cm dia.) germanium detectors and only high-multiplicity events are studied. To achieve a reasonable coincidence rate, the individual detector channels must handle high rates with minimum pile-up losses. Ten microseconds was chosen as the total processing time for a signal which means that the shaped signal peaks in about 4us. The combination of short pulse shaping and the fluctuating long charge collection times (up to 400ns) in the detectors exaggerates the energy resolution degradation due to ballistic deficit effects. We describe a method of producing a flat-topped pulse with a simple time-invariant network that satisfies GAMMASPHERE requirements and eliminates ballistic deficit effects.

1. INTRODUCTION

GAMMASPHERE(1) is a detector system consisting of 110 detector assemblies each containing a large germanium detector surrounded by a hexagonal BGO scintillator Compton shield. These detector assemblies are mounted to completely cover the surface of a sphere surrounding the target and are used to observe the simultaneous emission of many gamma rays from highly deformed short-lived nuclei spinning with high angular momentum. Trigger conditions are imposed to permit acceptance only of events that produce signals in M germanium detectors (where M is typically 4 or more). In order to give adequate statistics in the coincidence spectra in a reasonable experimental time, very high singles rates must be present in individual channels (typically 10,000 to 20,000 counts/second). To reduce dead-time losses, the design of GAMMASPHERE is based on only 10us total processing time for germanium detector signals, implying that the shaper must generate a signal that peaks in about 4us. Here we are assuming that we use a time-invariant analog shaper since, in our judgment, the alternative of digital signal processing and/or time-variant shaping would increase the complexity of the processor considerably while gaining little in performance.

Because the system uses large-diameter detectors (7.2 cm) with charge collection times fluctuating out to 400ns and because short processing times must be used, ballistic deficit effects become a major limitation to energy resolution, particularly for the high-energy (typically 300KeV to 3MeV) gamma rays of interest for GAMMASPHERE applications. This paper deals with the design of the signal processor to achieve the required spectroscopy performance within these constraints.

2. COMPARISON OF PULSE SHAPERS

Modern time-invariant pulse shapers are invariably based on the shape(2) represented by:

$$S(t)=P_0\, e^{-3kt} \sin(kt)^n \qquad \text{---- Eqn 1}$$

where S(t)is the signal, P_0 and k are chosen to normalize the amplitude and time scales, and n is typically 6. This shape (usually called a sin ^{n} shape) is conveniently derived using a single RC differentiator and a cascade of active integrators with complex poles (three stages for n=6).

This basic shape is frequently modified by mixing the outputs of the three active integrator stages to generate a pulse shape generally referred to as the quasi-triangle (3). This shape approximates a symmetrical triangle which results in the lowest possible series (or delta) noise for a given total width. Unfortunately, this shape (and the sin ^{n} waveform) exhibits a rather sharp peak so the amplitude output is sensitive to the arrival times of components of the input signal; it therefore results in large ballistic deficit effects on energy resolution.

Much work has focused on methods to correct for ballistic deficit effects and our plans early in the GAMMASPHERE project were to use the Hinshaw method(4) to achieve the correction. This method consists of measuring the difference in amplitude of the output of two shapers with different peak times. It is obvious that the shaper with narrower peak will exhibit the larger ballistic deficit. The gains in the two shapers are made equal for a pure step function input and the shorter of the two waveforms is stretched to provide the delay needed to allow measurement of the amplitude difference in the two channels. This difference is then multiplied by an experimentally determined factor and added to the longer

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signal to correct it for ballistic deficit. Figure 1 shows an equivalent way of deriving the "Hinshaw" correction in a completely linear system that facilitates noise analysis. Here a sin^6 waveform is generated as the main spectroscopy signal (signals are shown for a true step function input). The output of the 2nd stage of the shaper (3 stages total) is delayed to peak at the same time as the 3rd stage (final) output and its gain is adjusted to make the amplitudes equal. A corrected Hinshaw waveform is then generated by combining waveforms A and B (Output = 2A-B) as shown in the figure. The resulting waveform has a relatively flat top and, consequently, the system exhibits only little ballistic deficit. The noise parameters shown in the figure can be determined in the well-known manner(5) from the weighting function which is the same as the pulse shape for a time-invariant system. Here Ns^2 is the step (parallel) noise residual function, NΔ^2 is the delta (series) noise residual function and FoM is a figure of merit (Sqr(Ns^2 x NΔ^2)) that is related to the 1/f noise performance of the shaper. The results given here are a significant improvement over the original Hinshaw method that used an RC-differentiated version of the output waveform as the narrower pulse shape. Figure 2 shows the weighting function for the linear version of the original Hinshaw corrector and its noise parameters. Note that the relative noise values for series and parallel noise are proportional to the square root of the Ns^2 and NΔ^2 values in the tables of Figs. 1 and 2. Note also that these linear versions of the Hinshaw corrector, while useful for noise analysis, involve the use of delay lines and the temperature coefficient of such lines effectively prohibits their use in a practical amplifier for high energy high-resolution applications.

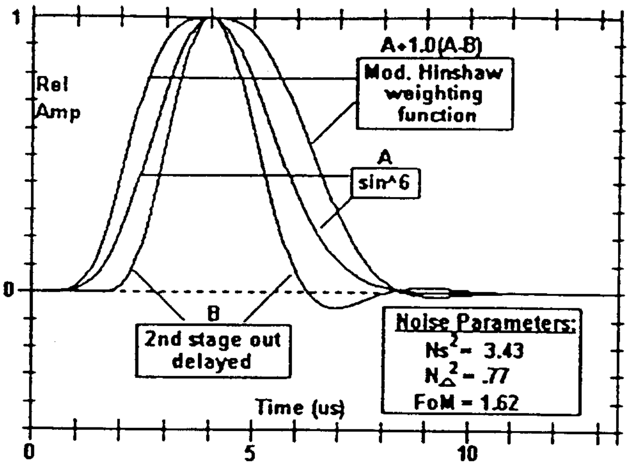


Fig. 1. Method of generating and analyzing a modified version of the "Hinshaw" ballistic deficit correction.

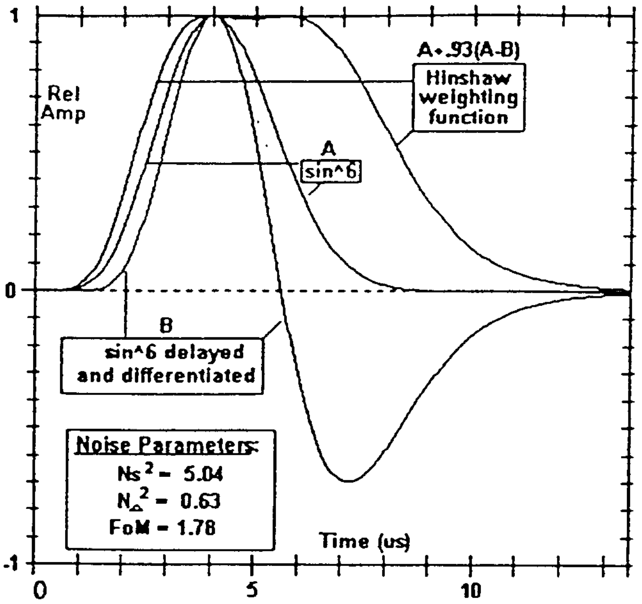


Fig. 2. Method of generating and analyzing the original" Hinshaw" ballistic deficit correction.

Another type of corrector(6) for ballistic deficit uses a measurement of the delay in the peak time for each shaper output signal compared with that expected for a pure step function input. This delay is related to the particular input signal rise time and it can be used to develop a correction that is added to the main signal. It has been shown(7) that the behavior of this type of corrector and that of the Hinshaw design results in complex interactions between the effects of ballistic deficit and charge trapping in the detector. Also, both involve adjustable parameters that must be determined by experiment to optimize their performance. In a detector system as complex as GAMMASPHERE we judged that these problems were not acceptable. This led to an effort to separate the effects of trapping and ballistic deficit by producing a simple flat-topped pulse shaper that would completely eliminate ballistic deficit effects and, in parallel, to derive a signal that could be used independently for a trapping correction. The work on trap correction is discussed in another paper at this meeting. It is well known that a gated integrator(8) can be employed to derive a flat-topped response that eliminates ballistic deficit effects. This approach requires the use of a low-level discriminator to provide the signal recognition to start the integration process. Also, not only does the weighting function of a gated integrator emphasize low frequency noise, but the integrator itself gives equal weight to any input over the whole integration time. We have found that this emphasizes low-frequency extraneous noise sources such as microphony and power supply ripple. We therefore eliminated the gated integrator as our method of choice.

3. THE QUASI-TRAPEZOIDAL SHAPER

It has been known for some time that the addition of waveforms from stages in a cascade of active integrators can result in pulse shapes with very useful properties. The quasi-triangle(3) is an example of this. We therefore explored this general technique to derive a flat-topped pulse shape and discovered that appropriate mixing of the outputs of a $\sin^8$ shaper could give the desired result. The processor consists of a single RC differentiator ($a_0 = 1/R_0C_0$ where R_0C_0 is expressed in microseconds) followed by 4 stages of active integrators of the general type shown in Fig. 3. The two versions of active integrators shown in this figure have the same time response if circuit values are appropriately chosen; the Modified Bridged-T circuit produces an inversion of the signal, while the Salen Key circuit, that is used in our design for all four stages, produces no inversion. The Laplacian of the time response of these stages is given by the relationship shown in this Fig. 3. Table 1 shows the values of a_0, a_1 and a_2 for the stages. These values are chosen to generate a harmonic series of sine terms in the response of the successive stages; the highest frequency stage is the first one in the cascade.

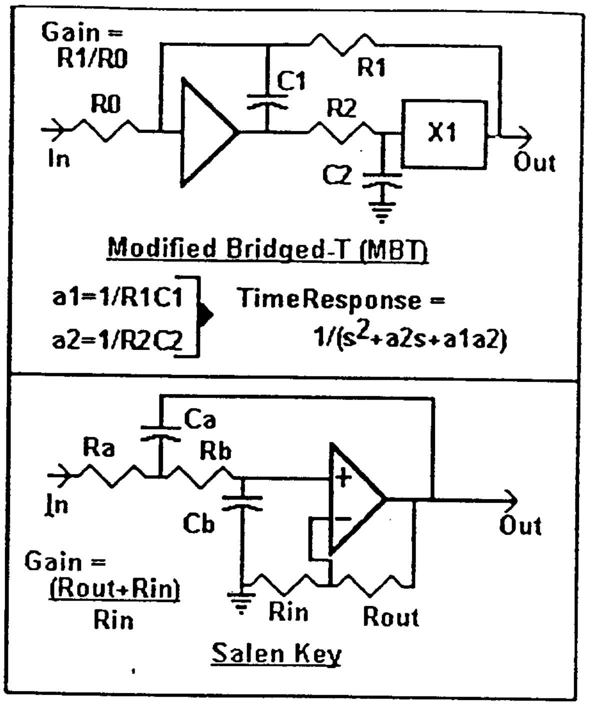


Fig. 3. Active integrator stages.

TABLE 1 : Parameters for Shaper Stages

	Diff	Stage 1	Stage 2	Stage 3	Stage 4
a_0	0.701				
a_1		2.843	1.752	0.974	0.502
a_2		1.402	1.402	1.402	1.402

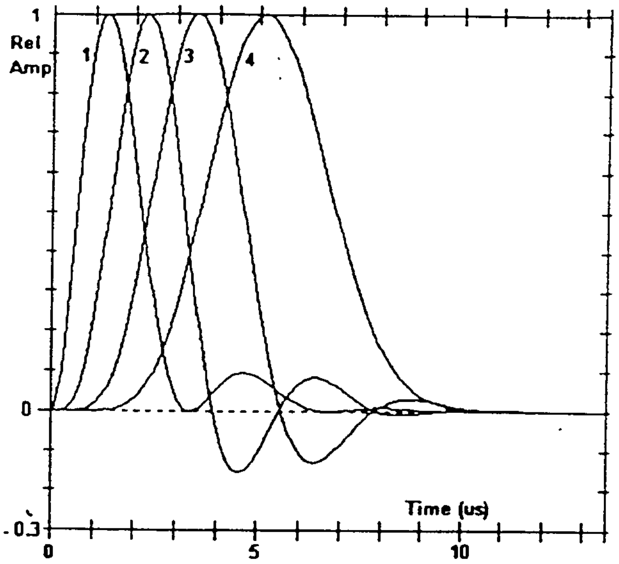
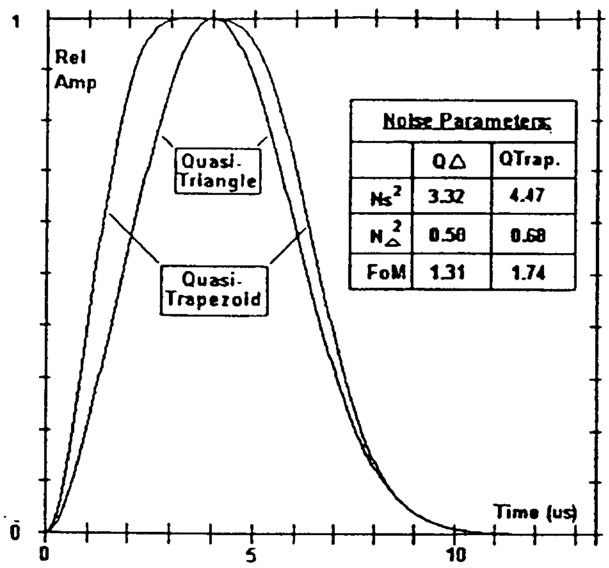


Fig. 4. The outputs of four stages used in cascade to produce a $\sin^8$ waveform.

The waveforms produced at the outputs of the stages are shown in Fig. 4. and these can be added in the ratios 0.35, 0.63, 0.53 and 1.0 to produce the quasi-trapezoidal shape shown in Fig. 5. The same figure shows the quasi-triangular waveform, referred to earlier, for comparison. We see that the quasi-trapezoidal shape has essentially a flat top for a period of 1us. The noise behavior of the two pulse shapers is also shown in the figure. It is evident that a shape that is constrained to end in a fixed time, and to have a flat top, must exhibit worse series and parallel noise than one with no flat top - because it necessarily has more area (affecting parallel noise) and the rise and fall must be faster (affecting series noise). The Table in Fig 5 illustrates this, but the series noise degradation is only about 9% and parallel noise plays little part in detector systems used at short shaping times such as GAMMASPHERE. Moreover, we observe that interest here is mainly in high-energy gamma rays and noise is less of a consideration than ballistic deficit. The behavior in regard to this factor is perhaps best demonstrated by determining the response to events located at three radii in a GAMMASPHERE detector, the radii being chosen to produce the fastest signal (r = 22mm), the longest convex signal (r = 4mm) and the longest concave signal (r = 35mm). Table 2 shows the deficit for the two shapes of Fig. 5.



Noise Parameters:		
	QΔ	QTrap.
Ns^2	3.32	4.47
N_Δ^2	0.50	0.68
FoM	1.31	1.74

Fig. 5. The Quasi-trapezoidal waveshape produced by adding the shapes of Fig. 4 in the ratios .35, .63, .53 and 1.0.

Table 2: Deficits for shapers

Radius of event	4mm	22mm	35mm
Q.Triangle	.0024	.0006	.0019
Q.Trapezoid	.00008	.00004	.0001

These results show that the Quasi-trapezoidal shaper exhibits essentially no ballistic deficit while the Quasi-triangle shows deficits that are comparable to that basic detector resolution at 1MeV. Since many GAMMASPHERE experiments involve energies in the several MeV range, the value of the new shaper is obvious.

4. CIRCUIT IMPLEMENTATION

Figure 6 shows in block form the actual circuit used. The design uses surface mount techniques to result in a small daughter board (see the photograph in Fig. 7) that mounts on the main VXI processing board together with the rest of the signal processing, logic and readout for two complete detector channels.

The four active integrator stages shown in the figure are implemented using a single integrated circuit containing four operational amplifiers with the shaping and mixing components mounted on the daughter board. The output stage performs the waveform mixing operation with weights determined by R1 - R4. A "wrap-around" gated base line restorer is used in this stage to remove any DC offsets from the previous stages. The main shaper is driven by a limiter stage preceded by a computer-controlled gain stage to permit full-scale output (5V) to correspond to 2, 4 or 20MeV. The RC differentiator that feeds this stage is driven by an input amplifier handling the ramp signal from a transistor-reset preamplifier located at the detector. The overall design is able to handle very large overloads with minimal recovery time, an important consideration where dead-time losses must be minimized.

Tests on the amplifier have shown that the theoretical output shape is achieved and that component tolerances of 1% in the shaping and mixing stages produce virtually no distortion of the pulse shape. The spectroscopy performance shows the expected result that ballistic deficit effects are eliminated with only a slight cost (about 100eV FWHM) in energy resolution at low energies.

5. ACKNOWLEDGMENTS

The GAMMASPHERE concept owes its origin to a proposal made by F. Stephens of LBL to DOE in 1987. The general design of the detector is the result of the deliberations of a steering committee set up by DOE. Our work has benefited from discussions with several members of the committee and particularly with members of the GAMMASPHERE experimental group at LBL.

6. DISCLAIMER

Reference to a company or product names does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

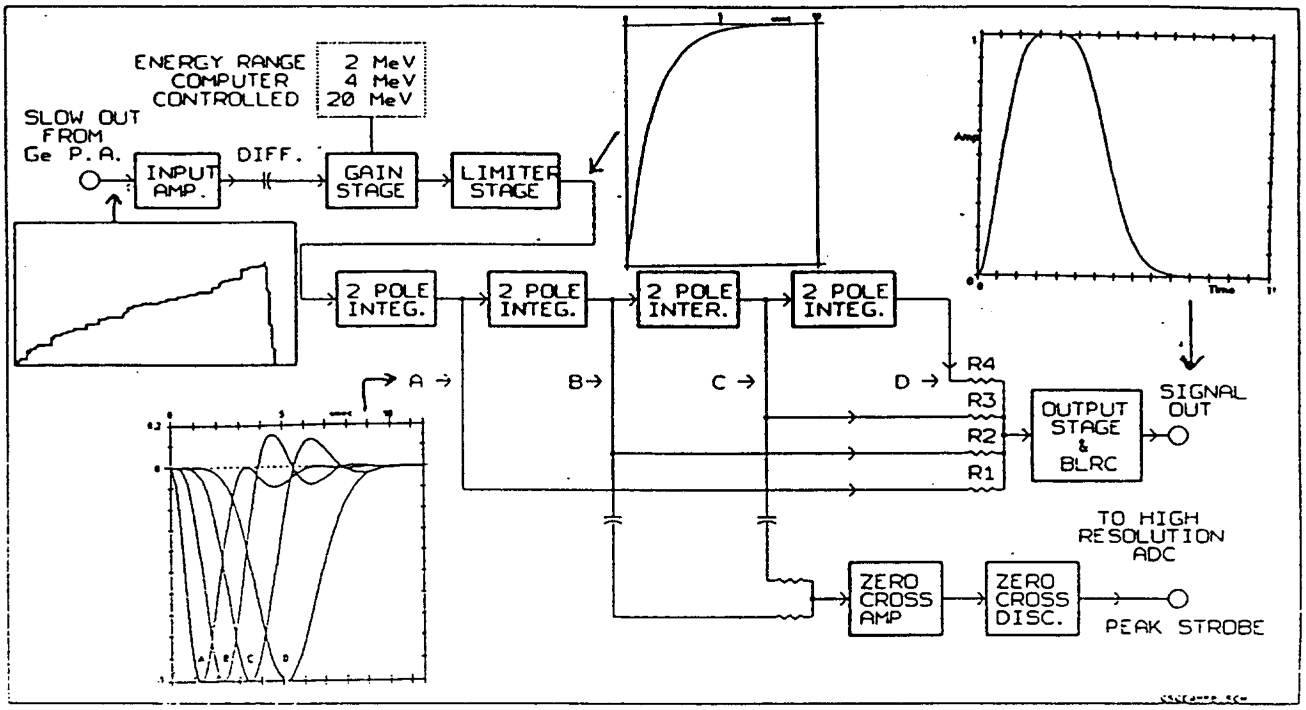


Fig. 6. A block diagram of the shaper used to produce the quasi-trapezoidal waveform.

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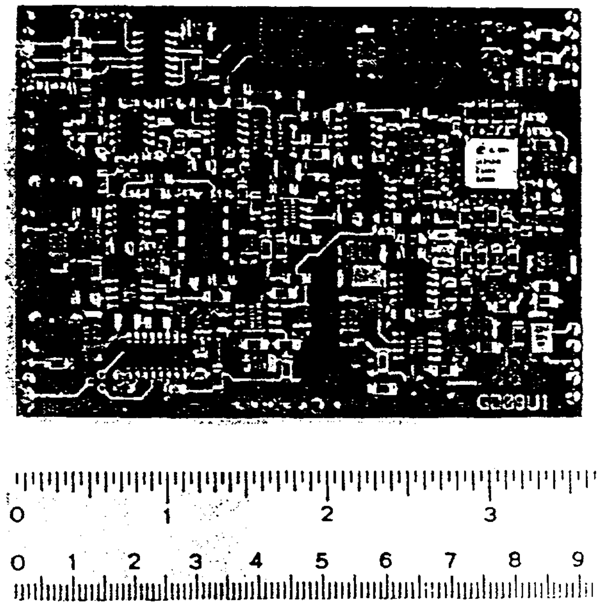

Fig.7. A photograph of the shaper board used in GAMMASPHERE.