MECHANICALLY COOLED LARGE-VOLUME GERMANIUM DETECTOR SYSTEMS FOR NUCLEAR EXPLOSION MONITORING

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ABSTRACT

Compact maintenance-free mechanical cooling detector systems are being developed to operate large-volume (~ 570 cm^3, ~ 3 kg, 140 % or larger) germanium detectors for field applications. These detector systems are necessary for remote long-duration liquid-nitrogen free deployment of large-volume germanium gamma-ray detector systems. The Radionuclide Aerosol Sampler/Analyzer (RASA) nuclear explosion monitoring systems will benefit from the availability of such detector systems by allowing the very largest available germanium detectors to be utilized for the highest sensitivity measurements. To reliably provide such detector systems, three fundamental technical issues are being investigated: temperature, vacuum, and vibration. Two prototype detector systems (RASA 1 and RASA 2) have been developed, fabricated, and tested. The cryostats have been demonstrated to cool very large (slightly greater than 10$^+$-cm long and 10-cm diameter) detectors to temperatures as low as 50 K. The vacuum design has been demonstrated to show no measurable degradation over long time periods. The detector systems have been demonstrated to successfully instrument high-purity germanium detectors. Microphonic noise from the vibrating cooler has been completely eliminated in one case, serving as a demonstration of the total detector system viability. Microphonic noise remains the largest technical issue for these detector systems. The third generation, RASA 3, design incorporates mechanical changes to eliminate microphonic noise issues.

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OBJECTIVES

PHDs Co. is developing mechanically cooled detector systems for large-volume germanium detectors (~ 570 cm^3, ~ 3 kg, ~ 140 %, or larger). Maintenance-free Stirling-cycle mechanical coolers are being used. These coolers have operating lifetimes exceeding five years. The relatively large heat lift of these coolers quickly cools a detector to a very low operating temperature for gamma-ray measurements. Lower operating temperature improves the reliability of germanium detectors by lowering surface leakage currents (Pehl et al., 1973). These features will make liquid-nitrogen free operation of the largest (~200%) germanium gamma-ray detectors viable and convenient for nuclear explosion monitoring. The RASA detector system will benefit from the availability of such detectors (Bowyer et al., 1997; Miley et al., 1998).

Mechanical cooling of germanium detectors has historically been a difficult endeavor. The success or failure of mechanically cooled germanium detector systems arises from three main technical issues: temperature, vacuum, and vibration. These factors can affect one another. Previous years have seen analysis of these factors and their effects on detector performance (Hull et al., 2006), and the first prototypes thermally tested (Hull et al., 2007). This year, results are available from the study of the first prototype and a second-generation prototype with detectors in the detector systems. These endeavors include successful coaxial detector fabrication, detector-cryostat integration, cooling, and full- detector-system tests demonstrating operation with no measurable microphonic noise. The detector systems cool detectors to extremely low operating temperature (as low as 50 K), in a vacuum environment showing no measurable degradation with time. The remaining technical issue is microphonic noise from the vibrating cooler.

RESEARCH ACCOMPLISHED

The second year of this project has seen several major accomplishments. The first prototype (RASA 1) was fully integrated and made to function with a p-type coaxial germanium detector. A detector fabrication technique was developed specifically to make the detectors for these detector systems. The fabrication technique has been repeatedly demonstrated to produce a functional germanium coaxial detector having good leakage current and reasonable noise characteristics. The RASA 1 detector, cooler, and front-end electronics have been integrated and function together as a single compact unit. A photograph of the complete RASA 1 detector system is shown in Figure 1. The detector is cooled to temperatures below 50 K when the cooler is operating at full power, ~ 200 W input power. After a few attempts, the detector was brought to working order after electronic interconnect issues were addressed. The detector is 70 mm in diameter and 70 mm long, and is made from p-type high-purity germanium. The detector depletes at 2,300 V and shows reasonably good charge collection at 2,400–2,500 V. The energy resolution was measured to be FWHM ~ 2.4 keV at 1332 keV using a peaking time of 5 μs. This measurement was made with the cooler switched off briefly. Initially, the resolution was on the order of 20 keV with the cooler running due to microphonic noise.

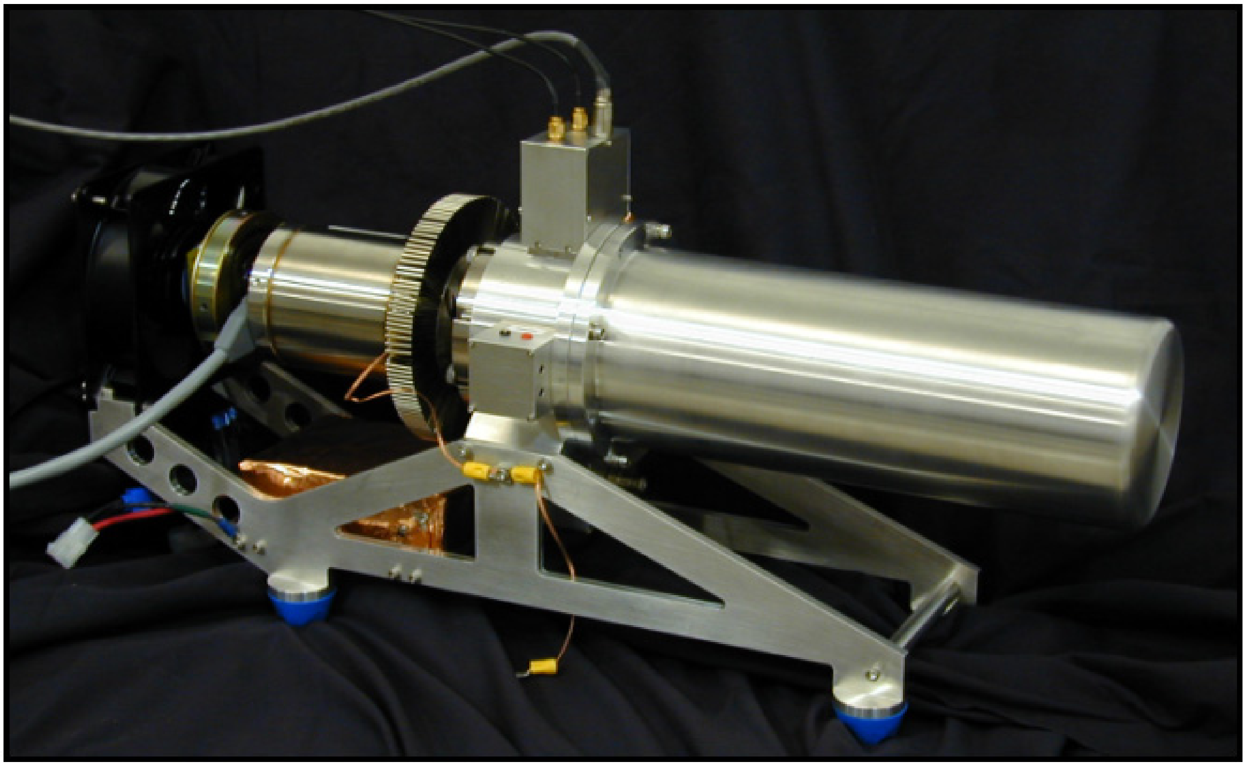

Figure 1. The RASA 1 prototype holds, cools, and instruments a detector as large as 10-cm diameter and 10-cm long. Pictured here it holds a 70-mm diameter x 70-mm long coaxial detector.

The microphonic noise issues were dealt with by making mechanical and electronic changes to the detector system at room temperature, pumping on the detector system with a turbo-molecular pump, verifying vacuum integrity with a helium leak checker, and cooling the detector system. The next day, the detector was biased, and the noise was measured. The most basic measurement was made by simply looking at the noise on an oscilloscope compared to known gamma-ray energies at a peaking time of 6 μs. This was determined to be the only method for troubleshooting the microphonic noise problems. Many tens of such thermal cycles were completed during the past year, each one taking several days. Some changes improved the microphonic noise; others made it worse. Fortunately, the cooler has no trouble with the repeated thermal cycles. The detector was also very robust. Overall, the detector was damaged only a handful of times as a result of these thermal cycles. The detector problems were usually the result of poor handling of the detector at room temperature. However, in most cases only a partial detector reprocessing cycle, taking less than one day, was sufficient to restore the detector. The most significant mechanical changes included improving the support of the detector while still maintaining a high thermal barrier between the cold surfaces and the room temperature surfaces. Vibration itself is not a problem. Rather, vibration of the sensitive JFET gate lead relative to other objects is the problem. Using this thinking, the internal parts were stabilized together to lessen the extent of the relative motion during cooler operation. A step that had a particularly good impact was the addition of a spring-loaded stabilization spider between the detector mount and the inside of the outer vacuum cap. After that step and several similar attempts, the microphonic noise was altogether eliminated from the gamma-ray energy spectrum from the detector in RASA 1. A 1332-keV resolution of full width at half maximum (FWHM) = 2.4 keV was observed with the cooler off or on. This measurement was made using a peaking time of 5 μs.

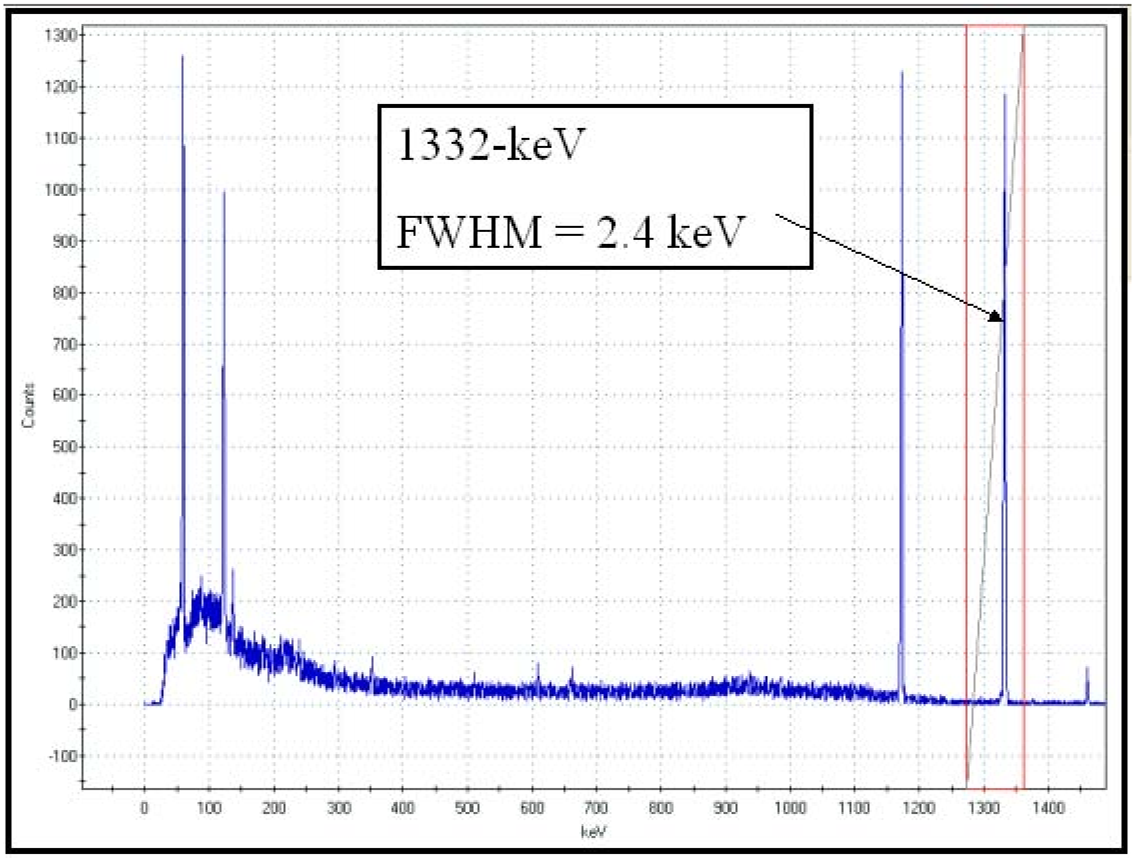

Figure 2. This energy spectrum was accumulated from the detector in the RASA 1 detector system using a unipolar peaking time of 5 μs with the mechanical cooler operating at full power.

Aside from the spectroscopy shown in Figure 2, the microphonic noise was analyzed on the oscilloscope. The signals from the detector preamplifier were shaped in a TC244 shaping amplifier using a peaking time of 6 μs. No microphonic noise was visible on the baseline. This was established with the 122-keV gamma-ray peak set to 6 V on the oscilloscope. This allows the baseline JFET channel noise to be easily observed on the 100- and 200-mV voltage scales. Channel noise from the JFET dominates when the cooler was not running at 6 μs. When the cooler was switched on, there is a brief burst of noise when it starts vibrating, then the noise almost immediately returns to the cooler-off level. This result, along with the spectroscopy was heralded as a great success initially. However, over a period of days, a small but significant amount of microphonic noise crept into the detector system. After a few days, the 1332-keV peak was significantly degraded to an FWHM ~ 3.5 keV. No changes were made to the detector system during that time. This result was repeated. Some part of the internal cryostat assembly must be loosening up over time with the cooler operating. The good microphonic noise results were always measured the morning following the cool-down of the detector. The insides of the cryostat may not have come completely to thermal equilibrium by that time. The detector was cold enough to operate well, but all the metal and ceramic parts may not have come to full equilibrium. It is not unusual for a detector to continue to creep down in temperature by a few degrees over the days following the cool-down. RASA 1 continues to be an excellent test unit for pursuing issues related to microphonic noise. The elimination of the microphonic noise from the energy spectrum and the excellent vacuum integrity of the detector system stand as proof that this detector-cryostat-cooler combination can ultimately serve as a viable detector unit for RASA detector systems.

During the pursuit of the microphonic noise issues with RASA 1, the RASA 2 prototype was designed. The RASA 2 was designed to accommodate all of the modifications and reworks required to make RASA 1 cool and operate a detector. In this case, the detector to be cooled came from a broken unit from another detector vendor. The RASA 2 design had to accommodate the different geometry of the detector and a rather different detector-mounting scheme, so RASA1 and RASA 2 were somewhat different in places. The detector system was assembled, and the detector was loaded into the detector system. The detector was suspected to be in working order. Indeed, the detector recovered rather handily after overnight baking of the detector at 60°C while pumping with a turbo molecular pump. The detector takes full bias and has excellent gamma-ray energy resolution in the RASA 2 detector system when the cooler is turned off. The detector can be cooled as low as ~ 50 K inside the detector system. Unfortunately, the detector system exhibits rather poor microphonic noise performance at this stage of the development. At this time, the sources of microphonic noise are being addressed much in the same manner as they are being addressed with RASA1. The detector is cycled from room temperature to operating temperature and back again to allow testing of various mechanical and electronic component changes inside the cryostat.

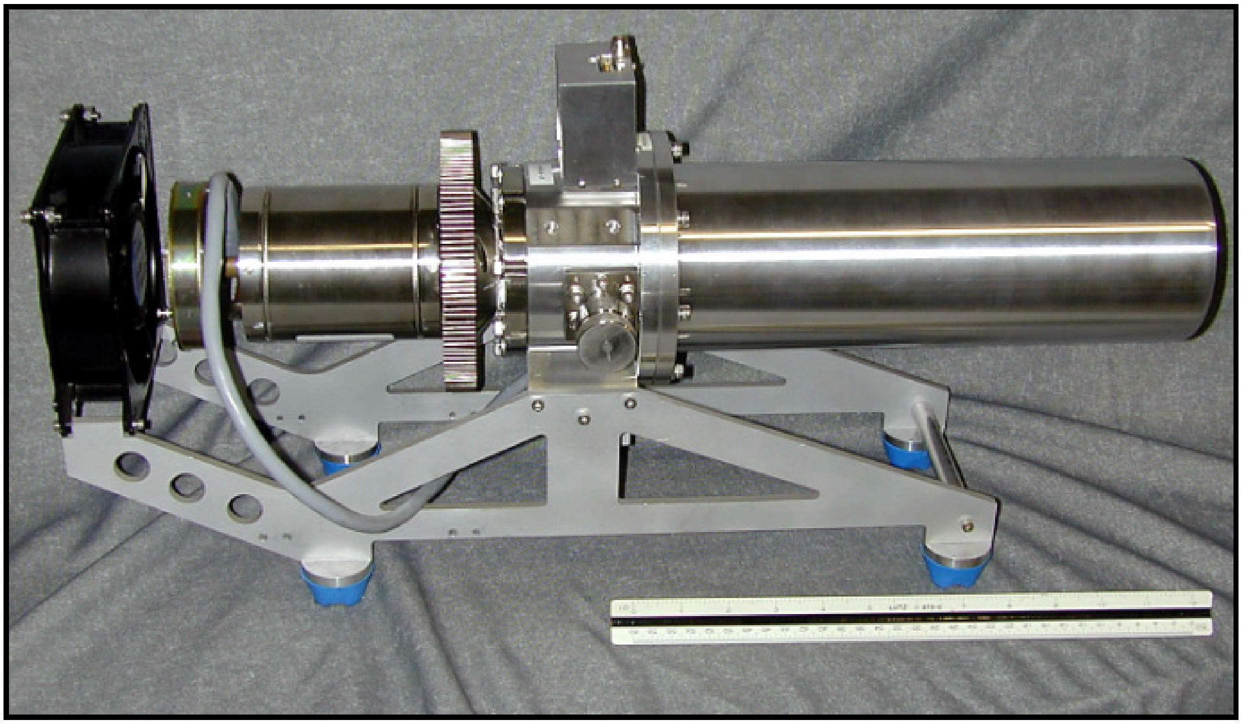

Figure 3. The RASA 2 prototype is very similar to RASA 1. The detector system holds, cools, and instruments a coaxial detector that is 79 mm diameter and 106 mm long.

The RASA 1 and RASA 2 developments have led to the design of a third-generation prototype, RASA 3. RASA 3 is being fabricated at this time. RASA 3 will preserve the vacuum and cryogenic designs of RASA 1 and 2 while improving the microphonic noise problems. RASA 3 has a cryostat design that addresses issues critical to the manufacturability of a germanium detector system using such a compact and powerful cooler. As in the RASA 1 and 2 design phases, care has been exercised to work with the AFTAC RASA users to insure the detector design works in harmony with the existing RASA detector system constraints.

CONCLUSIONS AND RECOMMENDATIONS

The RASA 1 and RASA 2 prototypes have been designed, fabricated, and tested as demonstrations of a new integrated mechanical cooling detector system suitable for use with RASA stations. The third generation prototype, RASA 3, has been designed. Good technical progress has been made to overcome the problems associated with a compact, mechanically cooled germanium detector system. These new detector systems will have extremely long operating lifetimes with no maintenance requirements. At the end of this project, PHDs Co. will offer a new product line: the MCX mechanically cooled detector product line for use with RASA and similar remotely deployed detection systems.

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