



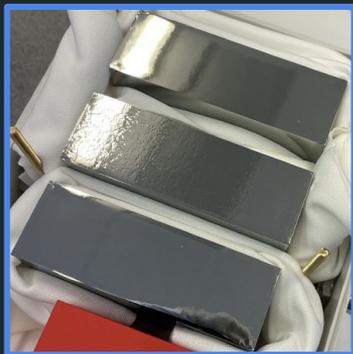
INFN

Cryogenic BGO-KID veto

Update on the analysis of the latest run

Concept

A Simpler, Cheaper Veto



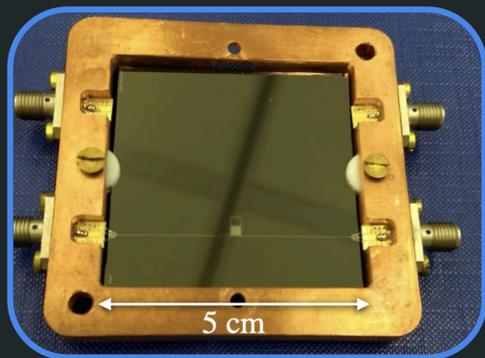
HPGe:

- Complex manufacturing
- Complex readout
- Slow (Charge drift)



BGO:

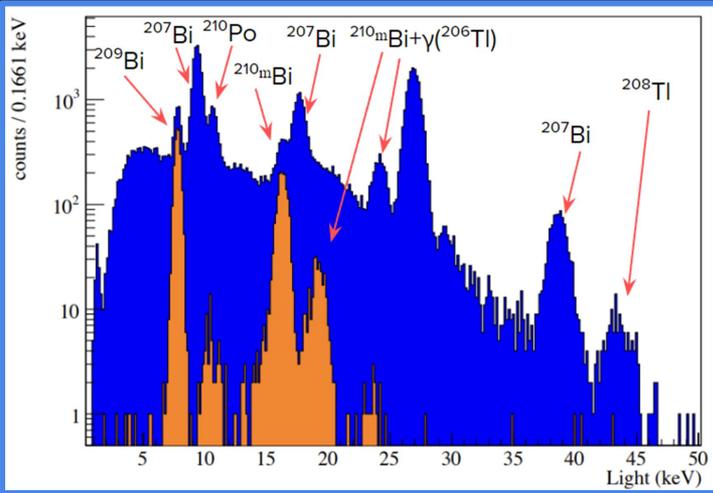
- Denser
 - Mass produced in industry
- Light readouts usually limit utility



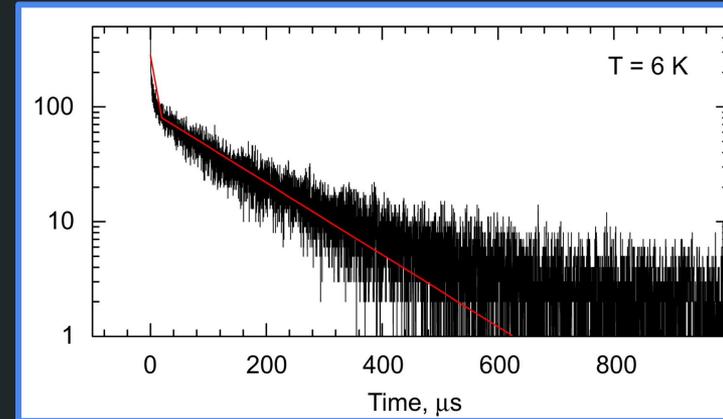
→ Kinetic Inductance Detector - based light readout:

- Very low threshold
- Fast response
- Simple readout (Homogeneous det.)
- Naturally multiplexable
- Easy and cheap to iterate upon

BGO - scintillating crystal

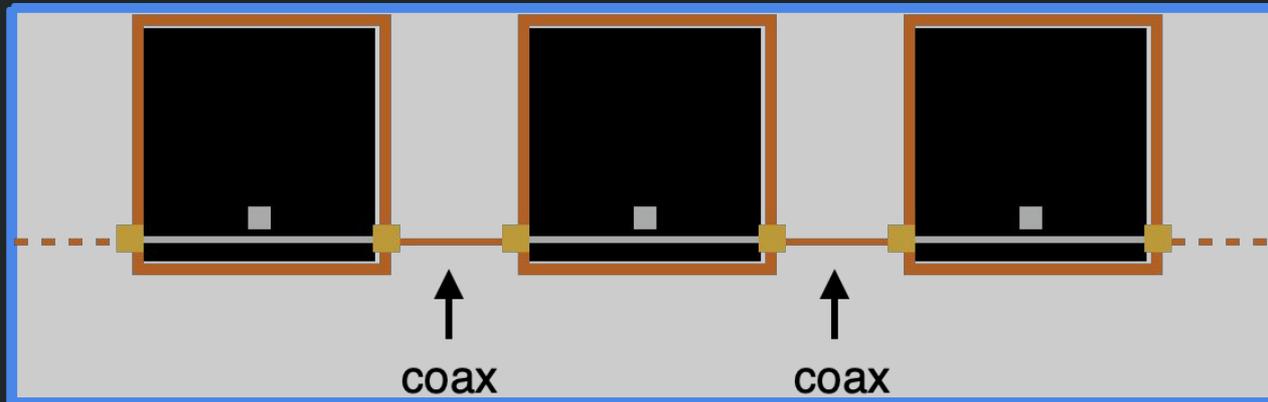


BGO below 6K has an energy to light conversion rate of 16.62 keV/MeV [1]



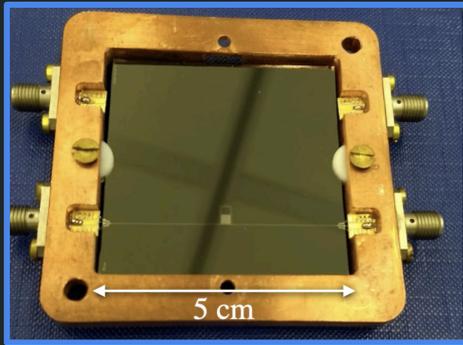
KID - Cryogenic light detector

- Ease of readout: KID readout and analysis can be conducted effectively with the same electronics as the central experiment [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.

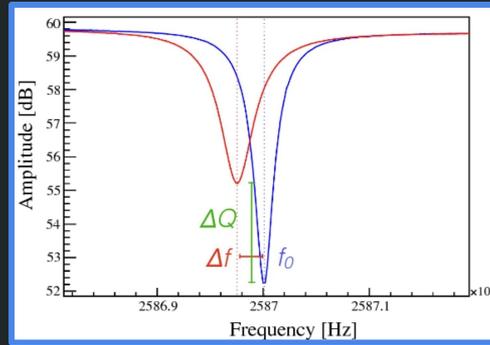


KID - Cryogenic light detector

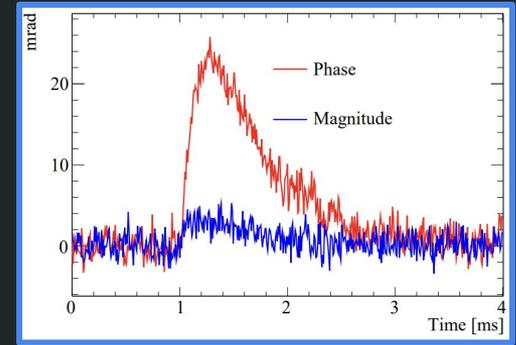
- In-group expertise of KID fabrication and data analysis, the demonstrator light readout chip has also already been characterised [4].
- The CALDER experiment managed to obtain excellent resolution (34eV noise RMS with Pulse Tube vibration decoupling systems, currently present in NUCLEUS), and a fast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



Detector chip with 1 KID deposited on a 25 cm² 650 μ m thick substrate [4].



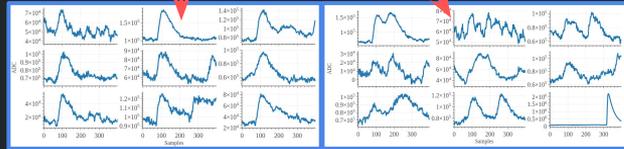
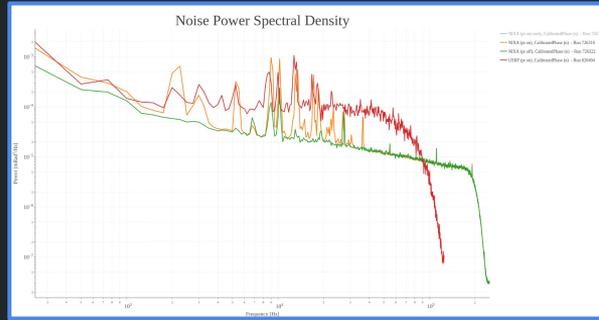
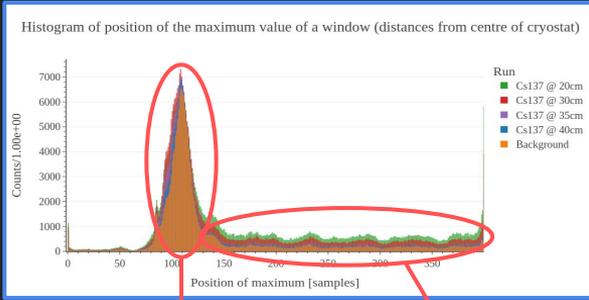
Resonance of a KID at steady state and when perturbed by a phonon-mediated signal [4].



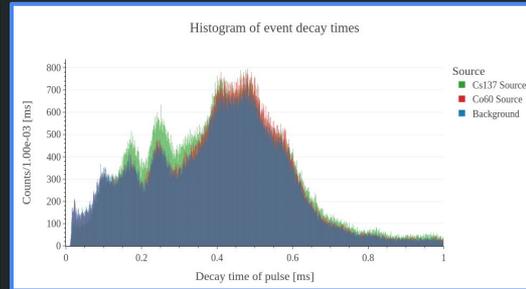
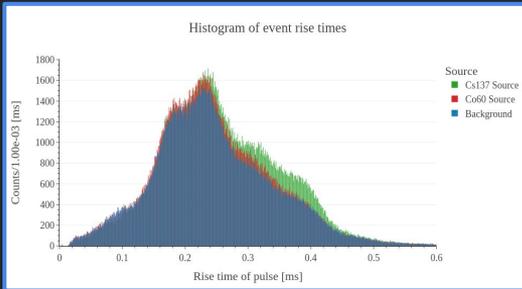
Triggered 1.3 keV signal in the phase (red) and amplitude (blue) directions [4].

Status of the project

Previous status:



label	RMS [mRad]
NIXA (pt on)	2.17
NIXA (pt off)	1.62
USRP (pt on)	2.87

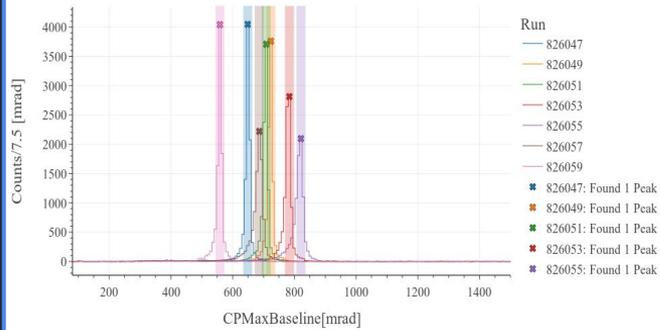


NIXA DAQ I/Q RF Mixers:
0.5 - 2 GHz

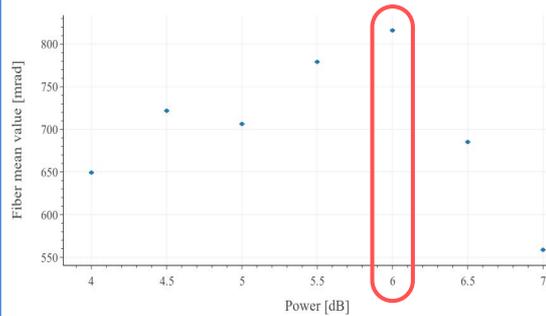
CALDER resonance:
2.33 GHz

Power Scan

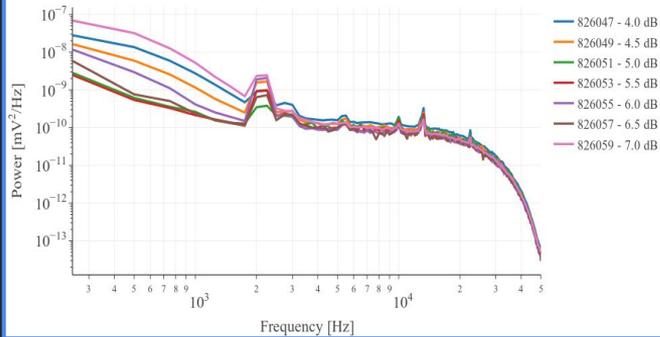
Peak Finding



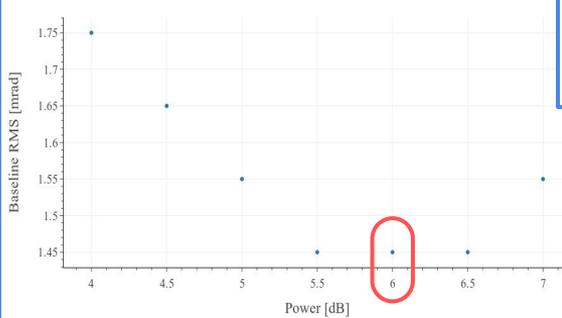
Signal amplitude



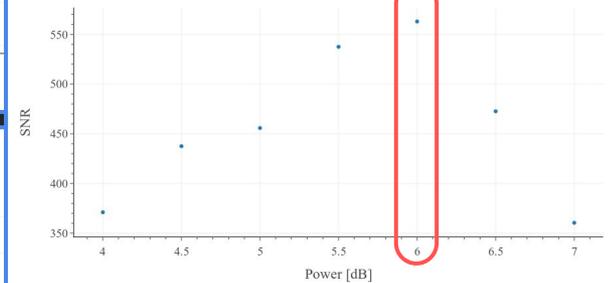
Average noise power spectrum of channel 1



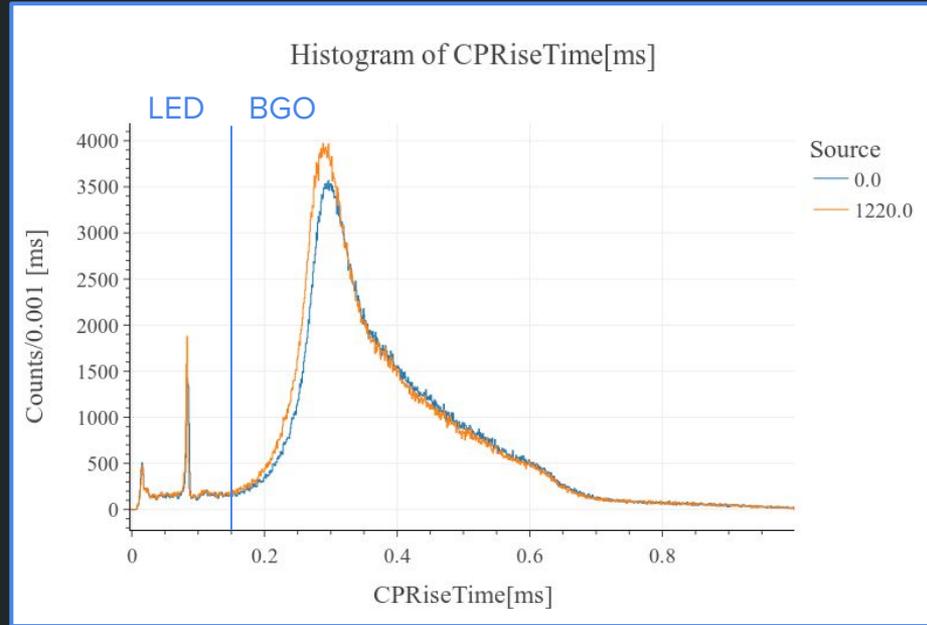
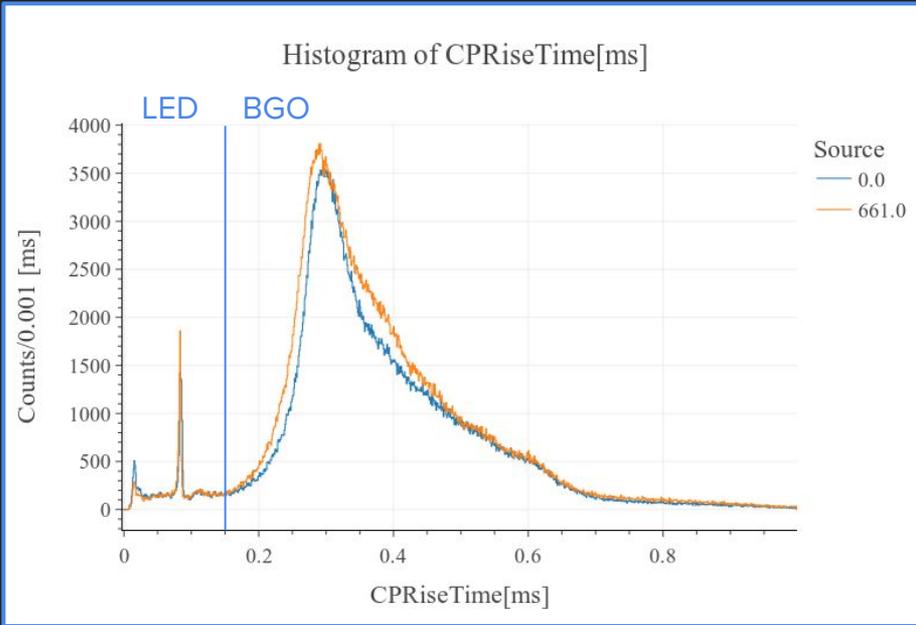
Root mean square of baseline of signals



Signal to Noise ratio, based on RMS

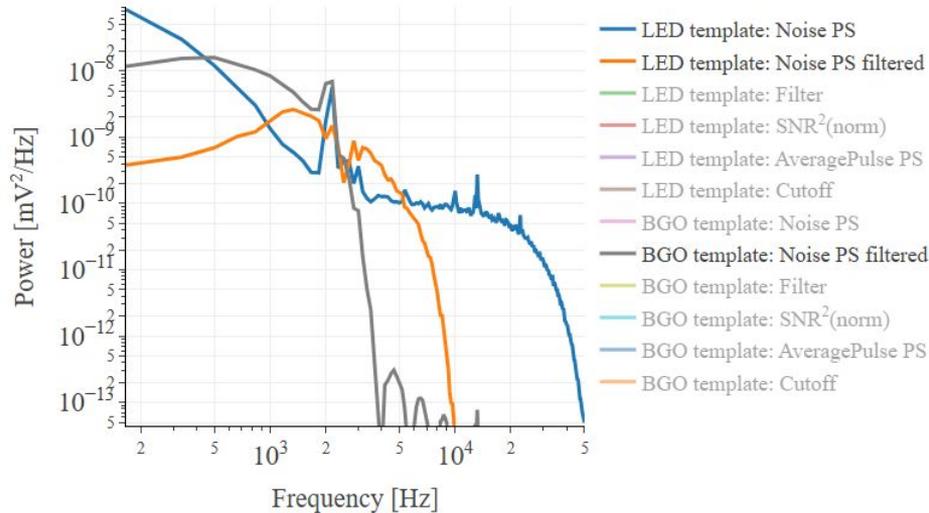


Risetime LED vs BGO

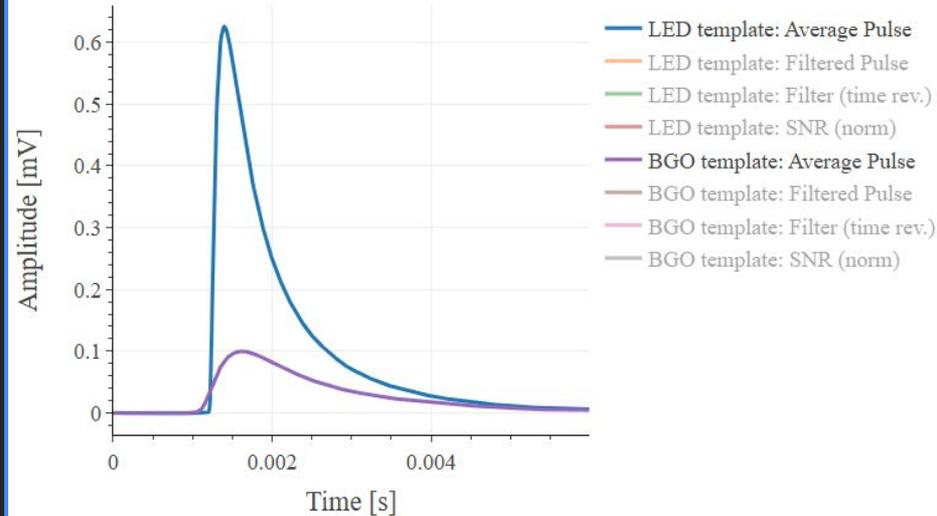


Optimum Filter

Average noise power spectrum of channel 1 (CalibratedPhase)



Average pulse of channel 1 (CalibratedPhase)



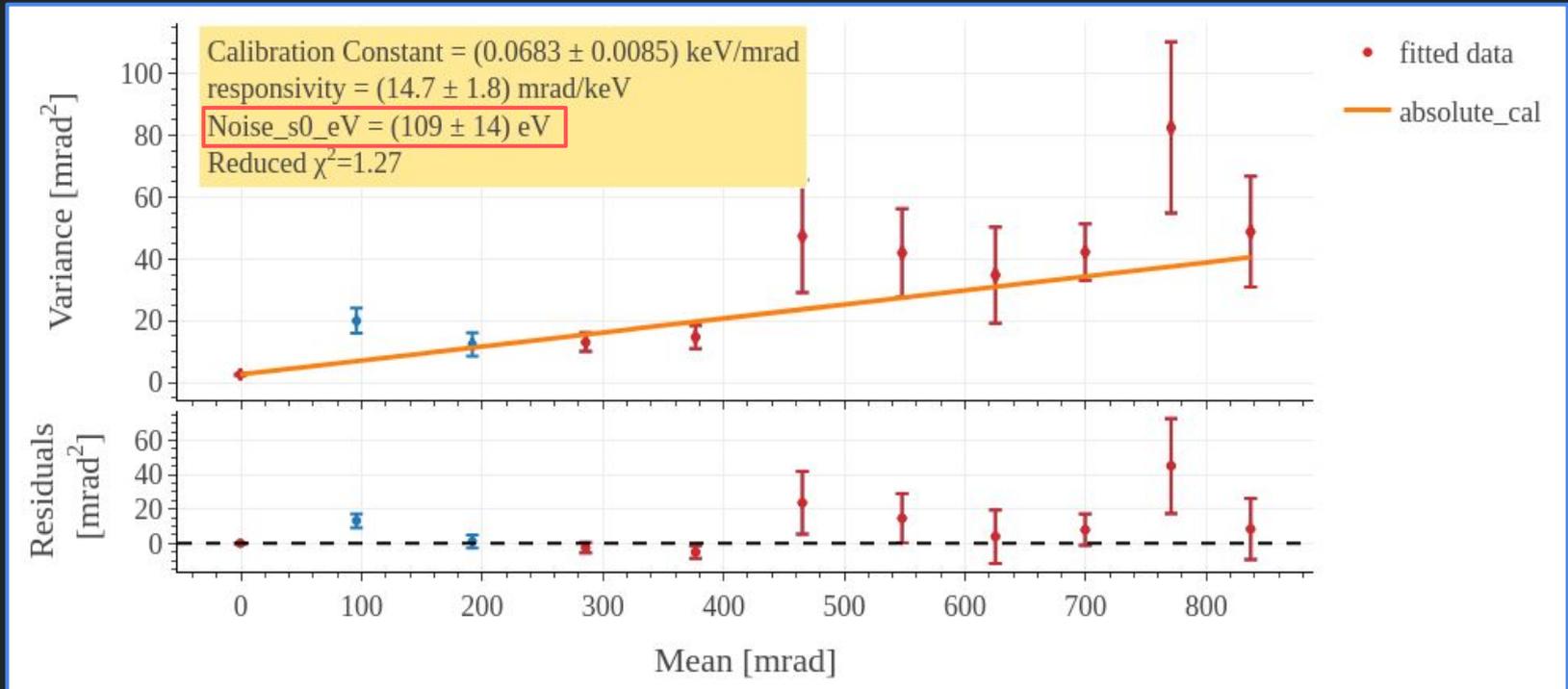
LED:

RMS of original noise:	5.13502e+03 [ADC counts]
RMS of filtered noise:	2.11981e+03 [ADC counts]
SNR after the filter:	2.94853e+02 [mV/mV]

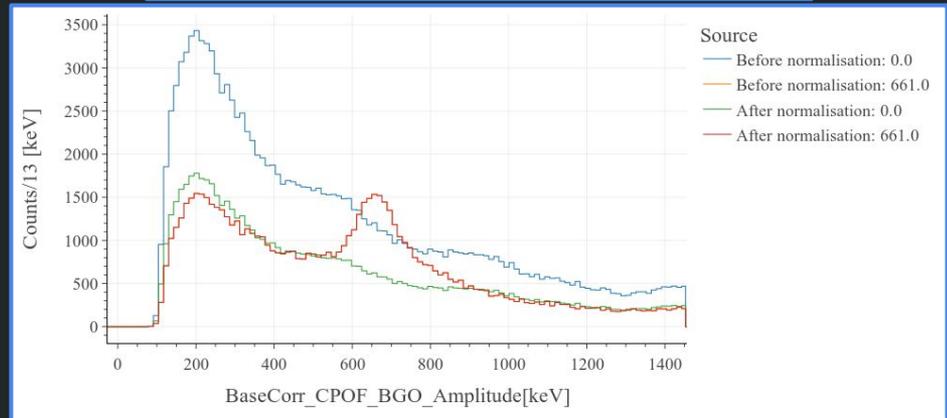
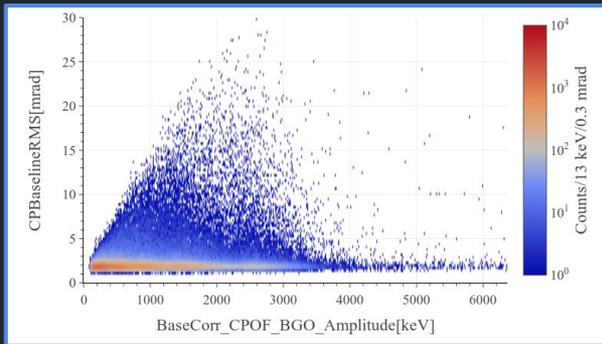
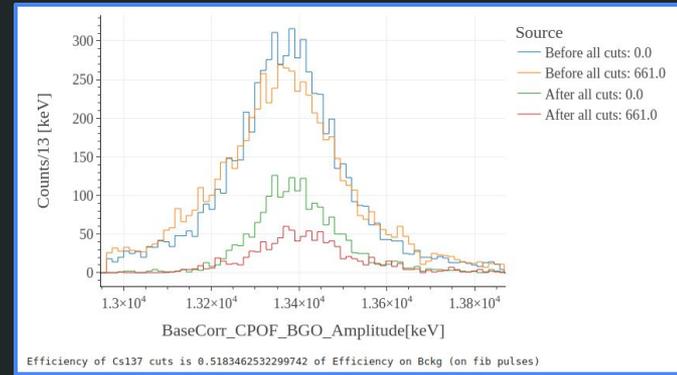
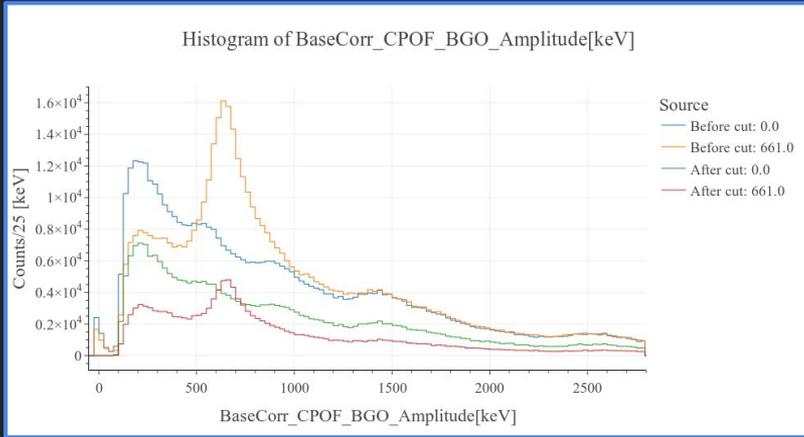
BGO:

RMS of original noise:	5.13502e+03 [ADC counts]
RMS of filtered noise:	4.25821e+03 [ADC counts]
SNR after the filter:	2.34153e+01 [mV/mV]

CALDER LED calibration

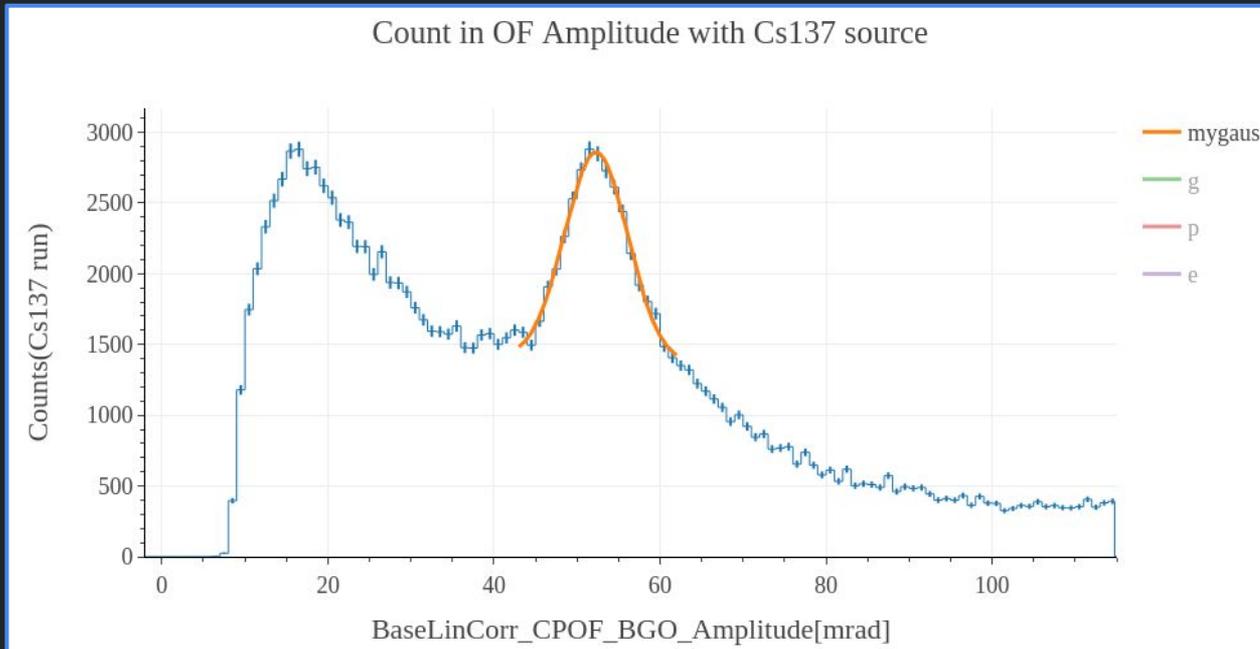


Pileups



Cs137

Cs137 → 1 peak: 662 keV, high rate, used for calibration on γ



Variables	Values	Errors	Units
Constant	1.471e+03	3.651e+01	-
Mean	5.231e+01	8.411e-02	mrad
StdDev	3.800e+00	1.392e-01	mrad

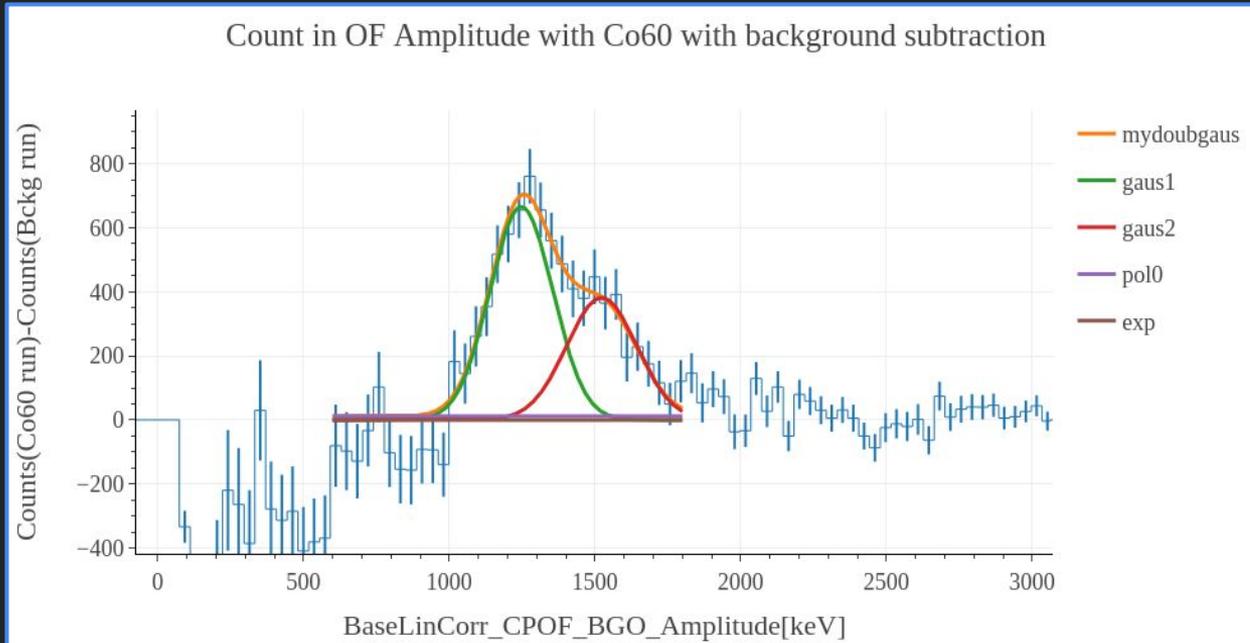
$$\begin{aligned}\text{Calib} &= 662 \text{ keV}_\gamma / 52.31 \text{ mrad} \\ &= 12.66 \text{ keV}_\gamma/\text{mrad}\end{aligned}$$

$$\sigma_{\text{rel}} = 3.8/52.31 = 7.3\%$$

$$\begin{aligned}\text{LY} &= 56 \text{ eV}_{\text{LED}} / 12.66 \text{ keV}_\gamma \\ &= 4.47 \text{ keV}/\text{MeV} \\ &\rightarrow \text{Unchanged}\end{aligned}$$

Co60

Co60 → 2 peaks: 1121 keV & 1332 keV, small rate, region of ^{40}K peak
→ Subtract bckg spectrum to fit double gaussian:



Variables	Values	Errors	Units
Constant	1.802e+05	1.301e+00	-
Mean	1.247e+03	1.150e+00	keV
StdDev	1.080e+02	1.518e+00	keV
IntensityRatio	5.825e-01	1.645e-02	-
MeanRatio	1.221e+00	3.096e-03	-
StdDevRatio	9.121e-01	2.887e-02	-

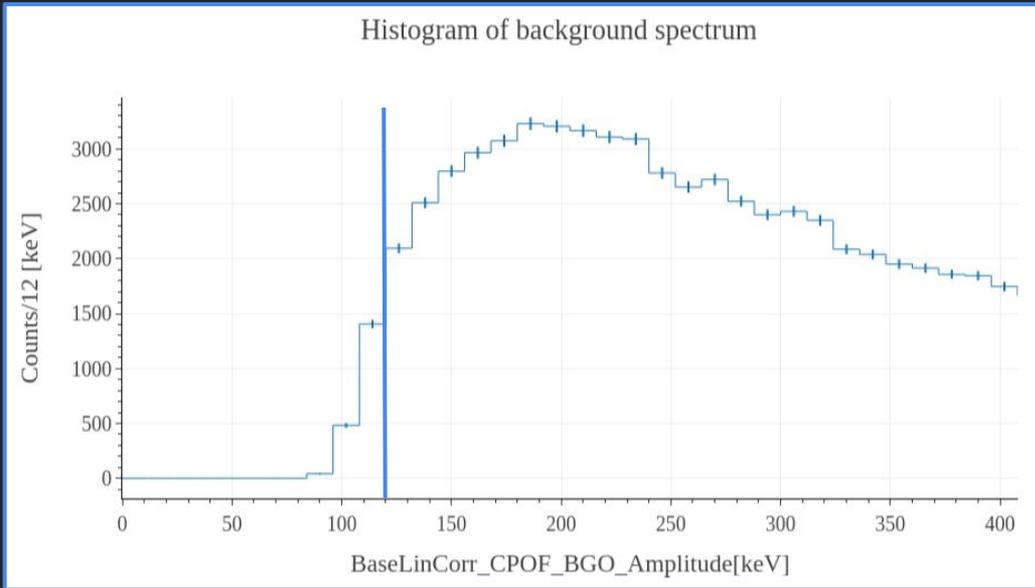
1st peak Mean: 110% of expected value

Peak mean ratio: Compatible with expected value

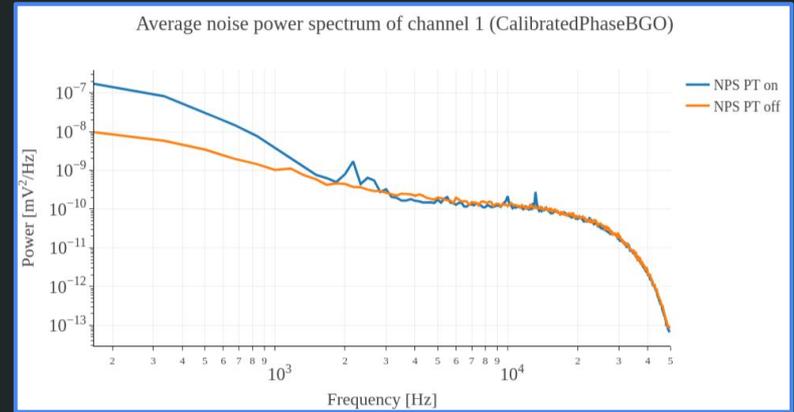
$$\sigma_{\text{rel}} = 8.62\%$$

Threshold

Theoretically: $5\sigma = 5 * 109 \text{ eV} / 4.47 \text{ keV/MeV}$
= 121.9 keV



→ Still presenting PT-related noise effects:

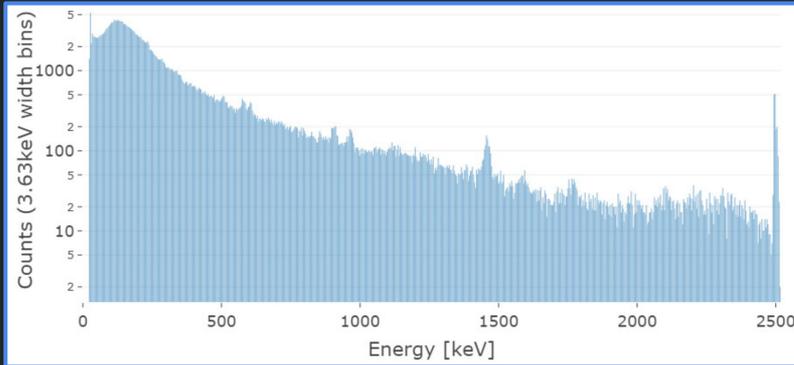


	PT ON:	PT OFF:
RMS of original noise:	7.47766e+03 [ADC counts]	2.73276e+03 [ADC counts]
RMS of filtered noise:	6.21700e+03 [ADC counts]	2.45485e+03 [ADC counts]
SNR after the filter:	1.60378e+01 [mV/mV]	4.06165e+01 [mV/mV]

→ PT OFF SNR = 2.5 × PT ON SNR

→ Still losing light collection efficiency
due to time mismatch

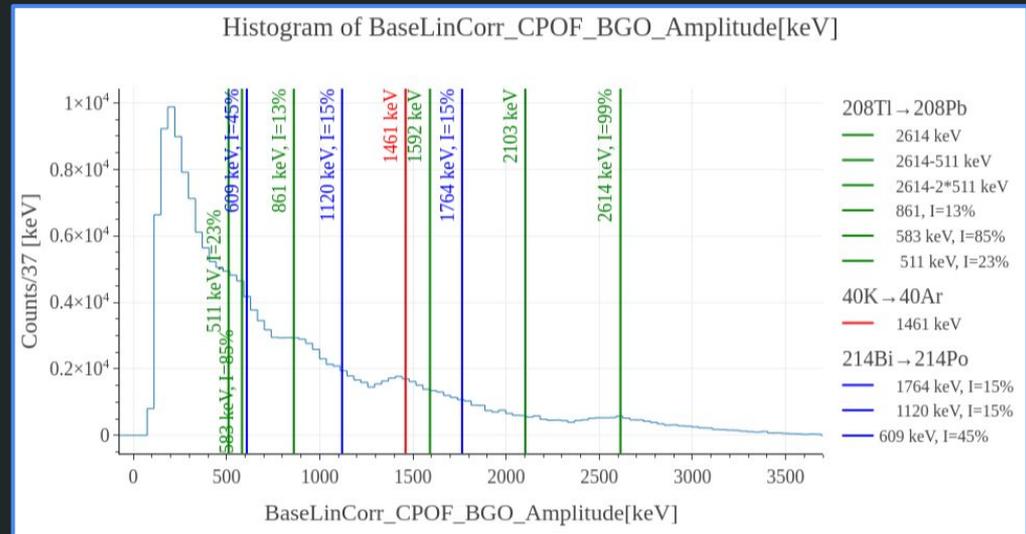
Background - models



Environmental contamination of Rome cryostat: spectrum measured w/ NUCLEUS HPGe COV prototype.

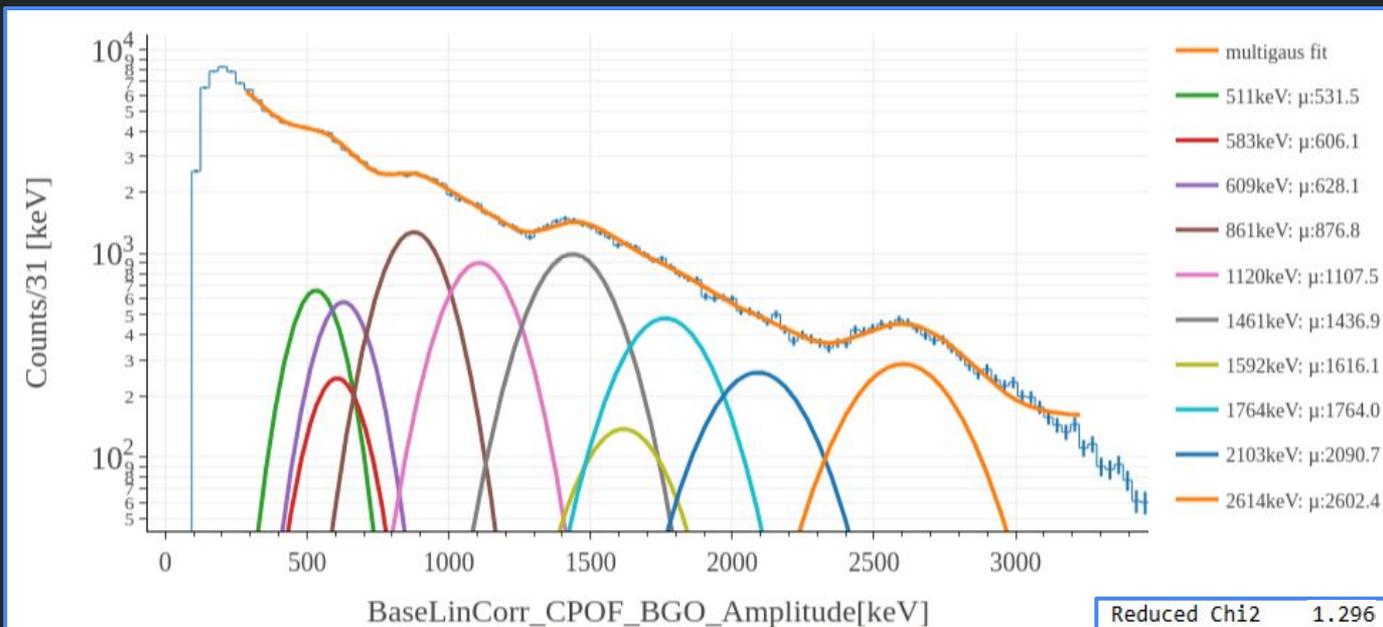
Based on energies, generated by Th decay chain (\rightarrow ^{208}Tl , ^{214}Bi), and ^{40}K .

All lines visible on COV spectrum, plus 2614 keV (^{208}Tl)



Background - fit

Multi-gaussian fit based on background model (gaussians w/ $\sigma^2 = \sigma_0^2 + kE$, $\sigma_0 = 109 \text{ eV} * LY = 24.2 \text{ keV}$)
 Seems to closely fit spectrum \rightarrow Internal contamination sub-dominant.

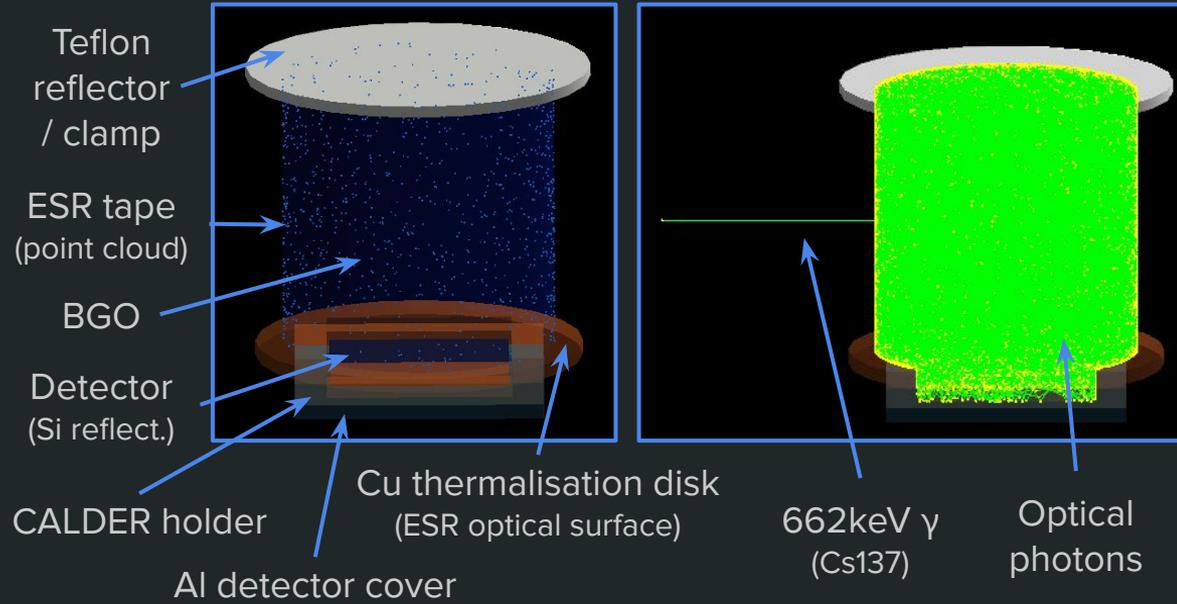


Expected energy [keV]	Fit gaussian mean [keV]	σ_{rel} [%]
511	490±6	17.5±2.7
583	559±30	16.3±8.5
609	633±6	15.3±2.4
861	862±5	13.0±2.3
1120	1086±8	11.5±2.7
1461	1413±7	10.0±2.3
1592	1664±2	9.22±1.91
1764	1728±14	9.05±3.51
2103	2068±14	8.25±3.35
2614	2598±7	7.35±2.35

Simulation

Geant4 scintillation simulation:

- Optical photon transport
- All reflectivities from lit.
 - ESR refl.: 0.98
 - Si refl.: ~ 0.4
- BGO optical index: 2.15
- BGO attenuation lengths:
 - λ -dep. L_{att} from [5]
 - $L_{att} = 4m$ ([6])
 - $L_{att} = 1000m$
- BGO scint. time:
 - from [2]
 - $300\mu s$ (from meas. risetime / toy model)

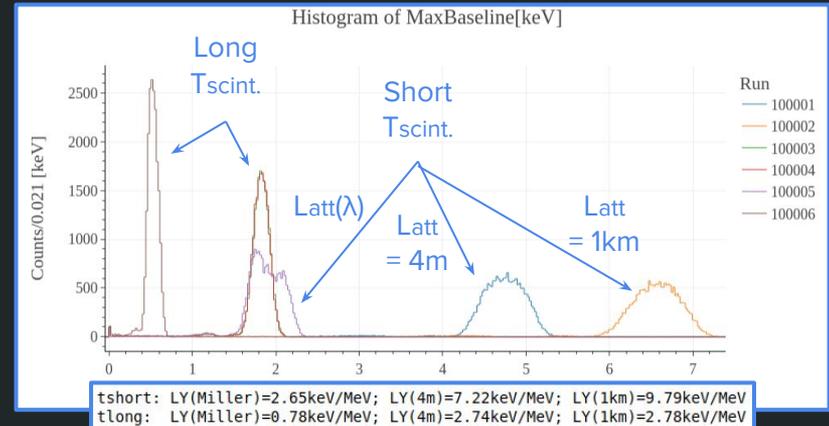
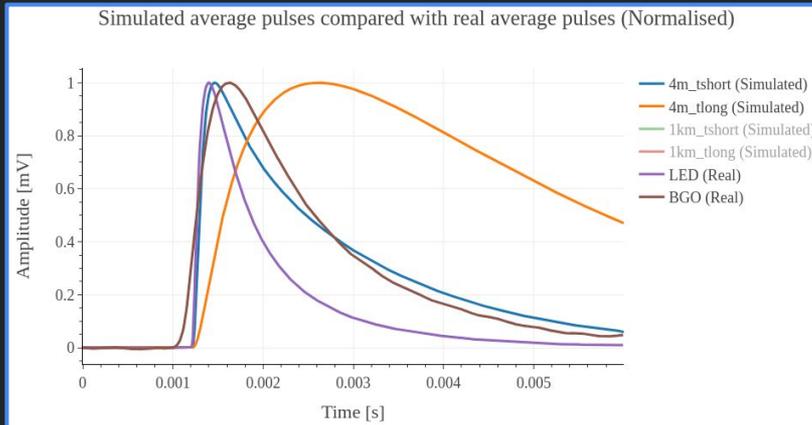


→ Record time & E of photon hits in Si volume (not reflected), then add scaled LED OF template pulses at hit times to form simulated signal. (→ No electronic/KID noise)

Simulation: Light Yield

Simulated 20 000 Cs137 γ events ($E=662\text{keV}$):

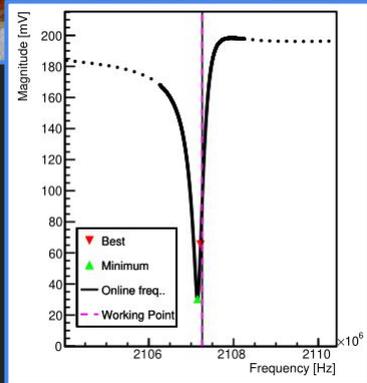
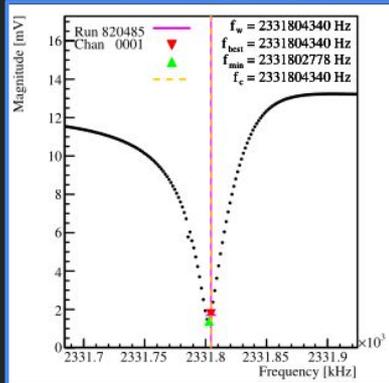
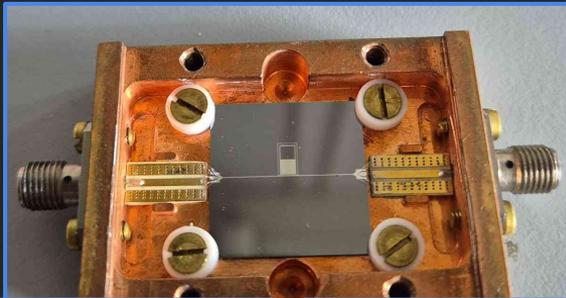
$L_{\text{att}}(\lambda)$ [5]:	Average number of optical photons produced per event: $1.48\text{e}+04 \pm 1.74\text{e}+03$ Average number of optical photons detected per event: $1.49\text{e}+03 \pm 222$	$\gamma_{\text{det}}/\gamma_{\text{tot}}$: 10.1%
$L_{\text{att}} = 4\text{m}$:	Average number of optical photons produced per event: $1.48\text{e}+04 \pm 1.78\text{e}+03$ Average number of optical photons detected per event: $3.57\text{e}+03 \pm 466$	$\gamma_{\text{det}}/\gamma_{\text{tot}}$: 24.1%
$L_{\text{att}} = 1\text{km}$:	Average number of optical photons produced per event: $1.48\text{e}+04 \pm 1.79\text{e}+03$ Average number of optical photons detected per event: $4.93\text{e}+03 \pm 632$	$\gamma_{\text{det}}/\gamma_{\text{tot}}$: 33.3%



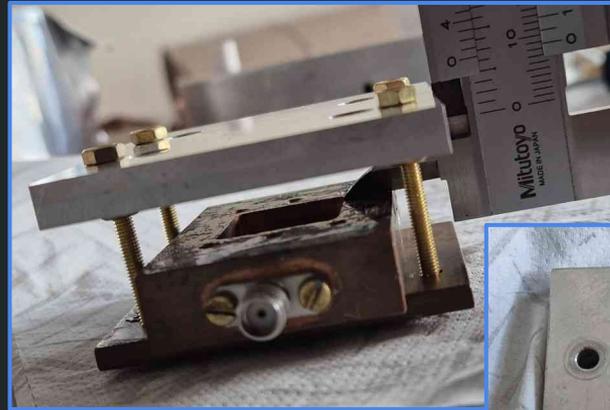
→ BGO scintillation time @O(100mK) still not understood → Light Yield varies noticeably with KID timing and attenuation length

Small crystal testbench

Light detector identification:



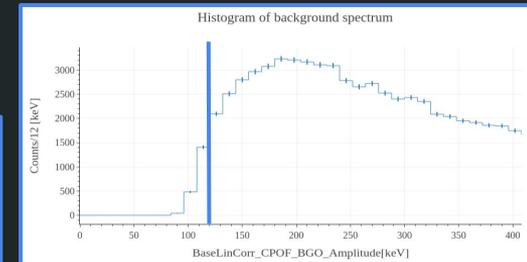
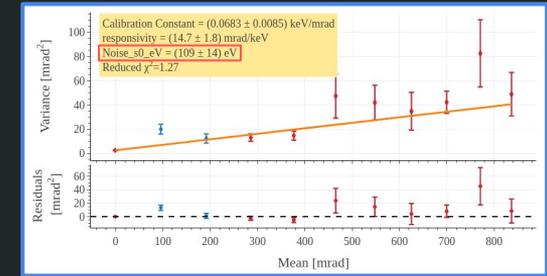
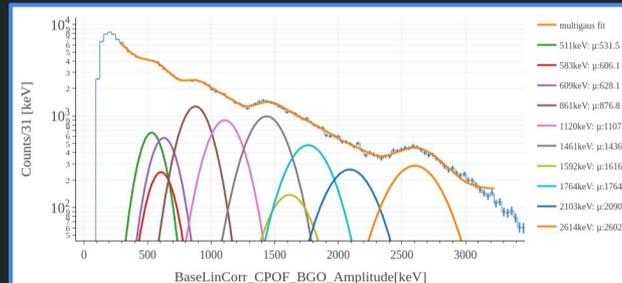
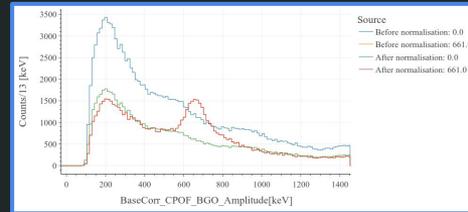
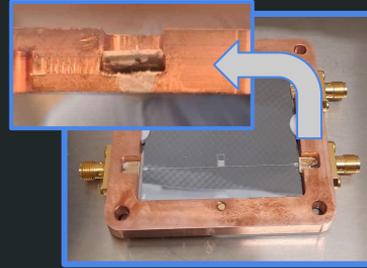
Mechanical setup:



Conclusion

Done:

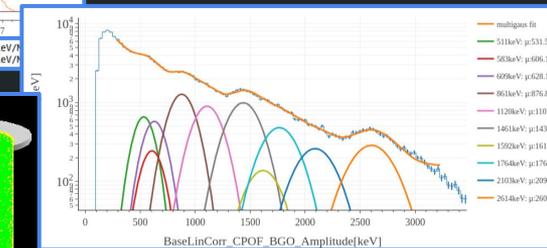
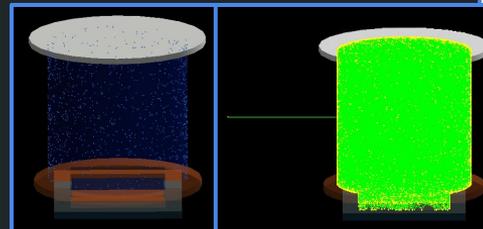
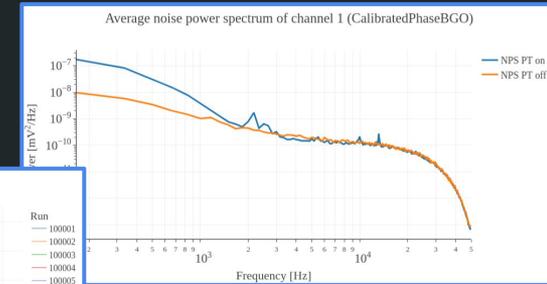
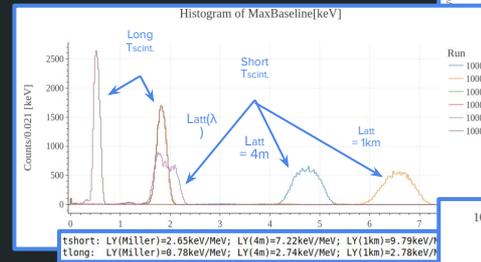
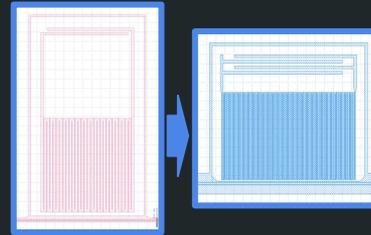
- Identified & corrected sources of strong PT-dependent noise.
- OF-based trigger & analysis.
- Compensation for pileup rate developed.
- 120 keV threshold reached.
- Background in Rome cryostat characterised.



Next steps

To do:

- Production of new BULLKID-design light detectors
- Investigate remaining PT dependence.
- Investigate further discrepancy in LY from Cardani et al.
- Statistical analysis to establish limits on crystal internal contamination
- Dedicated simulations for background validation?



Thank you for your
time

References:

- [1]: Cardani, L., Di Domizio, S., Gironi, L. (2012). “A BGO scintillating bolometer for γ and α spectroscopy”. *JINST* **7**, P10022 . <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 (2022). “BULLKID: Monolithic array of particle absorbers sensed by kinetic inductance detectors”. *Appl. Phys. Lett.*, **121** (p21). <https://doi.org/10.1063/5.0128723>
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- [5]: L. Miller, A. Chapman, K. Auchetl and J. M. C. Brown, (2024). "Material Properties of Popular Radiation Detection Scintillator Crystals for Optical Physics Transport Modelling in Geant4". *IEEE Transactions on Nuclear Science*, <https://doi.org/10.1109/TNS.2024.3517563>
- [6]: M. Sasano, H. Nishioka, K. Hayashi *et al.*, (2013). “Geometry dependence of the light collection efficiency of BGO crystal scintillators read out by avalanche photo diodes”. *Nuclear Instruments and Methods in Physics Research Section A* **715** (p105-111). <https://doi.org/10.1016/j.nima.2013.03.022>.