FCCD Determination of Ge Detectors at HADES

LEGEND Detector Characterisation Meeting
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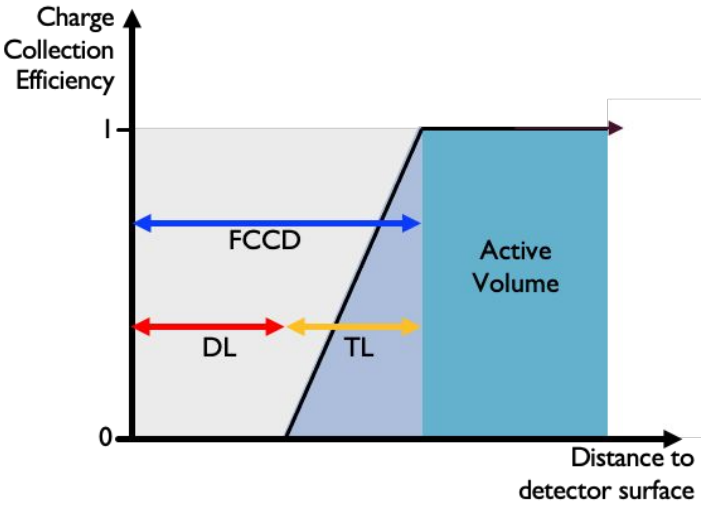
Introduction

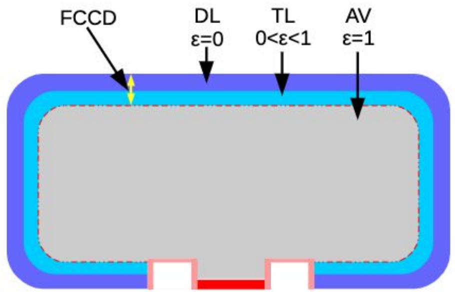
HPGe detectors have a dead layer:

- Dead Layer (DL) = region of no charge collection on surface of semiconductor detectors. A conductive layer, created by Lithium diffusion.
- Transition Layer (TL) = partial charge collection
- Full Charge Collection Depth (FCCD) = TL + DL
    - *NB: TL is ignored at first order such that FCCD=DL*



The DL, and hence active volume, determination is important because:

- The 0νββ half-life is a function of active mass
- Degraded events could mimic 0νββ signature



We estimate the DL empirically by comparing characterisation data of detectors exposed to known radioactive sources with MC simulations

Analysis Flow

Simulations:

g4simple GEANT-4 MC simulations of detector, test stand and radioactive source

DL Post Processing:

Position based weighting and removal of energy deposits to simulate different FCCD values

Analysis:

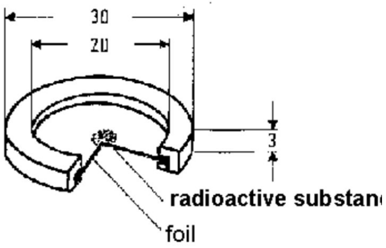
Compare post-processed MC of varying FCCDs with the data by constructing an FCCD sensitive observable: a gamma line count ratio → infer best fit FCCD

Data:

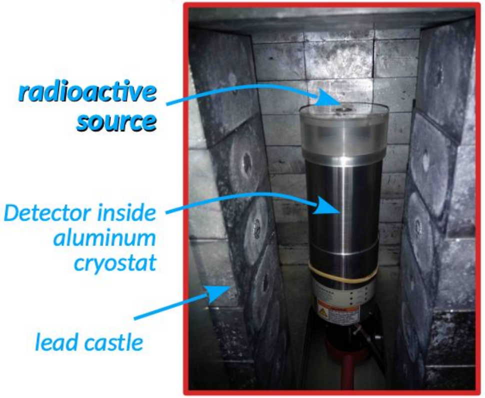
HADES data: detectors exposed to ^{133}Ba and ^{241}Am (low energy spectrum→ FCCD sensitive)

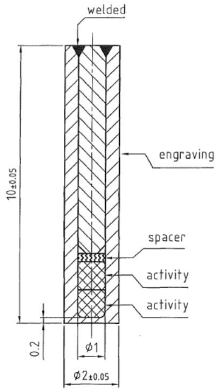
HADES Data

	Source	Activity	Collimated?	Run time	Position	Material
^{33}Ba	ba_HS4	116 kBq	no	30 minutes	Top: 81 and 198 mm	HD1000
^{241}Am	am_HS1	4330 kBq	yes	5-6 hours	Top: <10mm	??
^{241}Am	am_HS6	396 kBq	no	4-5 hours	Top: 198 mm	Acrylic

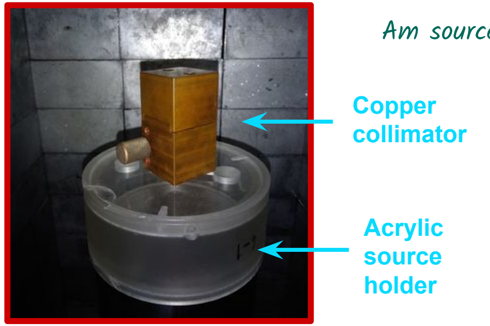


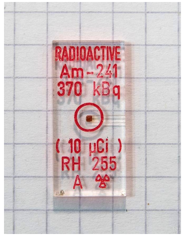
Ba source





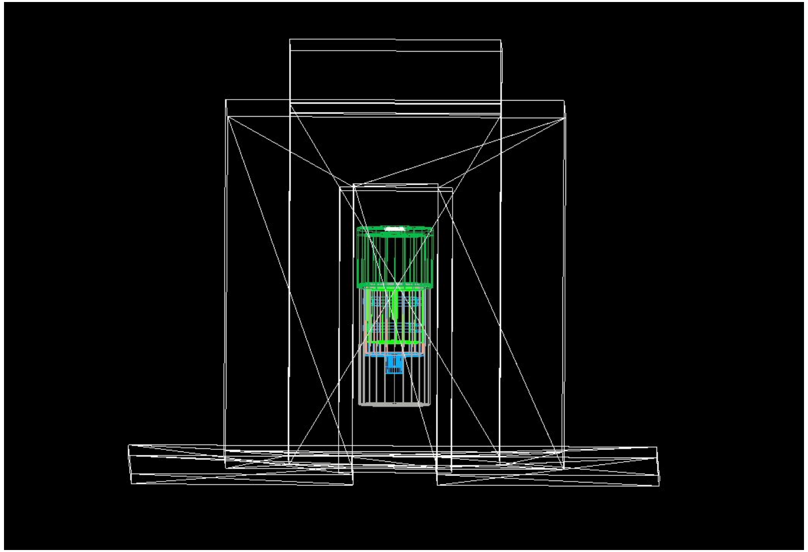
Am source (HS1)





Am source (HS6)

G4simple Simulations



Components to simulate:

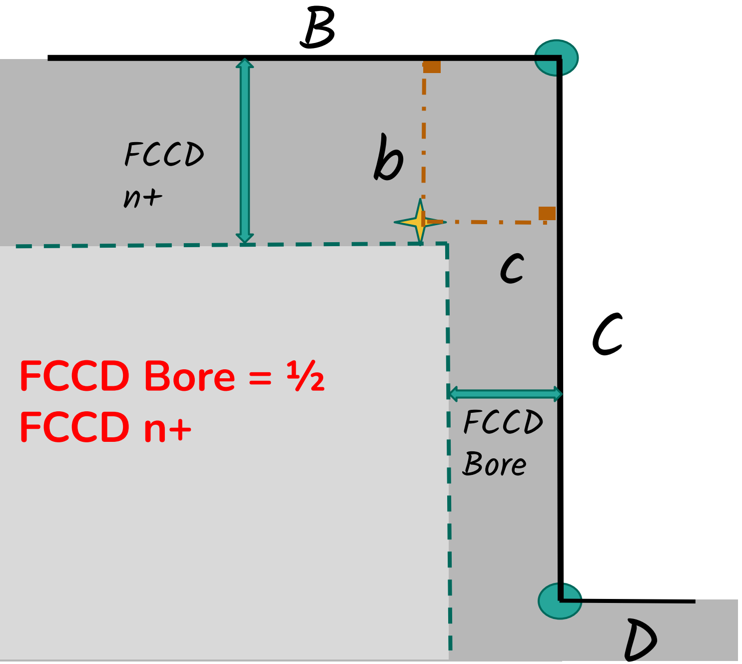
- Lead castle
- Aluminum alloy cryostat
  - Enriched germanium detector
  - Aluminium alloy detector holder
  - HD1000 wrap
  - Mylar foil (for BEGes)
- Acrylic source holder
  - Radioactive source and casing

Automation software **`legend-g4simple-simulation`** used for rapid generation of geometry files and simulations for each new detector

Resources:

- *G4simple github: https://github.com/legend-exp/g4simple*
- *Legend-g4simple-simulation automation Github: https://github.com/legend-exp/legend-g4simple-simulation*
- *G4simple + automation LEGEND software tutorial: https://indico.legend-exp.org/event/561/*

Post-Processing



This is also handled in the automation software `legend-g4simple-simulation`

Post-Processing:

1. FCCD post processing on raw energy depositions
2. Sum of energy depositions to build event energies
3. Gaussian resolution smearing

A. Takes the minimum distance between the event point and each vector of **n+**

B. Gets the '*ChargeCollectionEfficiency*' for this distance, considering a step function for the FCCD, so it can be equal to 0 or 1

C. Does the same for the minimum distance between the event point and each vector of the **bore**

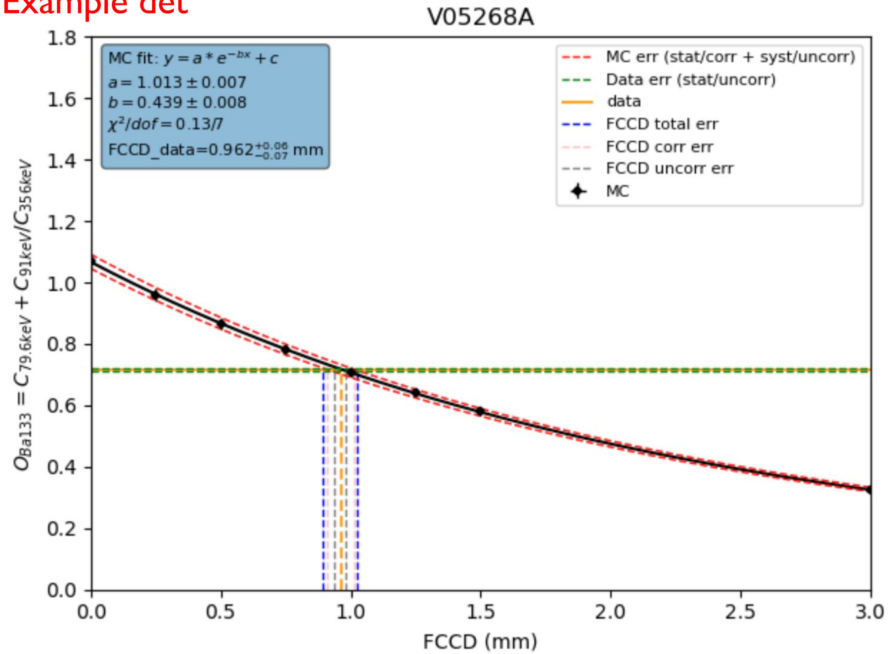
D. Returns the minimum of the two '*ChargeCollectionEfficiency*' values to be then multiplied by the energy deposited by the event

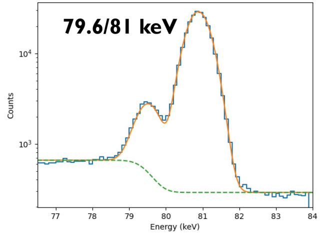
In the drawing, the minimum distance is **c** but, actually, the code returns the 'efficiency' of the distance **b** which is 0.

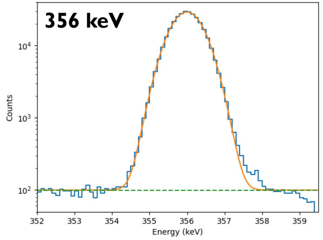
Analysis: ^{133}Ba

$$O_{133\mathrm{Ba}} = \frac{C_{79.6\,\mathrm{keV}} + C_{81.0\,\mathrm{keV}}}{C_{356.0\,\mathrm{keV}}}$$

Example det

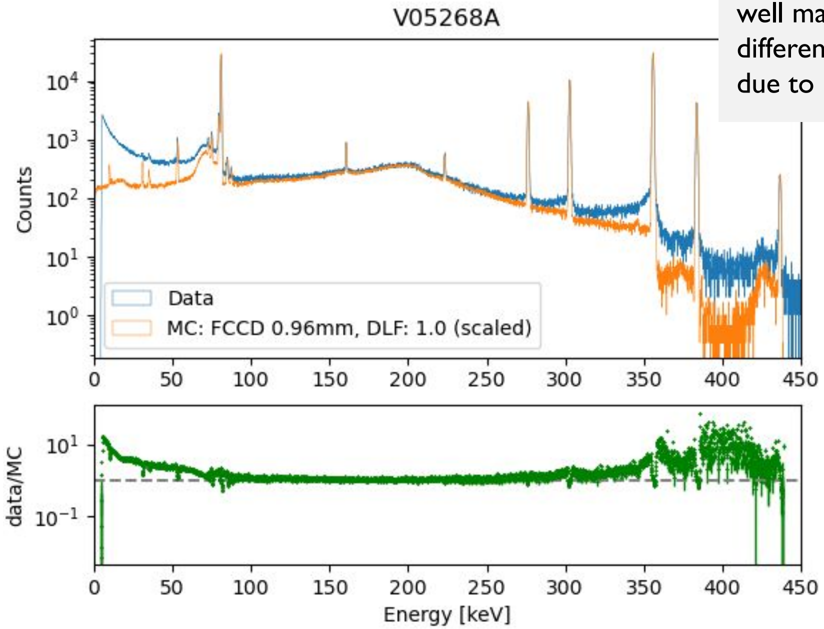






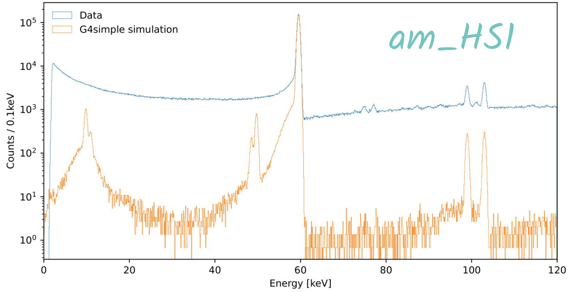
Following method in Bjoern's thesis

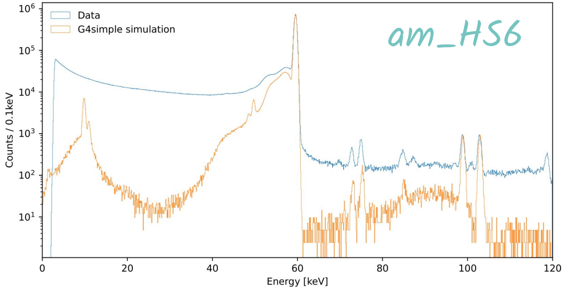
Full energy peaks well matched, but difference in tails due to lack of TL

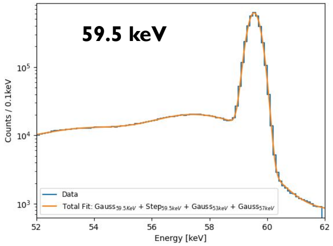


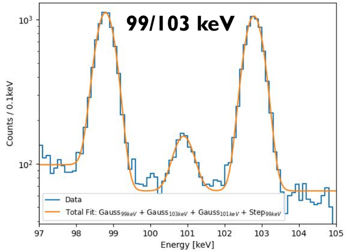
Analysis: ^{241}Am

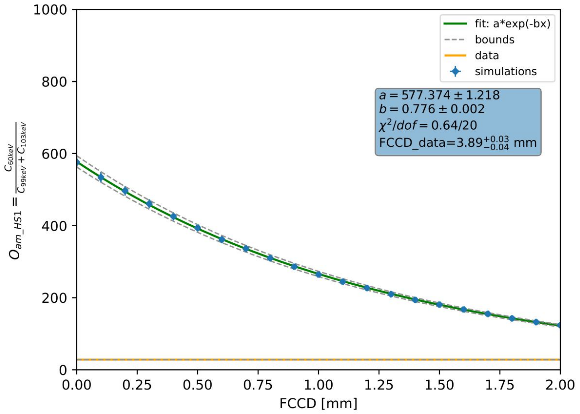
$$O_{^{241}\mathrm{Am}} = \frac{C_{59.5\,\mathrm{keV}}}{C_{99.0\,\mathrm{keV}} + C_{103.0\,\mathrm{keV}}}$$



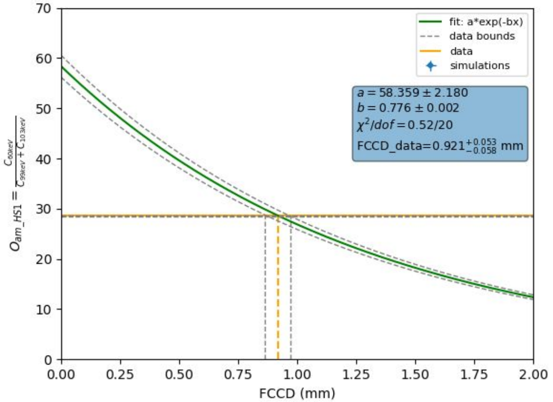




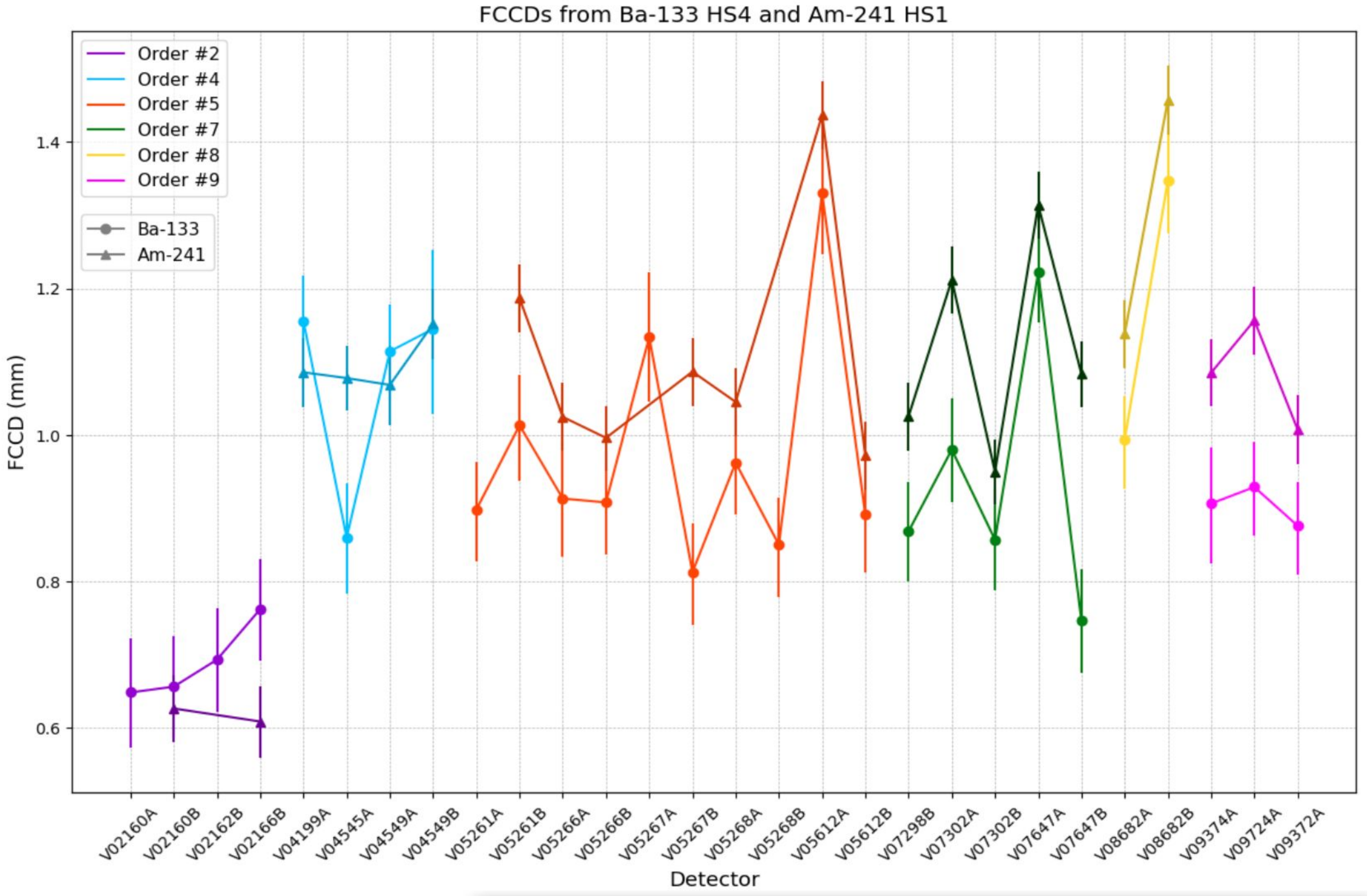




After calibration with am_HS6



Results: FCCDs



- FCCDs computed for all ICPCs characterised at HADES so far

Results: FCCDs


```json
{
    "V02160A": {
        "FCCD_ba": 0.6482393374830786,
        "FCCD_ba_err_up": 0.07417223259448869,
        "FCCD_ba_err_low": 0.0750211846962957,
        "FCCD_ba_err_corr_up": 0.05369480229103729,
        "FCCD_ba_err_corr_low": 0.054699669962277264,
        "FCCD_ba_err_uncorr_up": 0.02739931161907294,
        "FCCD_ba_err_uncorr_low": 0.02726518198449912
    },
    "V02160B": {
        "FCCD_ba": 0.6561419698875735,
        "FCCD_ba_err_up": 0.06974623389459522,
        "FCCD_ba_err_low": 0.07033450691017085,
        "FCCD_ba_err_corr_up": 0.05389790893996227,
        "FCCD_ba_err_corr_low": 0.054548776090944884,
        "FCCD_ba_err_uncorr_up": 0.02348693531262014,
        "FCCD_ba_err_uncorr_low": 0.023062544858269196,
        "FCCD_am1": 0.6263494561576082,
        "FCCD_am1_err_up": 0.0451019017729406,
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        "FCCD_am1_err_uncorr_up": 0.011985138521309557,
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    },
    "V02162B": {
        "FCCD_ba": 0.6930170049523673,
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        "FCCD_ba_err_corr_up": 0.05347685257530732,
        "FCCD_ba_err_corr_low": 0.05373257234357265,
        "FCCD_ba_err_uncorr_up": 0.024326400510057855,
        "FCCD_ba_err_uncorr_low": 0.023425005864014525
    },
    "V02166B": {
        "FCCD_ba": 0.761995054280591,
```
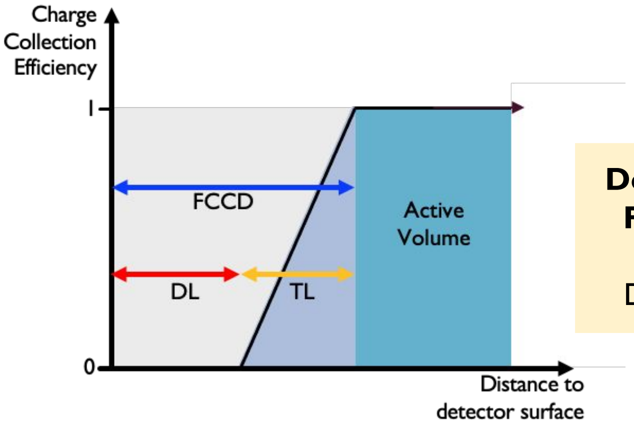


- Full results with correlated and uncorrelated errors ready
    - Currently in a json file -> soon in a table

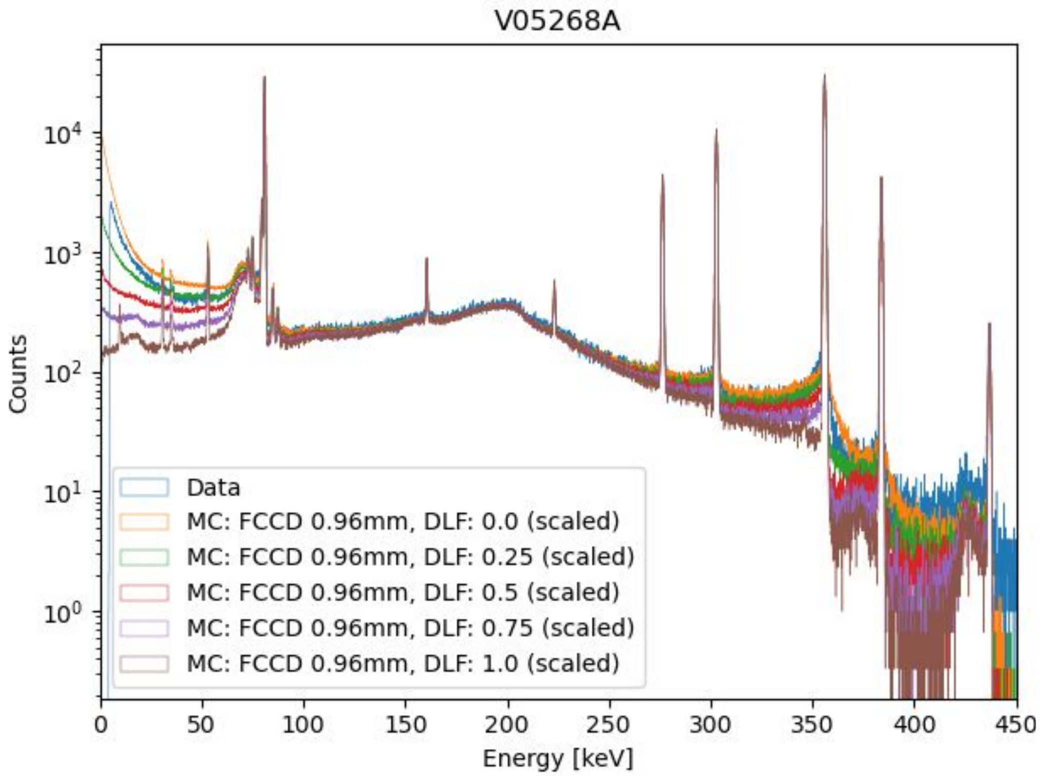
Ongoing work: TL Investigations

- **Next steps:** explore **Transition Layer** profiles for the best fit FCCDs to improve data/MC agreement

- Linear TL only is shown here, but can also try more complex profiles: e.g. sigmoidal



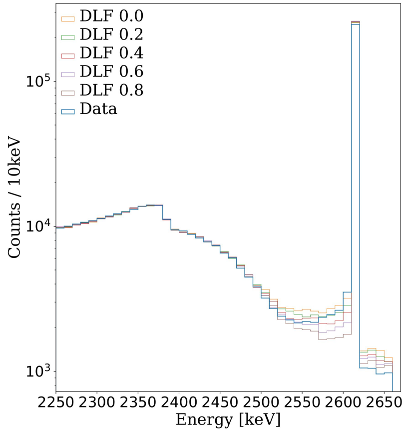
Dead Layer Fraction:
DLF = DL/FCCD

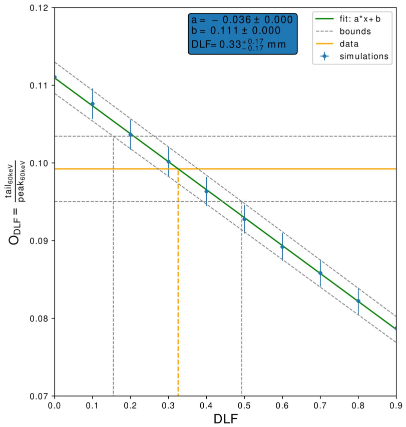


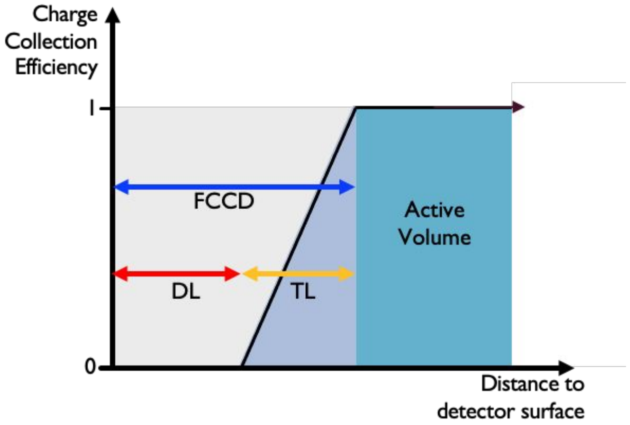
Ongoing work: TL Investigations - Th source

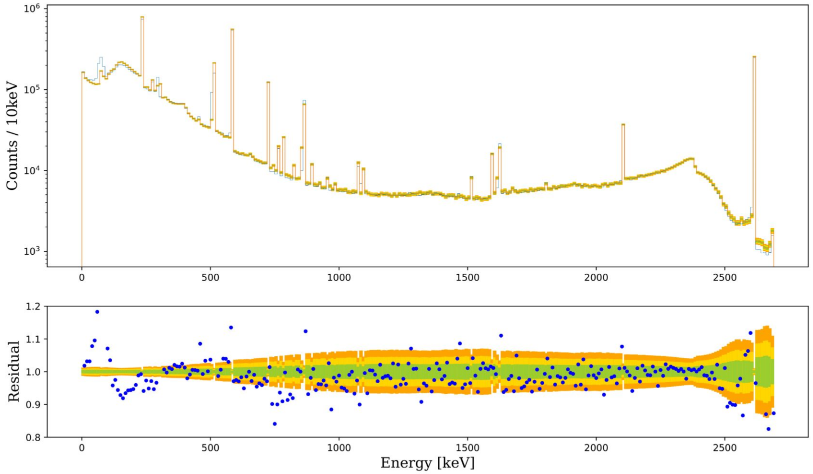
- **Transition Layer** effects are visible at the left tail of peaks, like the one at 2615 keV of the Th spectrum

- Linear TL models with different dead layer fractions (DLF) are compared to the data via the count ratio of the main peak









New work: DL Homogeneity - ICPC

- Computation of the ratio between the mean counts at the lateral side and top side

$$r = \frac{R'_{LAT}}{R_{TOP'}} \qquad \sigma_r = r \cdot \sqrt{\left(\frac{\sigma_{R'_{TOP}}}{R'_{TOP}}\right)^2 + \left(\frac{\sigma_{R'_{LAT}}}{R'_{LAT}}\right)^2}$$

- The difference in FCCD between top and lateral is

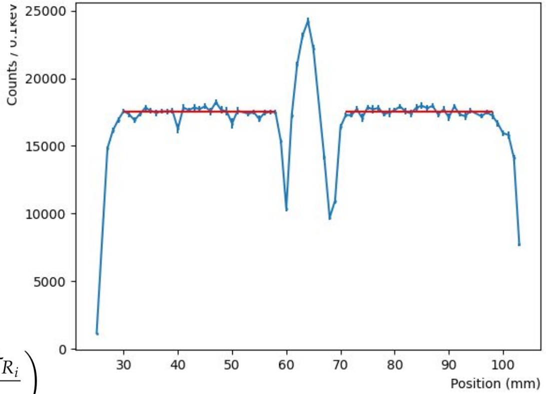
$$\Delta FCCD = -\frac{1}{\mu \cdot \rho} \cdot \ln r$$

$$\sigma_{\Delta FCCD} = \frac{1}{\mu \cdot \rho} \cdot \frac{\sigma_r}{r} \qquad \delta FCCD_i = \frac{1}{\mu \cdot \rho} \cdot \ln\left(\frac{R_i - \tilde{\sigma}_{R_i}}{R_i}\right)$$

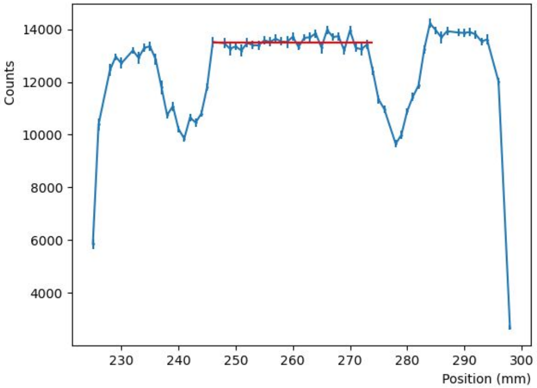
FCCD variation for a given surface

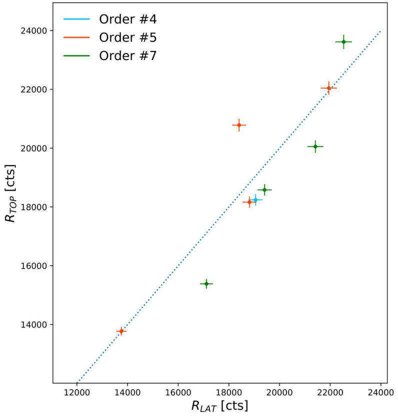
ICPC	$\Delta FCCD \pm \sigma_{\Delta FCCD}$ [mm]	$\delta FCCD_{TOP}$ [mm]	$\delta FCCD_{LAT}$ [mm]
V04199A	-0.04 ± 0.02	0.01	0.01
V05261B	-0.03 ± 0.02	0.01	0.01
V05266A	0.10 ± 0.02	0.01	0.01
V05266B	0.004 ± 0.02	0.01	0.01
V05612A	0.001 ± 0.02	0.01	0.01
V07298B	-0.06 ± 0.02	0.01	0.01
V07302A	-0.04 ± 0.02	0.01	0.01
V07302B	0.04 ± 0.02	0.01	0.01
V07647A	-0.09 ± 0.02	0.01	0.01

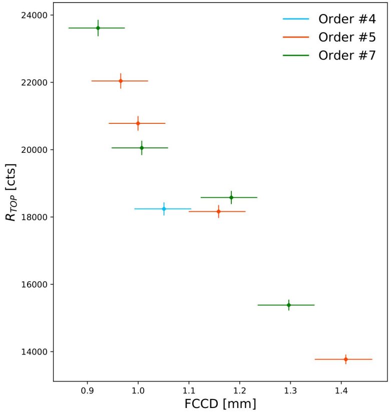
TOP



LATERAL



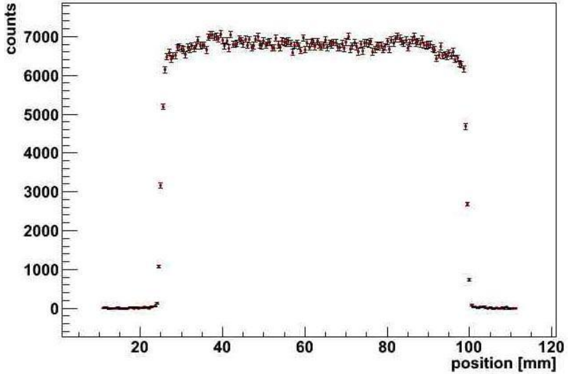




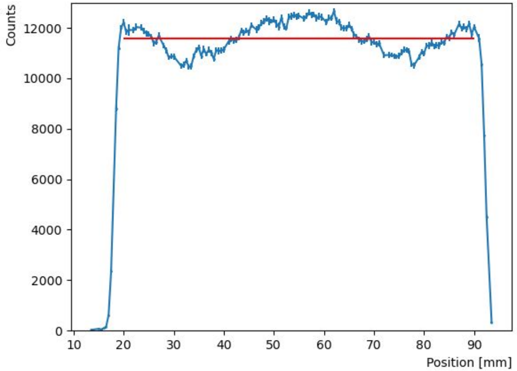
New work: DL Homogeneity - BEGe

TOP

Brahma

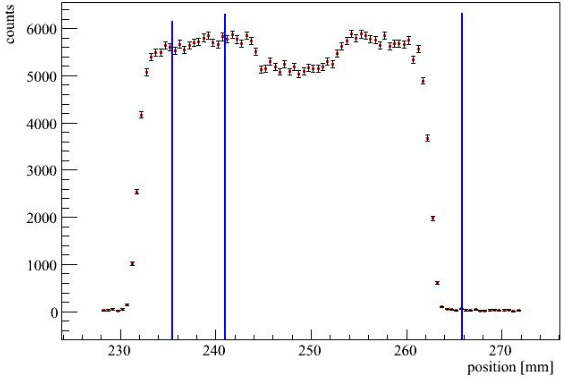


B0000D

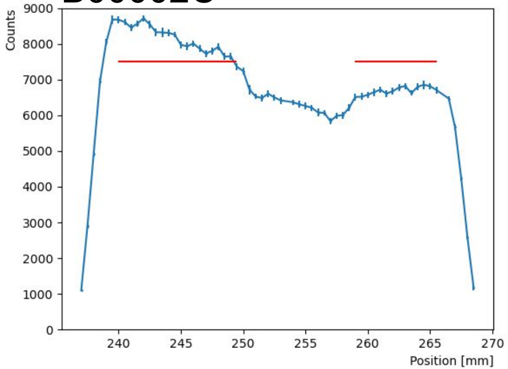


LATERAL

Centaur

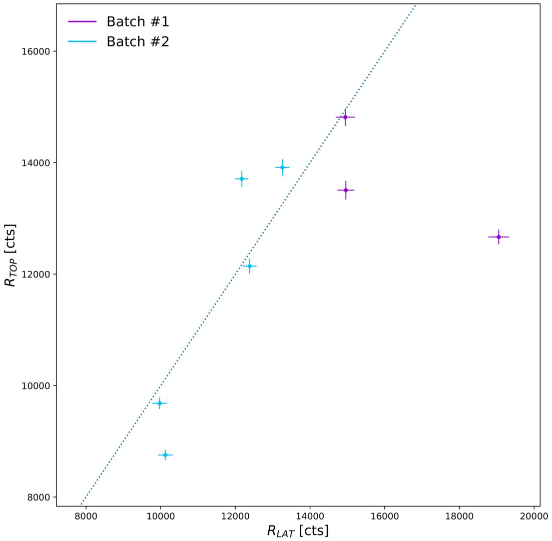


B00002C

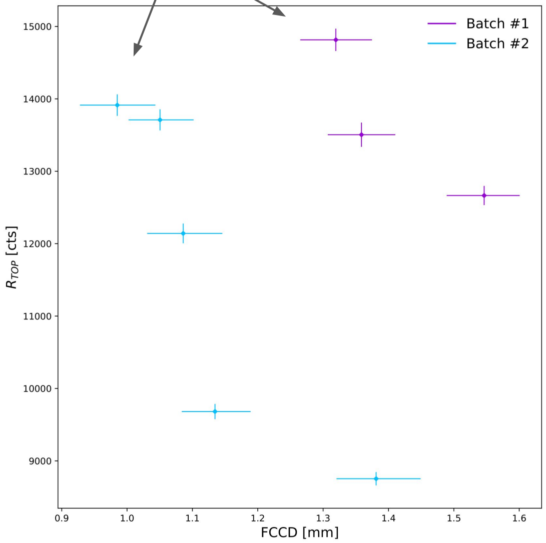


- Homogeneity - top and lateral - **not valid** anymore after the FCCD growth
- How to correctly compare the results of first and second measurements?

New work: DL Homogeneity - BEGe



Two groups?



ICPC	First characterization		
	$\Delta FCCD \pm \sigma_{\Delta FCCD}$ [mm]	$\delta FCCD_{TOP}$ [mm]	$\delta FCCD_{LAT}$ [mm]
B00000B	0.01 ± 0.00	0.03	0.05
B00032B	0.07 ± 0.01	0.03	0.02
B00091B	0.02 ± 0.00	0.02	0.03
B00000D	0.01 ± 0.00	0.03	0.02
B00002C	0.00 ± 0.00	0.01	0.03
B00035B	0.03 ± 0.01	0.01	0.00
B00061C	0.02 ± 0.00	0.02	0.05
B00076C	0.00 ± 0.01	0.01	0.01

ICPC	Second characterization		
	$\Delta FCCD \pm \sigma_{\Delta FCCD}$ [mm]	$\delta FCCD_{TOP}$ [mm]	$\delta FCCD_{LAT}$ [mm]
B00000B	-0.03 ± 0.02	0.01	0.01
B00032B	-0.09 ± 0.02	0.04	0.02
B00091B	-0.01 ± 0.02	0.01	0.03
B00000D	0.10 ± 0.02	0.04	0.06
B00002C	-0.03 ± 0.02	0.05	0.05
B00035B	-0.12 ± 0.02	0.04	0.04
B00061C	0.04 ± 0.02	0.04	0.04
B00076C	-0.02 ± 0.02	0.06	0.07