Scintillation Light Detection in Polycrystalline Diamond Using Single Photon Detectors

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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6th International Workshop on new Photon-Detectors

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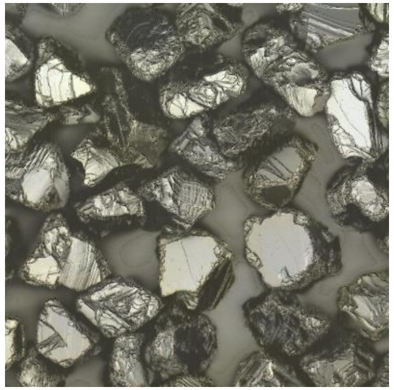
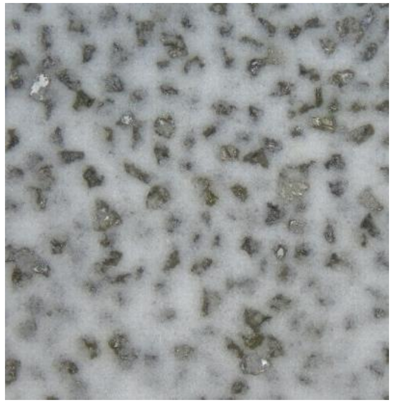
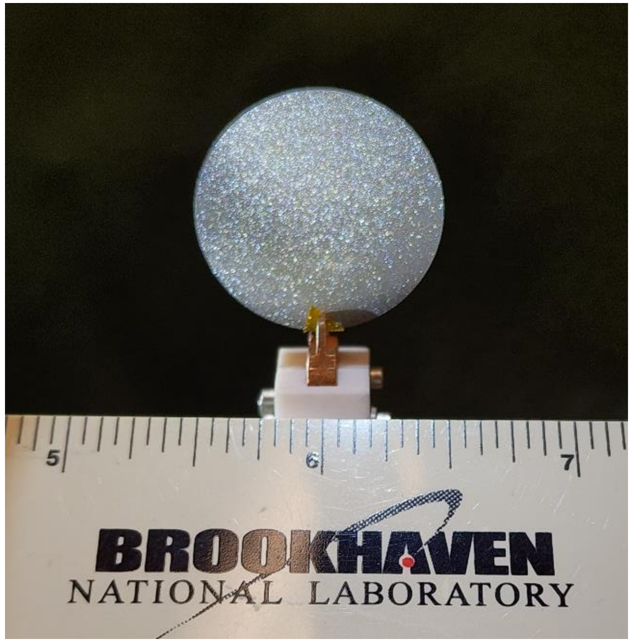
PD24

Outline

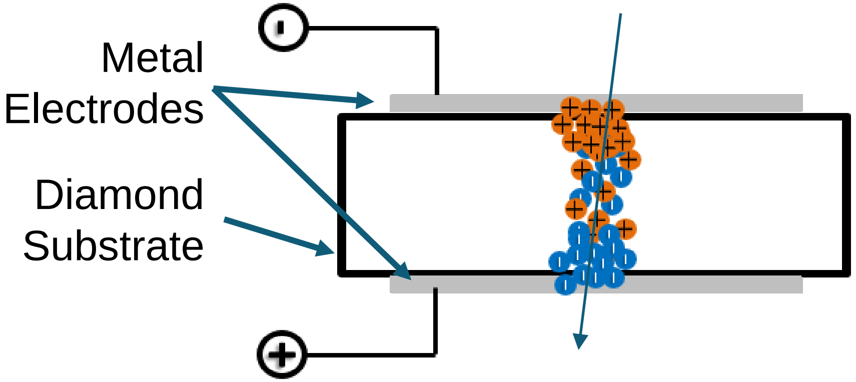
- Charge collection vs light collection in diamond
- Photoluminescence in diamond
- Scintillation in diamond
  - Light Yield
  - Imaging
- Neutron detector development
  - Concept and simulations
  - Compare with ^{3}He detector
- Paths forward
- Conclusions

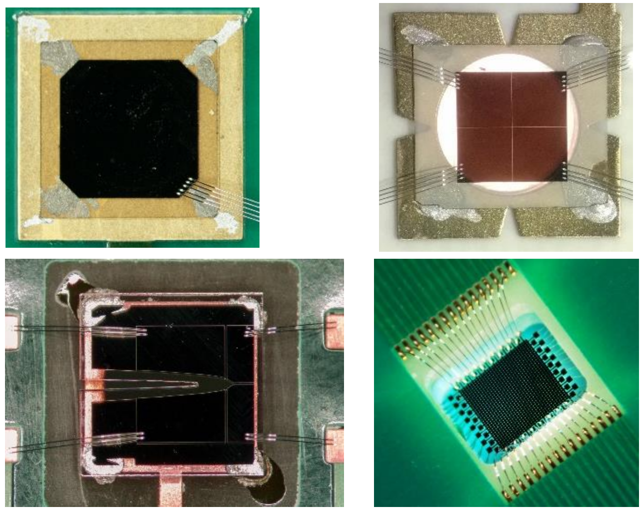






Diamond detectors (charge readout)

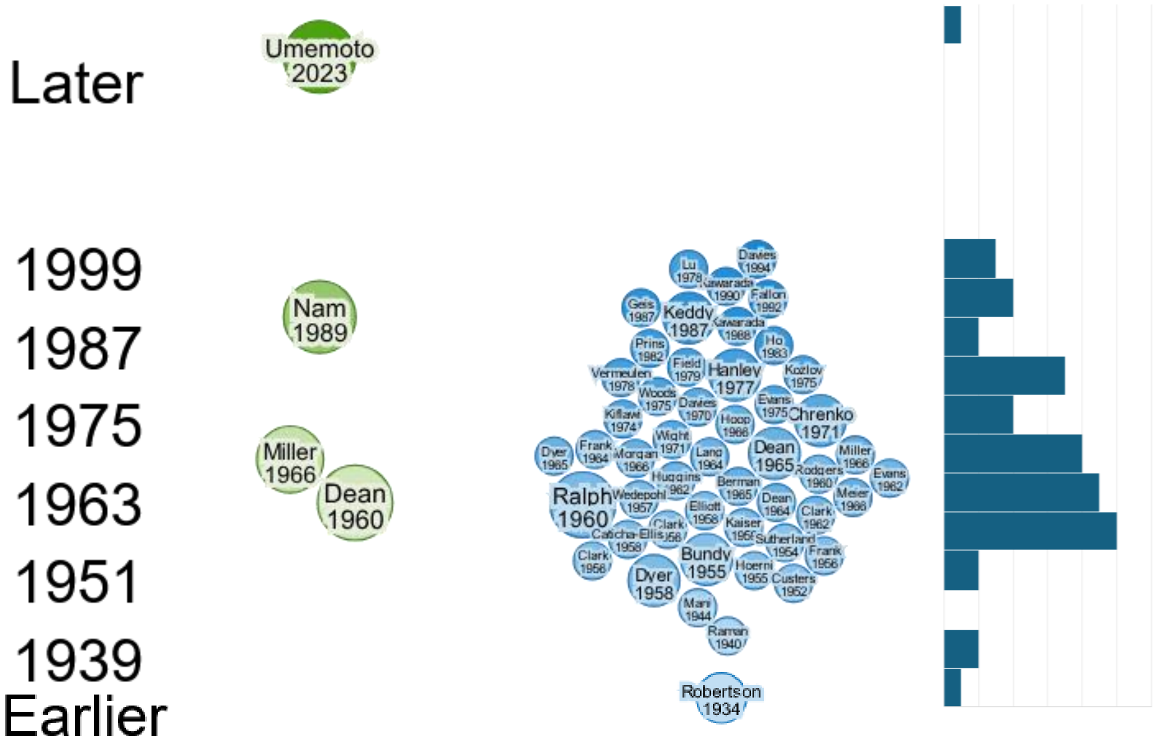




Advantages:
- Rad Hard
- Gamma “blind”
- Fast (100s of ps)
- Thermal Cond.
- Large bandgap, low leakage
- Lithography – Spatial Res.

Disadvantages:
- Small (5mm x 5mm)
- Expensive (~$2k each plate)
- Limited availability
- Need high purity (~10ppb N_2)
- Single crystals, high crystallinity
- Lithography – Time

Diamond detectors (scintillation?)



- Four papers reporting on diamond scintillators as input to “research rabbit”
- Peak of activity around ~60s/70s, and a few papers in the early 90s
- Note that most of them study impurities through TL (ThermoLuminescence) for charge readout
- Then…

- Now new interest seems to arise, given developments in diamond growth

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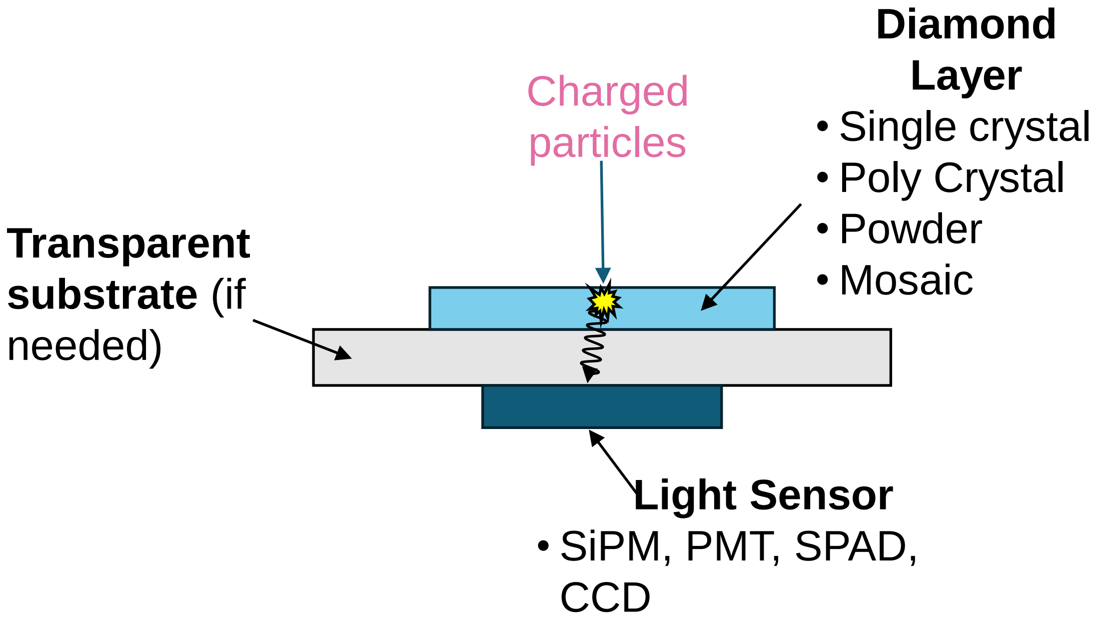
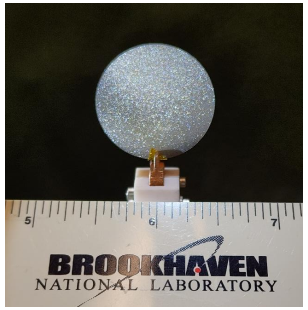
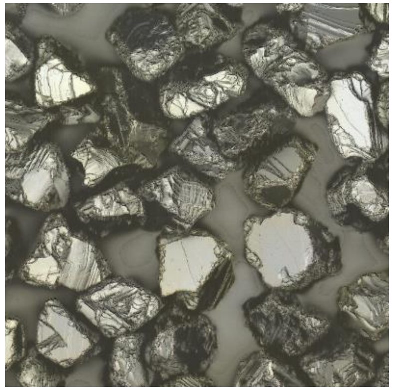
Diamond detectors (scintillation!)







Advantages:
- Rad Hard
- Gamma “blind”
- Fast (rise times ~1ns)
- Low quality diamond
- Large areas
- Relatively inexpensive
- Promising light yield

Disadvantages:
- Geometry needs optimization
- Light yield needs optimization
- Very high refractive index
- Thick layers may not be transparent

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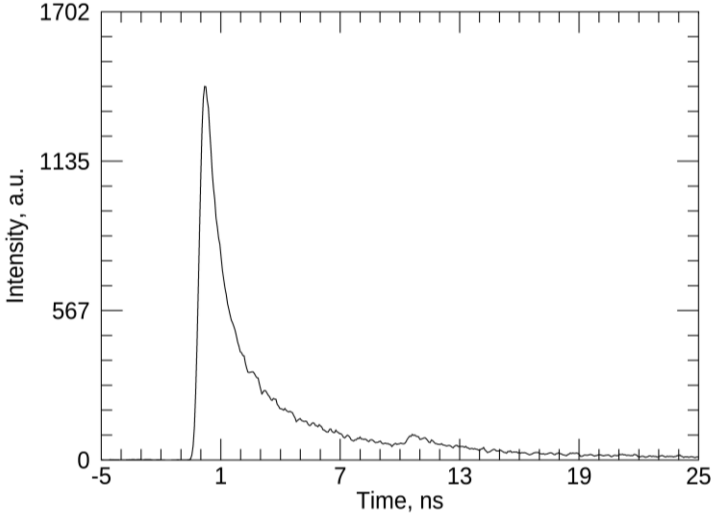
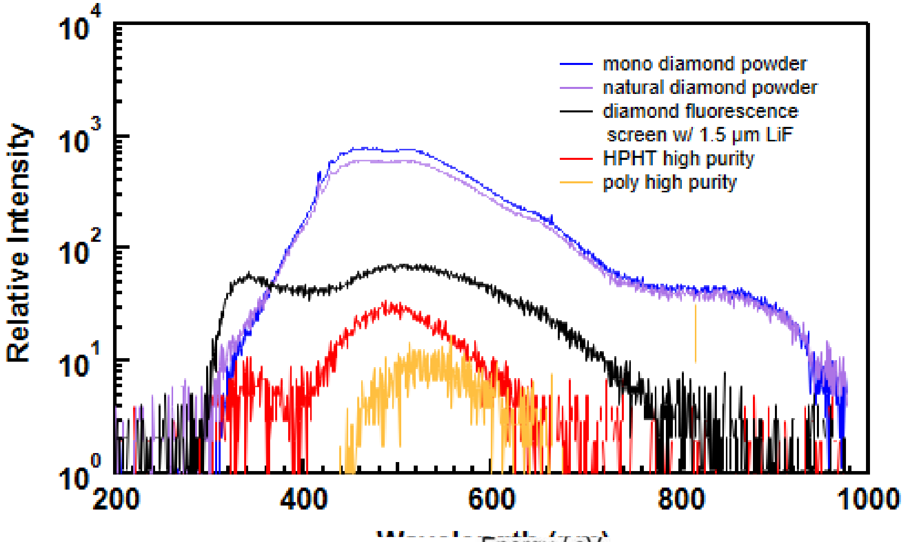
Photoluminescence in diamond

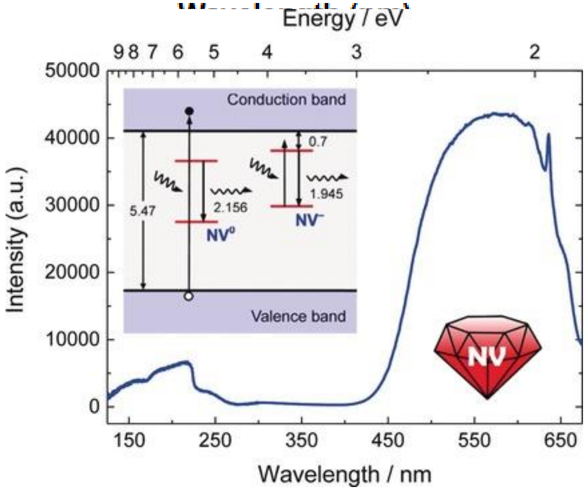
Timing



Photoluminescence from different diamonds

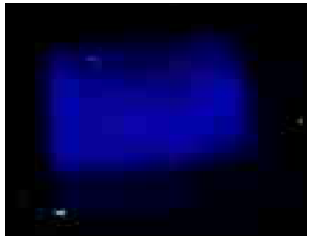


- XID:YAG 266 nm laser (20 ps)
- Ocean optics spectrometer (195-995 nm)
- ThorLab SPAD with < 40 ps time response

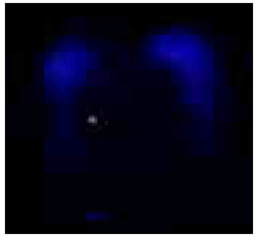


H.-C. Lu, et al., *Angew. Chem. Int. Ed.* **2017**, *56*, 14469.

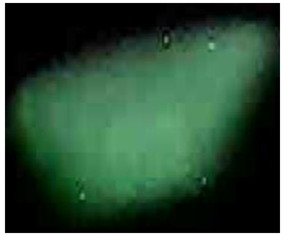
HPHT



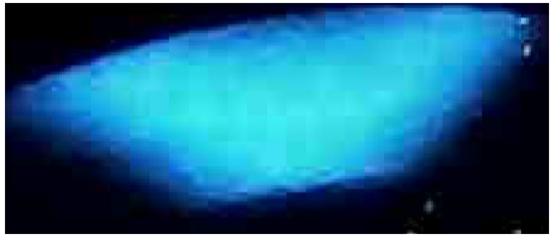
E6 poly



E6 single

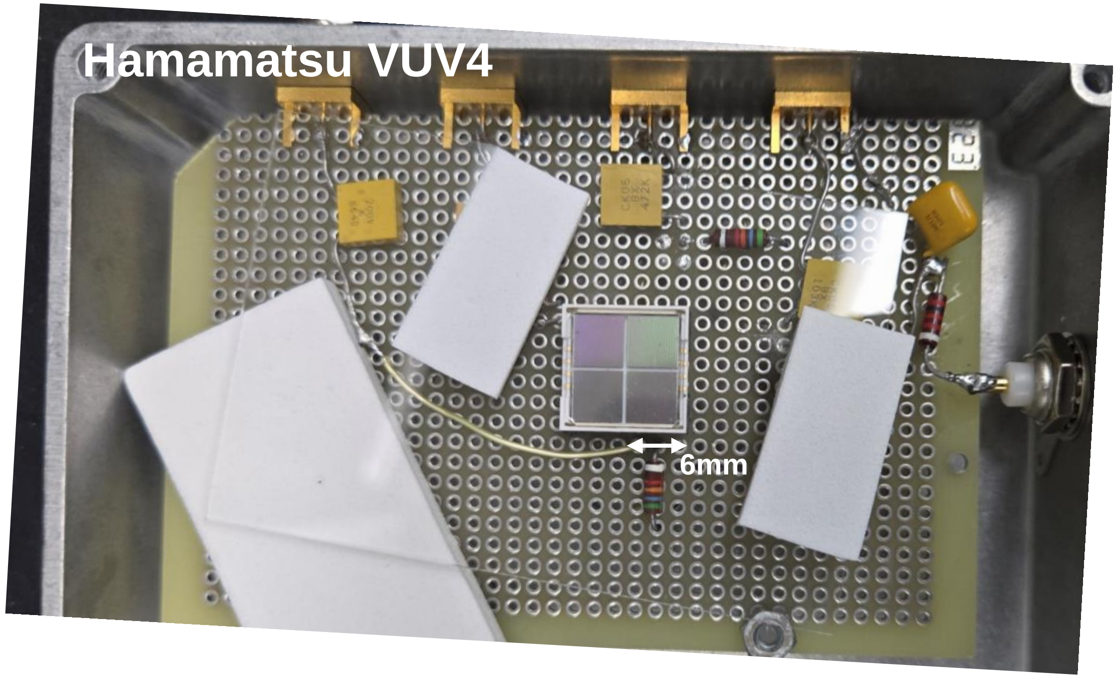


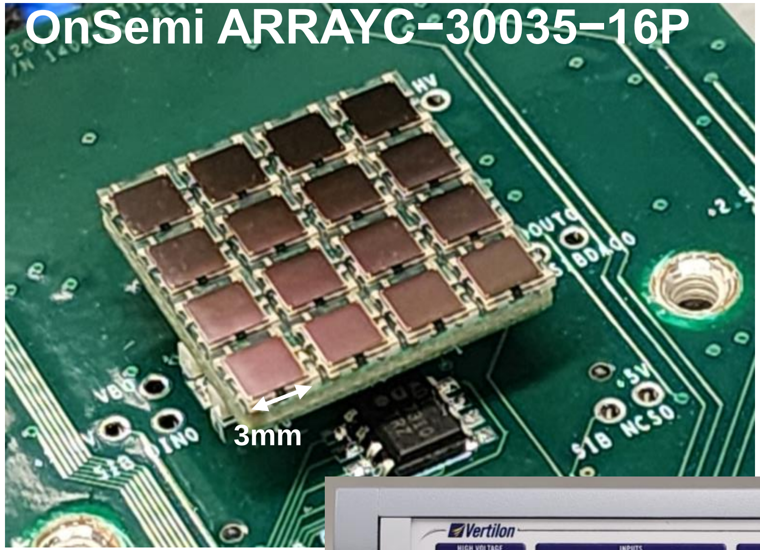
Diamond powder on tape



Diamond powder on tape

Scintillation in diamonds: setups



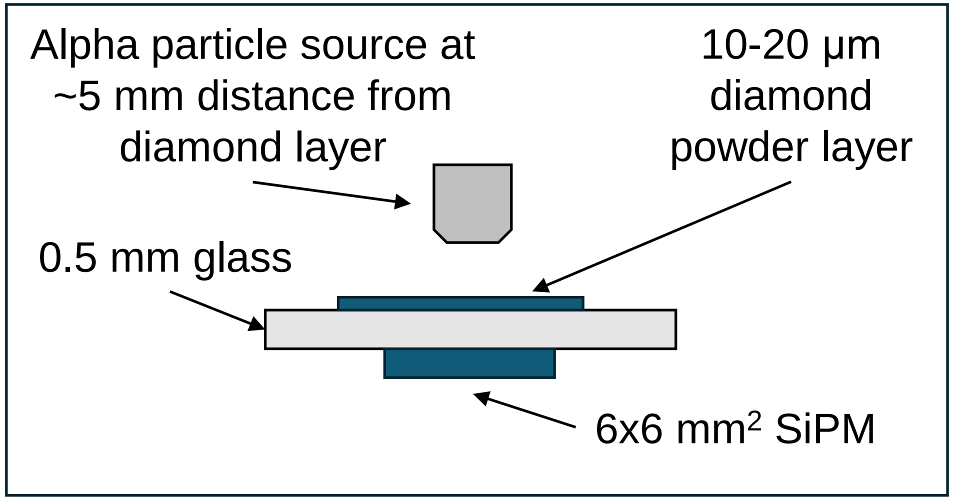


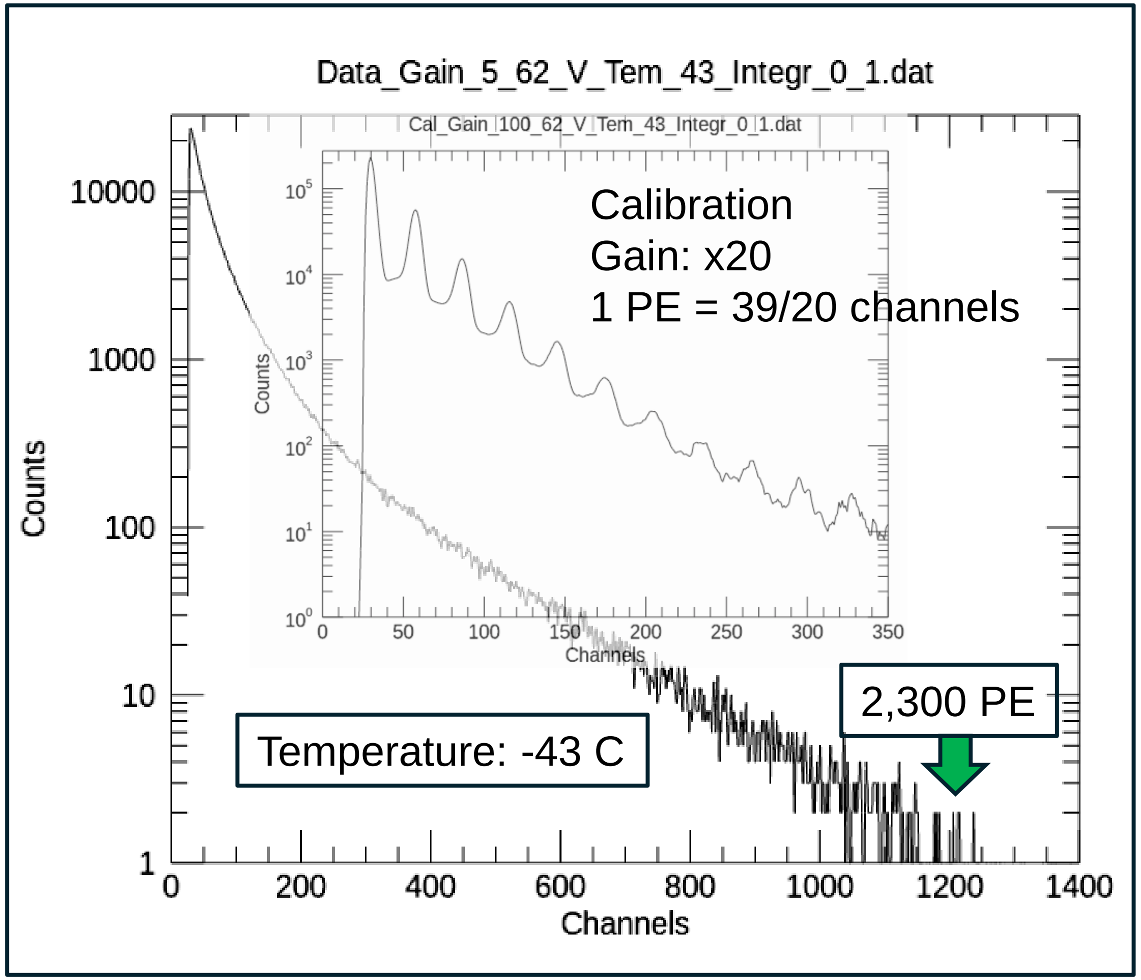
- Hamamatsu VUV4 S13371 (6mm x 6mm)
- Readout: MCA

- OnSemi C-Series 35 µm (3mm x 3mm)
- 32 channel SiPM readout
- Recording charge per channel per trigger

Scintillation of natural diamond powder (10-20 µm)

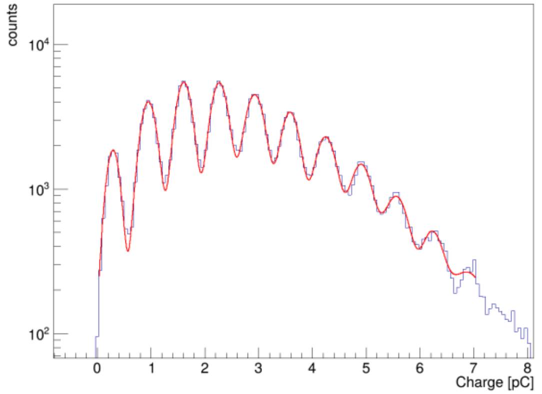
- 5.5 MeV alpha particles from ^{241}Am
- Light variations due to powder non-uniformity and solid angle

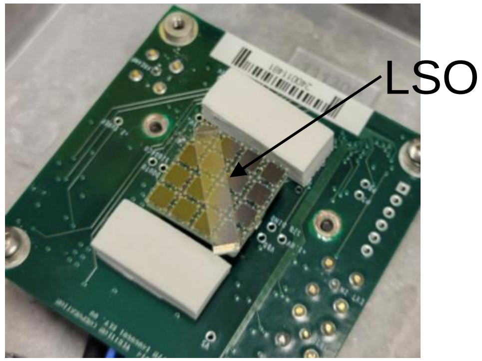


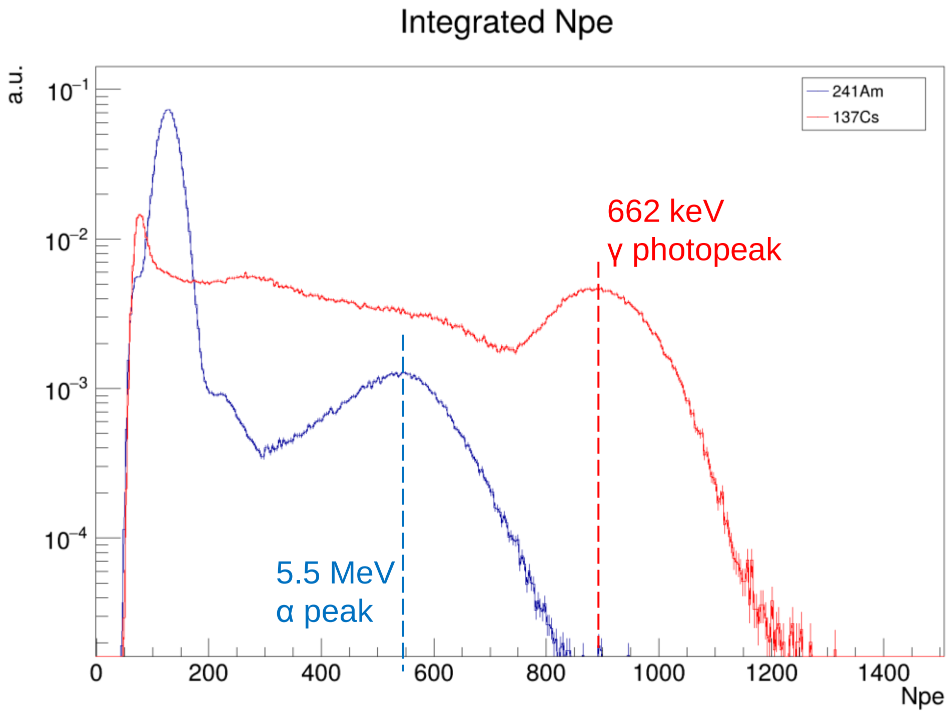


Sensor calibration and reference sample

- Single photon calibration
  - A laser is used to illuminate the array and trigger the acquisition
  - Multi-gaussian fit to extract gain for each SiPm
- Used an LSO crystal as reference sample
  - Irradiated under γ (^{137}Cs) and α (^{241}Am)
- Fitting the peaks:
  - γ →1.3 detected pe*/keV
  - α →0.1 detected pe/keV
  - Resulting in α/γ~0.08







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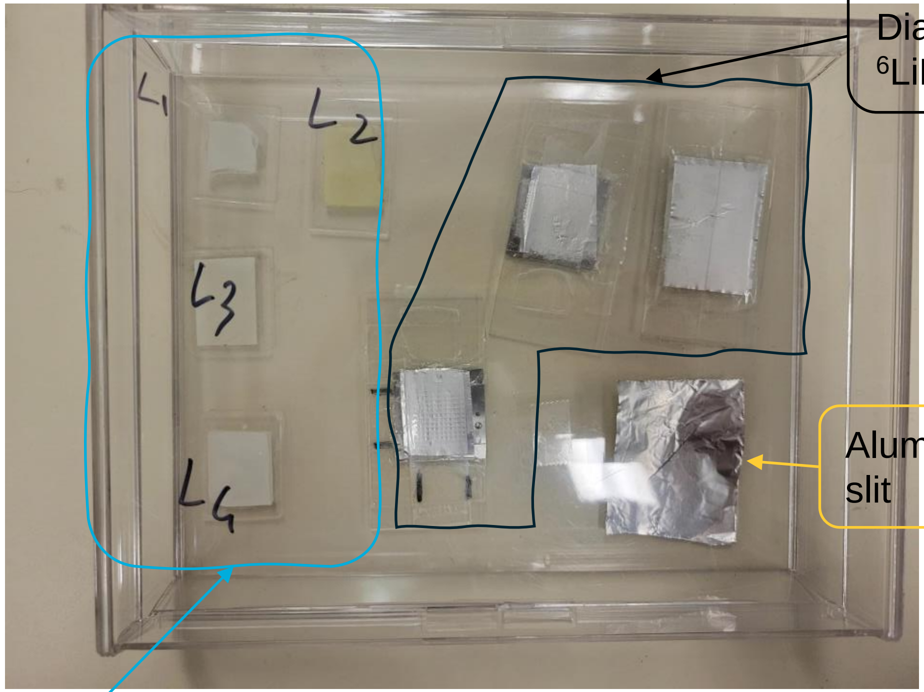
*pe: photoelectrons

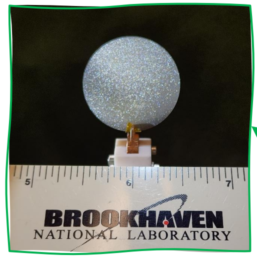
Systematic study: samples and setup



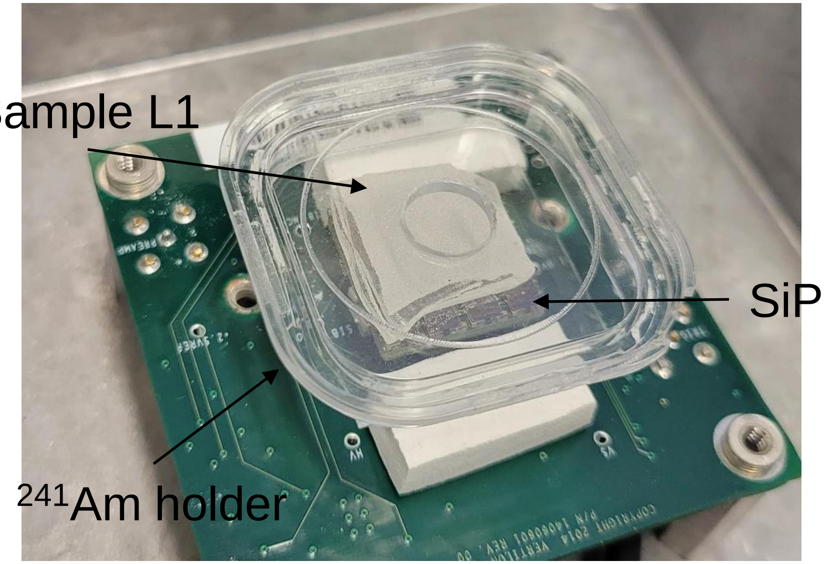
Glass substrate + Diamond powder + ^{6}LiF powder

Aluminum foil with slit

Glass substrate + Optical tape + Diamond powder



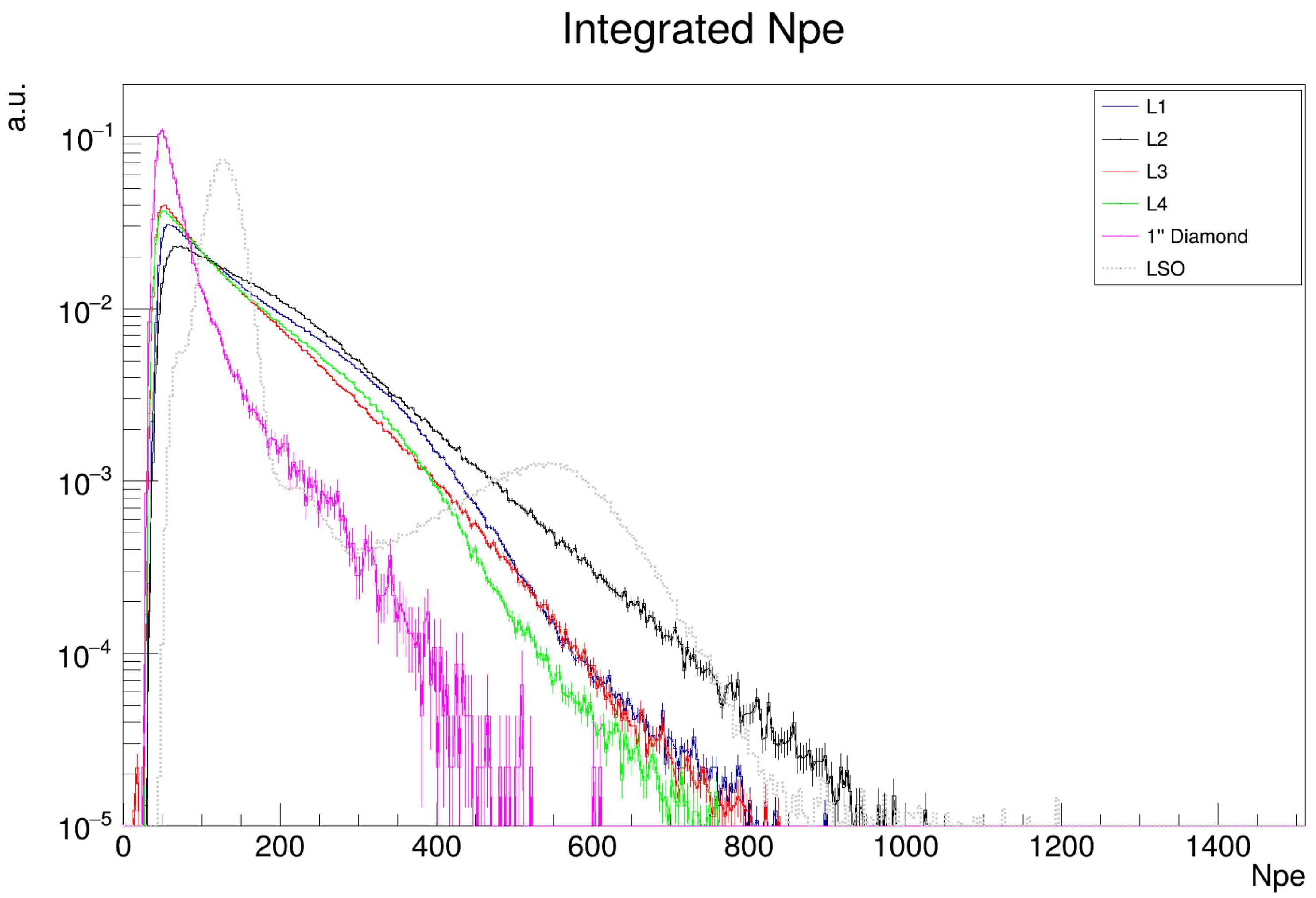
1'' CVD high purity diamond + ^{6}LiF coating on one side



- The sample is laid on the SiPM array
- An alpha source (^{241}Am) is placed on top of the holder
- Data are acquired triggering on the sum signal of all the array

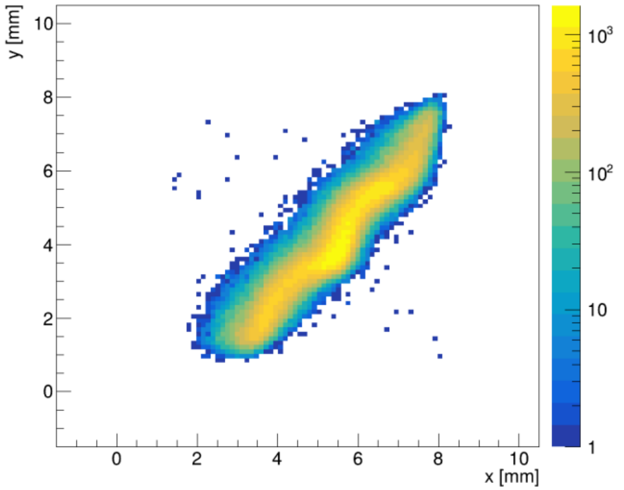
Diamond scintillation: spectra

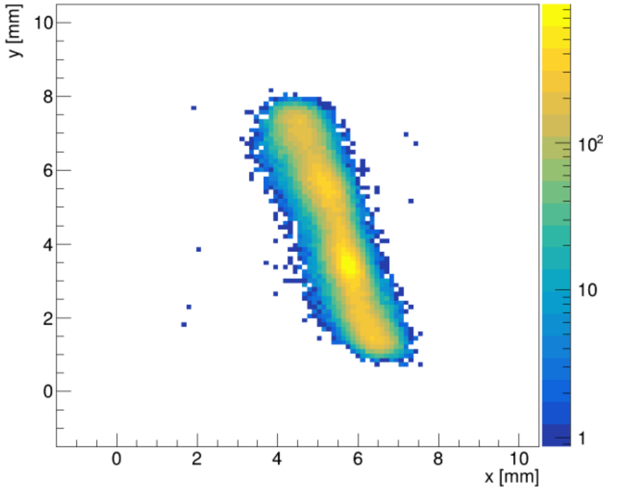
- Spectra of the five samples in terms of detected photoelectrons
- The 1'' diamond shows a lower light yield: this is a low impurity sample
- L2 show the longer tail at higher Npe: its yellow color might indicate higher levels of impurities (dopants)
- Various unknowns: uniformity, thickness, transparency, doping concentrations



Diamond scintillation: position sensitive

- A slit is cut through an aluminum foil and placed on the sample (L4)
- The alpha source is placed at about 0.5 cm on top of it
- Then, the slit is then rotated in the opposite direction
- For each event, the center of mass is computed:
  - $\bar{x}_{cm} = Q_{tot}^{-1} \sum_{i=1}^{n_{SiPM}} Q_i \bar{x}_i$





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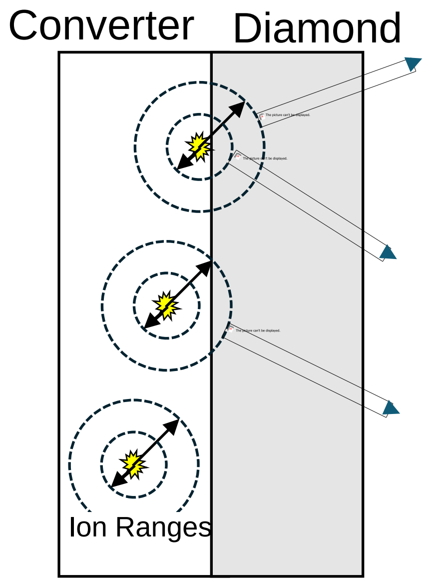
Designing a diamond neutron detector

$^{6}Li + ^{1}n \rightarrow ^{4}He$ (**2.05 MeV**) + ^{3}H (**2.73 MeV**)

Ion ranges of reaction products	
Cross Section (25meV)	955 barn
Attn. Length ($\lambda = 1/n \cdot \sigma$)	~171 µm (^{6}LiF)
Triton escaping ^{6}LiF	33.7 µm
α escaping ^{6}LiF	6.05 µm
Triton into Diamond	20.9 µm
α Into Diamond	3.63 µm

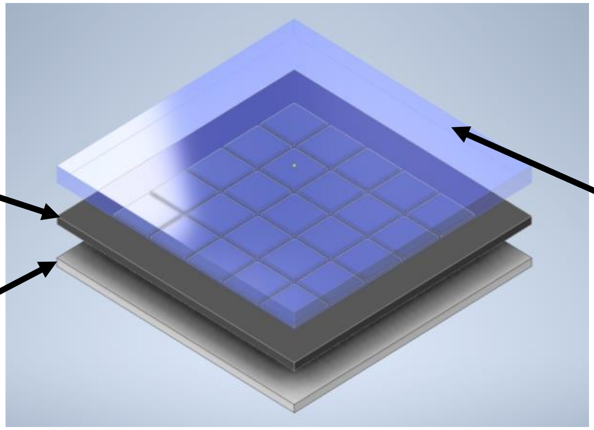
$^{10}B + ^{1}n \rightarrow ^{7}Li$ (**0.84 MeV**) + ^{4}He (**1.47 MeV**)

Ion ranges of reaction products	
Cross Section (25 meV)	3840 barn
Attn. Length ($\lambda = 1/n \cdot \sigma$)	~18.8 µm
Triton escaping ^{10}B	1.83 µm
α escaping ^{10}B	3.53 µm
^{7}Li into Diamond	1.17 µm
α Into Diamond	2.52 µm



SiPM array

DAQ



Diamond/Converter
- Paraffin (fast neutrons)
- ^{6}Li or ^{10}B – thermal neutron
- Engineered structure

Other possible converter materials

- h^{10}BN
- Gadolinium / Gadolinium oxide
  - Transparent
  - Cross section: 2.54×10^{5} barns

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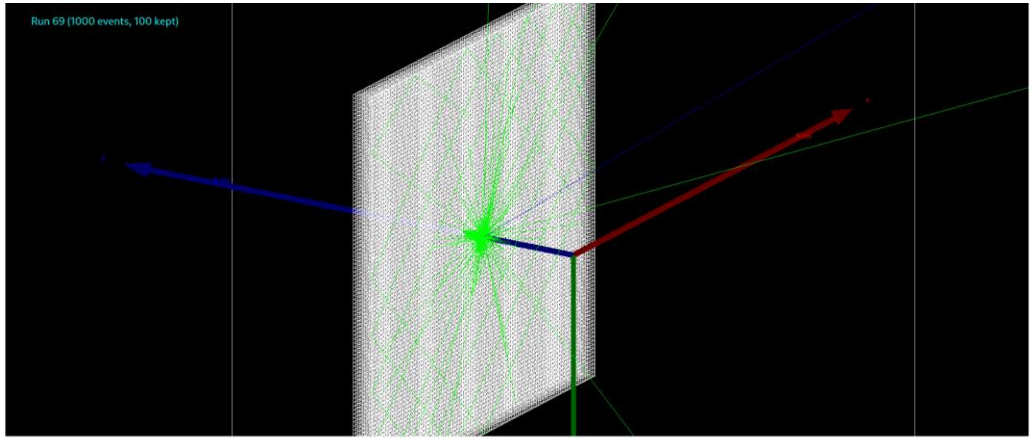
Single layer design: simulation

- A 100 µm thick diamond is placed orthogonally to the incoming thermal neutrons (25 meV)
- One side of the diamond is coated with a ^{6}LiF film
- The other side of the diamond is coupled to a highly pixelated sensitive volume mocking a photodetector
- FTFP_BERT_HPT Physics is used
- Optical photons propagation included
- The neutron detection efficiency is evaluated vs the 6LiF thickness
  - A neutron is considered detected if the detected photons are >20
  - $\text{Efficiency} = \text{detected neutrons}/\text{impinging neutrons}$

	Diamond	^{6}LiF	Detector
Refractive index	2.46	1.4	1.5
Attenuation length	1 mm	0.5 mm	NA
Light yield	3000 ph/MeV	N/A	NA
Thickness	100 µm	0.1-1.8 µm	1 mm



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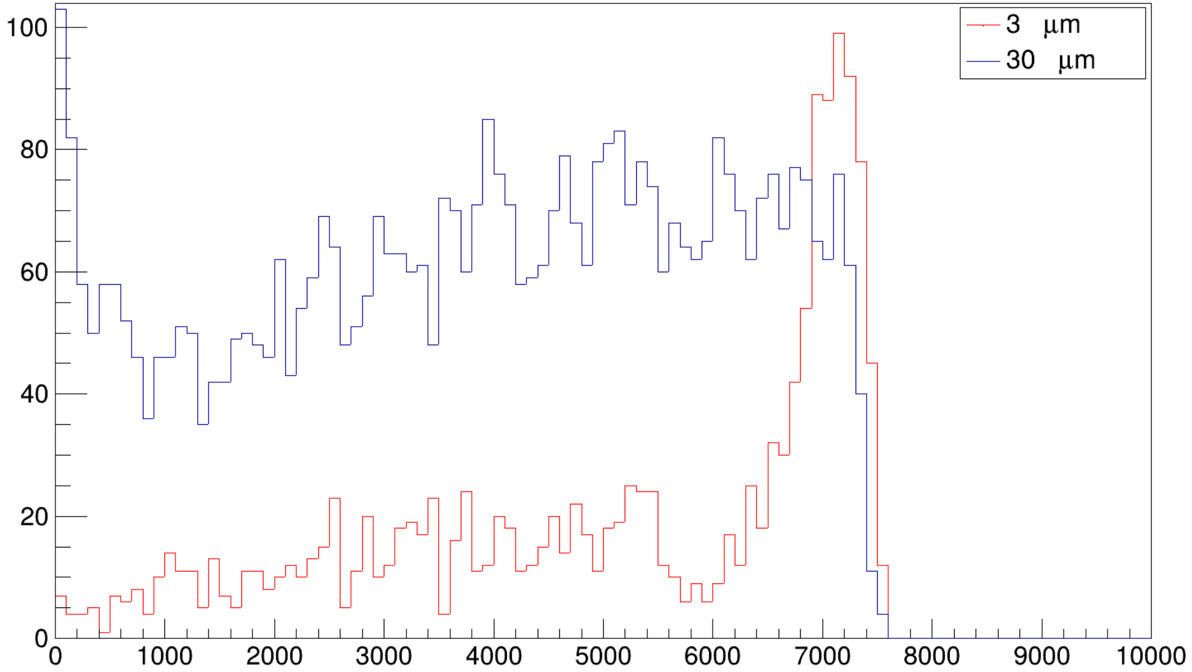

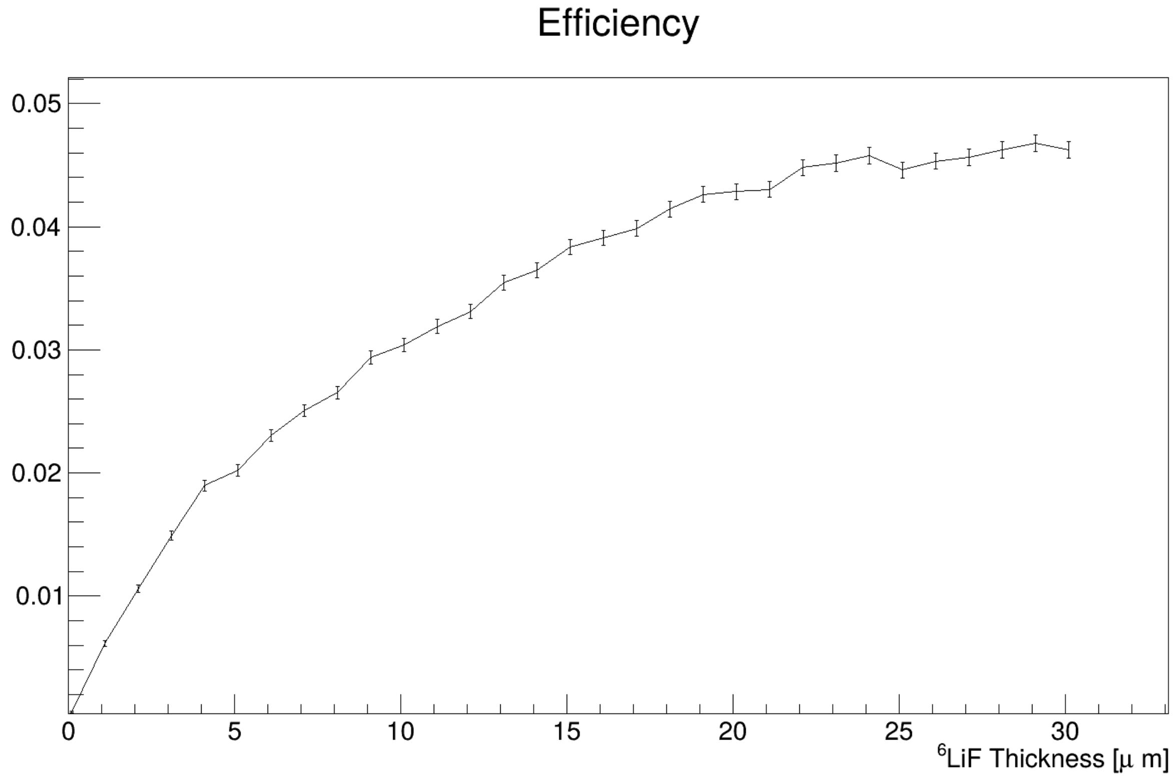

(Left) Spectra for ~3 µm, ~29 µm ^{6}LiF thickness. (Right) Efficiency vs ^{6}LiF thickness.

- 10 µm → ~3% efficiency. Stacking 10 layers, it is possible to reach ~30% (assuming transparency)

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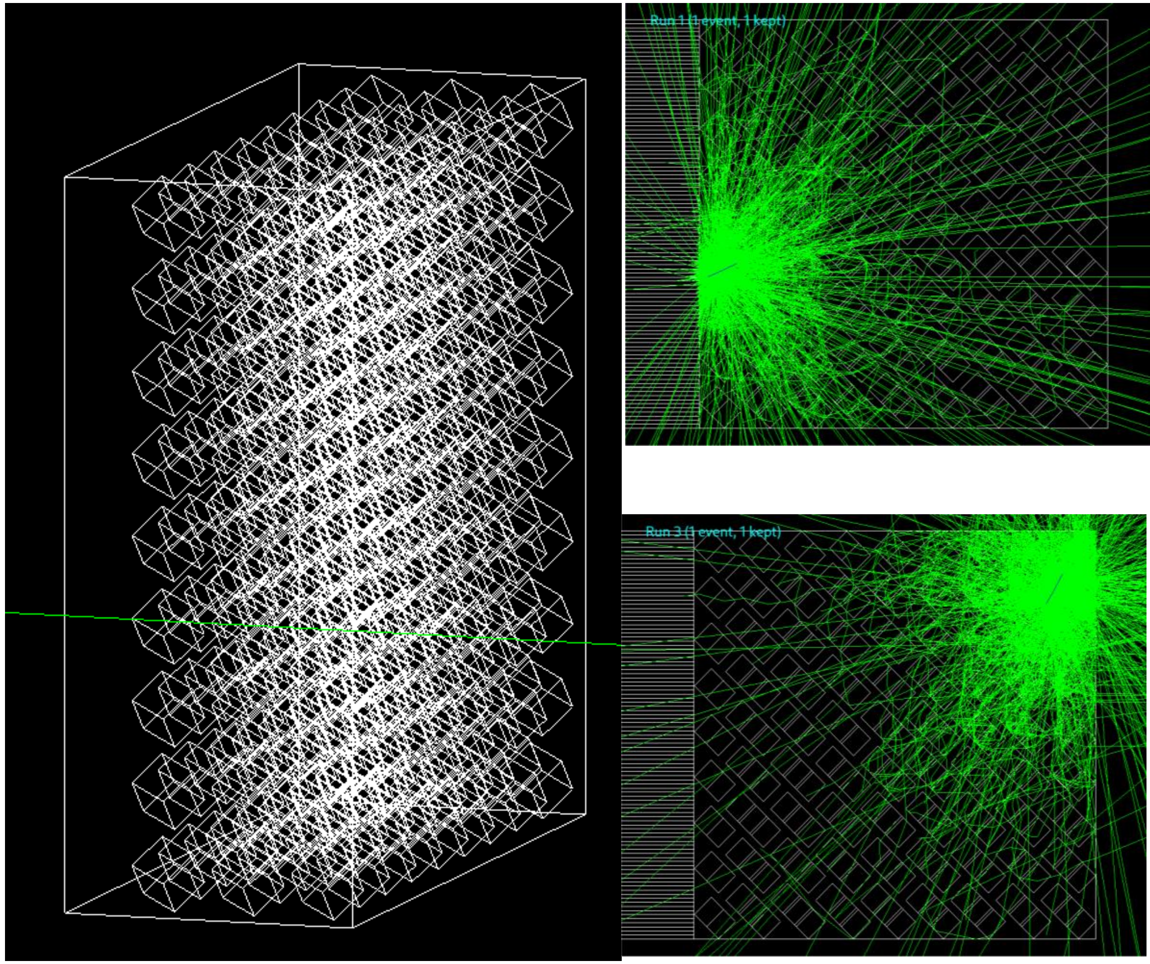
Diamonds embedded in converter: simulation

- Diamond crystals (~20 μm) are modeled as cubes and placed on a lattice pattern
- The surrounding is made of a ^{6}LiF block
- Detector dimensions reduced to 0.3 mm x 0.3 mm to limit computation time
- Same material properties and physics as before



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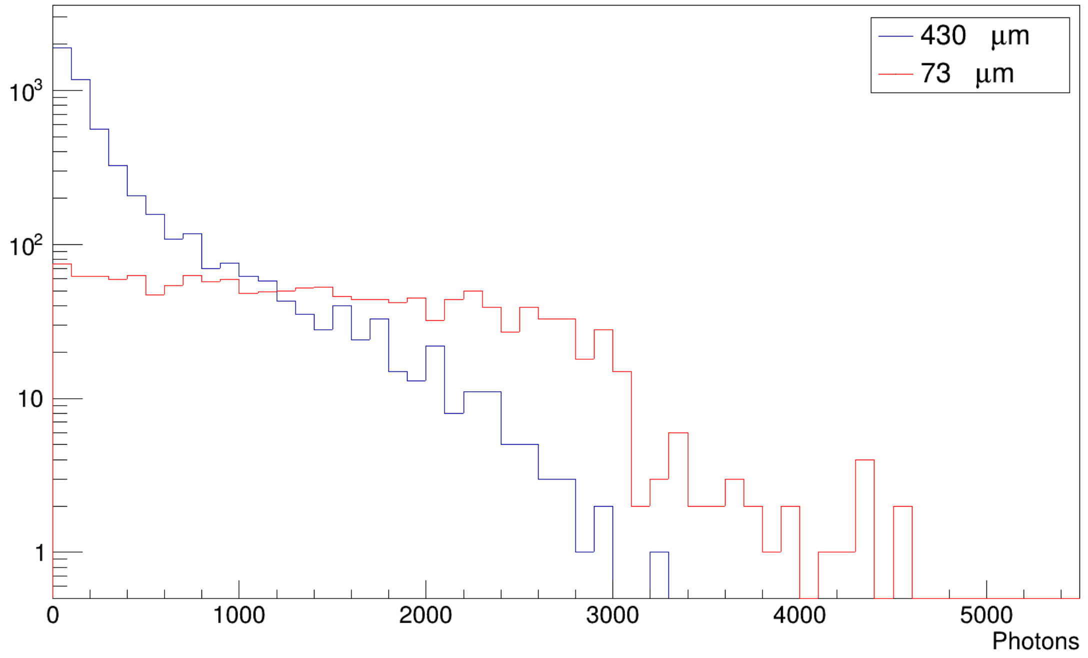
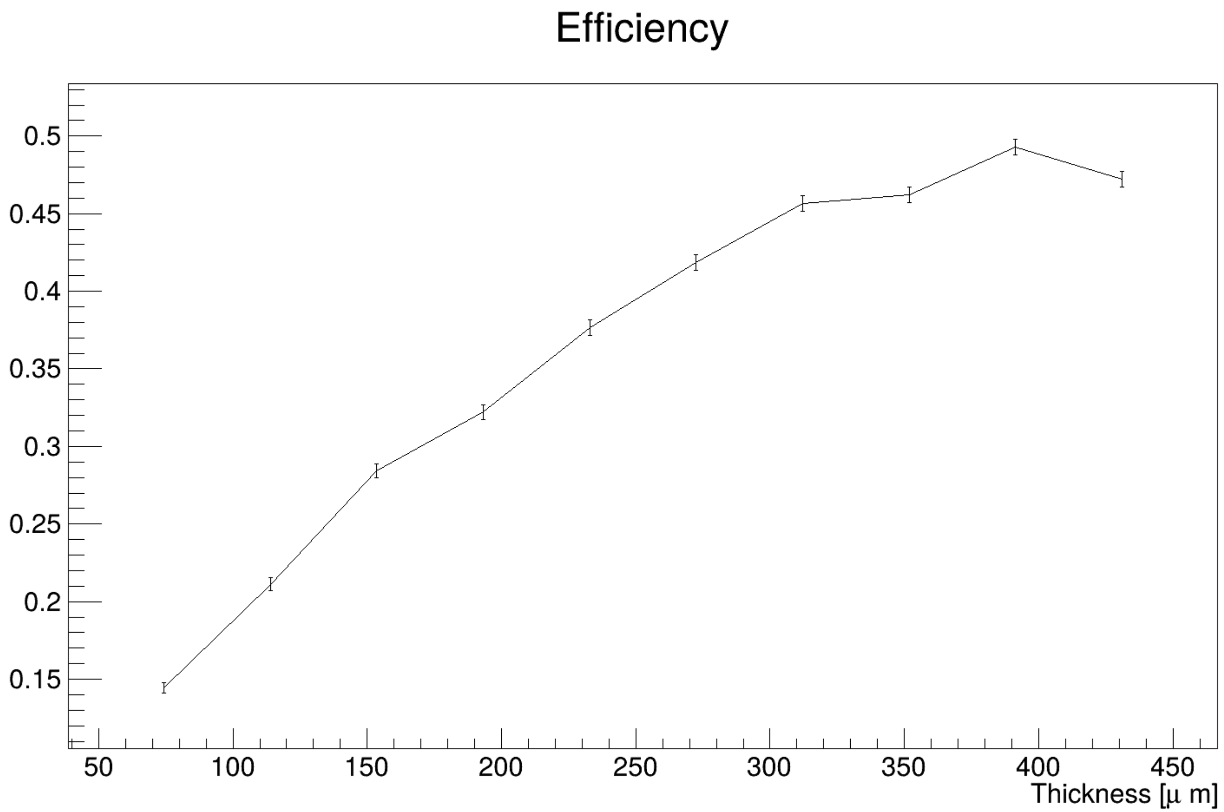
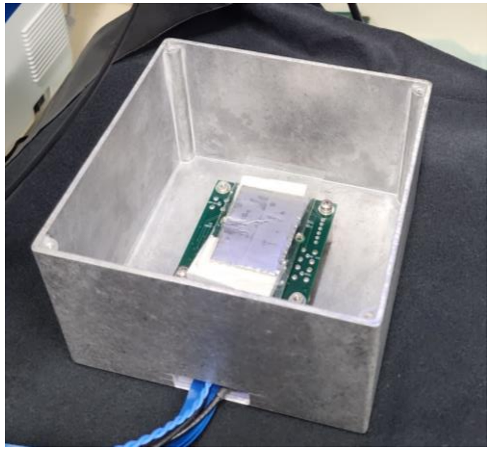
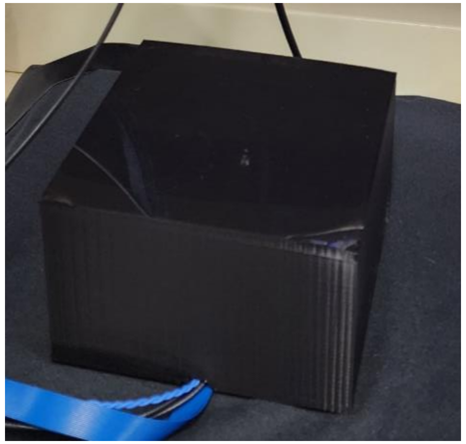
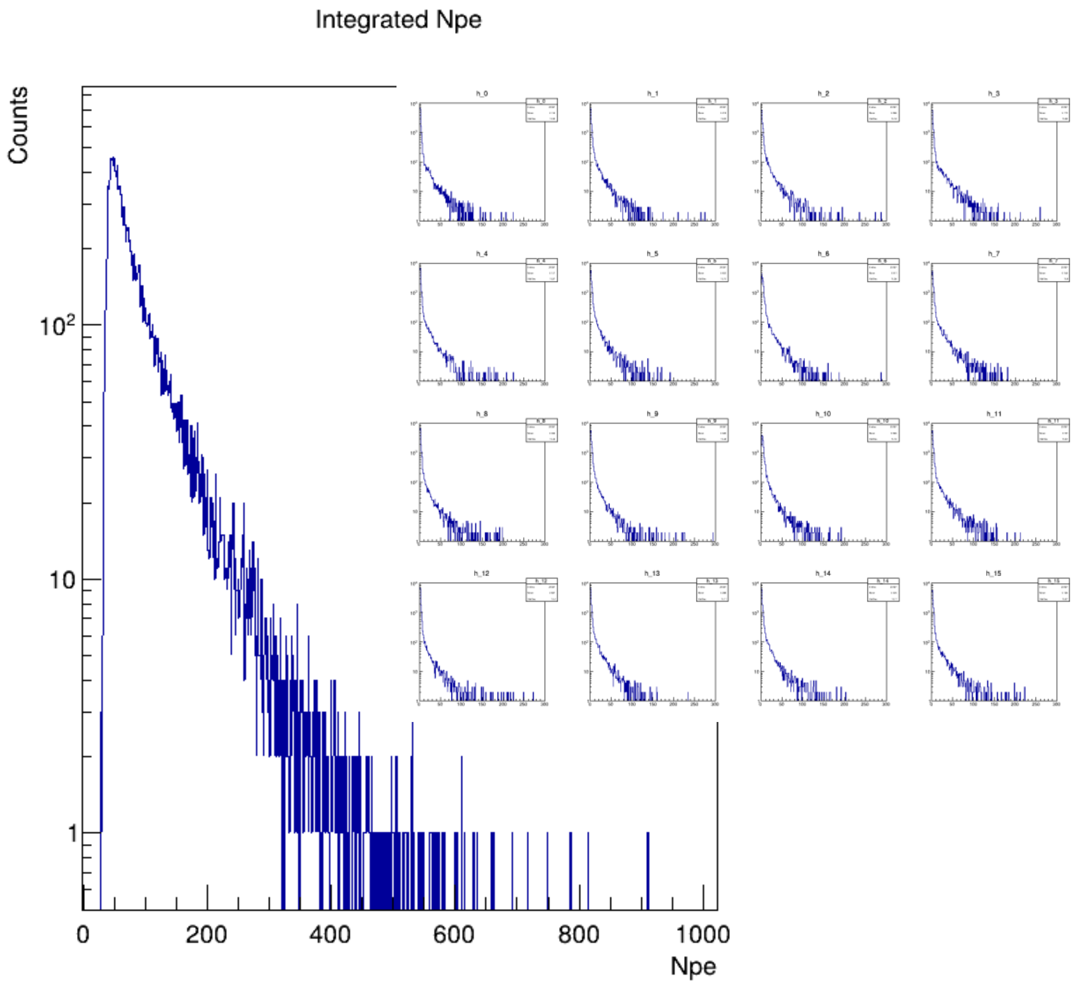




Neutron detection with diamond powder + ^{6}LiF







- Diamond powder (10-20 µm particle size) mixed with ^{6}LiF powder
- Dissolved/suspended in water, painted over mesh on glass slide
- Placed over SiPM array (OnSemi ArrayC)
- Placed in light-tight enclosure
- Neutrons: ^{252}Cf/^{250}Cf (260 µCi) thermalized by 10-20 cm of polyethylene

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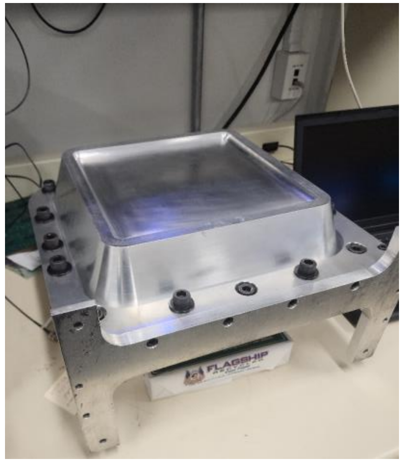
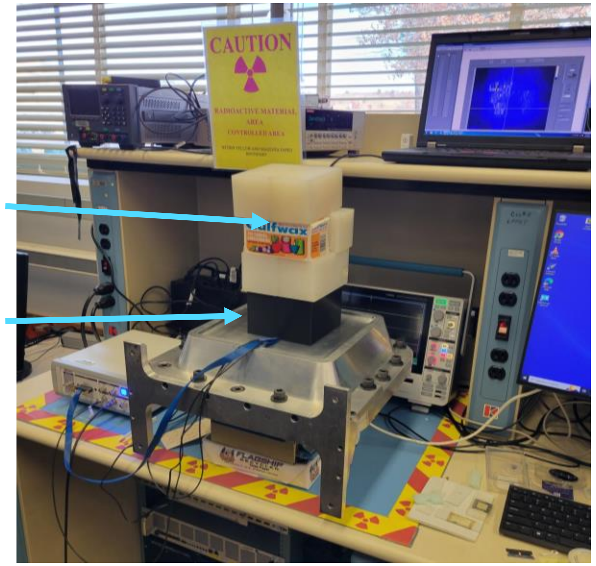
Preliminary estimate of detector efficiency

^{3}He detector

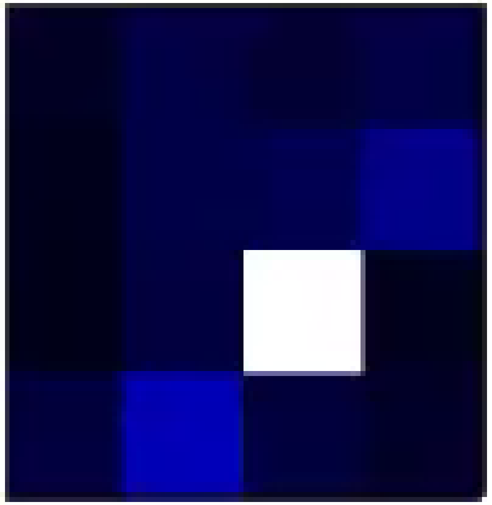


Cf source

Diamond sensor



Live data



Efficiency of ^{3}He detector

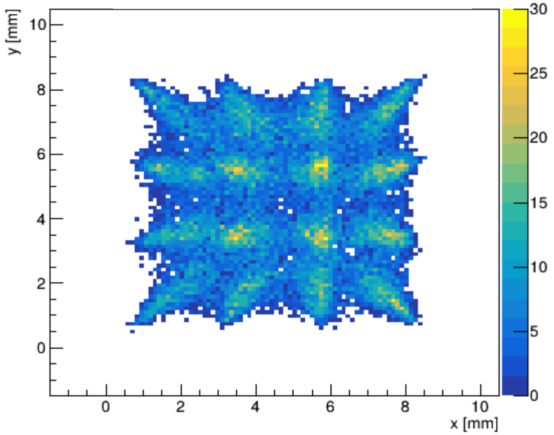
- ^{3}He detector (24 cm x 24 cm)
- Al window ~90% transmissive
- $^3He/CF_4$ mixture: ~50% probability of stopping neutron
- Rate: 147 Hz
- **Overall ^{3}He efficiency estimated to be ~30-40%**

Efficiency by comparison

- Compare rates from ^{3}He detector with diamond detector
- SiPM area: 1.44 cm^2
- Rate: 0.44 Hz
- Normalize by relative area
- **Overall diamond detector efficiency estimated to be ~1.2 x ^{3}He = 36-55%***

*rough estimate from source activity and geometry

Center of mass



Reconstruction artefact introduced by reconstruction and thermal noise

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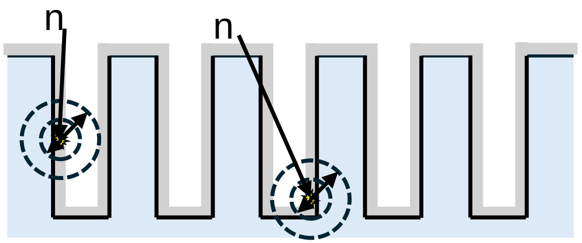
Paths forward: Diamond and converter integration

Micro Structured Surfaces

Trenches lined with converter



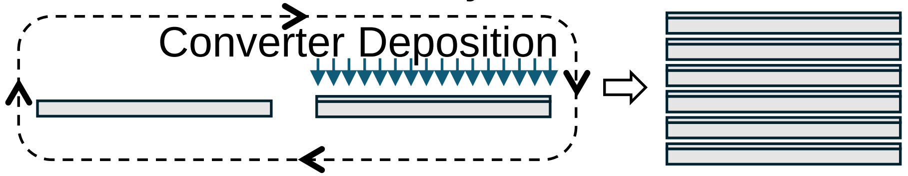
Patterned diamond

Engineered Powders

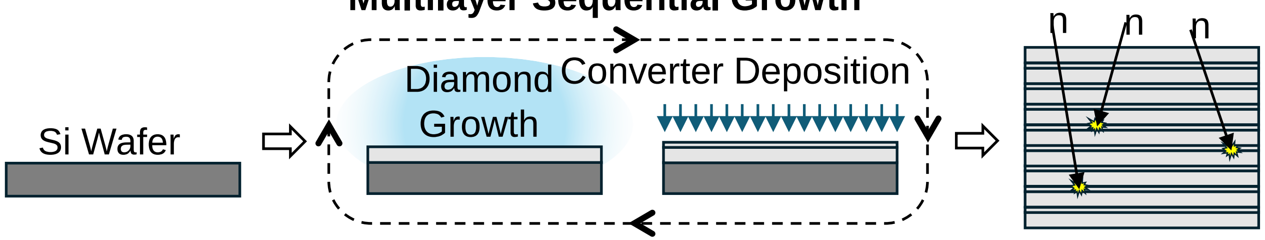
Fused silica substrate
LiF or hBN coated diamond powder

Mechanical assembly

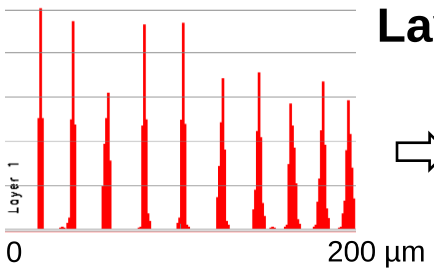
Diamond Substrate



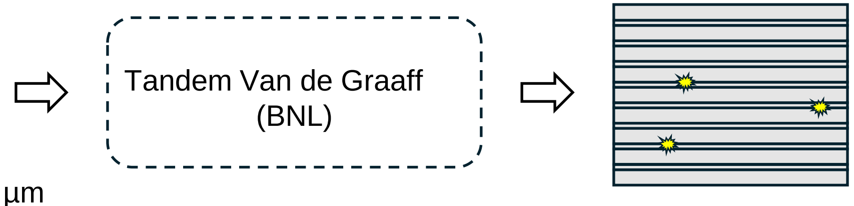
Multilayer Sequential Growth



Layered Ion Implantation



SRIM/TRIM ion depths



Summary and future perspective

- A diamond charge particle detector using scintillation light detection is under development
- Diamond has good light yield with fast response (< 1 ns rise time)
  - Not limited to ultra high purity electronic grade diamond
  - Works with inexpensive powders
- Diamond coupled with converter material makes an efficient neutron detector for applications with high background and gamma rejection
- Diamond powder + ^{6}LiF estimated efficiency of ~36-55%
  - Gamma “Blind”
- Working on optimizing neutron detector
  - Increasing transparency
  - Increasing light yield
  - Increasing neutron capture
- Adding scope:
  - Neutron imaging: integration of positions sensitive photodetector (digital sipm, spad camera, …)
  - Directional capabilities: coded masks
  - Higher TRL product: integrate electronics for readout towards a compact device

THANK YOU!

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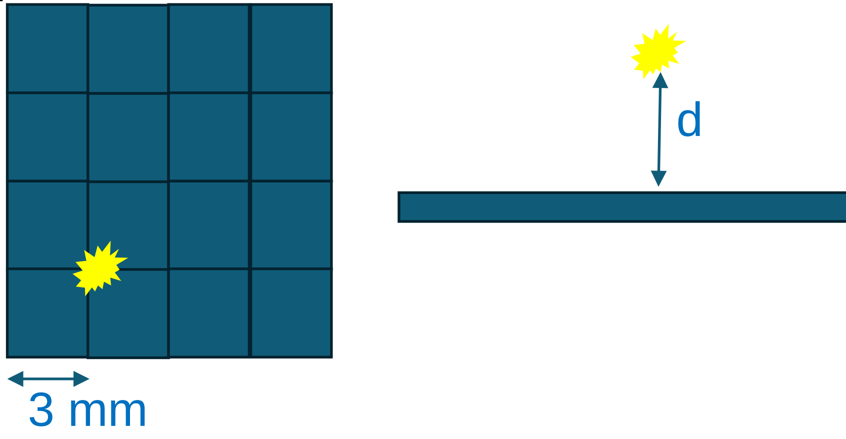
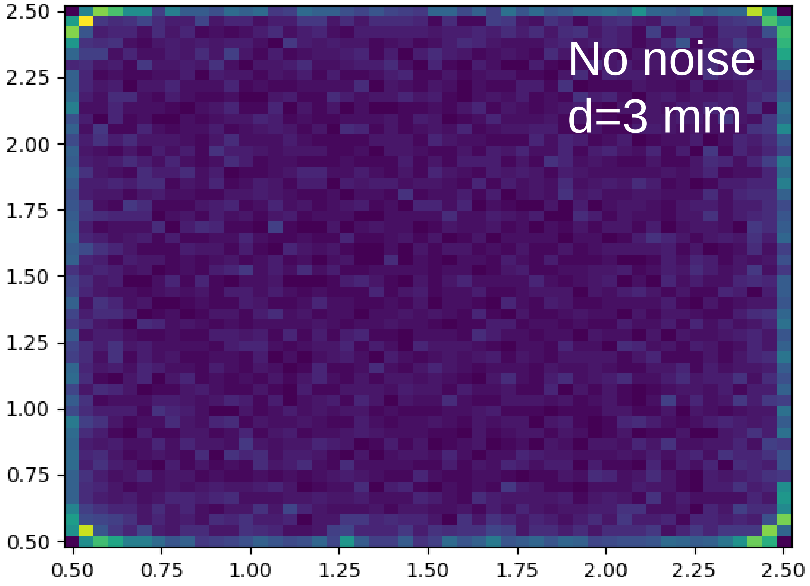
Backup

Center of mass computation

To understand the distribution of center of mass in case of uniform illumination a toy Montecarlo was developed:

- 300 photons are generated with a Poisson distribution at a distance d from the SiPM
- For each SiPM the solid angle is computed
- 10000 events are generated and the center of mass is computed as $\bar{x}_{cm} = Q_{tot}^{-1} \sum_{i=1}^{n_{SiPM}} Q_i \bar{x}_i$





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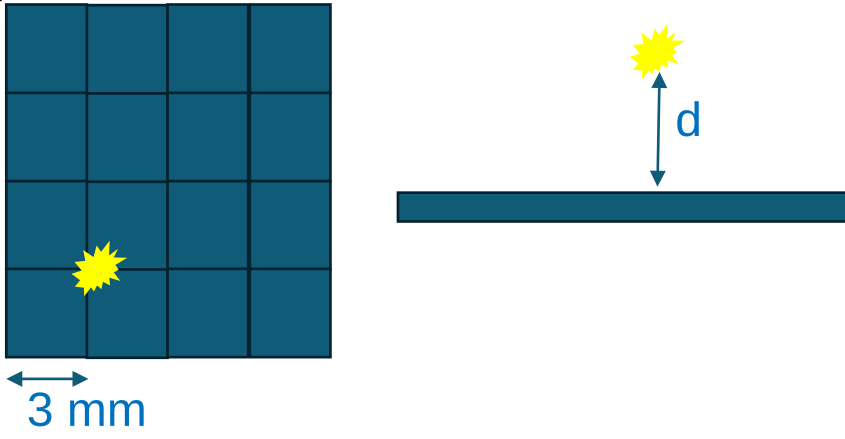
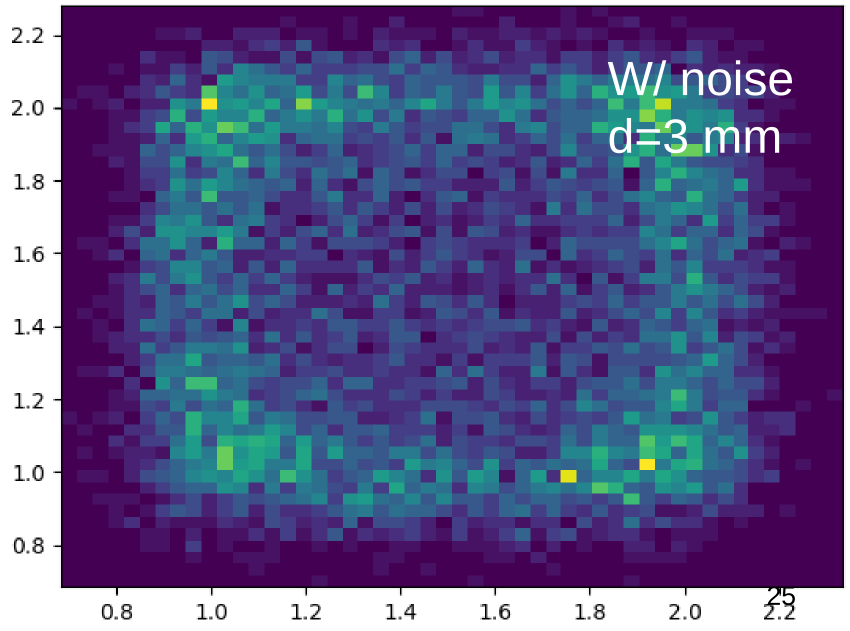
- For each SiPM the solid angle is computed
- 10000 events are generated and the center of mass is computed as $\bar{x}_{cm} = Q_{tot}^{-1} \sum_{i=1}^{n_{SiPM}} Q_i \bar{x}_i$
- Then, noise is activated per each SiPM with a Poisson distribution around 3 photons

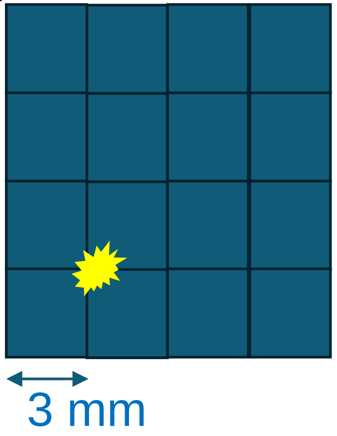


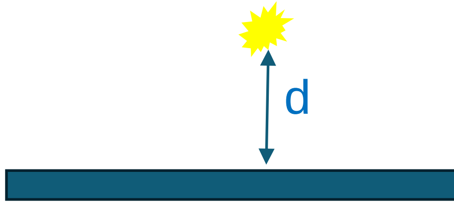


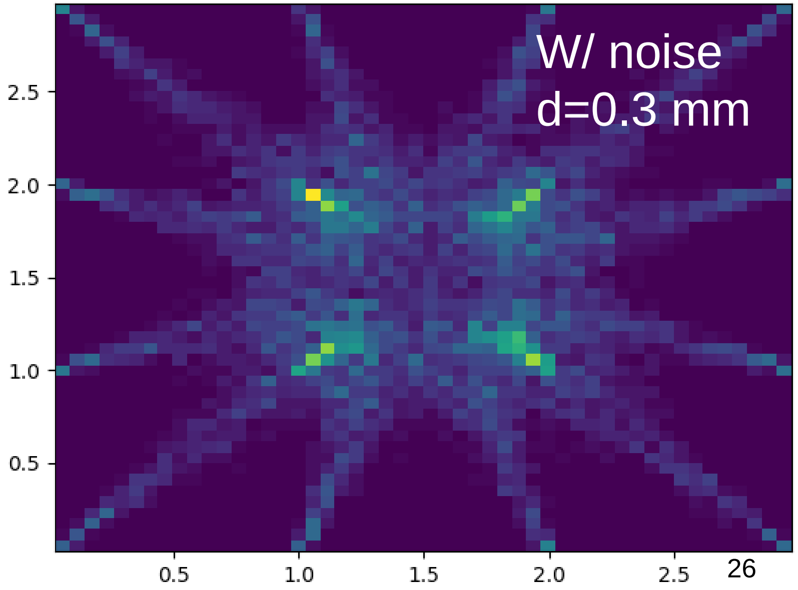
Center of mass computation

To understand the distribution of center of mass in case of uniform illumination a toy Montecarlo was developed:

- 300 photons are generated with a Poisson distribution at a distance d from the SiPM
- For each SiPM the solid angle is computed
- 10000 events are generated and the center of mass is computed as $\bar{x}_{cm} = Q_{tot}^{-1} \sum_{i=1}^{n_{SiPM}} Q_i \bar{x}_i$
- Then, noise is activated per each SiPM with a Poisson distribution around 3 photons
- If the light source becomes really close…







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