Cryogenic BGO scintillator with KID light readout

A cheap and high Z cryogenic γ detector

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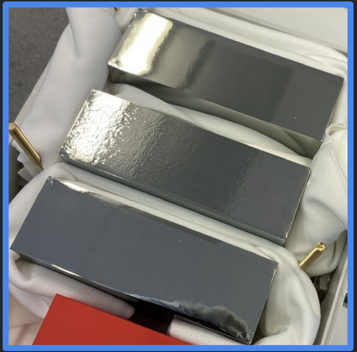
Concept

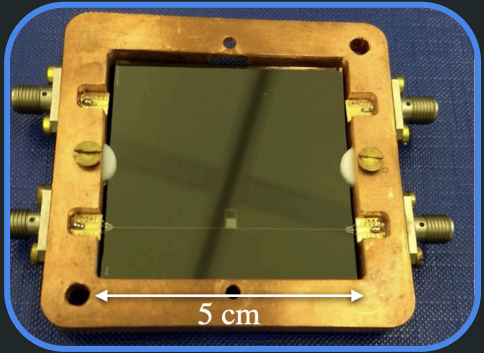
A Simpler, Cheaper Veto



HPGe:
- Expensive
- Complex manufacturing
- Complex readout
- Slow (Charge drift)

BGO:
- Cheaper
- Mass produced in industry

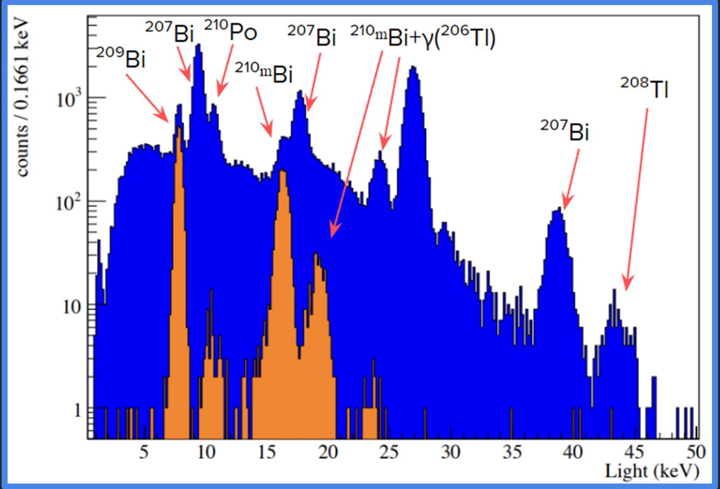
=> Light readouts usually limit utility



=> Kinetic Inductance Detector - based light readout:

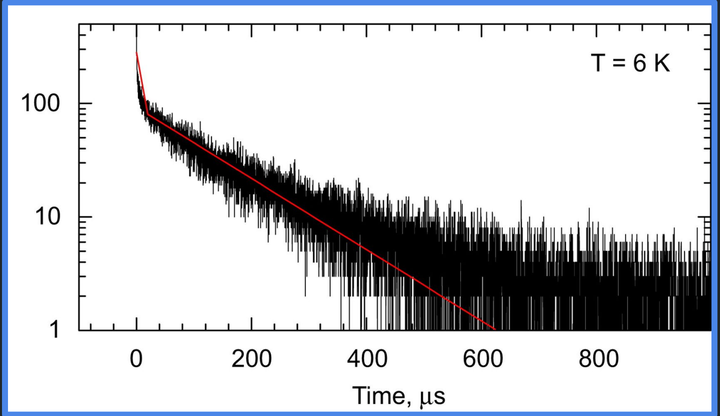
- Very low threshold
- Fast response
- Simple readout (Off-the-shelf SDR)
- Naturally multiplexable
- Easy and cheap to iterate upon

BGO - scintillating crystal



Light Spectrum of a 5×5×5 cm³ BGO crystal for a ≍ 455 hours background measurement. Blue: total spectrum. Orange: α events. [1]

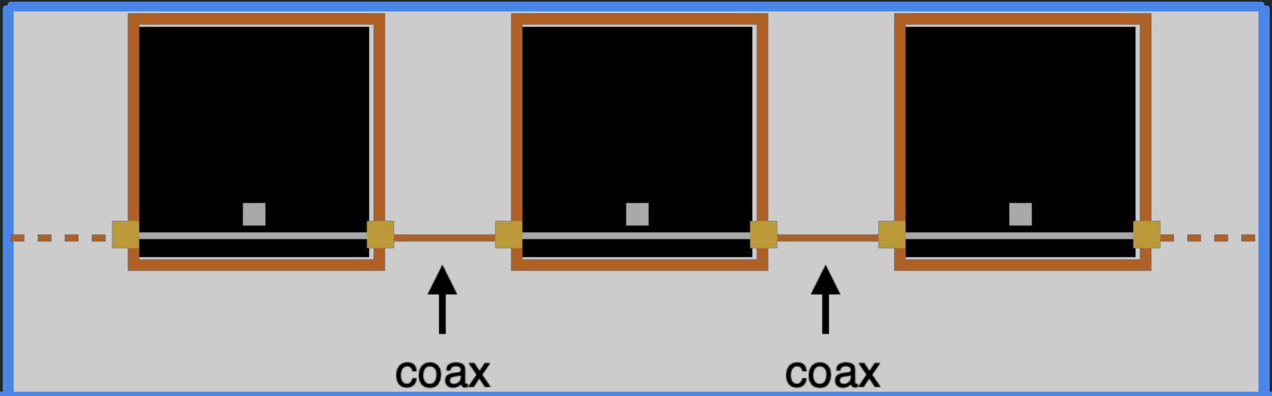
BGO below 6K has an energy to light conversion rate of 16.62keV/MeV [1]



Scintillation decay curves of BGO (at T=6K) in a.u. BGO scintillates fast compared to other crystals. [2]

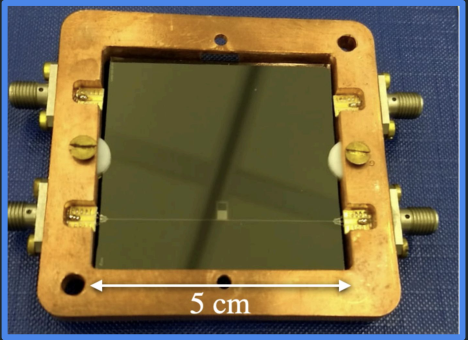
KID - Cryogenic light detector

- Ease of readout: KID readout can be done effectively with off-the-shelf commercial components [3].
- Natural multiplexing (daisy-chain): Simplifies set-up and commissioning, as the entire setup could be powered and read-out using only 2 RF lines, one input and one output, avoiding complications of multiple stage cryogenic design.

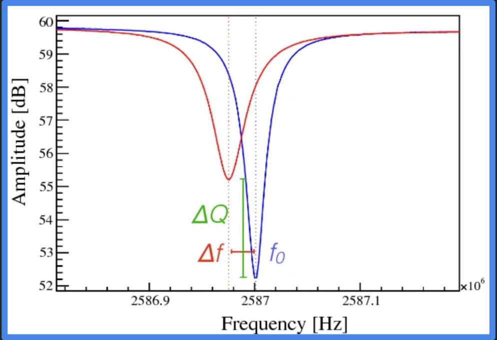


KID - Cryogenic light detector

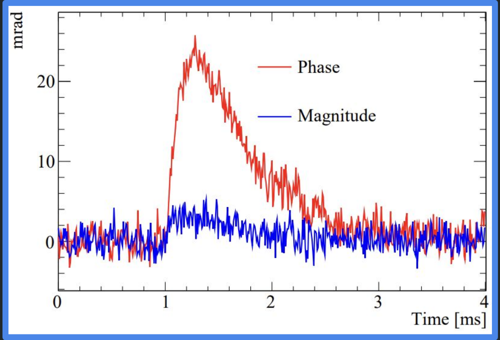
- In-group expertise of KID fabrication and data analysis, the demonstrator light readout chip has also already been characterised [4].
- The CALDER experiment managed to obtain excellent resolution (34eV noise RMS with Pulse Tube vibration decoupling systems, currently present in NUCLEUS), and a fast response time (rise time of 120µs [4]).



Detector chip with 1 KID deposited on a 25 cm^2 650 µm thick substrate [4].



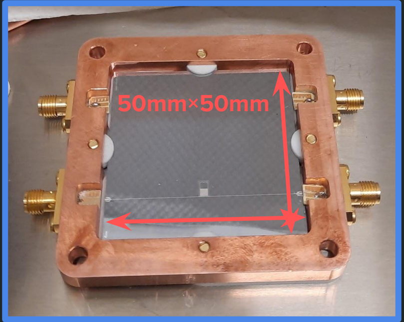
Resonance of a KID at steady state and when perturbed by a phonon-mediated signal [4].

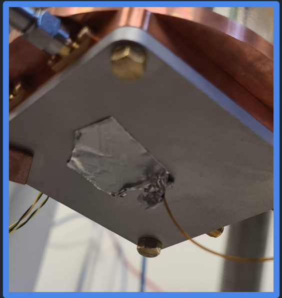


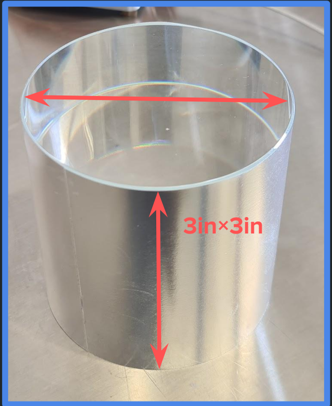
Triggered 1.3 keV signal in the phase (red) and amplitude (blue) directions [4].

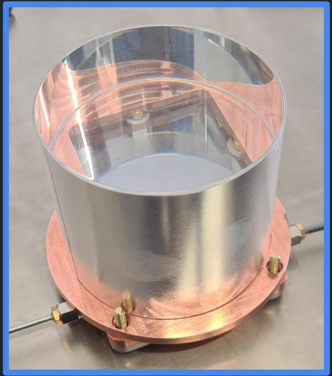
Status of the project

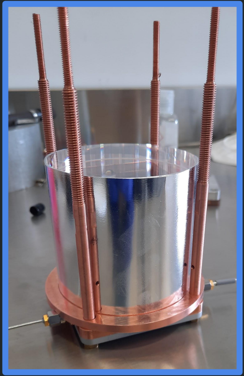
Setup

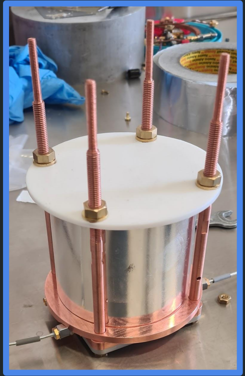


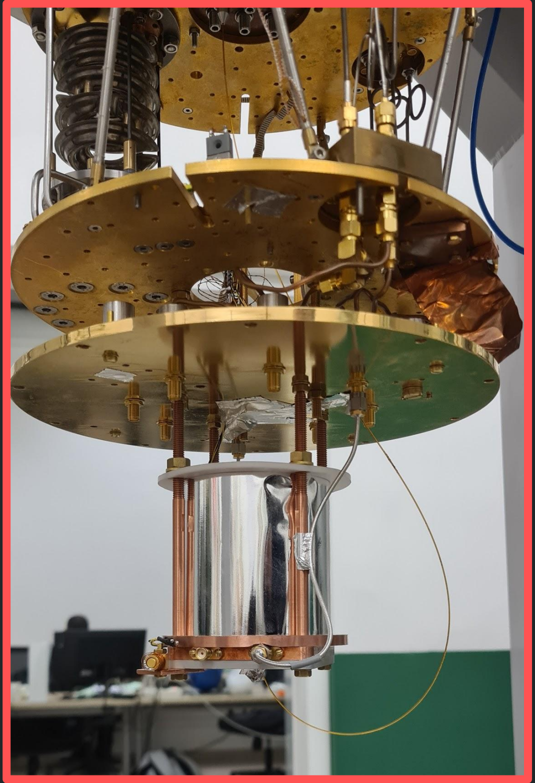




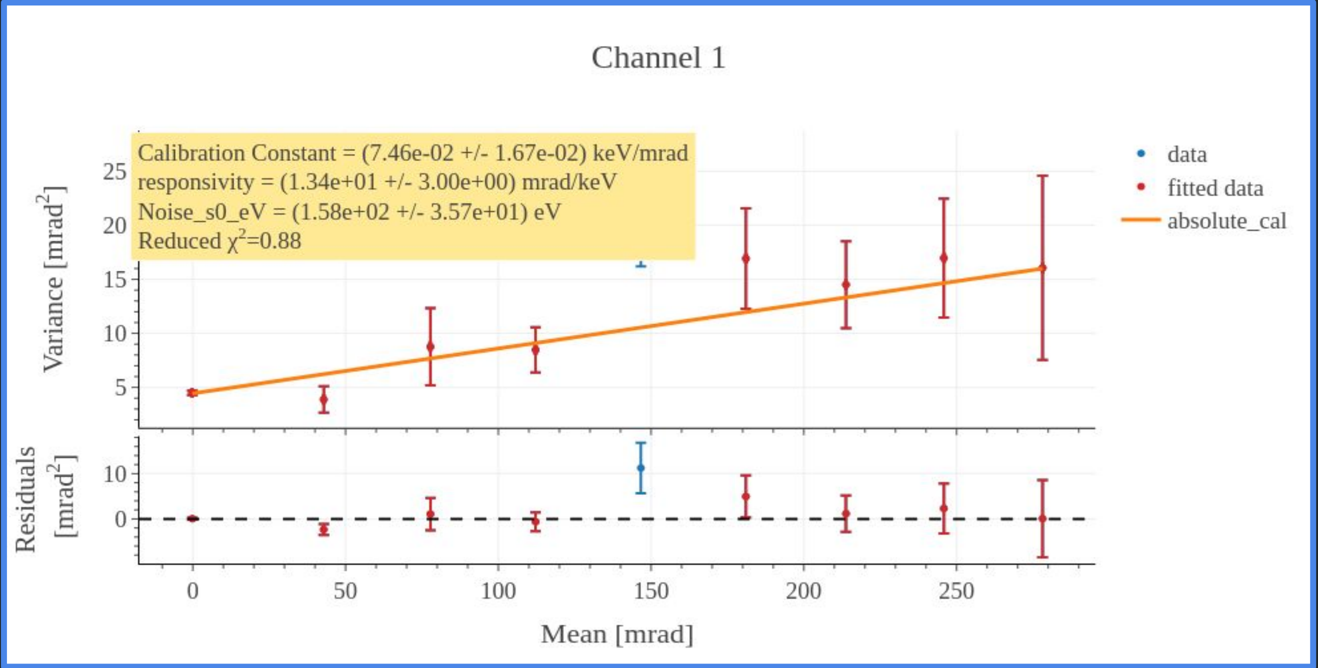








Results - KID LED calibration:



With LED calibration, resolution (pulse tube active) of 0.16±0.03 keV on light incident on light detector

NB: `RMS of noise: 4.38169e+03 [ADC counts]` PT on → `RMS of noise: 1.63138e+03 [ADC counts]` PT off

Factor ~2.7 reduction in σ_{Noise} with pulse tube off

Results - full setup spectrum

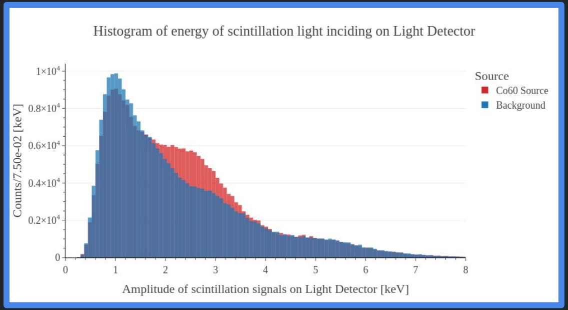
Co60:
2 peaks:

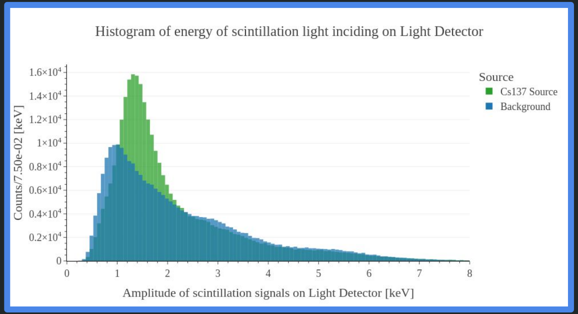
1173.2 keV

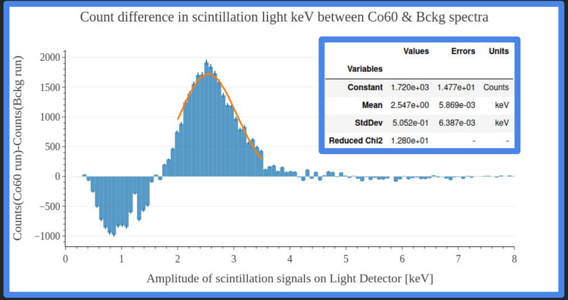
1332.5 keV

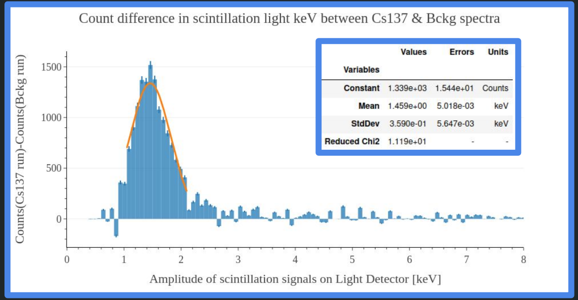
➜ Relative amplitude: < 15%

➜ Average energy: 1252.9 keV









Cs137:
single peak:

661.7 keV

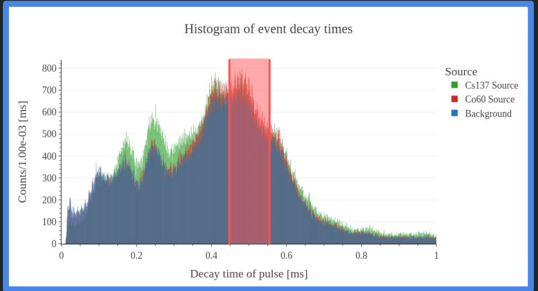
➜ 57% of average energy of Co60

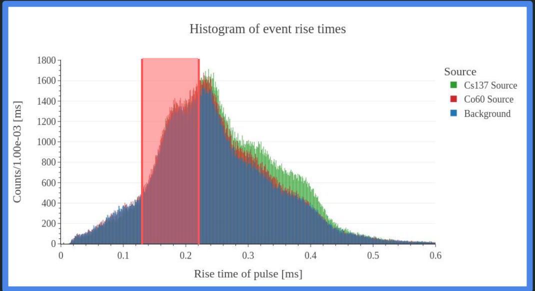
➜ Here, 53% of peak amplitude

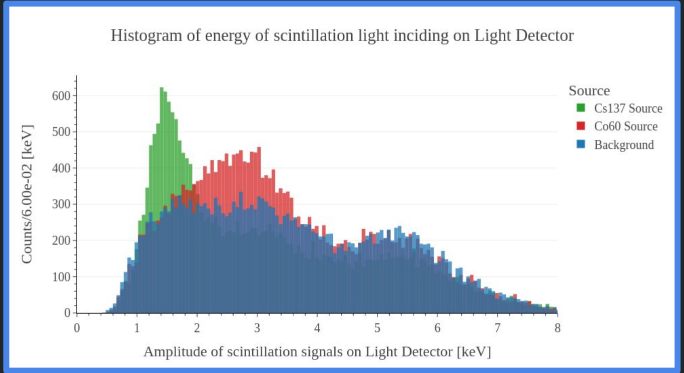
However, StdDev of peaks > $2\sigma_0$

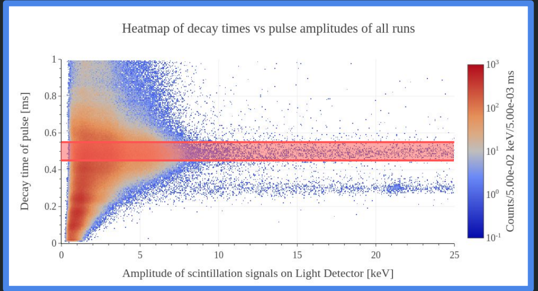
Results - full setup spectrum - cuts

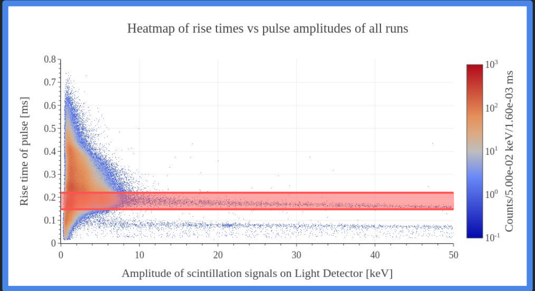
With very stringent cuts on pulse shape parameters, a resolution close to what is expected (0.23 keV vs 0.16±0.03 keV) is recovered for Cs137 (Co60 forms 2 overlapping peaks, cannot be differentiated due to poor statistics)

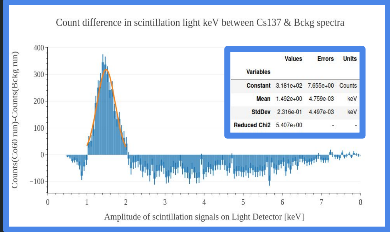


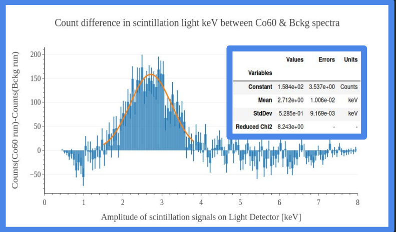








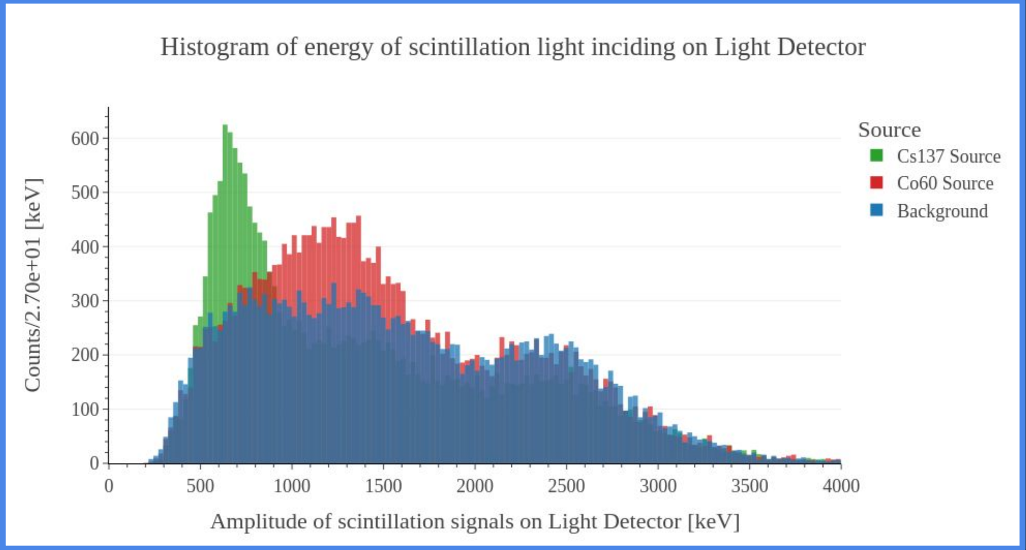


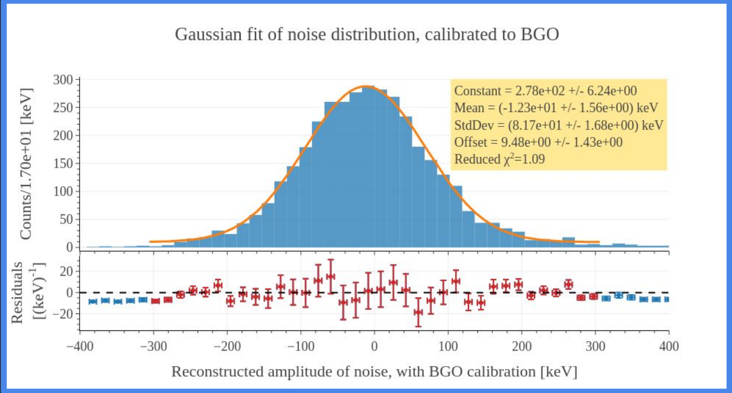


Results - full setup spectrum - BGO calibration

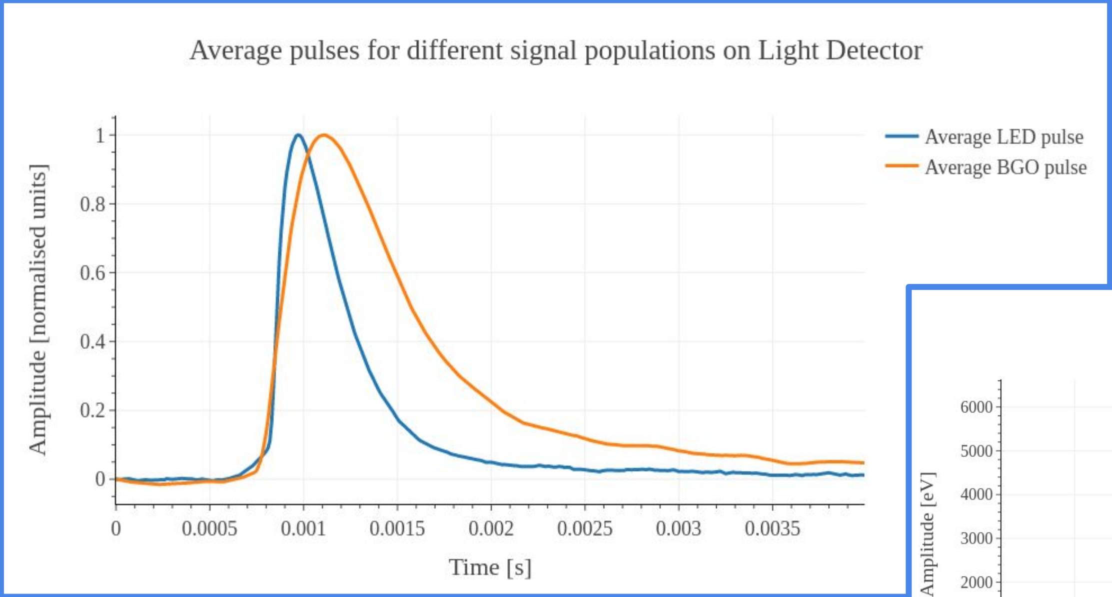
Using Co60 mean to calculate a Light Yield calibration constant (value of 2.1±0.6 keV/MeV), we find a noise resolution of 81.7 keV, meaning for a 3σ veto threshold: 245.1 keV.

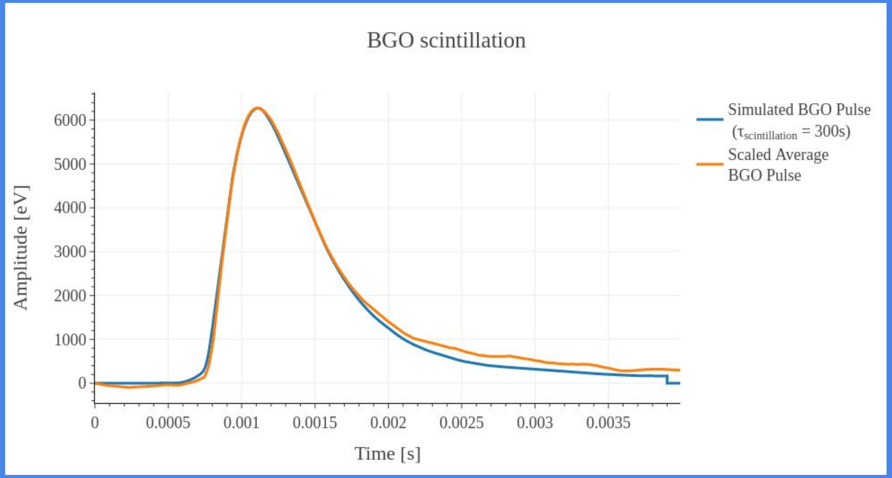
Notably, the Light Yield is much lower than literature values, and can probably be raised.





Light Yield loss - pulse timing mismatch:



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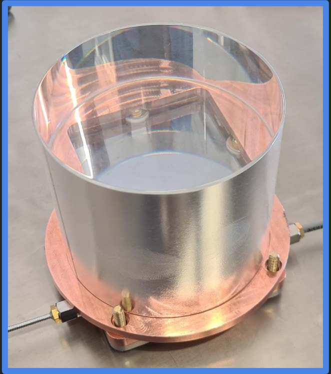
For Cs137 γ (662keV), assuming Light Yield from Cardani et. al.
Energy yielded by scintillator: 11.0±0.013 keV
Average amplitude of simulated detector pulse: 5.97±0.06 keV
Ratio of average simulated pulse amplitude to energy yielded: 0.541±0.006
```

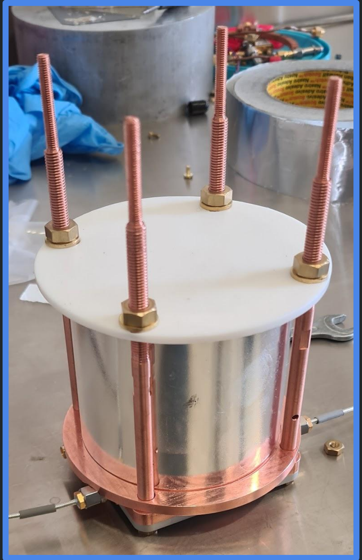
Light Yield loss - Current setup

VM2000-like reflective tape is used to enhance reflection on the sides of the crystal

The copper holder, about 45% of the lower face, is left bare to allow for better thermalisation of BGO.

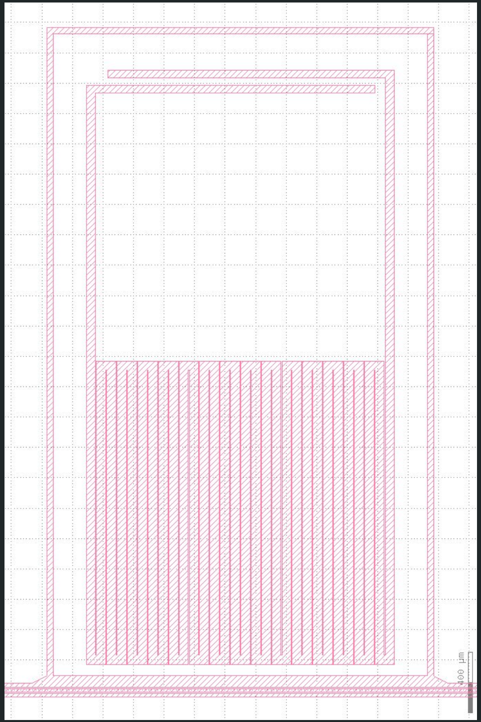
This could cause significant L.Y. loss (up to almost a factor 2), which could be counteracted.



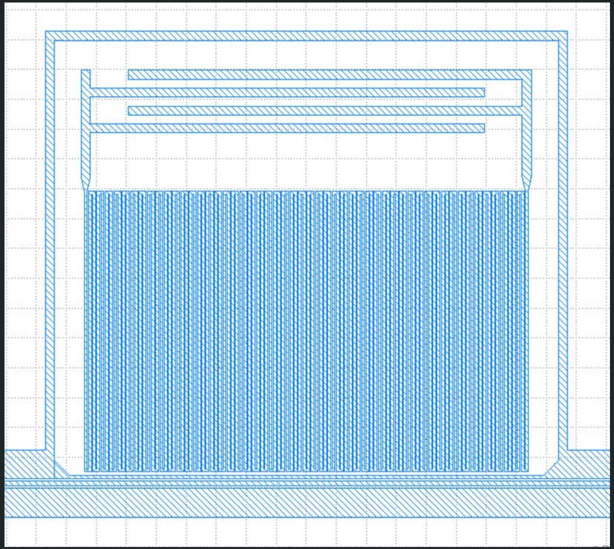


Similarly, the upper face is held in place with bare PTFE, which might be made more reflective.

Next steps - adapting light detector design

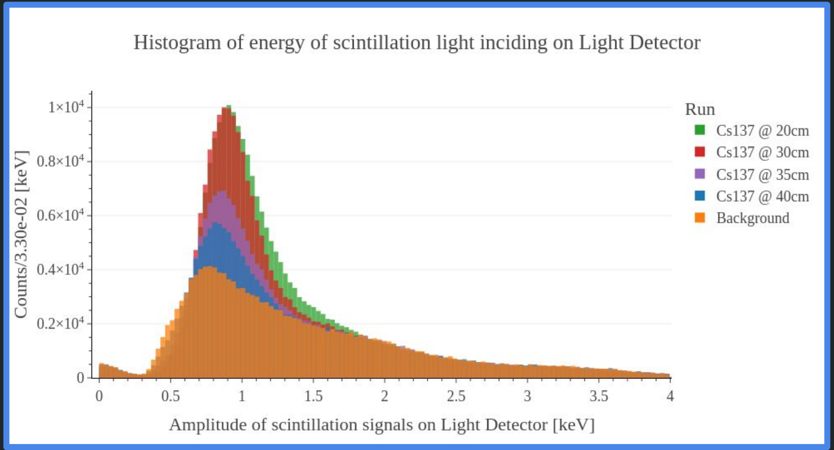


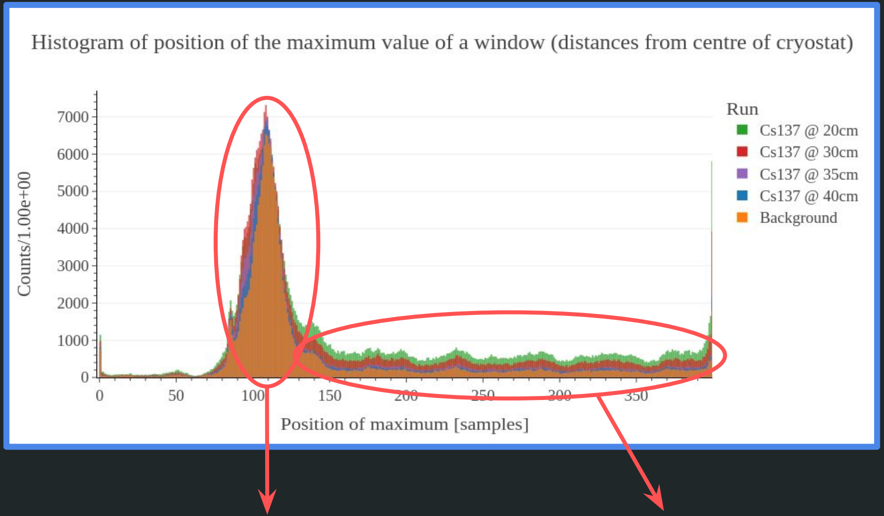
Moving from an old CALDER resonator (t_{decay}~0.3ms) to a slower BULLKID-like resonator (t_{decay}~2ms) should recover the amplitude lost due to timing mismatch.



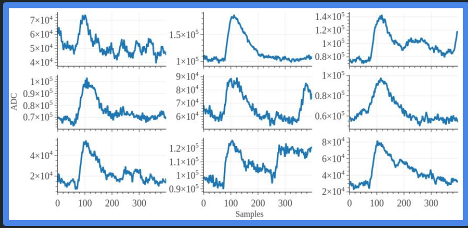
The design constraints of BULLKID resonators ≠ veto Light Detectors
➔ Can iterate on resonator design to further improve threshold.

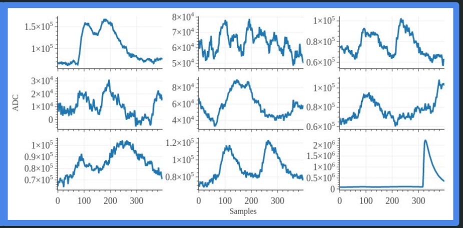
Next steps - Lower background rate further





Rate of background is still very high ➔ pileups might contribute to distortion of spectrum/pulse shape (still to be investigated)





Try to understand through analysis, and measuring with a BGO crystal with a smaller volume (currently using a 7.62cm [3in] diam. x 7.62cm tall crystal), INFN Pisa will loan a smaller crystal.

Next steps - alternative crystals

BGO		PWO		GSO	
Density [g/cm^3]	7.13	Density [g/cm^3]	8.28	Density [g/cm^3]	6.7
Scintillation @ 300K [% NaI(Tl)]	20	Scintillation @ 300K [% NaI(Tl)]	1	Scintillation @ 300K [% NaI(Tl)]	20
				Much higher neutron σ than the others, however possible magnetic properties could interfere with KID operation.	

Conclusion - current status

- The light detector in use has a resolution of 0.16±0.03 keV (/ ~2.7 if pulse tube off or decoupled)
- The BGO+KID setup has successfully measured peaks of known particle energy overlaid on radiogenic background.
- Noise σ of the combined setup is 81.7 ±1.7 keV, meaning a vetoing threshold of 3σ of 245.1 keV.
- Light Yield of BGO scintillator is 2.1±0.6 keV/MeV, much lower than literature's 16.67 keV/MeV
- Distortions in pulse shape at low energies ➔ resolution on radioactive source peaks was much worse than expected.
- Expected spectrum can be recovered with tighter cuts on pulse shape, but efficiency on such cuts is low.
- Timing mismatch between scintillator and light detector leads to an important (×2) loss of signal amplitude.
- Current setup might lead to loss of scintillation light due to poor reflectivity (×2?)

Conclusion - next steps

- Smaller crystal, to lower background rate, will show if too high rate, causing pileups, is the reason for pulse shape distortion.
- Internal reflectivity of setup will be improved to recover as much light as possible.
- Switch from CALDER resonator to BULLKID-style should lead to a nearly doubled SNR simply from timing changes, before accounting for other improvements in design.
- Future iteration on the design of the Light Detector resonator could further improve threshold.
- Different crystals can be investigated for advantageous properties.

Thank you for your time

References:

- [1]: Cardani, L., Di Domizio, S., Gironi, L. "A BGO scintillating bolometer for γ and α spectroscopy". *JINST* **7**, P10022 (2012). https://doi.org/10.1088/1748-0221/7/10/P10022
- [2]: Gironnet, J., Mikhailik, V. B., Kraus, H., de Marcillac, P., & Coron, N. (2008). "Scintillation studies of Bi4Ge3O12 (BGO) down to a temperature of 6K". *Nuclear Instruments and Methods in Physics Research Section A*, **594**(3), p358–361. https://doi.org/https://doi.org/10.1016/j.nima.2008.07.008
- [3]: A. Cruciani, L. Bandiera, M. Calvo, N. Casali, I. Colantoni, G. Del Castello, M. del Gallo Roccagiovine, D. Delicato, M. Giammei, V. Guidi, J. Goupy, V. Pettinacci, G. Pettinari, M. Romagnoni, M. Tamisari, A. Mazzolari, A. Monfardini, M. Vignati; "BULLKID: Monolithic array of particle absorbers sensed by kinetic inductance detectors". *Appl. Phys. Lett.* 21/11/2022; **121** (21): 213504. https://doi.org/10.1063/5.0128723
- [4]: Cardani, L., Casali, N., Colantoni, I. *et al.* Final results of CALDER: kinetic inductance light detectors to search for rare events. *Eur. Phys. J. C* **81**, 636 (2021). https://doi.org/10.1140/epjc/s10052-021-09454-5.