INDet: Lessons Learnt from Boron-Coated 3-D Silicon Detector Production 2023/06/28

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Content

- **Motivation**
  - Where, why, and how
- **Design**
  - Silicon chip, alterations, geometry
  - https://**doi**.org/**10.1088/1748-0221/18/01/c01056**
- **Simulations**
  - Geant4
- **Results**
  - IV
  - PSI
    BNC

Motivation

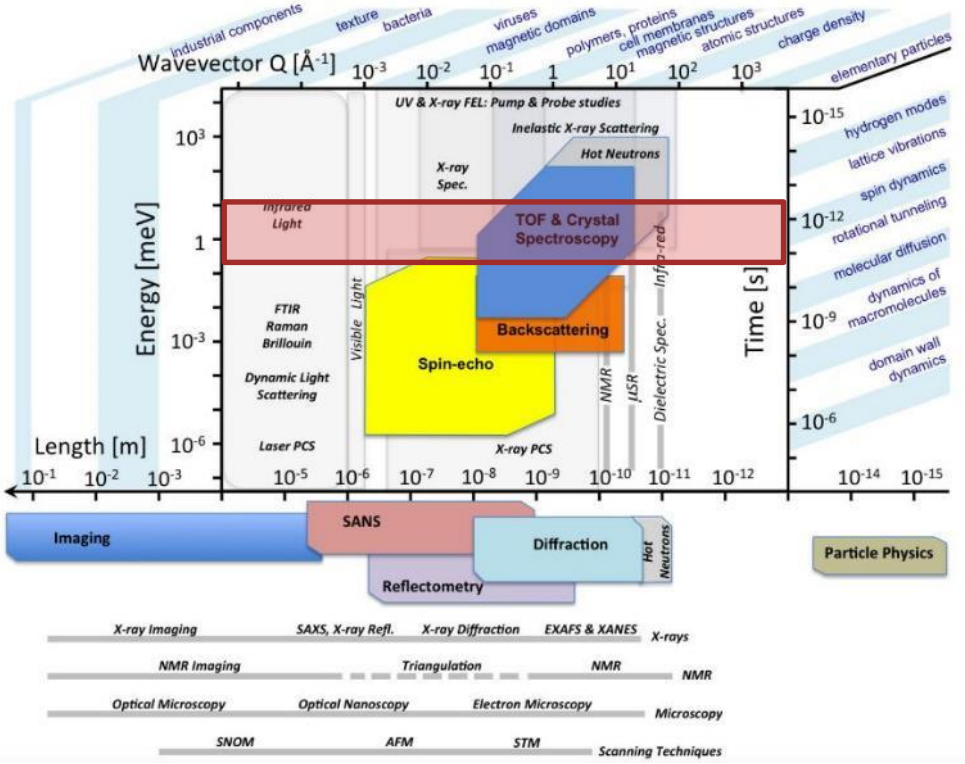
Relativity

Reactors

Room ℃

Funda-
mental

Ultrafast
Fast
Intermediate
Epithermal
Thermal
Cold
Very-cold
Ultracold



Modified from [*ESS: Technical Design Report*, 2013]

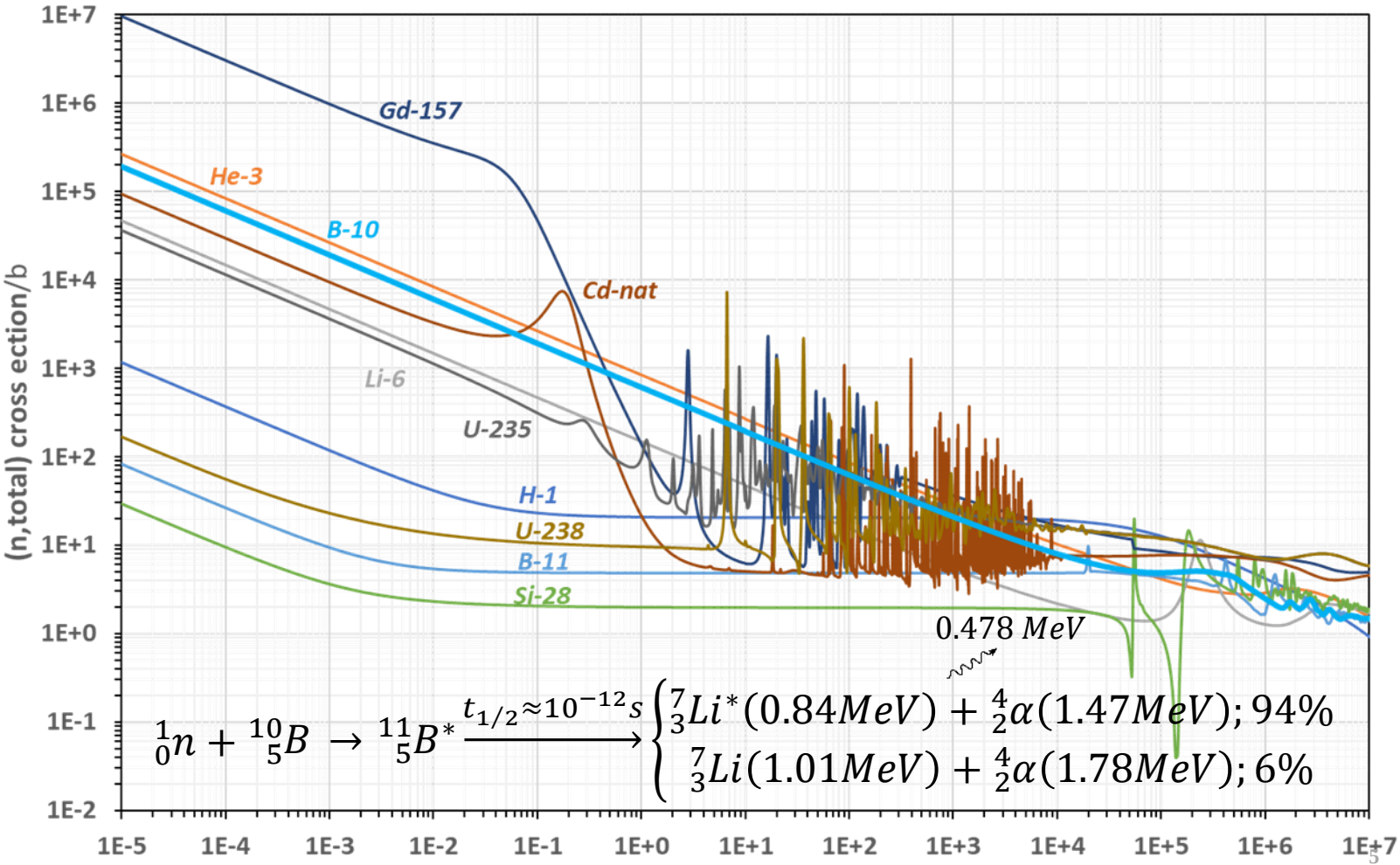
Detecting Neutrons

- Limited interaction with most materials
- Typical devices include ^3He, BF_3
  - Big
  - Expensive (> $5,000/L)
  - Toxic
- Applicable to huge range of research
- But silicon is not useful here…

^3He price (L^{-1})

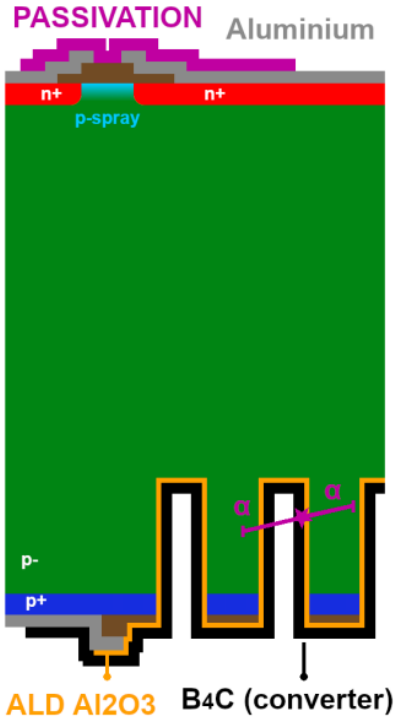
Customers	2009	2010	2011
Federal agencies and their grantees	450	365	600
Commercial and nonfederal agencies	450	365	1000
Medical users	600	485	720

[Government, U.S. *Managing Critical Isotopes: DOE's Isotope Program needs Better Planning for Setting Prices and Managing Production Risks: Report to Congressional Requesters*; U. S. Government Accountability Office: Washington, DC, USA, 2013]

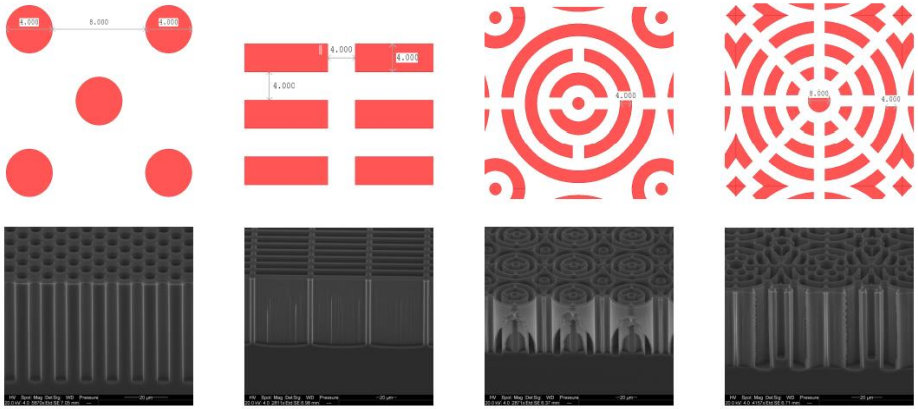


Data: [D.A. Brown, et al., "*ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data*", Nuclear Data Sheets (2018) vol. 148, pp.1-142]

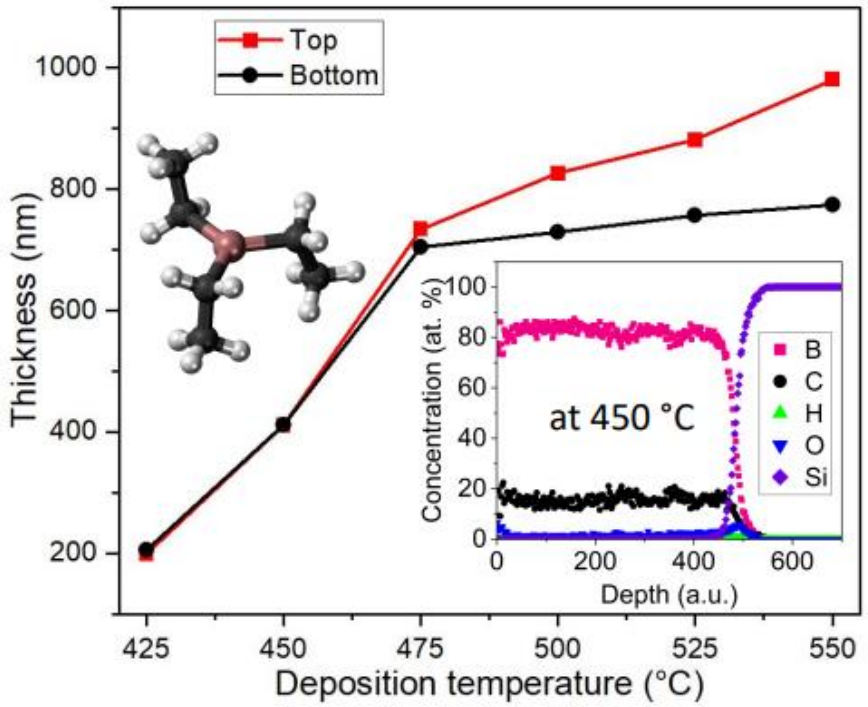
INDet – Improved Neutron DETection



- 3-D silicon
  - Structures created via DRIE
- Thin passivation layer
- Conformal converter layer
- Minimal dead layer
- Optimised geometry via Geant4



CVD Deposition

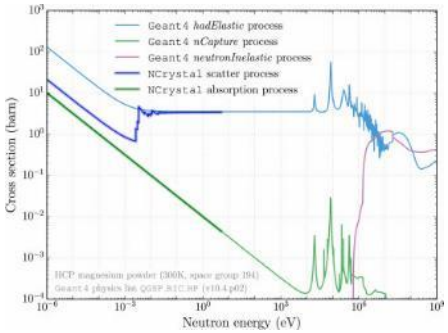


$B(C_2H_5)_{3\,(s)}$ (TEB) —Heat; H_2/50 mbar→ $B_xC_{(s)}$ + byproducts

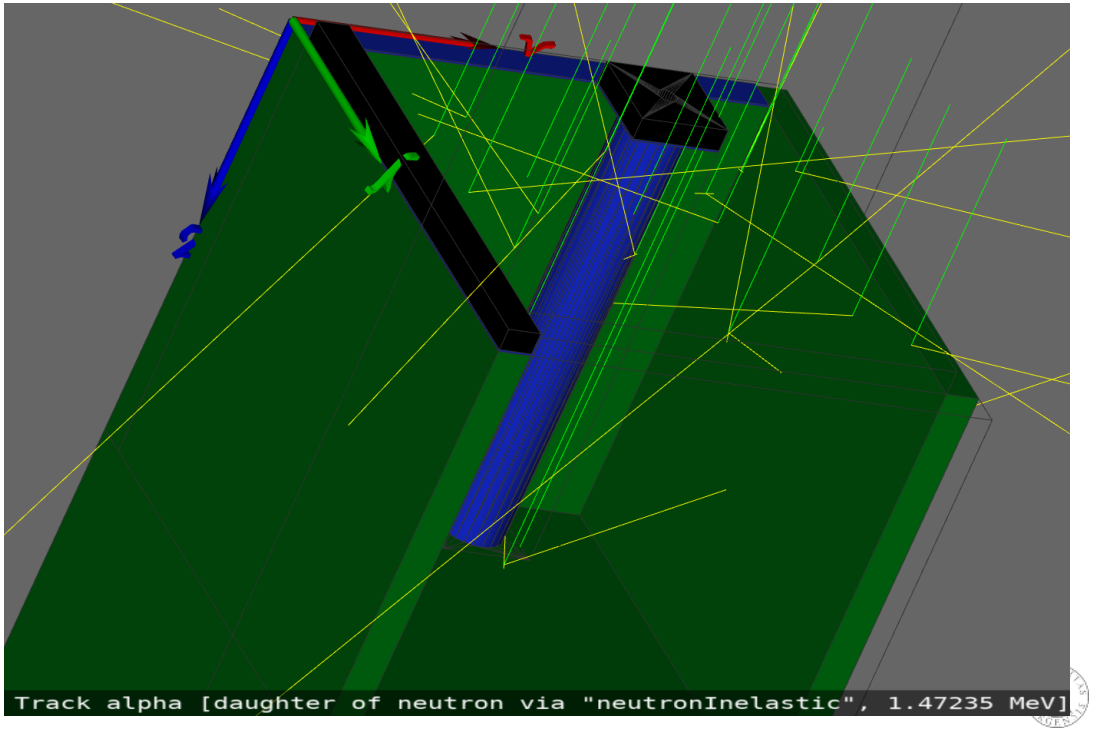
- Needs high temperatures
- Very conformal
- Very clean
  - Very few contaminants
- Triethylborane difficult to get enriched
  - Means a loss of up to 75 % efficiency
    - ^{10}B 19% abundancy

Geometry

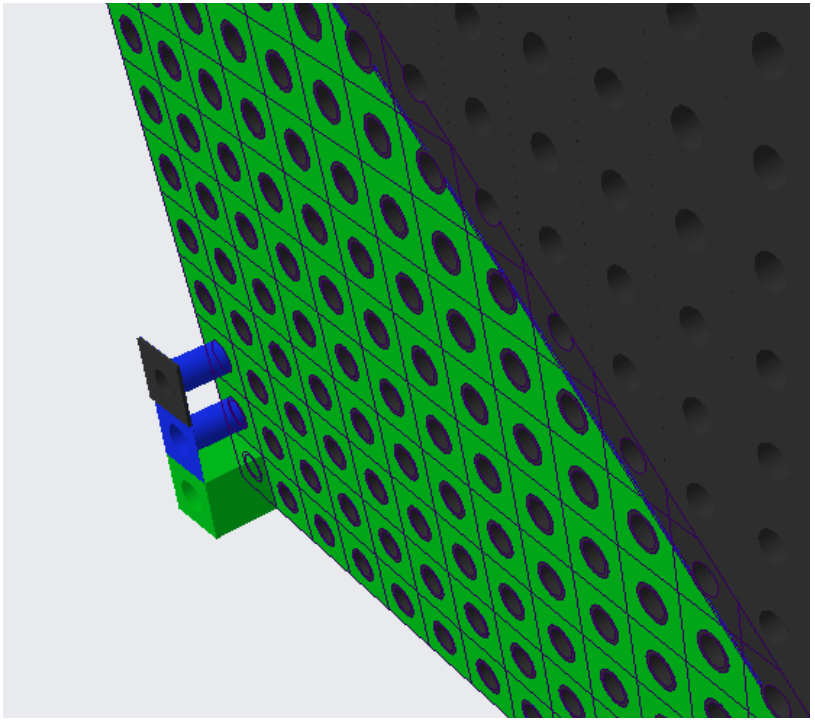
- Fabrication expensive
- Many parameters to optimise
- Parameterised volume
  - Geant4 kit available
    - git.esss.dk/dgcode
- Allows for 3-D shapes
  - Trenches, cylinders, cuboids, triangles…
- Chemical composition
  - Enriched ^{10}B %
- Exportable to NeXus (2024)



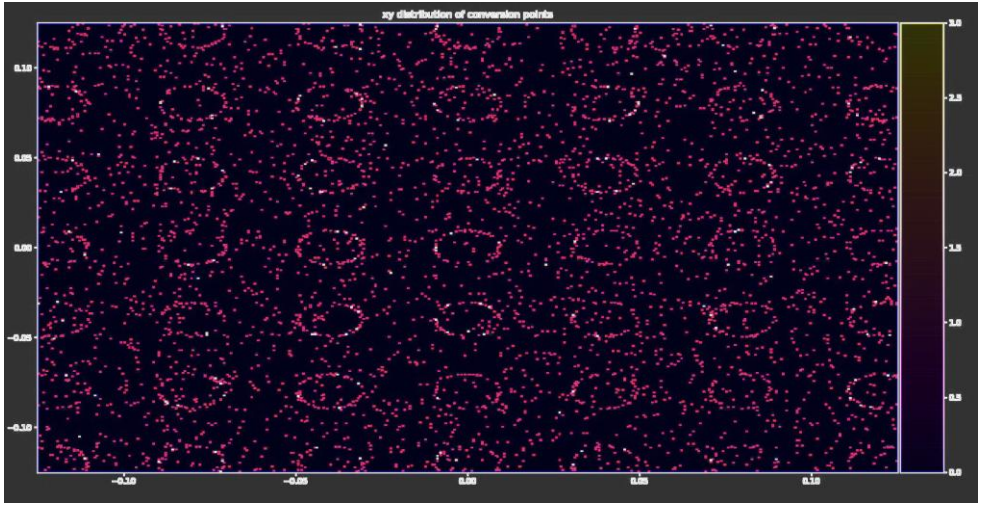
[X.-X. Cai and T. Kittelmann, NCrystal: A library for thermal neutron transport, Computer Physics Communications 246 (2020) 106851, https://doi.org/10.1016/j.cpc.2019.07.015]



Geometry

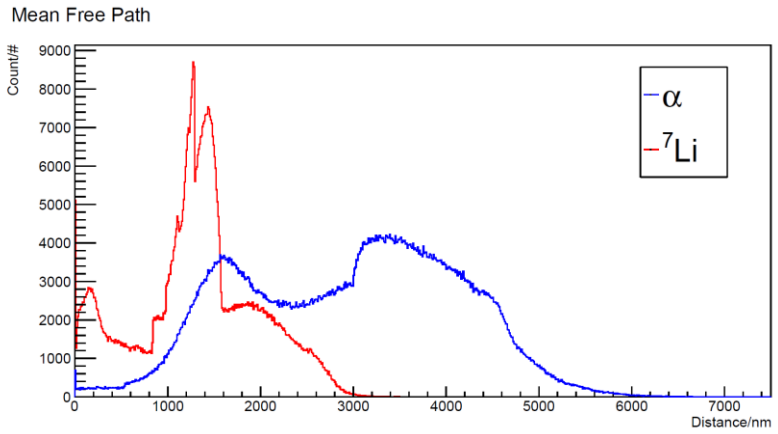


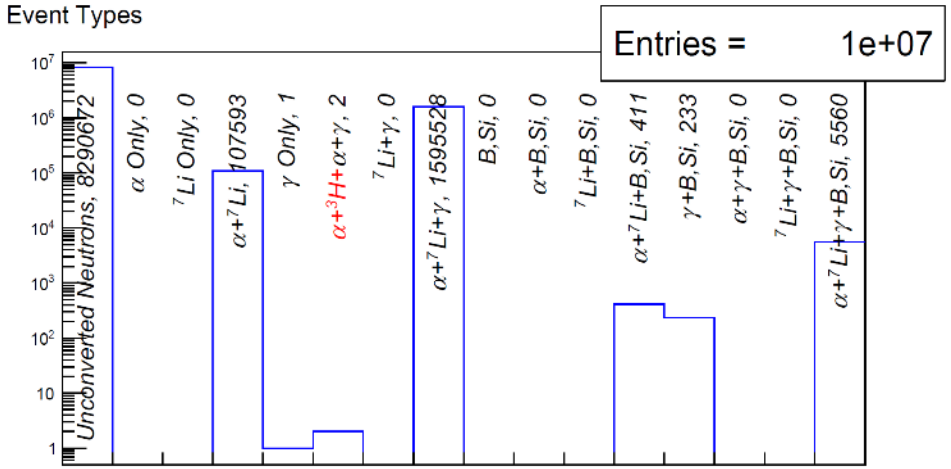
- Layered construction of each pixel
- Increased apparent thickness clear from maps of conversion location



20 µm ⌀, 20 µm _, 20 µm |, 1 µm natB$_4$C

Geometry – Validation





- Aim to understand processes
- Optimised path through detector
  - Maximise conversion probability

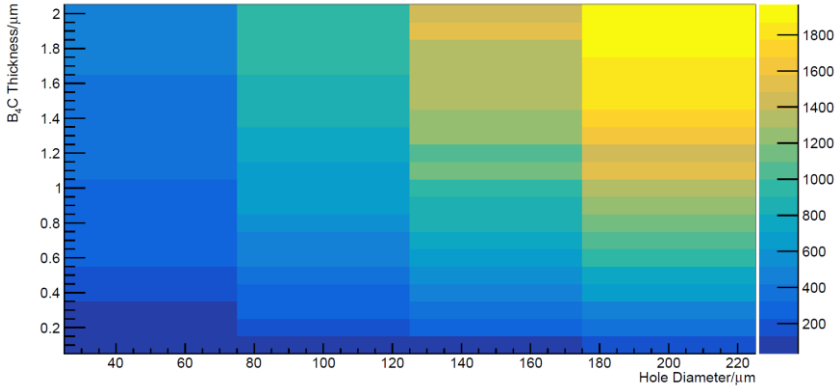
Geometry – Optimisation

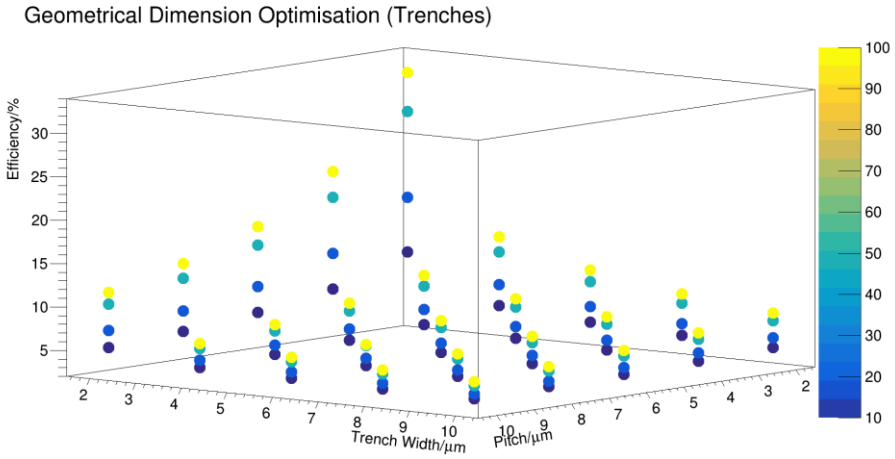
Conversion *v* transmission

Sensitivity to γ?

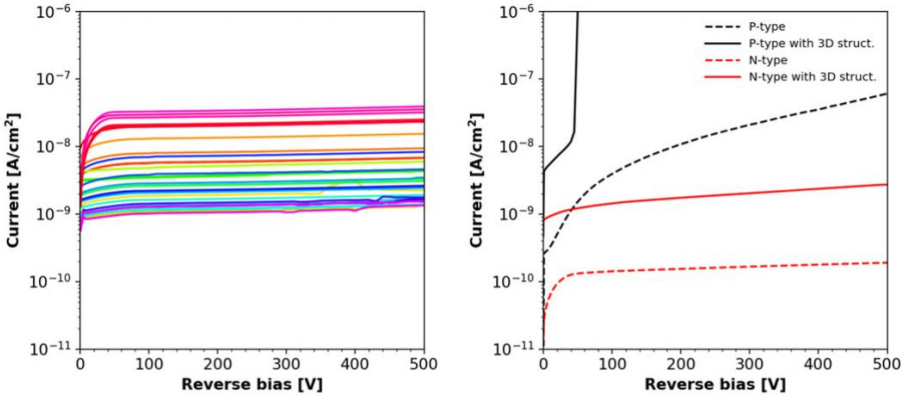
Surface area *v* depth

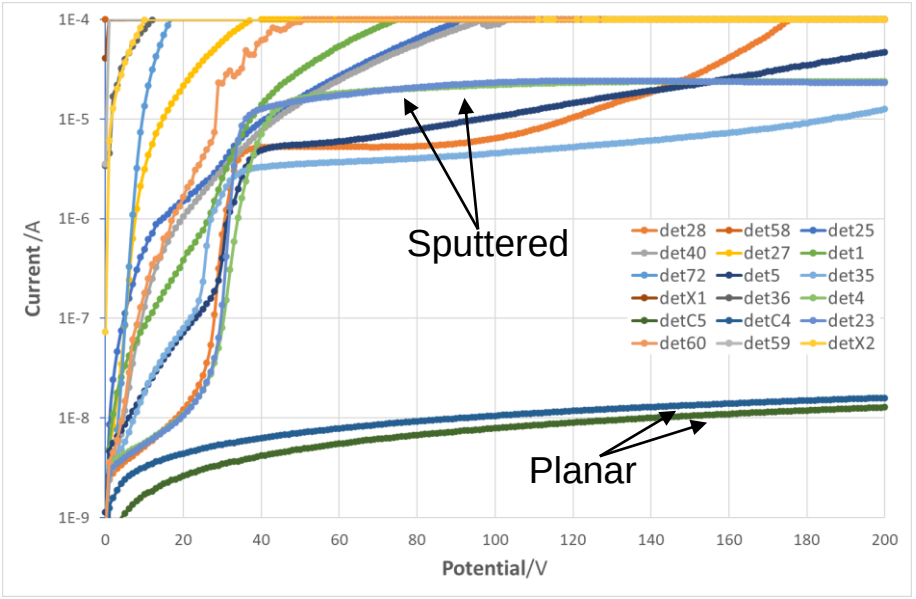
Optimised via multi-dimensional Pareto curves





IV

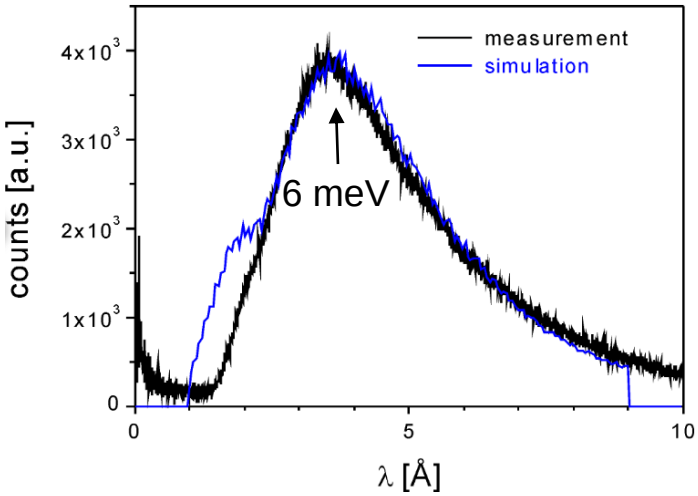




- Coating application increases noise
  - Breakdown of B_4C at high potential?

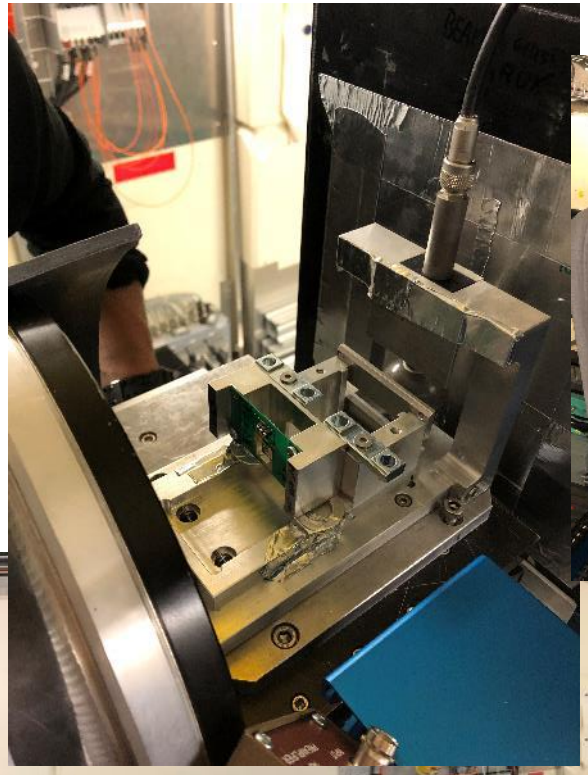
PSI - Tests

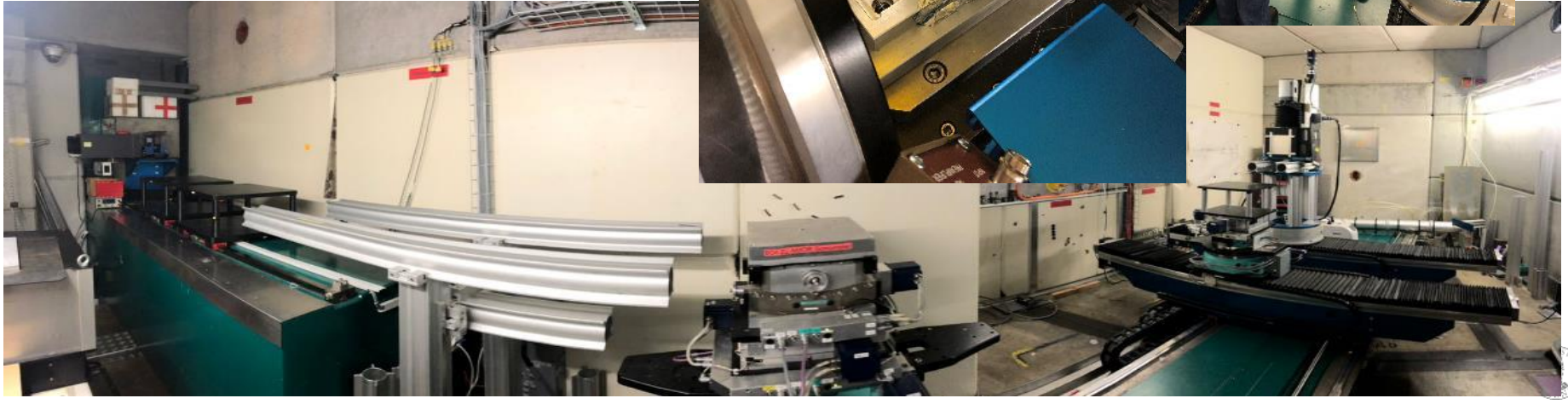
- **PSI (Switzerland)** – 28th October ‘22 0900 –> 31st 1100
- Several diode characterisations intended
- 2×10^7 $ns^{-1}cm^{-2}$
- Peak at cold neutrons
  - Better efficiency



PSI - Setup

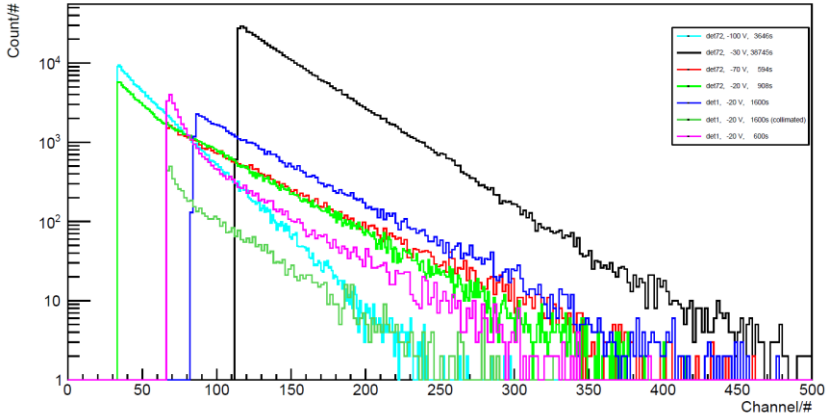
- Easy access
- Tested several devices



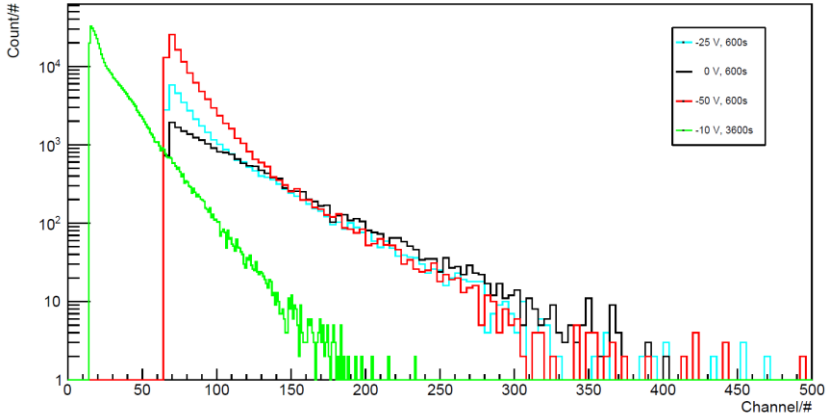


PSI - Results

Detector 72, Detector 1

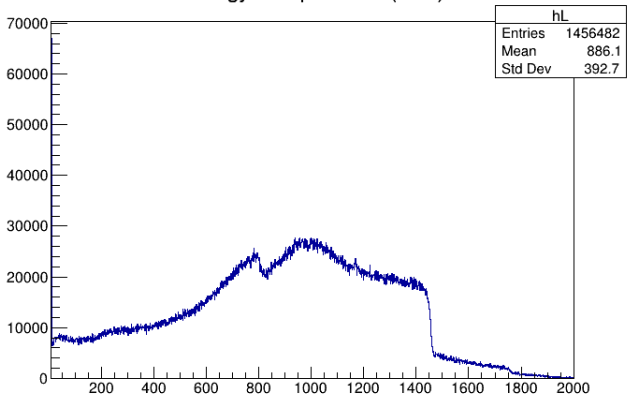


Detector 27 (trenches, 3 µm ∅, 3 µm _, 0.5 µm B_4C)



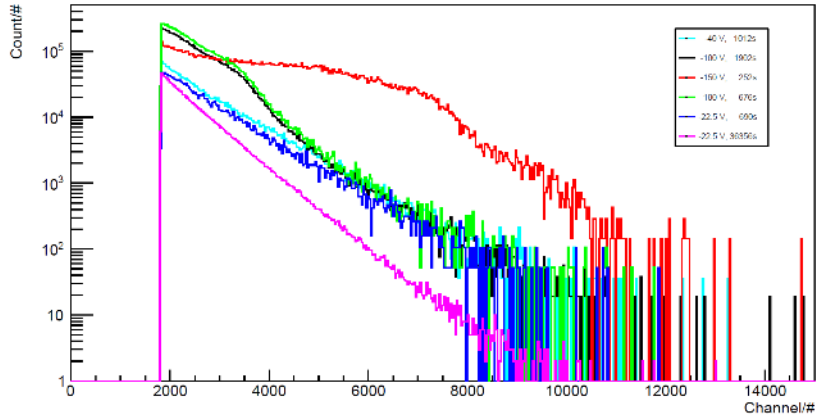
- Optimum detectors not great
- Shallow deposition did not show peaks from neutrons
- No ions in structures?

Energy v Depth Total (Last)

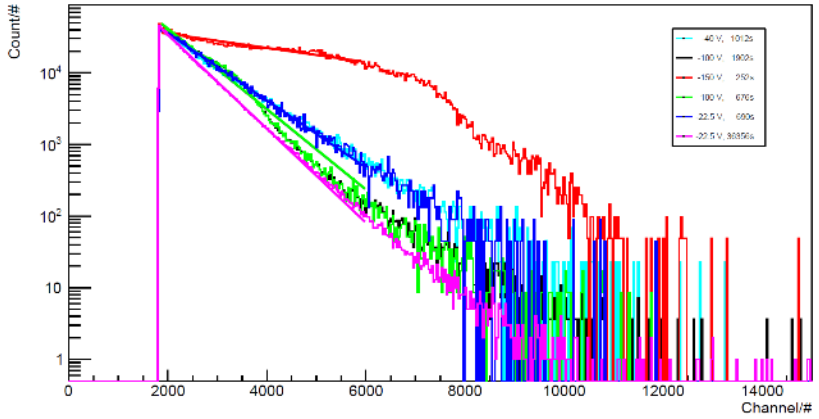


PSI - Results

Detector 28 (trenches, 3 μm ∅, 3 μm _, 1.2 μm B_4C), *normalised in t*

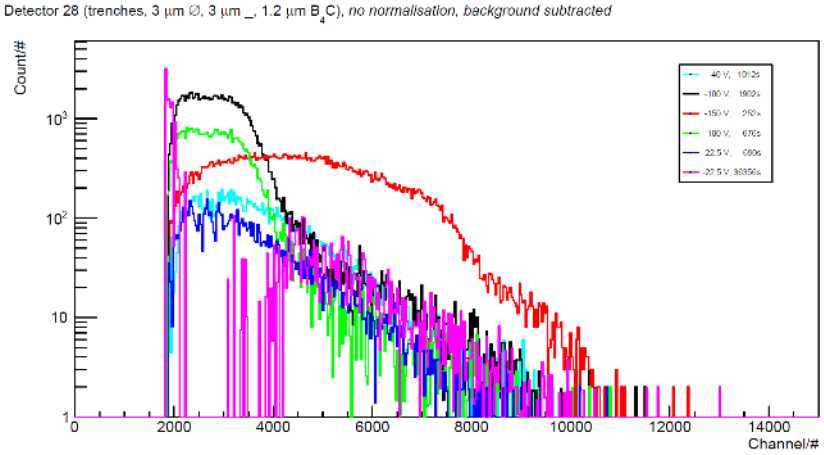


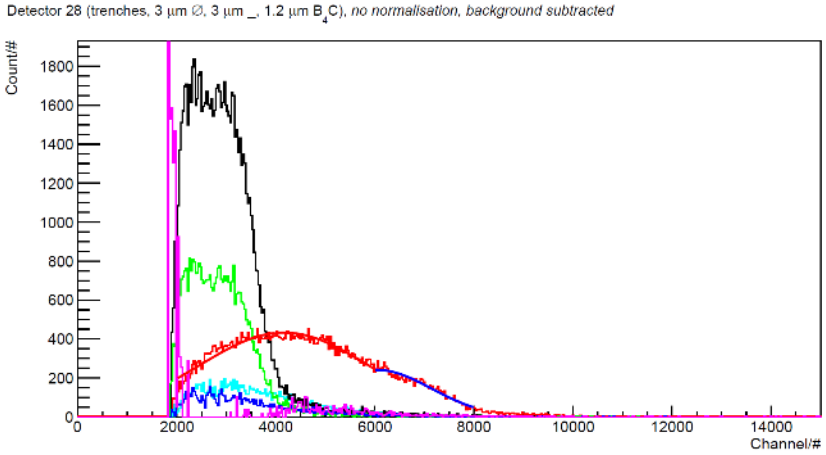
Detector 28 (trenches, 3 μm ∅, 3 μm _, 1.2 μm B_4C), *scaled in counts*



- CVD deposition does not create good detectors
- Interesting bump in detector 28 with high bias

PSI - Results

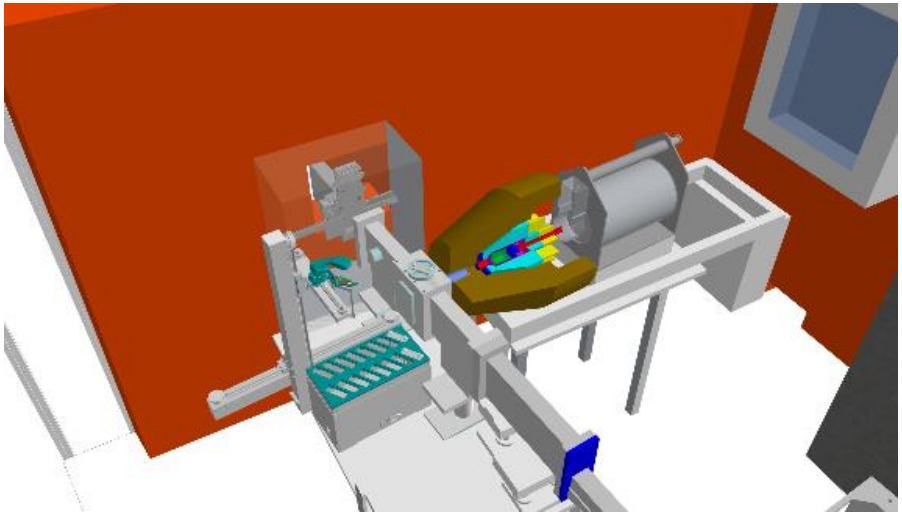




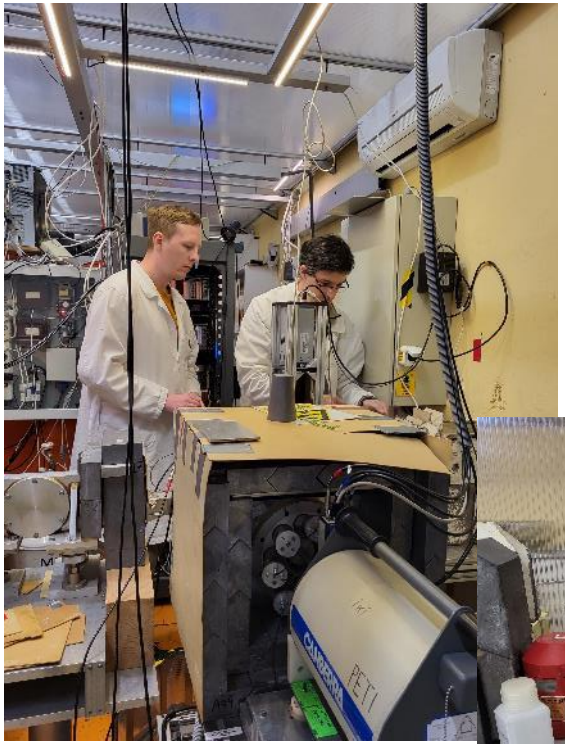
- First step is to subtract background
- Fit using modified Gaussian

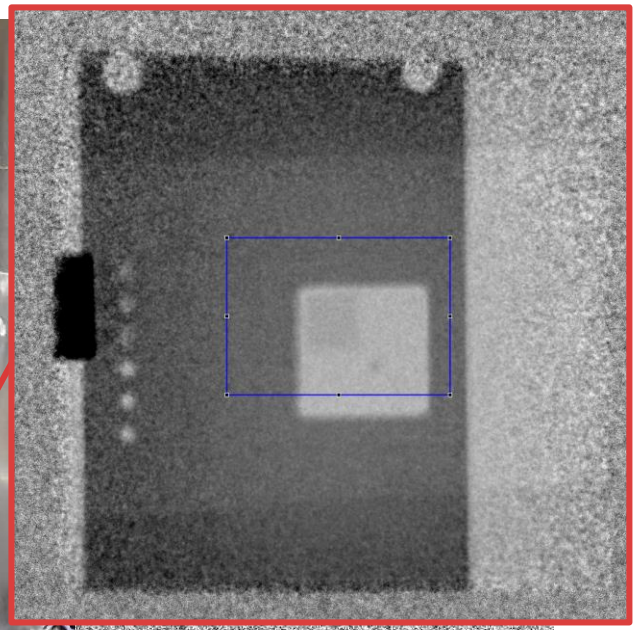
BNC - Tests

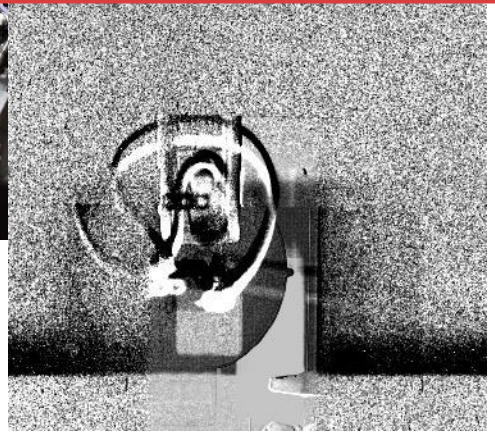
- **BNC (Hungary)** – 16th January ‘23 1400 –> 21st 1100
- Focus on best performing diodes
- 8×10^6 $ns^{-1}cm^{-2}$
- Germanium detector



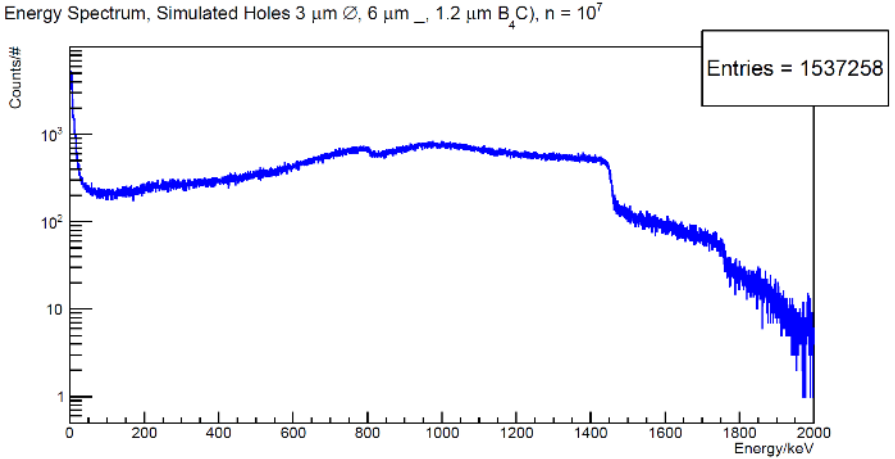
BNC - Setup

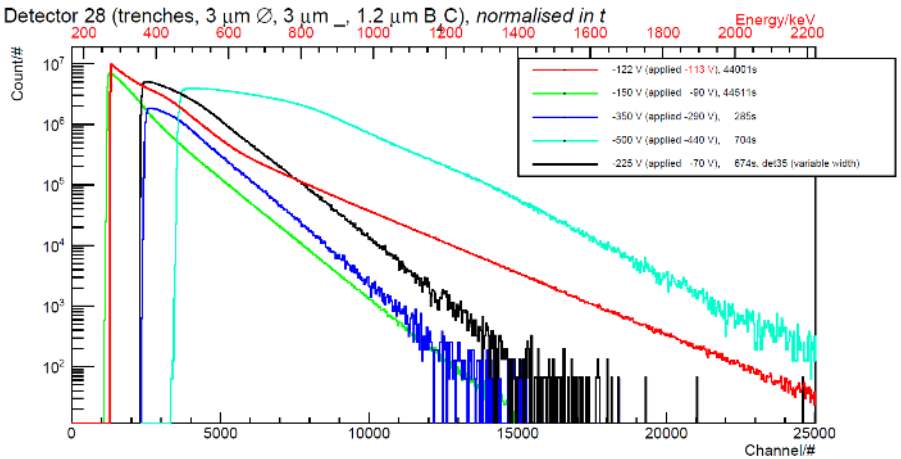






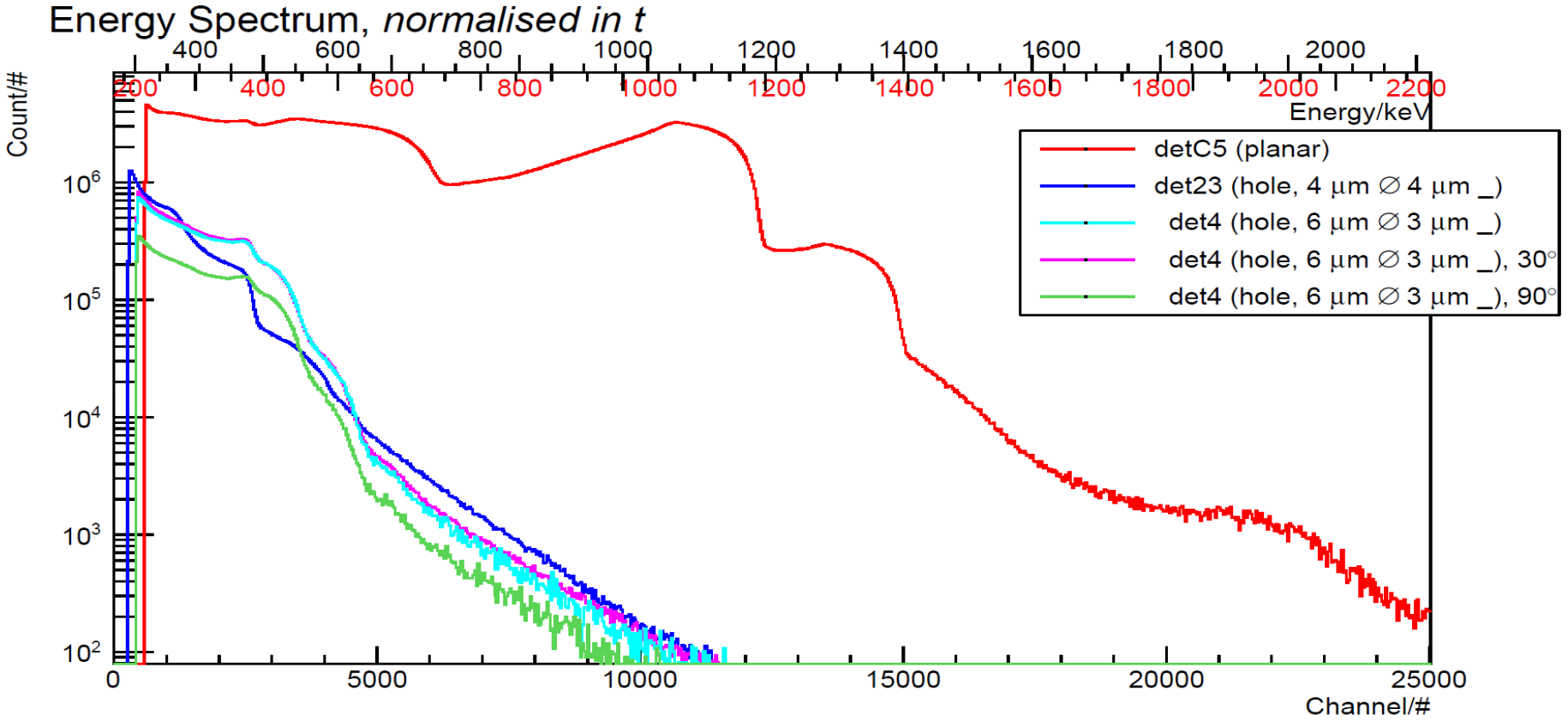
BNC - Results



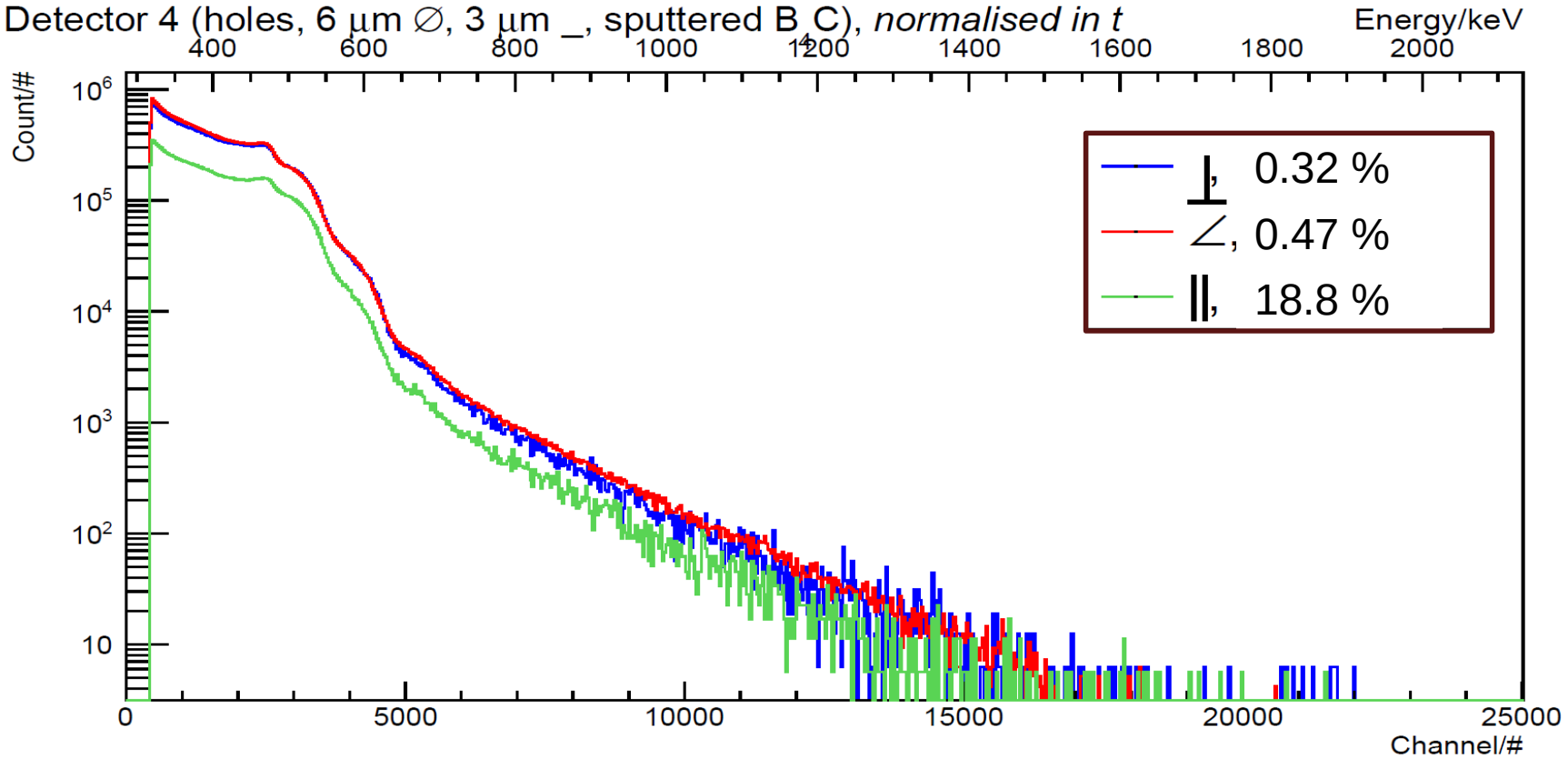


- CVD deposition does not create good detectors
- Detector 28 was statistical fluctuation

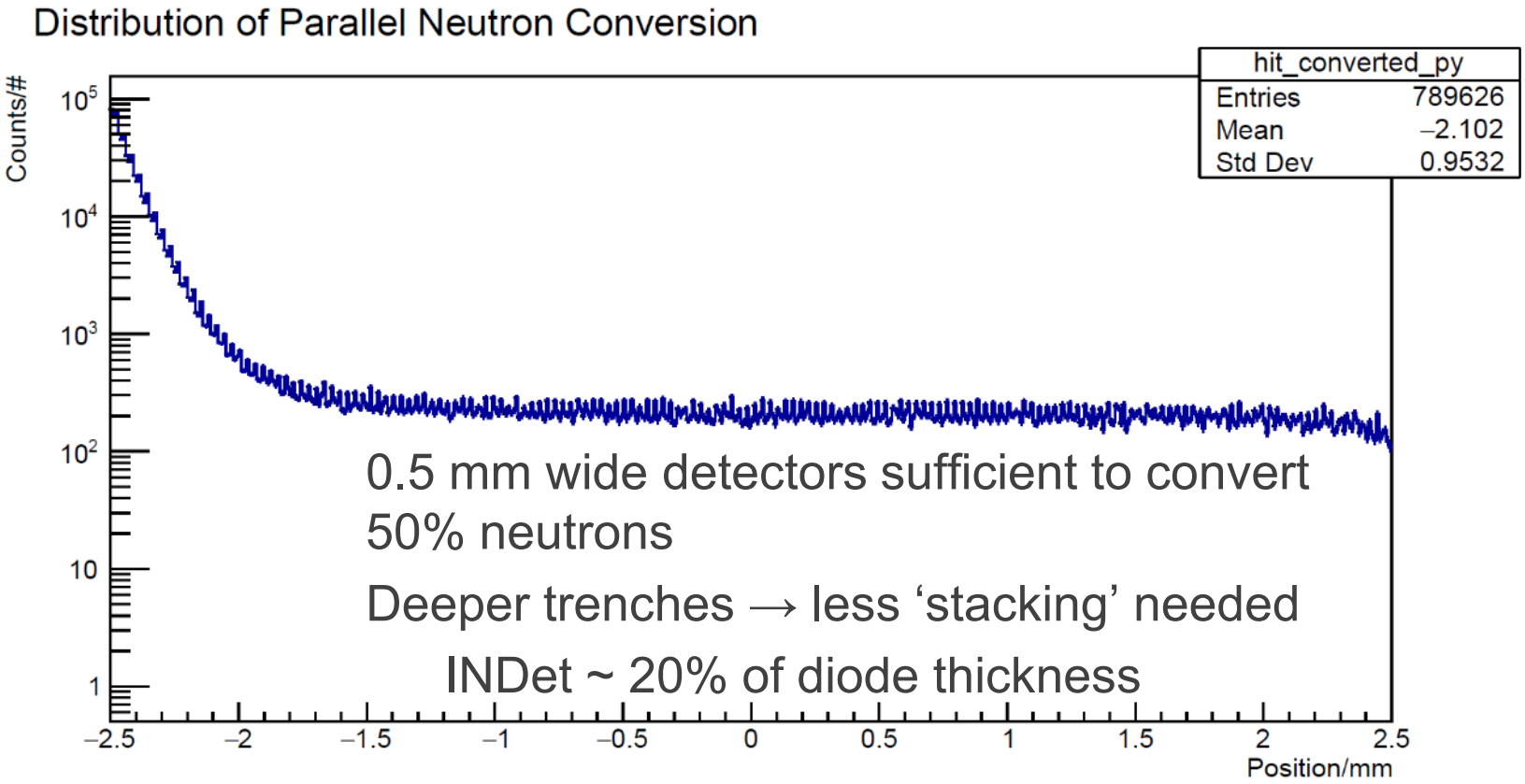
BNC - Results


Energy Spectrum, normalised in t
Count/#
Energy/keV
Channel/#
detC5 (planar)
det23 (hole, 4 µm ∅ 4 µm _)
det4 (hole, 6 µm ∅ 3 µm _)
det4 (hole, 6 µm ∅ 3 µm _), 30°
det4 (hole, 6 µm ∅ 3 µm _), 90°

BNC - Results

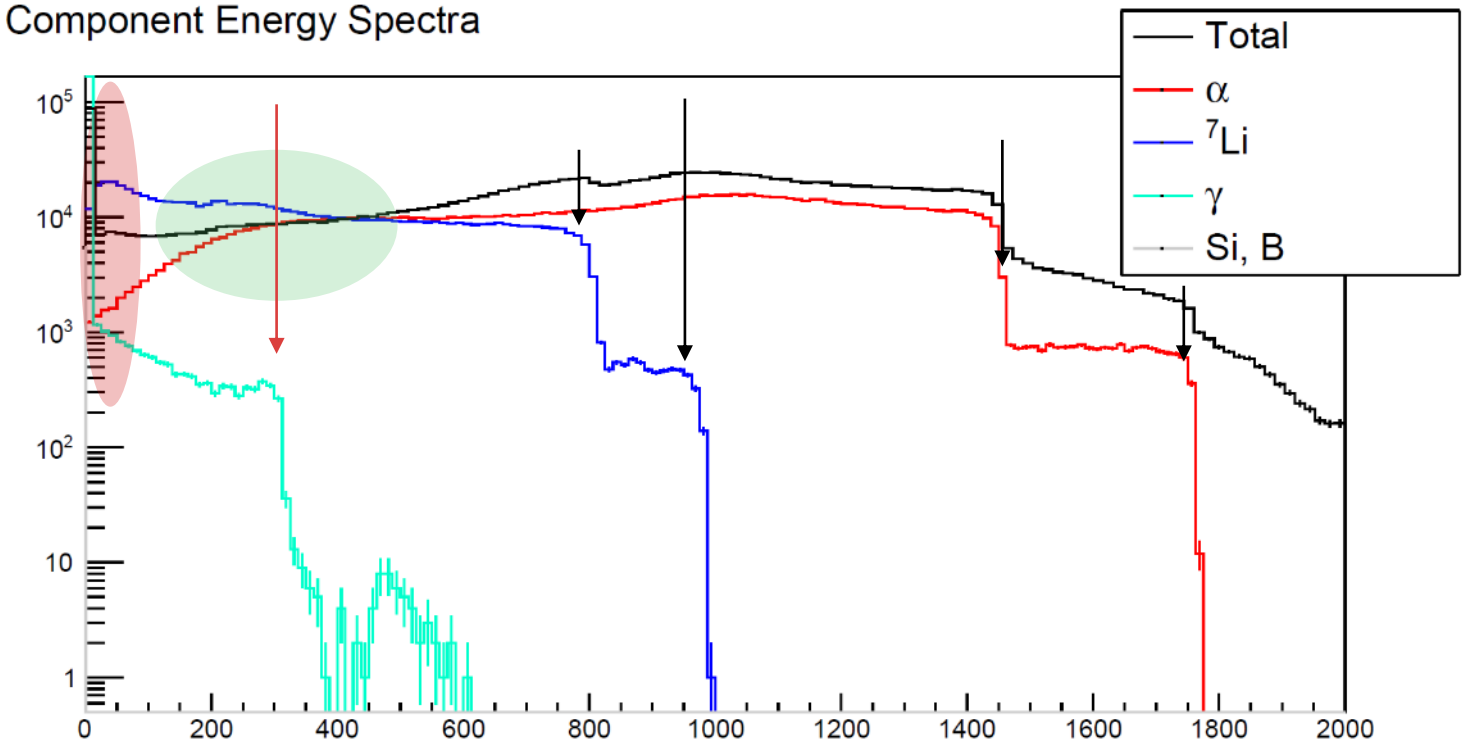

Detector 4 (holes, 6 µm ∅, 3 µm _, sputtered B4C), *normalised in t*
Energy/keV
400
600
800
1000
1200
1400
1600
1800
2000
Count/#
10^6
10^5
10^4
10^3
10^2
10
0
5000
10000
15000
20000
25000
Channel/#
⊥, 0.32 %
∠, 0.47 %
∥, 18.8 %

BNC - Results


Distribution of Parallel Neutron Conversion
hit_converted_py
Entries 789626
Mean −2.102
Std Dev 0.9532
Counts/#
Position/mm
0.5 mm wide detectors sufficient to convert 50% neutrons
Deeper trenches → less 'stacking' needed
INDet ~ 20% of diode thickness

BNC - Results

- Individual components ‘smeared’
- Look for discontinuities

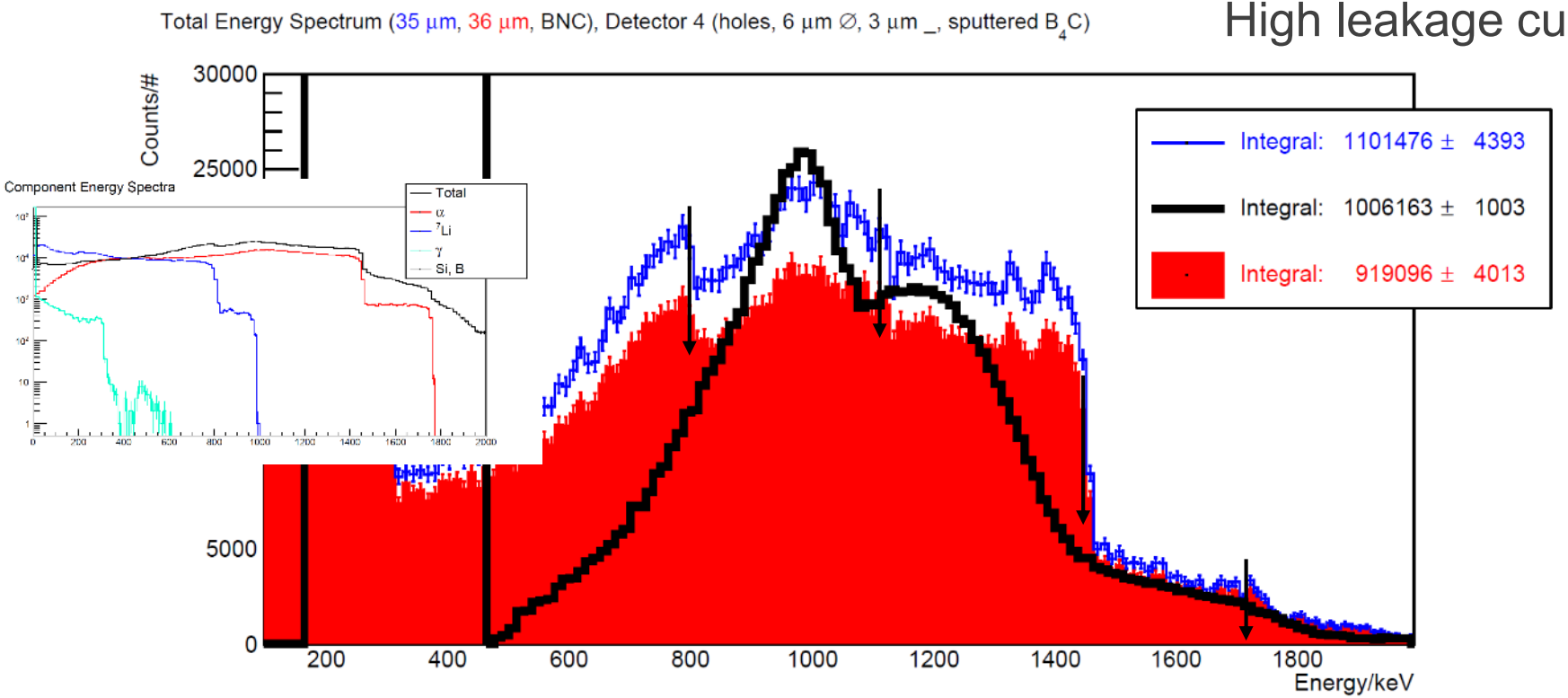


BNC - Results

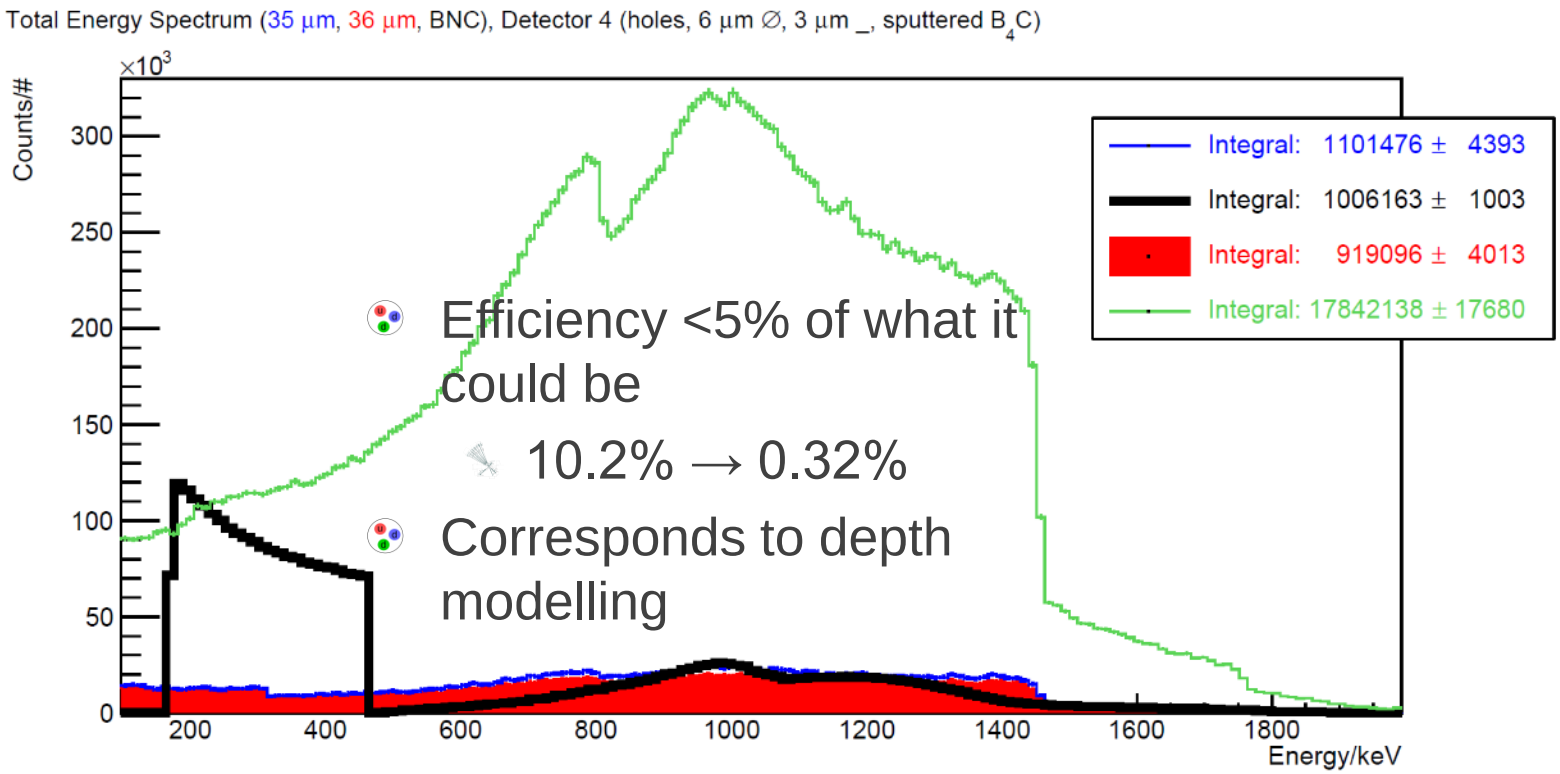
^{7}Li missing

Resolution lost

High leakage current



BNC - Results


Total Energy Spectrum (35 µm, 36 µm, BNC), Detector 4 (holes, 6 µm ∅, 3 µm _, sputtered B4C)
Counts/#
×10^3
300
250
200
150
100
50
0
200
400
600
800
1000
1200
1400
1600
1800
Energy/keV
Integral: 1101476 ± 4393
Integral: 1006163 ± 1003
Integral: 919096 ± 4013
Integral: 17842138 ± 17680
Efficiency <5% of what it could be
10.2% → 0.32%
Corresponds to depth modelling

Summary – What Lessons Learnt?

Monte Carlo simulations allow for inexpensive testing of 3-D silicon for neutron applications

- Modification required for real-world conditions

B_4C deposition on top of DRIE structures leads to high noise

Alter bias contact points

90° angles allows for slim, efficient stacked detectors that could fully replace tubes

- If noise issues identified and fixed

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[3]University of Linkoping, Sweden
[4]Bruno Kessler Foundation, Trento, Italy
[5]European Spallation Source (ESS), Sweden
[6]Institute for Energy Technology, Oslo, Norway
[7]Czech Technical University, Prague, Czechia

Thank you!