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Portable Electro-Mechanically Cooled High-Resolution Germanium Detector

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Portable Electro-Mechanically Cooled High-Resolution Germanium Detector*

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Abstract

We have integrated a small, highly-reliable, electro-mechanical cryo-cooler with a high-resolution germanium detector for portable/field applications. The system weighs 6.8 kg and requires 40 watts of power to operate once the detector is cooled to its operating temperature. The detector is a 500 mm^2 by 20-mm thick low-energy configuration that gives a full-width at half maximum (FWHM) energy resolution of 523 eV at 122 keV, when cooled with liquid nitrogen. The energy resolution of the detector, when cooled with the electro-mechanical cooler, is 570 eV at 122 keV. We have field tested this system in measurements of plutonium and uranium for isotopic and enrichment information using the MGA and MGAU analysis programs without any noticeable effects on the results.

Introduction

There is a need for portable/fieldable high-purity germanium (HPGe) detectors capable of performing high-resolution measurements of gamma-ray signatures for isotopic information. Current HPGe detectors are constrained in field and unattended applications due to their requirement for cooling to liquid-nitrogen temperature and the concomitant weight, size, and power requirements. We have used a new cryo-cooler technology to develop an electro-mechanically cooled HPGe detector for unattended and field-deployable gamma-ray measurement systems.

There are a number of ways to cool a high-purity germanium detector. Conventional methods are liquid nitrogen, large scale mechanical helium or special freon coolant pump systems. Others are small Stirling cycle electro-mechanical coolers and high pressure gas systems. Each method has its liabilities and unique applications. First, liquid nitrogen requires some way of venting for boil-off, is heavy in weight, and must be replenished at given intervals. Second, large scale electro-mechanical cryo-coolers, weighing about 90 kg, are not easily fieldable and are microphonic. High pressure gas systems require venting, in addition to a source of high pressure gas. Stirling cycle coolers offer potential for cooling detectors as they are small, light weight and very efficient in power; however, they are mechanically microphonic and have a short life expectancy of about 1000-4000 hours.

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Current mechanically cooled detector designs depend on the following methods to deal with the microphonic problems. Some manufacturers add weight to absorb the vibration and dampen the vibrations from the coolers. Another method used is to suspend the detector in a maze of support wires to decouple the vibration. This technique increases the heat loads on the detector cooling mechanism, requiring a larger cooler that increases vibration and power requirements. These approaches only mitigate the mechanical vibration problem and do not address the root cause. Another issue that is often over looked, is that a mechanical cooler in continuous operation is sensitive to axis orientation. In a field environment requiring a portable device, one cannot predict the orientation of the detector system.

Background

Through an assessment of current commercial high-purity germanium detectors, we found that the cooling requirements vary over a wide range of cryostat configurations. Portable dewar (liquid nitrogen) designs seem to require the least amount of cooling, ranging from 1-3 watts including dewar losses. Data from the manufacturers estimate the dewar losses to be between 0.2-0.5 watts. This defines the cooling requirements for the detector system to be between 0.5-2.5 watts. We studied many off-the-shelf HPGe detector configurations and found a vendor that could provide the lowest heat load detector at 0.5-1.2 watts.

Miniature helium gas cryo-coolers are the most efficient refrigeration units for their size, that are available today. There is a large selection to choose from ranging from a few milliwatts to thousands of watts of cooling power. Some limiting factors to help narrow the choices are reliability, mechanical vibration, sensitivity to orientation, physical size, cooling power @ 77 K, cost and operational power requirements. Mechanical vibration is the most important factor, because it can seriously degrade the resolution of the gamma-ray measurement. One wants little or no mechanical vibration to interfere with the measurement besides the unwanted acoustical noise.

Cooling requirements for a Canberra detector range between 0.5-1.2 watts (others are much higher), therefore the electro-mechanical cooler should provide a minimum of at least 1.2 watts of cooling, if no other precautions to minimize heat loads are applied. Reducing cooling requirements to minimum levels lower the overall heat dissipation in the final designed package. A detector requiring 2.5 watts of cooling would need to dissipate about 80 watts of heat in the total detector-cooler package. A detector requiring 0.8 watts would only dissipate 37 watts.

Reliability would be the second factor of importance, most coolers have a life expectancy of 4000 hours or less. Long term detector applications would demand at least 5 years (45,000 hrs.) or more. This reduces the number of manufactures of a cooler to about three.

In the past four years, infrared detector imaging technology has driven improvements in refrigeration to packages weighing less than four pounds with dimensions smaller than most HPGe detector capsules. Most of the new developments have been in the areas of mechanical balancing, closed loop controllers that lower the mechanical vibration and reduce power consumption. The latest developments in cooler technology include designs with estimated lifetimes of more than 10 years. Discussion with other developers of alternative HPGe detector cooler technology reflects agreement that our proposed efforts bring much needed refinement to miniature, portable HPGe detector systems.

Solution

We use a new cryo-cooler technology to provide an electro-mechanically cooled high-purity germanium gamma-ray detector for unattended and field-deployable gamma-ray detection systems. This detector system is a major improvement over existing electro-mechanically cooled detectors that are plagued with poor resolution by reducing the mechanical vibration at the source.

The electro-mechanical cryo-cooler cold head contains no cold moving parts with critical tolerances and no potential wear-out mechanisms, because of the gas bearing design. These features afford the cooler a considerable system advantage over standard Stirling cooler in reliability, lifetime, and vibration at the cold head. Efficient cold-head design is the key to low input power, low system weight, reduced cooler size, and minimized vibration in the regenerative cooler. The compressor is driven by a linear motor with a moving coil and for maximum efficiency, the compressor is operated at its mechanical resonance frequency.

The vibration of the compressor piston is measured using an force measurement device whose output controls the active damper stroke. The active damper operates 180° out of phase with the compressor and is used to cancel the force imbalance at the fundamental frequency created by the compressor motion. Using this newly developed electro-mechanically cooler, we have developed a germanium detector system that is smaller, lighter in weight, require infrequent service, and has a lifetime as long as there is a power source.

Description of system

The portable, electo-mechanically cooled HPGe detector system was developed using a Sunpower cryocooler with an integrated counterbalance mass. The cancellation system is an assembly of several components tailored to accomplish the required vibration reduction with minimum power consumption and volume. The diminished vibration makes it practical to use the active cooler to cool a germanium gamma-ray detector.

It is designed to be powered by a 18--32 Volt battery. Up to ten harmonics of the 58.65 Hz drive frequency are controlled. In addition to the vibration cancellation, the electronic system produces the drive signal for the cryocooler and regulates the cooler temperature. The system employs a sinusoidal drive to reduce the amount of higher harmonic vibration. The system achieves significant reduction in vibration on the fundamental frequency and several of its harmonics. RMS acceleration reduction on the fundamental is 60 dB. Overall acceleration levels were reduced from greater than 1 g to 1--10 mg. This sensor system is most effective when thermal noise is reduced by maintaining the detector at very low and constant temperature.

A digital signal processor (DSP) is used to perform the high speed vibration control. The processor is housed on a third-party board. A second board has analog-to-digital (A/D) and digital-to-analog (D/A) converters. The DSP was programmed in C. The physical system consists of two sets of electronics. The first is housed in a case that is separate from the detector unit. It consists of the DSP boards and a custom board for power conditioning, some signal processing, and diagnostic LEDs. The other set of electronics includes an analog signal conditioning board and a digital pulse width modulated (PWM) amplifier board that drives the two voice coil actuators in the cryocooler.

Figure 1 shows the basic system components. The cryocooler extracts heat from the detector while under control of the cancellation system. The cancellation system uses no direct measurement from the detector. Instead, acceleration of the instrument body is minimized. Since the detector is mounted to this body, motion there is reduced as well.

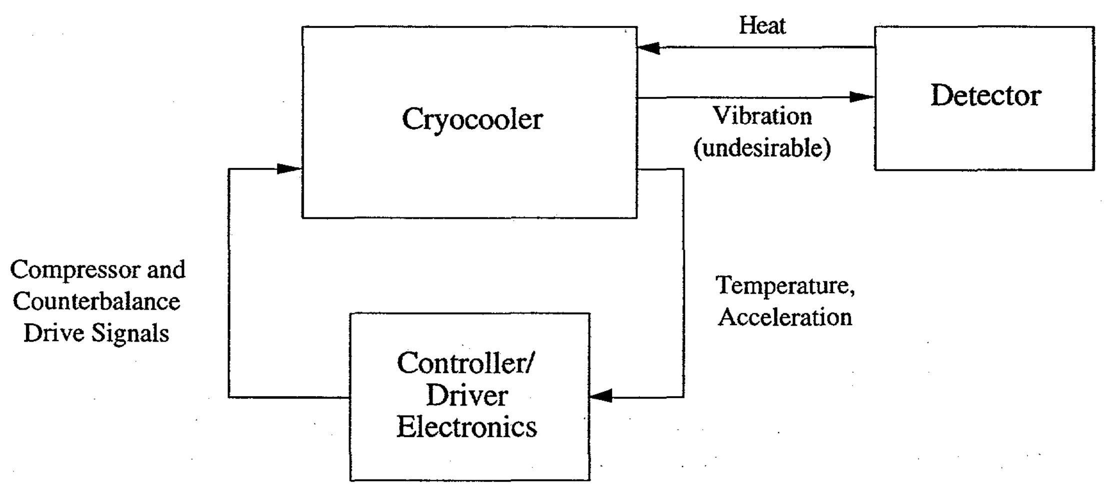

Figure 1: The control electronics were designed to allow active cooling without exposing the detector to detrimental vibration.

Our cryo-cooler is capable of delivering 4.25 watts of lift @ 77K with 94 watts of input power. Once the detector is cooled down to its operating temperature, it does not always require the full cooling capacity of the mechanical cooler to maintain temperature. The EM cooler electronics package has an option that can be used to reduce the cooling power, once the detector has reached operating temperature to further reducing the overall heat loads and power requirements. This feature is not usually available in electro-mechanical coolers.

Electromechanically-cooled, HPGe Detector System Specifications

Weight	6.8 kg
Size	56 cm long 13.7 cm diameter
Time to cool down	4-6 hours
Power consumption	37-97 watts
Life, continuous operation	5-10 years

Detector Specification and Performance Data

Physical Characteristics

Active diameter	25.2 mm
Active area	500 mm^2
Thickness	15 mm

Resolution and Efficiency Isotope (with amp time constant of 4 us)	LN_2 cooled*	EM cooled*	EM cooled**
^{241}Am 59.536 keV			
FWHM (eV)	410	450	550
^{57}Co 122.05 keV			
FWHM (eV)	523	570	720

* Lab environment
** Field environment

Results

We have tested the electro-mechanically cooled detector system under various field conditions in the measurement of uranium and plutonium samples for isotopic information using the MGA[1] gamma-ray analysis program without any detectable impact on the results. Comparison of plutonium isotopic results obtained with both a liquid-nitrogen cooled HPGe detector and our electro-mechanically cooled HPGe detector are shown in Table 1.

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[1] R. Gunnink, *MGA: A Gamma-Ray Spectrum Analysis Code for Determining Plutonium Isotopic Abundances*, Lawrence Livermore National Laboratory, UCRL-103220, April, 1990.

	LEPS (FWHM 534 eV@122 keV) WEIGHT PERCENT	%ERROR	LEGe_PCC(FWHM 723eV@122keV) WEIGHT PERCENT	%ERROR
^{238}Pu	0.1303	1.75	0.1235	1.49
^{239}Pu	75.46	0.29	75.51	0.23
^{240}Pu	21.56	0.91	21.57	0.71
^{241}Pu	2.001	0.76	1.962	0.54
^{242}Pu	0.8494	(10)	0.8334	(10)
^{241}Am	1.872	0.98	1.848	0.71

Table 1. Results from MGA analysis of Pu gamma-ray spectra taken with a liquid-nitrogen cooled LEPS detector and our portable cryo-cooled LEGe detector. Data were collected in one hour (8% dead time) livetime, using the PIDIE#5 reference standard.

Conclusion

It is clear that the electro-mechanical cryo-cooler that we have selected can cool HPGe detectors without degrading its energy resolution. We have obtained performance measurement results that are comparable with similar HPGe detectors cooled by liquid nitrogen. The size, weight and power requirements of our detector system truly permit portable/field applications.

Work remains to be done to reduce the cost of electro-mechanical cryo-coolers, that have long life expectancy, and their supporting electronics. Trade-offs between size and performance will have to be made until the cryo-cooler technology matures.