NEW COOLING METHODS FOR HPGE DETECTORS AND ASSOCIATED ELECTRONICS

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Abstract

Despite the on-going development of room temperature semiconductors for use as gamma-ray detectors, the only material which can provide a solution to the combined requirements of stability, high-energy resolution and high-detection efficiency (at useful energies) is still germanium (HPGe). These properties of HPGe gamma-ray detectors make them invaluable in meeting the demands of the newly emergent and increasingly important applications relating to homeland security and the interdiction of smuggled nuclear material.

However, HPGe detectors require cooling to cryogenic temperatures (<120 °K) to operate as gamma-ray detectors. Traditionally, this cooling has been accomplished with liquid nitrogen (LN2). The use of LN2 as a coolant is, at best, inconvenient. Maintenance, operating cost, availability at remote locations, and the hazardous nature of the material all combine to limit the practicality of a LN2-cooled device, no matter how desirable it might be from other standpoints. Mechanical methods of achieving cryogenic temperatures have existed for many years. The first mechanically-cooled HPGe systems appeared commercially in the early 1980s[1]. These systems had high cost, high power requirements, degraded system performance, were bulky in size, and unreliable. Other developments have produced prototype versions of portable (or transportable) mechanically-cooled HPGe systems.

More recent advances in mechanical cooling technologies have the potential to make HPGe detectors easily adaptable to a wide variety of applications including battery-operated, truly man-portable systems for use in inspection, unattended monitoring, and Homeland Security. The major problems of mechanical coolers are degraded performance due to vibration and power consumption. The systems described here have reduced both of these to useable limits. The vibration or microphonic noise created in real-world systems is significantly reduced by optimizing the digital filter technology in the signal processing electronics associated with such detectors. Data presented here show reliability and performance results of the mechanically-cooled systems. These results show the improvements gained through the use of the optimally-matched digital filters.

Introduction

High Purity Germanium (HPGe) gamma-ray detectors have been widely used in the nuclear and industrial sectors for many applications over many years. The advantages of HPGe detectors in terms of energy resolution, efficiency, sensitivity, and ease of spectrum analysis have been clear in a wide range of applications both fixed-installed and in situ. The drawback to using these detectors, though, has always been the need to cool them to near cryogenic temperatures. As a general rule, HPGe detectors operate at a temperature range of 90-120K. To get to these temperatures, liquid nitrogen has traditionally been used with a cryostat and dewar combination designed to provide the cooling path. However, using liquid nitrogen, even in a dewar configuration, poses health risks as well as operational problems.

In an effort to overcome this drawback, much effort has been put into the development of compound semiconductor materials that operate at room temperature or near room temperature. These efforts include cadmium zinc telluride[2] (CZT), mercuric iodide[3,4], cadmium telluride, and more recently pixellated CZT arrays[5]. However, in every instance, these detectors suffer from physical size limitations and thus efficiency, thereby restricting their use to only a small number of applications.

Today's applications demand higher sensitivity AND selectivity along with ease of use, especially in the case of portable instrumentation. Scintillation detectors remain the standard for sensitivity due to availability in large volume and ambient temperature operation. However, poor energy resolution of these devices means that they are not suitable for applications in radiochemistry, environmental monitoring, and now Homeland Security.

Until recently, practical mechanical coolers for HPGe detectors have been uncommon, and, if available, have caused performance degradation in the HPGe resolution. We will demonstrate below that not only are there innovative technologies available for mechanical coolers that operate from either mains-powered or battery-powered sources, but also a new digital signal processor that can correct the signal for the resolution degradation typically seen in these detectors.

Mechanically-Cooled HPGe Detectors

Laboratory-based Mechanical Coolers

Mechanical coolers for HPGe detectors have existed for many years. Early mains-powered devices included the Solvay-cycle device reported by Marler and Gelezunas as early as 1973[6]. The detectors tested using this cooler were shown to have poor performance due to microphonic noise present in the system.

Microphonic noise comes from the vibration created either by a moving piston in a compressor or from boiling of the refrigerant gas near the HPGe detector. Electronically, microphonic noise appears as low frequency, near-cyclic noise on the baseline of the signal pulses. This noise degrades HPGe performance which is shown as a degradation in the resolution of the detector. It is typical in the industry to specify mechanically-cooled detector resolution performance as degraded by some percentage compared to liquid nitrogen performance.

In the Marler and Gelezunas systems, the degradation was as much as 260% at 5.9keV and 92% at 122 keV. Because noise contribution is added in quadrature, the effect of microphonics decreases as an absolute percentage as the energy of the photons increases.

ORTEC introduced a modified Solvay-cycle cooler in 1986. In this design, the detector was physically separated from the piston-driven compressor thereby reducing the effects of the microphonics shown in earlier devices. Stone et al reported performance degradation of only 8% at 5.9 keV as typical for this type of arrangement. This device however required periodic maintenance (every 5000 operating hours) thus making it expensive for routine applications.

In 2000, ORTEC introduced a modified Joule-Thompson, or J-T, cooler known as the X-Cooler®. The X-Cooler offers many advantages over previous J-T coolers like the CryoTiger® sold by many manufacturers of HPGe detectors in that it is not expensive (typically 25% of the cost of other coolers), small, and lightweight. Reliability and maintenance were addressed by using a patented technique for self-cleaning the refrigerant every time it cycles through the system[7]. By constantly removing contaminants, such as compressor oil and particulates from the gas, the X-Cooler solves the inevitable problem of clogging seen in other similar coolers. This clogging results in the failure to properly cool HPGe detectors.

Portable Coolers

As shown above, laboratory detectors using mechanical coolers have advanced to a stage where they are affordable and reliable. These coolers are not portable or even transportable, however, due to their use of compressors that require oil as a lubricant. The presence of the oil typically requires that the cooler not be tipped by more than 30 degrees from horizontal at anytime. This limitation is due to the oil contaminating the coolant gas which impedes the mass flow of the gases through the closed-cycle systems. Additionally, many of the systems are large or require high power to operate. The best of these systems, the X-Cooler, still weighs 25 pounds without the detector and uses 300W of power in steady-state operation.

Stirling cycle coolers, however, offer the promise of portability in mechanically-cooled HPGe detectors. Unlike J-T or Solvay-cycle coolers, Stirling coolers use a piston and springs driven at very high rates to compress the refrigerant gas (often helium). The piston/spring arrangement is oil-free thus eliminating completely the contamination of the gas and thus the possibility of clogging. These coolers have been used for years in prototype HPGe systems as well as many other cryogenic applications. Stirling coolers have not been offered as a commercially available system because they tend to be large and expensive.

One such prototype system is the LLNL-designed Stirling cycle cooler used in the Field Radiometric Identification System, FRIS[8]. The Stirling cooler used in the FRIS is manufactured by Sunpower and coupled to an HPGe detector. In the LLNL-designed FRIS, the Stirling cooler was shown to be transportable and battery operated. The FRIS was demonstrated in several applications including border security and chemical weapons detection as superior to scintillation detectors because it uses HPGe with its better resolution[9]. The FRIS, while transportable, requires significant battery capacity to operate it at a power consumption of nearly 60 Watts when at operating temperature. Such battery consumption makes the weight of the FRIS too high to be truly portable.

In 2002, LLNL presented a new mechanical cooler attached to an HPGe detector called the Cryo3. The Cryo3 is unique because it offers a truly portable system with smaller batteries. The miniature Stirling cooler requires only 15 Watts of power input. However, the cooler itself is limited in its cooling capacity to the point that the Cryo3 can only operate a small HPGe detector element. Additionally, it requires the use of a Peltier cooler to cool an internal infrared shield[10]. This driven inner shield reduces the radiative heat load of the HPGe detector element. The Cryo3 also suffers from poor energy resolution with measured values of 3.5 keV Full Width Half Max at 662 keV.

Reducing Microphonics

As mechanical cooling becomes common for HPGe detectors, the issue of microphonics will become more important. As was shown earlier, many HPGe detectors coupled to mechanical coolers suffer from degraded performance. Many attempts have been made to reduce this degradation. It is possible to limit the affects of microphonics in mechanically cooled detectors through design considerations in the cryostat. These mechanical options, however, have adverse trade-offs in portable applications.

Early attempts by Sakai et al used a specially designed anti-microphonic crystal mount design. These designs often employ techniques to remove high voltage from the mount. In the Sakai mount, it was shown that a clear improvement could be made with the antivibration mount but only at shorter shaping times[11].

The most common method in use today is to separate the detector from the moving compressor as much as possible. Twomey et al showed that detectors attached to the X-Cooler had on average a 7% degradation in performance versus the same detector cooled on liquid nitrogen[12]. While this has shown promise in recent laboratory systems, use of the X-Cooler is not feasible in portable instruments. The mechanically cooled system used in the transportable FRIS device (Lavietes et al) uses a software algorithm embedded into a DSP device to control a mechanical balance which reduces the affect of vibrations caused by the moving pistons[13]. This method attempts to correct the microphonics not at the detector but at the compressor. The drawback to this method is the additional electronics and thus power needed to control the balance as well as the additional weight created by the balance itself.

An Improved Portable Mechanical Cooler with Active Microphonics Correction

In 2002, ORTEC began development of a small, handheld, battery-powered HPGe detector system. The system uses a larger capacity compressor thus allowing for performance enhancements over the currently available design in the LLNL Cryo3. Additionally, an effort was undertaken to create a modified digital filter for processing the preamplifier signals such that it can correct for the microphonics with software rather than through any mechanical means.

The Portable Mechanical Cooler

The SAX101-002B cooler from Hymatic Engineering, Ltd. is the next generation of the Stirling cooler design used in the Cryo3. The SAX101 differs in that it uses a dual opposed piston arrangement rather than the single in-line piston of the Cryo3 system. The dual-piston design increases the cooling capacity by a factor of 4. By having this capacity available, the ORTEC design is able to use a larger (e.g., 50 mm x 30 mm) crystal element for higher efficiency and, more importantly, a cooled FET for improved energy resolution. The power consumption of the ORTEC design is still less than 16 Watts, making battery operation in a portable unit possible.

Figure 1 below shows the completed detector/cooler assembly. The first detector measurements on two different coolers showed an energy resolution performance of 2.1 keV at 1332 keV, a substantial improvement in a bigger detector than the Cryo3; and no active damping was necessary, in contrast to the FRIS.

While developing the mechanical cooler, ORTEC also addressed the issue of microphonics by developing a new digital filter capable of correcting the pulse output signal for change in the baseline caused by the microphonics. 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. The difficulty in the measurement is to precisely determine the height of the step pulse, because the baseline contains noise. A fairly obvious estimate of the step signal is obtained by averaging the digitized samples of the signal before and after the step. M samples immediately after the event are first ignored, to allow for a maximum rise time of M times the sample interval. 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 noise arising only from the detector leakage (parallel noise) and the FET current (series noise).

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 is approximately a sine wave as illustrated in Figure 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

A digital filter is proposed that rejects low frequency noise from the signal input (patent applied for). 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. If the slope is known, so is the error introduced by the microphonics. An excellent estimate of the slope can be obtained by using the trapezoidal filter itself to measure the slope 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 from an InSight™ trace from the ORTEC DSPEC jr™ in Figure 4. A suitably weighted and averaged value of the before and after slope measurement is then subtracted from the energy measurement producing a measurement essentially free of microphonic noise.

Figure 5 shows the calculated frequency response of the typical trapezoid filter (dashed line) and the LFR-enabled filter (solid line). The graph shows the output of the systems for a typical ten µsec rise time setting of both filters. The x-axis is the frequency of the noise in the system. At 3 kHz, the improvement in response to the noise is roughly an order of magnitude with the LFR-enabled filter.

Experimental Improvements using LFR

Testing with a Pulser and Sine Wave Generator

The first test of the theory for the LFR used a pulser to simulate a typical pulse output from HPGe detectors input to a modified ORTEC DSPEC jr with the LFR digital filter. To simulate microphonic noise, a sine wave generator was also connected to the input of the DSPEC jr with a frequency of 3 kHz. This arrangement verified the hypotheses set forth in the discussion.

The pulser measurement with the microphonic noise using a standard trapezoid weighting function resulted in a peak width at half max of 30 channels. After enabling the LFR-enhanced weighting function in the DSPEC jr, the pulser peak width at half max was reduced to 3 channels. This improvement matches well with the predicted output from Figure 5.

Results and Conclusions

It was shown that the LFR can make a significant improvement to microphonic detector systems in the case of a pulser and sine wave generator. In that system set up, the improvement was from a full width at half max of 30 channels to 3 channels. It is believed that this improvement can also be achieved in a portable, mechanically-cooled HPGe system. Future experiments will be conducted to verify and improve the LFR using a variety of detector models (planar, small coax, large coax, etc.) as well as the different types of mechanical coolers currently used by ORTEC such as the J-T and Stirling cycle units referred to above.

Furthermore, it has been shown that a truly portable, mechanically-cooled detector system can be delivered using the SAX101-002B cryocooler. When coupled to digital electronics which employ the LFR, the complete device shows excellent system performance with resolution values of 2.1 keV at ^{60}Co, far better than other reported results.

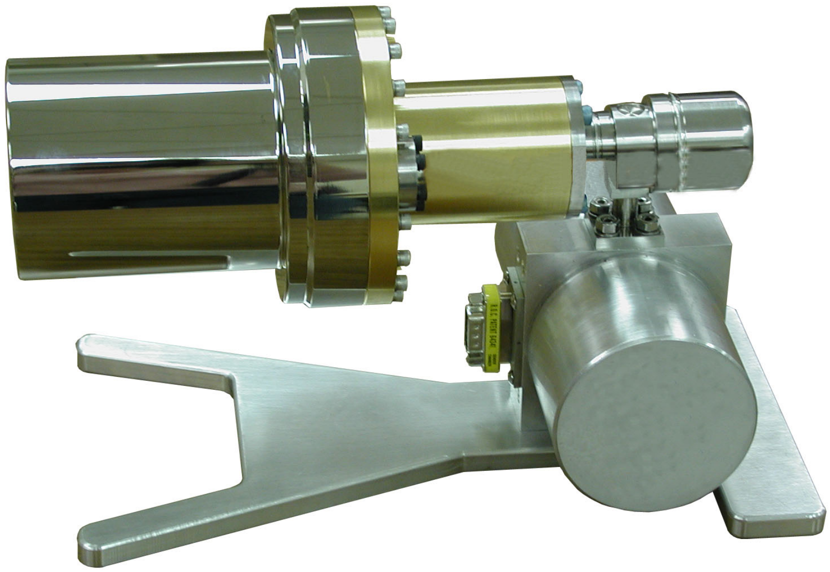

Figure 1. Detector Cooler Assembly.

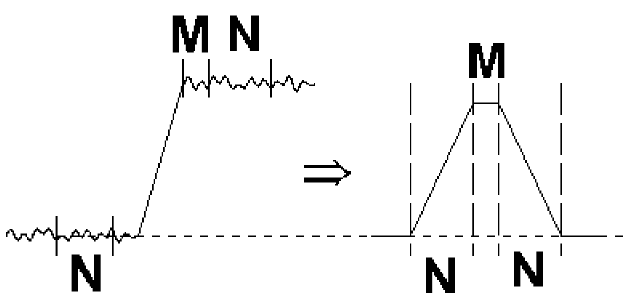

Figure 2. Typical trapezoidal weighting function (right) arising from detector preamplifier output signal (left).

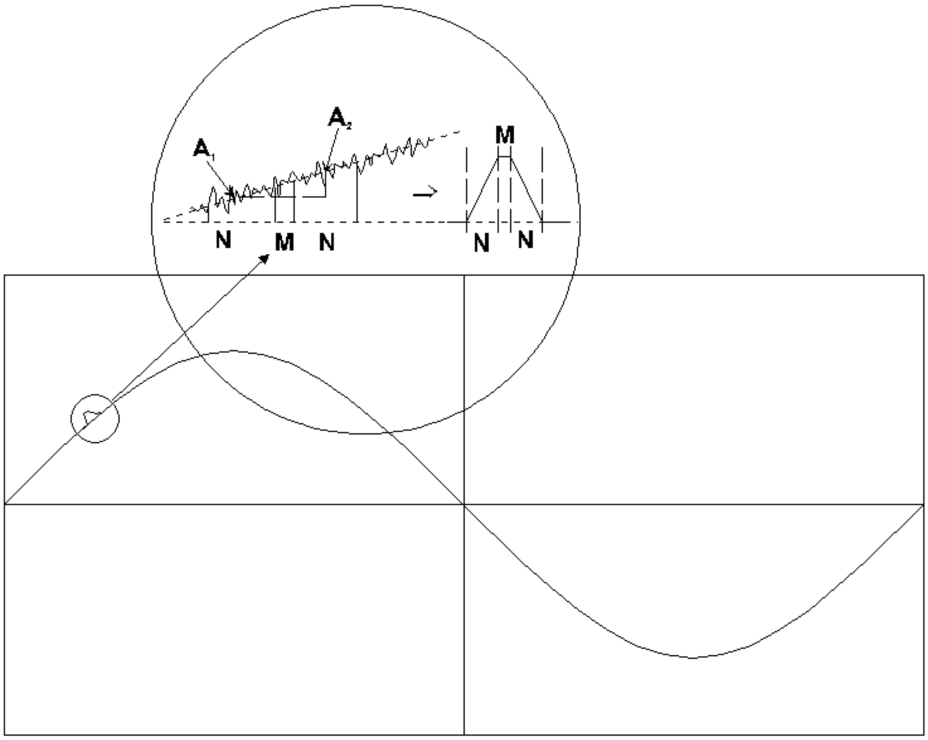

Figure 3. Example of weighting function output resulting from the positive slope due to low frequency noise (shown as a sine wave).

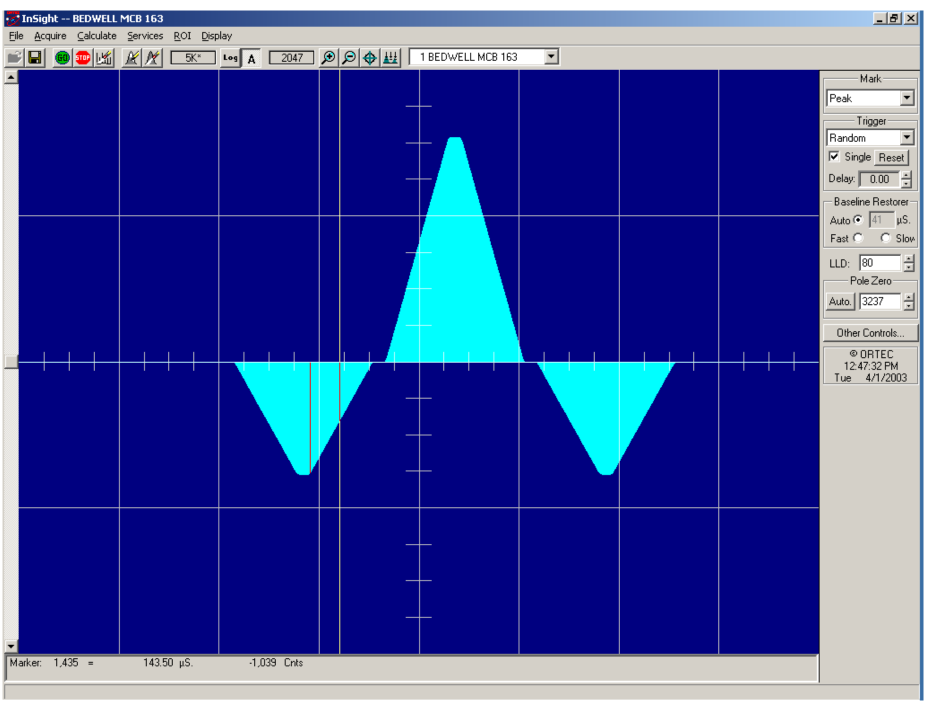

Figure 4. LFR-enabled digital filter from DSPEC jr.

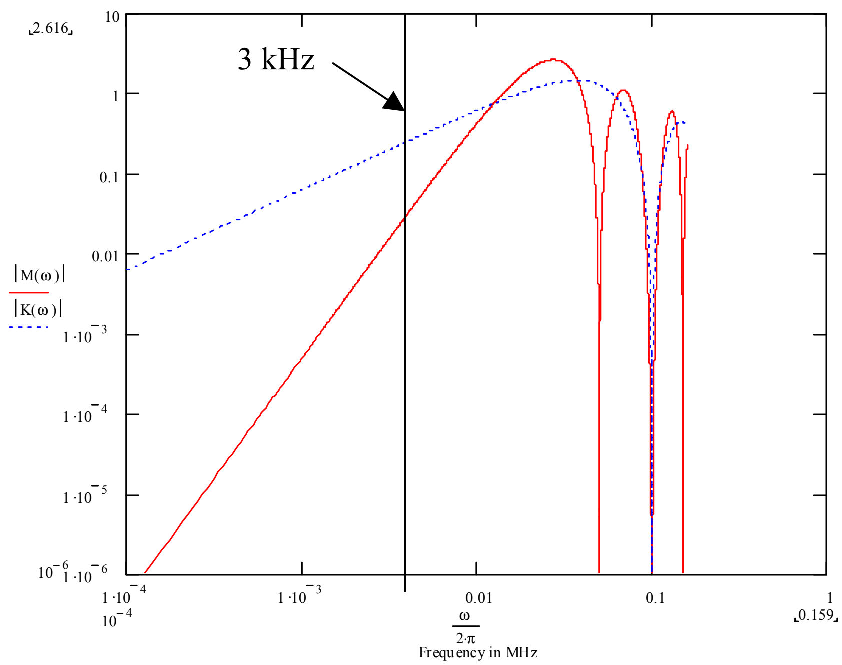

Figure 5. Theoretical output of typical (dashed line) and LFR (solid line) weighting functions using 10 µsec rise times.

Acknowledgements

The authors would like to thank Rex Trammel and Eric Broerman for their assistance and contributions to this work.

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