



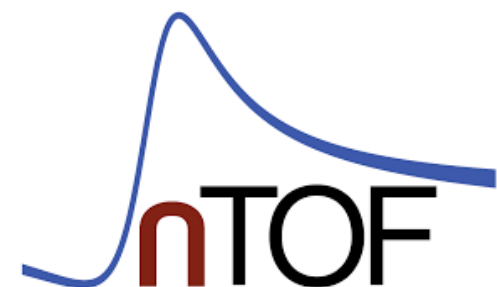
Side-on GEMpix detector characterization for charged-particle tracking via ^6Li reaction products at n_TOF

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ENEA Frascati & INFN - LNF

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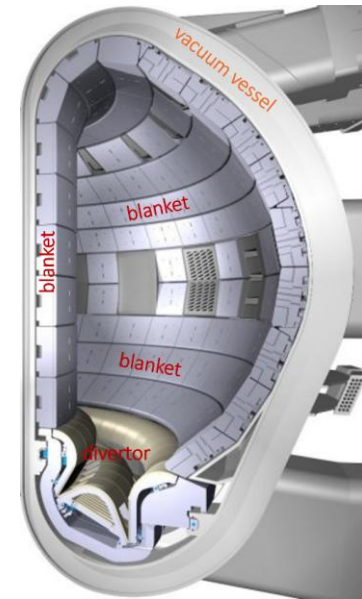
OUTLINE

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4. Time-of-Flight measurements on the n_TOF facility
5. Track analysis of the experimental results
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1. Scientific background

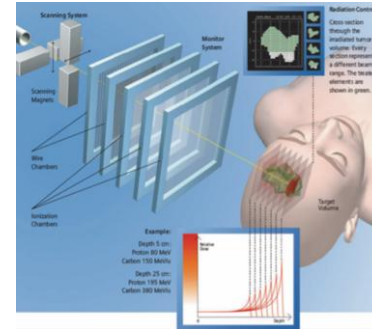
nuclear energy

- ✓ Study of (n, cp) reactions (cp = light charged particle) to evaluate the effects of radiation damage on structural materials in the inner part of the tokamak (blanket and divertor).
- ✓ Cross sections for (n, cp) reactions are particularly required for a variety of elements, such as Be, Fe, Mo, and W.
- ✓ The ^{35}Cl cross-section needs to be studied to optimize next-generation nuclear fission reactors, predict long-lived radioactive waste, and model stellar nucleosynthesis.



Astrophysics and nuclear medicine

- ✓ **Astrophysics (Low-mass AGB stars):** Nuclear reactions are crucial for synthesizing elements heavier than iron through the *s-process* and *r-process*. Key reactions include $^{16}\text{O}(n, \alpha)^{13}\text{C}$ and those acting as "neutron poisons" in the *s-process*, specifically $^{14}\text{N}(n, p)^{14}\text{C}$ and $^{26}\text{Al}(n, p)^{26}\text{Mg}$.
- ✓ **Nuclear Medicine (Hadron-therapy and BNCT):** Advanced cancer therapies require more accurate dose estimations in human tissues. This creates a need to resolve current inconsistencies regarding the (n,p) and (n,d) cross-sections of essential body elements, namely oxygen, nitrogen, and carbon.

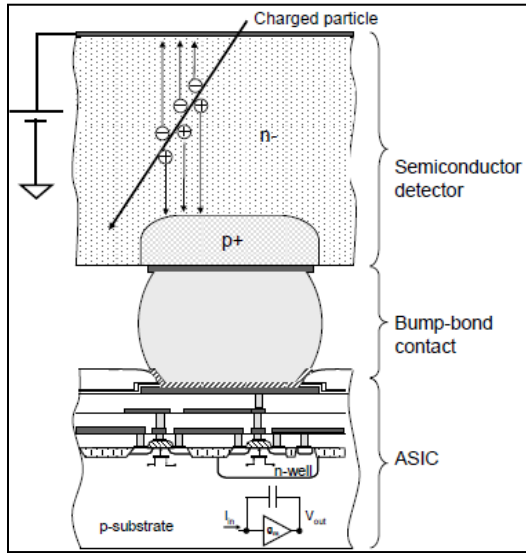


For higher energy charged products (> 2 MeV), silicon detectors and other detection systems are used effectively, and the development of more refined ones is underway.

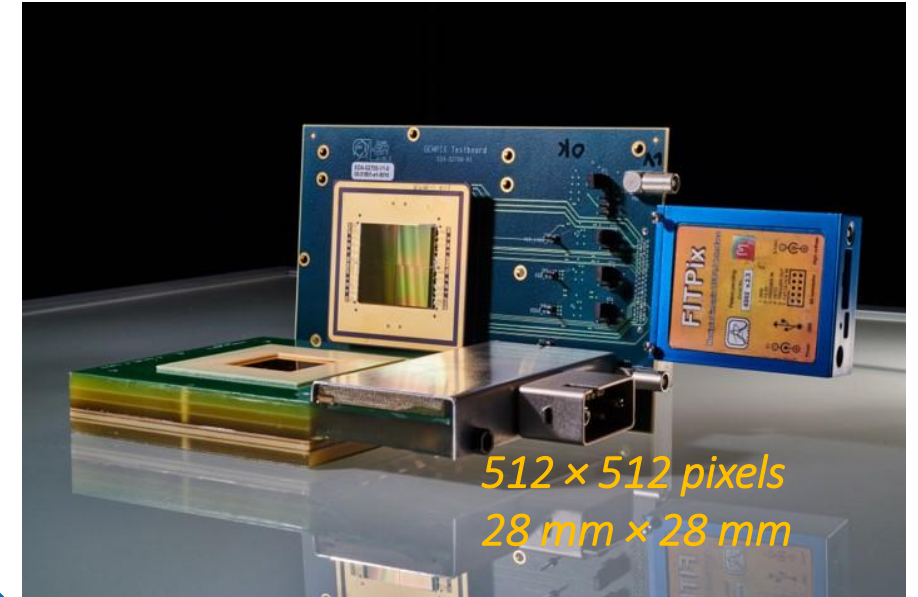
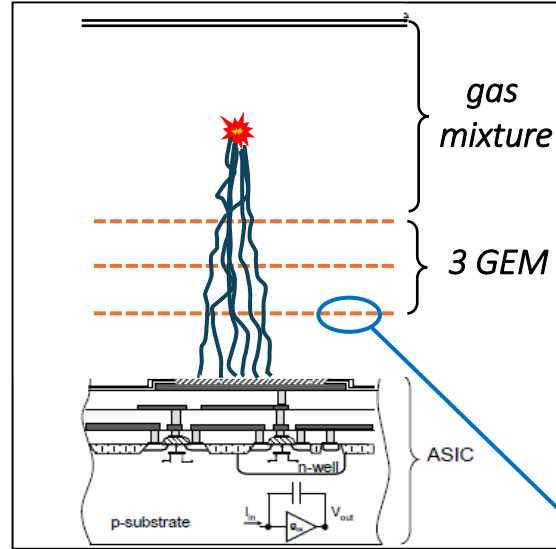
For lower energies, other diagnostic systems are needed and GEMPix has been proposed as a dedicated system to measure lower energy products, in particular for low-Z charged particles like protons, deuterons, tritons and alphas.

GEMPix needs to be optimized for these specific applications!

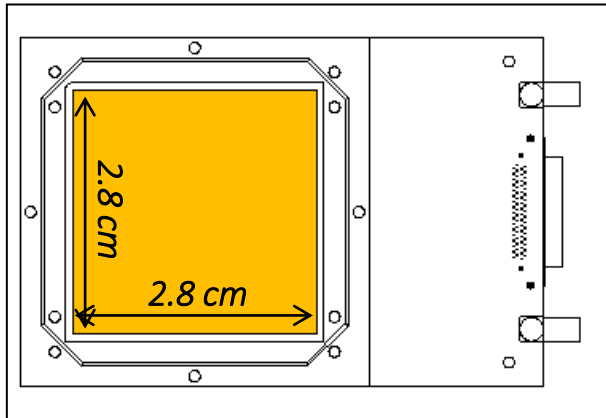
2. GEMPix detector and its side-on configuration



from Silicon
to Triple-GEM



High Dynamic Range and high spatial resolution ($55 \times 55 \mu\text{m}^2$ pixels)

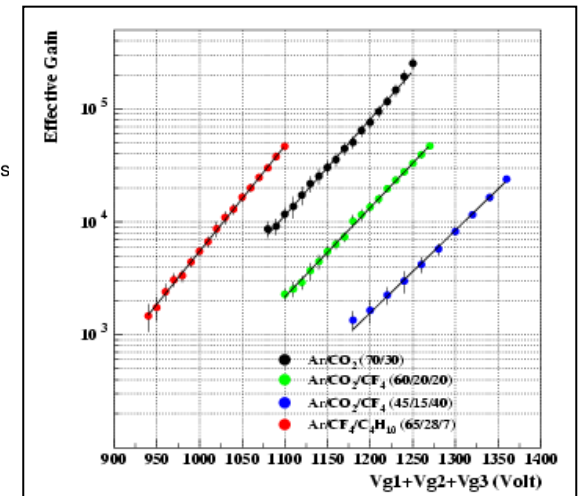
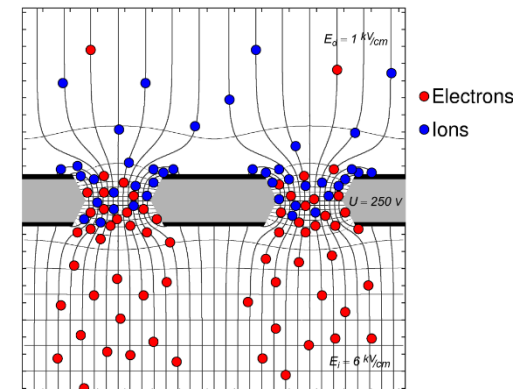


The quad Medipix is made of 4 Medipix chips held together (512×512 pixels).

The triple-GEM (Gas Electron Multiplier) gain can range over at least 4 orders of magnitude, so this detector can work with a **high dynamic range**.

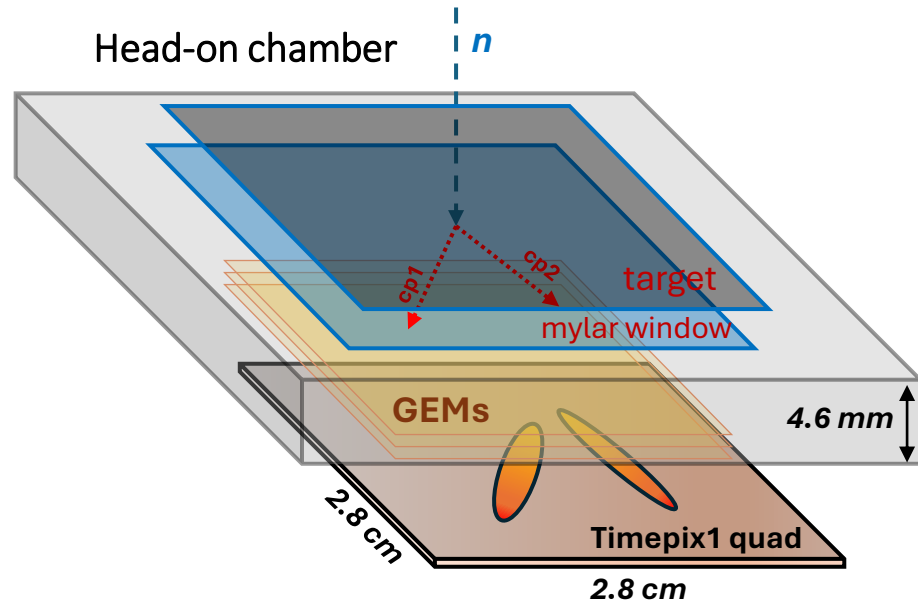
It is based on the Timepix1 chip and can therefore work in **counting, ToT or ToA, separately**. In addition, **acquisitions are frame-based**, so it is possible to acquire in defined time intervals limited also by ToT measurements.

GAS ELECTRON MULTIPLIER (GEM)

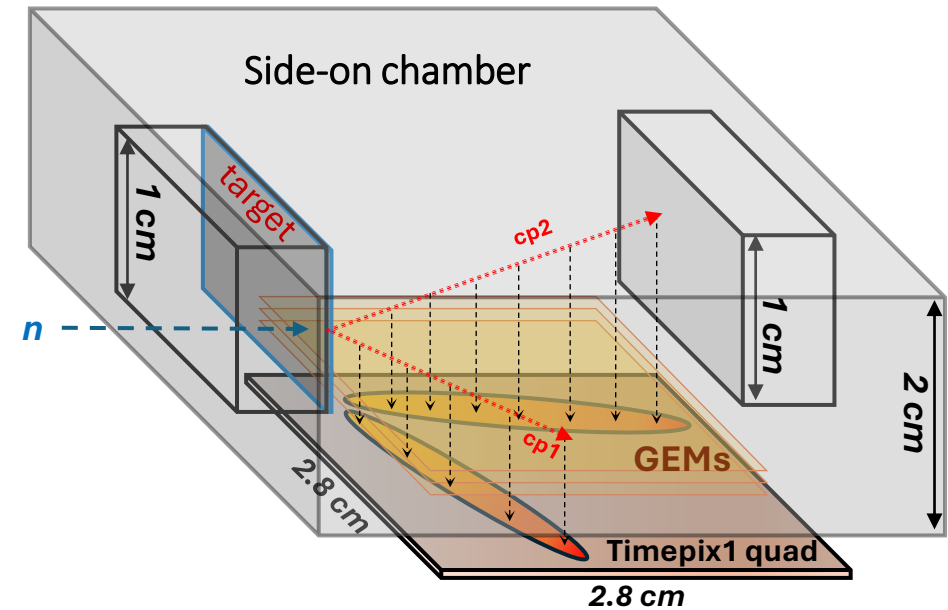


2. GEMPix detector and its side-on configuration

Generally, this type of measurement involves the neutron irradiation of a target (the material to be studied) which emits charged particles that must be identified and measured by dedicated diagnostics (in this case a GEMPix detector).

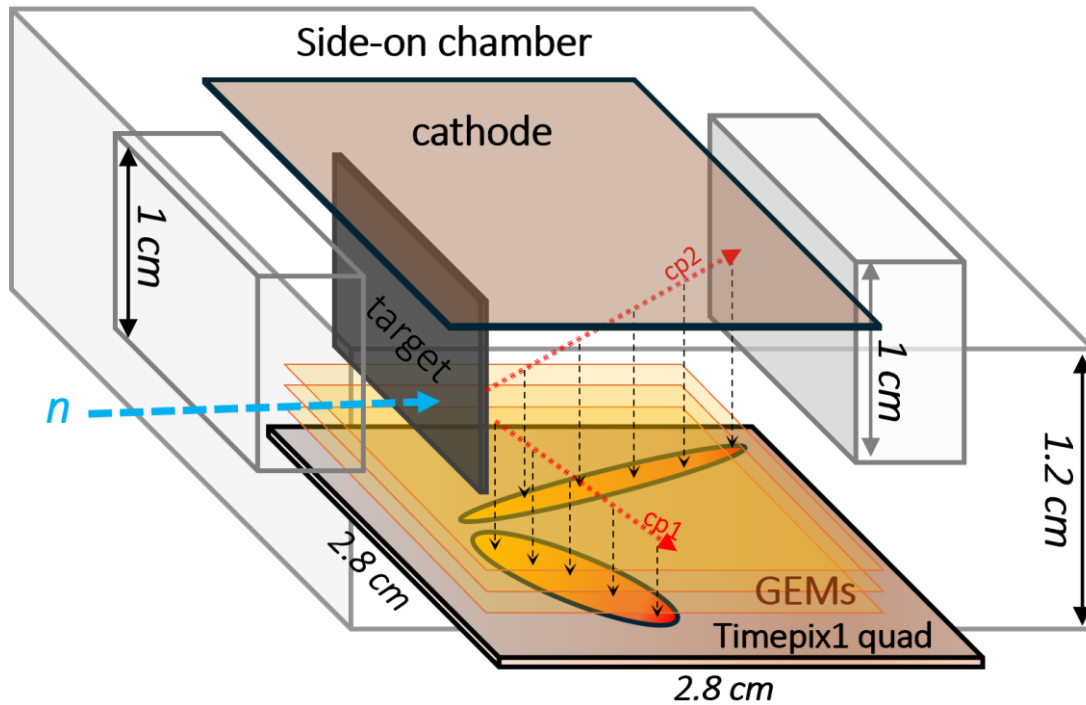


- The target must be outside and produced charged particles **lose part of their energy when traversing the aluminized mylar window**.
- The **active volume is small (3 mm gap)** and the deposited energy is not enough to discriminate the particles
- Due to proton recoils on the aluminized mylar window **a background higher than 90%** was observed and the discrimination of charged particles coming from the target is difficult.



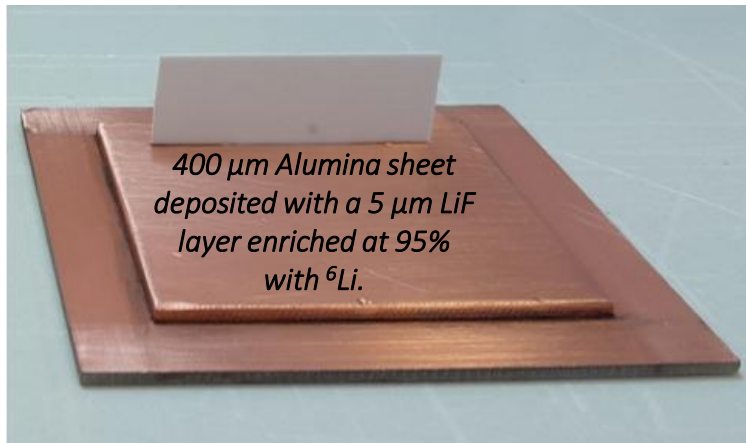
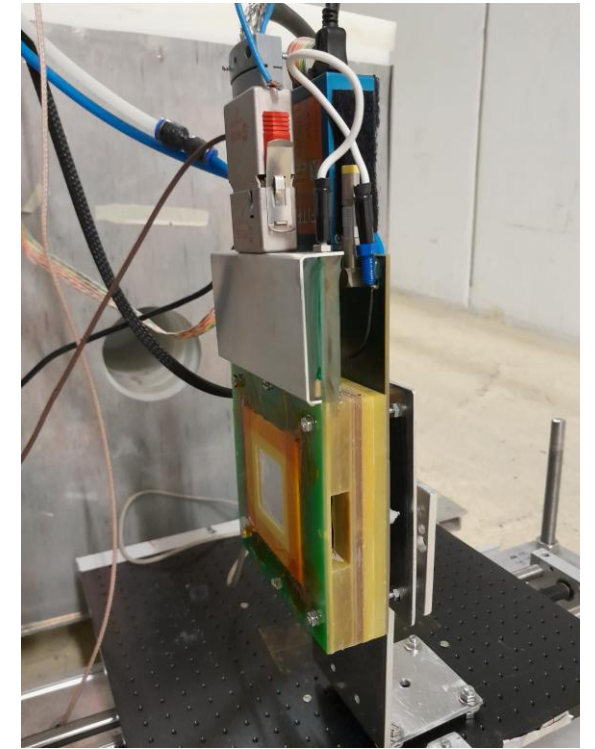
- In side-on geometry, **the target can be put inside**, and the produced particles are collected directly in the gas
- The **gas volume is larger (10 mm gap)** and particles can be stopped completely or deposit more energy inside the gas.
- **Entrance windows** are on side walls of the chamber and have been made **in glass (SiO₂)**, so that the background (due especially to proton recoils) is reduced.

2. GEMPix detector and its side-on configuration



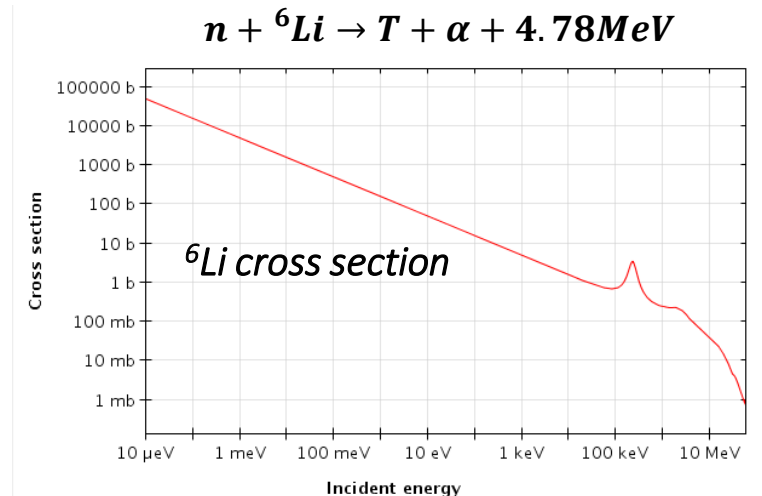
Cathodes have been realized with copper-plated fiberglass and **equipped with Alumina sheets with and without LiF deposition**. Each cathode can be removed and substituted with another one.

To ensure electric field uniformity and avoid discharge, experimental tests have been performed to evaluate the optimal voltage to apply in the active region. **The best value is 1.2 kV, i.e. an electric field of 1 kV/cm.**

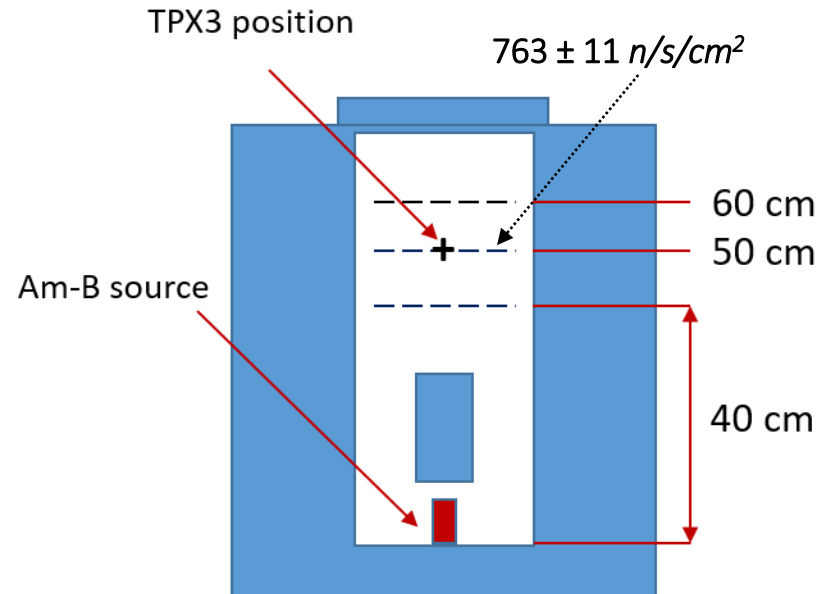
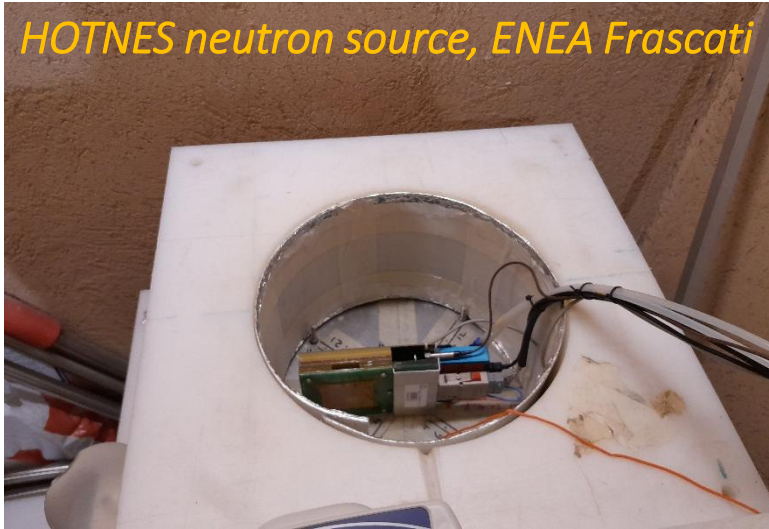


In order to validate the capability of the GEMPix to measure and discriminate particles for cross-section measurements, it was decided to use a well-known isotope with a known cross-section widely used in the field of neutronics: Li-6 (Lithium-6).

To this end, two cathodes were prepared using 1 × 3 cm **alumina targets**: one deposited with a 5 μm thick layer of lithium fluoride (LiF), and the other with alumina only.



3. Characterization tests with thermal neutrons



To best characterize and discriminate the observed clusters, a set of morphological parameters have been defined:

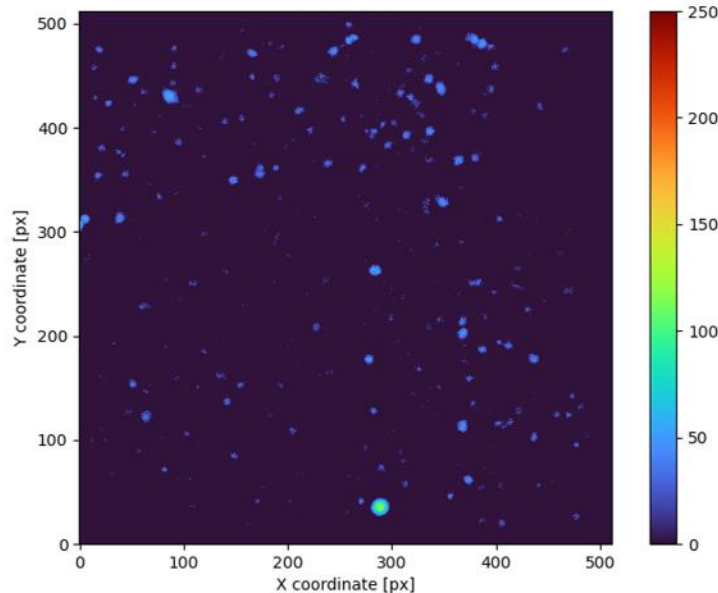
Cluster Size: sum of the pixels constituting the cluster (cluster dimension).

ToT volume (ToTv): sum of all the ToT values of the cluster (deposited energy). It must therefore be calibrated in energy.

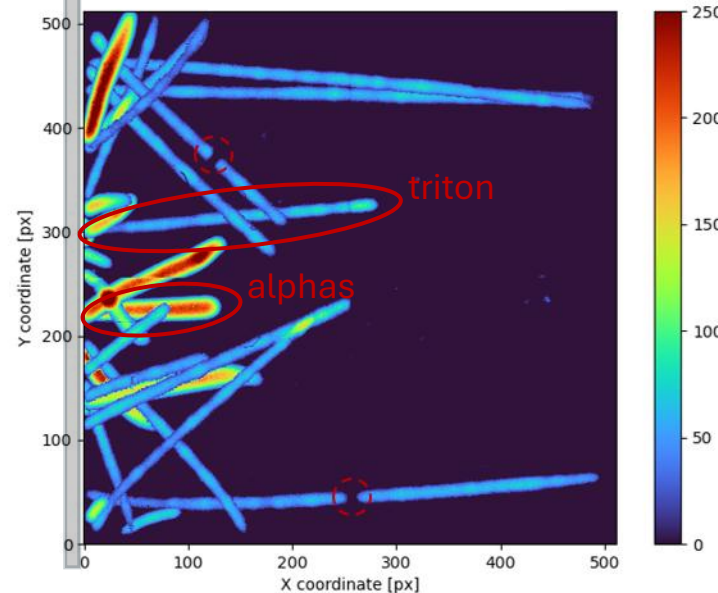
Roundness (Rnd): ratio of the Cluster Size to the area of the circle spanning its two most distant pixels.

HV = 870 V (gain = 140)

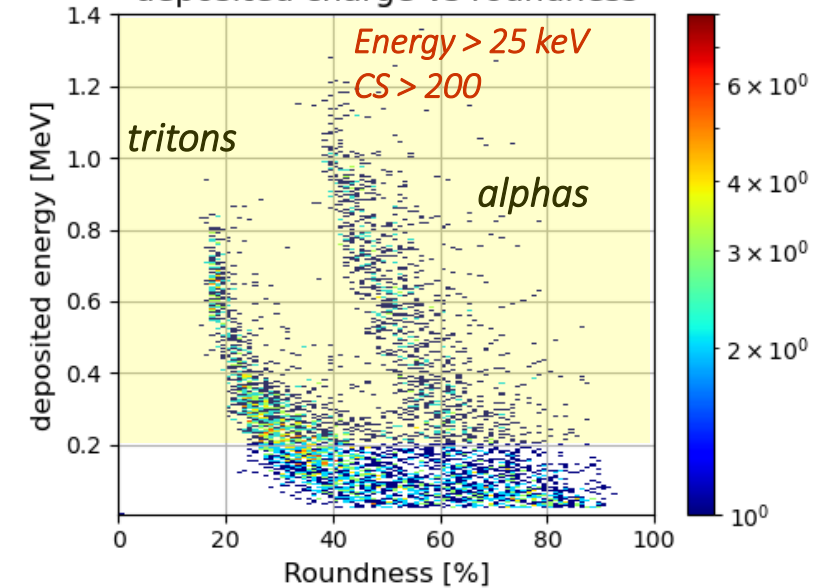
Alumina with no LiF



Alumina with LiF

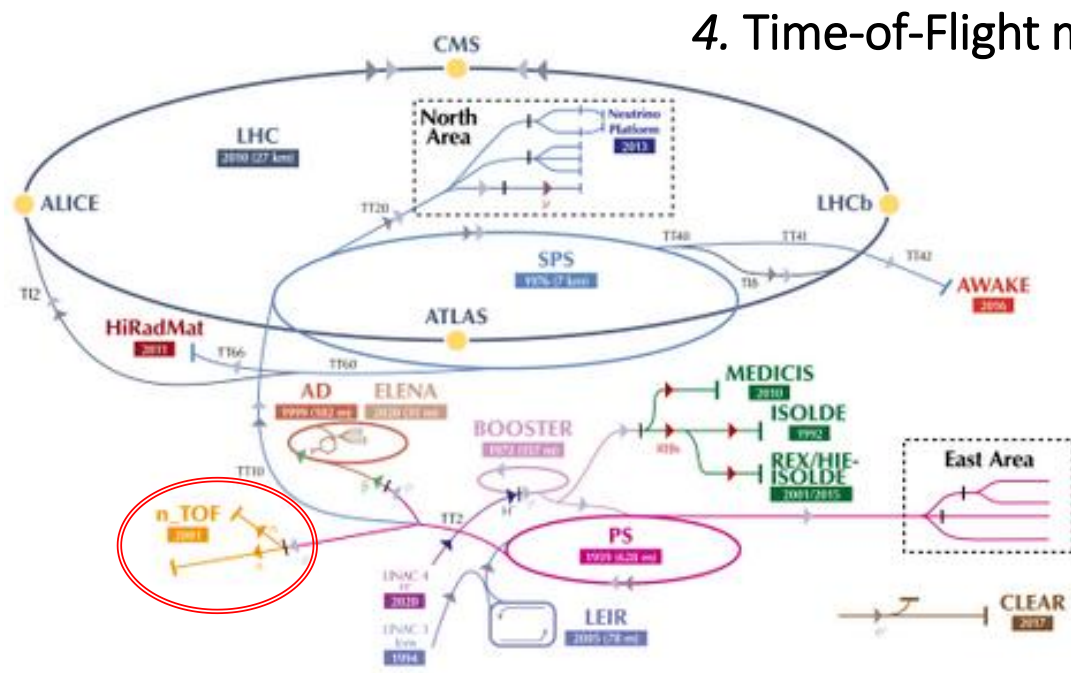


deposited charge vs roundness



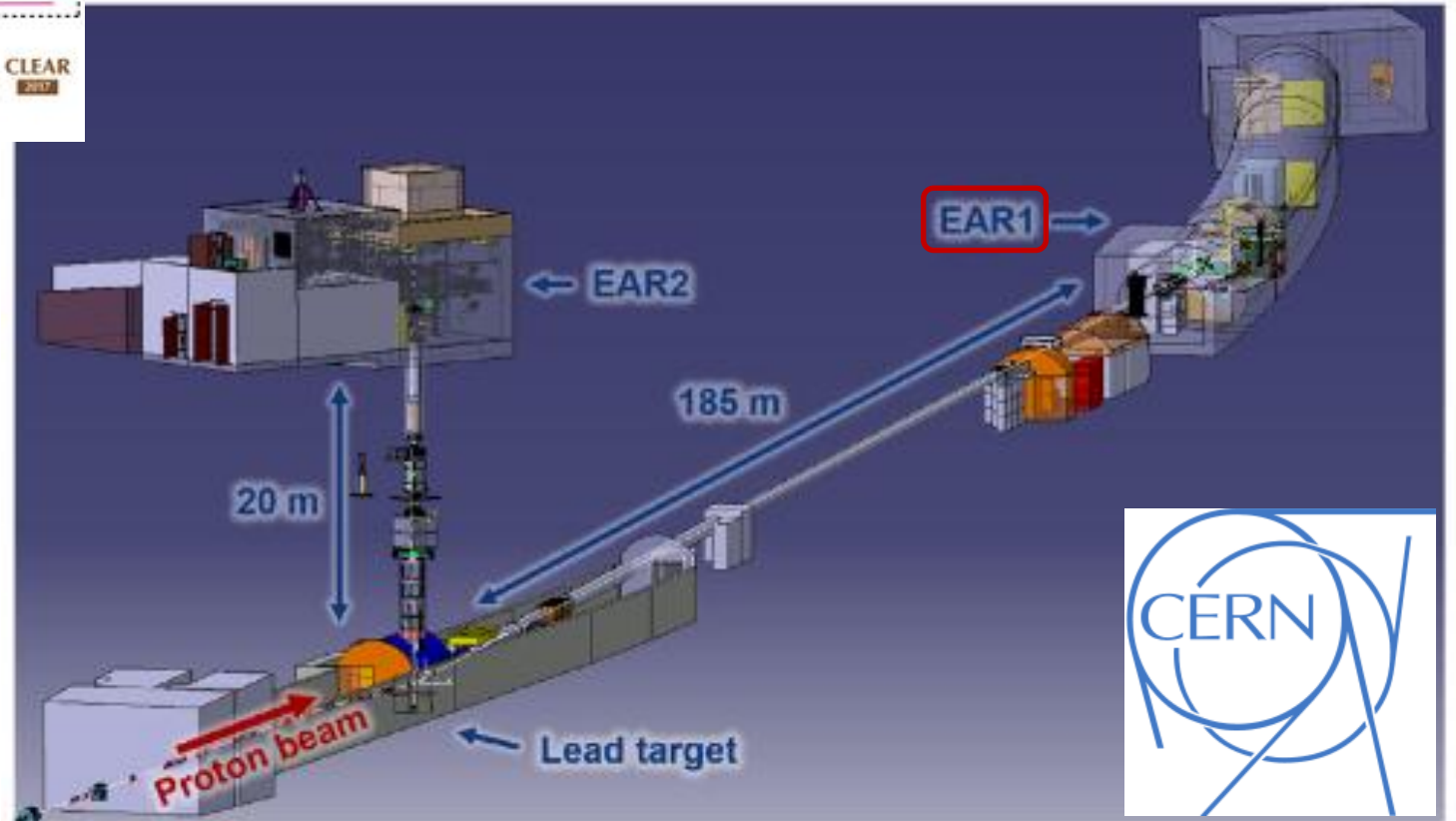
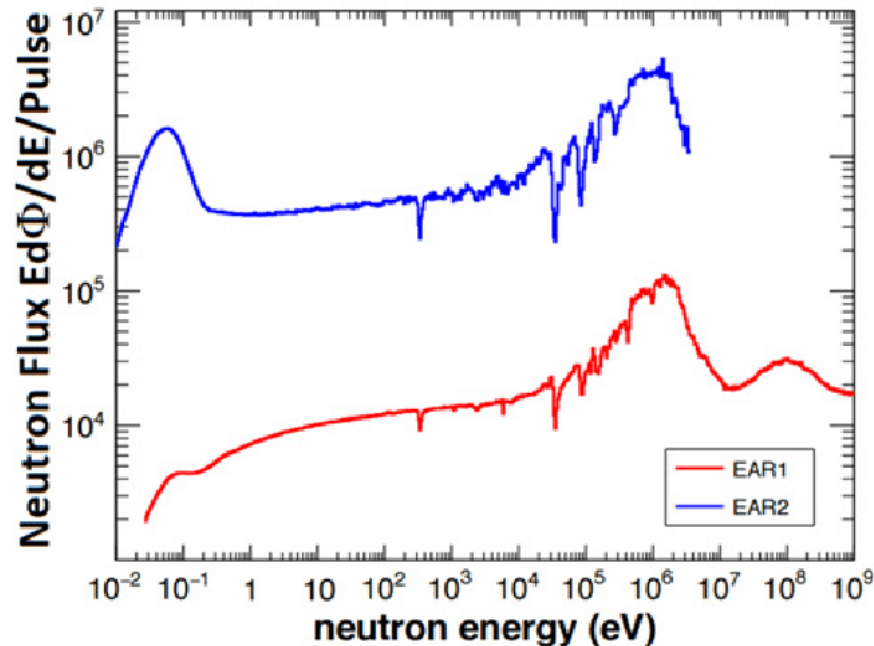
The measurements with thermal neutrons allowed to define the **minimum energy** at which the ${}^6\text{Li}$ products (alphas and tritons) can be discriminated: **200 keV**

4. Time-of-Flight measurements on the n_TOF facility

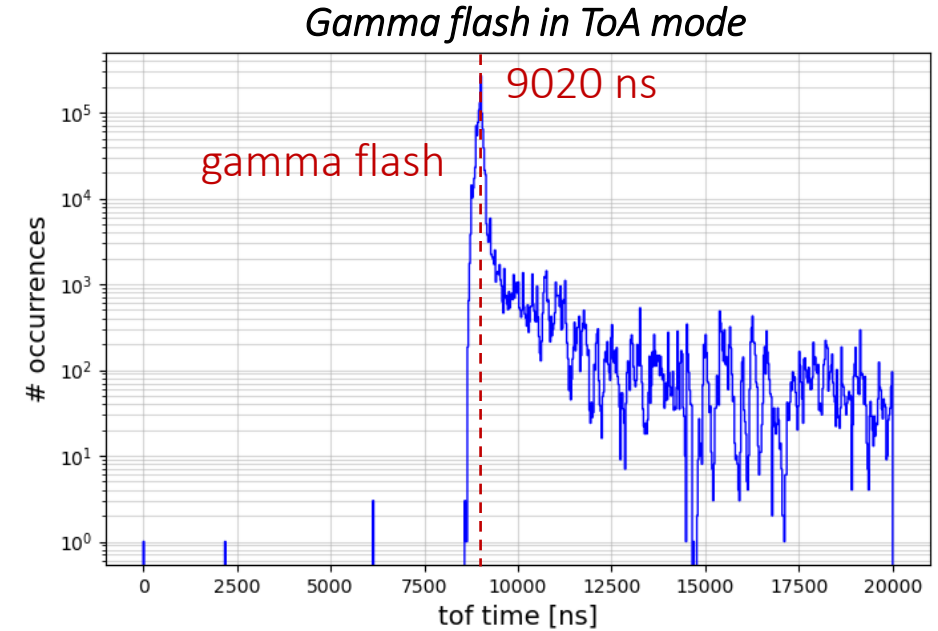
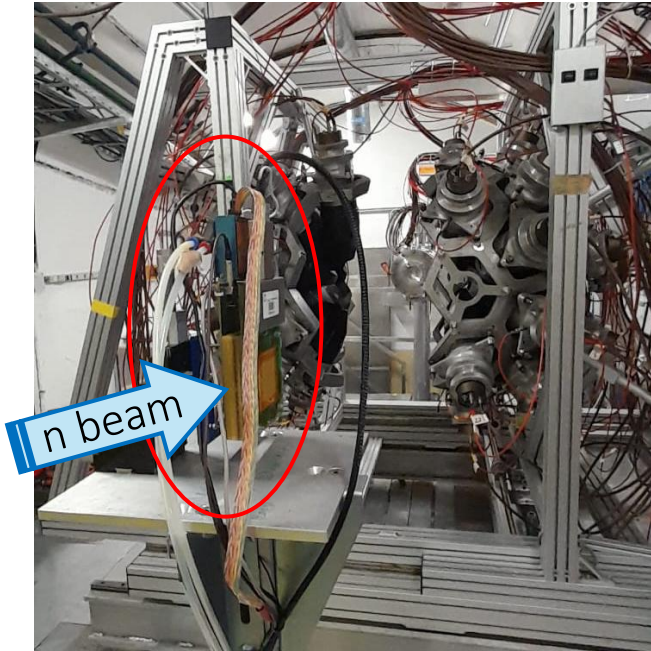


Neutrons are produced through the process of spallation by a beam of pulsed protons (with momentum of 20 GeV/c) from the PS. The target is lead, coated with a borated water moderator layer to slow fast neutrons.

There are three experimental areas: one close to the proton interaction point (NEAR) and the other two located at 20 m (EAR2) and 185 m (EAR1) from the target. In addition, there is also the beam dump area at 197 m beyond EAR1.

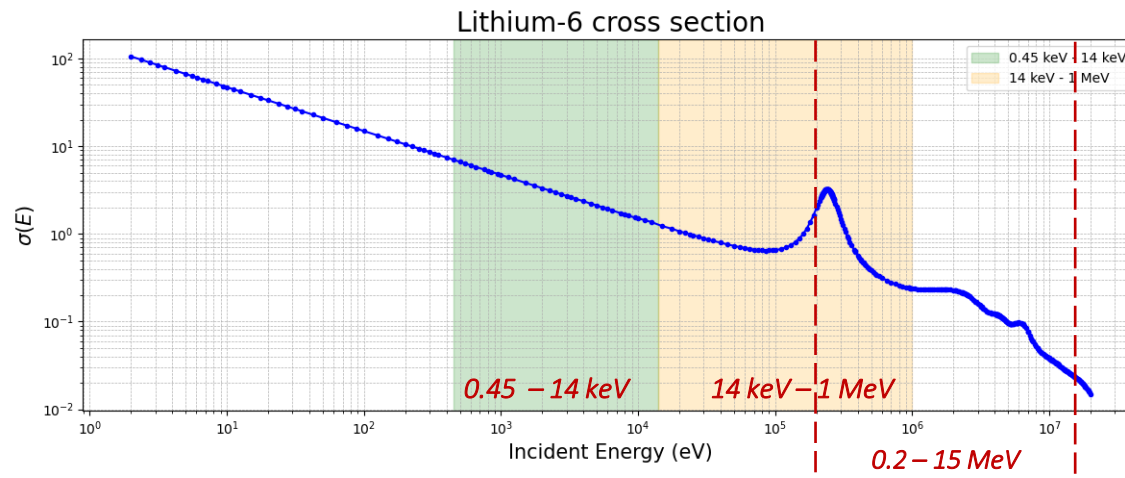


4. Time-of-Flight measurements on the n_TOF facility



By defining a trigger delay with respect to the gamma flash and the acquisition time window, **it was possible to investigate defined energy ranges.**

Among all the measurements performed on the n_TOF facility, a preliminary analysis has focused on three energy ranges of increasing values, up to 15 MeV.



Parameters settings:

Gas mixture: Ar/CO₂ (70/30)

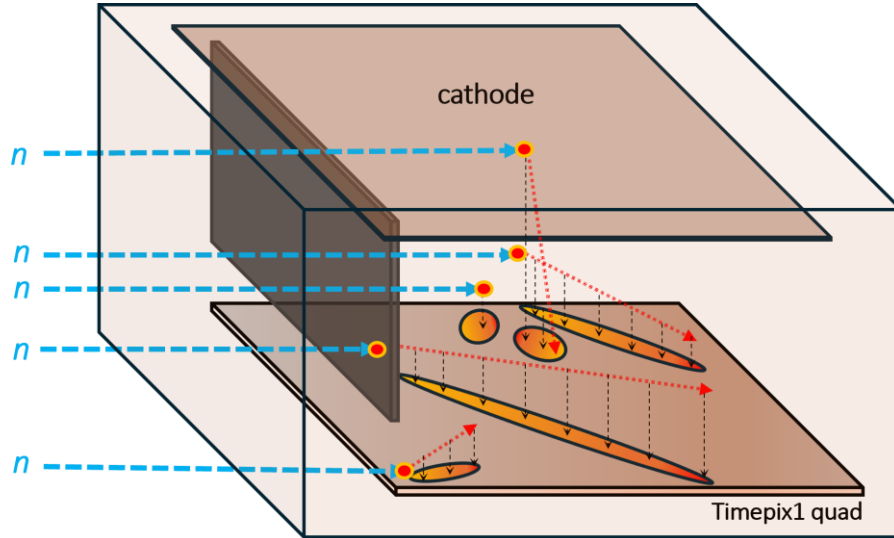
Drift field = 1 kV/cm

HV = 870 V (gain = 140)

lkrum = 15

Acq. Mode = ToT (frame-based)

5. Track analysis of the experimental results



Besides CS, ToT volume and Roundness (Rnd), additional parameters have been introduced:

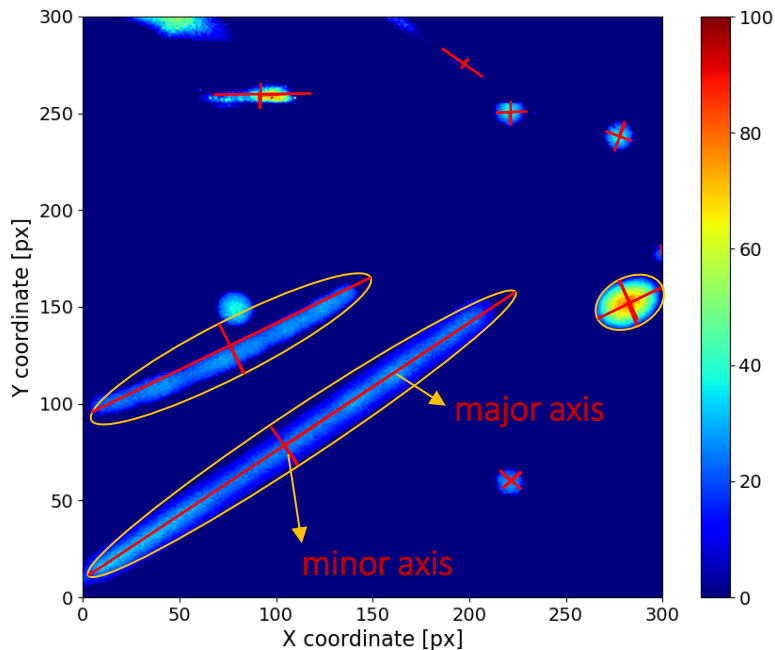
Solidity parameter* (Sld): ratio of the cluster size to the convex hull area (the smallest convex set containing the track). In this way overlapping tracks can be excluded.

ToT mean: ToT value (mean deposited energy) calculated as the average pixel ToT intensity within the cluster.

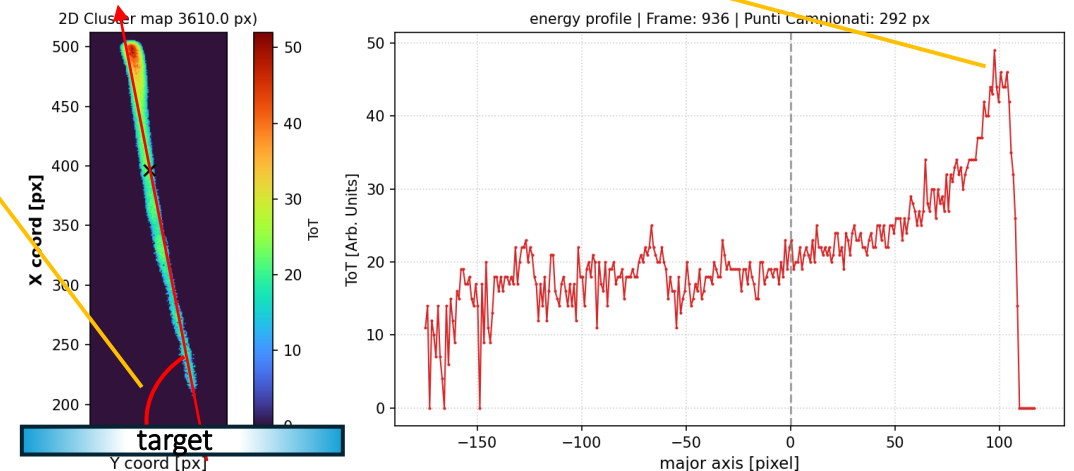
Eccentricity* and ellipse axes: eccentricity of the ellipse that has the same second-moments as the region. The eccentricity is the ratio of the focal distance over the major axis length. Ellipse axes are the lengths of the minor and major axes of the ellipse.

ToT height: the ToT pixel value that can correspond to the maximum released energy (when particle completely stopped, the Bragg peak).

Angle with respect to the target.



Single track energy profile



5. Track analysis of the experimental results

Side-on GEMpix validation measurements:

For the measurements, a 5 μm LiF layer enriched at 95% with ^6Li has been used and the main purposes of the experiment were:

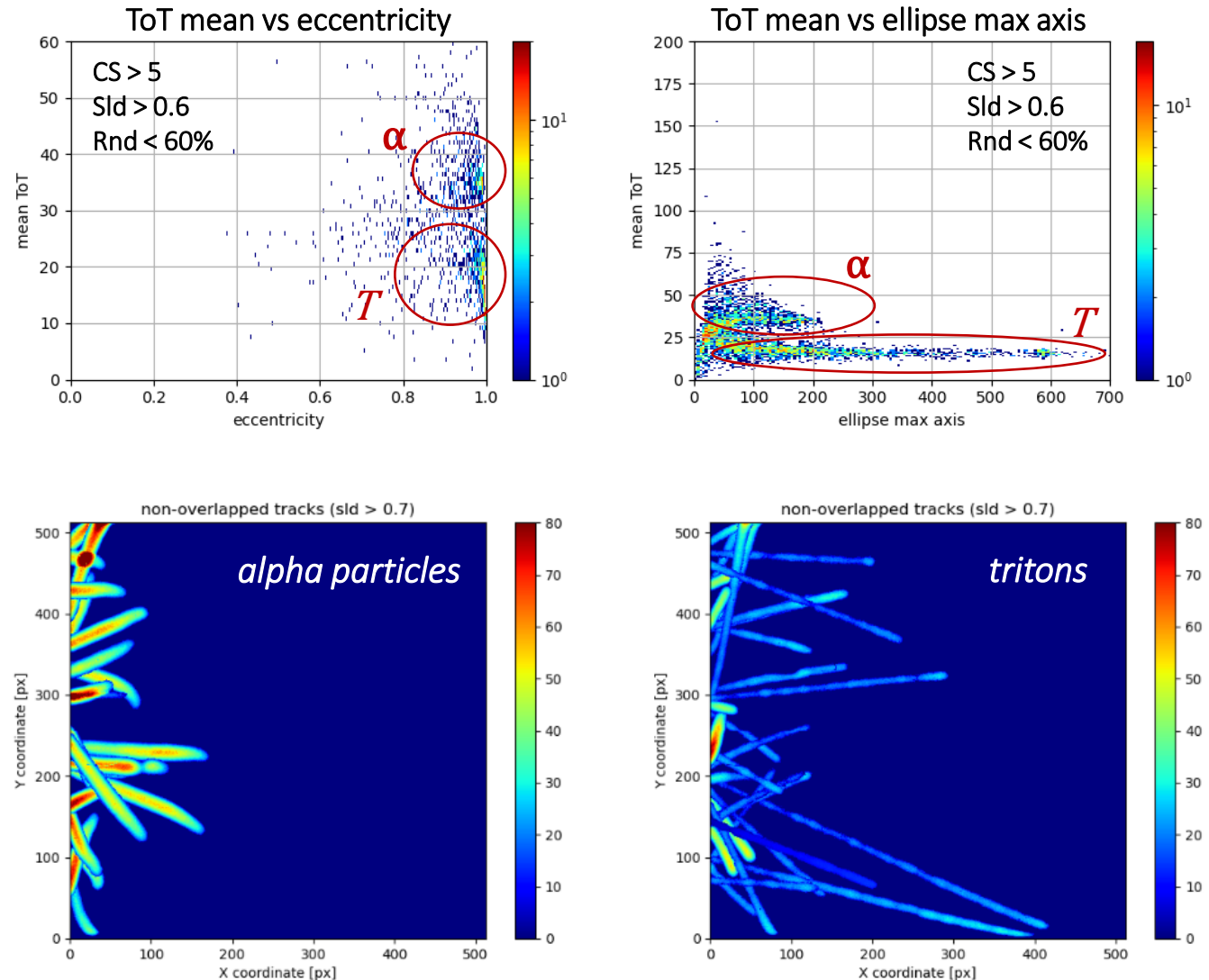
- Test of *the discrimination capability of the side-on GEMpix* on the alphas and triton particles produced by neutron interaction with ^6Li .
- Estimate *the minimum energy at which the two charged products are separated* (0.2 MeV from thermal-neutron measurements).
- Estimate *the amount of track background with respect to the charged products from ^6Li* , especially in the higher energy range (0.2 – 15 MeV) where other reaction channels open on the detector constituent materials.

It has been demonstrated that:

- ✓ introducing the new cluster parameters (like ellipse eccentricity, ellipse max axis, mean ToT or ToT height)
- ✓ selecting clusters having an origin on the target side,

the *contribution of background ions* was *significantly reduced* and the two populations due to alpha particles and tritons from ^6Li are *clearly distinguished*.

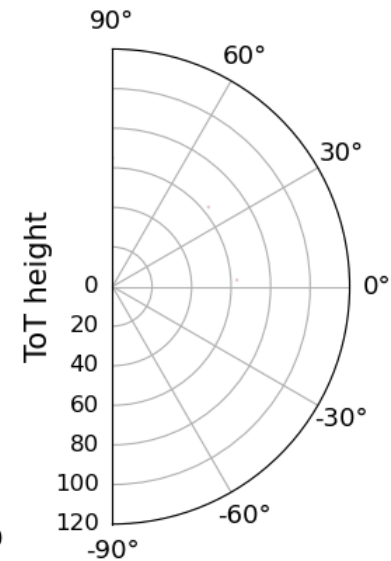
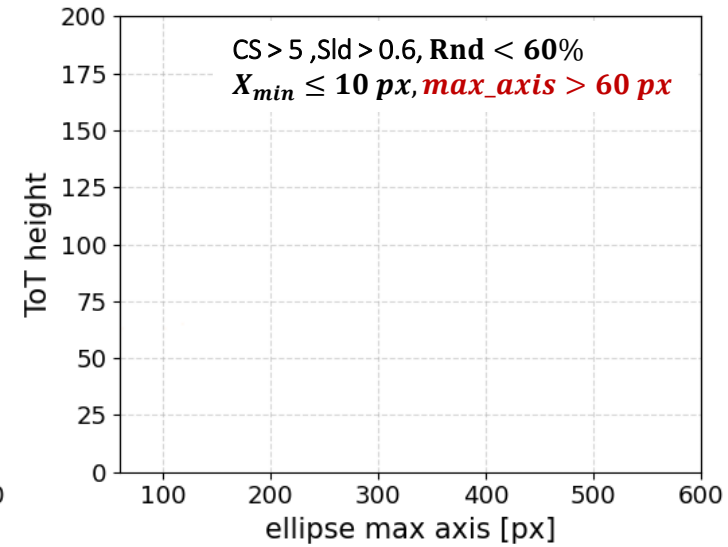
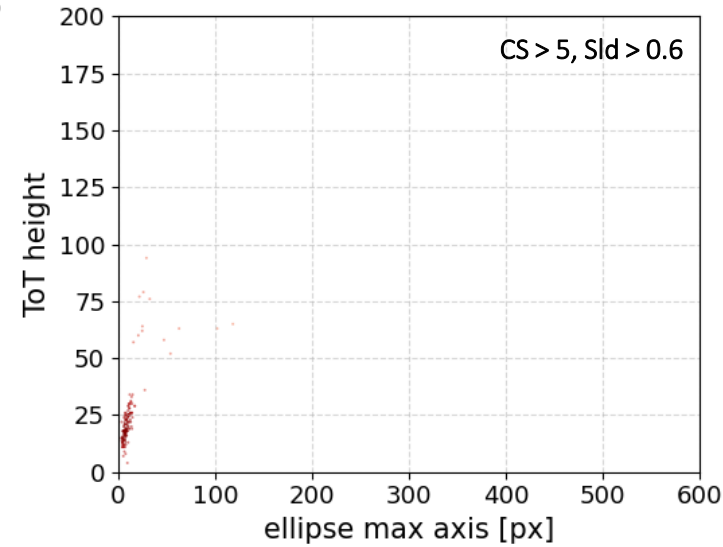
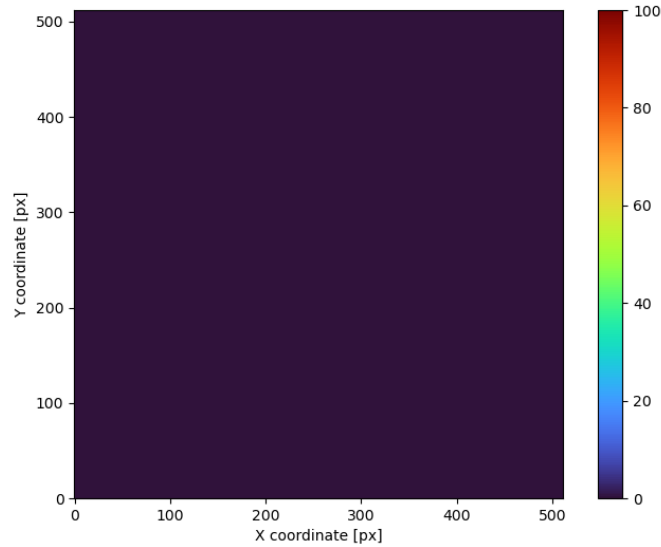
*Alumina with LiF:
thermal neutrons*



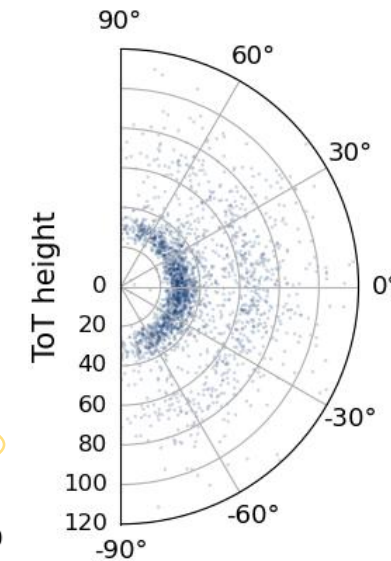
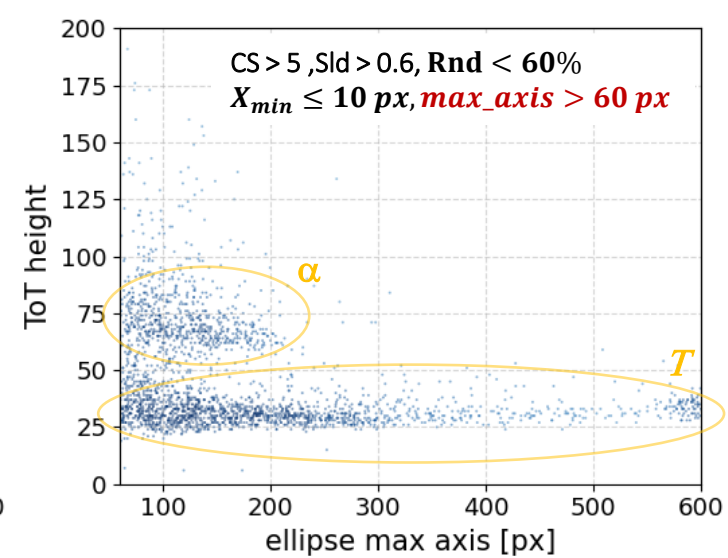
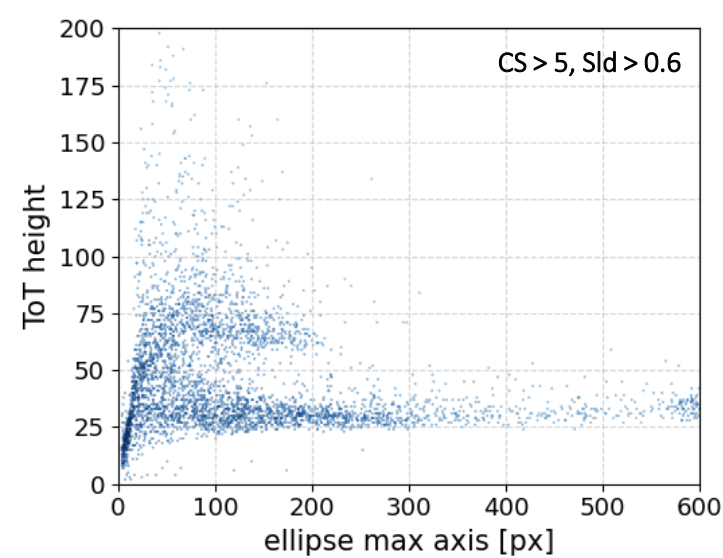
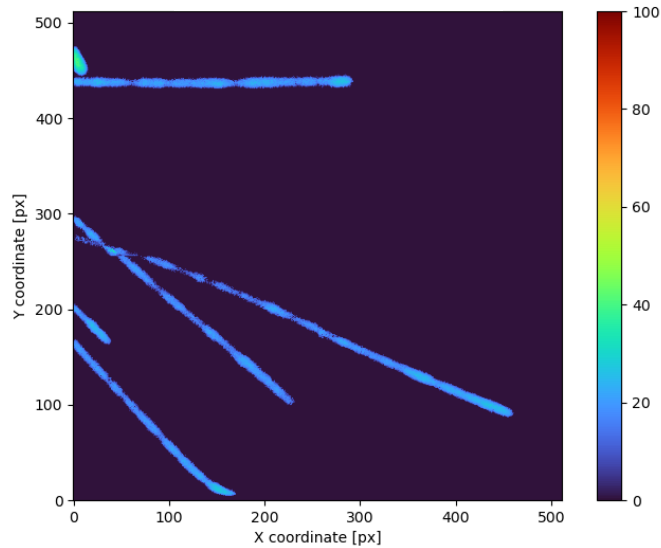
5. Track analysis of the experimental results

Neutron energy range: 0.45 - 14 keV

Alumina with no LiF



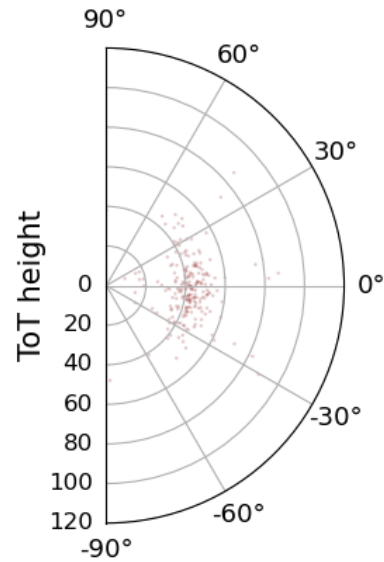
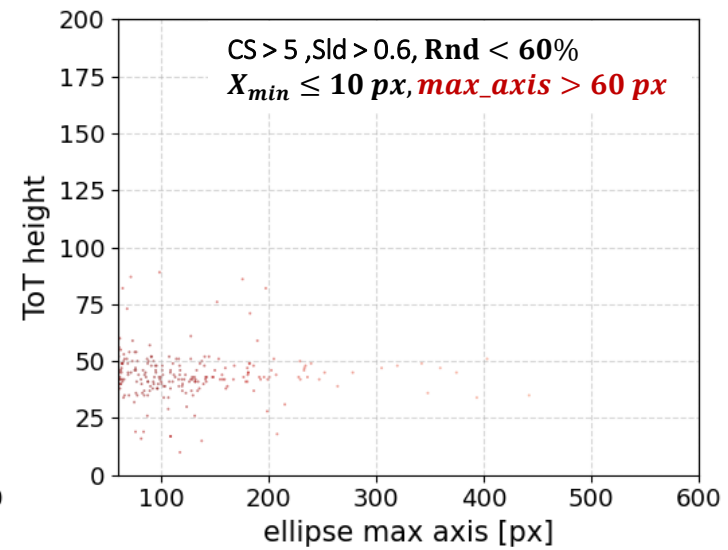
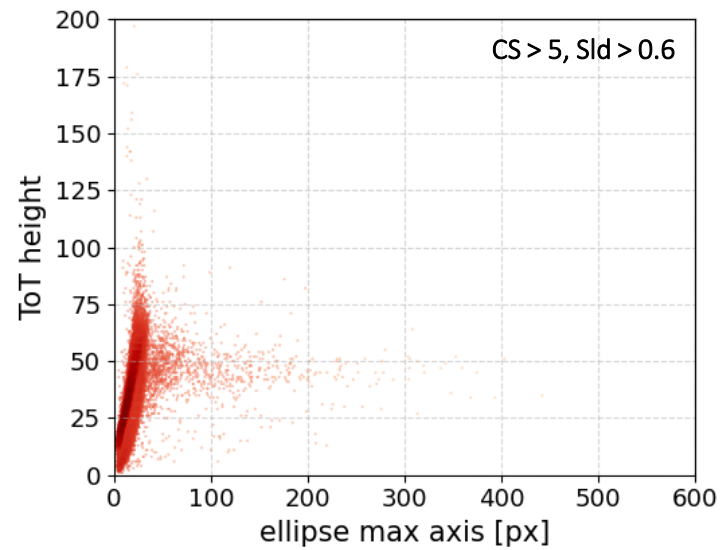
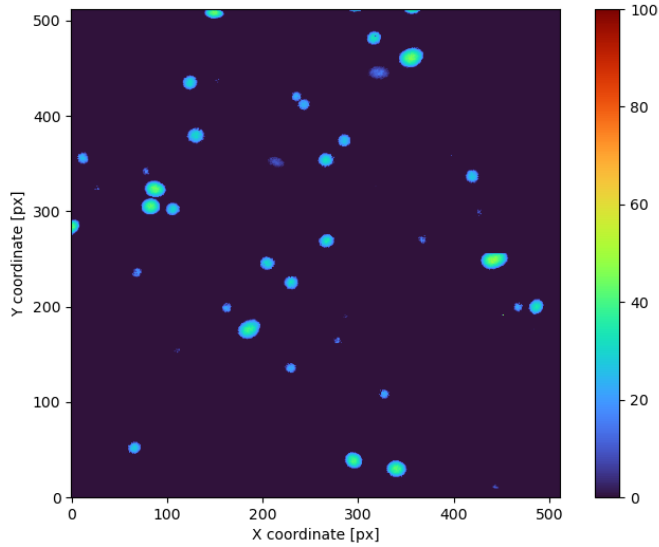
Alumina with LiF



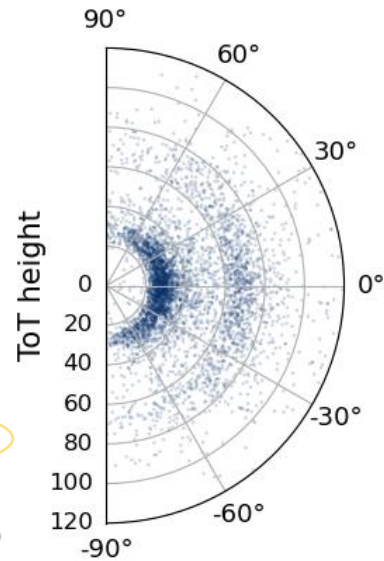
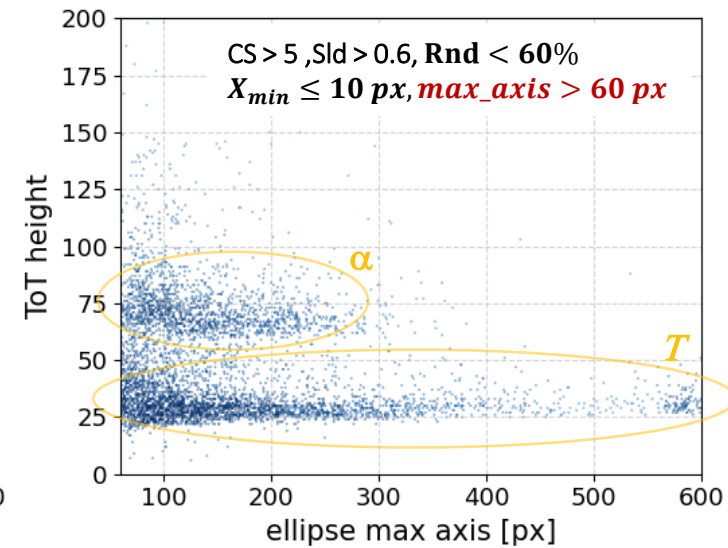
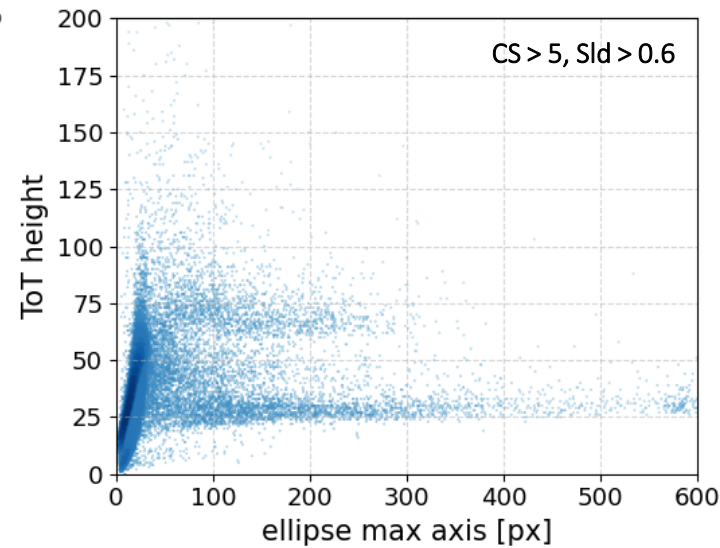
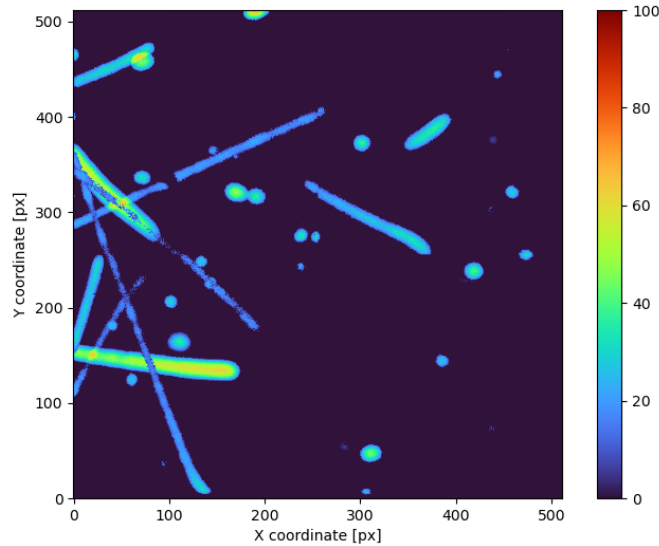
5. Track analysis of the experimental results

Neutron energy range: *14 keV - 1 MeV*

Alumina with no LiF



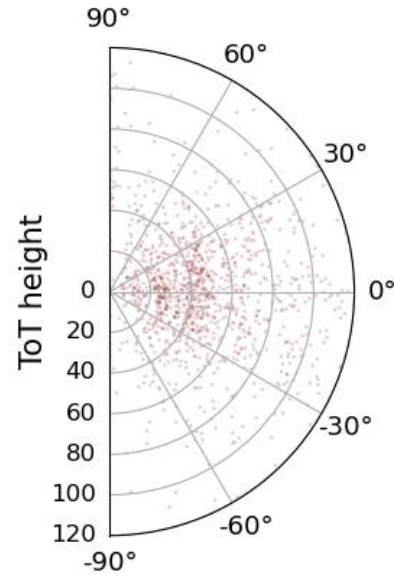
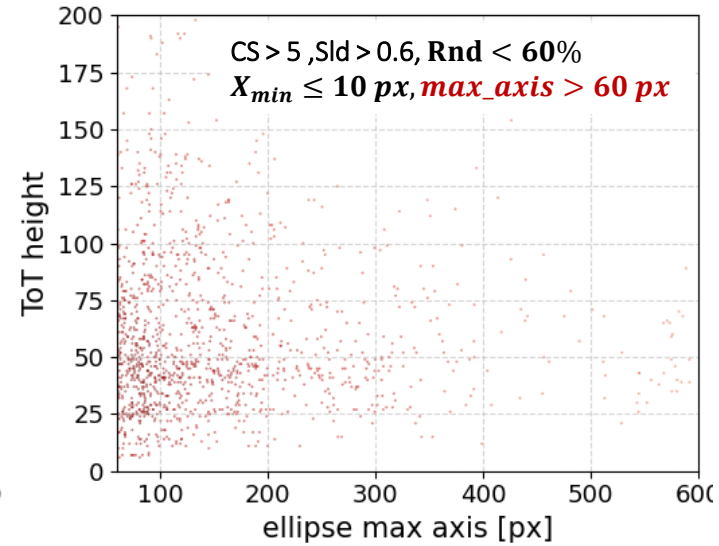
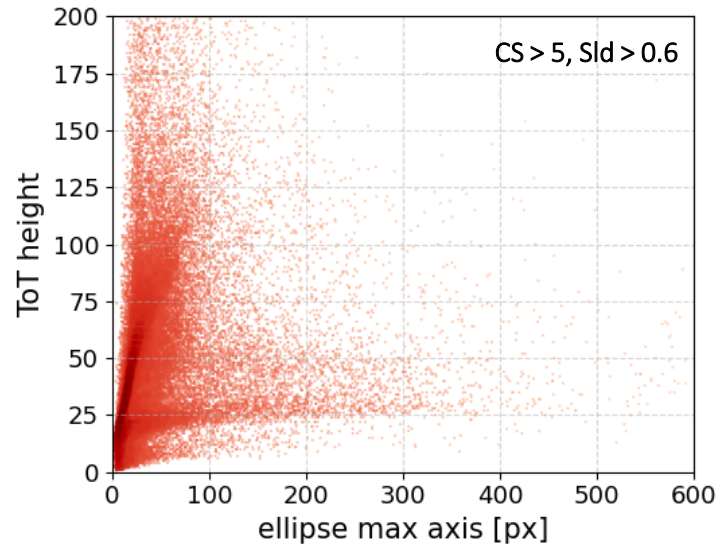
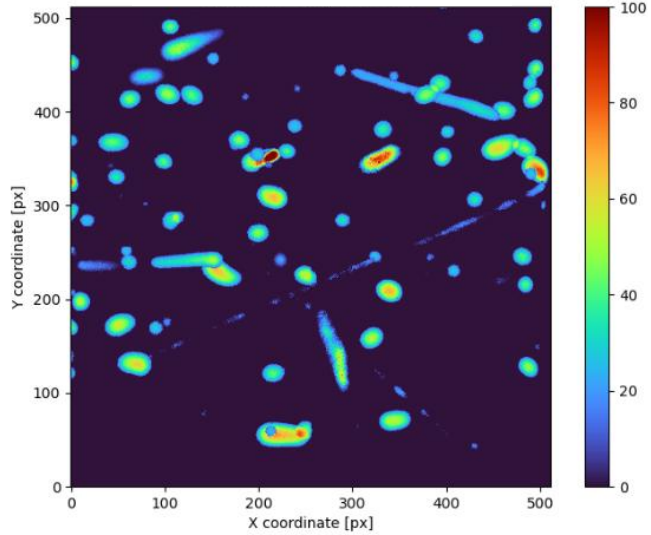
Alumina with LiF



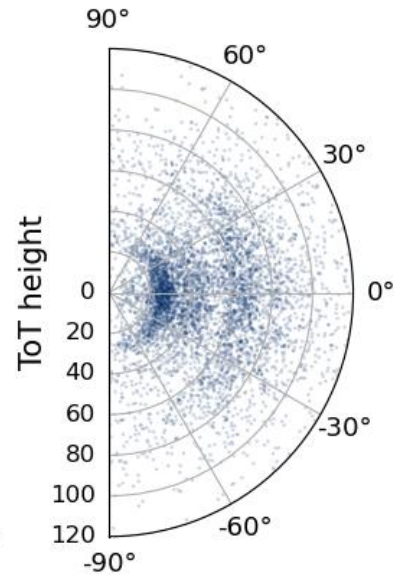
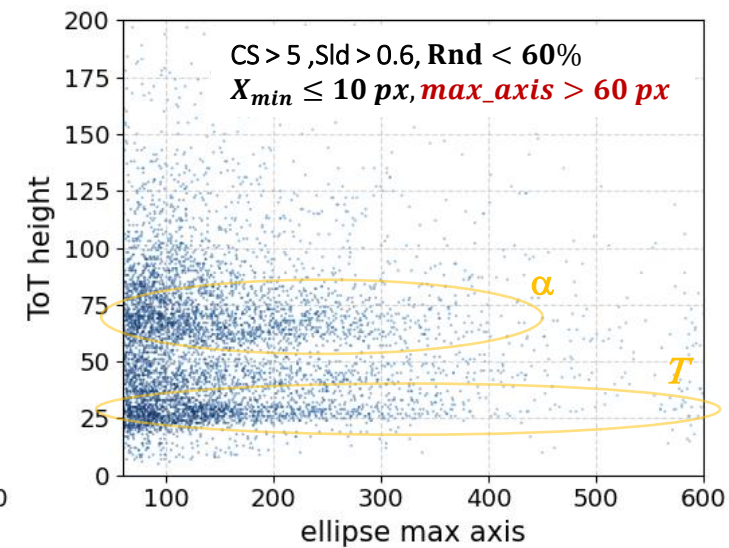
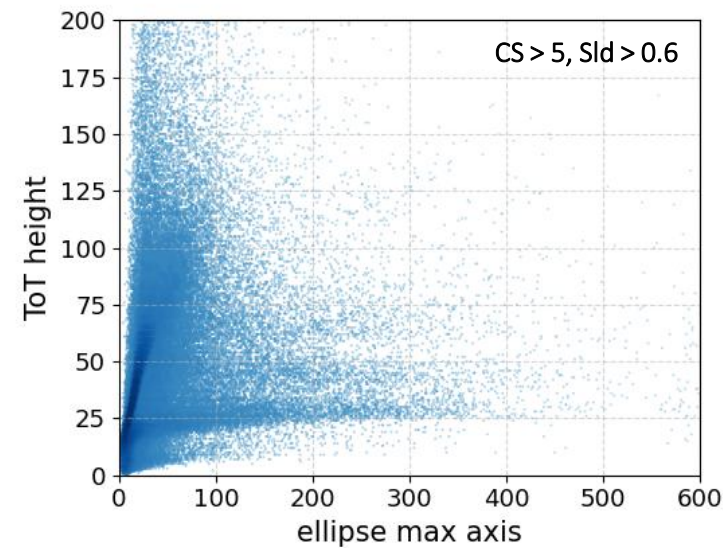
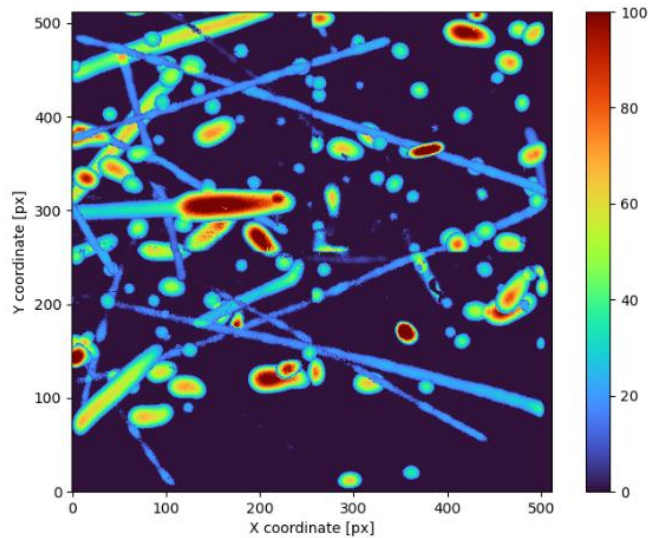
5. Track analysis of the experimental results

Neutron energy range: *0.2 MeV - 15 MeV*

Alumina with no LiF

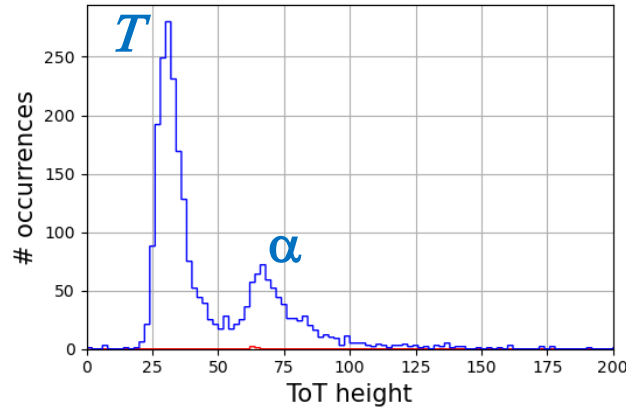
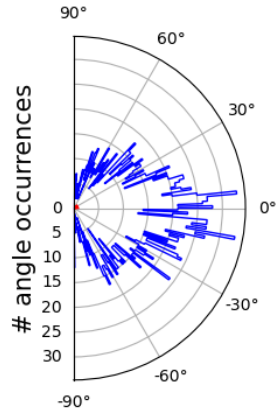


Alumina with LiF



5. Track analysis of the experimental results

0.45 - 14 keV

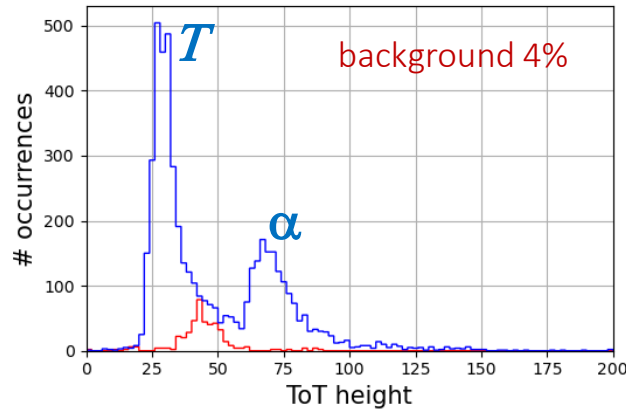
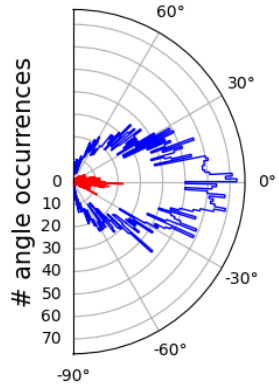


Parameter cuts: $CS > 5$, $Sld > 0.6$, $Rnd < 60\%$, $Xmin \leq 10$ px, $e_max_axis > 60$ px

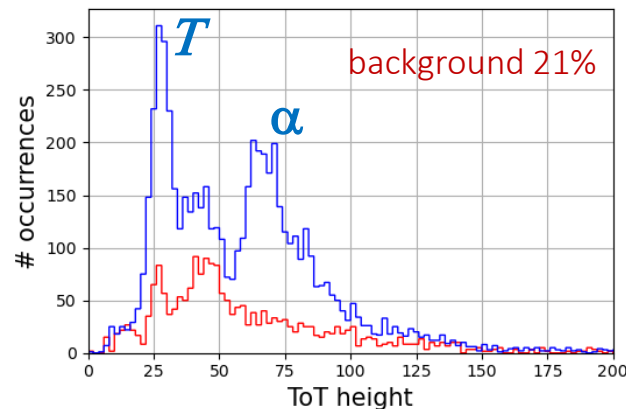
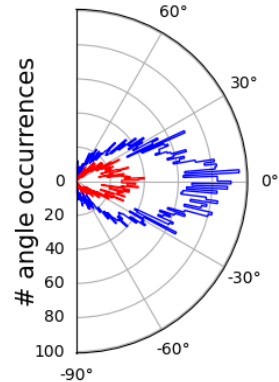
*This type of GEMpix offers the possibility to host **the target inside the active region** and exploit a **larger gas volume** with respect to a standard GEMpix camera. These first results demonstrated that:*

- *The application of these parameter cuts allows a **clear discrimination against heavy ions**.*
- *Low-energy measurements allowed to define appropriate cuts on a set of cluster parameters and obtain **a clear discrimination between alpha particles and tritons**.*
- *It is possible to discriminate between alpha particles and tritons coming from neutron interaction with ${}^6\text{Li}$ down to a **minimum energy of 0.2 MeV**.*
- *As expected, the estimated **background contribution** increases, going from practically zero for thermal neutrons **to 4% and 21% for higher energy neutrons up to 1 MeV and 15 MeV**, respectively. These results represent **a significant improvement with respect to a standard GEMpix camera with 3 mm of active gas region and target outside**.*

14 keV - 1 MeV



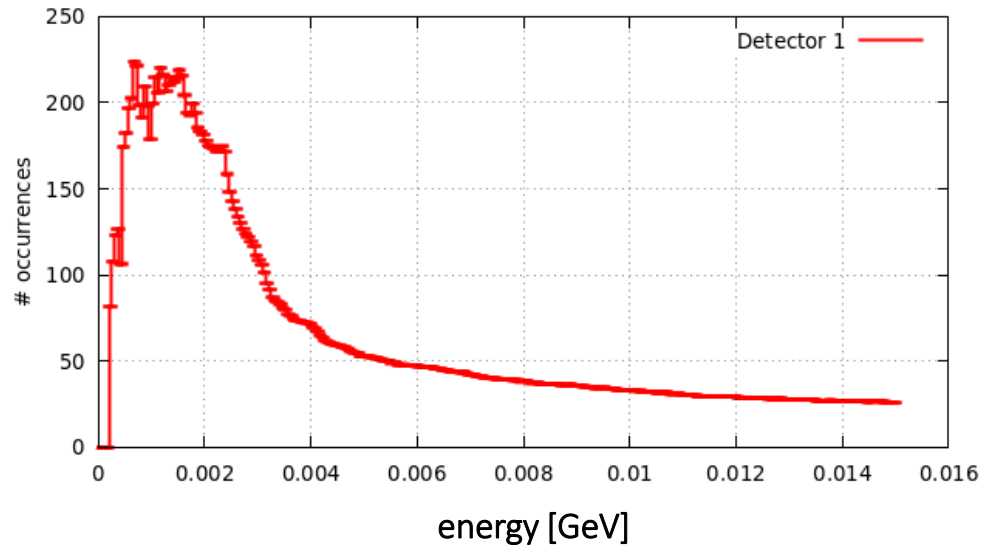
0.2 MeV - 15 MeV



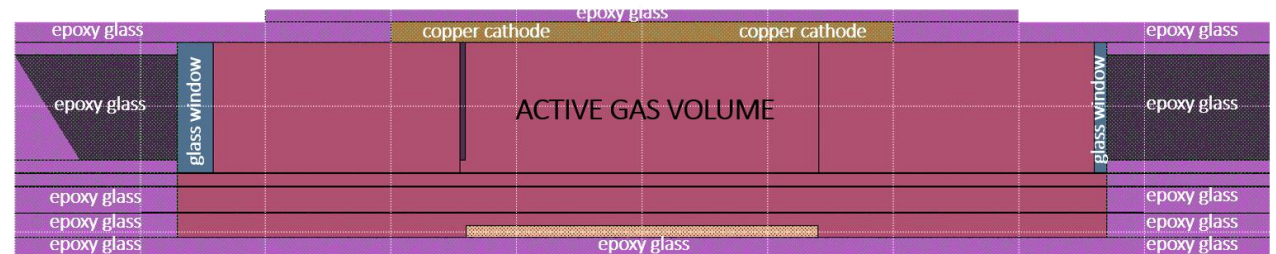
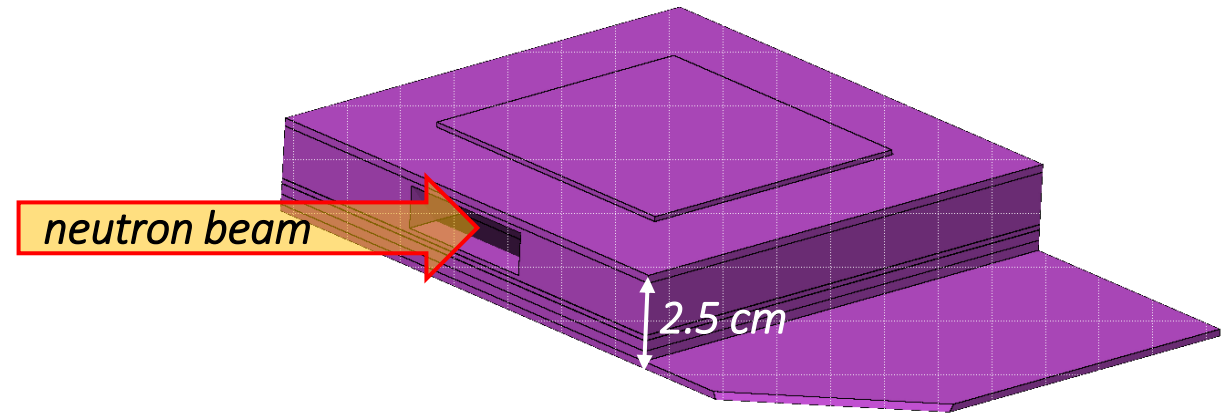
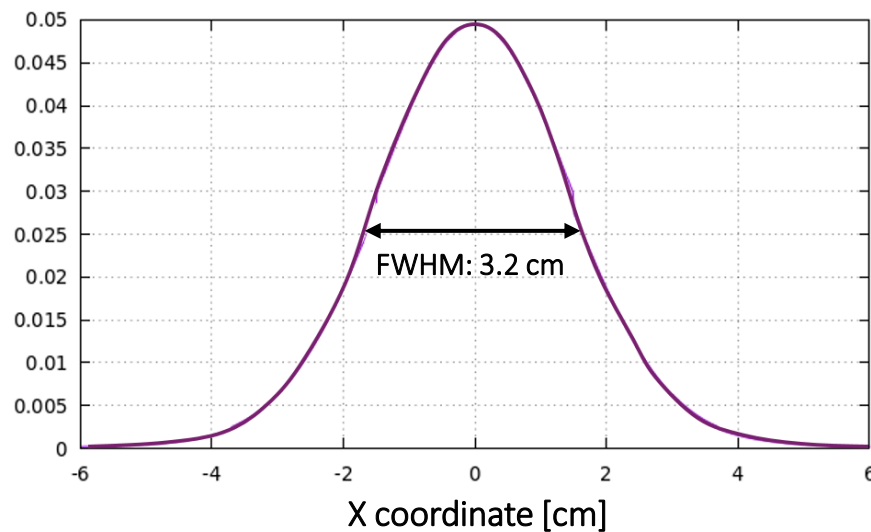
To reduce background and improve detector particle discrimination, simulations have been performed and more are underway.

6. MC simulations for background evaluation

INCIDENT NEUTRON SPECTRUM



NEUTRON BEAM PROFILE



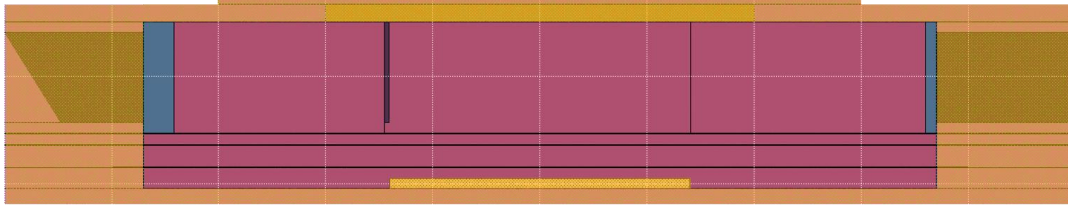
*FLUKA simulations have focused on the **ACTIVE GAS VOLUME**.*

Inside the active volume, each track due to a proton, an alpha, a triton or a heavy ion has been reconstructed in 3D and the corresponding neutron reaction in a defined region associated to it.

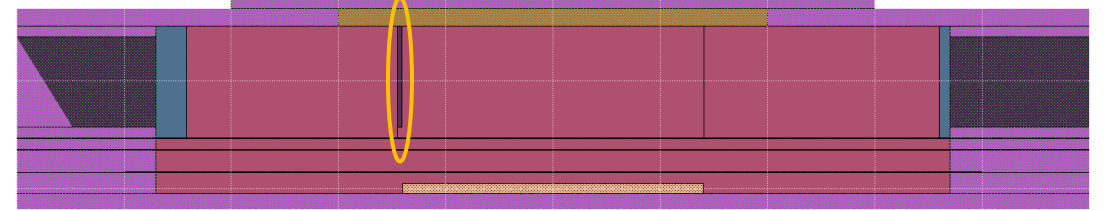
Simulated reactions give all the products with their energies.

6. MC simulations for background evaluation

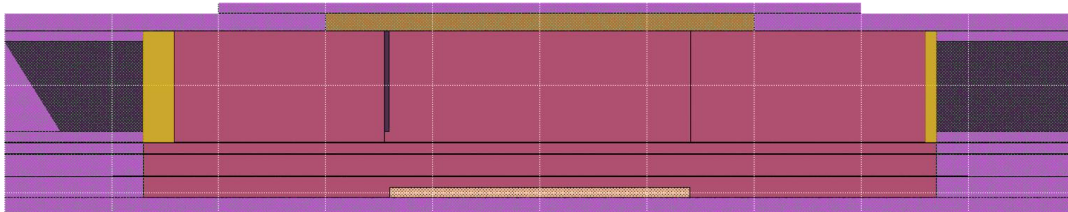
CASE: epoxy glass + Cu cathode + Tpx anode (Si)



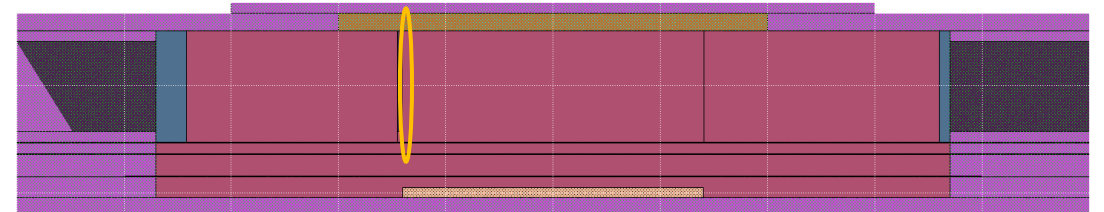
400 μm Alumina substrate: Al_2O_3



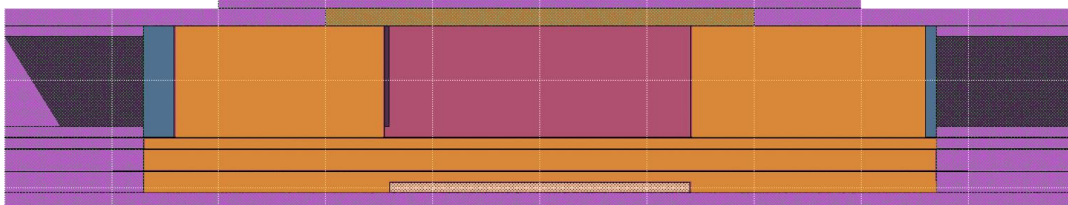
SIDE WINDOWS: SiO_2



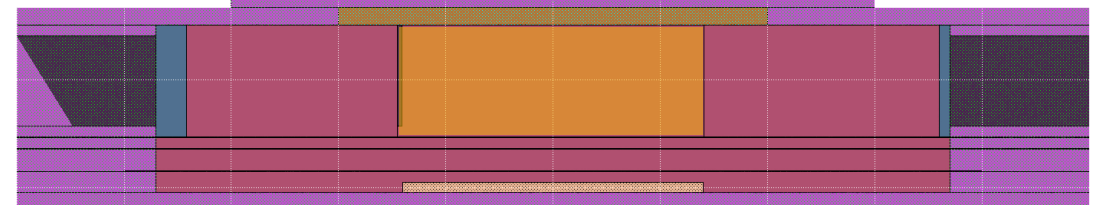
5 μm target: LiF with ^6Li at 95%



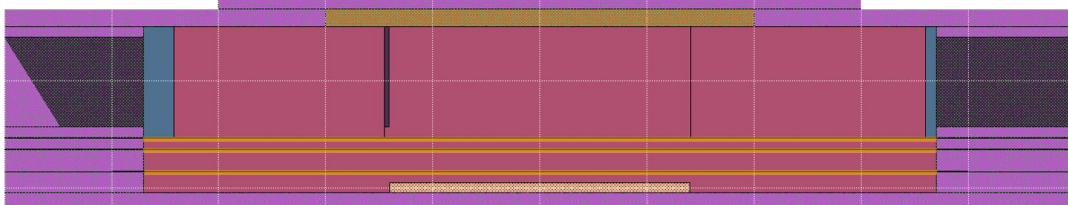
GAS: Ar/ CO_2 (70/30)



ACTIVE GAS VOLUME: Ar/ CO_2 (70/30)

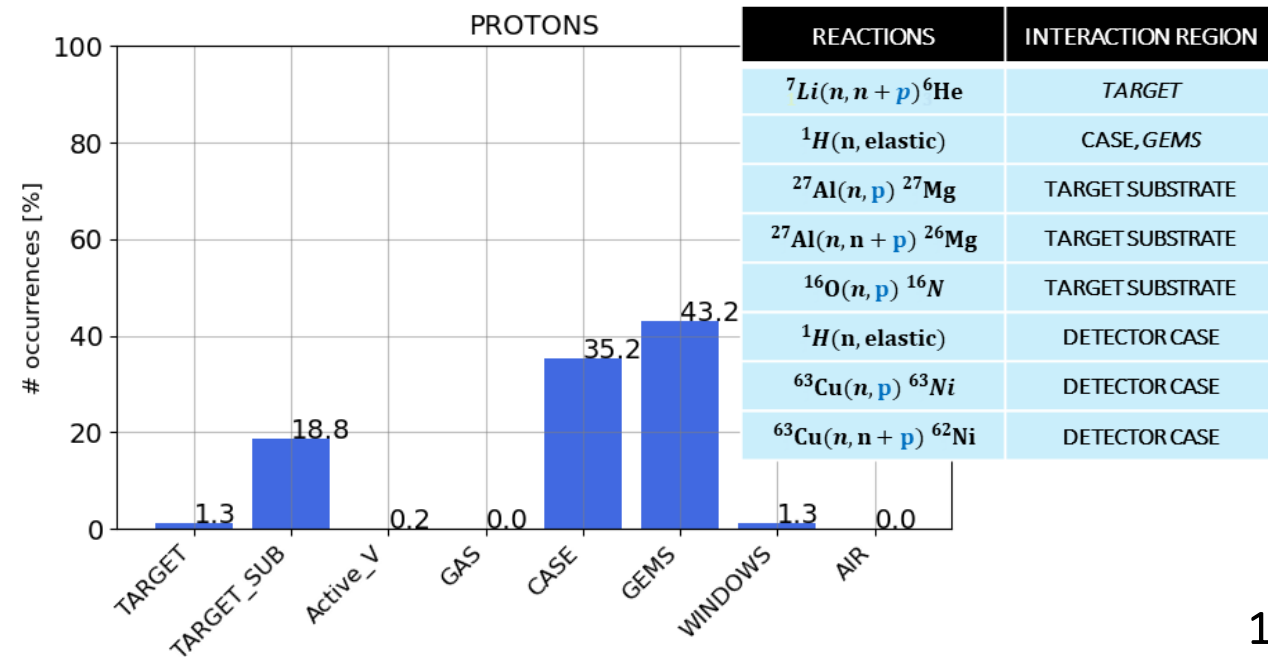
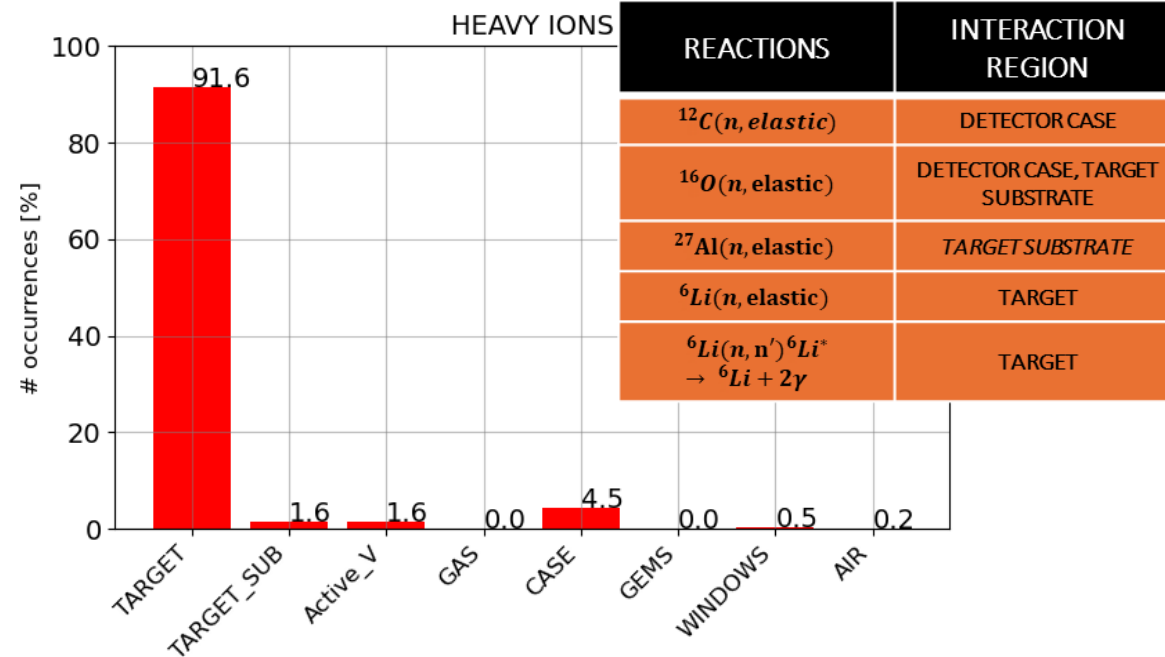
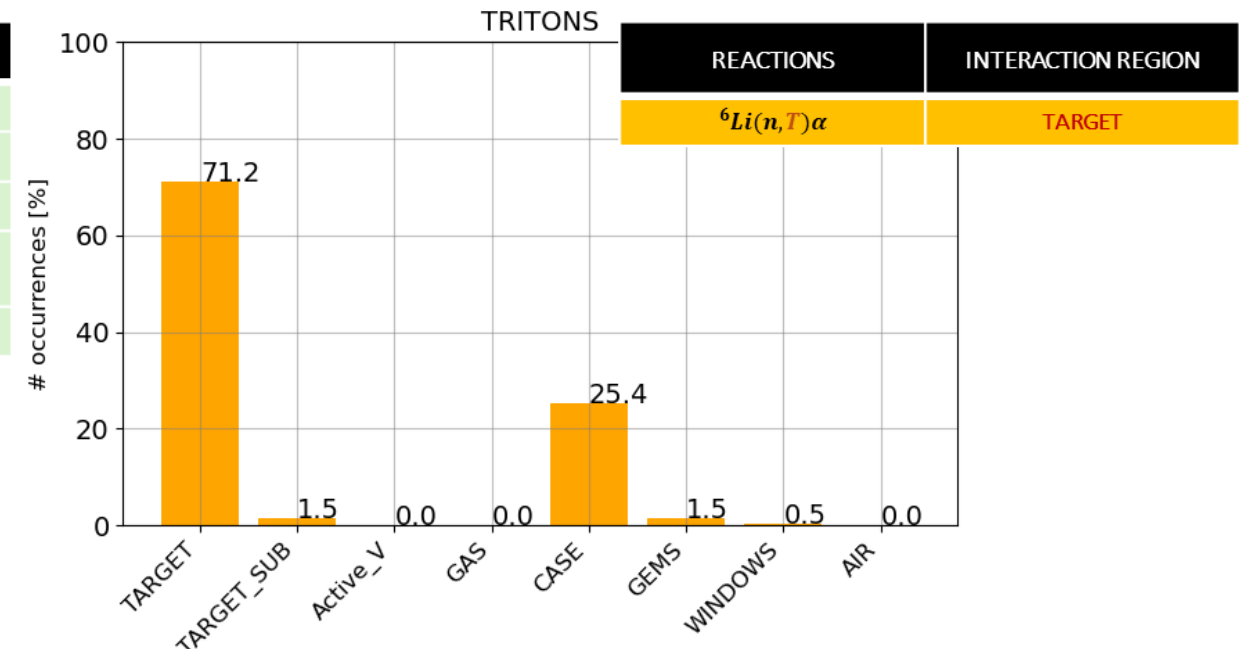
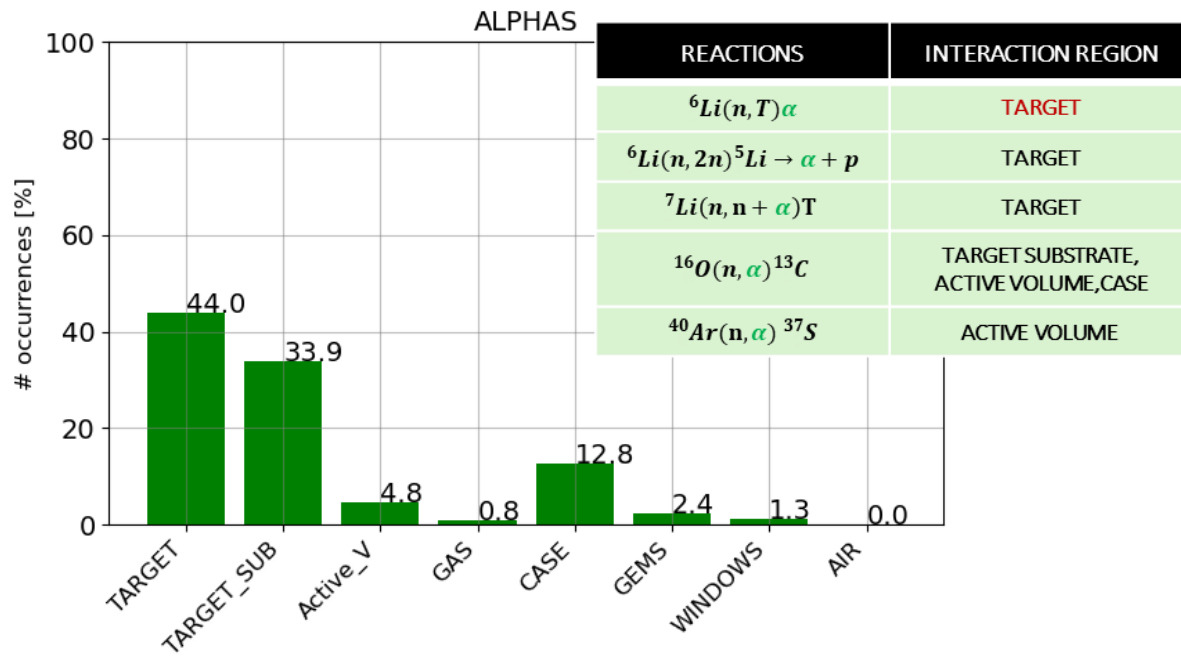


GEM foils: Kapton + Copper



Simulations had the objective to evaluate the contribution of these detector components in terms of **produced charged particles in the active gas volume**. For this study, four types of charged particles have been considered: **protons**, **tritons**, **alphas** and **heavy ions**.

6. MC simulations for background evaluation

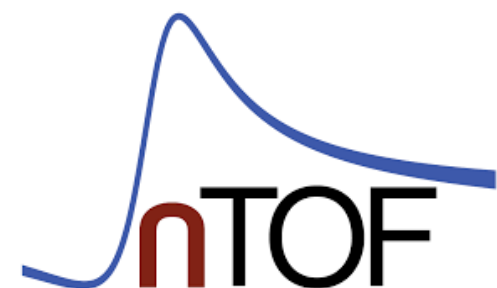


7. Conclusions

- The GEMpix detector, in side-on geometry, offers the possibility to have a compact particle tracker that can be effectively used to measure and discriminate charged products, enabling neutron cross-section measurements. The GEMpix proved to be particularly efficient in the detection and discrimination of charged particles down to 0.2 MeV. In addition, by applying track analysis, the contribution of background can be reduced, even if it is still significant at high energies ($\sim 20\%$).
- Monte Carlo simulations identified the main background sources:
 - ✓ Background alpha particles: primarily from the oxygen in the alumina substrate.
 - ✓ Recoil protons: From kapton and epoxy, which hinder triton discrimination.
 - ✓ Heavy ions: mostly ${}^6\text{Li}$ recoils in the target itself, plus recoils from the detector case, limiting low-energy particle discrimination.
- The evaluation of potential solutions is underway and new simulations will be implemented to realize a new prototype:
 - ✓ Removing the substrate by using thicker samples or alternative materials like Silicon.
 - ✓ Increasing the case geometry to move GEM foils away from the neutron beam and block ions from the active region.
 - ✓ Using low-hydrogen case materials such as metallic materials or polymers like Teflon (C_2F_4).
- The upcoming prototype will feature the Timepix4 chip, introducing simultaneous charge and time measurement, packet-based acquisition, 200 ps time resolution, and 3D track reconstruction to significantly improve particle discrimination.



Many thanks for your attention!



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