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Characterization of the First Prototype of the L1K65n Differential-Output Charge-Sensitive Preamplifier ASIC for High-Performance, Low-Background HPGe Detector Readout

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***Abstract*—Next-generation neutrinoless double-beta ($0\nu\beta\beta$) decay searches require a large detector/isotope mass and very low radioactive backgrounds. The upcoming LEGEND-1000 experiment will constitute a ton-scale array of several hundred HPGe detectors enriched in ^{76}Ge, the isotope of interest. It aims to reach a sensitivity beyond 10^{28} years on the $0\nu\beta\beta$ decay half-life of ^{76}Ge, necessitating an order of magnitude reduction in background with respect to the state of the art. This will require the implementation of a dedicated application specific integrated circuit (ASIC) preamplifier that will significantly lower background contribution compared to the conventional low-mass front end (LMFE) employed in the** MAJORANA DEMONSTRATOR **and LEGEND-200 experiments, while maintaining or improving energy resolution and other performance parameters. Features include a high (9 MeV) dynamic range with noise low enough to achieve a trigger threshold of <1 keV, a single power supply to reduce background-inducing cabling, and a differential output to maintain signal integrity over several meters of transmission line. The chip would be optimized to operate in liquid argon (87 K), and able to do so reliably for 10 years. Following on from an earlier 180-nm prototype, we have developed a differential-output charge-sensitive preamplifier ASIC fabricated in a 65-nm process, 1 mm × 2 mm in size, that addresses these needs. We present recent results from the successful testing and characterization of the first version of this device.**

***Index Terms*—ASIC, Charge-sensitive amplifier, Cryogenic, Differential, Germanium Detector, Low-Background, Neutrinoless Double-Beta Decay, Preamplifier**

I. INTRODUCTION

DOUBLE-beta decay entails the simultaneous conversion of two neutrons in the nucleus to protons, with the emission of two β particles and two antineutrinos ($2\nu\beta\beta$). It occurs in even-even nuclei, where regular single beta decay is energetically forbidden. Neutrinoless double-beta ($0\nu\beta\beta$) decay [1], [2] is a theoretically-predicted, lepton-number-violating mode predicated on the hypothesized Majorana nature of the neutrino, wherein the two antineutrinos annihilate virtually and the full decay energy ($Q_{\beta\beta}$) is carried by the two β particles. This as-of-yet unobserved decay has significant implications for fundamental physics questions, including the origin of mass and the matter-antimatter asymmetry of the universe. Because $0\nu\beta\beta$ decay would be extremely rare, searching for it requires a detector containing a very large mass of the candidate isotope and a very low radioactive background, as well as good energy resolution. The latter is important because the $0\nu\beta\beta$ signal in a beta spectrum measurement would manifest as a small monoenergetic peak at the decay energy, $Q_{\beta\beta}$, which would need to be resolved from the much larger $2\nu\beta\beta$ continuum background.

The future LEGEND-1000 (Large Enriched Germanium Experiment for Neutrinoless double-beta Decay) [3] project will utilize a ton-scale array of ∼400 high-purity germanium (HPGe) detectors enriched to >90 % in ^{76}Ge—the isotope of interest. With this significant mass and the excellent energy resolution intrinsic to HPGe detectors, LEGEND-1000 aims for a sensitivity beyond 10^{28} years on the $0\nu\beta\beta$ decay half-life of ^{76}Ge; however, this necessitates an order of magnitude reduction in background with respect to the state of the art. This requires the implementation of a dedicated application-specific integrated circuit (ASIC) preamplifier that will significantly lower background contribution compared to the “conventional” low-mass front end (LMFE) [4], [5] employed in the MAJORANA DEMONSTRATOR and LEGEND-200 experiments. The CC4 charge-sensitive preamplifier [6], used in the latter, represents the best achieved radiopurity performance for high-performance, large-scale, low-background germanium detector readout with discrete component electronics, and it is still much too radioactive to meet the LEGEND-1000 targets.

The new ASIC will need to be implemented while maintaining or improving energy resolution and other performance parameters. These include a high (9 MeV) dynamic range with noise low enough to achieve a trigger threshold <1 keV, a single power supply to reduce background-inducing cabling, and a differential output to maintain signal integrity over several meters of transmission line [3]. The chip would be optimized to operate in liquid argon (87 K), and be able to do so reliably for 10 years.

To address these needs, the Lawrence Berkeley National Laboratory (LBNL) Engineering Division’s Integrated Circuit Design Group is developing the L1K65n ASIC preamplifier.

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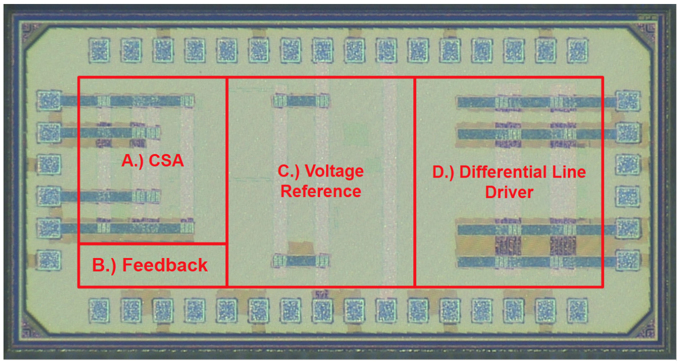

Fig. 1. A photograph of the L1K65n ASIC chip from the first production batch as reported in this work, with key sub-components of the integrated circuit labeled: (A) CSA, (B) feedback with, (C) voltage reference, (D) differential output buffer. From the second version onward, an LDO is included.

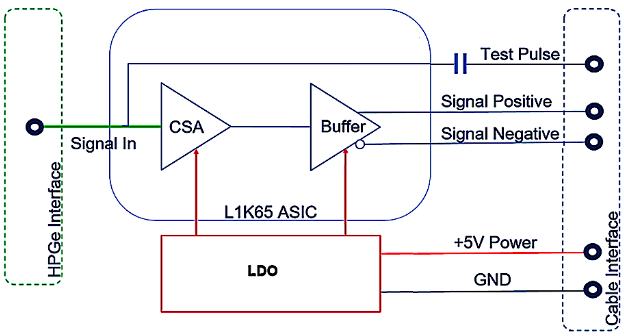

Fig. 2. A block diagram of the complete system. Blocks shown in blue are implemented in the first version of the L1K65n ASIC as reported in this work. Blocks shown in red are included from the second version onward.

This is one of two ongoing efforts to develop an ASIC preamplifier for LEGEND-1000, the other being carried out by European collaborators, with first results demonstrated in [7]. The first iteration of the L1K65n device was fabricated and tested, with the results of this initial characterization presented in this manuscript.

II. The L1K65n Charge-Sensitive Preamplifier ASIC

The L1K65n differential charge-sensitive preamplifier (CSA) ASIC follows on the earlier 180-nm L1Kv1 prototype [8], also developed at LBNL. It is fabricated in the TSMC 65-nm process, has external dimensions of 1 mm $\times$ 2 mm, weighs $<$0.5 mg, and is intended for deployment in the immediate vicinity of the HPGe detector it reads out.

L1K65n is a self-contained device that includes the CSA proper, a feedback circuit with a 540 fF capacitor, continuous reset, and a differential driver. A photograph with the key components labeled is shown in Fig. 1, and a block diagram in Fig. 2. The charge amplifier core is a p-input regulated cascode with a boosted output follower, optimized for noise and dynamic range in cryogenic conditions, using previously-verified cryogenic models developed at Fermilab for the DUNE project [9]. DUNE has not only validated these models, but also assessed the limited aging of the 65-nm devices for

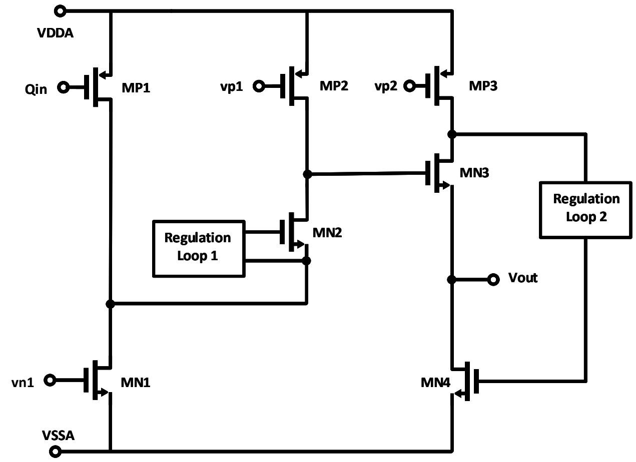

Fig. 3. A circuit diagram of the CSA portion of the L1K65n ASIC preamplifier.

over 10 years stability. This influenced our choice of this technology and our general design philosophy for L1K65n. A transistor-level circuit diagram of the CSA is given in Fig. 3.

The differential output driver is important for our application because the geometry of large detector arrays like LEGEND typically entails long cables between the preamplifier and the other electronics. The innovative aspect of the driver we use comprises replacing a feedback transconductor with a resistor to lower noise. The architecture of this device, including detailed schematics and discussion, is presented in [10]. Starting from the second iteration of L1K65n, an improved version of this circuit is to be used.

A single supply voltage of 2.5 V to 2.8 V is required, dissipating sufficiently little power to avoid boiling the liquid argon in the LEGEND cryostat. Noise performance was optimized for a detector load of 4 to 10 pF, with $\sim$20 pA leakage current. The first prototype of L1K65n discussed in this paper lacks an on-chip low-dropout regulator (LDO); a low-noise capacitor-less LDO [11] is included in the second version and will be present in any future iterations. The addition of the LDO is expected to improve the preamplifier's line and load regulation performance, including tolerance towards noisier power supplies, unregulated supply disturbances, and long power/ground cables.

III. Measurement Setups and Methodology

A. Benchtop Characterization Setup

We carried out benchtop characterizations to determine some of L1K65n's performance parameters. Our setup is diagrammed in Fig. 4. It includes a pulser for injecting charges into the ASIC, an amplifier connected to a signal analyzer, a storage oscilloscope acting as a data acquisition system (DAQ), and a computer for signal processing and analysis. The benchtop testing was performed in the absence of a detector, so pulses are injected via a capacitor, which stands in for the detector capacitance. The value of this capacitor is 3 pF, which is a close approximation of the capacitance of point contact-style detectors like the ones used in the LEGEND experiment.

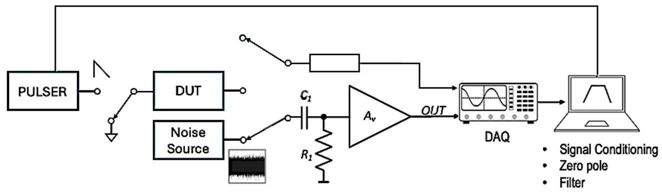

Fig. 4. Block diagram of our benchtop characterization setup, used to evaluate noise performance, linearity, and power consumption.

In all of our testing, as in LEGEND, raw preamplifier pulses are collected by the DAQ. Signal conditioning, including filtering, trapezoidal shaping, and pole-zero correction, is done in software. The pole-zero correction is empirically determined by measuring the preamplifier pulse decay times, and the shaping time is selected to minimize noise. With this setup, we measured noise, linearity, and power consumption. The measurements were conducted at both room temperature and 77 K, achieved by simply submerging the ASIC and its carrier board in liquid nitrogen.

B. Setup for Testing with HPGe Detector

We used the L1K65n ASIC to read out a germanium detector to evaluate its realistic performance as a preamplifier in its intended application. The detector in question is an in-house HPGe p-type point contact (PPC) detector [12], fabricated at LBNL's Semiconductor Detector Laboratory (SDL). It is housed in a liquid-nitrogen-cooled "dipstick" test cryostat. Essentially, this consists of a vacuum chamber with electrical feedthroughs and an internal infrared radiation shield housing the detector and preamplifier, attached to a cold finger that is submerged in a dewar filled with liquid nitrogen. A diode thermometer mounted near the preamplifier and detector monitors their temperature. We measured the base temperature to be $\sim$90 K, which is appropriate given that the LEGEND detectors and preamplifiers will be submerged in liquid argon, the temperature of which is 87 K (in a sealed cryostat with overpressure to avoid boiling). The interior of our test cryostat, with the PPC detector and L1K65n ASIC inside, is shown in Fig. 5, with key elements labeled and other items shown schematically.

The PPC detector is fabricated from a cylindrical $\sim$900-g high-purity germanium crystal, and operates as a reverse-biased diode. The sides and top face (as oriented in our setup and shown in Fig. 5) are doped with lithium, forming the n+ contact of the diode. The bottom face comprises a passivated surface with the p+ point contact in the middle. The p+ contact is the anode, and is connected to the preamplifier. Outside the cryostat, a high-voltage power supply biases the detector to 2.6 kV on the n+ side via a low-pass filter and vacuum feedthrough. This voltage is sufficiently high to fully deplete the detector, ensuring full charge collection and high-quality pulses with fast rise times.

With the detector biased, in the absence of radiation, only a small leakage current at the level of picoamperes can be observed at the p+ contact. When radiation is absorbed by the bulk of the detector, ionization occurs, and a charge carrier

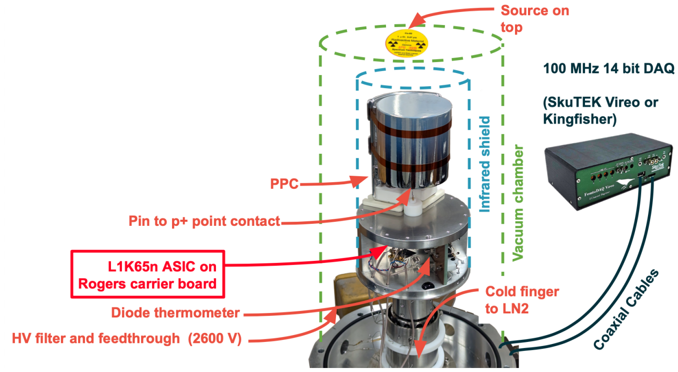

Fig. 5. HPGe PPC detector used for L1K65n ASIC preamplifier characterization inside its "dipstick" cryostat (shown open), with components labeled. The board carrying the ASIC is mounted just below the detector itself, also in vacuum and at the same temperature. Items not visible in the photograph (radioactive source, infrared shield, vacuum chamber cover, and readout DAQ) are depicted schematically.

cloud forms. The electric field created by the bias voltage quickly transports the charge cloud to the p+ contact, where it is collected and read out by the charge-sensitive preamplifier as a voltage pulse. The differential signal is taken outside of the cryostat via a vacuum feedthrough and two separate coaxial cables, connecting to two separate DAQ channels. We use the SkuTEK Vireo and Kingfisher DAQs, which provide a 100-MHz sampling rate and 14 bits, to record the positive and negative waveforms. We also test the differential buffer's suitability for driving sufficiently long cables. We do so by varying the length of the coaxial cables between the cryostat and the DAQ.

In software, pulse quality cuts are applied to remove noise and pileup events, and pole-zero correction and trapezoidal shaping are applied. Again, the pole-zero correction comes from preamplifier pulse decay times, and the trapezoidal shaping time is optimized for minimal noise. The flat-top time of the trapezoidal shaping is specifically constrained by the charge collection time of the detector to avoid position-dependent ballistic deficit.

IV. Results

A. Noise

Good baseline noise performance is a critical aspect of the L1K65n ASIC's specifications, essential to achieving good energy resolution and a sufficiently low energy threshold (<1 keV for LEGEND). Thorough computer simulations of the preamplifier's noise at various temperatures were carried out at the design stage. For this, we used previously-verified cryogenic models developed at Fermilab for the DUNE project [9]. Actual noise was measured at 300 K and 77 K using our benchtop test setup, with a 3-pF injection capacitor acting as a placeholder for detector capacitance. Raw preamplifier noise was collected, and passed through our usual signal processing and shaping treatment. Fig. 6 shows the measured trapezoidally-shaped noise at room and liquid nitrogen temperatures as a function of shaping time. At 300 K, with a shaping time of 4 – 5 μs, we observe a minimum noise of 92 e^-

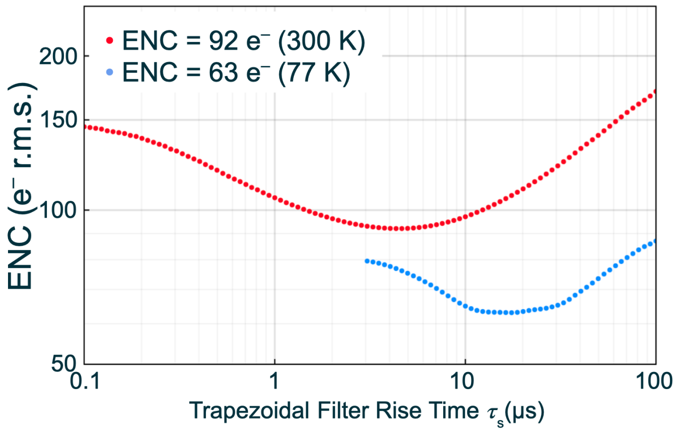

Fig. 6. RMS baseline noise of the L1K65n ASIC preamplifier, measured in our benchtop setup at room and liquid nitrogen temperatures, as a function of shaping time (trapezoidal filter rise time). $C_{inj} = 3$ pF.

RMS. At 77 K, which is much closer to the design operating temperature of 87 K, the minimum noise is reduced to 63 e^- RMS, though this requires increasing shaping time to 10 – 11 μs, which is not a problem in a low-rate application such as ours. The design simulations indicated lower values—38 e^- RMS and 26 e^- RMS respectively. The design simulations include external noise-forming elements, such as interposer parasitics from off-chip components of the test setup, up to 1 pF, which may be insufficient for our measurement setup. Specifically, the parallel noise contribution (proportional to shaping time, visible in the right half of each curve in Fig. 6) behaves as expected, while the series white noise contribution (inversely proportional to shaping time, visible in the left half of each curve) is higher than in simulation, and exhibits flattening, suggesting an unexpected flicker-like noise source. Nonetheless, the performance achieved is within our specifications, and may improve in the second version of the L1K65n chip thanks to the incorporation of an LDO.

B. Linearity

When a charge-sensitive amplifier is used to readout a germanium detector, which in turn measures events over a broad energy range—the LEGEND-1000 experiment will need to detect particles up to 9-MeV—it is very beneficial for the relationship between pulse amplitude and event energy to be linear. We measured the L1K65n ASIC's linearity on the benchtop by injecting events of various energies with a pulse generator via a capacitor. The injection capacitor value was 500 fF at room temperature, and 3.0 pF at liquid nitrogen temperature. We injected pulses at energies between 0.1 MeV and 3 MeV, calculating said energies analytically using the pulse amplitude in volts, pulse length, and the injection capacitor value. For each amplitude/energy data point, 100,000 individual events were recorded and averaged.

Measured preamplifier pulse energy vs injected pulse energy at 300 K is plotted in Fig. 7 and at 77 K in Fig. 8, with linear model fits. At room temperature, deviation from the linear model is within ~1.5 keV for all measured values, or within 1.5%, with the largest disagreement seen at lower energies. At

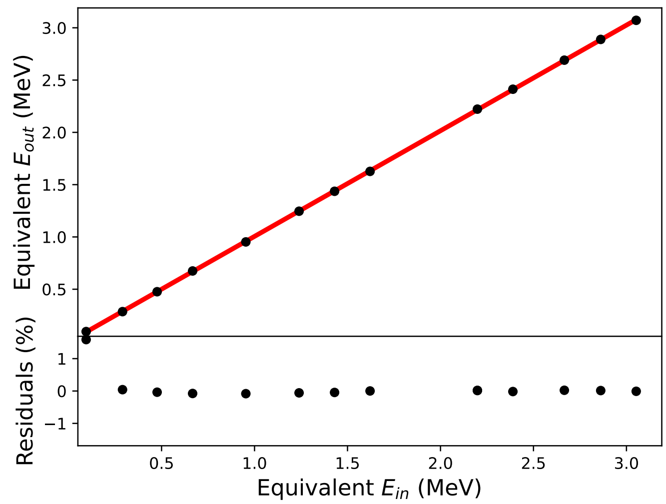

Fig. 7. L1K65n benchtop amplitude linearity scan carried out at 300 K temperature, with the pulse generator coupled via a 500-fF injection capacitor.

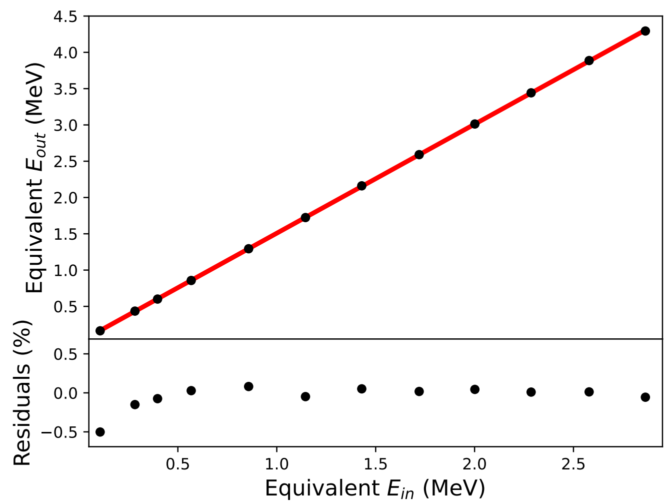

Fig. 8. L1K65n benchtop amplitude linearity scan carried out at 77 K temperature, with the pulse generator coupled via a 3.0-pF injection capacitor.

liquid nitrogen temperature, which is much closer to the design application operating temperature, agreement over most of the energy range improves and is within 0.5% for all energies.

Subsequently, measuring in the cryostat at a temperature of 90K, we carried out another pulser scan between 0.8 and 4.3 MeV, where deviation from the linear fit was within 0.4% for all data points. These results are plotted in Fig. 9. There does appear to be a greater *systematic* deviation from the linear trend in this measurement compared to the benchtop ones. Since this behavior was not observed in the benchtop tests at either room or liquid nitrogen temperatures, we believe it stems from other elements in the setup, and not the L1K65n ASIC. Nonetheless, this phenomenon is assumed to be present in other measurements taken with the cryostat.

C. Energy Resolution

We used our PPC detector setup, as described in II.B, with a ^{60}Co radiation source, to evaluate the L1K65n's real-world

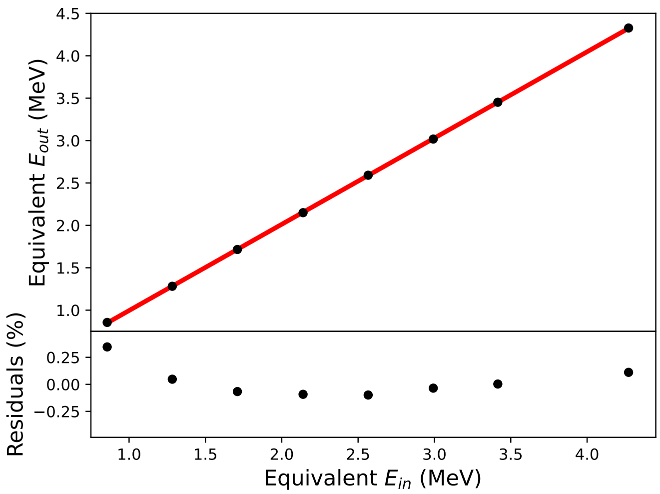

Fig. 9. L1K65n in-cryostat amplitude linearity scan carried out at 90 K temperature, with the pulse generator coupled via a 500-fF injection capacitor.

TABLE I
SDL PPC ^{60}Co Energy Resolution with L1K65n vs discrete preamplifiers

Energy (keV)	L1K65n FWHM (keV)	qAmp FWHM (keV)	2017 Verification FWHM (keV)
1173.24	2.51 ± 0.02	2.75 ± 0.05	$1.96 - 2.50$
1332.5	2.79 ± 0.02	3.05 ± 0.06	$2.13 - 2.72$

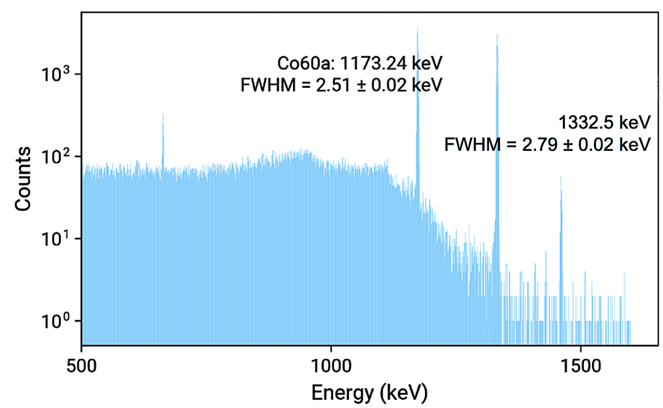

Fig. 10. ^{60}Co gamma spectrum as measured by our PPC detector read out by the L1K65n ASIC preamplifier.

energy resolution performance. ^{60}Co emits gamma rays at two energies: 1173 keV and 1333 keV. Our measured gamma spectrum is given in Fig. 10. Table I shows the full width at half maximum (FWHM) energy resolution for both gamma lines, with uncertainty, from Gaussian fits where the peak energies are set to literature values. For comparison, numbers are given for the same PPC detector in the same cryostat and in the same room, as read out by both the L1K65n ASIC (column 1) and the qAMP conventional high-performance differential CSA that was developed in the context of LEGEND-200 R&D (column 2). The result achieved with the ASIC is comparable to or better than the amplifier made from discrete components.

Taking the Fano factor for germanium to be 0.13, we can calculate the estimated non-Fano contribution, which includes electronics and external noise, the variance of collected charge in the detector (which includes ballistic deficit), and additional noise caused by detector bias voltage. The resolutions measured with the L1k65n ASIC correspond to an estimated non-Fano contribution of 281 e^- RMS at 1173 keV and 320 e^- RMS at 1333 keV, which is noticeably higher than the 63 e^- RMS ENC measured on the benchtop (Fig. 6). Due to this discrepancy, we believe the ASIC itself is not the limiting factor in the observed energy resolution, which needs to be improved. Due to equipment limitations, both the L1K65n and qAMP discrete preamplifier measurements were carried out with the two legs of the differential output being digitized separately. This increases noise by about 40% compared to a true differential ADC, worsening observed resolution accordingly. In the third column of Table I, we quote ^{60}Co resolution ranges from this PPC detector's post-fabrication verification tests, carried out in February 2017. These numbers are slightly better but not inconsistent; they were measured with a single-ended preamplifier, in a quieter laboratory, and before this detector had spent the most of eight years stored at room temperature (which tends to degrade performance). Given these facts, we believe there is a meaningful detector and measurement setup-derived limitation to the observed energy resolution.

D. Energy Calibration

Analogous to the ^{60}Co measurement above, we also measured the gamma spectrum from a ^{232}Th source (Fig. 11). The thorium chain comprises a series of radioactive daughter nuclei, so the source emits gamma rays at several different energies between 500 keV and 3000 keV, making it a standard choice for detector calibration. From this spectrum, we performed a fit to the seven individual gamma lines labeled in Fig. 11. The fit model includes a Gaussian for the peak, low-energy tail, and flat background, as illustrated in Fig. 12. The parameters of peak location and FWHM peak width are extracted from the Gaussian component of the fit in ADC units. Gamma ray energies known from literature are plotted against these values, and a calibration curve is fitted (Fig. 13). Two data points corresponding to the 1592-keV and 2104-keV lines are excluded from the fit due to low quality. As seen previously with benchtop pulser scans, the L1K65n preamplifier's behavior is highly linear.

Using the same data, we also perform a fit of the FWHM energy resolution as a function of energy, presented in Fig. 14. Energy values are taken from literature, as in the calibration fit, and the 1592-keV and 2104-keV lines are, again, excluded due to low quality. The fit model is the square root of a first-order polynomial. Keeping in mind the main application of the LEGEND-1000 experiment, we use this curve to estimate energy resolution at 2039 keV—the full decay energy of ^{76}Ge, $Q_{\beta\beta}(^{76}\mathrm{Ge})$. This value is found to be 3.52 ± 0.04 keV. Taking the Fano factor for germanium to be 0.13, this resolution corresponds to an estimated non-Fano contribution of 408 e^- RMS, which is much higher than the L1K65n ASIC's 63 e^- RMS ENC measured on the benchtop (Fig. 6). As discussed in the previous section on energy resolution, we believe this value to be limited by our measurement setup, environment,

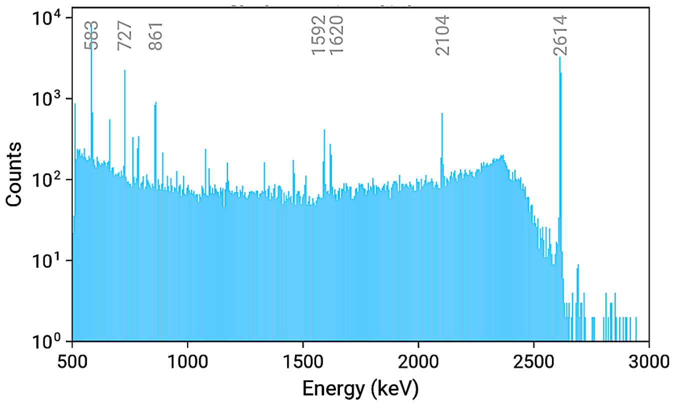

Fig. 11. ^{232}Th gamma spectrum as measured by our PPC detector read out by the L1K65n ASIC preamplifier. The seven lines we fit in our energy calibration analysis are labeled with their literature values.

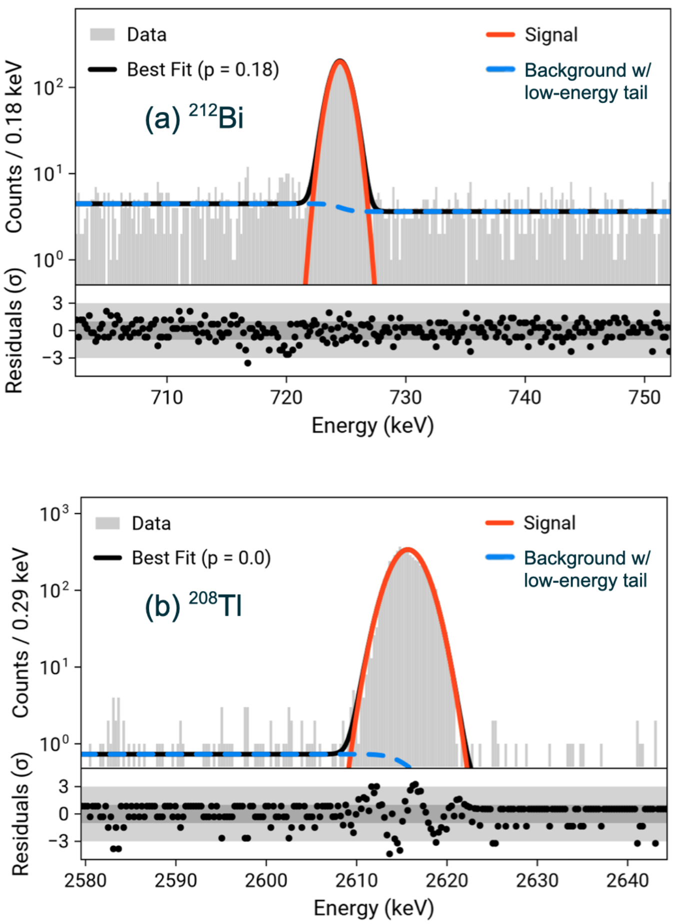

Fig. 12. (a) ^{212}Bi and (b) ^{208}Th gamma line fits from the ^{232}Th spectrum measured with our PPC detector read out by the L1K65n ASIC.

and detector, rather than by the L1K65n ASIC itself.

E. The Effect of Cable Length

The L1K65n ASIC's anticipated application in the LEGEND experiment involves mounting one preamplifier in the immediate vicinity of the p+ contact of each of the several hundred germanium detectors. This entails transmitting the

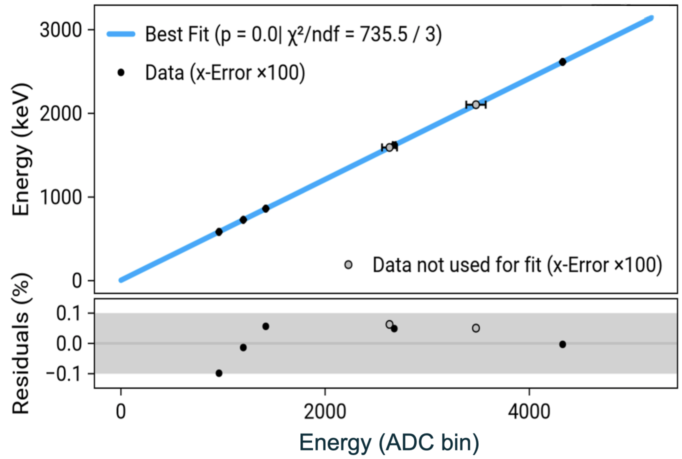

Fig. 13. ^{232}Th calibration result for PPC detector read out by the L1K65n ASIC.

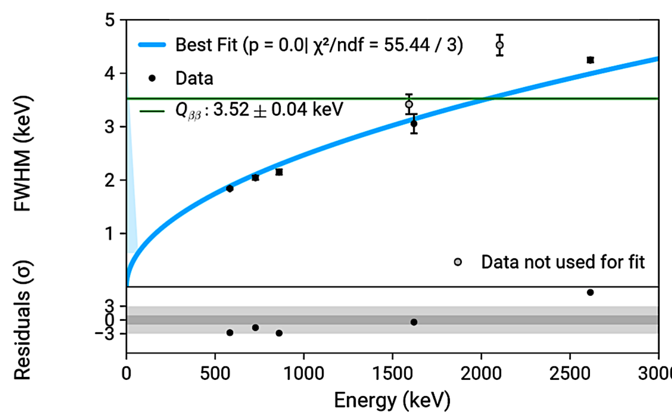

Fig. 14. Plot and fit of measured ^{232}Th gamma ray line FWHM resolution vs. energy (literature values). The green line shows $Q_{\beta\beta}$ for ^{76}Ge, the isotope of interest in the LEGEND $0\nu\beta\beta$ experiment.

amplified signals to the DAQ, which is located outside the cryostat, via cables several meters long. For this reason, the L1K65n is a differential-output design. We evaluated the differential buffer's ability to drive coaxial cables with 100-Ω differential termination of various representative lengths, without degradation of the signal as measured by energy resolution. We used the aforementioned PPC detector setup shown in Fig. 5, reading out a ^{60}Co source, varying only the length of the cables between the preamplifier and the DAQ. For each of three cable lengths, we measured a spectrum with 100,000 counts in each of the two ^{60}Co gamma ray peaks. A Gaussian fit determined to each peak was used to determine the FWHM energy resolution. The results are summarized in Fig. 5 and Table II. We do not observe a meaningful change in the energy resolution for the two ^{60}Co gamma lines, indicating the effectiveness of the L1K65n differential driver.

V. Conclusion

We developed the L1K65n ASIC preamplifier for high-performance, low-background HPGe detector readout in the context of the LEGEND-1000 $0\nu\beta\beta$ decay experiment. L1K65n is a self-contained differential charge-sensitive am-

TABLE II
THE EFFECT OF CABLE LENGTH ON ENERGY RESOLUTION: ^{60}CO SOURCE, PPC DETECTOR, L1K65N PREAMPLIFIER.

Cable Length (cm)	FWHM at 1173 keV (keV)	FWHM at 1333 keV (keV)
185	2.51 ± 0.02	2.79 ± 0.02
405	2.52 ± 0.02	2.76 ± 0.02
645	2.52 ± 0.02	2.75 ± 0.02

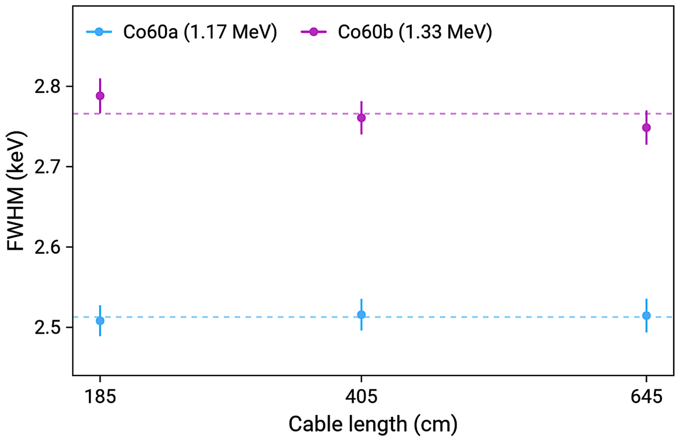

Fig. 15. The effect of cable length between the L1K65n ASIC preamplifier's output and the DAQ on the measured ^{60}Co gamma ray energy resolution of our SDL PPC detector. Each data point corresponds to 100,000 counts.

plifier. We carried out thorough benchtop testing of the first iteration of L1K65n to assess noise and linearity, both of which were found to be satisfactory. Baseline RMS noise when operated at 77 K was measured to be 63 e^-. Characterization with an HPGe detector was performed to evaluate energy resolution and spectral measurement performance. An energy resolution of 2.51 ± 0.02 keV FWHM was achieved at the ^{60}Co 1173-keV line. Energy calibration with a ^{232}Th source is highly linear, with resolutions at the various lines between 1.5 keV and 4.5 keV FWHM. Estimated resolution at $Q_{\beta\beta}(^{76}Ge)$ is 3.52 ± 0.04 keV FWHM, which is as-of-yet unsatisfactory for the LEGEND-1000 use case, but appears to be limited by the detector and measurement setup—not representative of that experiment—rather than the preamplifier. Thus, the first iteration of the L1K65n ASIC preamplifier performs well. Subsequent iterations of L1K65n will feature an on-chip LDO, among other improvements, and superior performance. This work is actively ongoing.

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