SuperCDMS Detector Testing at CUTE

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Abstract

The Super Cryogenic Dark Matter Search (SuperCDMS) experiment uses cryogenic semicondutor detectors to look for evidence of dark matter interactions with Standard Model matter. The next phase of the experiment is currently under construction at SNOLAB. In July 2021, a new SuperCDMS detector was operated at CUTE, a low-background test facility. This is the first characterization of such a detector under high bias voltage.

SuperCDMS

- Searches for dark matter with cryogenic detectors operated at $\sim$30 mK
- Under construction at SNOLAB
- Uses different detector materials (Ge, Si) and types (iZIP for background discrimination, HV for low threshold)
- Initial payload: four stacks ("towers") of six detectors each, 2 HV and 2 iZIP

CUTE: A Cryogenic Underground TEst Facility

CUTE is designed to test SuperCDMS detectors in a low-background environment

- Can operate up to 6 SuperCDMS detectors (one tower) at a time
- Shielding - sides and bottom: water tank and Pb around cryostat; top: internal Pb and polyethylene above cryostat
- Background: $<$7 events/keV/kg/day
- Cooling ($\sim$12 mK): dilution refrigerator with pulse tube cooler
- Suspension system: system for vibration mitigation (particularly pulse tube related)

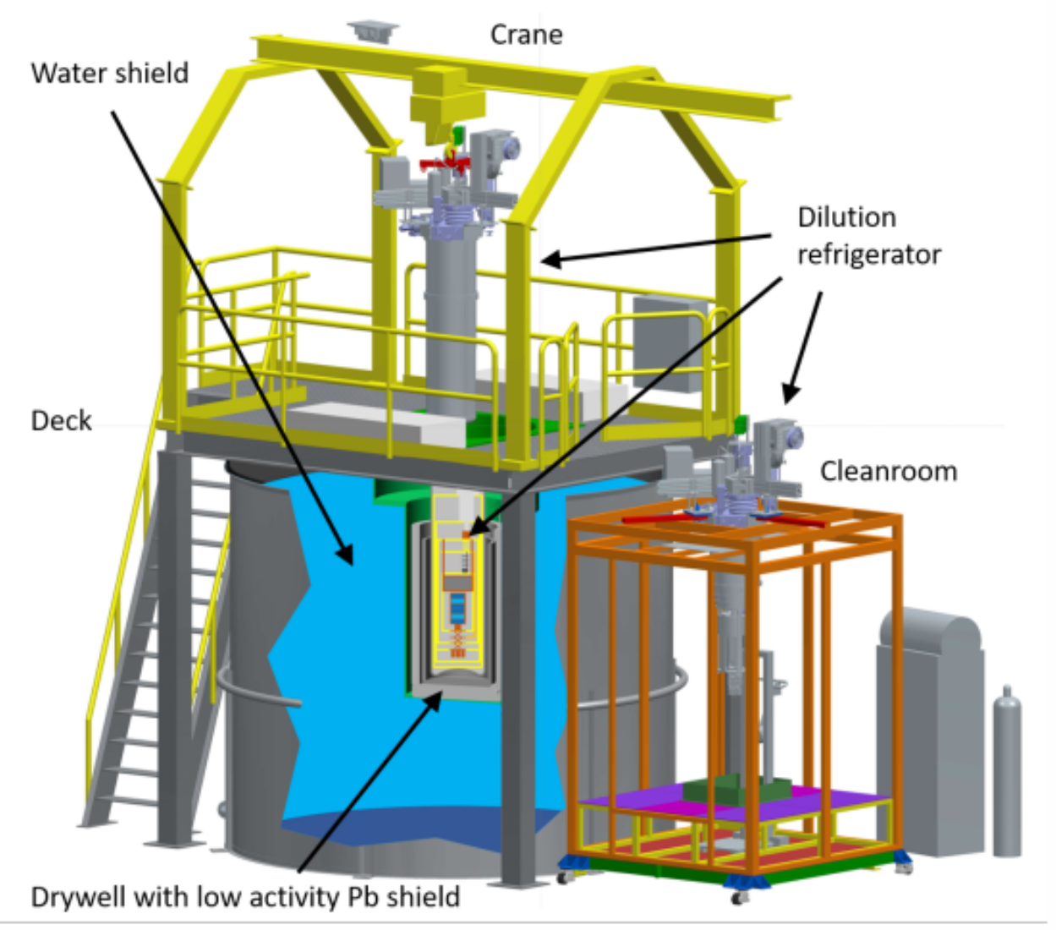
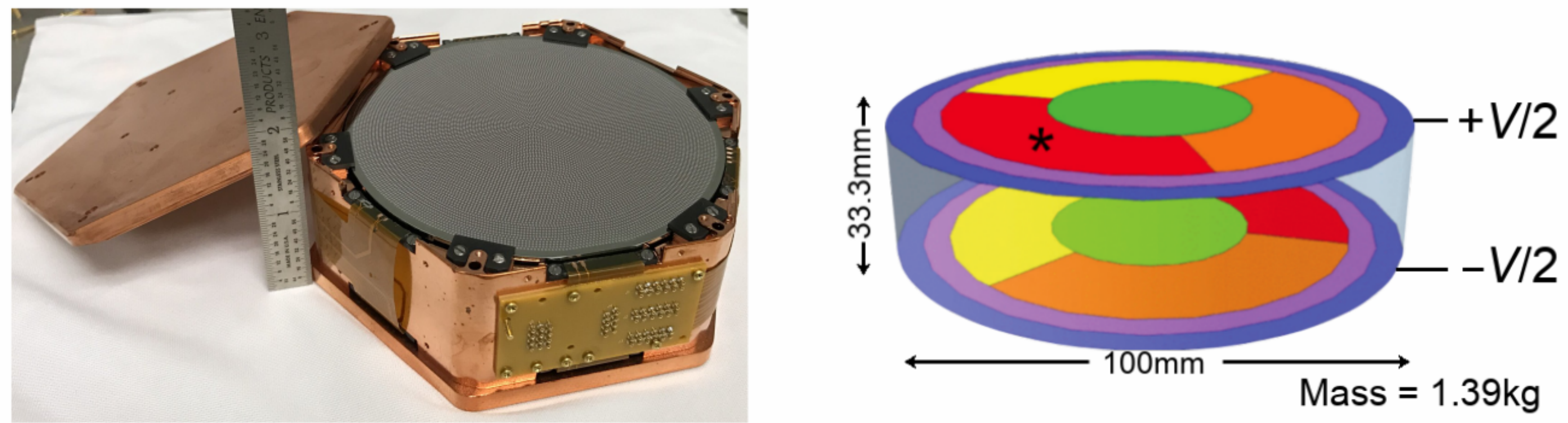


Figure 2: Diagram of CUTE, from Ref. [1].

SuperCDMS SNOLAB Ge HV Detector

- SuperCDMS SNOLAB high voltage (HV) detectors [2] are designed to be operated at a detector bias of $\sim$100 V, applied symmetrically ($\pm$50 V on top/bottom of detector)
- The Neganov Trofimov Luke (NTL) [3, 4] effect amplifies charge signals into large phonon signals
- Phonon signal measured using tungsten film in transition between superconducting and normal state (transition edge sensor, TES)



(a) A SuperCDMS SNOLAB HV detector in its copper housing. Ruler shown for scale.

(b) HV detector phonon channel layout, from Ref. [2]. Only one channel, indicated by an asterisk (*), is used in this analysis.

Figure 3

In the NTL effect, drifting charge carriers interact with the lattice, converting electric potential energy into phonons. The magnitude of the amplification of the original recoil energy is dependent on the detector bias voltage. For a given detector bias voltage, V_b, the expected amplification factor is

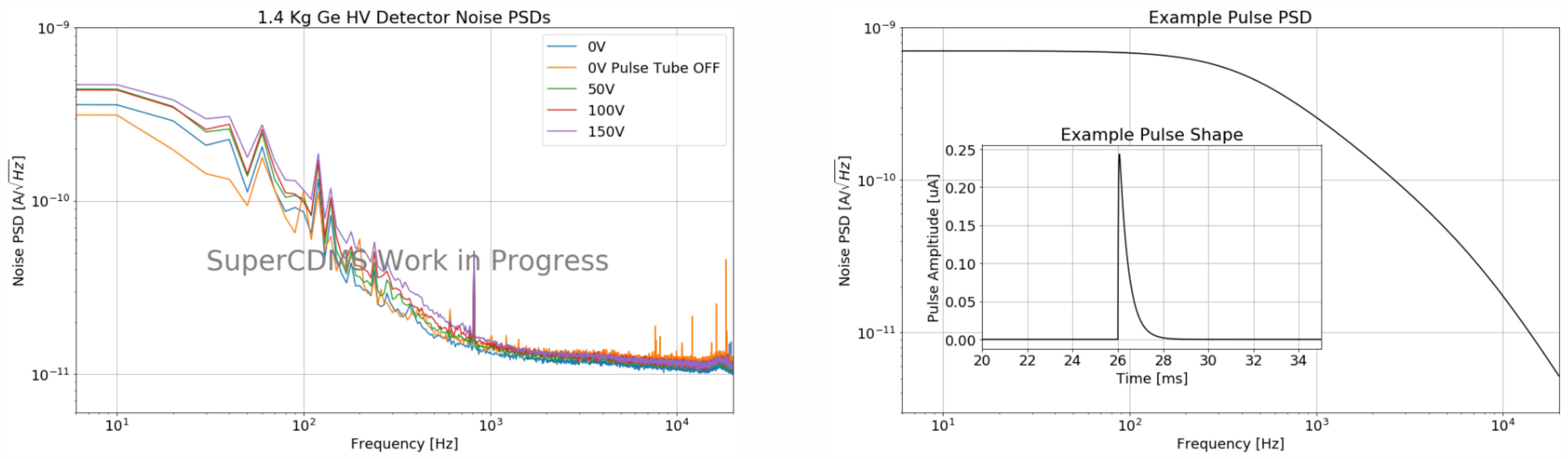
$$A(V_b) = 1 + \frac{Y\,V_b}{\varepsilon} \quad (\text{Primary interaction} + \text{NTL contribution}) \tag{1}$$

where Y is the ionization yield ($Y = 1$ for electron recoils), and ε is the energy required to generate a single electron hole pair (3 eV for Ge).

The main goal of CUTE Run 21 was to characterize the noise and behaviour of a SuperCDMS SNOLAB Ge detector at HV. An important test was to demonstrate that the HV is properly applied by observing NTL amplification.

Noise Characterization

Frequency information is used in our event analysis, in particular for our event energy estimator. Hence, we look at the noise as a function for frequency. The detector noise was characterized for various bias voltages, using a 0 V detector bias as a baseline, as shown in Figure 4a.



(a) Ge HV detector noise power spectral densities (PSDs) at 0 V and HV. Comparison to 0 V with the pulse tube off demonstrates that the pulse tube is not the dominant source of LF noise.

(b) PSD of a typical signal pulse. The shape is similar to that of the observed LF noise, which makes LF noise mitigation crucial. Inset shows the pulse in the time domain.

Figure 4

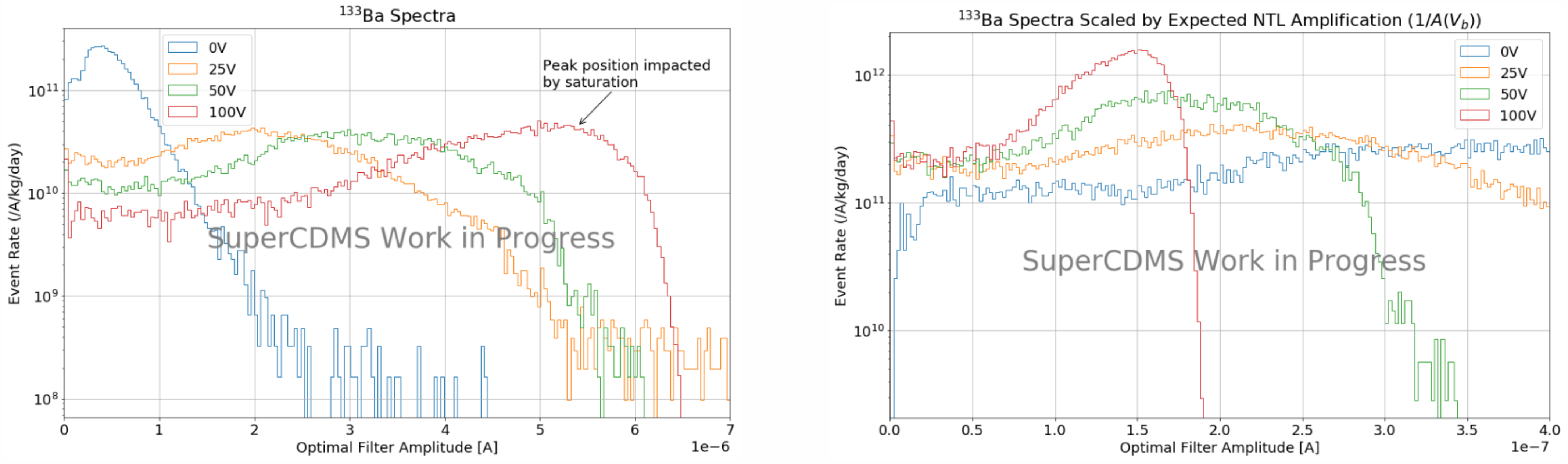
All data show a significant enhancement at low frequency (LF). Without the suspension system, the pulse tube contributes significant LF noise; however, the "Pulse Tube OFF" data indicate that this is not the dominant source of LF noise here.

Increasing the detector bias voltage leads to a noticeable, but small, increase in LF noise, which can be an indication of leakage current. Individual charges liberated or injected by the applied HV drift across the detector; they would create tiny pulses, not visible above noise, but still contribute to LF noise in the same way as pulses do. A PSD of an example pulse is shown in Figure 4b. LF noise from leakage has the same frequency content and is thus difficult to differentiate from signal. We need to investigate the LF noise and understand if the HV dependence can be removed by modifying operational parameters.

^{133}Ba Calibration Spectra and NTL Amplification

A retractable ^{133}Ba calibration source is installed at CUTE, and was used for preliminary studies of the detector bias voltage amplification. The easiest and most effective way of quantifying the amplification factor is by measuring the position of a peak. This is demonstrated schematically in Figure 4, which shows the expected behaviour of a flat spectrum with a single gaussian peak under NTL amplification.

For this initial measurement we did not have all channels available, so we are only analyzing data from a single channel. Due to strong position dependence of the signal, the energy resolution of a single channel is poor and the peaks in the Ba spectrum cannot be resolved. However, inferences about the observed NTL amplification can be made by looking at the overall stretch of the spectrum (refer again to the behaviour in Figure 4).



(a) ^{133}Ba calibration spectra at 0 V, 25 V, 50 V, and 100 V detector bias voltage. The optimal filter amplitude is an energy estimator extracted from the pulse. Saturation effects dominate at high energies.

(b) The same spectra as in Figure 5(a) but scaled based on the expected NTL amplification. The reduction in amplification compared to the expectation is stronger as the voltage increases.

Figure 5

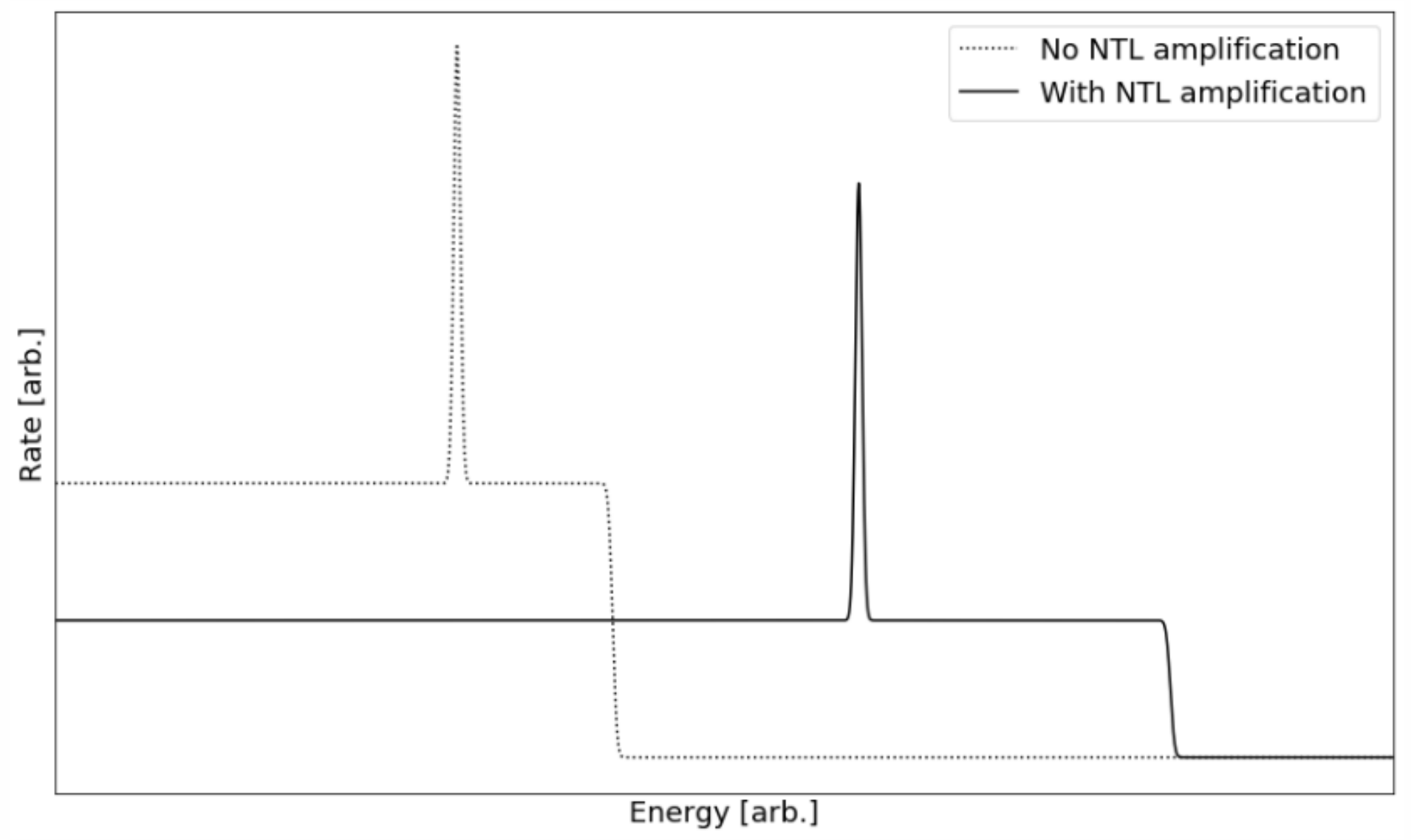


Figure 4: Schematic of NTL amplification: interactions appear at a higher energy and the rate (per measured energy window) is reduced accordingly.

^{133}Ba calibration spectra acquired with different V_b are shown in Figure 5(a). We see evidence for increasing NTL amplification when applying HV.

In Figure 5(b) each spectrum is rescaled by the expected amplification factor, $1/A(V_b)$. The spectra do not line up as they should. The apparent reduction in NTL amplification may be caused by a reduced voltage at the detector related to a leakage current observed on one side of the HV supply. This will be investigated in upcoming measurements at CUTE which will include tests with symmetric and asymmetric bias.

Conclusion

The first operation of a SuperCDMS Ge HV detector at the Cryogenic Underground TEst facility shows promising results in terms of noise performance and signal amplification.

Further testing is required to understand the sources of the excess noise at low frequency, the impact of operational parameters on the noise increase as a function of voltage, and the origin of the reduction in amplification.

References and Acknowledgments

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Discovery, accelerated