A Prototype High Purity Germanium Detector for High Resolution Gamma-Ray Spectroscopy at High Count Rates

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Abstract

Where energy resolution is paramount, High Purity Germanium (HPGe) detectors continue to provide the optimum solution for gamma-ray detection and spectroscopy. Conventional large-volume HPGe detectors are typically limited to count rates on the order of ten thousand counts per second, however, limiting their effectiveness for high count rate applications. To address this limitation, we have developed a novel prototype HPGe detector designed to be capable of achieving fine energy resolution and high event throughput at count rates in excess of one million counts per second. We report here on the concept, design, and initial performance of the first prototype device.

Keywords: Gamma-ray detectors, high-purity germanium, amorphous semiconductors, high count rate.

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25 **1.0 Introduction**

26 High Purity Germanium (HPGe) detectors remain the recognized gold standard for high-
27 resolution gamma-ray spectroscopy [1,2]. The excellent energy resolution that HPGe
28 detectors afford often makes them the detector of choice for applications as diverse as
29 nuclear physics research, medical imaging, homeland security, and environmental
30 monitoring [2]. Where isotope identification and quantification are required, the fine
31 energy resolution of HPGe detectors minimizes the systematic uncertainties associated
32 with the analysis of photopeaks in the presence of background continua. This is
33 particularly important in cases where complex gamma-ray spectra are likely to be
34 encountered.

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36 Historically, the use of HPGe detectors has been limited to applications where the count
37 rate is reasonably low. Conventional large volume HPGe detectors are typically limited
38 to operating at count rates of less than a few tens of kcps due to the combination of
39 relatively long charge collection times and significant signal rise-time variations that
40 characterize such devices, as well as the need to employ relatively long pulse shaping
41 times in order to minimize the effects of electronic noise. Various approaches to the high
42 rate operation of HPGe spectrometers have been proposed and typically focus on the use
43 of very small detectors, novel electronics and data acquisition systems, or algorithmic
44 solutions [3-6]. Typically, energy resolution, detection efficiency, or event throughput
45 (i.e. the fraction of absorbed events for which an energy may be measured) must be
46 sacrificed in order to achieve increased count rate.

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48 There are several nuclear safeguards applications that require high-resolution gamma-ray
49 spectroscopy to be performed at very high count rates. Prime examples are the assay of
50 spent nuclear fuel pins and assemblies for the verification of burn-up in the presence of
51 intense backgrounds from ^{137}Cs and other fission products, and non-destructive assay for
52 quantification of U and Pu isotopes in samples of various types [7]. In both of these
53 applications, the challenge is to maintain spectroscopic performance, efficiency, and high
54 event throughput at input count rates on the order of one million counts per second.
55 Energy resolution is required for quantitative isotopic analysis while high throughput and
56 good efficiency are required in order to minimize the measurement time.

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58 When considering the trade off between energy resolution and event throughput at very
59 high count rates, one is typically forced to decide which of the two competing
60 performance criteria is most important for the given application. Performance gains in
61 one area are therefore achieved at the cost of losses in the other. However, this trade off
62 is typically not a forgiving one and conventional HPGe spectroscopy systems that offer
63 high resolution and high throughput at low count rates quickly transition into a regime
64 characterized by both low throughput and poor energy resolution as the incident rate
65 becomes large. Often, the trade off is complicated further by the relationship between
66 detection efficiency, detector volume, and charge collection time. In many applications,
67 such as those in nuclear structure physics, for example, the desire to maintain detection
68 efficiency at high gamma-ray energies makes the use of large-volume detectors
69 appealing. The inherently long charge collection times associated with these detectors

then limits the count rate performance that may be realized given the length of the pulse shaping times required to achieve fine energy resolution.

For applications such as the non-destructive assay of spent nuclear fuel, the high statistics nature of the measurement scenario, as well as the ability to employ a multi-detector arrangement to increase the total detection efficiency at high energy, results in the prioritization of throughput and energy resolution over the need to achieve high detection efficiency with a single detector. In order to maximize the fraction of incident events that may be processed, pulse pile up must be reduced through the use of short shaping times. However, when these shaping times become sub-optimal for a given system, the energy resolution is degraded [8]. In the case of conventional digital trapezoidal shaping [9], two major components typically contribute to this degradation: ballistic deficit resulting from the selection of a gap time (i.e. flat top time) that is too short given the rise time of the signals from the detector, and insufficient filtering of the electronic noise due to the selection of a sub-optimal value of peaking time.

The current implementation of the Ultra High Rate Ge (UHRGe) system, developed at Pacific Northwest National Laboratory, comprises a standard closed-end coaxial HPGe detector read out through a wide dynamic range charge sensitive preamplifier. The data acquisition system employs standard digital electronics and custom pulse processing algorithms designed for high rate spectroscopy. The best performance achieved with this system to date is ~8 keV FWHM at 662 keV with 39% throughput at an input count rate of 1 Mcps. This is compared to around 2.0 keV FWHM at 662 keV and a throughput of

close to 100% at rates on the order of 1 kcps. A detailed discussion of this system and its performance can be found in Ref. [10].

In this work we present details of a novel prototype HPGe detector developed for the second generation UHRGe system. This device is based on a planar geometry and employs a modified single-sided strip electrode configuration. The device was designed to provide high performance while also offering a relatively low channel count over a large surface area, as well as a straightforward readout scheme. The electrode configuration features one-dimensional electrical segmentation of the front face of the detector and a continuous (i.e. full area) contact on the back. Electrical segmentation of HPGe detector contacts is increasingly common in state of the art device gamma ray tracking arrays as well as devices for gamma ray imaging. Large gamma ray tracking arrays such as AGATA and GRETINA [1, 2] employ radial, longitudinal, and azimuthal segmentation to the implanted outer contact of coaxial HPGe detectors in order to achieve improved position sensitivity. Each individual segment is typically several cubic cm in volume with each segment representing a reasonably large surface area. In a strip electrode configuration, the electrode on each face of a planar crystal may be individually segmented in one dimension, with segmentation occurring orthogonal to the axis in which charge is collected.

In designing a device capable of achieving improved resolution and throughput at Mcps rates, we have focused on a detector geometry that offers fast charge collection and short signal rise times, and a segmented electrode scheme that allows the incident rate to be

distributed over multiple channels. At the short shaping times required for this application, the contribution from capacitance-driven series noise dominates the electronic noise induced peak broadening [11]. Because of this, our prototype device features a segmentation scheme designed to offer only a modest capacitive load to the input of the preamplifiers. Our design philosophy is grounded in providing flexibility in the trade off between throughput and energy resolution, providing excellent energy resolution and high throughput at count rates on the order of 1 Mcps, while also allowing users to incur relatively small losses in energy resolution for significant increases in throughput and/or rate capability.

In this paper, we describe the design of the detector and present calculated predictions of its performance. We then summarize the measured performance of the prototype device and consider the future development of this technology.

2.0 Theoretical Methods

Prior to fabrication of the prototype detector, and in establishing the design, a combination of analytic and numerical calculations was used to estimate the theoretical performance of the device. In Ref. [12], idealized analytic expressions for the parallel, series, and $1/f$ contributions to the total electronic noise as a function of shaping time are presented. A framework for modeling the performance of a given detector design based upon these expressions, as well as analytic solutions to the device capacitance, was

established. This framework was used to assess the impact of various electrode designs on electronic noise and energy resolution.

For our design studies, we assumed a 15 mm thick planar HPGe detector with an active area of 80 mm x 80 mm. A single sided strip electrode configuration comprising ten strips was chosen in order to adhere to the constraints of large area, relatively low channel count, and straightforward readout scheme. We therefore assumed an electrode geometry with a strip pitch (P , defined as the center-to-center strip spacing) of 8 mm and strip length of 80 mm. Fig. 1 shows a schematic representation of the basic geometry employed in the design studies. For all calculations the detector was assumed to be fully depleted and with a leakage current of 20 pA per strip. This estimate is a conservative one in comparison with typical measured values of 10 pA per strip. Finally, we defined some additional properties related to an assumed preamplifier configuration operated with a warm front end, operating at 300 K. We assumed a Field Effect Transistor (FET) with a leakage current of 1 nA, a capacitance of 1 pF, and a transconductance of 5 mA/V and a feedback circuit comprising a 1 pF capacitor and 100 M Ω resistor. Our assumptions for the FET were based on typical values associated with a JFET while those of the feedback circuit were based on the known properties of our preamplifiers. Given a fixed strip pitch of 8 mm, the strip to full-area contact, inter strip, and total capacitance associated with a single strip were calculated as a function of strip width. No estimate of stray capacitance was made. For a given strip width, the width of the inter strip gap is the difference between the strip pitch and strip width. Using the calculated capacitance, and the standard parameters defined above, the electronic noise contribution was calculated as

a function of shaping time. The effect of trapezoidal shaping with a large peaking time to gap time ratio was approximated using the coefficients for triangular shaping presented in Ref. [13]. At each value of shaping time, the FWHM peak width associated with the electronic noise was calculated. The predicted FWHM of a 662 keV gamma ray peak was then calculated as the quadrature sum of the contribution from electronic noise and the statistical peak broadening.

To first order, a total input count rate of 1 Mcps uniformly distributed across ten channels results in a mean count rate of 100 kcps per channel. At such a rate, peaking times of 1 μ s or less are likely to be required in order to minimize the effects of pulse pile up. Fig. 2 shows the calculated FWHM peak width at 662 keV, for a single strip, as a function of strip width (lower x-axis) and corresponding inter strip gap (upper x-axis) at peaking times of 0.5 and 1 μ s. For comparison, the peak width at 2 μ s peaking time is also plotted. It can be seen that the FWHM peak width becomes smaller as the strip width is decreased and the inter strip gap becomes larger as a direct result of the reduced capacitance associated with narrow, well separated strips. The results in Fig. 2 suggest that in order to maintain good energy resolution (i.e. <2.5 keV FWHM) at a peaking time of 1 μ s, while also incurring minimal resolution loss at sub-microsecond peaking times, a configuration employing at most 5 mm wide strips separated by at least 3 mm wide gaps would be required. A well documented characteristic of HPGe strip detectors is that of incomplete charge collection resulting from events in which charge is collected to the detector surface in the inter-electrode gap region [14-18]. A standard strip configuration featuring inter strip gaps this wide would be likely to suffer from such high levels of

charge loss as to make the design infeasible from a practical standpoint. Instead, we therefore considered an alternative strip configuration designed to provide a compromise between the need for low capacitance (large inter strip gaps) and the need to maintain charge collection performance. This design features a narrow steering strip electrode placed between each pair of collecting strips. These steering electrodes are interconnected to form a grid around the collecting strips. By applying an appropriate bias to this grid, efficient charge collection is maintained by steering charge away from the gap and towards the charge collecting strips. An early implementation of such an approach was successfully demonstrated by Amman and Luke in Ref. [14] using an ad hoc steering structure on a small test device. More recently, a similar approach was also presented by Dion *et al.* in Ref. [15] where a relatively wide steering structure was employed on multiple-point contact HPGe detector with limited success.

In this design, the capacitance associated with a single collecting strip is dominated by the capacitance between the strip and the steering grid. The separation between a collecting strip and the steering grid, D , is given by

$$D = \frac{P - (W_{collecting} + W_{steering})}{2},$$

where $W_{collecting}$ and $W_{steering}$ are the widths of the collecting strips and steering electrodes, and the pitch of the collecting strips, P , is defined in the usual way.

For a geometry with a strip pitch of 8 mm and 1 mm wide steering electrodes, the electronic noise and energy resolution were calculated. Fig. 3 shows the calculated FWHM peak width at 662 keV, for a single strip, as a function of strip width (lower x-axis) and corresponding strip grid separation (upper x-axis) at peaking times of 0.5, 1, and 2 μ s. These calculations suggest that a design employing 4 mm wide strips and a strip-grid separation of 1.5 mm may achieve an energy resolution of 2.35 keV FWHM at 662 keV at a peaking time of 1 μ s. However, allowing for even a 10% uncertainty in the calculated energy resolution results in a value that exceeds 2.5 keV FWHM at 662 keV. In order to allow for such an uncertainty, we established a baseline design based upon 3 mm wide strips and a strip-grid separation of 2 mm. The energy resolution was calculated to be 2.11 keV FWHM at 662 keV at a peaking time of 1 μ s for this configuration.

In addition to analytic calculations of the predicted electronic noise and energy resolution, numerical simulations of depletion characteristics and electric fields were performed using the COMSOL Multiphysics software package [19], and simple charge transport simulations were carried out using codes developed in-house. Solving for the electric field distribution in a HPGe detector allows the position dependent charge collection time to be calculated using the parameterization of charge carrier mobility presented in Refs. [20] and [21]. For a 15 mm thick crystal with an impurity concentration of $2.5 \times 10^9 \text{ cm}^{-3}$ operating at a bias of 1000 V, the maximum charge collection time is calculated to be around 190 ns for holes drifting in the $\langle 100 \rangle$ direction. Signal calculations accounting for the weighting potential [22, 23] associated with 3 mm

wide strips and a simple preamplifier response suggest that the maximum signal risetime (defined here as the time taken for the signal to rise from 10% to 90% of its maximum value) is around 180 ns for the signals observed on the hole collecting face. It is therefore reasonable to assume that when applying standard trapezoidal filtering, a gap time in the range of 300-350 ns would be sufficient to avoid ballistic deficit effects, even accounting for the extended risetimes resulting from multiple interaction events.

In order to estimate the effect of pulse pile up on event throughput, we assume that the resolving time between two interactions is given by the sum of the peaking time and gap time employed in a digital trapezoidal filter that would be used to determine the energy of the events [10]. By simulating the arrival time of individual events according to a Poisson process governed by a mean rate, the effective event throughput may be estimated as a function of rate and peaking time for a fixed gap time of 350 ns. Fig. 4 shows how the estimated event throughput varies as function of peaking time for various input count rates. From the result presented in Fig. 4, it is estimated that with a mean input rate of 100 kcps per strip (i.e. 1 Mcps total over ten strips), the event throughput is slightly greater than 87% with a peaking time of 1 μ s and falls to approximately 80% with a peaking time of 2 μ s. Employing sub-microsecond values of peaking time would further allow very high input event rates to be processed while maintaining high throughput. At a peaking time of 500 ns, for example, an incident rate of 500 kcps per strip (5 Mcps over ten strips, to first order) could theoretically be processed with a throughput of approximately 65%. This would represent a significant improvement over the performance of the current UHRGe system of around 39% throughput at 1 Mcps.

3.0 Prototype Detector

Our prototype design is based on a 100 mm diameter x 16 mm thick planar HPGe crystal with a p-type impurity concentration of approximately $2.4 \times 10^9 \text{ cm}^{-3}$. The electrode pattern features ten 71 mm long, 2.85 mm wide charge collecting strips, each of which is surrounded by 0.95 mm wide steering grid strips. The collecting strip pitch is 7.6 mm. Fig. 5 shows a photograph of the prototype device. Each collecting strip is separated from the steering grid strips by a gap of 1.9 mm. In principle, one could envision the use of narrower strips and wider gaps in order to further reduce the capacitance. However, for our application, it is anticipated that multiple detectors will be employed in a stack configuration to increase the total detection efficiency for high energy gamma rays. As this will require the correlation of multiple energy depositions in multiple strips and multiple detectors, it is important that accurate event timing be achieved. For designs in which the area of the electrode is small compared to the thickness of the detector, timing accuracy is degraded.

The detector is operated with a positive bias applied to the full-area contact, the collecting strips connected to ground, and a positive bias applied to the steering grid. All of the electrical contacts on the detector were produced using amorphous germanium [14, 24-27]. As noted in Ref. [14], not only does the bi-polar blocking nature of amorphous contacts allow both the hole-collecting and electron-collecting contacts to be fabricated

using the same procedure, it also allows the biasing scheme required for the steering-grid configuration to be easily implemented.

Each collecting strip is read out using an individual DC coupled charge sensitive preamplifier. For the purposes of diagnostics and testing, the steering grid is also read out using a preamplifier of the same design except with AC coupling. The preamplifiers are based on a modified version of the resistive feedback design presented in Ref. [28]. In order to reduce the feedback voltage and prevent output saturation associated with large event currents, the standard 1 G Ω feedback resistor was replaced with a 100 M Ω resistor. Although this modification results in higher thermal noise associated with the resistor, the impact is negligible at the short shaping times relevant to high count-rate operation.

4.0 Measured Detector Performance

Following fabrication of the first prototype detector, initial measurements of its performance were carried out. The detector was found to fully deplete at approximately 350 V. When operated at 1000 V and with no bias applied to the steering grid, the total leakage current from all collecting strips is approximately 40 pA. With 200 V applied to the steering grid, the value found to provide optimum charge collection to the strips, the total leakage current from all strips is approximately 120 pA (12 pA per strip) while the leakage current from the grid is approximately 40 pA. The capacitance of a single, central strip was measured to be approximately 26 pF. This is in good agreement with

the calculated value of 20.6 pF (which includes an 18.8 pF contribution from interstrip capacitance), the excess being easily accounted for by the stray capacitance of the cables and feedthroughs as well as the uncertainty of the measurement.

The optimum value of steering bias was established by measuring the count rate on the collecting strips and the grid as a function of grid voltage, V_g , at the operating bias of 1000 V. Fig. 6 shows how the relative count rate in the 662 keV photopeak varies, as a function of grid voltage, for a single collecting strip and the steering grid. It is observed that the count rate measured on the grid quickly falls away as the voltage is increased. This is a direct result of the grid voltage acting to steer charge carriers away from the grid and towards the collecting strips. Conversely, the count rate observed from the collecting strip increases with grid voltage, reaching a maximum at 200 V (a value consistent with the results of numerical simulations of the device). Interestingly, the collecting strip count rate is seen to drop when voltages in excess of 200 V are applied to the grid. This effect is attributed to the creation of small, localized regions of very weak field directly beneath the steering grid in which charge transport properties are poor. These effects were well studied using numerical simulations and represented an important consideration during the design process. Given the application of sufficient bias to the steering grid, simulations suggest that these regions may quickly become undepleted, essentially creating dead volumes within the HPGe crystal that then continue to increase in size with increasing grid bias.

The total electronic noise of the prototype device was measured by feeding a square pulse through a small test capacitor into the input of one of the strip preamplifiers and then passing the preamplifier output to standard analog pulse processing electronics. Fig. 7 shows the width of the resultant peak as a function of Gaussian shaping time, displayed as circular data points. Overlaid on the measured data points are the calculated contributions from series and parallel noise. The calculations were performed using the aforementioned models, developed from the expressions in Ref. [12], and are based on known and measured properties of the detector and front end electronics (e.g. leakage current, FET capacitance, temperature etc.). The influence of Gaussian shaping on peak width was approximated using the coefficients in Ref. [13]. While keeping the calculated series and parallel components fixed, the contribution from 1/f noise was estimated by fitting an additional, shaping time independent term to the measured data. It is observed that the contribution from 1/f noise is significant at approximately 1.2 keV FWHM and appears to be the limiting contribution at and around the optimum analog shaping time of 2 μ s. Preliminary investigations suggest that the dominant source of this noise is the vacuum feedthrough situated between the HPGe crystal and the preamplifiers. It is anticipated that the source of this noise will be confirmed, and its contribution reduced, in future iterations of this detector design.

The energy resolution of the detector obtained with digital pulse processing was assessed with the device at the operating voltage of 1000 V and with 200 V applied to the steering grid. The collecting strips were individually read out using the nanoMCA [29] produced by labZY [30] which uses a trapezoidal filter for energy extraction. With the gap time

fixed at 350 ns, data were recorded in the presence of a ^{137}Cs source and a simultaneous pulser input. The total incident count rate was approximately 0.5 kcps. Energy spectra were recorded at a range of peaking times. In each case, fits were performed to the gamma ray and pulser peaks, and the energy resolution quantified according to the resulting values of FWHM. Fig. 8 shows the resulting values of energy resolution for the 662 keV gamma-ray peak and the pulser peak as measured for a typical strip. Selected values for the gamma-ray peak are also tabulated against peaking time in the inset table. The uncertainty associated with each value of energy resolution is typically around $\pm 3\%$ and results from the fitting procedure. The optimum peaking time was found to be 4 μs , where the energy resolution of the gamma-ray peak is 2.16 keV FWHM. At a peaking time of 1 μs , the energy resolution is 2.35 keV. It can be seen that reasonable values of energy resolution are maintained when using the very short values of peaking time required for high throughput operation at high count rates. Crucially, the degradation in energy resolution occurs reasonably slowly as the peaking time is reduced below one microsecond. Fig. 9 shows an example of a spectrum recorded at a total incident count rate of around 0.5 kcps with a peaking time of 500 ns. The spectral features appear sharp and the peak shape remains highly Gaussian, with a resolution of 2.69 keV FWHM, even at this very sub-optimal value of peaking time. The width of the pulser peak is 2.23 keV FWHM. Accounting for the uncertainty in the peak widths, the difference between the FWHM of the gamma ray and pulser peaks is consistent with statistical broadening, suggesting that any contributions from charge collection inefficiency and sub-optimal pulse shaping are small.

4.0 Summary

We have developed and tested a novel segmented planar HPGe detector designed to achieve fine energy resolution and high event throughput at high count rates. Our design employs a modified single sided strip electrode configuration and features a grid of narrow steering electrodes. The novelty of the design lies in the combination of a reduced capacitance strip electrode configuration and a narrow grid of steering electrodes that are able to maintain charge collection to the strips. Tests of our first prototype device demonstrate good charge collection performance, low electronic noise, and fine energy resolution at the short values of shaping time required for operation at very high count rates. Measurements performed on our first prototype device yield typical values of energy resolution of 2.35 keV FWHM at 662 keV when employing a trapezoidal filter with a peaking time of 1 μ s and a gap time of 350 ns. To first order, such filter times are expected to allow an event throughput close to 90% at an incident rate of 100 kcps per strip. Furthermore, peak widths of less than 4 keV FWHM at 662 keV have been achieved at a peaking time of just 100 ns. The device therefore shows promise in meeting the energy resolution and throughput requirements of applications such as assay of spent nuclear fuel.

We continue to investigate the performance of the device and validate simulations of the design. In particular, we are performing a detailed characterization of the charge collection performance of the strip electrode and steering grid configuration. Furthermore, we will assess the throughput and energy resolution of the device at

moderate and high count rates using standard digital electronics and trapezoidal filtering algorithms.

The prototype device will be integrated into the UHRGe system that will also comprise a custom designed, low noise preamplifier optimized for high rate operation, and novel time-variant adaptive trapezoidal filtering algorithm [10] developed by our collaborators. We continue to evolve our detector design through simulation studies and are investigating a range of new electrode configurations to further reduce capacitance and improve performance at short shaping time.

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455 Figure 1. Schematic representation of the basic geometry employed in the design study.

456 The electrically segmented front face of the detector is shown.

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Figure 2. Curves showing the calculated FWHM of a 662 keV gamma peak as a function of strip width and corresponding inter strip gap for a hypothetical strip detector with a strip pitch of 8 mm. The values of peak width were calculated using analytical models for the electronic noise (see text for discussion) and are presented for trapezoidal filter peaking times of 0.5, 1, and 2 μ s.

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474 Figure 3. Curves showing the calculated FWHM of a 662 keV gamma peak as a function
 475 of strip width and corresponding strip-grid separation for a hypothetical strip detector
 476 employing 1 mm wide steering electrodes and with a strip pitch of 8 mm. The values of
 477 peak width were calculated using analytical models for the electronic noise (see text for
 478 discussion) and are presented for trapezoidal filter peaking times of 0.5, 1, and 2 μ s.

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480 Figure 4. Curves showing the estimated event throughput as a function of peaking time
 481 for a range of input count rates. The calculations were performed assuming a fixed gap
 482 time of 350 ns and with the resolving time of the system defined as the sum of the
 483 peaking time and gap time. The time between events was simulated based on a Poisson
 484 process governed by a mean count rate.

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Figure 5. A photograph of the prototype HPGe detector in its mount, prior to integration into the test cryostat.

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499 Figure 6. Curves showing how the measured relative count rate in the 662 keV
 500 photopeak varies for a charge collecting strip (circles) and the steering grid (squares) as a
 501 function of the voltage applied to the steering grid. The rates are individually normalised
 502 to the maximum rate observed on each electrode.

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507 Figure 7. Plot showing the measured width (FWHM) of a pulser peak as a function of

508 Gaussian shaping time (circles). Overlaid on the measured data points are the expected

509 contributions from parallel and series noise, and the fitted contribution from 1/f noise.

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515 Figure 8. Plot showing the measured widths (FWHM) of the 662 keV gamma-ray peak
 516 from ^{137}Cs and pulser peak as a function of peaking time for a typical strip. The gap time
 517 was set to a constant value of 350 ns.

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522 Figure 9. A gamma-ray spectrum recorded in the presence of a ^{137}Cs source and

523 simultaneous pulser input at a peaking time of 500 ns and a gap time of 350 ns.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9