AlphaBeast: toward a 4D neutron monitoring system

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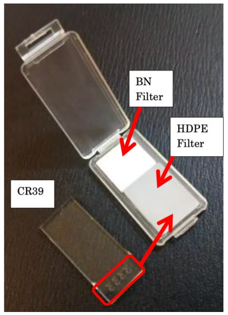
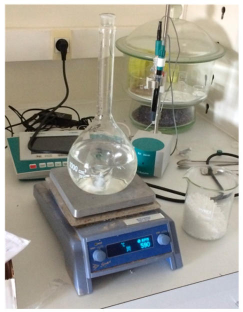
CNAO/IN2P3 – 24/10/2023

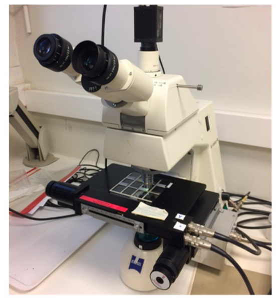
Neutron monitoring system

Solid Nuclear Track Detector (CR-39)

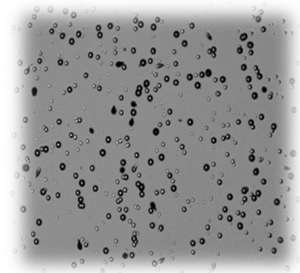




Chemical treatment



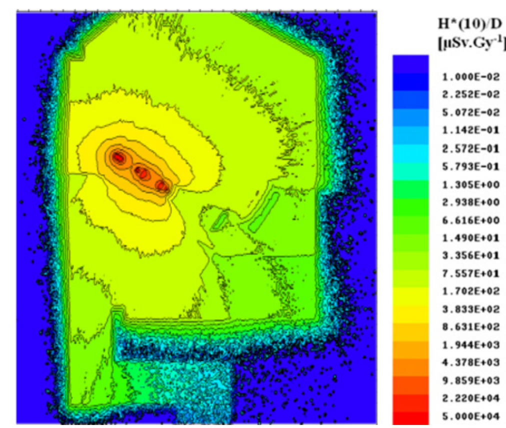
Detector reading



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



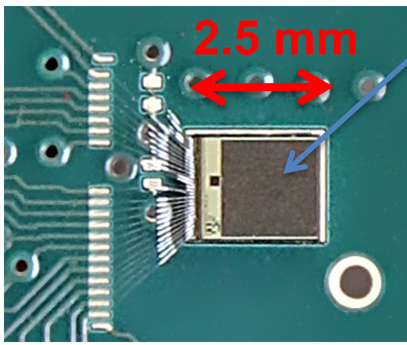
J. Farah, Phys. Med. Biol. **59** (2014)

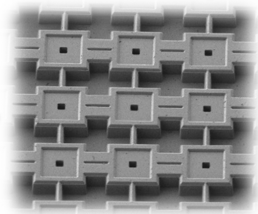
⇨ **CMOS technology**

AlphaRad3 (2017)

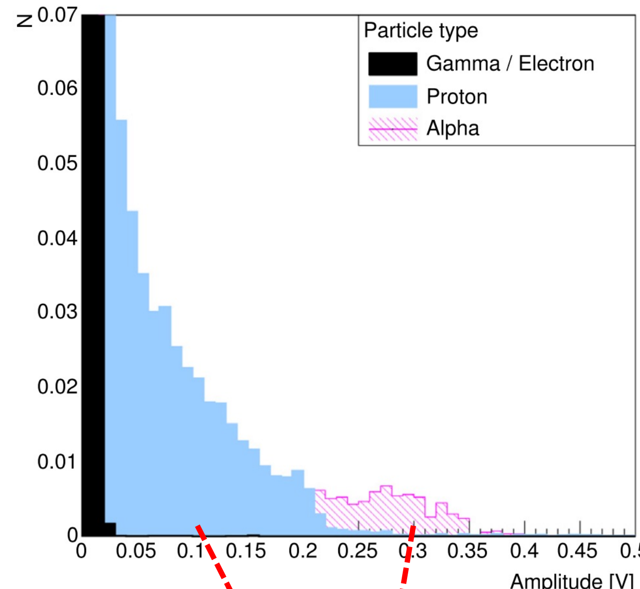
- Specially designed CMOS sensor for parallel detection of thermal and fast neutrons
- Compact and easy to use (real-time, integrated electronic, low power consumption)

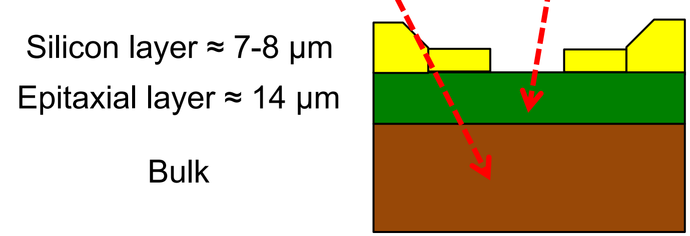
64x64 micro-diodes





alpha detection efficiency < 0.1% !





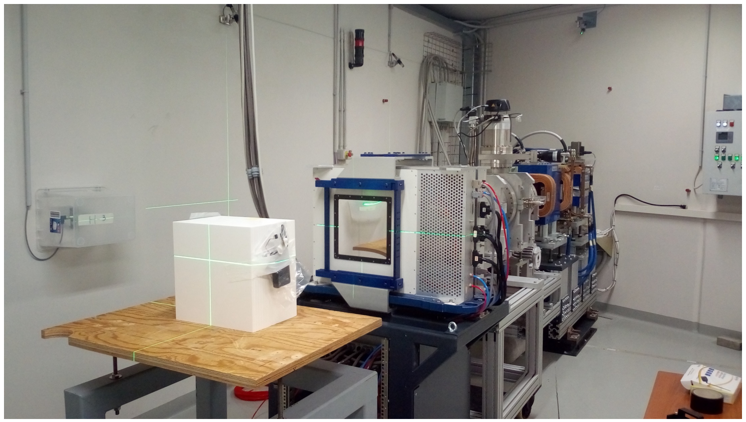
<u>Neutron detection</u>

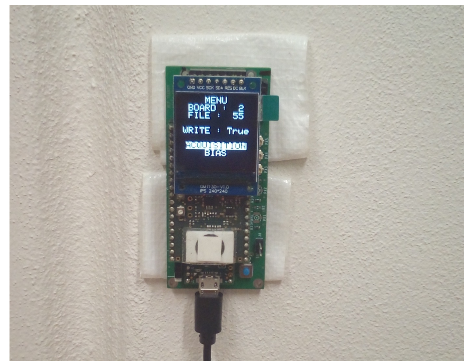
- Neutrons are converted into:
  - protons (n_{fast}, PE)
  - alpha particles (n_{therm}, ^{10}B)

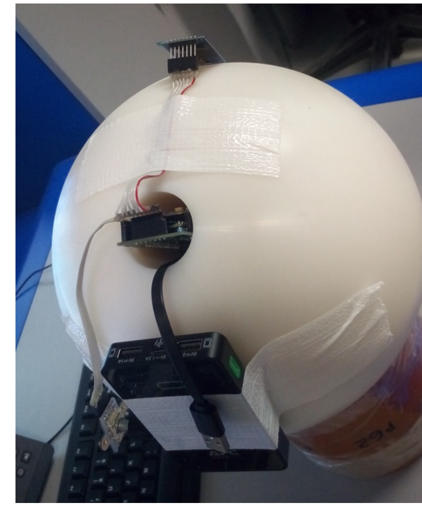
N. Arbor et al., PMB 62 (2017)
N. Arbor et al., NIM A 888 (2018)

AlphaRad3 (2017)

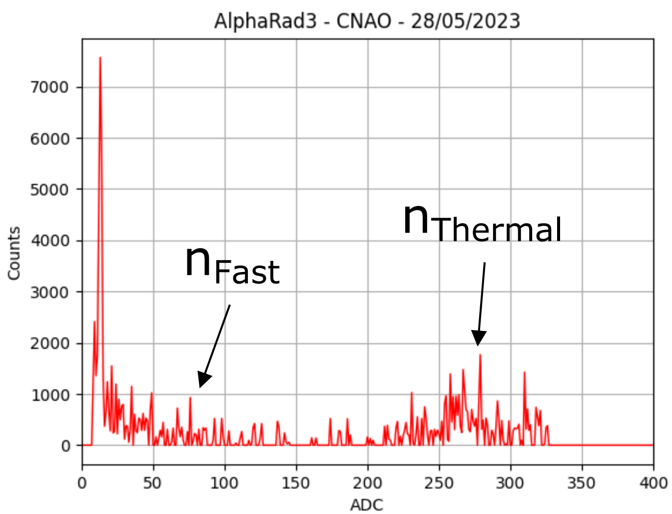
- CNAO (April 2023): test of a prototype for autonomous measurements







- It works !



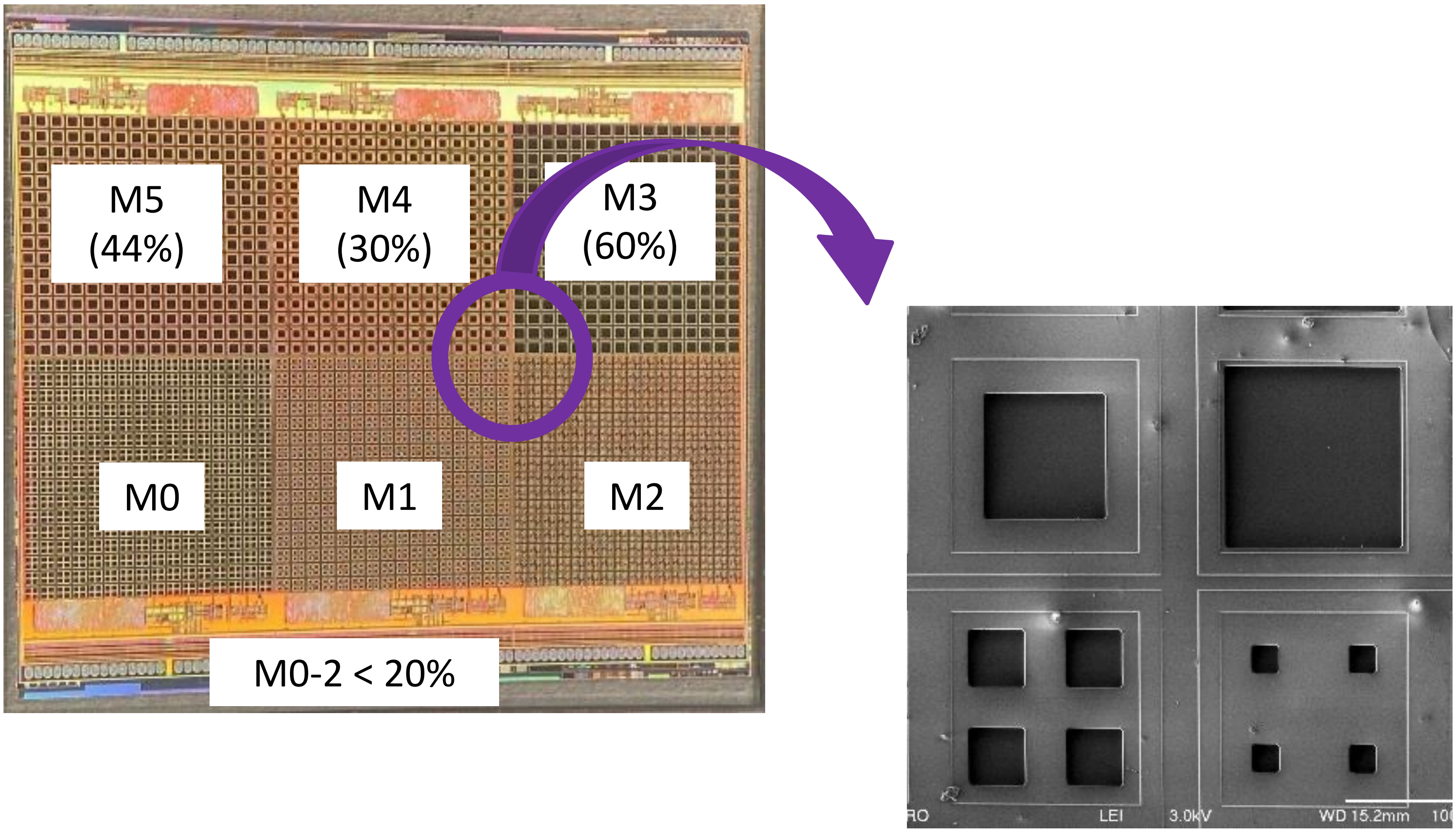
But:

- detection efficiency can be improved

- counting (thresholds on ADC signal) can be done by the CMOS itself

AlphaBeast (2023)

- New sensor designed in 2023 (coll. C4PI-IPHC platform)
- 6 different diodes configurations (matrix M0-M5)
- 3 internal thresholds (counters)



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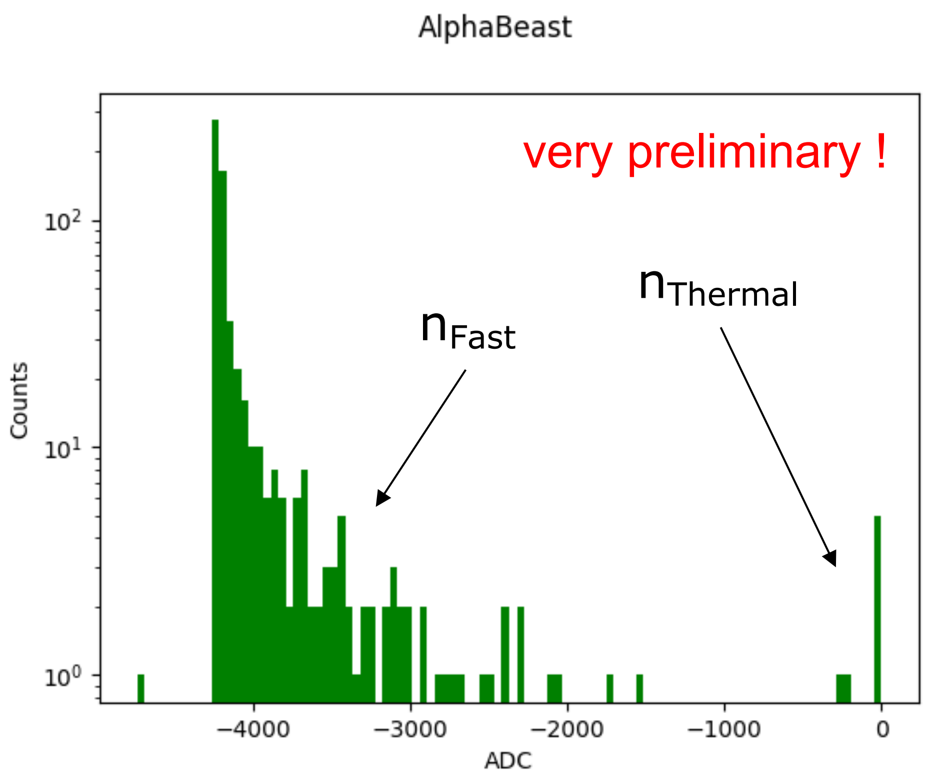
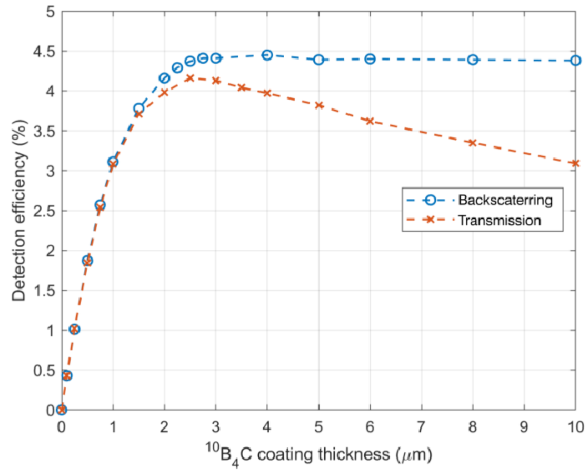
- CNAO (May 2023): very 1st measurements* with new sensor



* Bias parameters not optimized

Thermal neutron detection

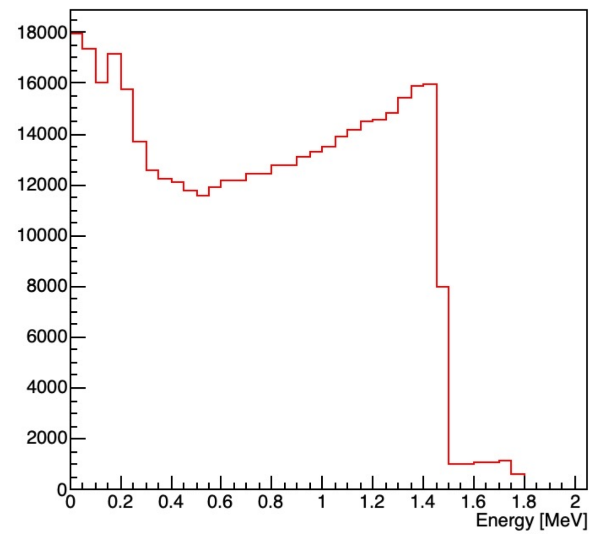
- ^{10}B converter on top of the sensor
- Conversion efficiency ≈ 4%



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 energy on AlphaBeast (Geant4 MC)

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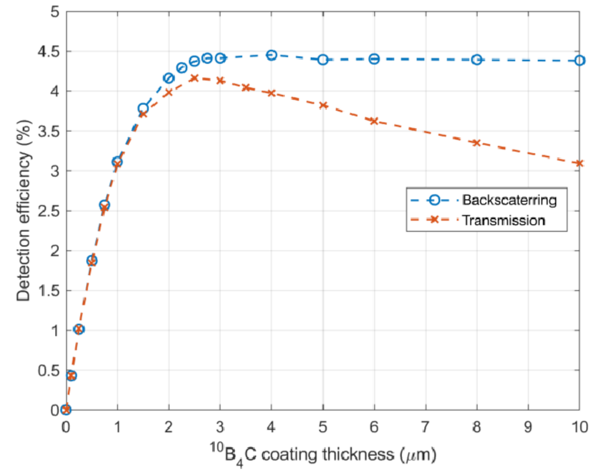

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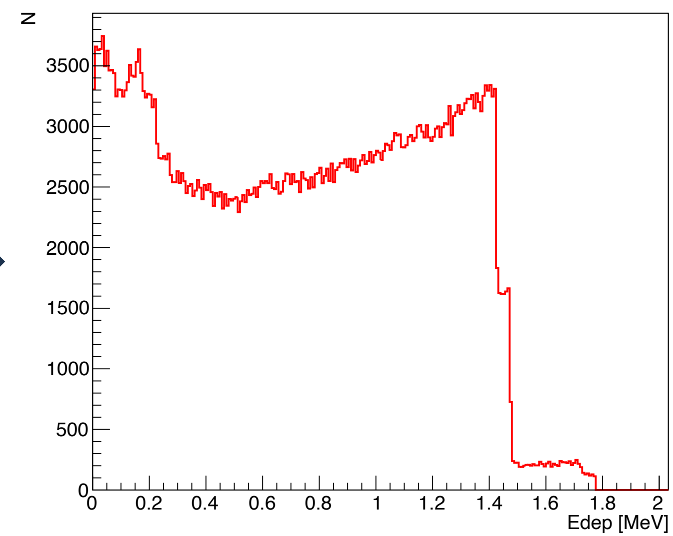
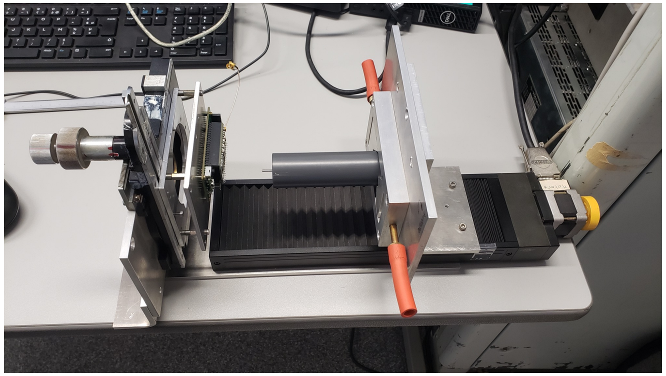


Alpha deposited energy
on AlphaBeast (Geant4 MC)

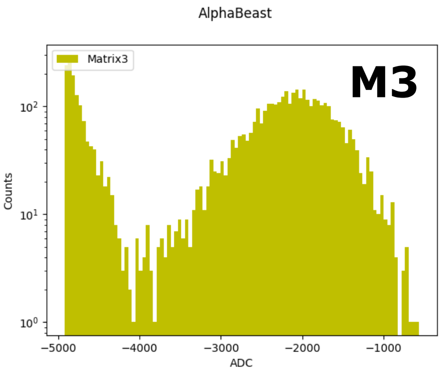
Alpha particles measurements

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

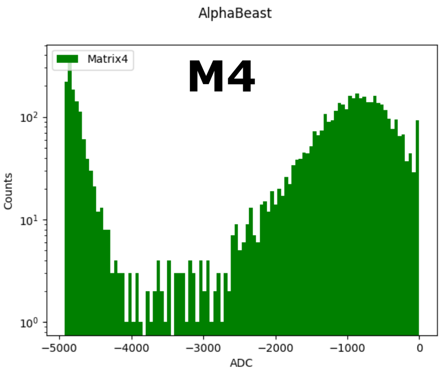


$E_{alpha} \approx 5.48$ MeV (d = 0 mm)

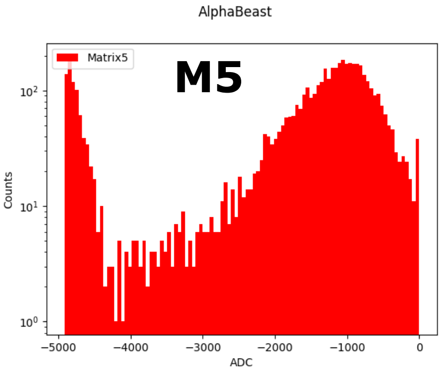
- Measurements for distance d = 35 mm ($<E_{alpha}> \approx 1.25$ MeV)



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



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



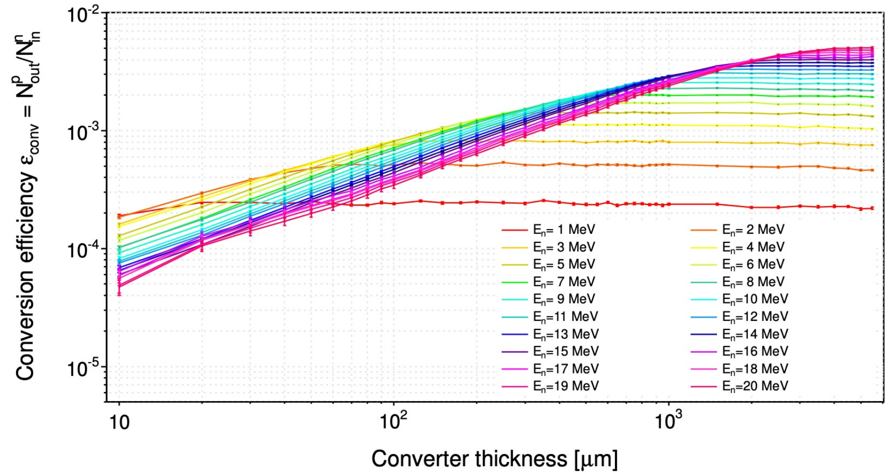
$\mathcal{E}_{det} \approx 43\%$
($\mathcal{E}_{geo} \approx 44\%$)

Intrinsic alpha detection efficiency > 99% !

Fast neutron detection

- PE converter (1 mm)

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



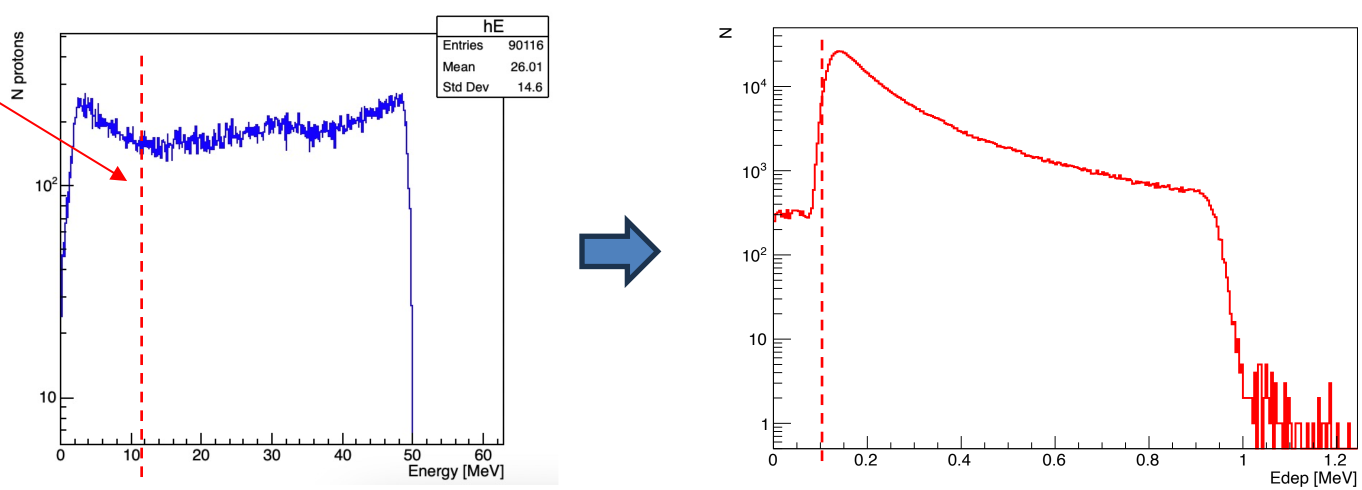
M. Vanstalle PhD (2010)

ΔE_{min} detection ≈ 100 keV

⇔

Proton E_{max} ≈ 10 MeV

Example:
neutron E = 50 MeV



(Geant4 MC)

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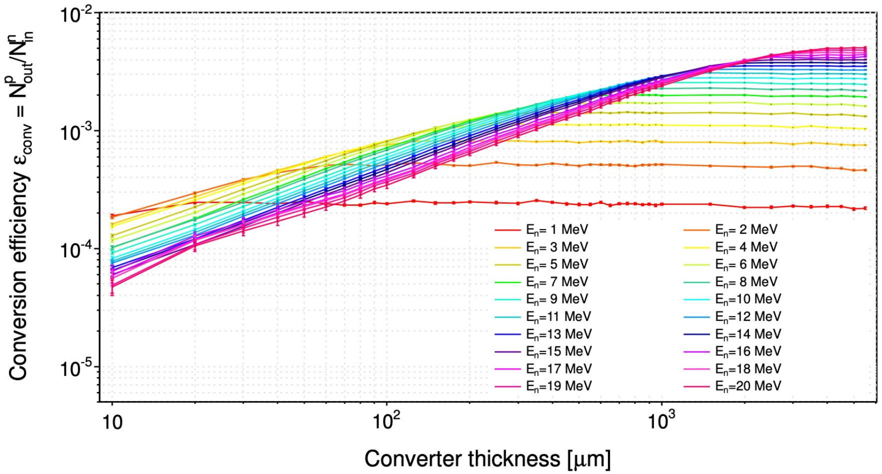

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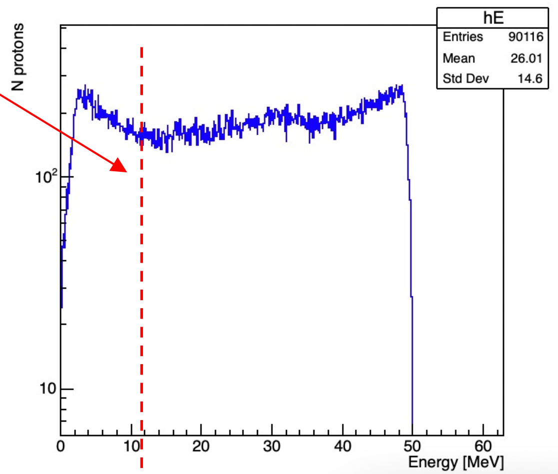
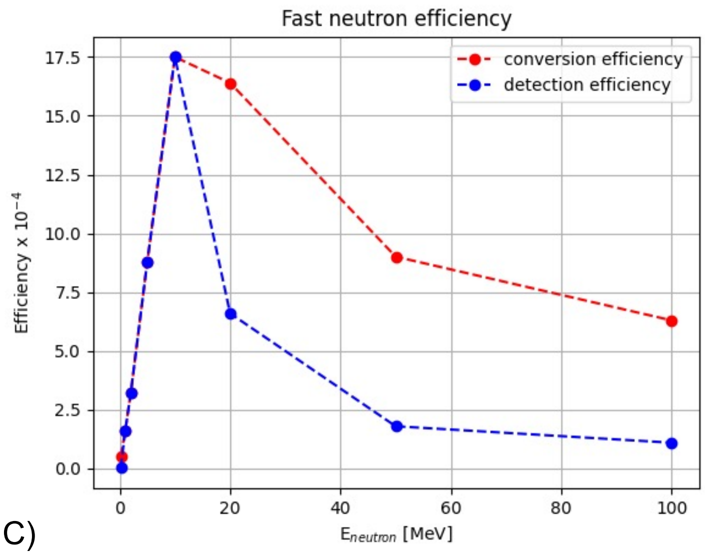
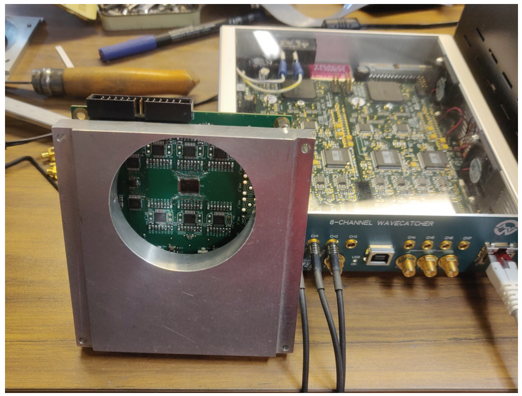


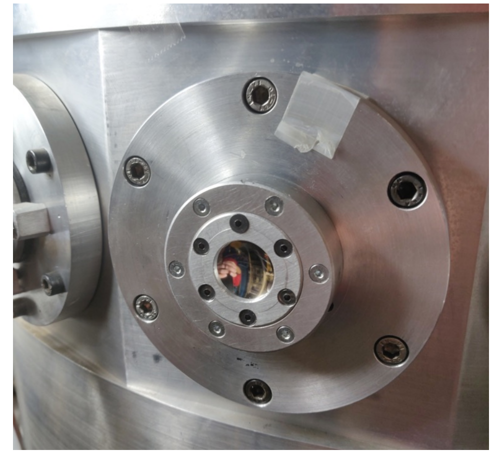


(Geant4 MC)

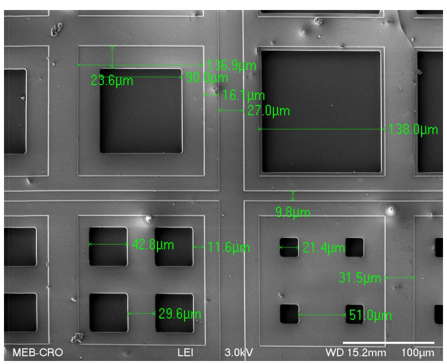
Proton measurements

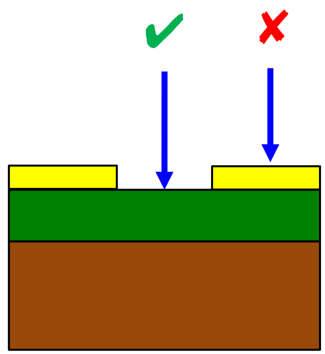
- Icube 4 MeV Van de Graaf accelerator (Au target RBS)

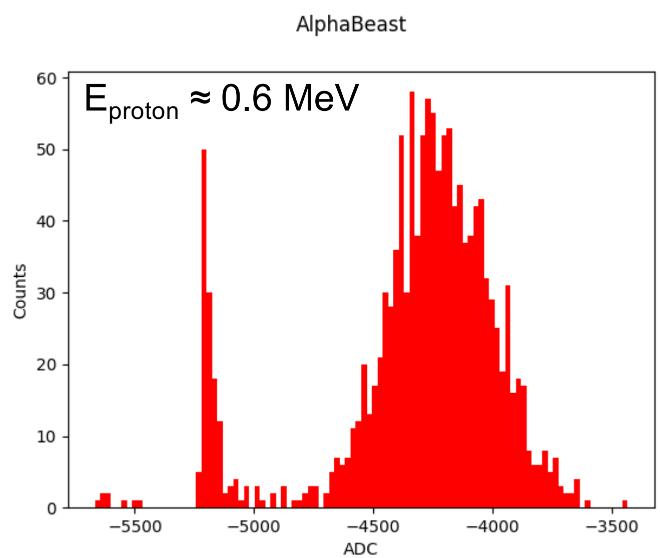




- Deposited energy sub-structures







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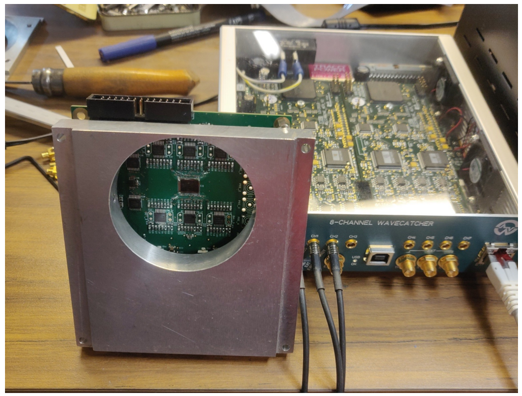

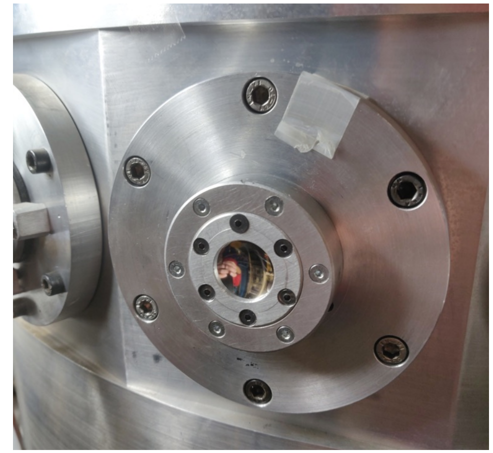

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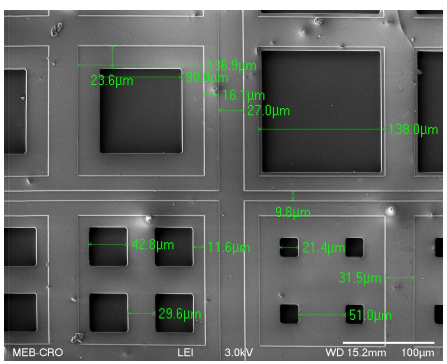

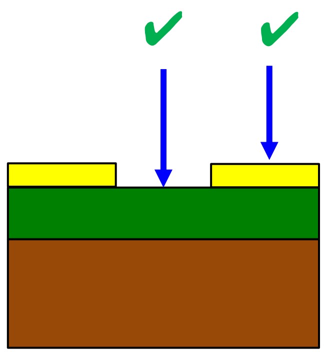

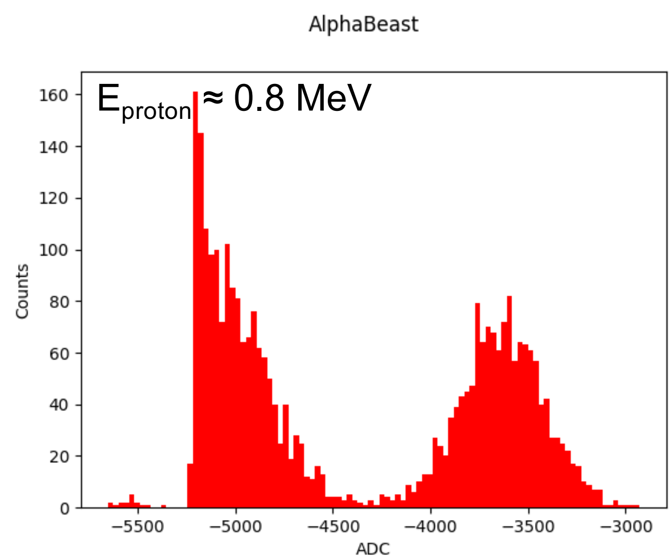

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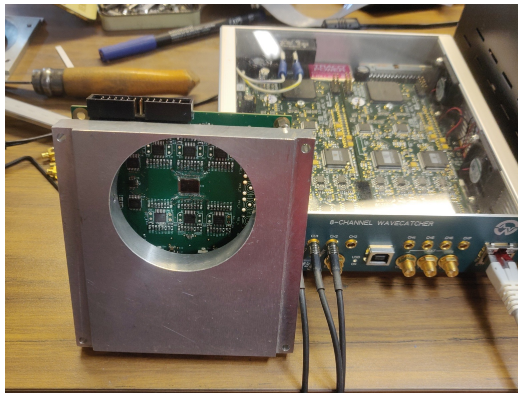

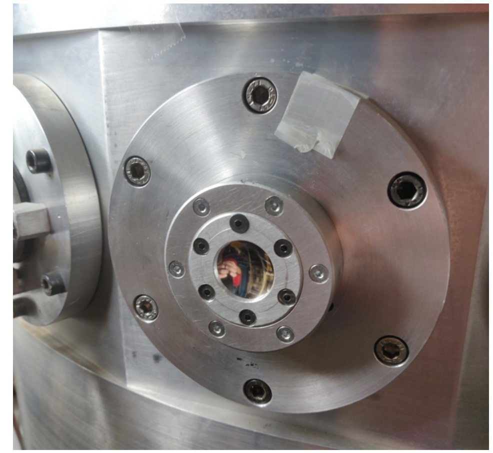

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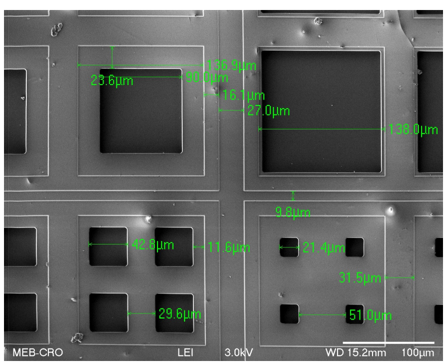

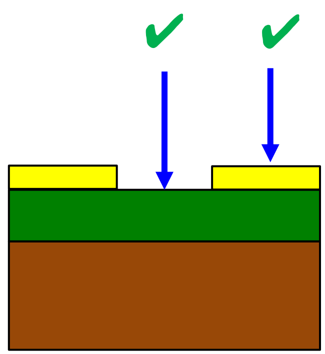

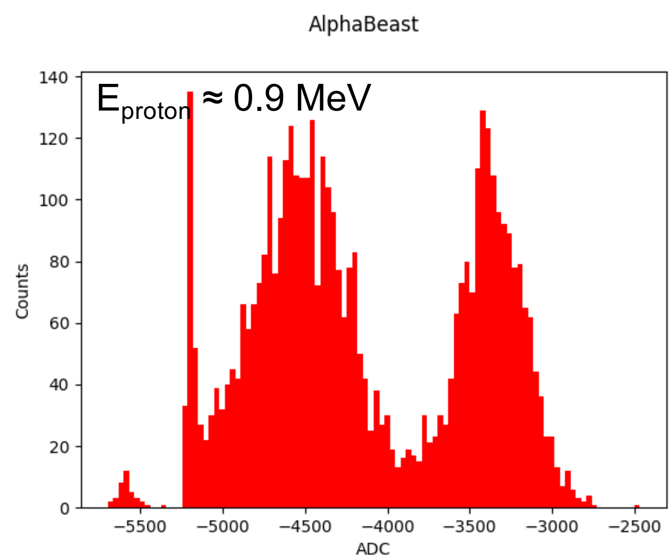

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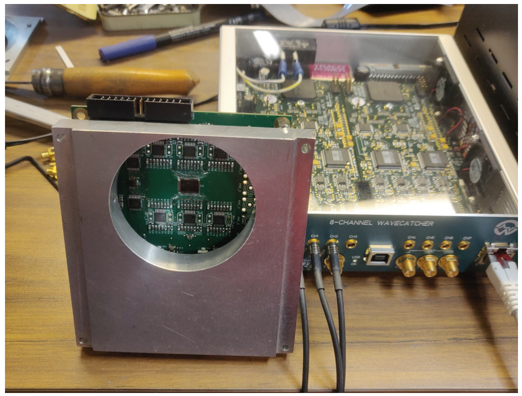

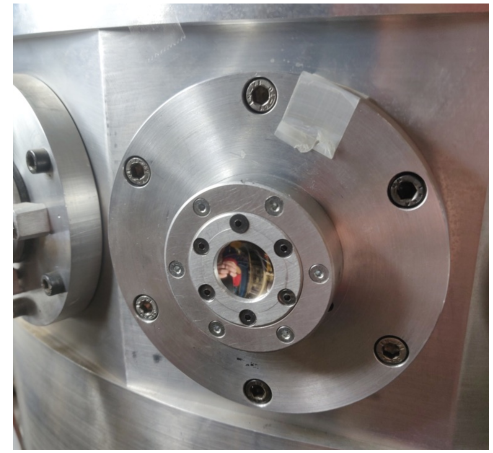

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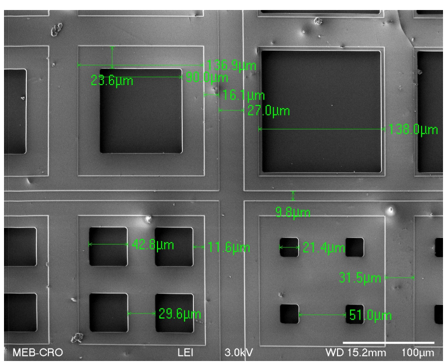
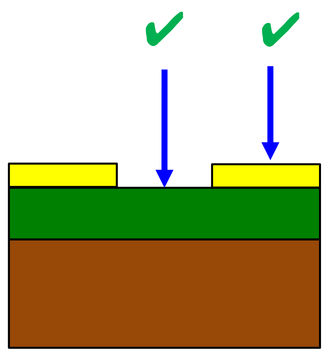
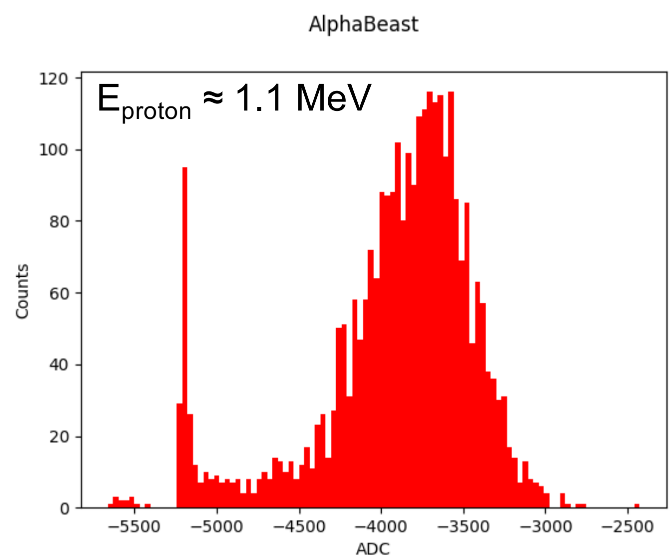
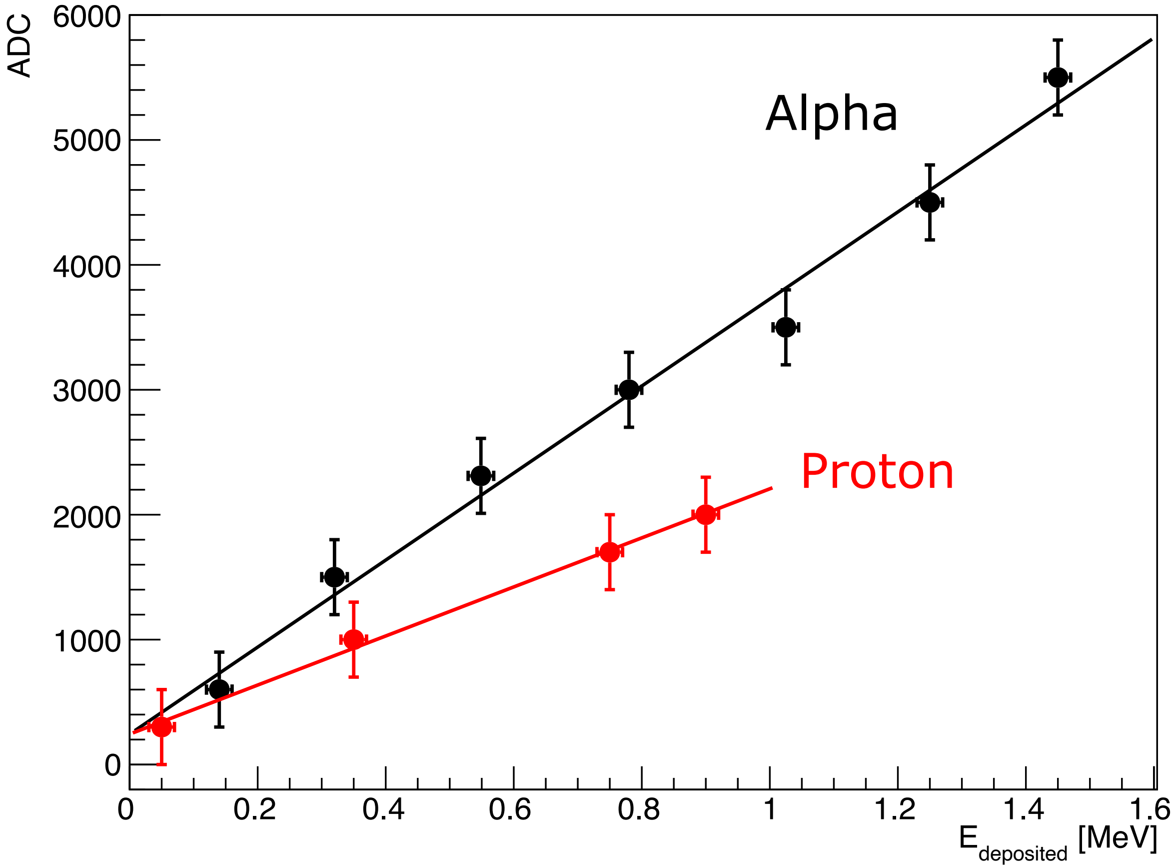






AlphaBeast energy calibration

- 1st hypothesis: 100% charge collection efficiency

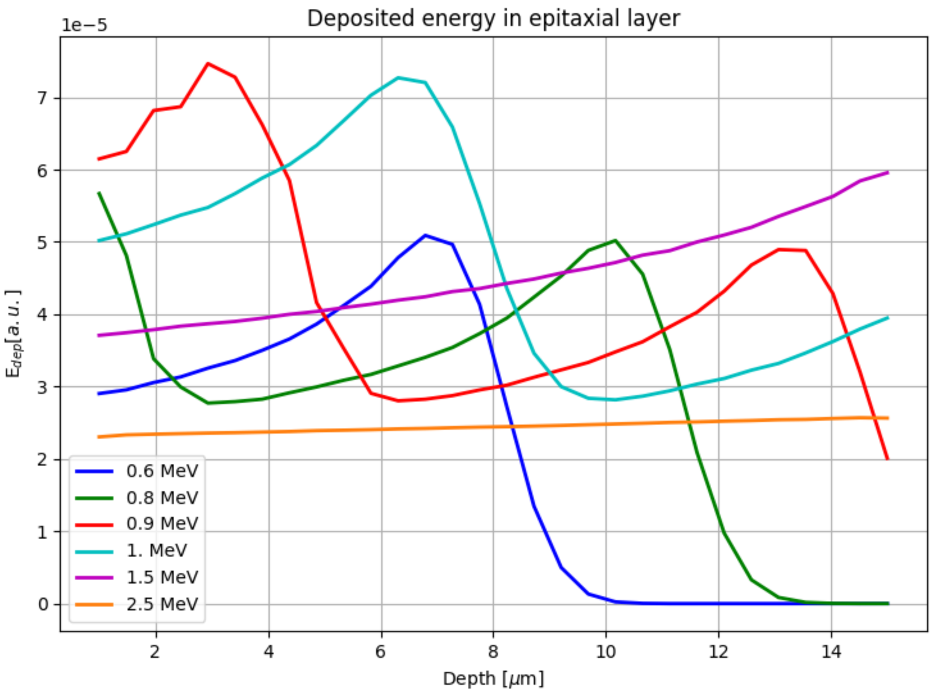


AlphaBeast energy calibration

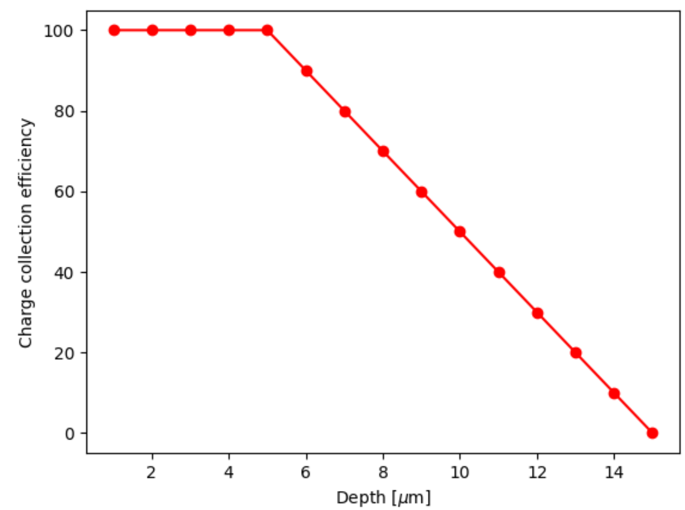
- 2nd hypothesis: charge collection inefficiency with depth in epitaxial layer

  ⟶ alpha particles deposit energy in 3-4 μm

  ⟶ protons deposit energy at different depths (btw 0 to 15 μm)



Charge collection efficiency



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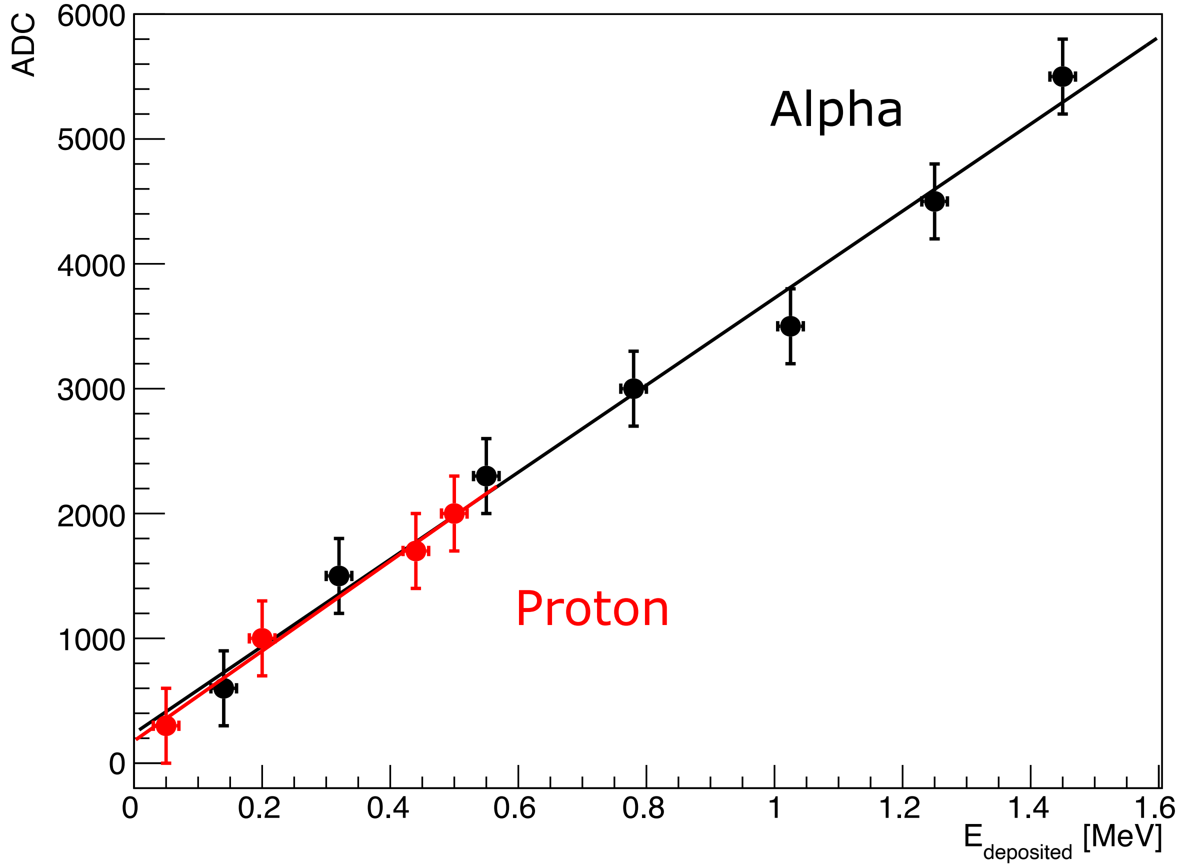
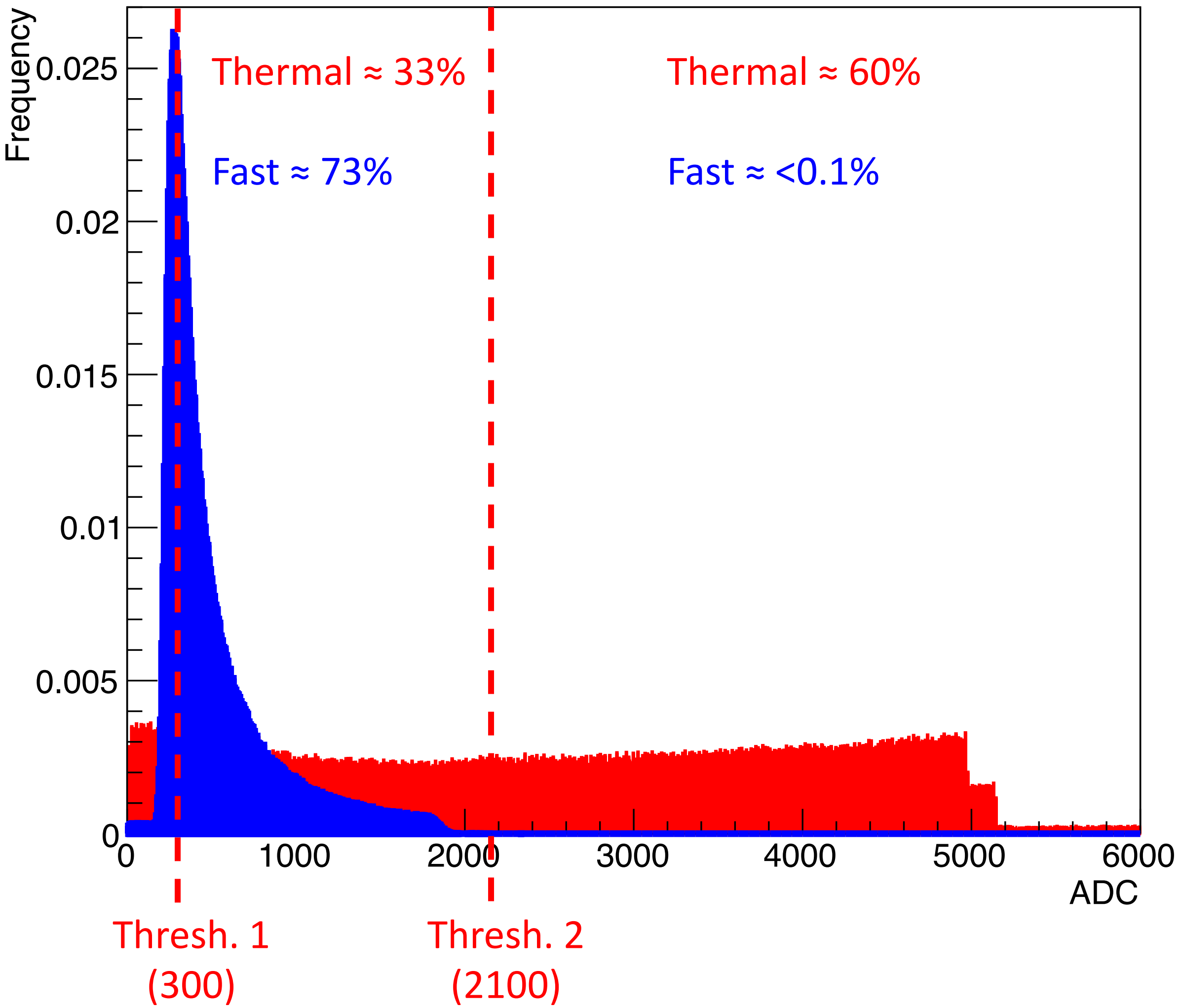


AlphaBeast settings (on-going)

- 3 internal thresholds to be set for autonomous counting



<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>

$\mathcal{E}_{th} \approx 4x10^{-4}$ hit/(n.s^{-1}.cm^{-2})

$\mathcal{E}_{fast} \approx 4x10^{-5}$ hit/(n.s^{-1}.cm^{-2})

Conclusion & Outlook

Important steps for the development of a 4D neutron monitoring system:

1) Prototype for autonomous measurements (*AlphaRad3* – CNAO 04/2023)

2) Characterization of new CMOS sensor *AlphaBeast*
   - alpha detection efficiency ≃ 100%
   - energy calibration alpha / protons
   - internal threholds setting (counters)

Next steps?

- tests in radiotherapy room (ICANS - Strasbourg)
- measurement of 3D charge collection efficiency map
  using alpha/proton micro-beam facility (AIFIRA – LP2i Bordeaux)
- applications @ CNAO for radiation protection (BNCT, … ?)