Modelling Neutron Damage Energy Loss in AGATA’s HPGe detectors

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Overview

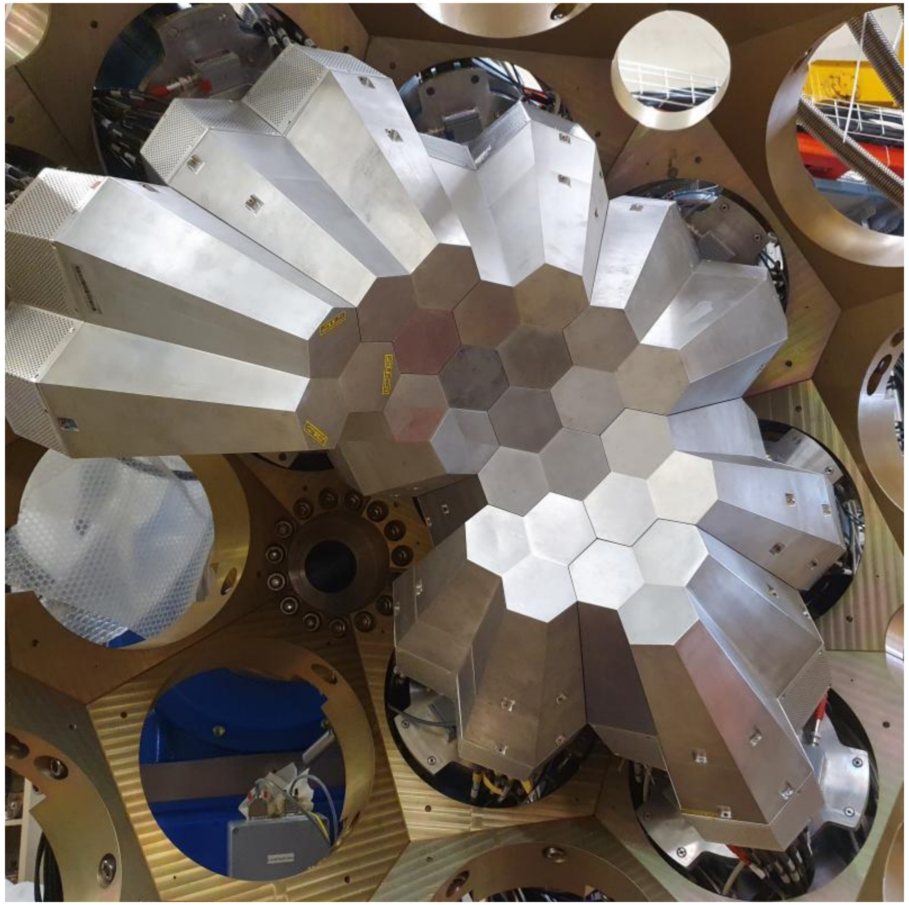
1. What is AGATA, what is neutron damage and how does it manifest?
2. How can we model the levels of damage?
3. How can we correct for the damage?
4. Why is this necessary?

What is AGATA?

- AGATA is a European collaboration working to realise a 4-pi gamma-ray spectrometer, with the final assembly containing 180 highly-segmented, high-purity germanium (HPGe) detectors.

- The spectrometer is designed to be transportable – it currently resides in Legnaro National Lab near Venice, and has previously been used at both GANIL and GSI.

- 4-pi maximises detection efficiency, and also allows near-complete tracking of gamma rays as they scatter.

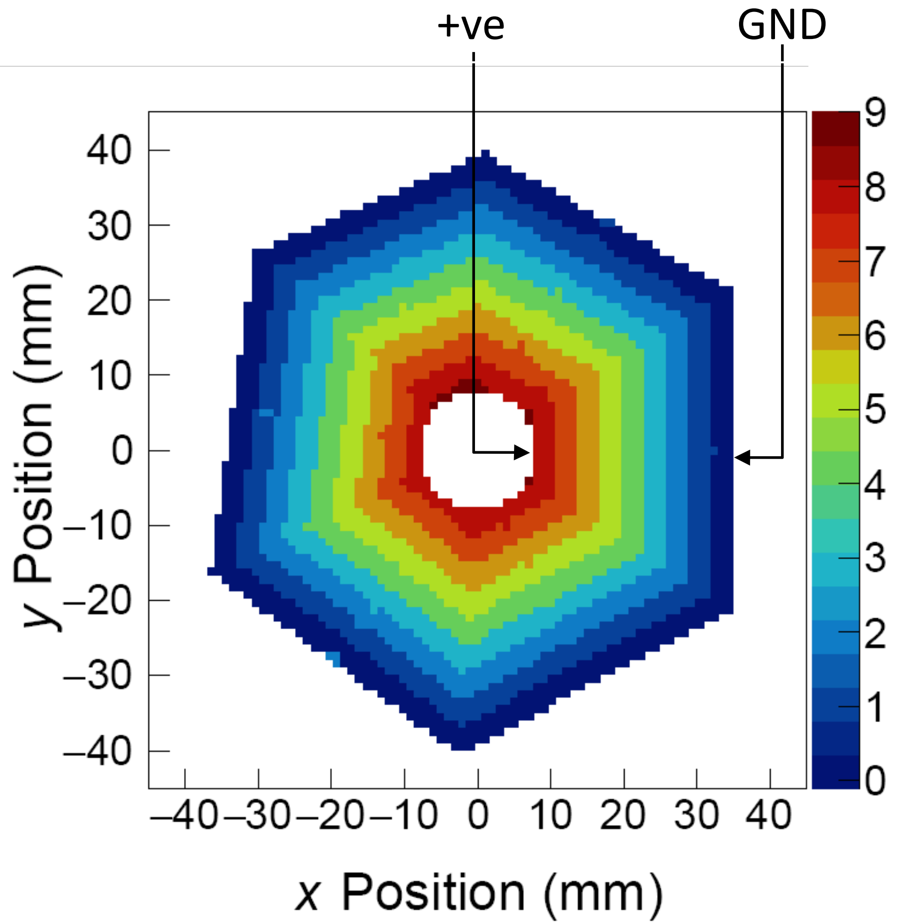


What is neutron damage?

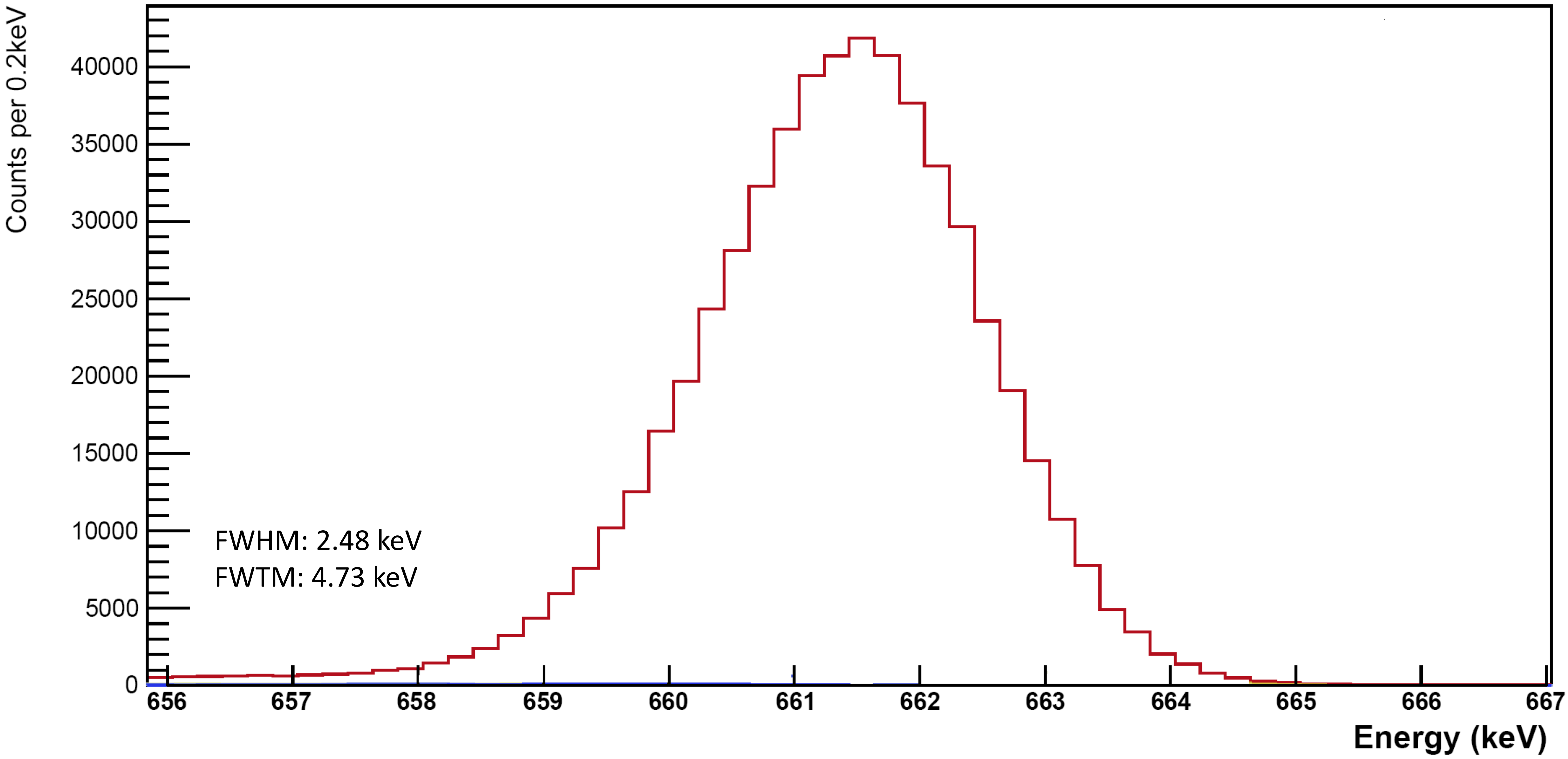
- Fast neutrons (~1 MeV) are produced in heavy ion collisions, fission-fusion reactions, etc. These are incident on the semiconductor detectors surrounding the target.
- These may knock atoms out of the structure of the lattice, creating “trapping sites” – areas in which charge carriers are able to become stuck. The greater the distance the carriers travel, the more that are lost.
- These stuck charge carriers are then not collected or recorded, leading to a reduction in measured energy.
- Due to their lower mobility, holes are far more likely to be trapped than electrons.

How does it manifest?

- In a planar detector, neutron damage manifests as a worsening of energy resolution. This is due to a position dependence on the measured energy.
- Interactions further from the collection contact will have lower measured energy, leading to a broadening of the photopeak.
- In a coaxial detector, the same happens - but now, there is also a variation in the detection volume.
- Instead of just a worsening of resolution, we get low-energy tailing.



Progress in the Development of CdZnTe Unipolar Detectors for Different Anode Geometries and Data Corrections - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Planar-configuration-of-a-semiconductor-detector-The-cathode-is-applied-with-a-negative_fig1_235690117 [accessed 6 Aug 2024]


Counts per 0.2keV
40000
35000
30000
25000
20000
15000
10000
5000
0
656
657
658
659
660
661
662
663
664
665
666
667
Energy (keV)
FWHM: 2.48 keV
FWTM: 4.73 keV

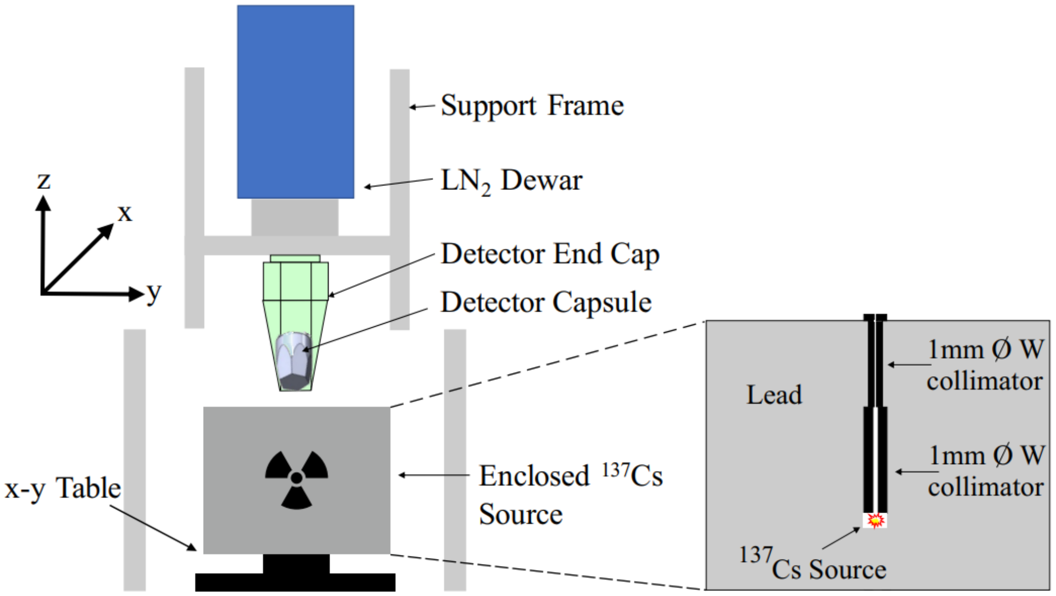
Collecting the data

- Data is taken using a collimated 1 GBq ^{137}Cs source on an x-y scanning table.

- The detector of interest was sent to Liverpool in a known neutron damaged state by the AGATA collaboration.

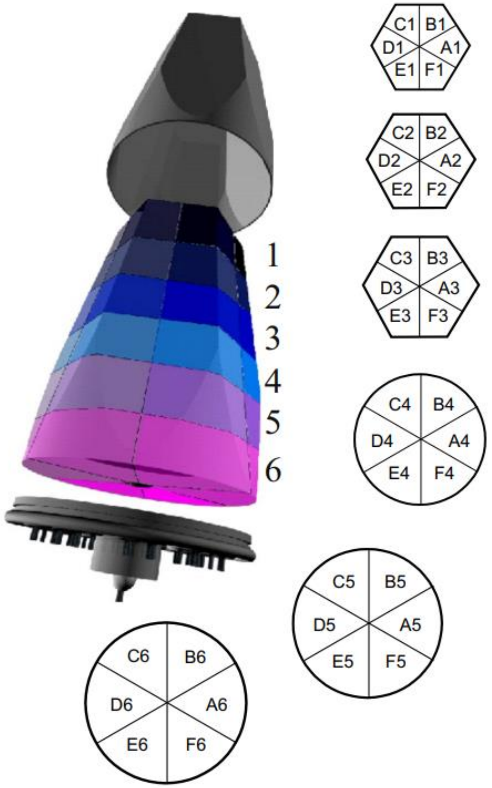
- All 37 channels (36 hole sensitive segments + 1 electron sensitive core) are readout if an event over a specific threshold is seen on the core.

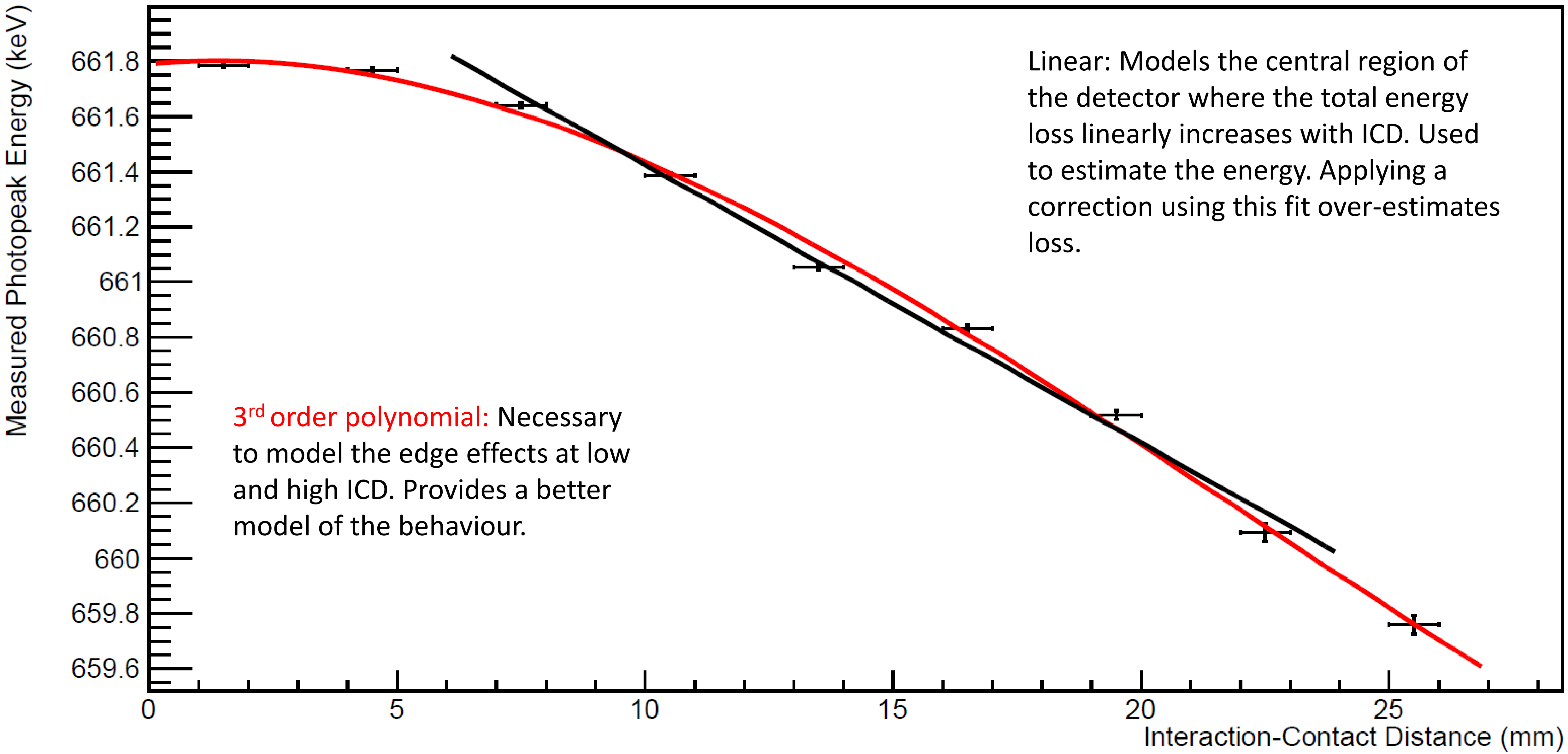
- The x-y position of the scanning table is used to infer the distance between the interaction and the readout contact.



Analysing the data

- Events are grouped into 3mm wide bins based on their distance from the measurement contact.
- This is done on a segment-by-segment basis – energy loss is not consistent throughout the volume of the detector.
- The energy spectra from each bin are modelled, the photopeaks measured, and plotted against the interaction-contact distance.

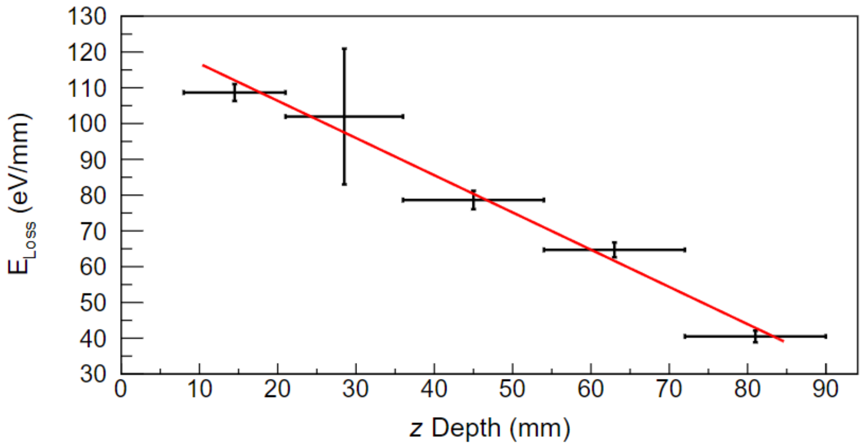



Measured Photopeak Energy (keV)
661.8
661.6
661.4
661.2
661
660.8
660.6
660.4
660.2
660
659.8
659.6
0
5
10
15
20
25
Interaction-Contact Distance (mm)
Linear: Models the central region of the detector where the total energy loss linearly increases with ICD. Used to estimate the energy. Applying a correction using this fit over-estimates loss.
3rd order polynomial: Necessary to model the edge effects at low and high ICD. Provides a better model of the behaviour.

What the linear fit tells us

- The linear fit returns a gradient of eV/mm, the expected energy loss - E_{loss} - suffered by an interaction in the detector
- E_{loss} is not found to be consistent azimuthally or in depth.
- For segment D3, an event occurring near the core contact would lose ~3.4 keV of energy before being measured – nearly 5000 holes.
- The energy resolution of this detector at 662 keV is about 1.9 keV – this is a meaningful loss.

Segment	E_{loss} (eV/mm)
A3	79.72 ± 4.11
B3	106.61 ± 4.71
C3	100.67 ± 4.64
D3	113.21 ± 4.21
E3	94.38 ± 2.34
F3	92.45 ± 3.83



What the polynomial fit lets us do

- Allows determination of E_{lost} for a given segment (i) and ICD (x).

$$E_{frac}(i,x) = \frac{a_i x^3 + b_i x^2 + c_i x + d_i}{Emax_i}, \tag{1}$$

where a, b, c and d are the fit coefficients, and $Emax_i$ is the maxima of the fit within the given range, in keV. The amount of energy lost by an interaction with $E_{measured}$ is therefore

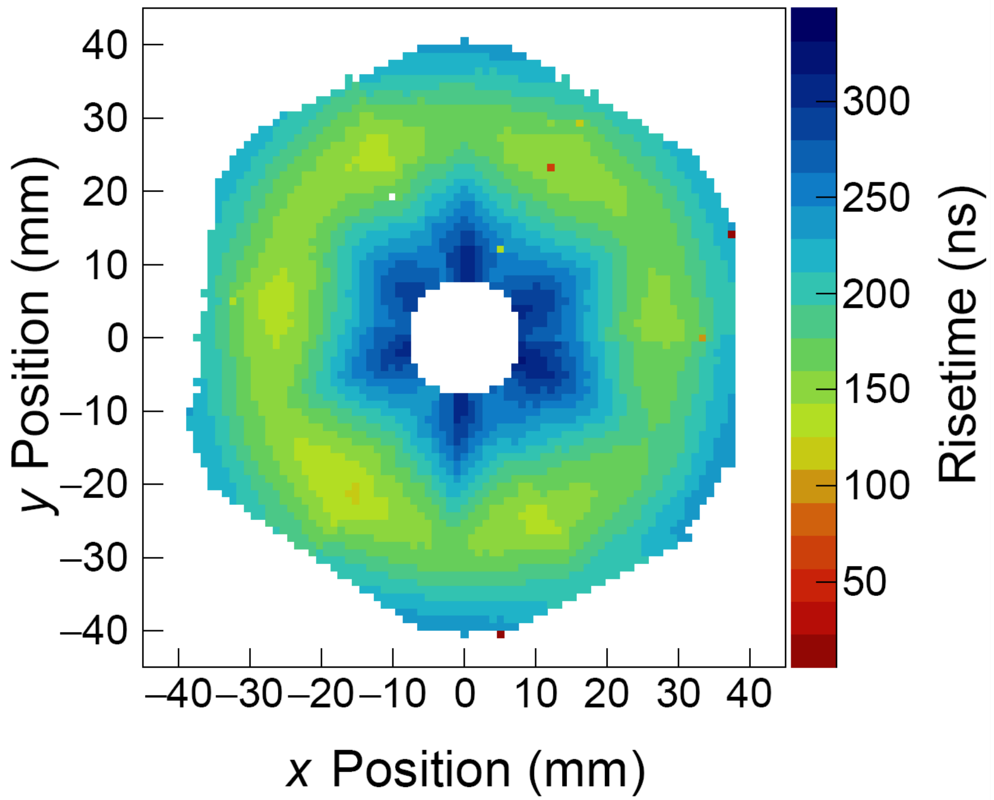
$$E_{lost} = \frac{E_{measured}}{E_{frac}(i,x)} \times (1 - E_{frac}(i,x)). \tag{2}$$

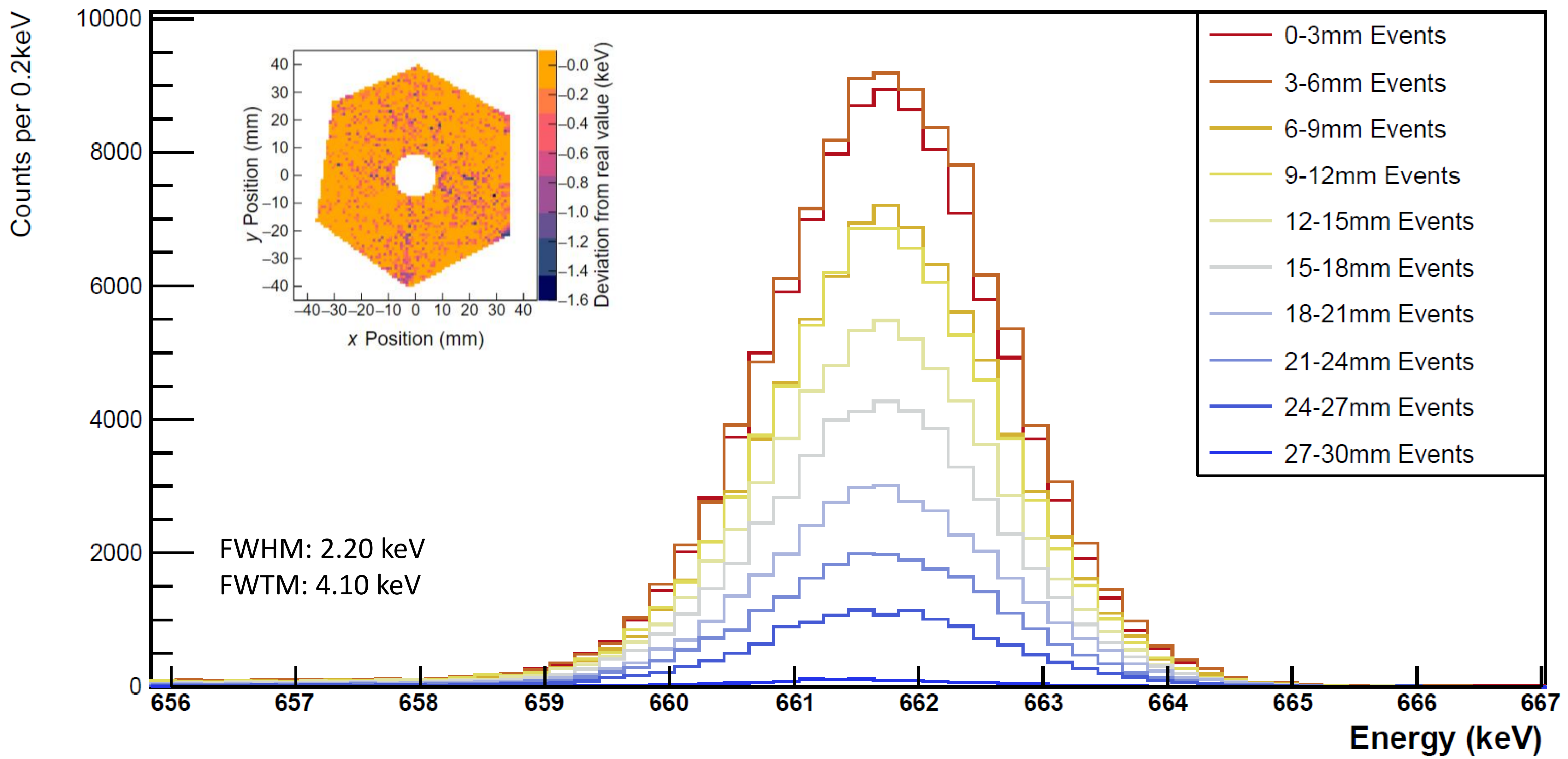
- The analysis is then repeated, this time with E_{lost} measured and re-added on a point-by-point basis.

An important thing to mention.

- Traces are saved to disk while taking data. These are time aligned, normalised and averaged to create an expected detector response for each 1 mm^2 scan position in every segment.

- The shape of the trace is analysed, with the times taken for a signal to rise to a given fraction of their total height being indicative of the interaction position.





Counts per 0.2keV
10000
8000
6000
4000
2000
0
656
657
658
659
660
661
662
663
664
665
666
667
Energy (keV)
0-3mm Events
3-6mm Events
6-9mm Events
9-12mm Events
12-15mm Events
15-18mm Events
18-21mm Events
21-24mm Events
24-27mm Events
27-30mm Events
y Position (mm)
x Position (mm)
Deviation from real value (keV)
FWHM: 2.20 keV
FWTM: 4.10 keV

Why do we need this?

- Neutron damage worsens the resolution of your detector, and creates an interaction point dependence on the energy measured.

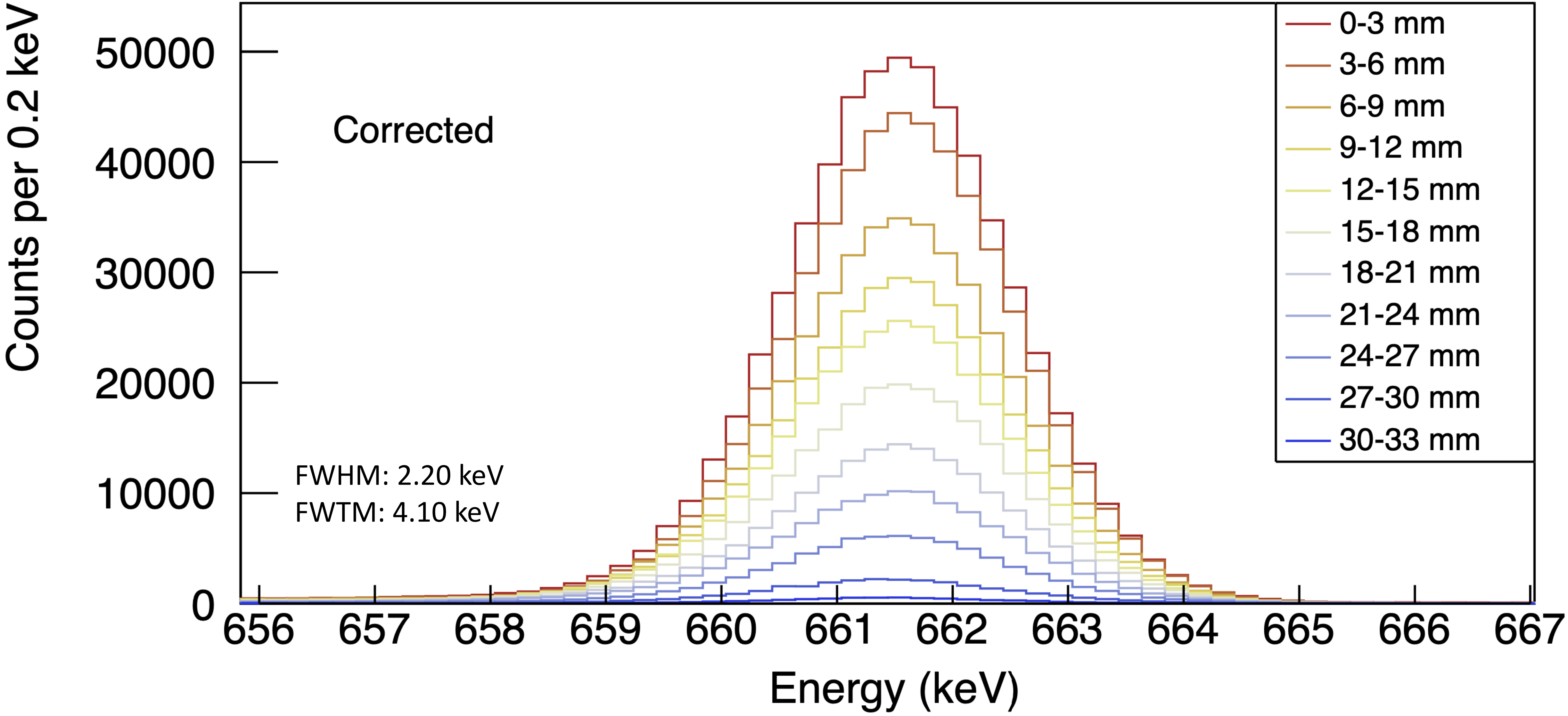
Not great if you're looking for previously unseen transitions, or need good resolution for gamma-ray tracking.

- Neutron damage is repaired by annealing – a process that involved heating the detector to – in the case of HPGe – 103^{o}C for 36 – 48 hours, to allow the lattice to reform.

This requires a detector to be removed from service. It's expensive, could lead to a high leakage failure mode, and may also reduce the detection efficiency.

- It is therefore beneficial to keep these detectors running and producing good data for as long as possible before having to anneal them – which is usually done when electron trapping starts to become noticeable.

Where next?


Counts per 0.2 keV
50000
40000
30000
20000
10000
0
Corrected
FWHM: 2.20 keV
FWTM: 4.10 keV
0-3 mm
3-6 mm
6-9 mm
9-12 mm
12-15 mm
15-18 mm
18-21 mm
21-24 mm
24-27 mm
27-30 mm
30-33 mm
656
657
658
659
660
661
662
663
664
665
666
667
Energy (keV)

Most importantly…

- This detector has been characterised, corrected, annealed, returned to service, and subject to high energy neutron fluences again.

All these measurements and corrections are no longer applicable!

- To complete the methodology, the metric requires an additional dimension – neutron flux.

This would mean repeated characterisations of an expensive, highly segmented, high purity detector between intentional irradiations of known doses of high energy neutrons.

So that's exactly what I'm doing.

Thank you for listening, any questions?