Improvement of Spectral Resolution in the Presence of Periodic Noise and Microphonics for Hyper Pure Germanium Detector Gamma-Ray Spectrometry Using a New Digital Filter

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Abstract

A digital filter has been developed for removing low-frequency periodic noise from the output signal of High Purity Germanium (HPGe) detectors. The filter was designed specifically for removing periodic noise induced from the use of mechanical-cooling devices employed as an alternative to liquid nitrogen cooling for HPGe detectors. An alternative to liquid nitrogen is particularly attractive for developing portable HPGe systems. The filter, termed the Low Frequency Rejector (LFR), removes microphonic noise by estimating the microphonic-induced error signal on a pulse-by-pulse basis and subtracting the estimated error signal from the trapezoid output. The error signal is proportional to the slope of the baseline during the energy measurement. If the slope is known, so is the error introduced by the microphonics. The estimate of the slope is obtained by using a trapezoidal filter to measure the slope before and after the energy measurement. The weighted, averaged value of the before and after slope measurements is then subtracted from the energy measurement producing a measurement essentially free of microphonic noise. In this paper, three distinctly different detector/mechanical cooler combinations were investigated. In addition, use of the LFR to remove the periodic noise induced from "outside" environmental sources, such as ground loops is investigated using an input sinusoidal wave generator. The LFR was successful in improving spectral resolution across all energies in two of three detector/mechanical cooler combinations. In cases where the microphonic contribution to the signal is small, the LFR does not improve resolution. In simulated tests, it is shown the LFR is effective in removing periodic noise from 100 Hz to 3 kHz.

Introduction

Sources of Noise in HPGe Spectrometry

One important quantity used to evaluate the performance of HPGe detectors is the resolution (or resolving power). In simple terms, this quantity is a measure of the "width" of peaks in the energy spectrum. In practice, resolution is a measure of how well a HPGe system can distinguish between gamma-ray peaks whose energies lie close together in the spectrum. Resolution is commonly specified in terms of the Full-Width at Half Maximum (FWHM) of energy peak; the width of the peak when measured at half of the maximum peak height (Fig. 1). Although the resolving power of HPGe detectors is superior to other detector types (e.g., sodium iodide NaI(Tl) or cadmium zinc telluride: CZT), the resolution of a given system can be degraded due to noise introduced to the detector output signal.

The sources of electrical noise that contribute to the width of peaks for germanium detectors is described in detail in numerous texts[1, 2]. For simplification, these sources can be divided into three categories:

1. Series noise from the input FET.

2. Parallel noise from the feedback resistor and from leakage currents in parallel with the capacitance to ground at the preamplifier input.

3. Periodic noise induced by outside sources, such as microphonics associated with vibrations and electrical sources, such as ground loops.

Here we focus on periodic vibration and electrical contributions. While noise contributions from sources one and two (above) are a function of the preamplifier and associated electronics of the system, the greatest sources of periodic noise can be from outside of the germanium detector and preamplifier mounting. These outside sources can be a much greater contributing factor to the overall noise present in the output signal. Of particular concern are contributions that are a result of ground loops and from mechanical coolers, now more widely used for germanium detector systems. In many cases, the source of ground loops and other environmental periodic noise can be difficult to trace, making the reduction in the source hard to accomplish. Here we present results of tests of the performance of a newly developed digital filter (termed the Low Frequency Rejector or LFR), designed to remove microphonic and other periodic noise from the output signal of HPGe detectors. The novel filter (patent pending) was developed by ORTEC®, and is implemented in a new digital signal processing based gamma spectrometer (DSPEC jr 2.0).

Digital Filters and the LFR

Digital signal processing (DSP) filters have been employed for various applications as early as 1973[3]. DSP has supplanted analog filters previously employed due to the inherent stability of the digital circuitry in comparison to the analog counterpart. For HPGe applications, DSP-based gamma-ray spectrometers have become the “industry standard” and are now widely used in “standalone” configurations and within larger measurement systems. It has rapidly become clear that the DSP technology has no performance disadvantages relating to spectroscopy; indeed, in almost every case, DSP offers improved resolution, throughput and stability; over long time periods and wide temperature changes[4, 5, 6]. In addition, a wide choice of operating parameters can be coupled practically and the latest instruments offer a high degree of setup automation. In some cases, this means that instrument performance can be “tuned” to make the optimum use of this performance for specific applications. Not surprisingly, a wide variety of systems have been developed incorporating digital spectrometers, in counting laboratories, remote monitoring, industrial on-line applications and non-destructive assay applications. DSP systems are proving capable of meeting the most demanding of applications. As mentioned above, microphonic noise can be large compared to other sources of noise. This fact is particularly important in optimizing systems that employ mechanical cooling technologies. Over the past several years, mechanical-cooling technologies have been more widely distributed for HPGe applications.

While developing the mechanical cooler, a new digital filter capable of correcting the pulse output signal for change in the baseline caused by the microphonics was also developed. In many ways digital filters are easier to understand than their analog counterparts. Figure 2 shows the voltage step output produced at the preamp by the collection of charge produced by absorption of a gamma-ray and the resulting trapezoidal weighting function in a digital spectrometer. Because the baseline contains noise, the difficulty in the measurement is to precisely determine the height of the step pulse. A simple estimate of the step signal is obtained by averaging the digitized samples of the signal before and after the step. N samples before the peak-detect signal are averaged. M samples immediately after the peak-detect signal are skipped, to allow for the pulse to return to the baseline. N samples after the rise time samples are then averaged, and the average subtracted from the average of the baseline before the event. This simple procedure produces a trapezoidal weighting function with a rise time of N sample intervals and a flat top of M sample intervals. The maximum value of the trapezoid output, occurring at the end of the flat top, is the best estimate of the step height and therefore the gamma-ray energy. With a proper selection of M and N, this filter is very nearly the optimum filter for a system with only parallel noise and series noise from the preamplifier.

The trapezoidal filter is essentially independent of DC offsets, since the averaging and subtracting removes the DC component of the signal. Unfortunately, it is just as sensitive as analog filters to slowly varying signals such as that produced in microphonic noise. Figure 3 shows the output of the trapezoidal filter is equal to the slope of the baseline signal multiplied by the full width at half maximum of the trapezoid. If a step pulse were to be measured on such a baseline, the filter output value will be too high by an error equal to the difference in the average values A_1 and A_2. Since the microphonic noise component in a signal had a period long compared to the gamma-ray signal (such as the sine wave illustrated in Fig. 3), the error induced can be positive, negative or zero. This error signal adds to the width of the spectral lines, thus appearing as degraded resolution performance from the detector and can, in many cases, be a dominant noise source especially at lower energies.

The Low Frequency Rejector (LFR) Filter

The LFR filter removes most of the microphonic noise by estimating the microphonic-induced error signal on a pulse-by-pulse basis and subtracting the estimated error signal from the trapezoid output. As noted above, the error signal is proportional to the slope of the baseline during the energy measurement. The simple trapezoidal filter assumes the baseline under the peak is a constant equal to the baseline at the beginning of the peak, and the LFR makes a better estimate of the baseline when the baseline is changing. An excellent estimate of the slope can be obtained by using the trapezoidal filter itself to measure the slope by sampling both before and after the energy measurement. Since the digital filter is always sampling the input signal, it is only necessary to store the values measured before the event is detected, store the gamma-ray energy measurement and store the values measured after the event is detected. The modified trapezoidal digital filter for LFR is shown in Fig. 4. A suitably weighted and averaged value of the before and after measurement of the slope is then subtracted from the energy measurement producing a measurement essentially free of microphonic noise.

Experimental Setup

A total of three detector/mechanical cooler systems were examined (Table 1). In two cases, the X-Cooler was used with a mixed-gamma, filter-paper-geometry (47 mm diameter) source was centered on the endcap of the detectors. In the other case, a Stirling-Cooler was used with a mixed-gamma point source placed at 10 cm on-axis from the center of the endcap. In all cases, the detector output signal was coupled to a DSPEC jr 2.0. The DSPEC jr 2.0 employs a digital trapezoidal filter, and the LFR. Flat top width was held constant for all detectors (0.8 μs). For each detector/cooler combination, a series of counts was conducted to measure the resolution (FWHM) at energies from 59 keV to about 2 MeV. Measurements were conducted with the LFR on and with the LFR off to determine the optimum rise time. The optimum rise time is defined as the lowest rise time value (best throughput) that results in the best resolution (lowest FWHM values across the energy range).

In a second test, the LFR was used to remove periodic noise induced from "outside" environmental sources, such as ground loops using an input sinusoidal wave generator. In this set up, a wave generator was connected to the Test Input of the detector. The amplitude of the test input signal was attenuated to reasonable limits. The frequency of the input sine wave was varied from 100 Hz to 3 kHz (in discrete steps). The energy resolution was measured for peak energies from 59 keV to 1332 keV at each step.

Results and Conclusions

Detector/Mechanical Cooler Test Case Results

The LFR was successful in improving spectral resolution across all energies in two of three detector/mechanical cooler combinations (Tables 2 and 3). In the case where the microphonic contribution to the signal is small, the LFR does not improve resolution (Table 4). In test case 1 (GEM65 P-Type detector/X-Cooler combination), the optimum risetime value was found to be 8.8 μs (Figs. 6 and 7), while an optimum value of 3.6 μs was determined to be optimum for test case 2 (GEM15 P-Type detector/Stirling-cooler combination, Figs. 8 and 9). Although improvements are apparent in two of the test cases, it should be noted that the observed deadtime for experiments with the LFR on were generally a factor of 2-3 higher than counts conducted with the LFR off, due to the greater length of the LFR filter.

Simulated Periodic Noise Test Results

In simulated tests, it is shown the LFR is effective in removing periodic noise from 300 Hz to 3 kHz. In the "worst case" scenario, periodic noise can not only cause spectral degradation (increases in peak width), but can cause "double peaks" (Fig. 10). Clearly, the spectral resolution that is achieved with the LFR on (as shown in Fig. 10 for a 2 kHz induced signal) is acceptable, while the result with the LFR off is not (due to the double peaking phenomenon). Figure 11 shows incremental results for peak resolution with energy as the signal is "swept" from 300 Hz to 3 kHz. The zero value represents a "clean" spectrum taken with no induced sine wave and the LFR on. It appears that as the induced signal approaches 3 kHz, the improvement in spectral resolution, by the LFR is reduced.

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Table 1 Detectors and mechanical coolers used for this investigation. The efficiency values are given in terms of the IEEE standard.

Detector Model	Type	Relative Efficiency (%)	Cooler Type (Manufacturer)
GEM65	P-Type	65	X-Cooler (ORTEC)
GMX15	N-Type	15	X-Cooler (ORTEC)
GEM15	P-Type	15	Stirling (Hymatic, SAX101)*

* Hymatic Engineering Company Limited, Redditch, Worcestershire, United Kingdom

Table 2 Selected peak FWHM maximum values by energy for Test Case 1 (GEM65/X-Cooler combination). Improved resolution is observed at the optimum risetime value (8.8 μs) at all energies.

Laboratory Based System	Resolution (FWHM, keV)	
Energy (keV)	LFR ON	LFR OFF
59.5	0.75	0.85
662	1.30	1.34
1173	1.65	1.73
1332	1.74	1.79

Table 3 Selected peak FWHM maximum values by energy for Test Case 2 (GEM15/Stirling-Type Cooler combination). Improved resolution is observed at the optimum risetime value (1.2 μs) at all energies.

Portable System	Resolution (FWHM, keV)	
Energy (keV)	LFR ON	LFR OFF
59.5	1.2	1.6
662	1.5	2.0
1173	1.9	2.3
1332	1.8	2.3

Table 4 Selected peak FWHM maximum values by energy for Test Case 3 (GMX15/X-Cooler combination). In this case, contribution of microphonics to the output signal is low and improved resolution is not observed with the LFR on.

Laboratory Based System	Resolution (FWHM, keV)	
Energy (keV)	LFR ON	LFR OFF
59.5	0.75	0.76
662	1.28	1.25
1173	1.59	1.63
1332	1.69	1.74

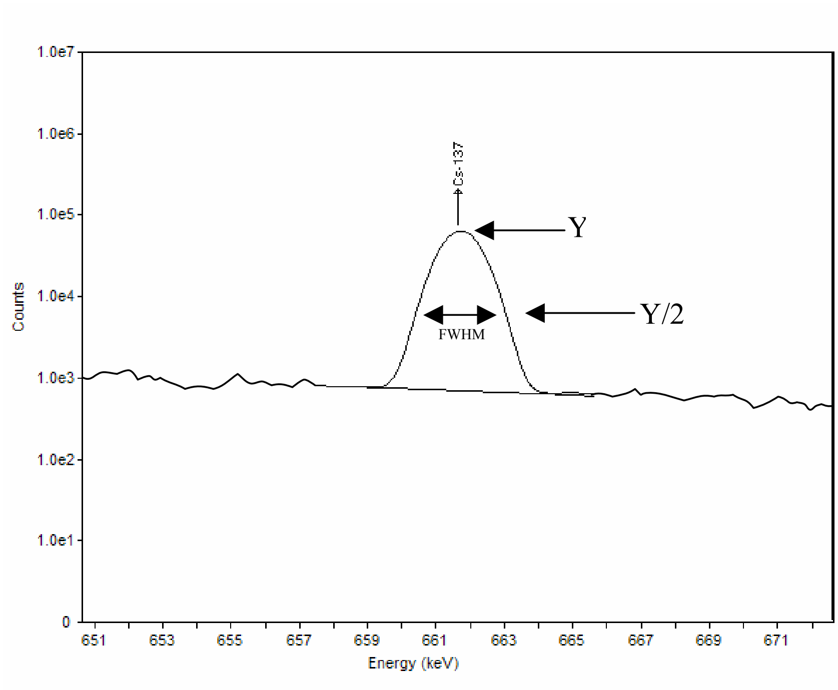

Figure 1 Definition of detector resolution in terms of FWHM.

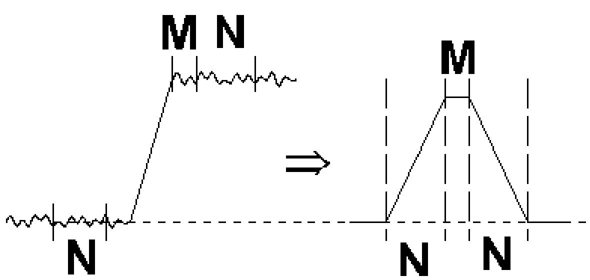

Figure 2 Typical trapezoidal weighting function (right) arising from detector preamplifier output signal (left).

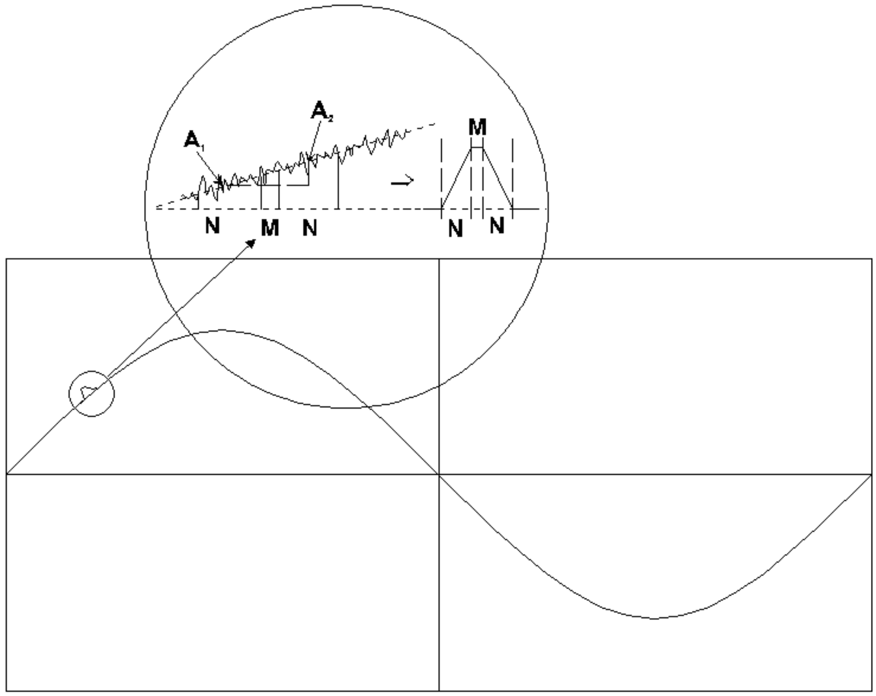

Figure 3 Example of weighting function output resulting from the positive slope due to low frequency noise (shown as a sine wave).

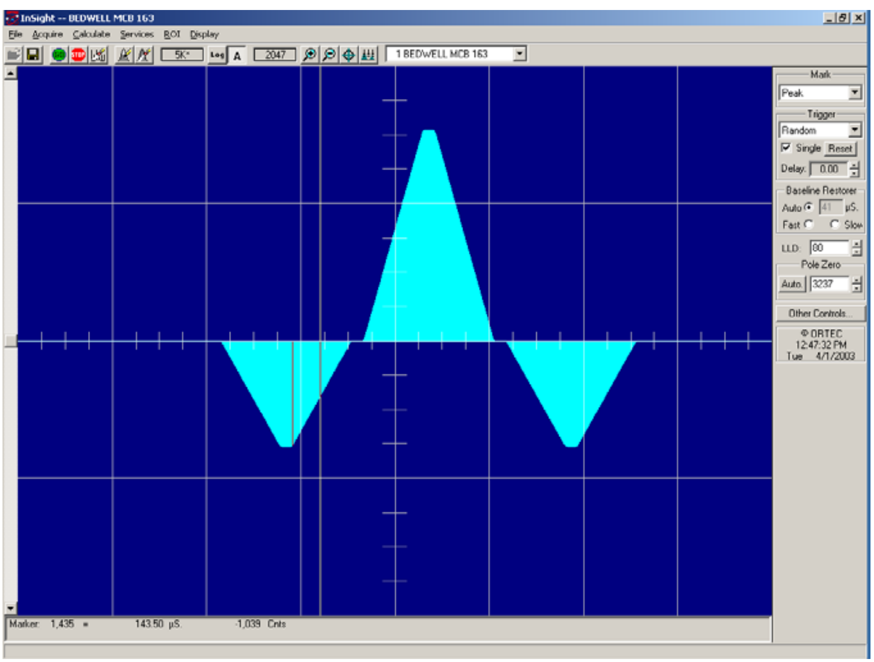

Figure 4 LFR-enabled digital filter from DSPEC jr. 2.0

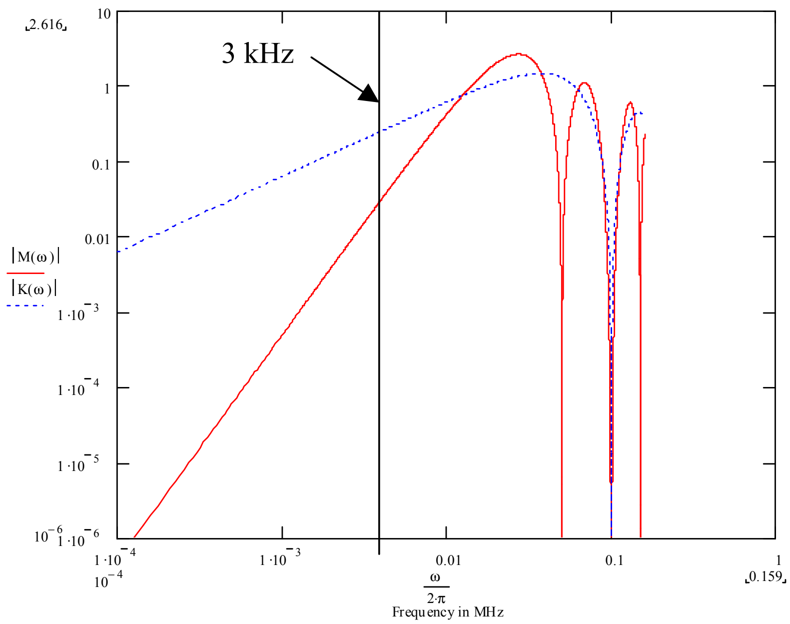

Figure 5 Theoretical frequency response of typical (dashed line) and LFR (solid line) weighting functions using 10 µs rise times.

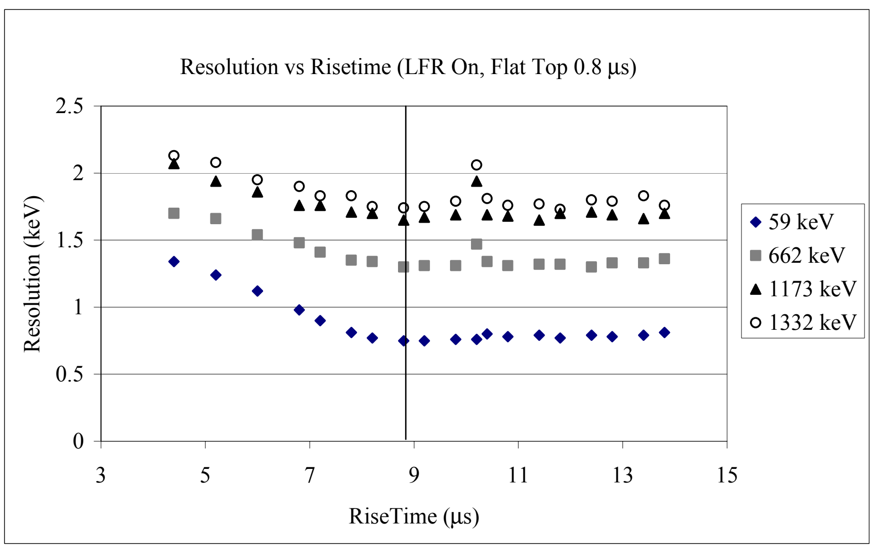

Figure 6 Resolution vs risetime for test case one (GEM65, P-Type detector and X-Cooler), with the LFR on. The best resolution was found at 8.8 µs rise time.

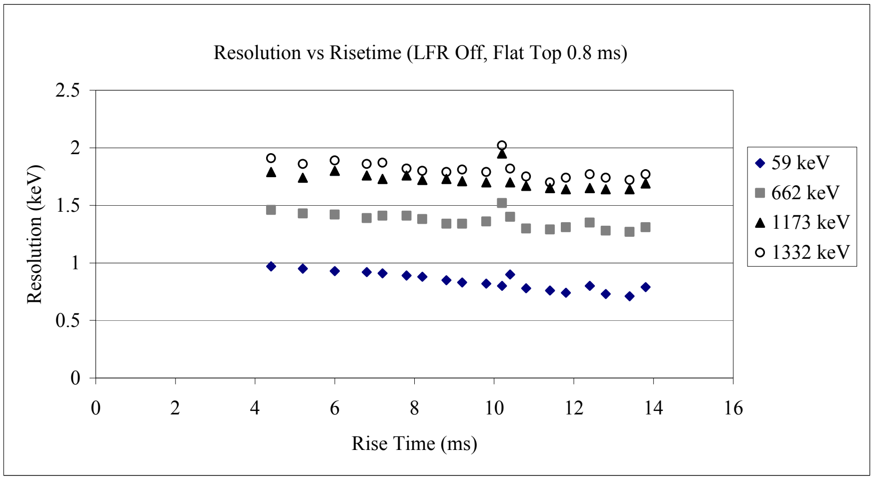

Figure 7 Resolution vs risetime for test case one (GEM65, P-Type detector and X-Cooler), with LFR off. The best resolution was found at long risetimes.

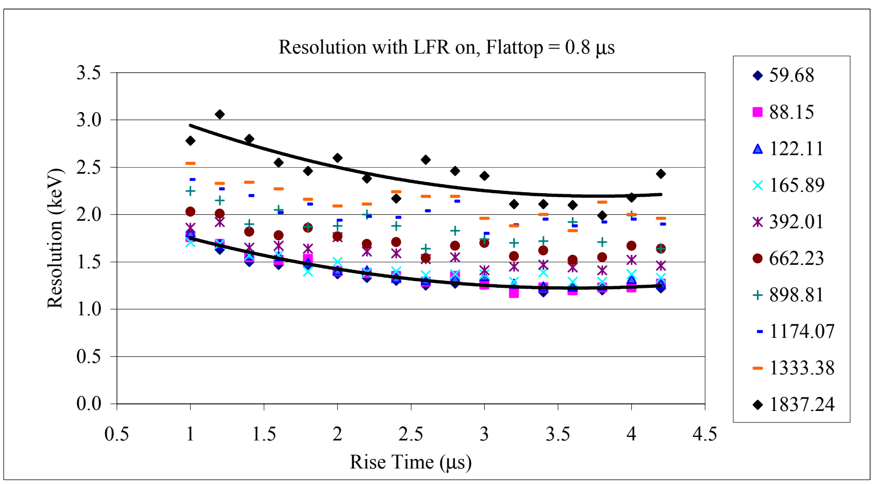

Figure 8 Resolution vs risetime for test case one (GEM15, P-Type detector and Stirling-Type Cooler), with LFR on. The best resolution was found at 3.6 µs risetime.

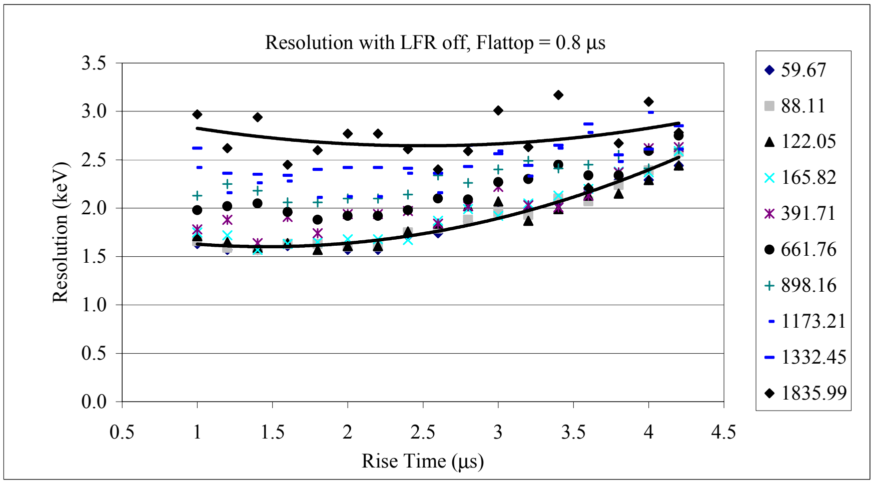

Figure 9 Resolution vs risetime for test case one (GEM15, P-Type detector and Stirling-Type Cooler), with LFR off. The best resolution was observed at 1.6 µs risetime.

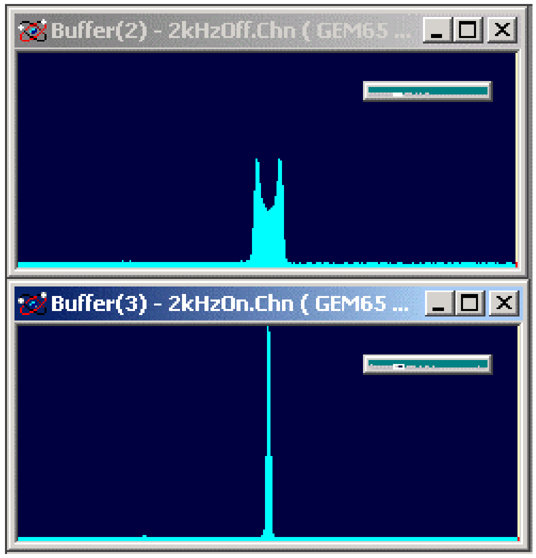

Figure 10 Comparison of spectral resolution with an induced periodic sine wave added to the output signal of a germanium detector. The top figure displays the resulting peak shape at 662 keV when the LFR is turned off. The bottom figure shows the improvement with the LFR on.

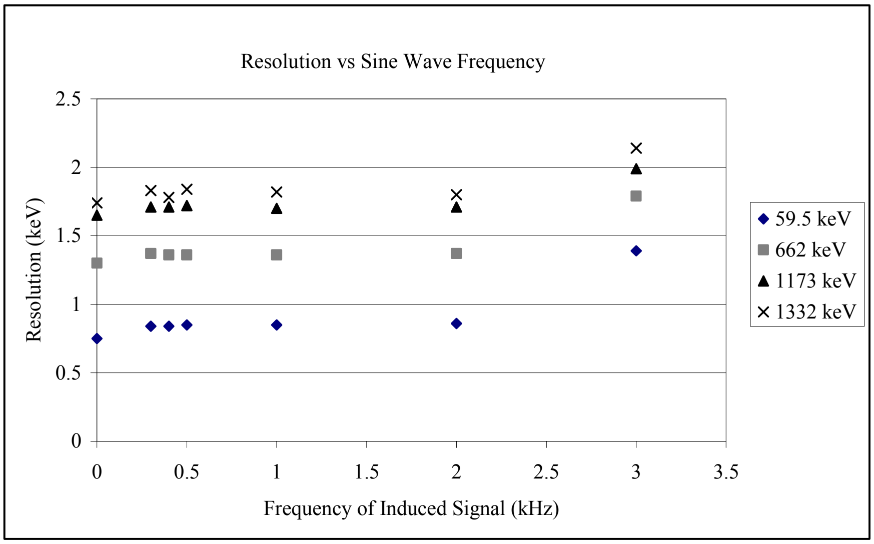

Figure 11 Resolution as a function of input sine wave using a wave form generator with the LFR on for the GEM65/X-Cooler system. Zero value for frequency represents data collected with the LFR on and no induced wave form.