Instrumentation for Radiation Protection

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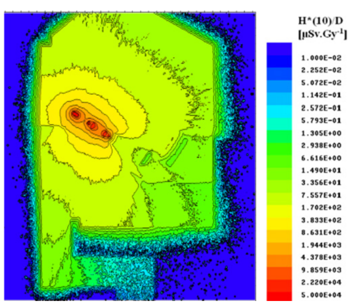
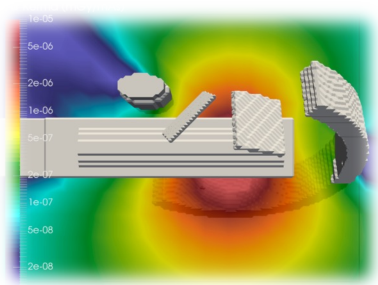
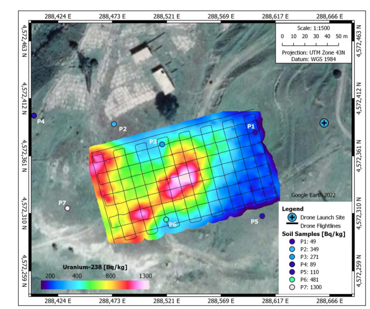
IPHC-DeSIs research team

Radiation protection

Hadrontherapy & Space radiations	Dosimetry	Radioactivity
• Ion fragmentation (secondary particles)	• Radiation therapy (photons, protons, ions)	• Low levels of radioactivity (cleaning / dismantling)
• Monte Carlo models	• Medical imaging (radiology)	• Nuclear activation (neutrons)







⇒ **Coupling Monte Carlo calculations and real-time detection of radiation fields**

IPHC-DeSIs research team

Radiation protection

Hadrontherapy & Space radiations

- Ion fragmentation (secondary particles)
- Monte Carlo models

Dosimetry

- Radiation therapy (photons, protons, ions)
- Medical imaging (radiology)

Radioactivity

- Low levels of radioactivity (cleaning / dismantling)
- Nuclear activation (neutrons)

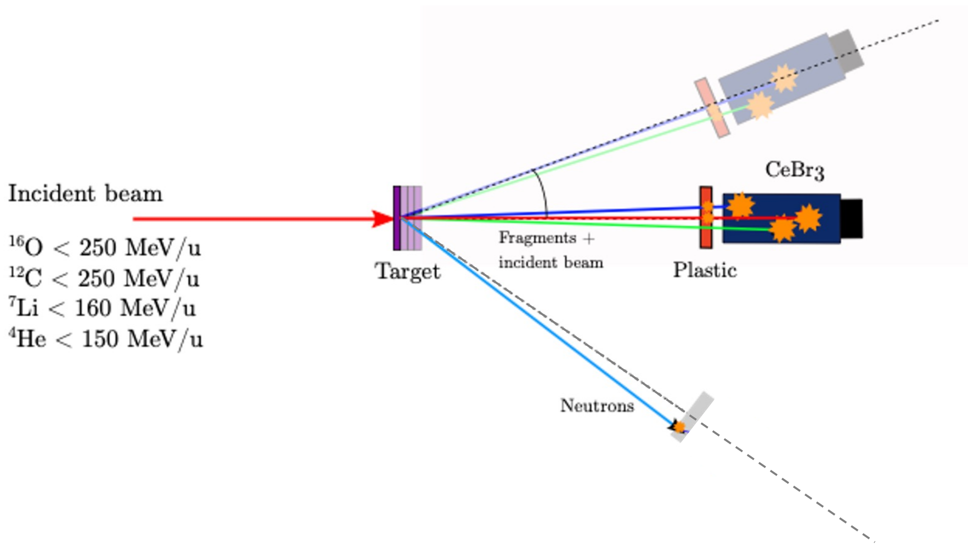
→ Development of a 4D neutron monitoring system

→ Development of a drone-borne gamma spectrometry system

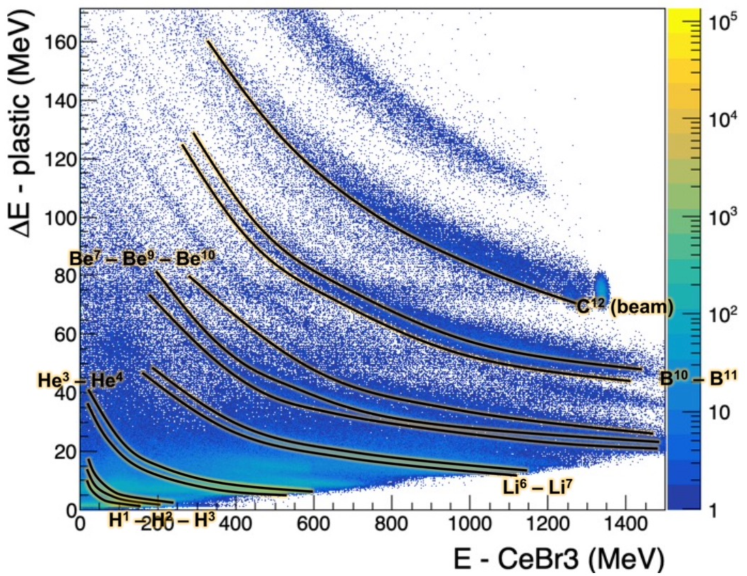
Neutron monitoring system

Project 1: Cross-section of Light Ions and Neutrons Measurements (CLINM)

- Master project FOOT-Xn
- ANR fundings 2023-2026 (coordinated by M. Vanstalle (IPHC))
- secondary particles from ion fragmentation (hadrontherapy / space radiations)
- parallel measurements of radiolysis effects (radiochemistry team (IPHC))



Courtesy of M. Vanstalle

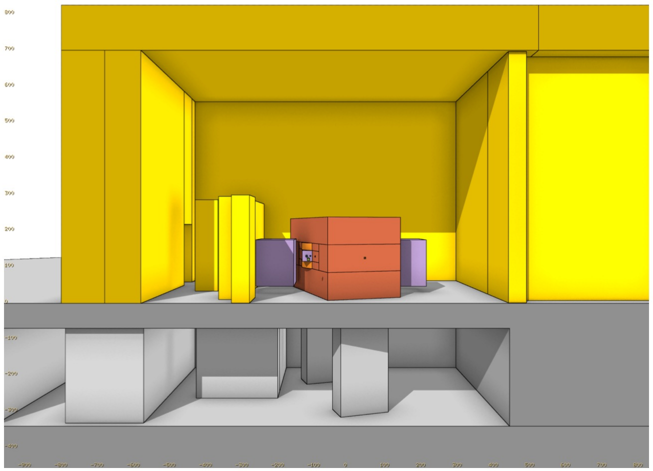


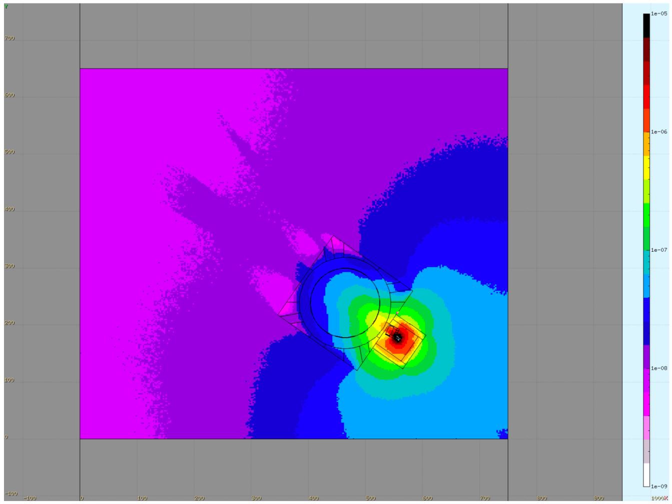
Neutron monitoring system

Project 2: β-emitters radionuclides produced by cyclotron activation (Simβ-AD)

- BPI fundings 2022-2025 (coordinated by JM. Horodynski (iRSD))
- characterization of neutron fields around cyclotrons
- calculation software for activated components inventory
- collaboration with IBA (accelerator) and TRAD (MC simulation)

Courtesy of JM. Horodynski

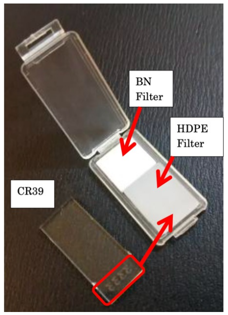


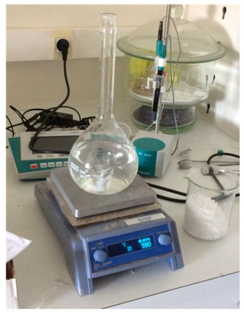


bpifrance iRSD IPHC iba TRAD

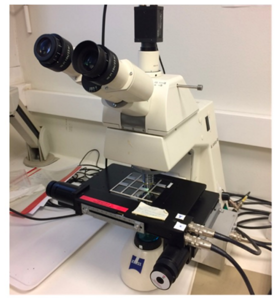
Neutron monitoring system

Solid Nuclear Track Detector (CR-39)

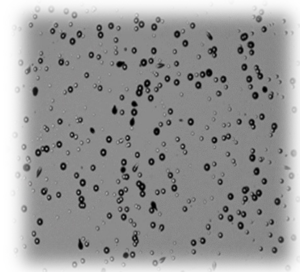




Chemical treatment



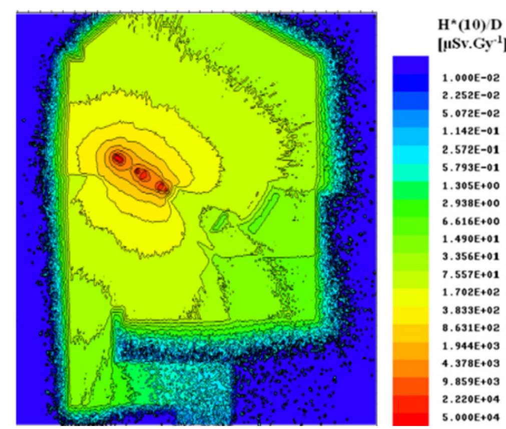
Detector reading



Tracks analysis

- Single use
- No real-time
- Time consuming

- Goal is to develop a 4D neutron monitoring system:
  - ⟶ sensor network (3D - space)
  - ⟶ real-time monitoring (1D - time)
- Coupling with Monte Carlo neutron fields calculations

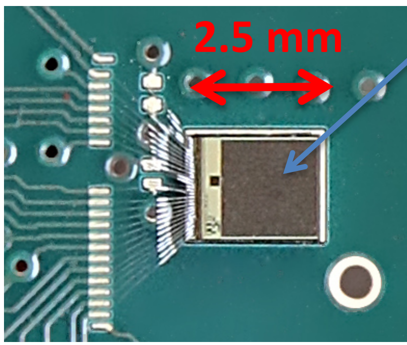


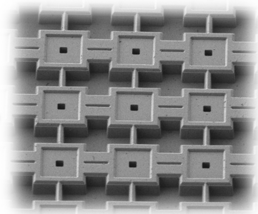
J. Farah, Phys. Med. Biol. **59** (2014)

AlphaRad3 (2017)

- Specially designed CMOS sensor for parallel detection of thermal and fast neutrons
- Compact and easy to use (real-time, integrated electronic, low power consumption)

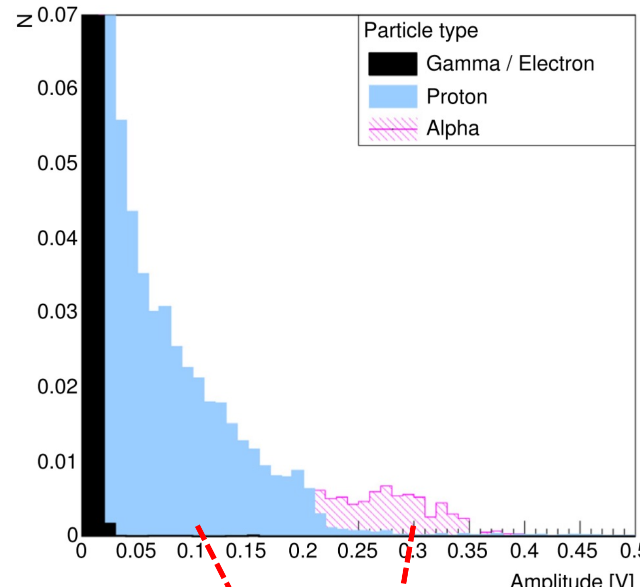
64x64 micro-diodes





(XFAB 0.35 μm)

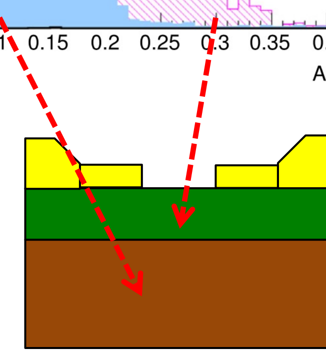
alpha detection efficiency < 0.1% !



Silicon layer ≈ 7-8 µm

Epitaxial layer ≈ 14 µm

Bulk



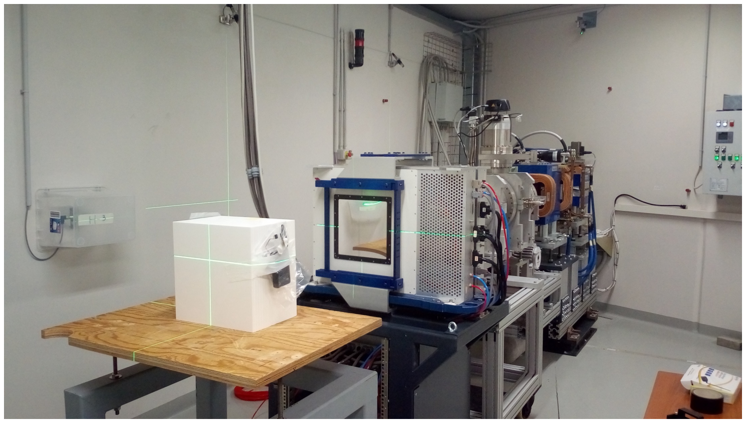
Neutron detection

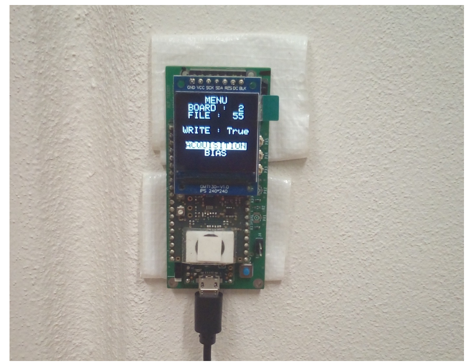
- Neutrons are converted into:
  - protons (n_{fast}, PE)
  - alpha particles (n_{therm}, ^{10}B)

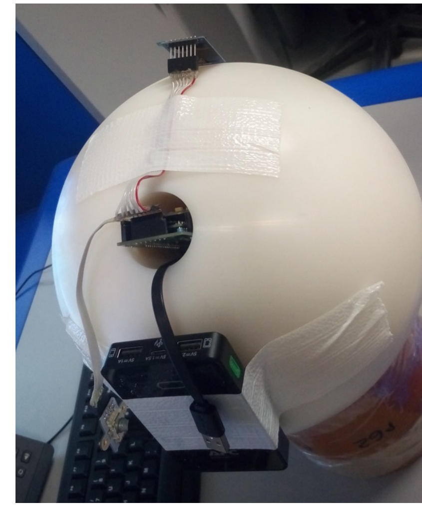
N. Arbor et al., PMB 62 (2017)
N. Arbor et al., NIM A 888 (2018)

AlphaRad3 (2017)

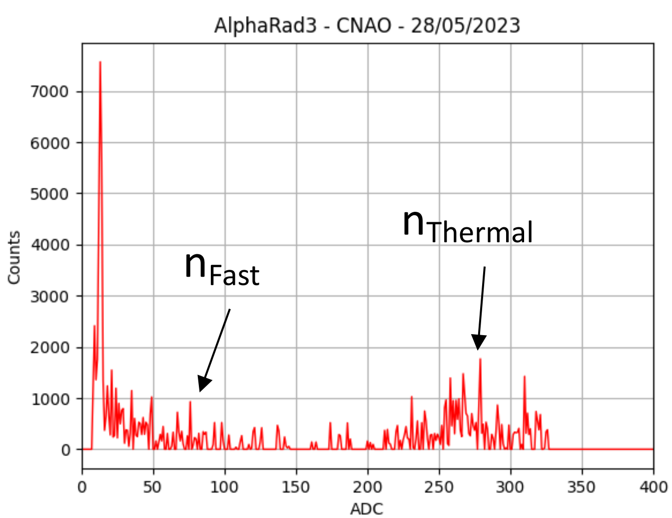
- CNAO hadrontherapy center (April 2023): test of a prototype for autonomous measurements







- It works !



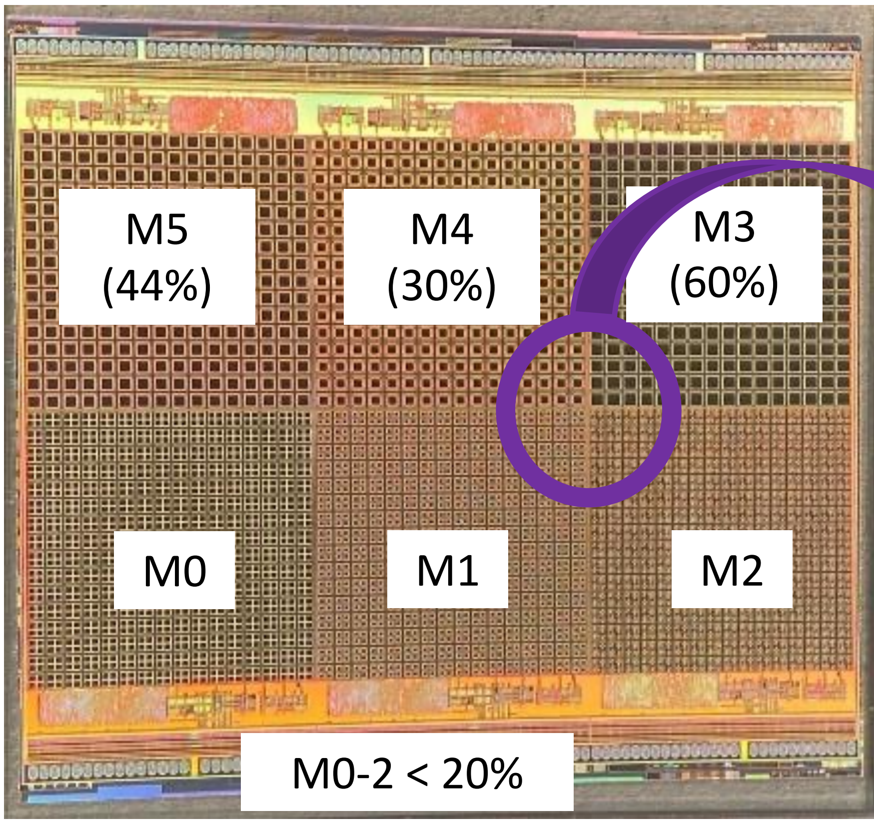
<u>To do list</u>:

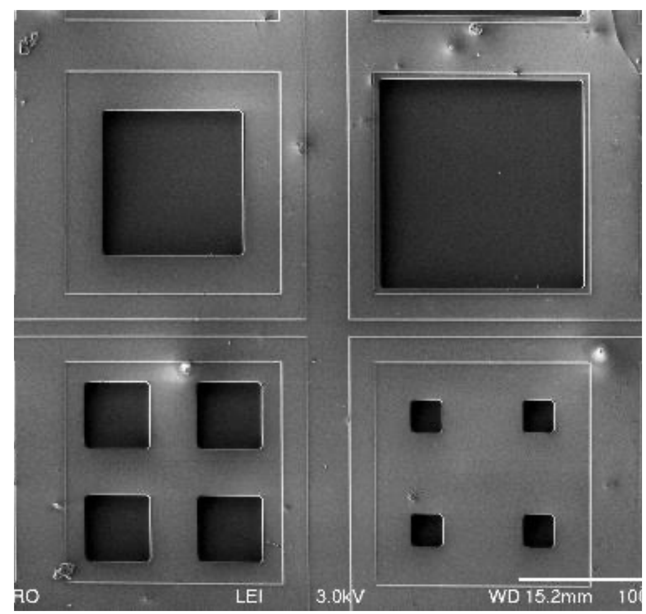
→ detection efficiency can be improved

→ counting (thresholds on ADC signal) can be done in the CMOS itself

AlphaBeast (2022)

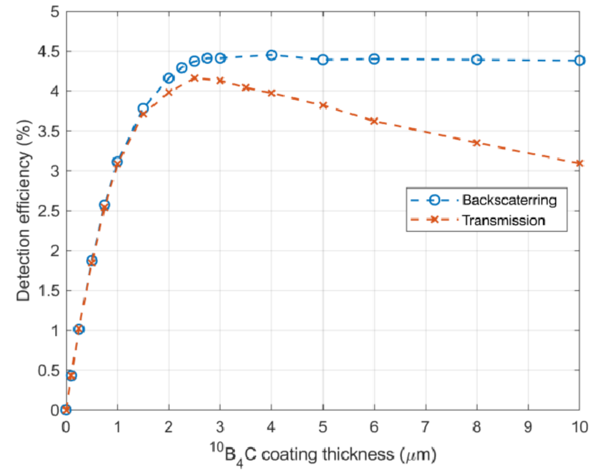
- New sensor designed in 2022 (collaboration with C4PI-IPHC platform)
- 6 different diodes configurations (matrix M0-M5)
- 3 internal thresholds (counters)





Thermal neutron detection

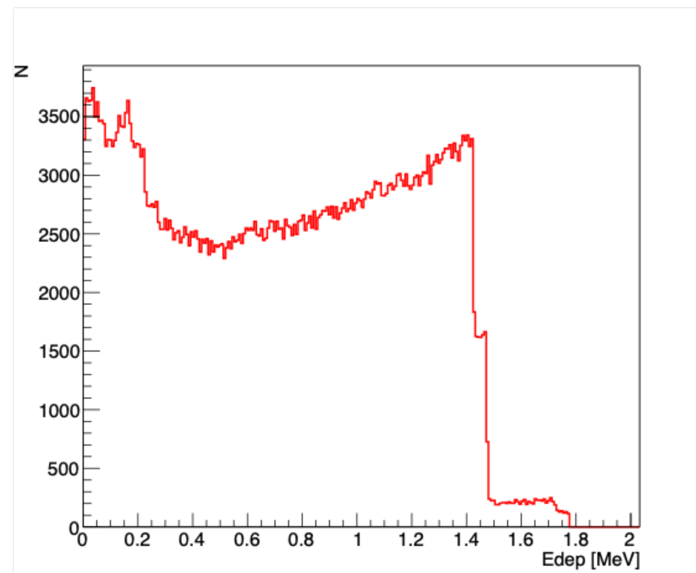
- ^{10}B converter on top of the sensor
- Conversion efficiency ≈ 4%



Duarte et al., 2022

Reaction (energies in MeV)	Q-value [MeV]	Cross-section [b]
$^3He + ^1n \rightarrow ^3H\,(0.191) + ^1p\,(0.573)$	0.764	5,333
$^6Li + ^1n \rightarrow ^3H\,(2.73) + ^4\alpha\,(2.05)$	4.780	920
$^{10}B + ^1n \rightarrow ^7Li\,(1.015) + ^4\alpha\,(1.777)$	2.792 (g.s., 6%)	3,837
$^{10}B + ^1n \rightarrow ^7Li^*\,(0.840) + ^4\alpha\,(1.470)$	2.310 (1st exc. s., 94%)	3,837
$^{113}Cd + ^1n \rightarrow ^{114}Cd + \gamma\,(0.56) + e^-_{conv.}$	9.043 [RJKcv$^+$13]	20,600
$^{155}Gd + ^1n \rightarrow ^{156}Gd + \gamma\,(0.09, 0.20, 0.30) + e^-_{conv.}$	8.5 [KCM13]	60,600 [KCM13]
$^{157}Gd + ^1n \rightarrow ^{158}Gd + \gamma\,(0.08, 0.18, 0.28) + e^-_{conv.}$	7.9 [KCM13]	253,929 [KCM13]
$^{235}U + ^1n \rightarrow$ fission fragments	210	583
$^{238}Pu + ^1n \rightarrow$ fission fragments	160	748

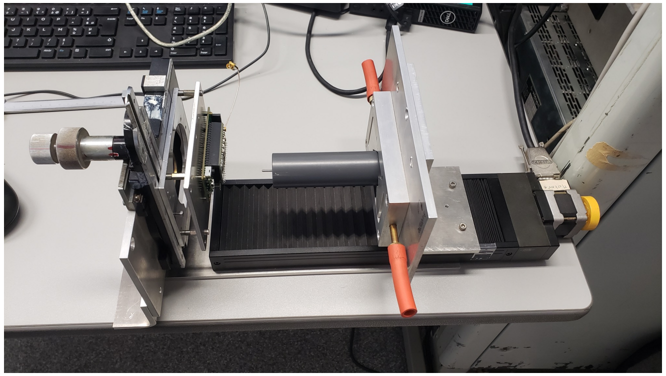
Table 3.1: Overview of reactions and reaction products exploited for neutron detection. After [Owe12].



Alpha deposited energy
in *AlphaBeast* (Geant4 MC)

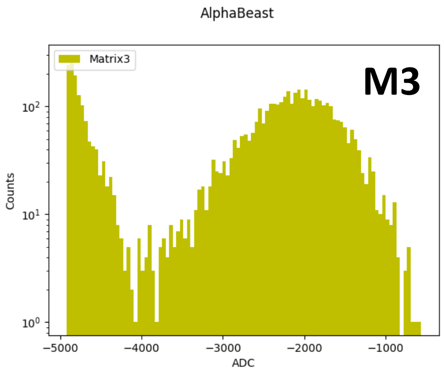
Alpha particle measurements

- Alpha detection from ^{241}Am source with various distances

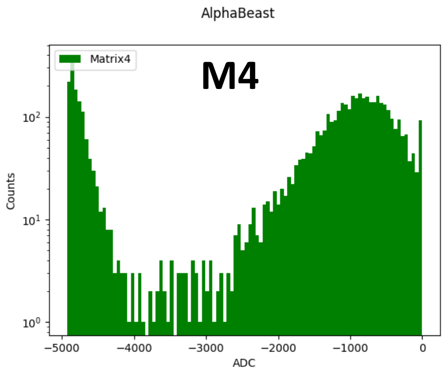


$E_{alpha} \approx 5.48$ MeV (d = 0 mm)

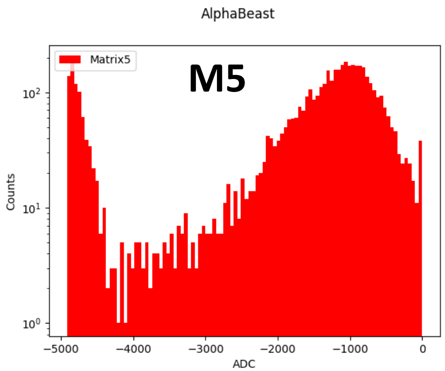
- Measurements for distance d = 35 mm ($\langle E_{alpha} \rangle \approx 1.25$ MeV)



$\mathcal{E}_{det} \approx 59\%$
($\mathcal{E}_{geo} \approx 60\%$)



$\mathcal{E}_{det} \approx 29\%$
($\mathcal{E}_{geo} \approx 30\%$)



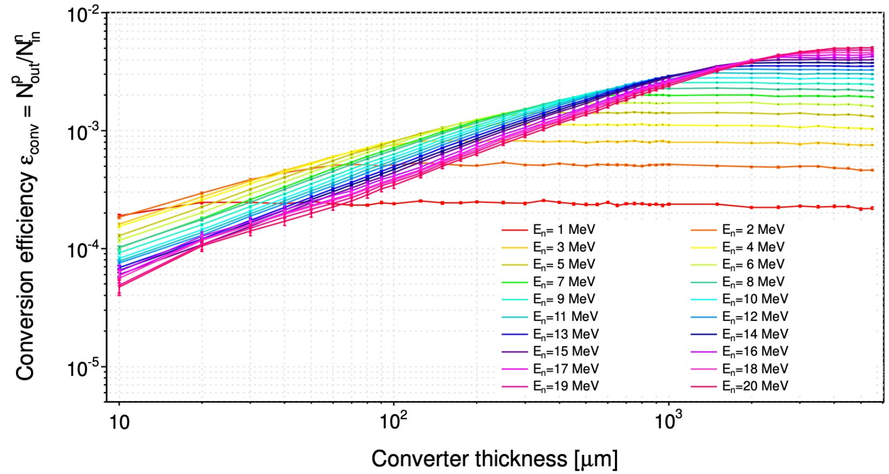
$\mathcal{E}_{det} \approx 43\%$
($\mathcal{E}_{geo} \approx 44\%$)

Intrinsic alpha detection efficiency > 99% !

Fast neutron detection

- PE converter (1 mm)

$$T = \frac{4Mm_n}{(M+m_n)^2} E\cos^2\theta \approx \frac{4A}{(A+1)^2} E\cos^2\theta$$



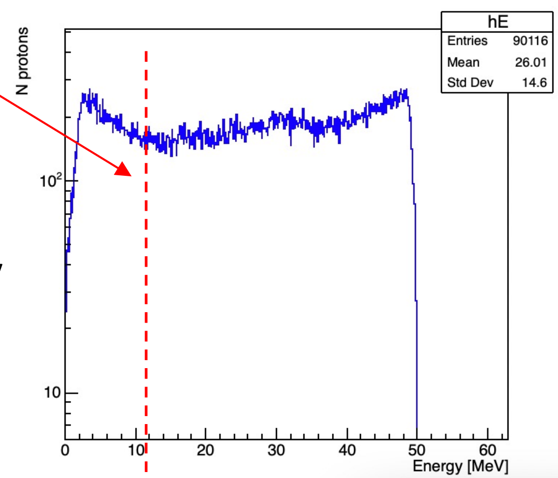
M. Vanstalle PhD (2010)

ΔE_{min} detection ≈ 100 keV

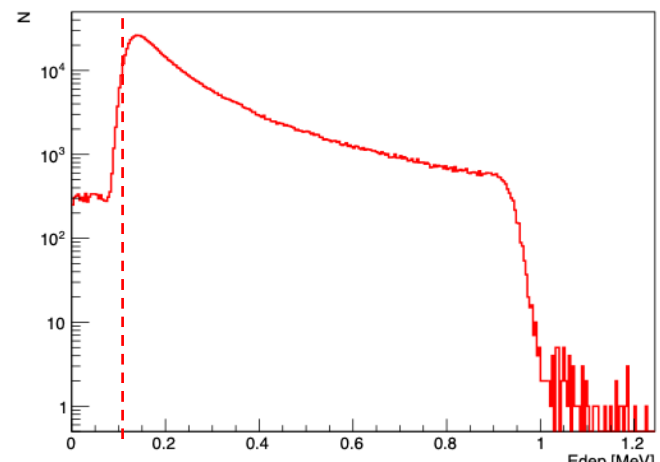
⇔

Proton E_{max} ≈ 10 MeV

Example:
neutron E = 50 MeV



Proton spectrum from 50 MeV neutron beam (Geant4 MC)



Proton deposited energy in *AlphaBeast* (Geant4 MC)

Fast neutron detection

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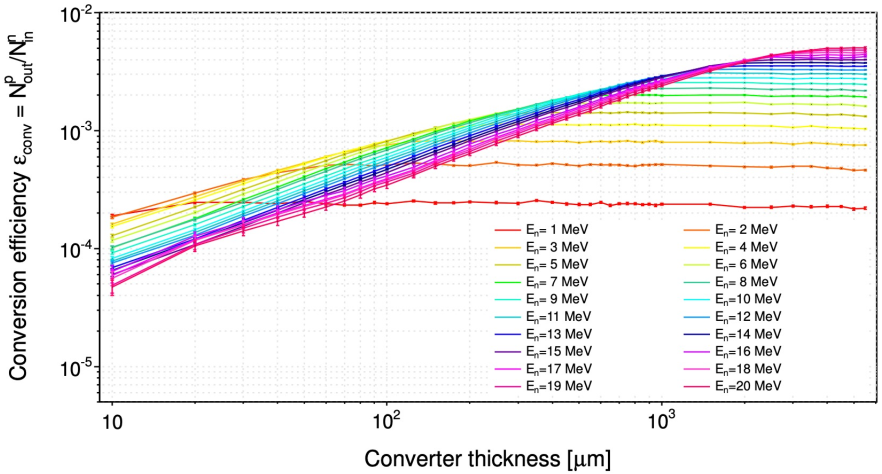

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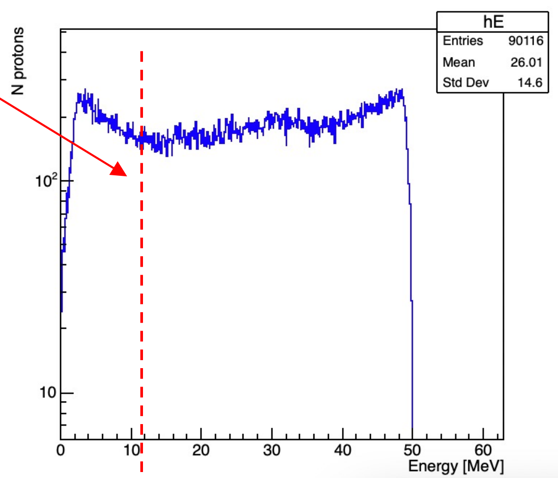

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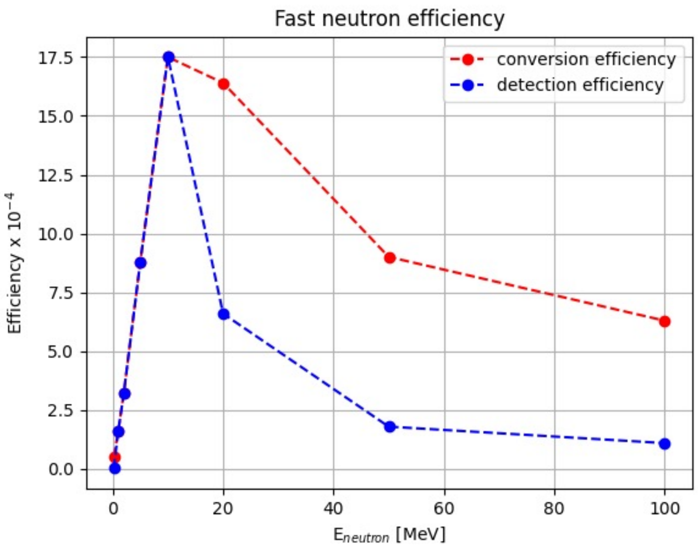
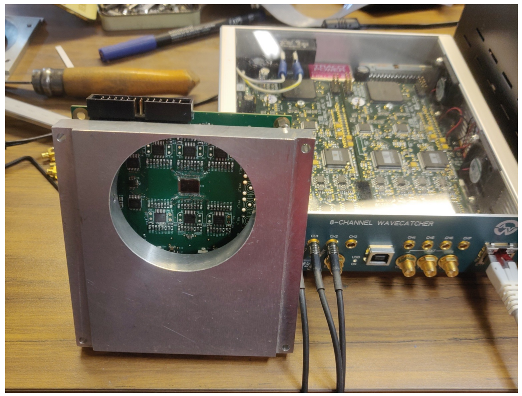
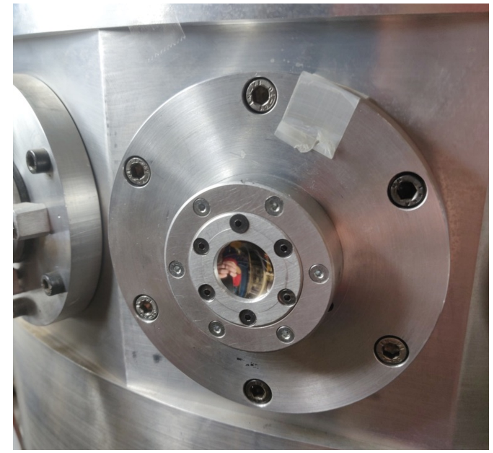


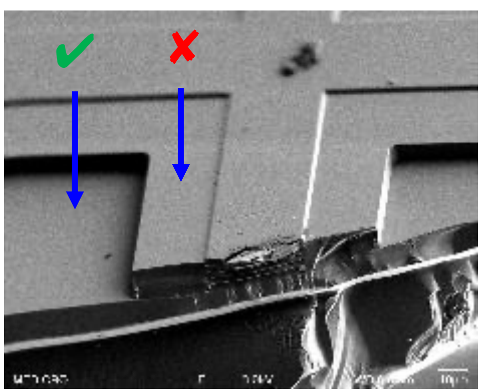
Proton measurements

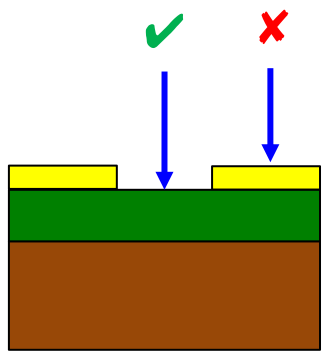
- Icube 4 MeV Van de Graaf accelerator (Au target RBS)

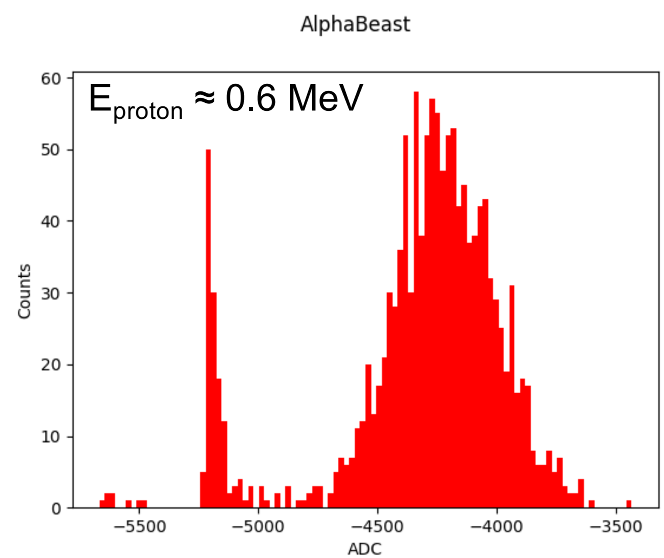




- Deposited energy sub-structures







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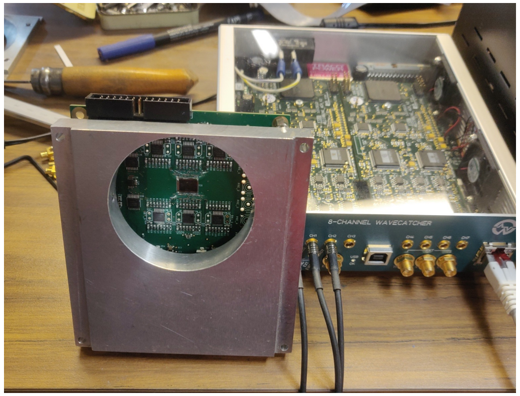

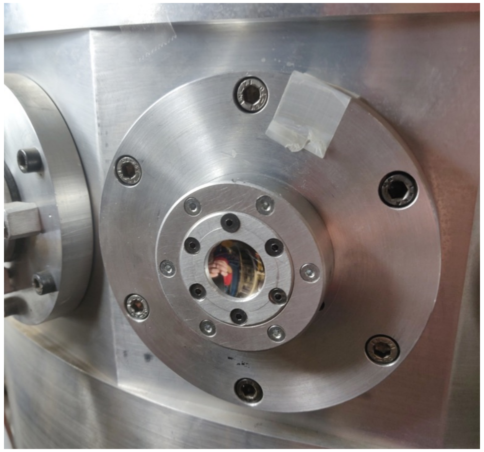

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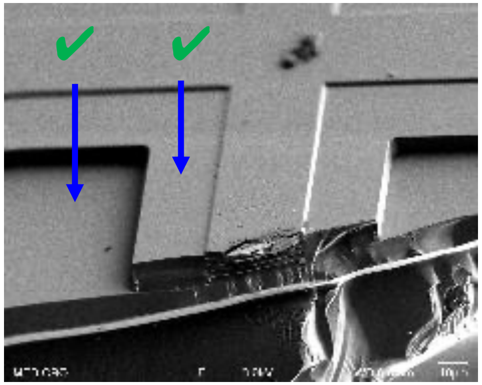

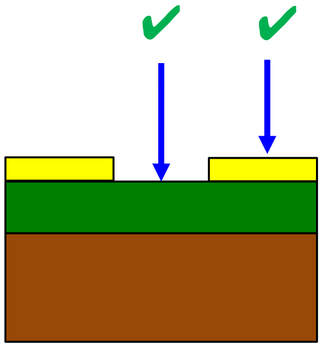

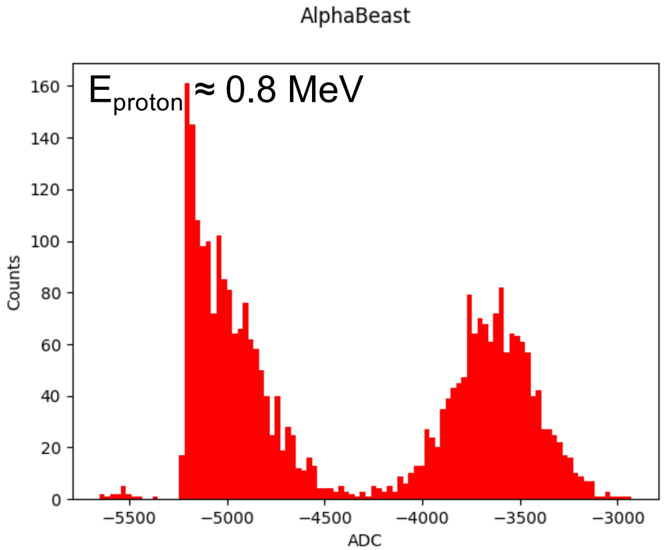

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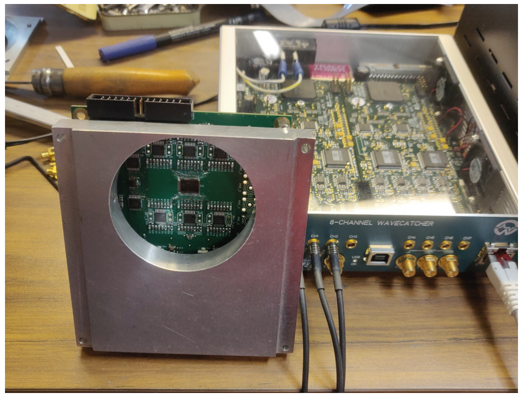

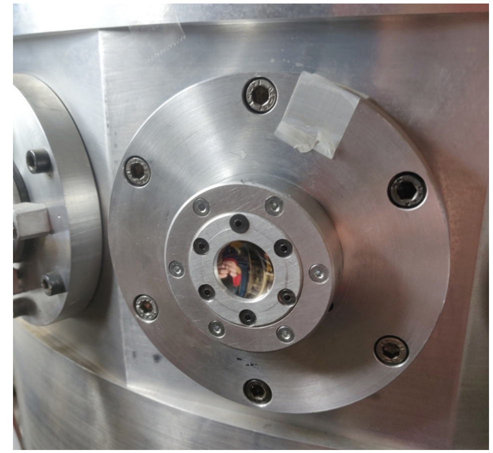

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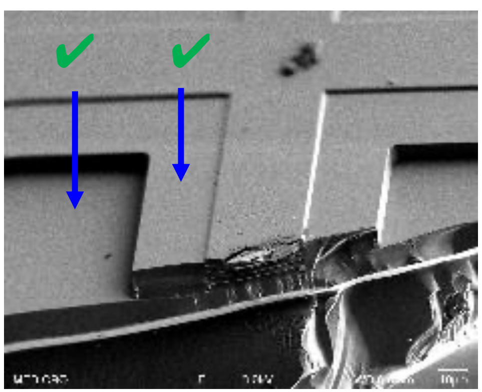

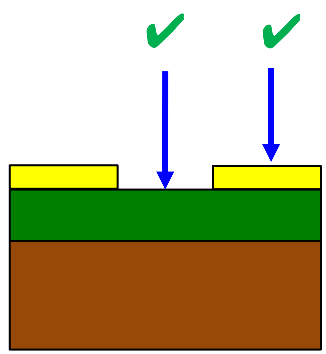

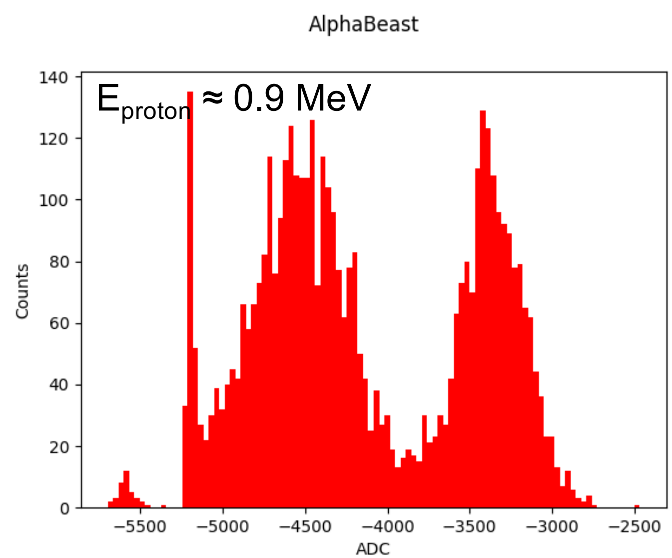

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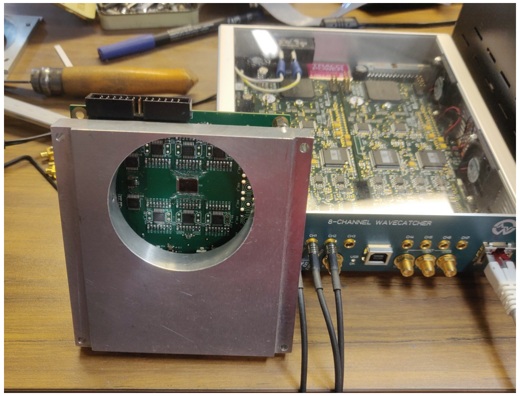

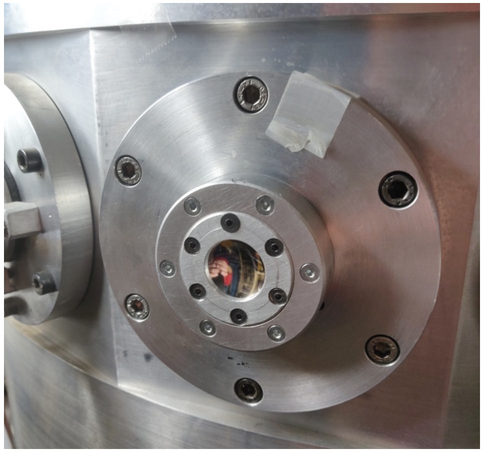

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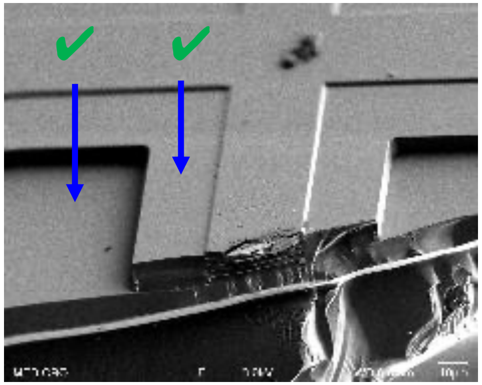
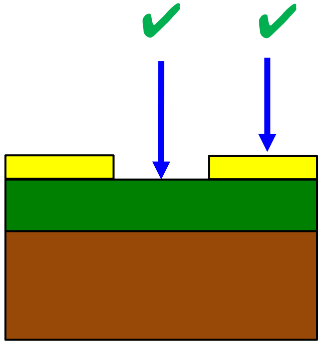
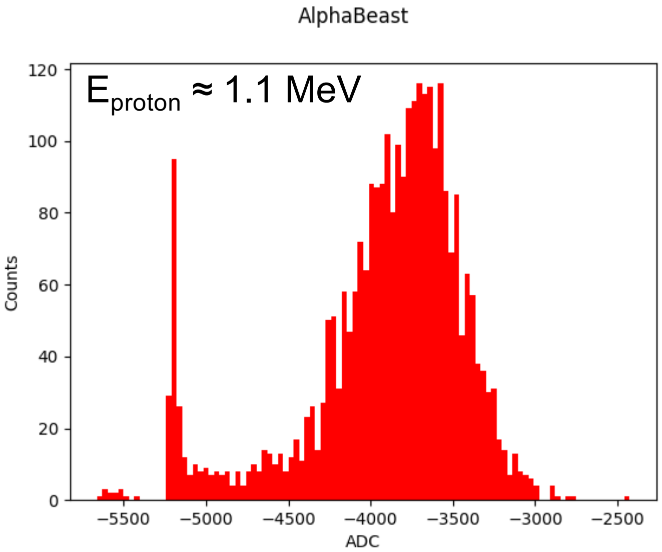
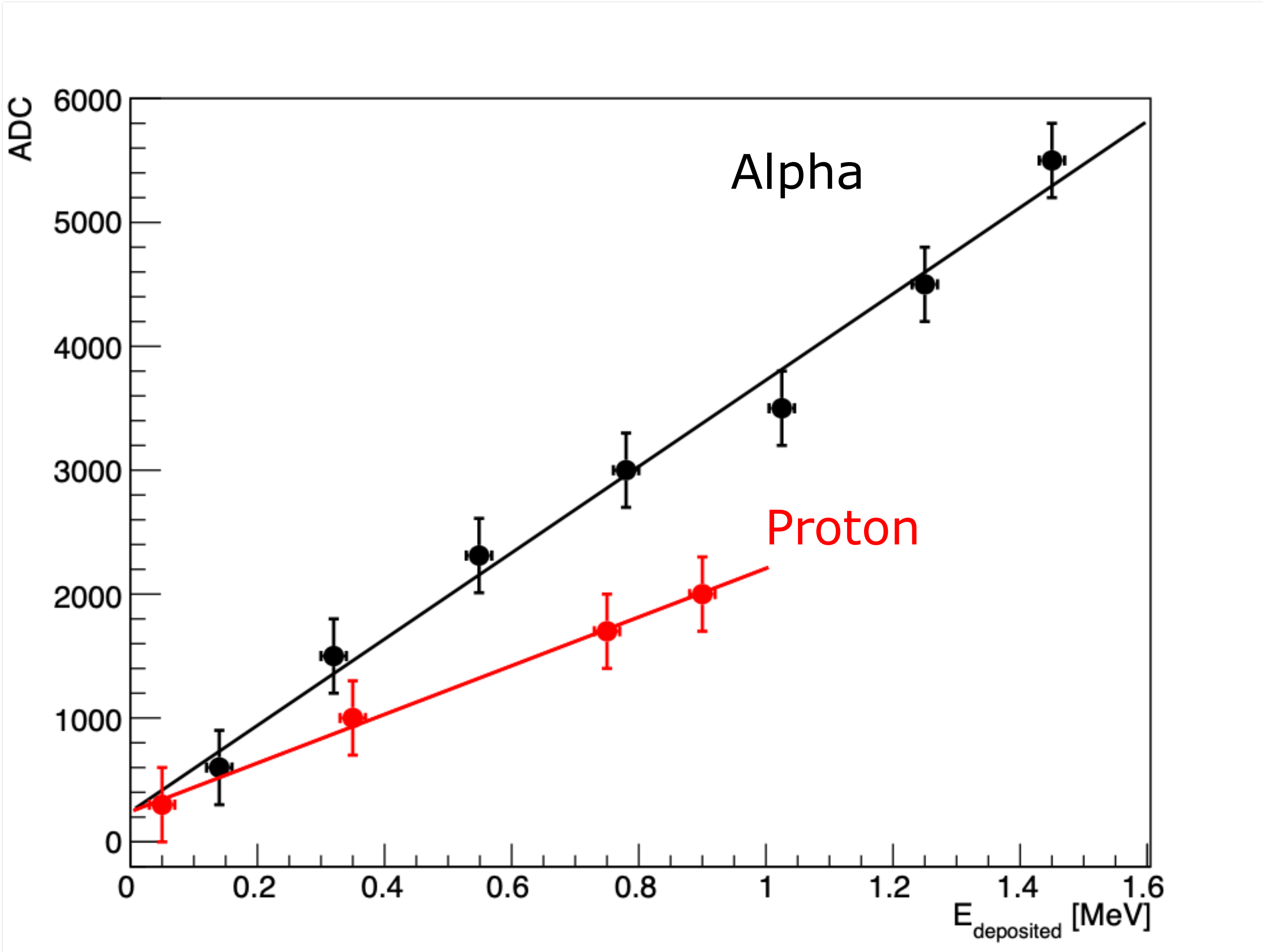






AlphaBeast energy calibration

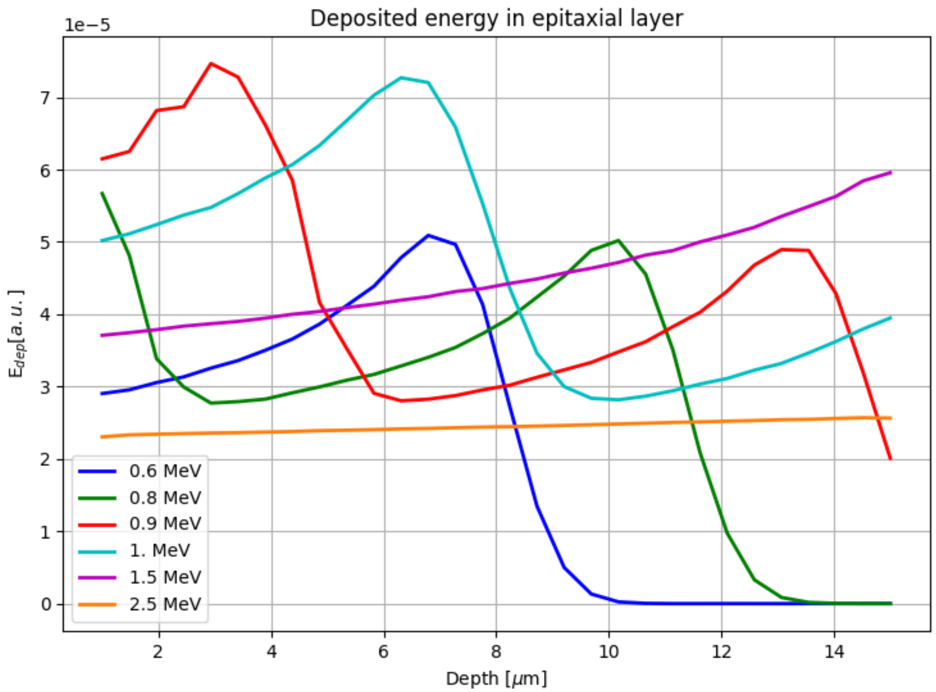
- <u>1st hypothesis</u>: 100% charge collection efficiency



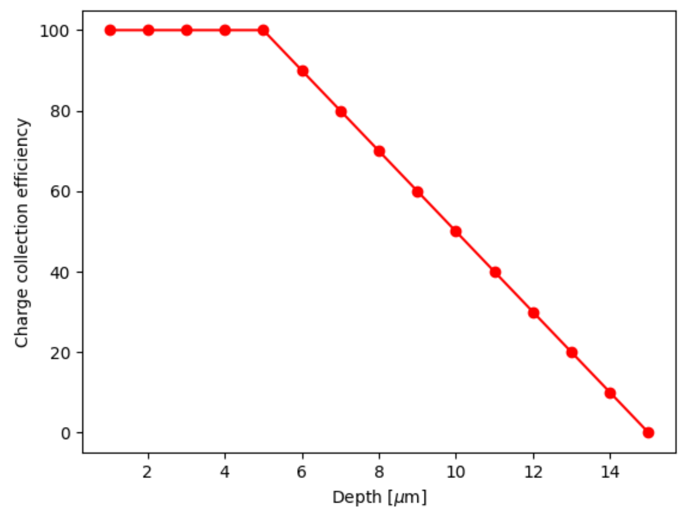
AlphaBeast energy calibration

- 2nd hypothesis: charge collection inefficiency with depth (epitaxial layer)

  → alpha particles deposit energy in 3-4 μm
  → protons deposit energy at different depths (btw 0 to 15 μm)



Charge collection efficiency (hypothesis)



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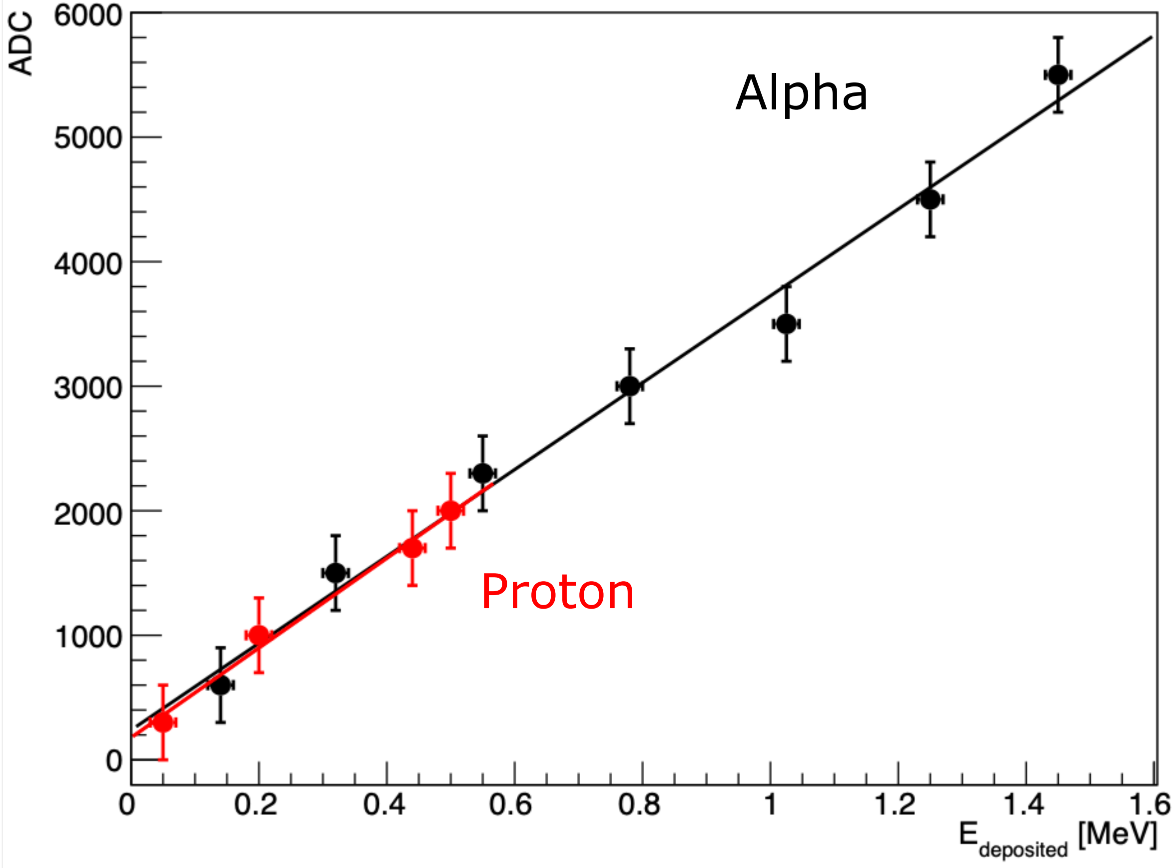
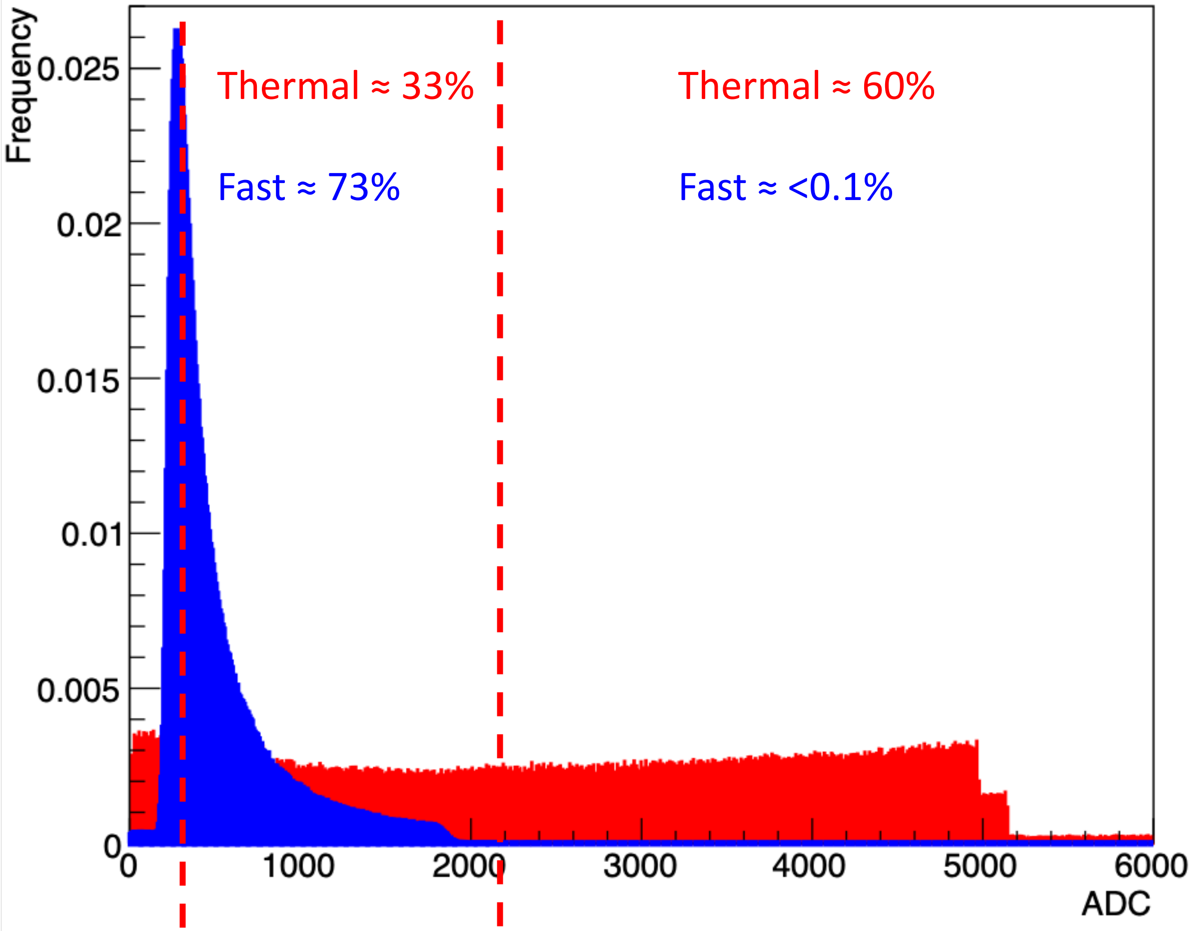
- <u>2nd hypothesis</u>: charge collection inefficiency with depth (epitaxial layer)



AlphaBeast settings (on-going)

- 3 internal thresholds to be set for autonomous counting



AlphaBeast signals from fast (1 MeV) and thermal neutrons (Geant4 MC)

<u>Detection efficiency :</u>

$\mathcal{E}_{th} \approx 1$ %

$\mathcal{E}_{fast} \approx 0.1$ % (10 MeV)

<u>Geometrical efficiency :</u>

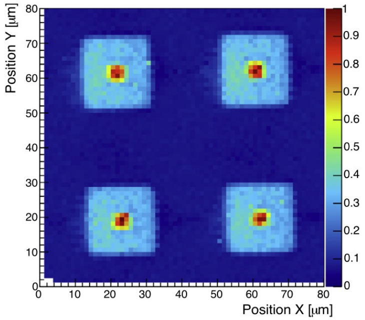
$\mathcal{E}_{geo} \approx 4$ % (cm^{-2})

<u>Total efficiency :</u>

$\mathcal{E}_{th} \approx 4\text{x}10^{-4}$ hit/($n.s^{-1}.cm^{-2}$)

$\mathcal{E}_{fast} \approx 4\text{x}10^{-5}$ hit/($n.s^{-1}.cm^{-2}$)

Next steps?

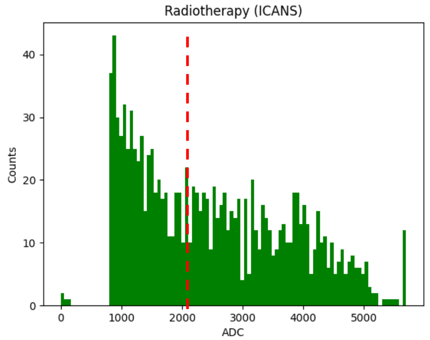


AlphaRad3 amplitude map
(proton - AIFIRA)

System characterisation

- Measurement of 3D charge collection map
  using alpha/proton micro-beam facility (AIFIRA – LP2i Bordeaux)

- Detector response in mixed field (gamma, proton, neutrons, …)
- Study of direct ^{28}Si+n reactions



AlphaBeast neutron measurements
radiotherapy room (ICANS)

Applications

- Secondary neutron fields from ion beam interactions (ANR CLINM project)

- Neutron fields around cyclotrons (BPI Simβ-AD project $\longrightarrow$ technology transfer)

- Applications @ CNAO for radiation protection (BNCT $\longrightarrow$ technology transfer)

Special thanks

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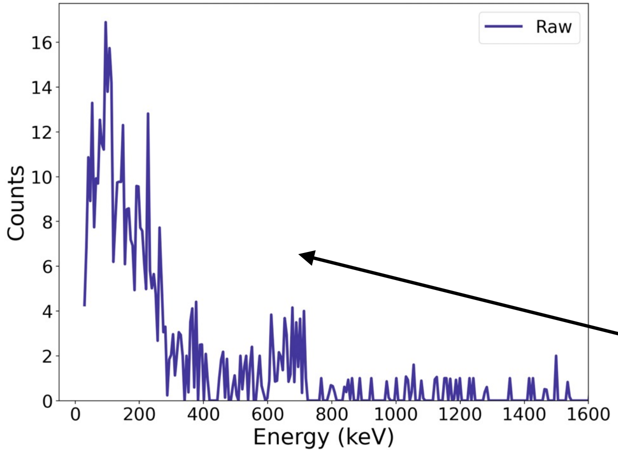
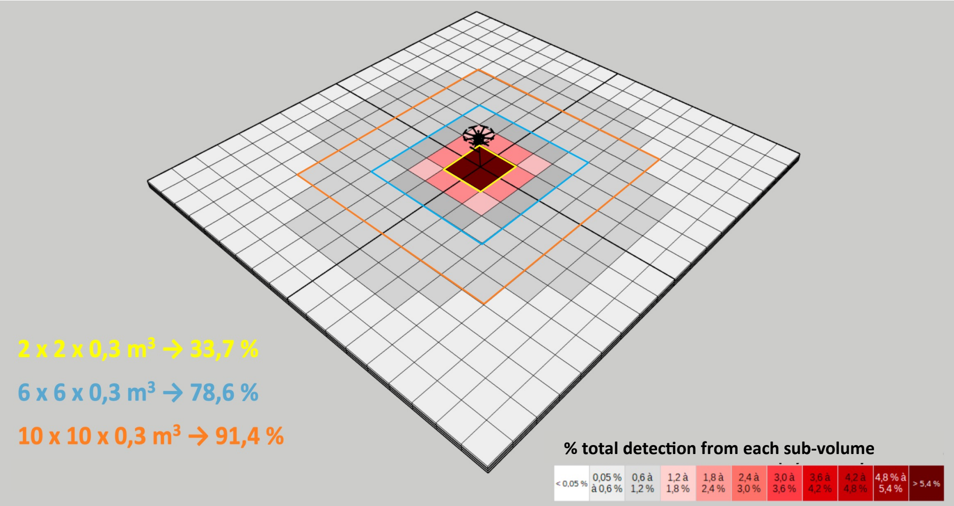
MEB platform
T. Ferté
C. Leuvrey

Drone-borne Gamma Spectrometry

- Development of a drone-borne system with dedicated analysis framework:
  - → low-altitude oriented measurements (< 10 m)
  - → focus on screened contamination (soil, trees, buildings, …)





1s spectrum (2m – 1Mbq ^{137}Cs source)

Drone-borne Gamma Spectrometry

- Various possible applications:

Brownfields

Emergency services

Former Uranium mines

Nuclear plants (dismantling)

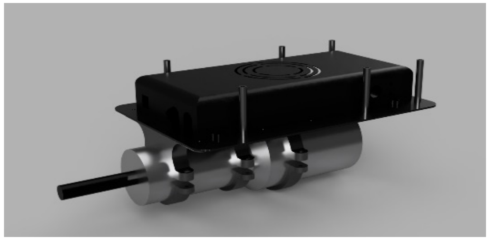
Security

MERCURE System @ IPHC

- Drone-borne system developed at IPHC laboratory (SATT Conectus fundings)

Terremys drone

+



Gamma spectacular NaI (3''x3'')
(+IPHC GPS/acquisition)

- Analysis software for environmental radioactivity monitoring with drone

- Laboratory tests:

  - **^{137}Cs**, ^{60}Co, ^{241}Am sources (surface, 12.2 cm depth in soil)
  - ^{137}Cs activity: 895 kBq (point source)
  - flight altitude: 2 meters
  - flight speed: 1 meter/second

Attenuation (air, soil) corrections

- Experimental corrections depend on various parameters: contamination distribution (3D), landscape, altitude, …
- Useful information can be extracted directly from measurements (spectra)

$\Rightarrow$ **Full spectrum reconstruction + machine learning**

Attenuation (air, soil) corrections

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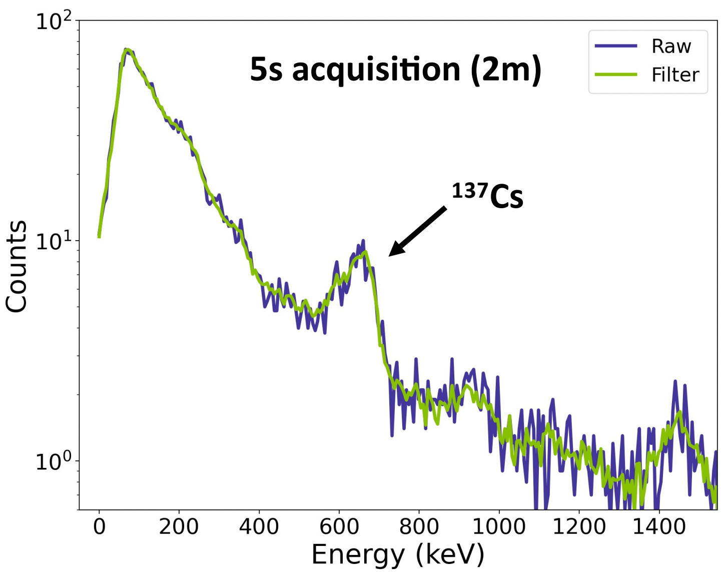
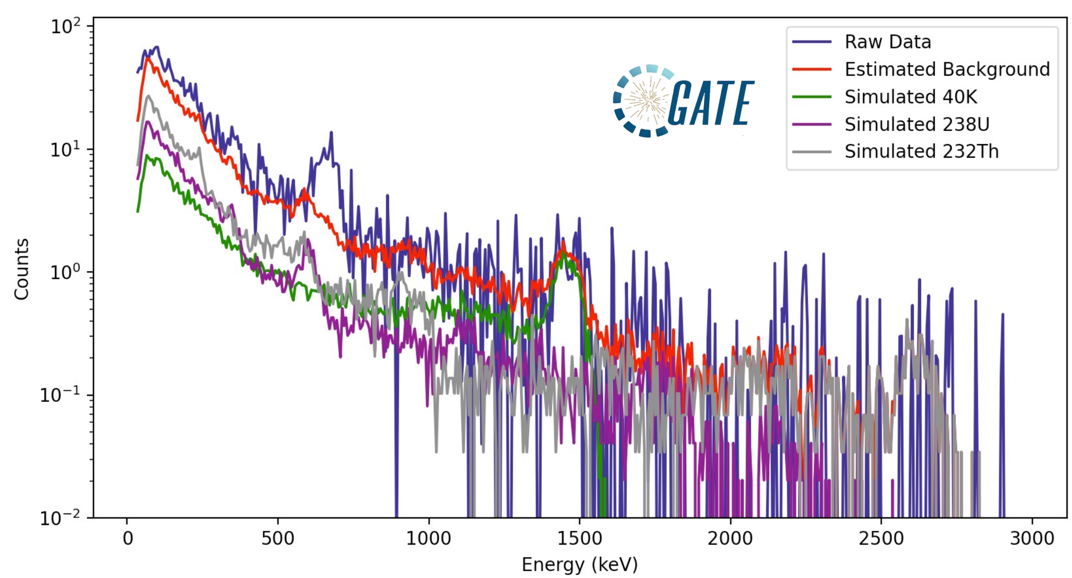
$\Rightarrow$ **Full spectrum reconstruction + machine learning**

- « Natural » background (^{40}K, ^{238}U, ^{232}Th, ^{137}Cs) deconvolution using Monte Carlo spectra



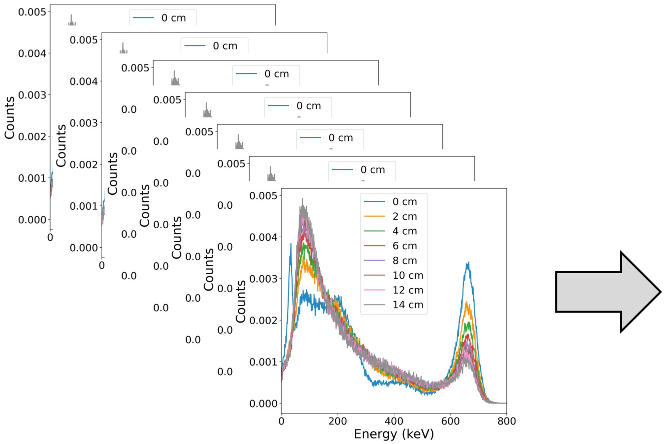


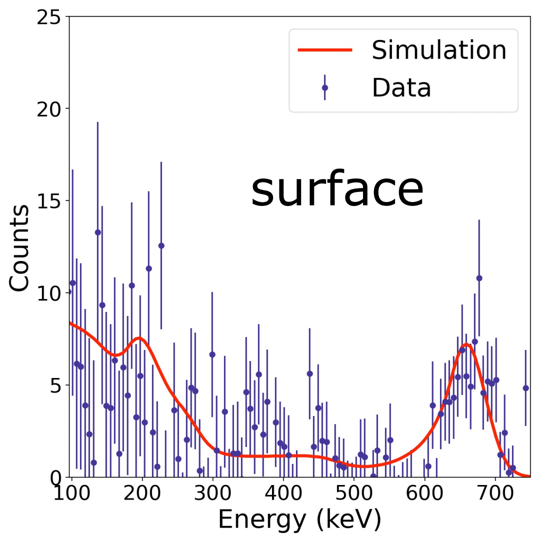
Attenuation (air, soil) corrections

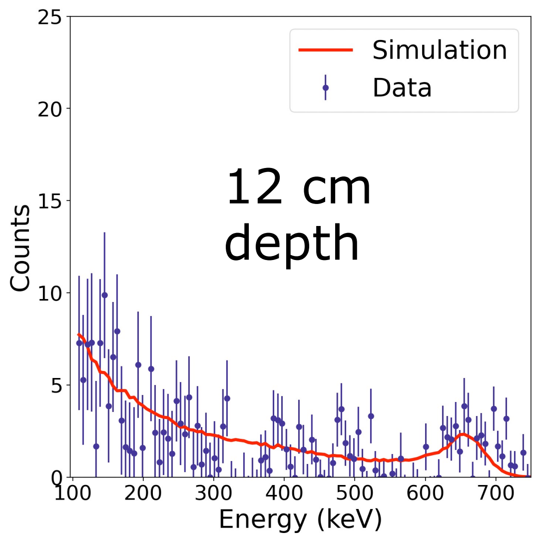
- Experimental corrections depend on various parameters: contamination distribution (3D), landscape, altitude, …
- Useful information can be extracted directly from measurements (spectra)

$\Rightarrow$ **Full spectrum reconstruction + machine learning**

- Machine learning algorithms trained on MC database
- Estimation of most probable attenuation correction to access « true » activity





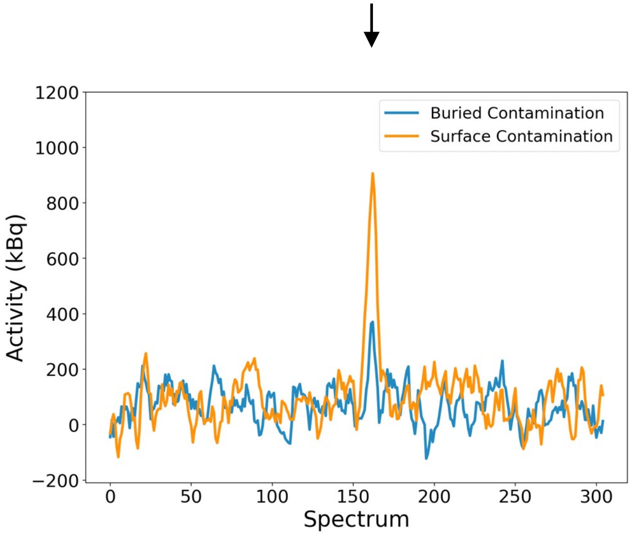


<u>Training</u>: altitude
materials
source distribution
radionuclides

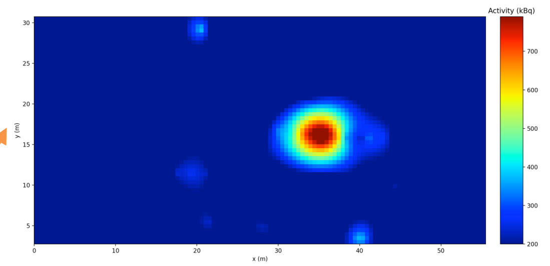
Radioactivity mapping

- Spectrum-by-spectrum calculations of ^{137}Cs activity
- Automatic correction of natural radioactivity, altitude and auto-attenuation in soil

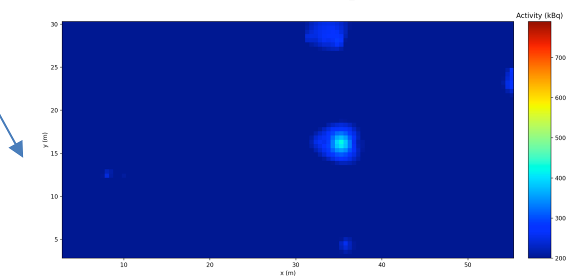
Drone above ^{137}Cs source



Surface raw



12cm deep raw



Radioactivity mapping

- Spectrum-by-spectrum calculations of ^{137}Cs activity
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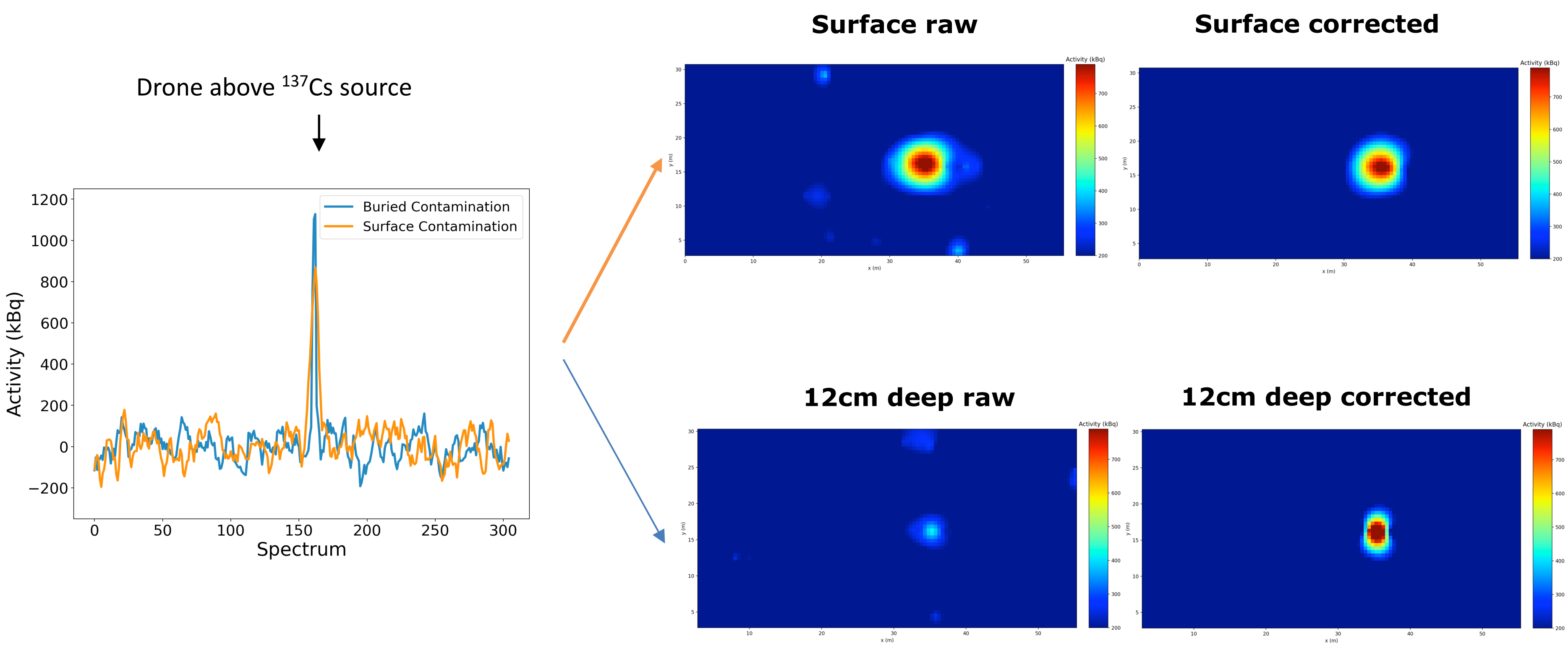


SMARTIUM start-up

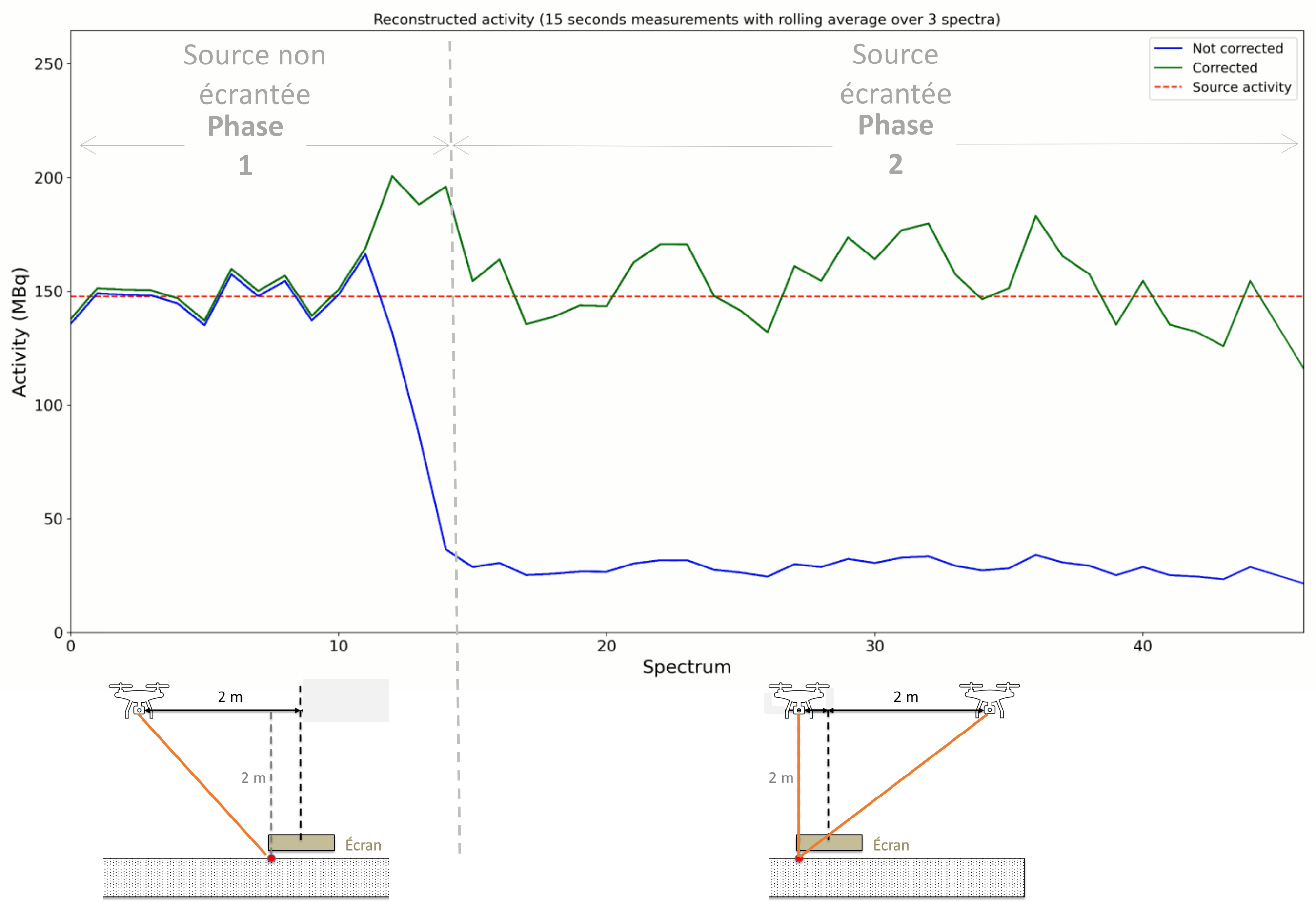
- **January 2019** : MERCURE SATT maturation project (18 months)
- **End 2020** : incubation phase
- **End 2021** : startup creation

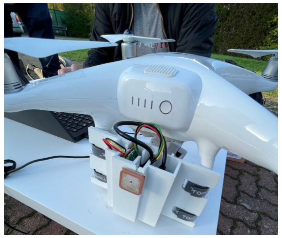
Embedded MC/AI solutions for radiological measurement data analysis

- **Today** : 3 full-time people
  (CEO (J. Thomann) + 2 data scientists / physicians (G. Bourgatte, E. Wilhelm)
  IPHC PhD students
- Close collaboration with IPHC-DeSIs team

SMARTIUM start-up

- Compact drone-borne system (coll. IPHC & SDIS 67)
- Automatic screening corrections (rubbles, vehicles, …)





Questions ?