Simulation and optimization studies of a micro bulk XY-Micromegas detector for neutron-induced charged particle tracking

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"Part of deliverable D1.1 Status: report submitted, attending approval"

Contents

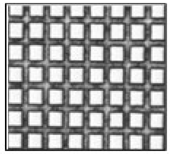
- Micromegas concept
- XY-micromegas detector
- Experimental results: at CERN, Orphee reactor (LLB) as neutron beam profiler
- New XY-micromegas detector: 10 x 10 cm^2
- Simulations: **FLUKA MC** → energy deposition spectrum
  Garfield++ → methods, magnitude of diffusion, induced charge, convoluted pulses, deposited charge spectrum
- Summary
- Outlook

Neutron detectors based on MICRO-Mesh Gaseous Structure (MICROMEGAS)

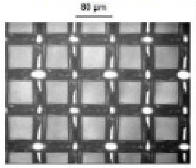
Micro-mesh (cathode)

The metallic micro-mesh must be 5 to 30 µm thick with needed equivalent wires densities ranging from 500 to 2000 Lines Per Inch (LPI). Stainless steel woven meshes, electroformed Nickel meshes, or chemically etched copper meshes are used.
New products are needed for high LPI thin meshes.

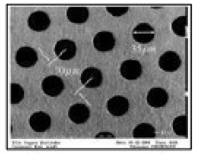
500 LPI Electroformed Ni mesh



500 LPI 304Lwoven mesh

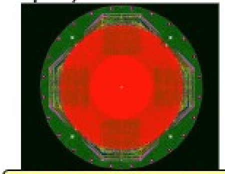


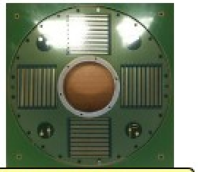
Chemically etched Copper mesh



Printed Circuit Board (anode PCB)

- ✓It can be up to 1- 3 m² and down to 100 µm thin.
- ✓Copper strips or pads can be ≈100 µm to few mm large and insulation between them as low as 50 µm.
- ✓Copper is usually covered by a Ni/Au layer for a total thickness which must be kept as low as possible (down to 5 µm) with a « smooth » surface.

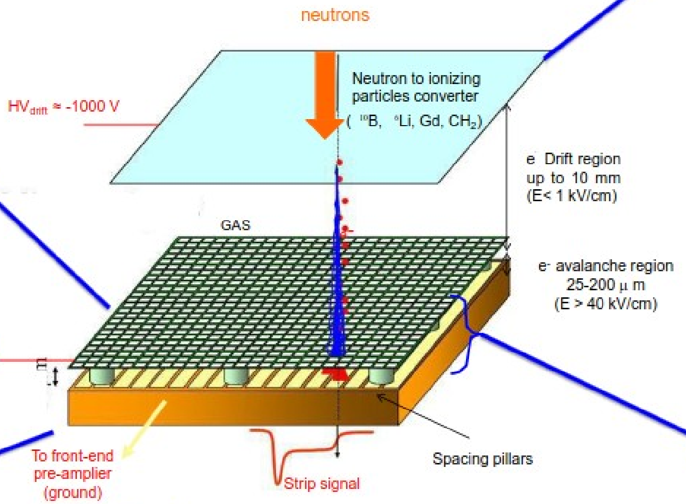




A Φ 30 cm 12 layers PCB with 4000 x 4 mm² pads for the MINOS TPC (18000 blind vias)

Patented technology (CEA – EOS imaging)
G. Charpak, Y. Giomataris, Ph. Rebourgeard, J-P Robert
Y. Giomataris *et al.*, NIM A 376 (1996) 29

MICROMEGAS is a parallel plate gaseous structure which uses a thin metallic micromesh to define the high electric field region in which primary electrons are amplified by avalanche and collected on a micro-segmented Printed Circuit Board



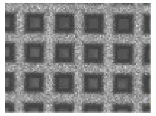
Performances

- ✓Intrinsic low sensitivity to γ photons (gas)
- ✓High spatial resolution (down to 100 µm)
- ✓Fast signals (< 1 ns)
- ✓Short recovery time (~150 ns)
- ✓High rate capabilities (> MHz)
- ✓High gain (up to 10⁶)

Drift electrode + neutron converter

✓For **thermal neutrons**, it can be a thin aluminum foil or a metallic mesh covered by a 1-2 µm thick layer containing ¹⁰B (such as B_4C) or by a ≈100 µm thick ⁶Li layer. Low cost industriallized processes needed

An electroformed Ni mesh covered by a 2 µm thick B_4C layer (Linköping Univ.)



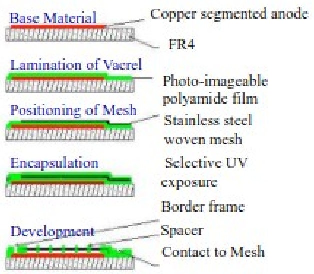
Micromegas technologies

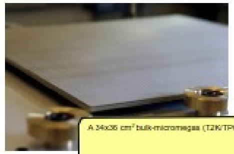
to realize the micro-mesh + anode PCB assembly

Bulk-micromegas

On-going technology transfer

Embedding of the mesh between two layers of insulating pillars by use of photolithography technics



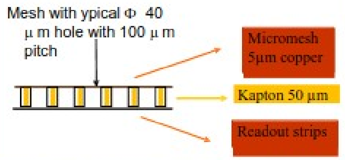


A 34x36 cm² bulk-micromegas (T2K/TPC)

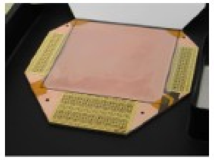
micro-bulk micromegas

Technology transfer to be done

Micromegas is built from a double sidded copper clad kapton foil by selective chemical etching of copper (mesh and anode strips) and kapton (insulating pillars).

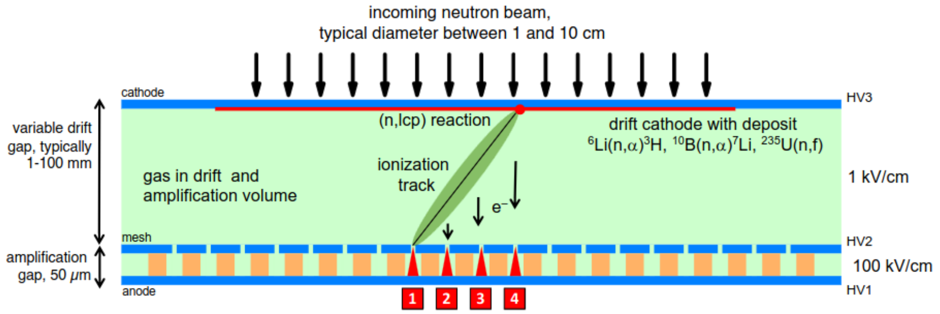


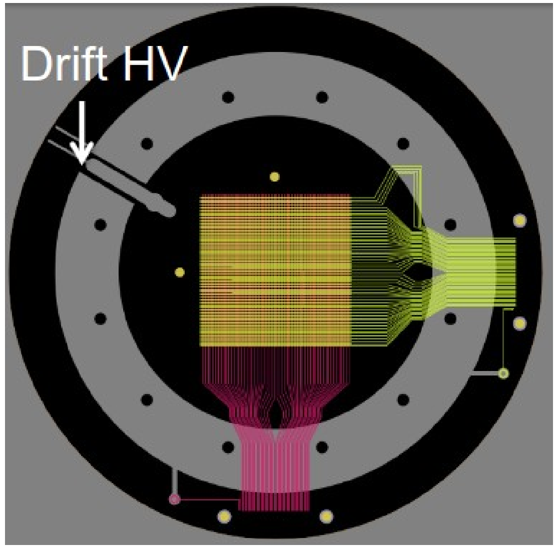
A 10x10 cm² micro-bulk (NEXT prototype)



2nd ATTRACT TWD Symposium in Detection and Imaging (Strasbourg), 4-5 November 2016

XY – micromegas detector





- Microbulk segmented mesh development
- Minimize in beam material budget (only 5μm Cu - 50μm Kapton – 5μm Cu in beam)
- Real XY scheme
- Use as neutron beam profile
- Aimed to be used as a TPC for fission studies
- Coupled to GET electronics → test alternative electronic (VMM3 based)

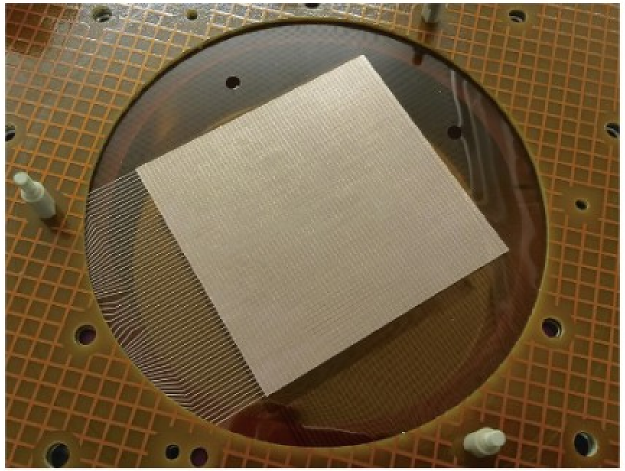


Fig. 2. (Colour online) Photo of the first 6 × 6 cm^2 segmented mesh microbulk detector produced, mounted on the thick PCB.

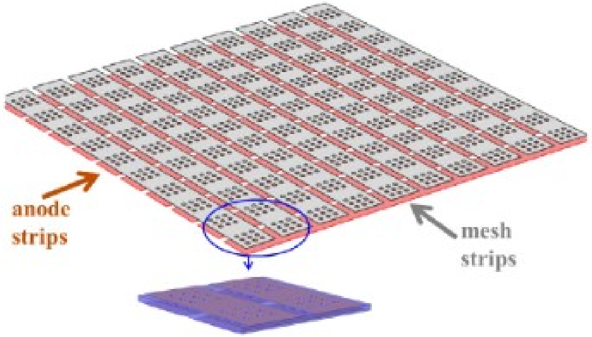
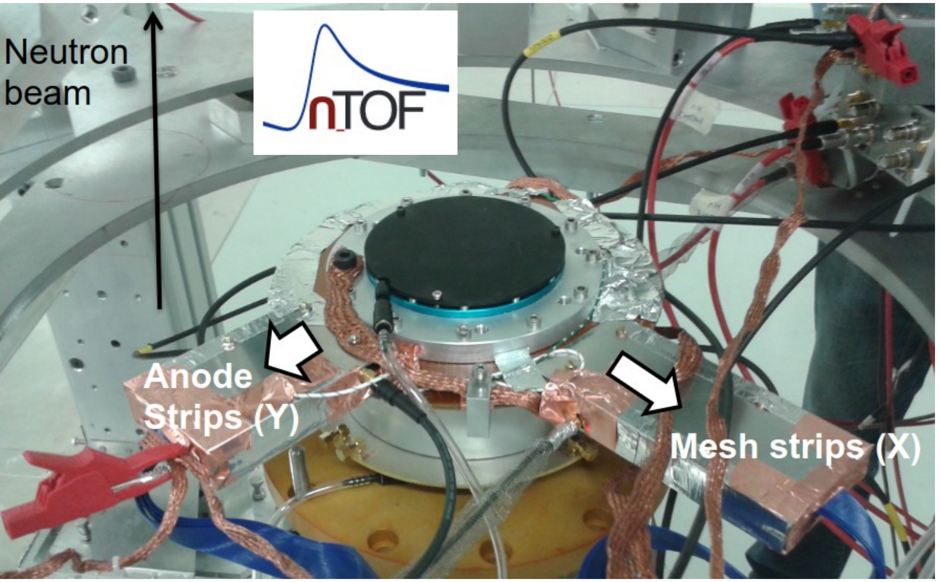


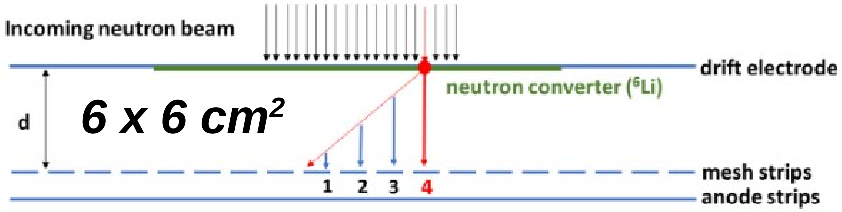
Fig. 1. (Colour online) Schematic view of the segmented mesh microbulk detector. The holes of the micromesh are arranged in matrices with a fixed number of holes/column in the overlapping region of mesh and anode strips.

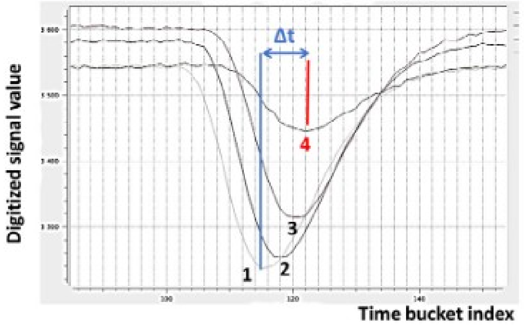
→ 60 x 60 strips (6x6 cm²)
→ Mesh hole ~ 60 μm
→ Pitch: 100 μm

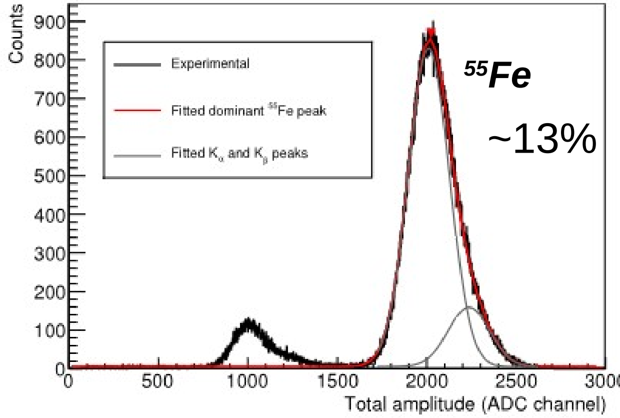
Development of a novel segmented mesh MicroMegas detector for neutron beam profiling, https://doi.org/10.1016/j.nima.2018.06.019, Nuclear Inst. and Methods in Physics Research, A 903 (2018) 46–55

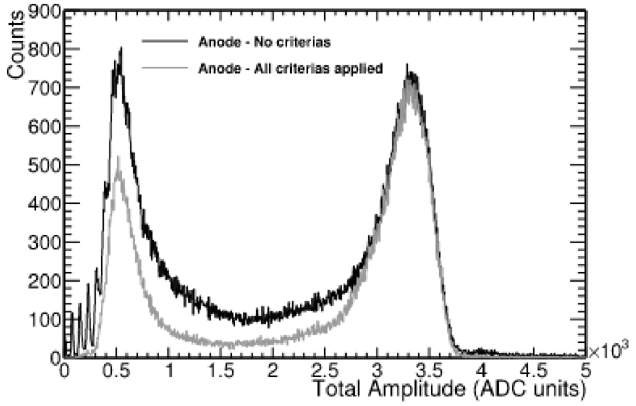
XY – micromegas detector at CERN | in Orphée reactor (LLB)











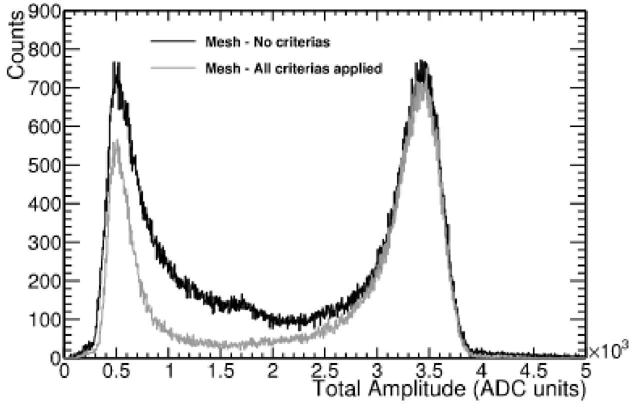
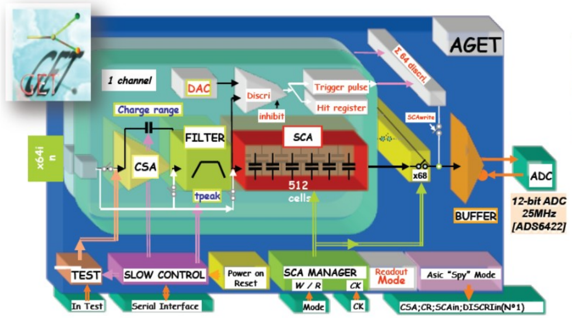
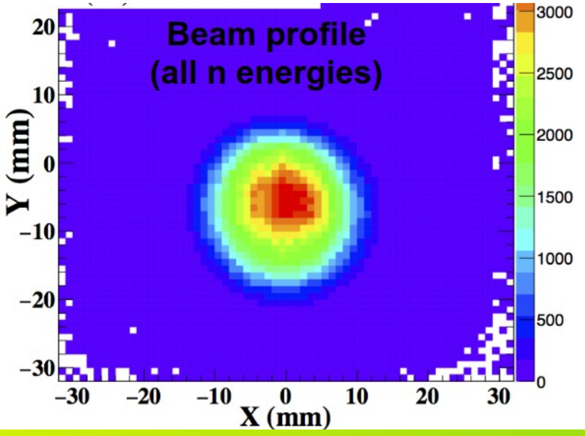


Fig. 11. Reconstructed total amplitude distribution histogram, by adding the amplitudes of all the strip signals in each event, for the anode (up) and the mesh (down), from all the events (black) and only from the selected ones with the criteria applied (grey).

AGET electronics





Development of a novel segmented mesh MicroMegas detector for neutron beam profiling, *https://doi.org/10.1016/j.nima.2018.06.019, Nuclear Inst. and Methods in Physics Research, A 903 (2018) 46–55*

→ Simulate the experiment
→ Reproduce the amplitude distribution histograms

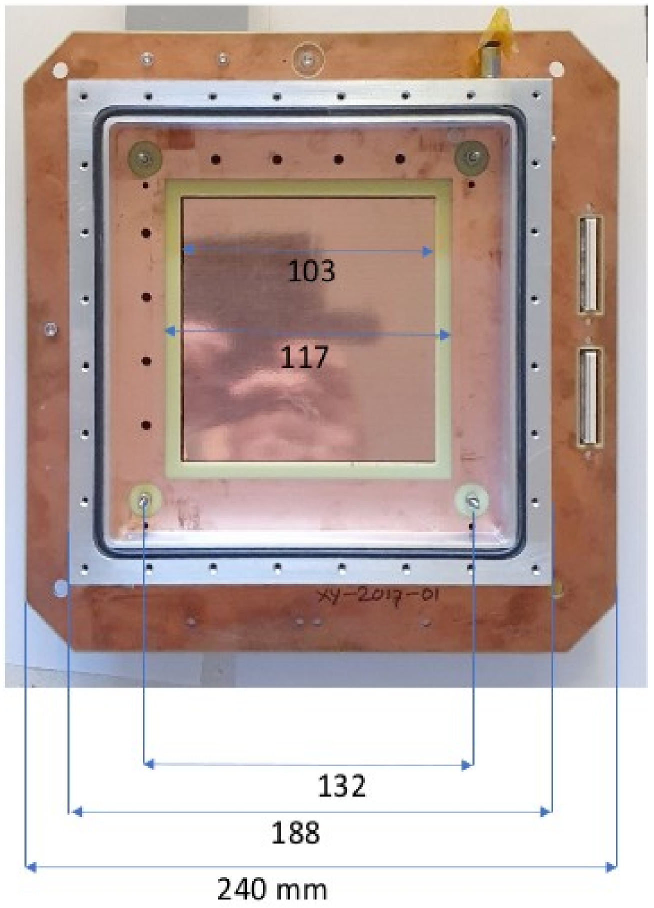
New XY-mmegas design

→ 100 x 100 strips (10x10 cm^2)
→ Mesh hole ~ 60 μm
→ Pitch: 100 μm

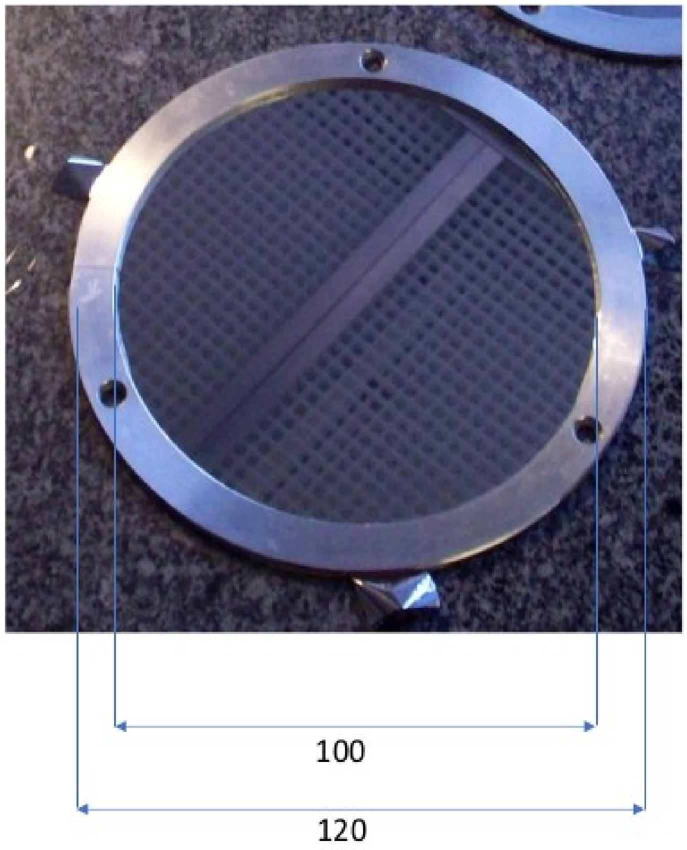
10 x 10 cm^2

Ar-iC_4H_{10} (5%), 1 Atm

Micromegas chamber



drift, ring Al 1 mm thick, ^{10}B deposit on mylar 10 μm



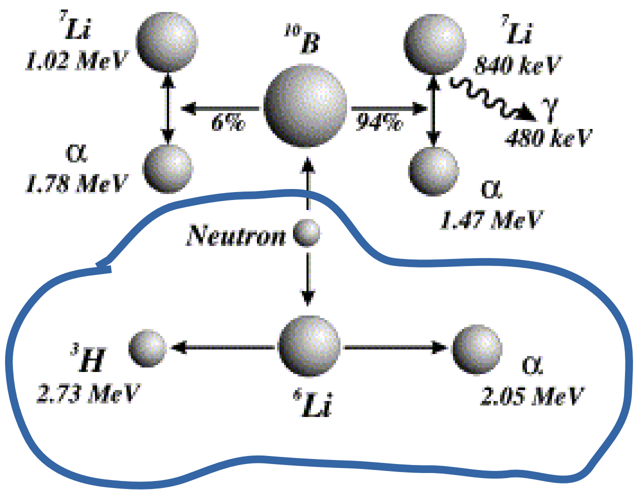
- Larger detector
- VMM3 electronics to replace AGET

- n_TOF facility (CERN) (thermal-GeV)
- GELINA (IRMM) (1meV-20MeV)
- NFS (GANIL) (1-40MeV)

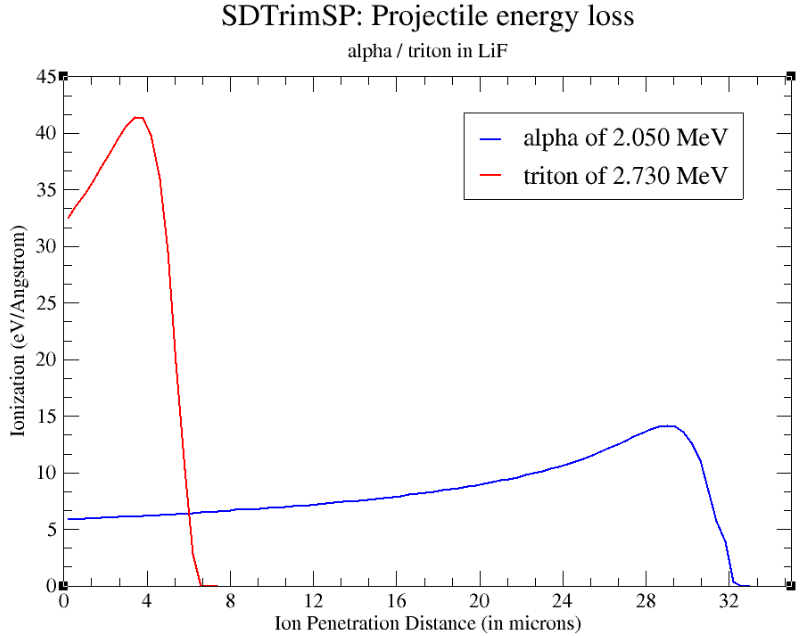
Microbulk segmented mesh detector : simulations

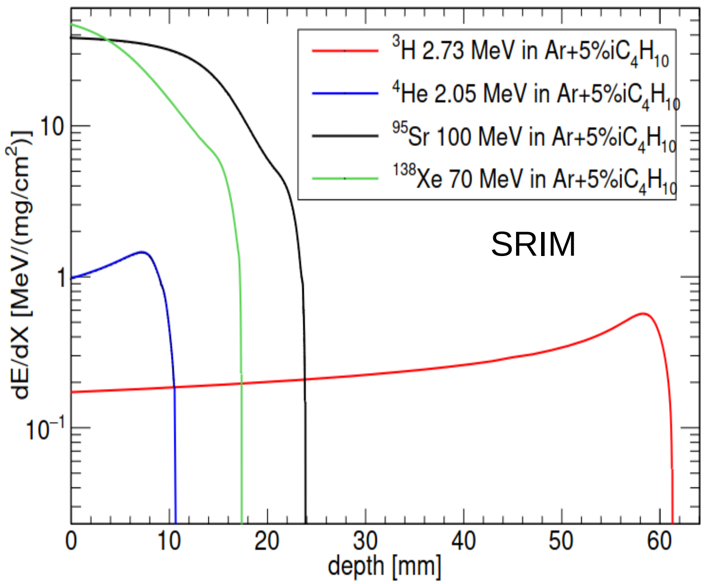
Aim to have a full understanding on how a segmented mesh microbulk MicroMegas behave

- Electric Field calculation using gmesh / COMSOL and/or neBEM
- Particle Energy loss using SRIM and FLUKA/GEANT4 ==> **Energy deposition spectra**
- Gas optimization (speed, energy and spatial resolution, …) using Garfield/Magboltz
- Full microscopic MC using Garfield++ (very time consuming) → extract useful infos to perform simplified calculation ==> **Deposited charge spectra**
- Main objective is to retrieve signal output (knowing electronic transfer signal [fC] function)
- Testing a simplified simulation scheme where thermal neutrons hit a ^{6}LiF target



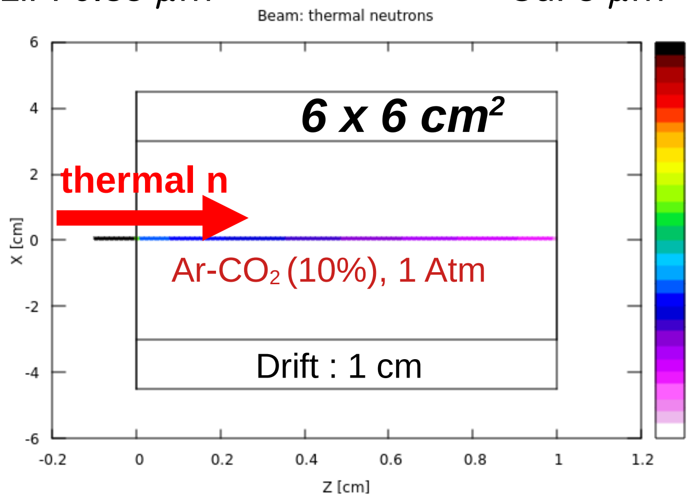
https://doi.org/10.1016/S0168-9002(02)02078-8



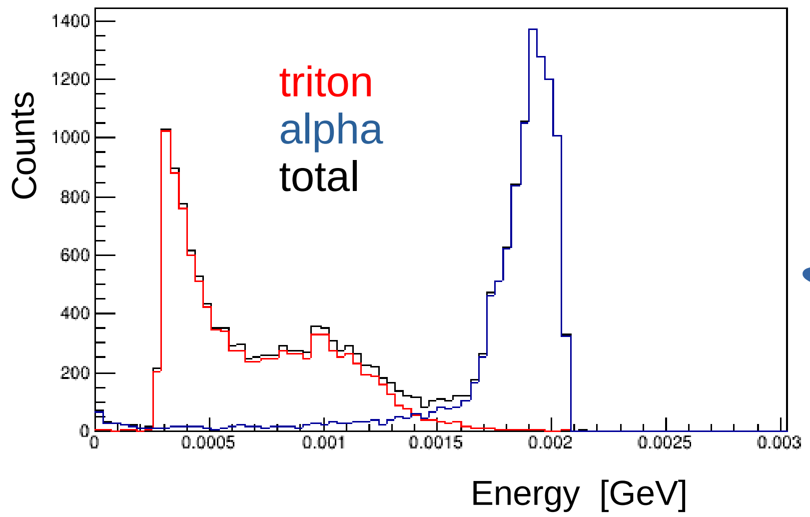


FLUKA simulations vs experimental data

^{6}LiF: 0.35 μm   Cu: 5 μm



FLUKA simulations



Experimental data

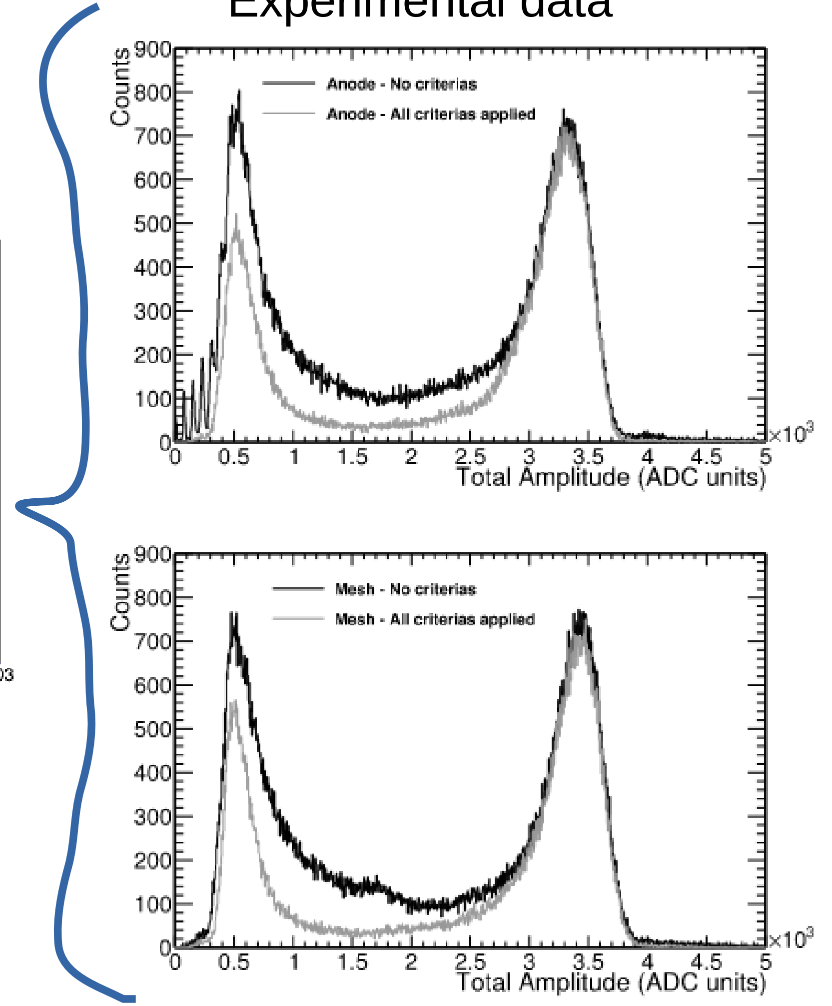
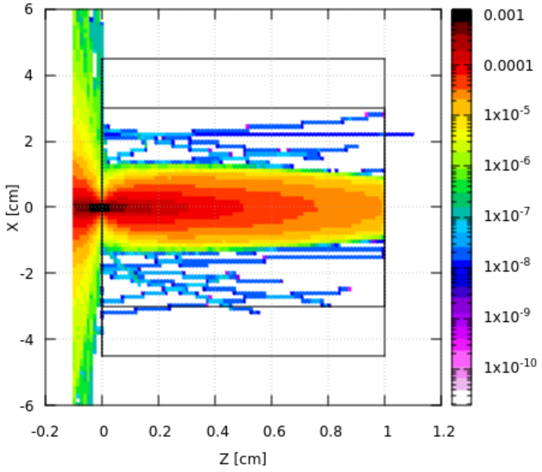
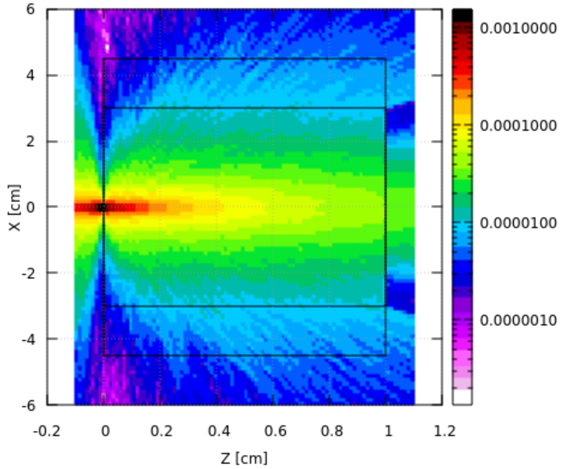


Fig. 11. Reconstructed total amplitude distribution histogram, by adding the amplitudes of all the strip signals in each event, for the anode (up) and the mesh (down), from all the events (black) and only from the selected ones with the criteria applied (grey).

alpha



triton

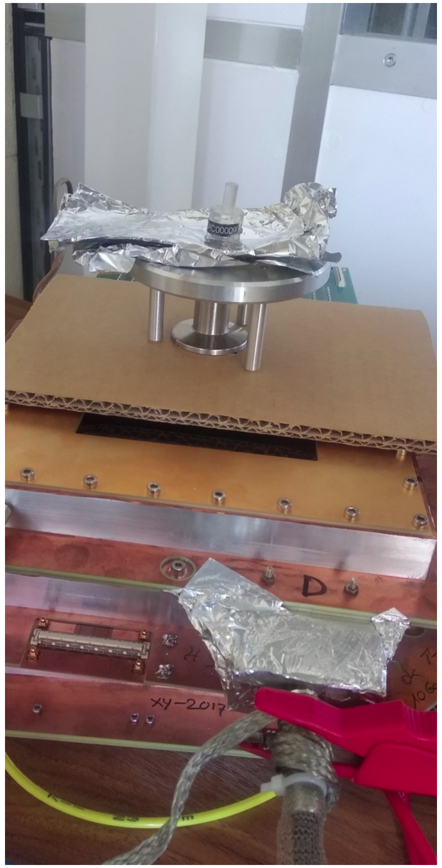


→ Fluence (Track-length density in particles/cm² per primary)

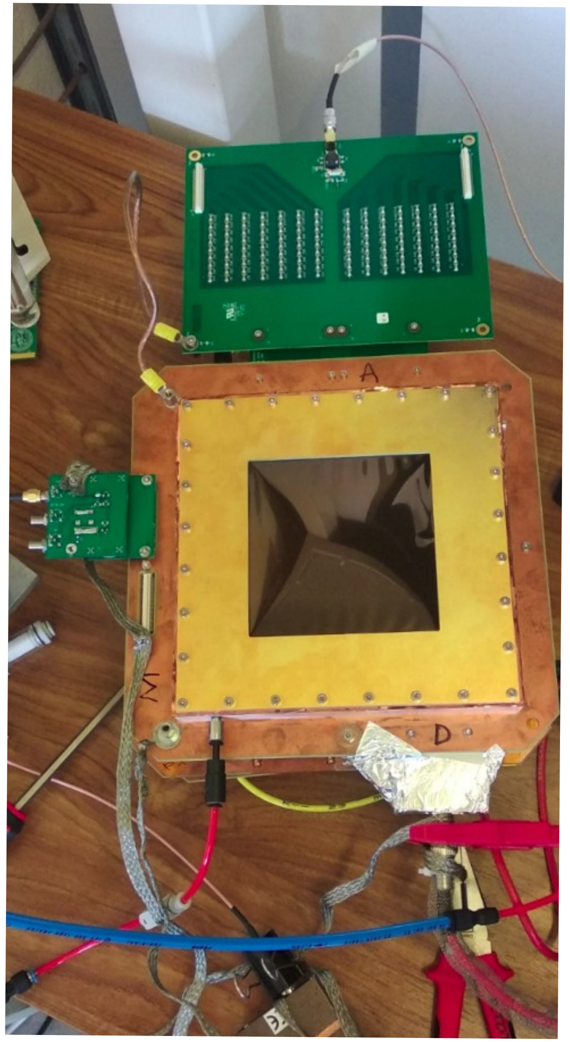
Frontiers in Physics 9, 788253 (2022).
Annals of Nuclear Energy 82, 10-18 (2015).
https://fluka.cern, https://flair.cern/

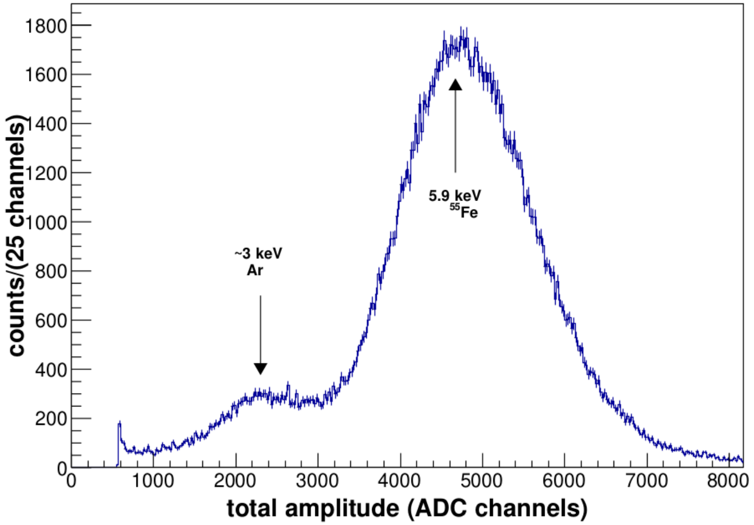
Development of a novel segmented mesh MicroMegas detector for neutron beam profiling, *https://doi.org/10.1016/j.nima.2018.06.019, Nuclear Inst. and Methods in Physics Research, A 903 (2018) 46–55*

Experimental set-up and first tests with the new XY micromegas



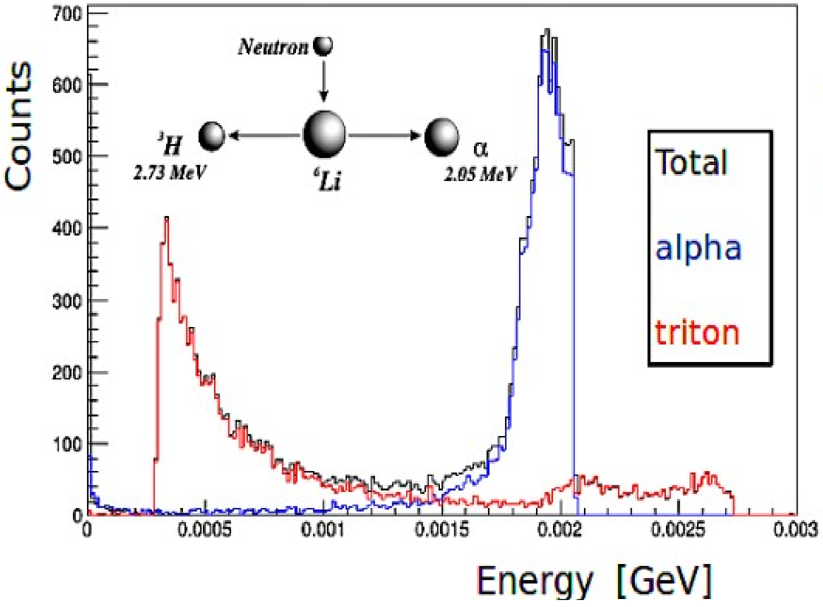
10 x 10 cm^2

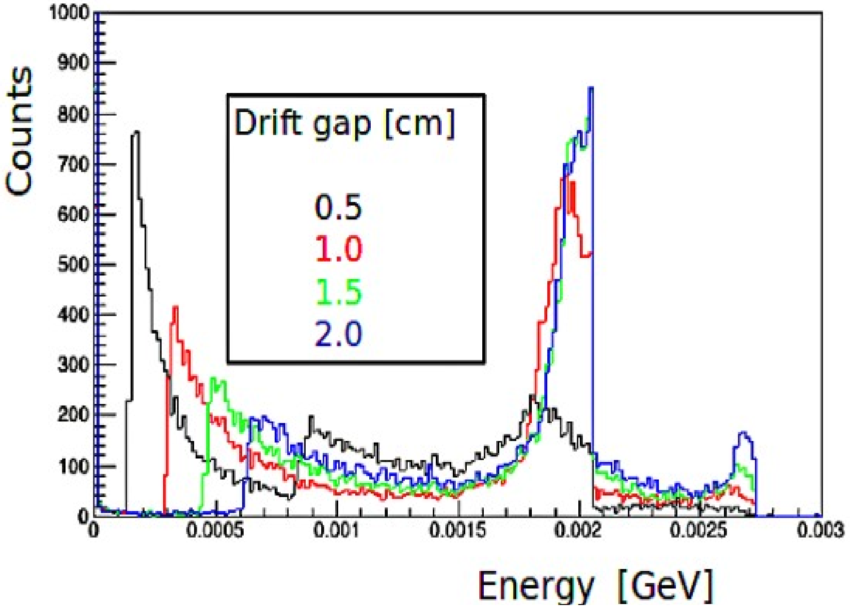


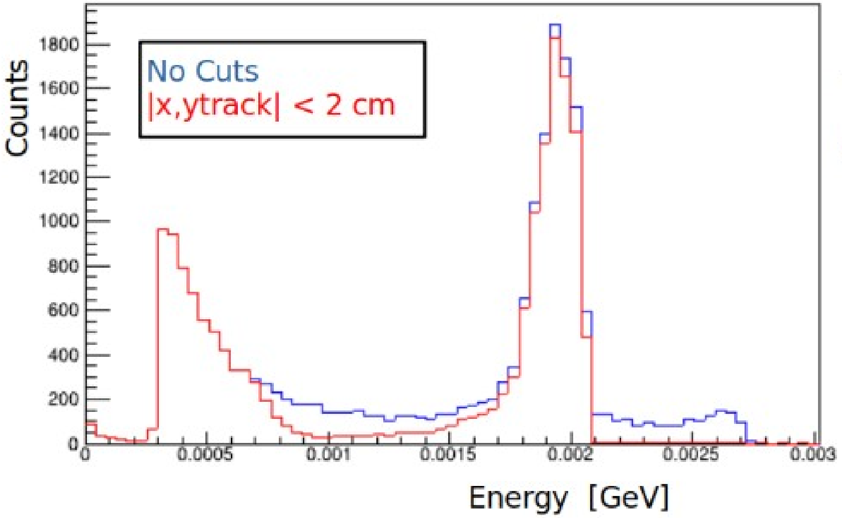


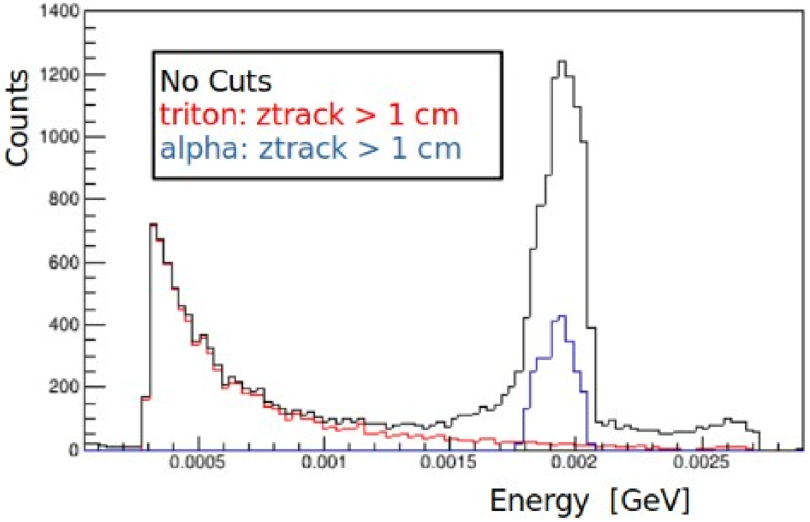
Energy deposition spectra – FLUKA simulations

10 x 10 cm²





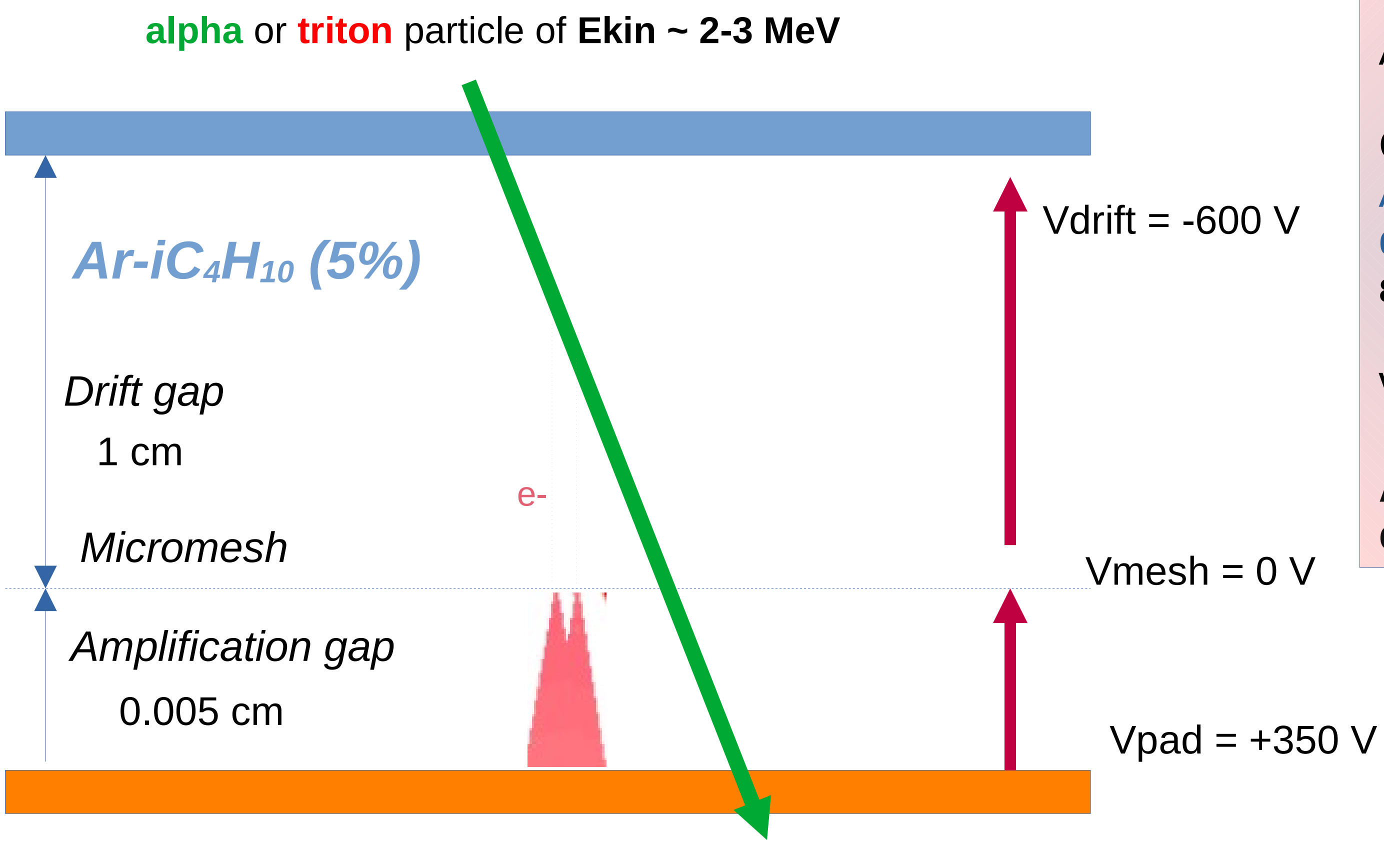




BUT not possible:

- to apply electric fields
- diffusion evaluation
- signal representation etc…

Garfield++ simulation of micromegas



In Ar, for creation of 1 pair e-/ion
→ W=26 eV (work function)
Alpha of 2 MeV → 2 MeV/ 26 eV = **7.7E+4** pairs

C = εA/d = 8.85 pF
A = 100 cm²
d = 1 cm
ε = 8.85E-12 F/m

V = 7.7E+4 ions x 1.6E-19 Cb/ion / 8.85E-12 F ~ **1.4 mV**

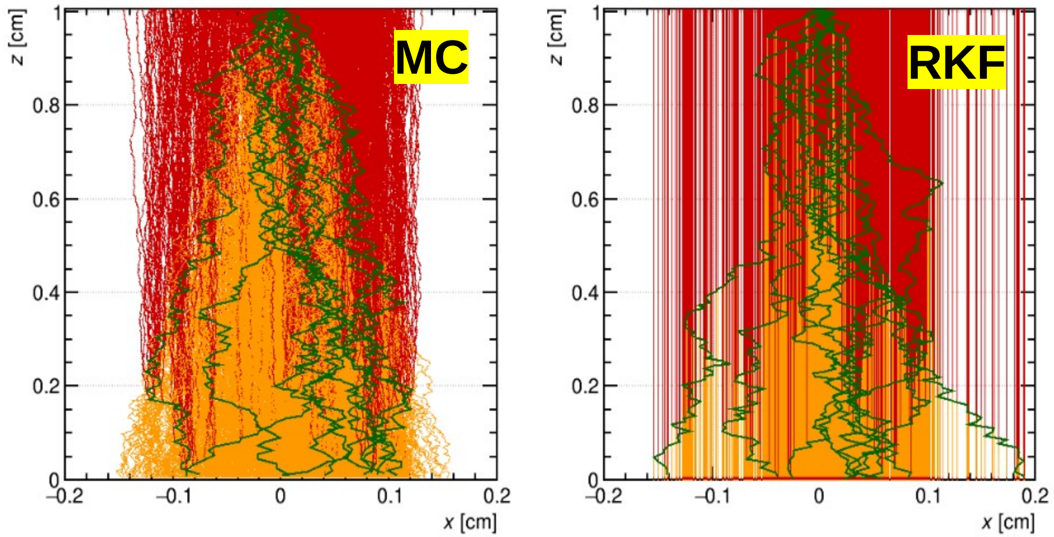
Approximation: Simplified geometry 2 || plate configurations (no mesh geometry implementation)

physical quantity	unit
length	cm
mass	g
time	ns
temperature	K
electric potential	V
electric charge	fC
energy	eV
pressure	Torr
electric field	V / cm
magnetic field	Tesla
electric current	fC / ns
angle	rad

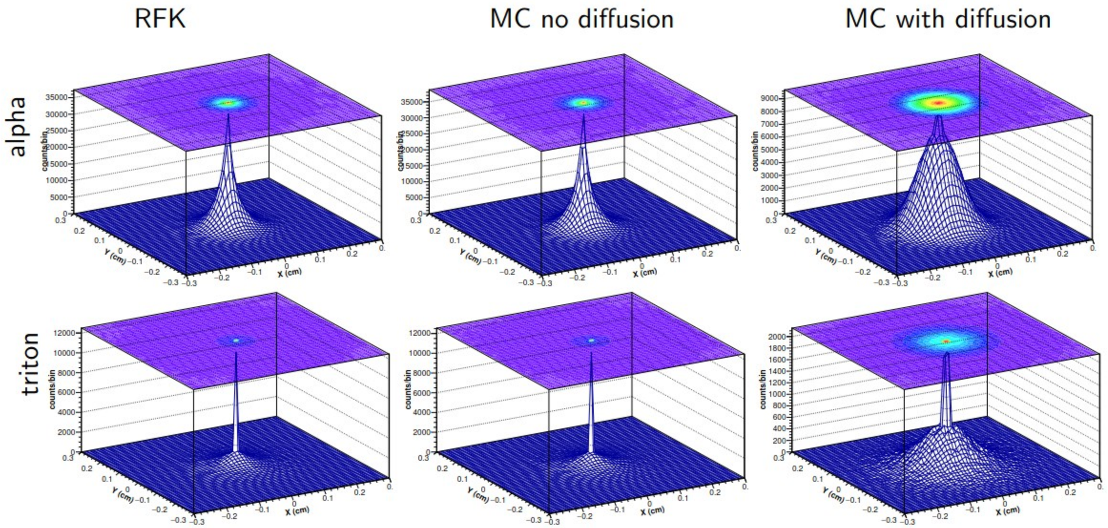
https://garfieldpp.web.cern.ch/garfieldpp/

Davis, M., Diakaki, M., Kokkoris, M., Michalopoulou-Petropoulou, V., & Vlastou, R. (2022). Simulation of a MicroMegas detector for low-energy α-particle tracking using Garfield++. HNPS Advances in Nuclear Physics, 28, 251–256. https://doi.org/10.12681/hnps.3715

Garfield++: methods to be used



10 alpha vertical tracks with energy of 2 MeV



→ **DriftLineRKF (RKF)** calculates the path of an electron or ion by numerical integration of the drift velocity vector. In the absence of a magnetic field, the drift lines will follow the electric field lines (using the previously computed tables of transport parameters to calculate drift lines and multiplication). The method is well adapted to fields that are smooth, such as analytic potentials.

→ **AvalancheMicroscopic (MC)** simulates electron trajectories using a “microscopic” Monte Carlo simulation based on the electron-atom/molecule scattering cross-sections where the electron is followed from collision to collision. Provides an accurate simulation of event-by-event fluctuations of the electron signal (very time consuming).

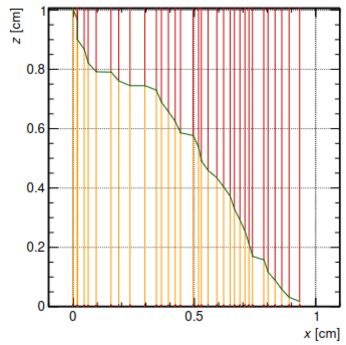
■ Use of the **MC** method for evaluation of the spread of the arrival points of the electrons in the mesh and estimation of the magnitude of the diffusion but tracking only the primary electrons without the tracking of the secondaries.

Method	RKF	MC no diffusion	MC with diffusion
σ_{alpha} (mm)	0.46	0.46	0.57
σ_{triton} (mm)	0.70	0.70	0.77

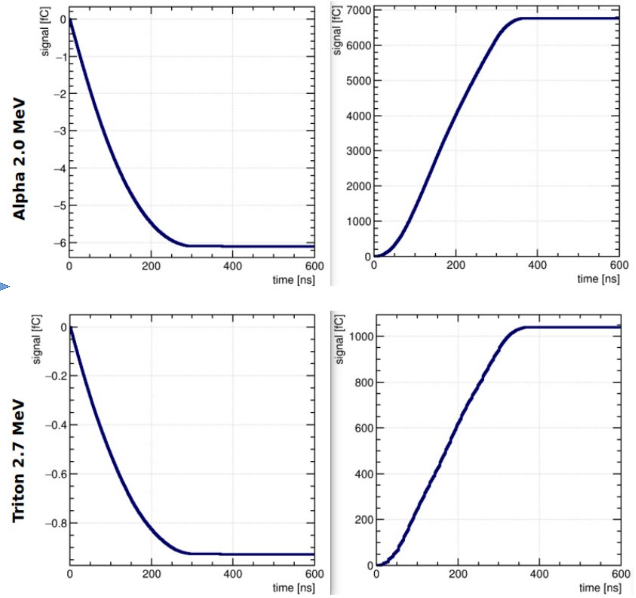
The standard deviations of the 2D distributions of the arrival positions of the primary electrons that are produced from 10000 vertical alpha / triton tracks with RKF and MC methods.

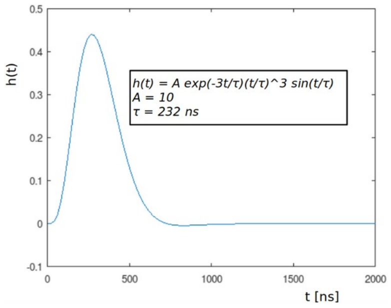
Pulse after convolution with a GET transfer function

triton



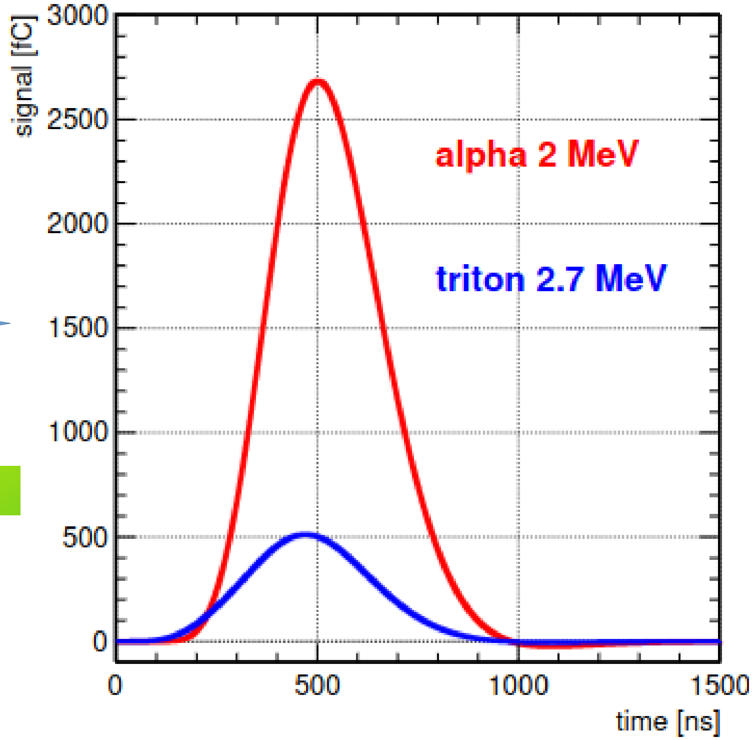
Induced charge



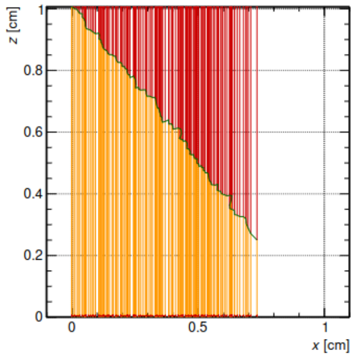


transfer function

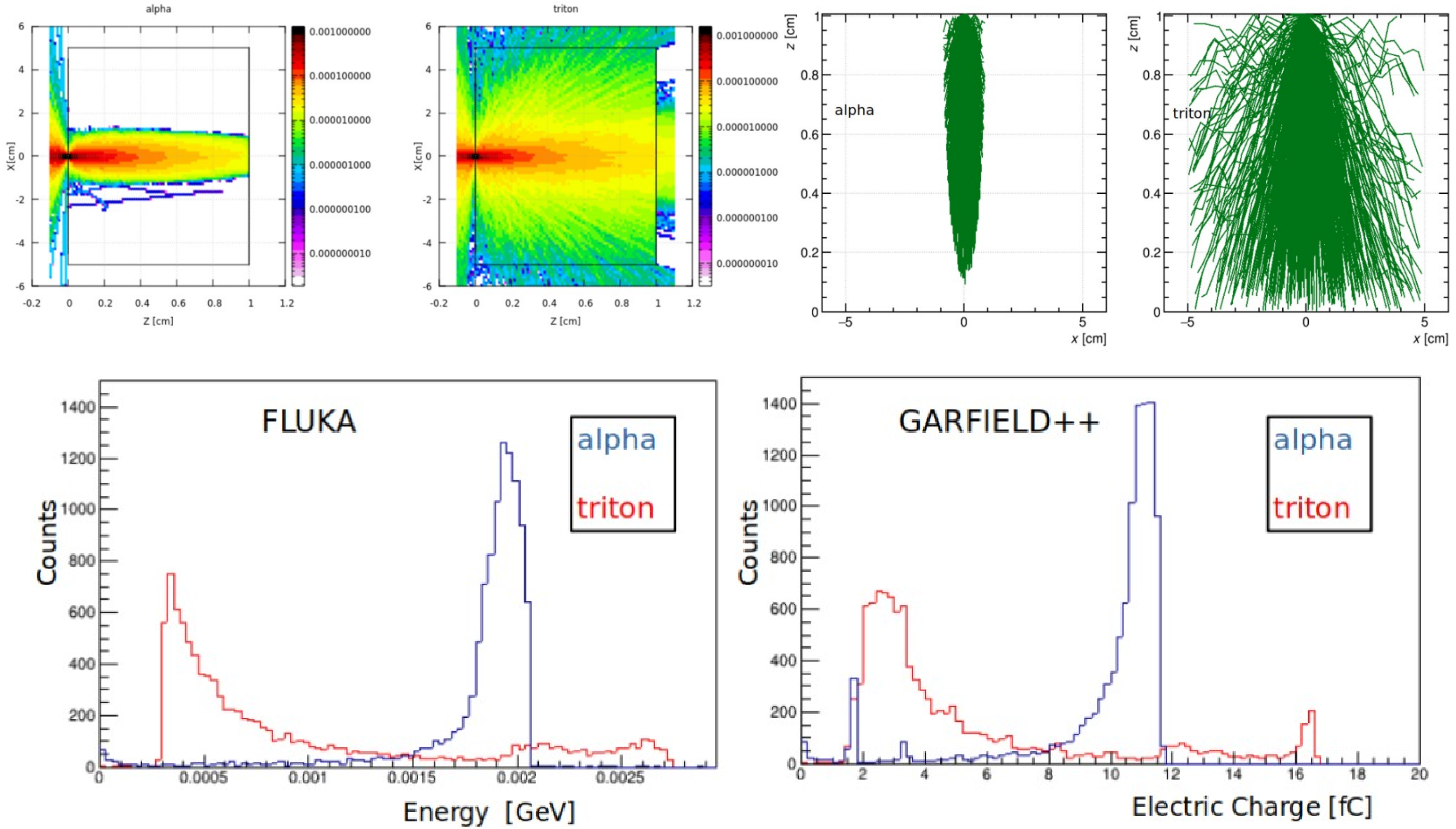
https://doi.org/10.1016/j.nima.2016.09.018



alpha



FLUKA energy deposition spectrum vs RKF deposited charge



~ 10000 alpha / triton tracks

- Insert E_{kin} and direction of alpha and triton (^{6}LiF → GAS) from FLUKA to Garfield++
- Generate a simulated spectrum of α-particle and triton tracks as exited from the ^{6}LiF target, having trajectories distributed within the whole detector volume, using Garfield++
- Compare it qualitatively with the simulated total energy deposition histogram as calculated by FLUKA.

Summary

- A solid simulation framework for the XY micromegas detector has been established using the current state-of-the-art MC computer codes FLUKA, GEANT4 and Garfield++, SRIM

- Extract at first with a transport MC code (FLUKA, GEANT4) the energies and direction cosines of the neutron reaction products and then use Garfield++ to transport them in the drift region and record all the primary electrons that arrive on the micromesh, using the full MC microscopic model enabling only the tracking of primary electrons

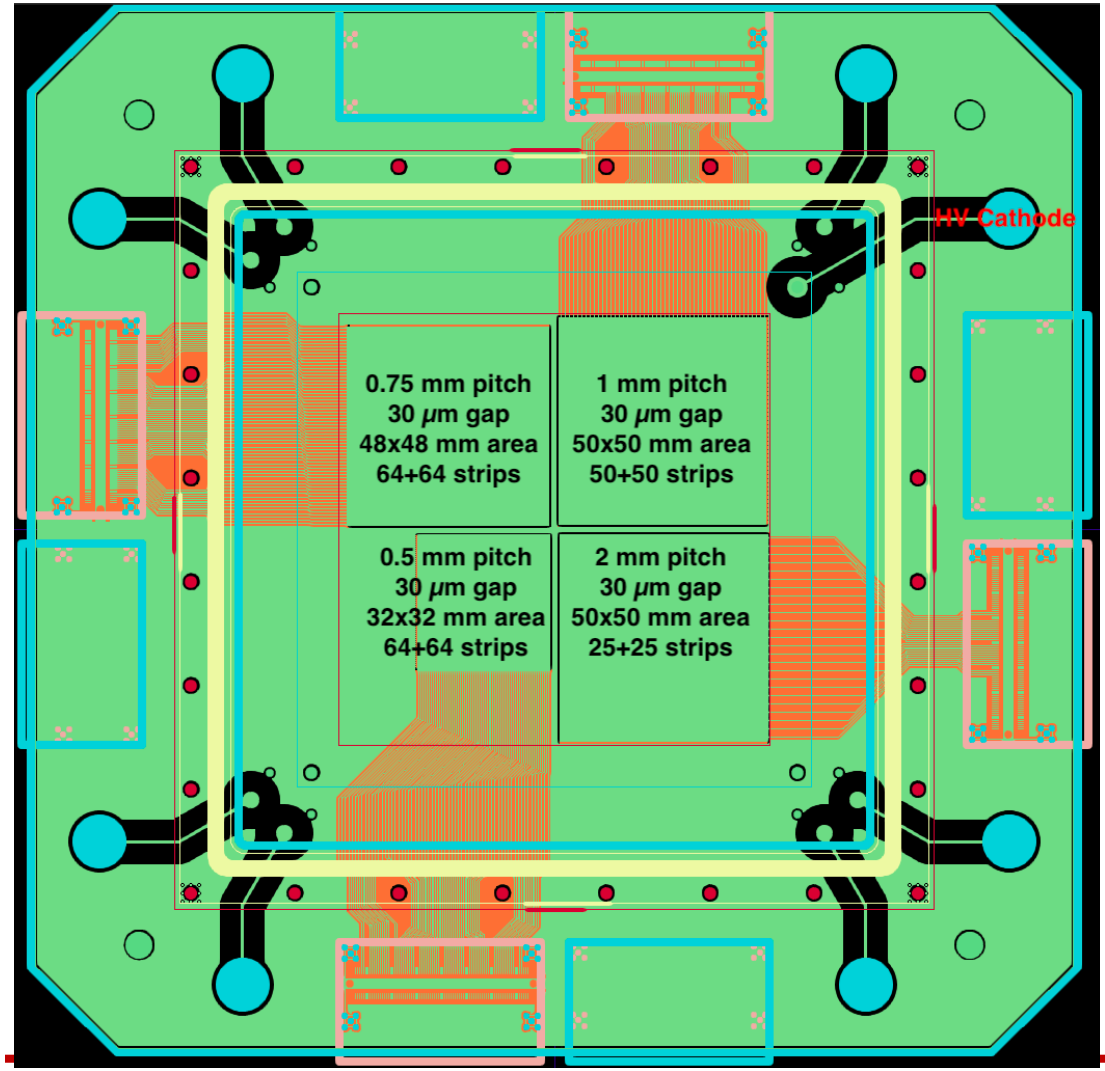
- Following this scheme of analysis, we plan to address and carry out studies using other type of converters and fission fragments

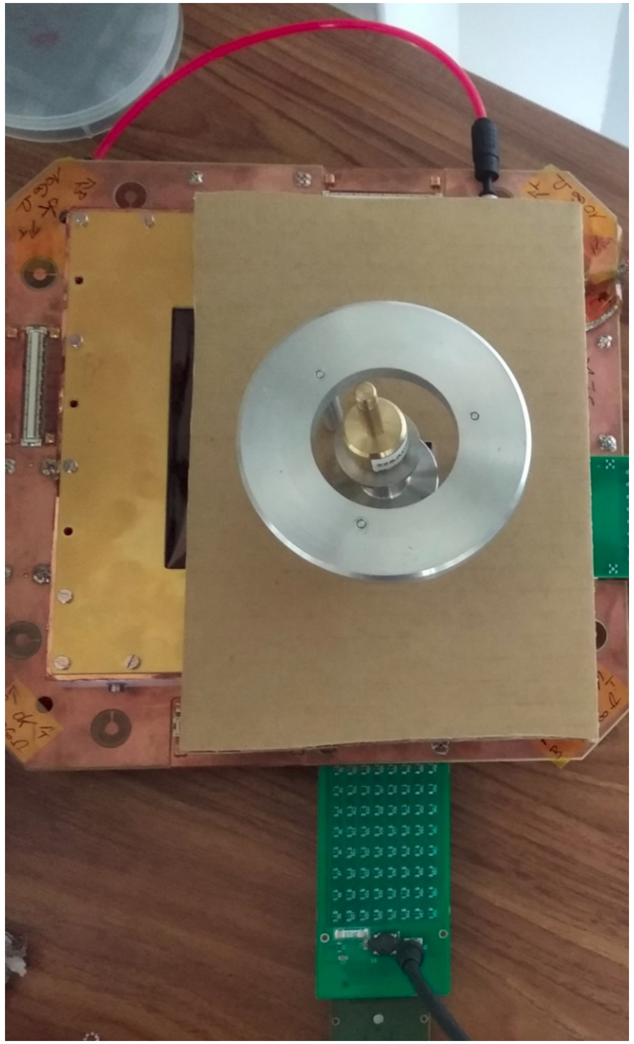
- The work for SANDA is done concerning the study and construction of new devices for precise fission cross section measurements

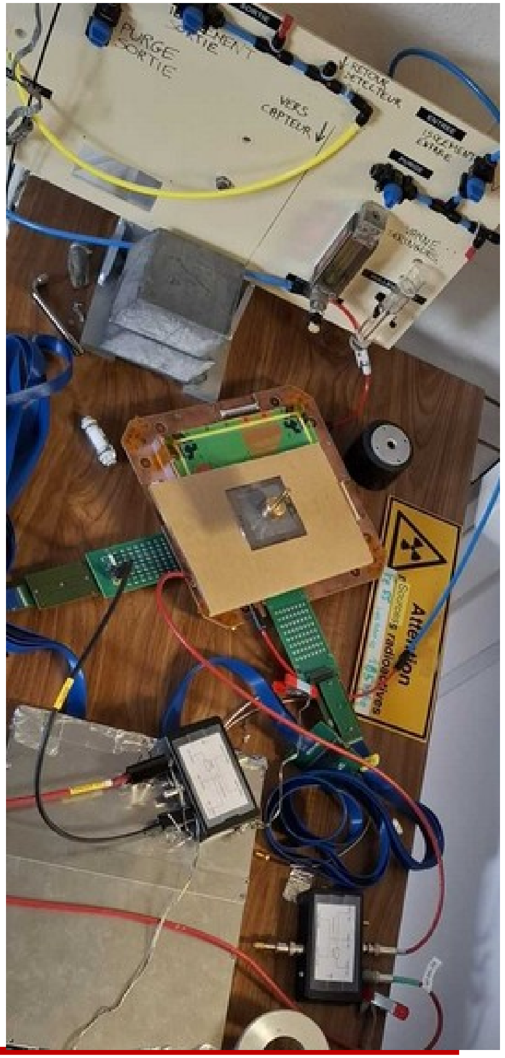
- Our ANR project to build a real device is a follow-up of the SANDA simulation work

Outlook

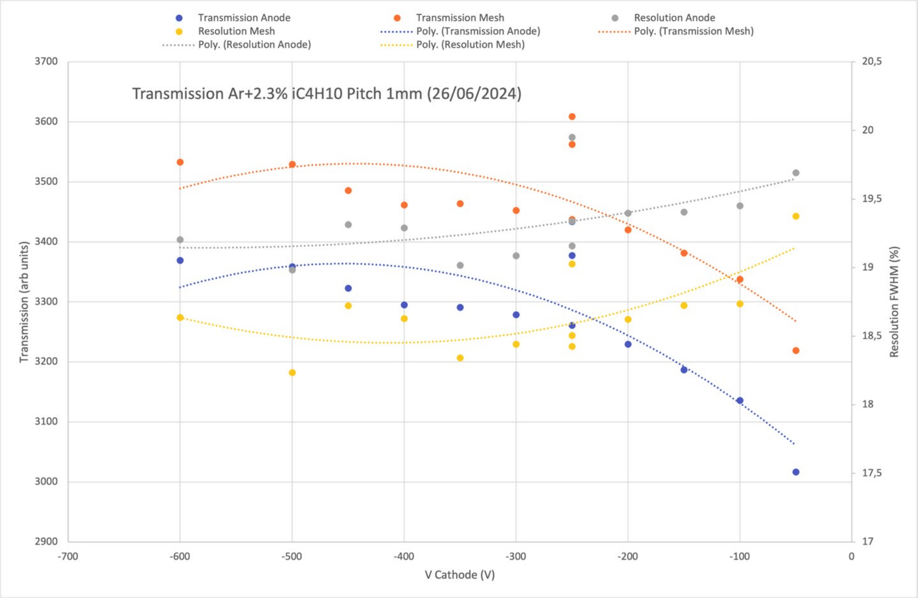
Characterizing various segmented mesh microbulk MicroMegas

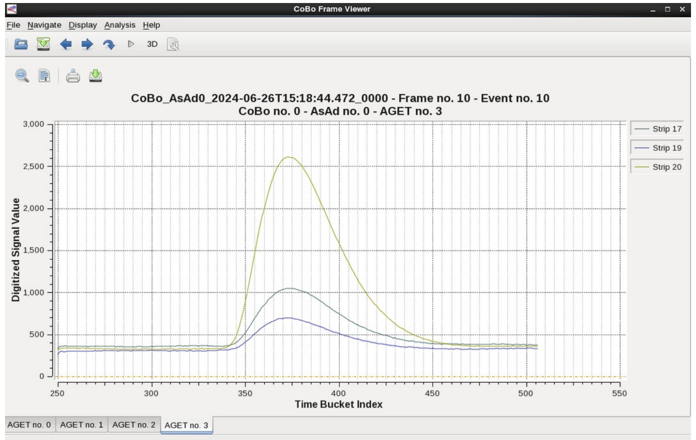


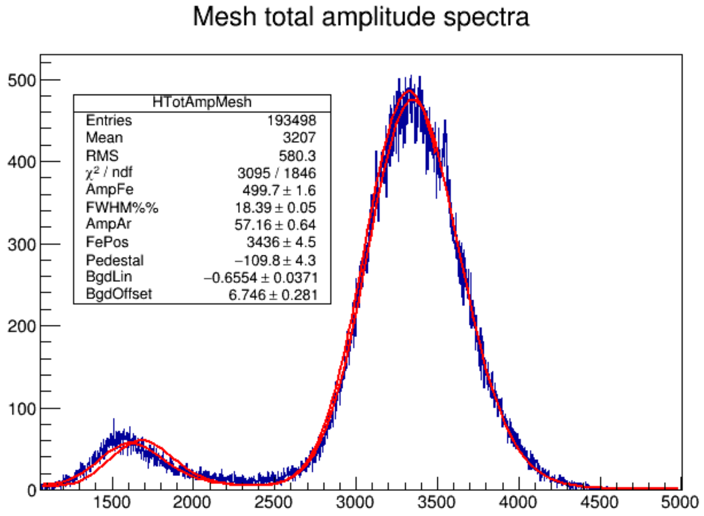




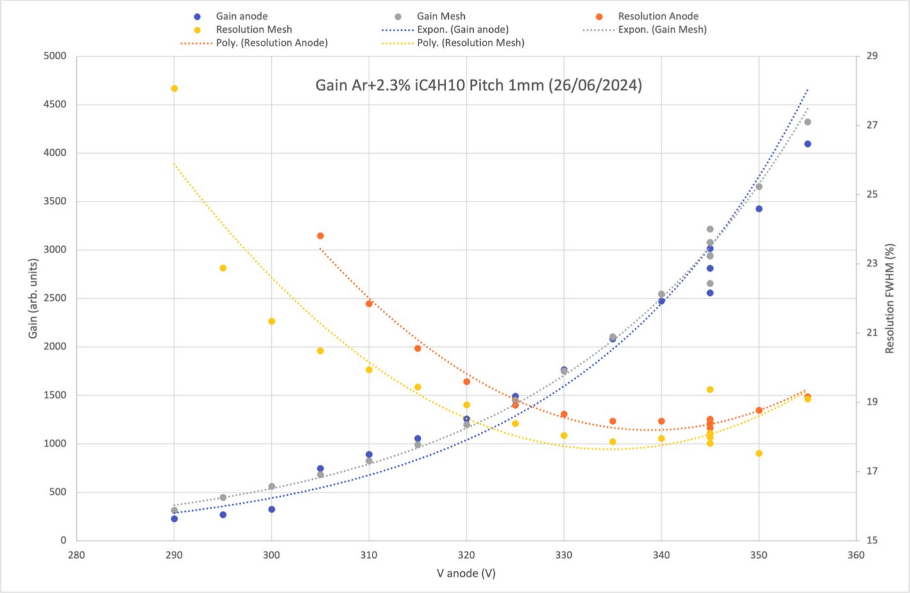
Preliminary results

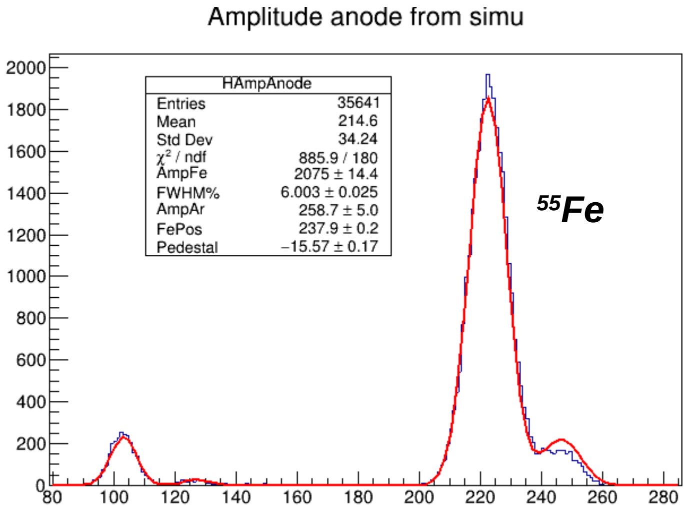


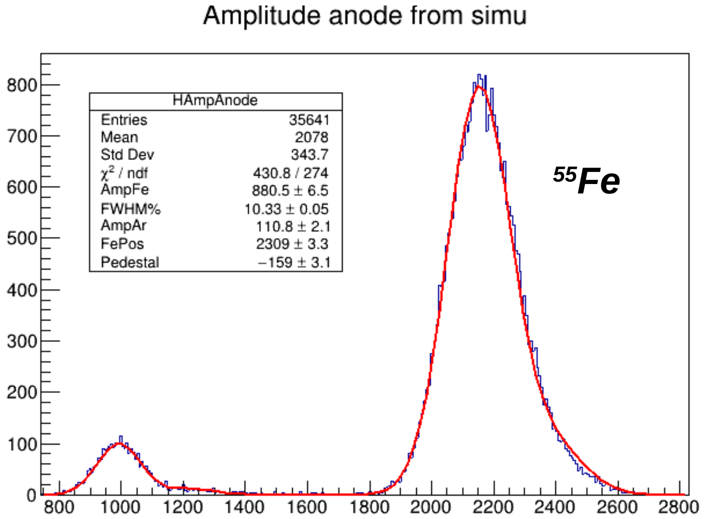




Experiment

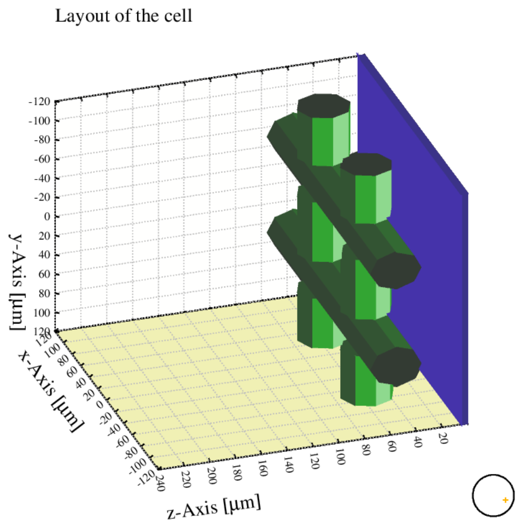


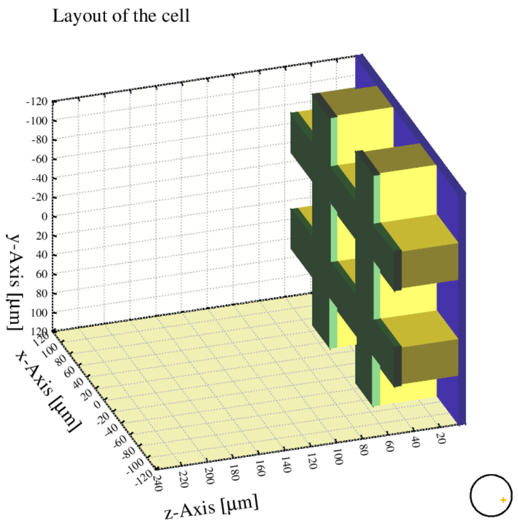


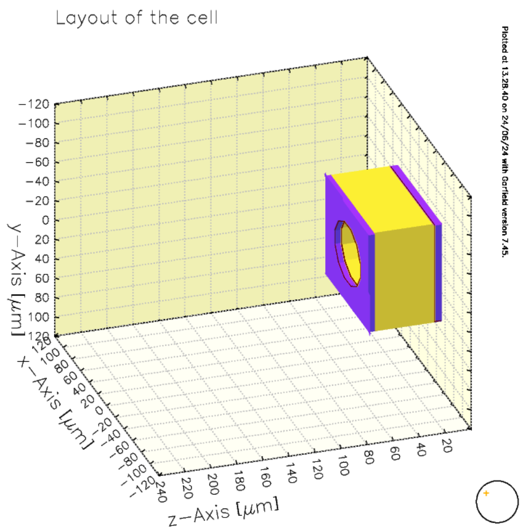


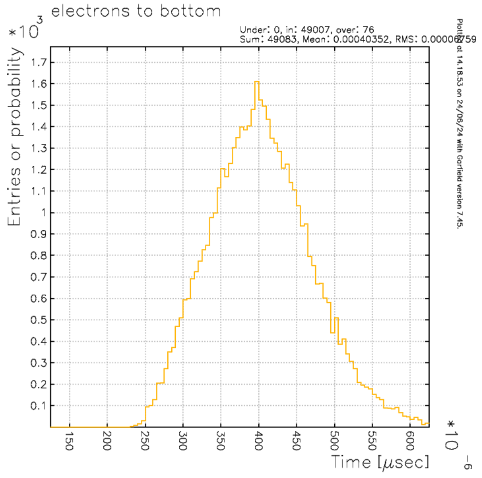
Simulations

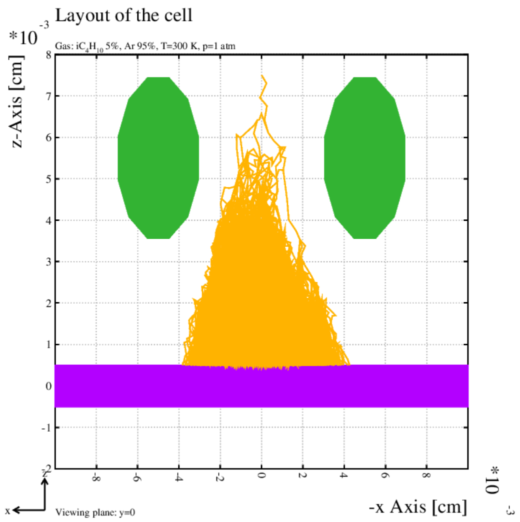
Preliminary results : Garfield+neBEM for gain evaluation

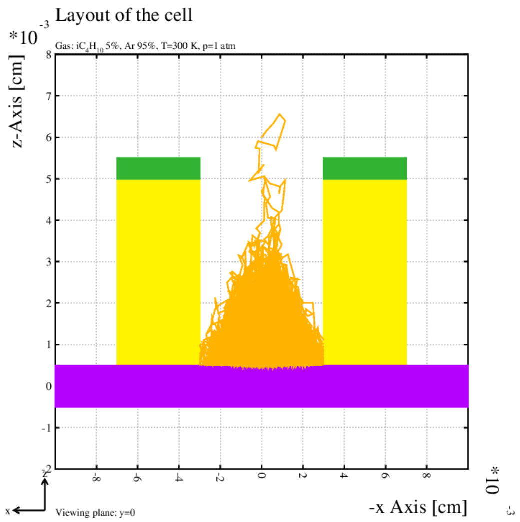


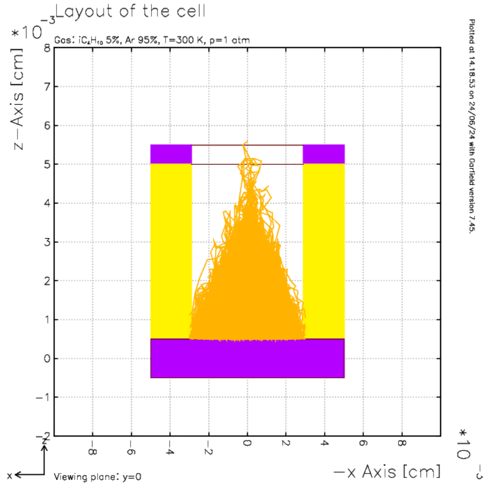


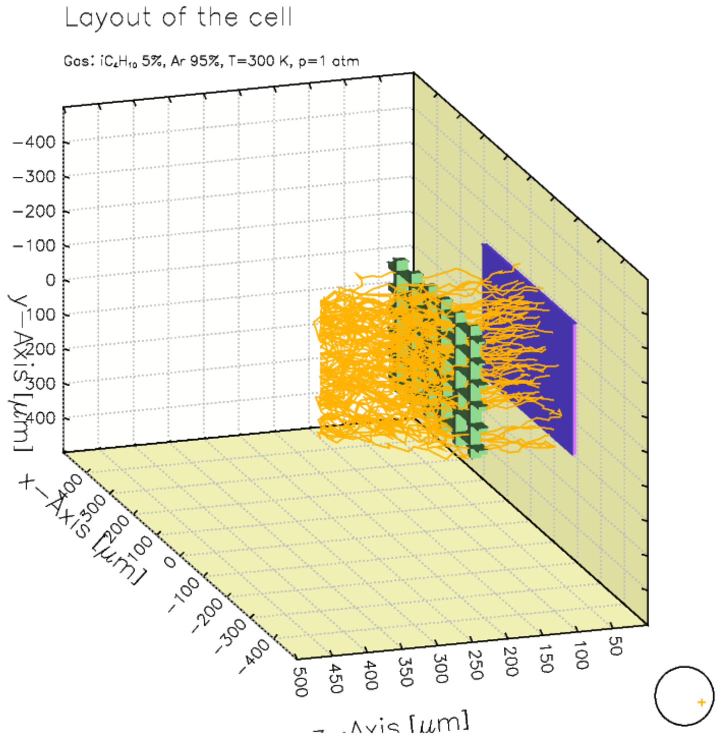






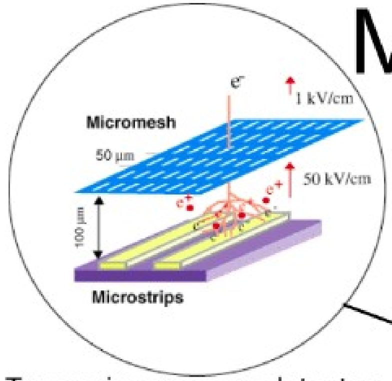






back-up

Micromegas concept

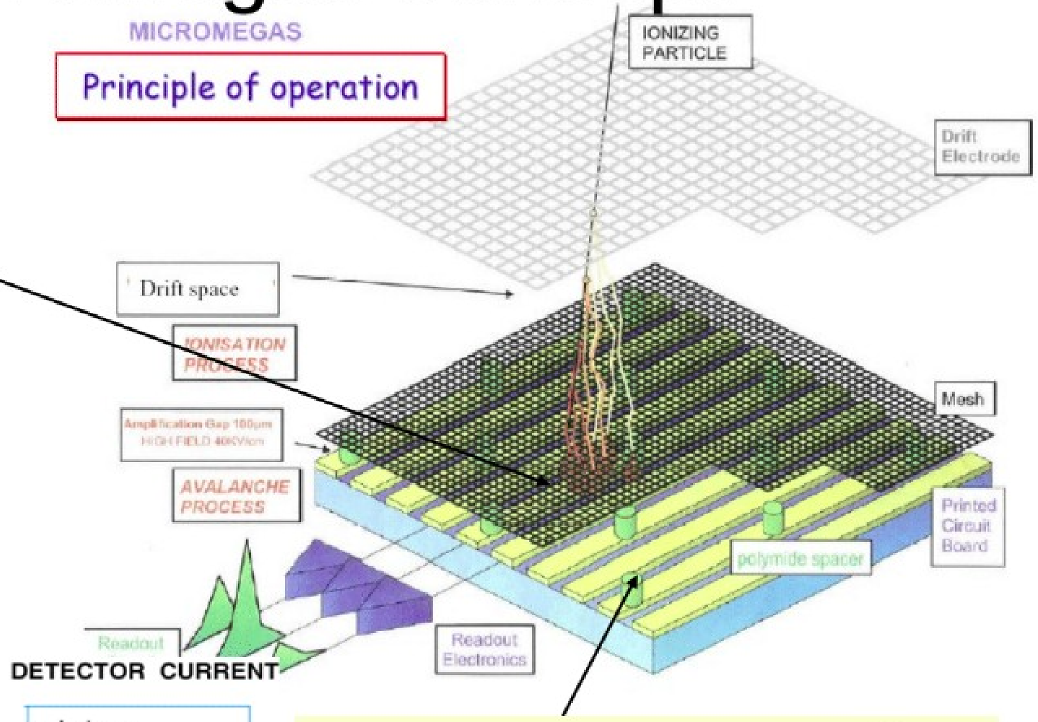


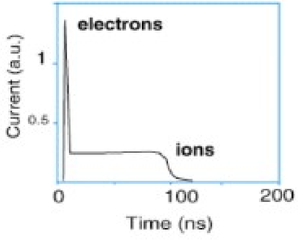
Two-region gaseous detector
separated by a Micromesh :

- Conversion region
  - Primary ionization
  - Charge drift towards A.R.
- Amplification region
  - Charge multiplication
  - Readout layout
  - Strips (1/2 D)
  - Pixels

==>Very strong and uniform E.F.

- simplicity
- single stage of amplification
- fast and natural ion collection
- discharges non destructive





keeping the gap constant ~100 µm gap

- **Ni or Cu micromesh + pillars on PCB**
- **Self-supported copper micromesh**
- **« bulk » and « micro-bulk » technologies**
- **Recent InGrid techniques** : mesh over Si pixel chip

Micro Mesh Gaseous Structure, Y. Giomataris, Ph. Rebourgeard, J-P Robert and G. Charpak, NIM A376, 1996, p29 (CEA-biospace patent)

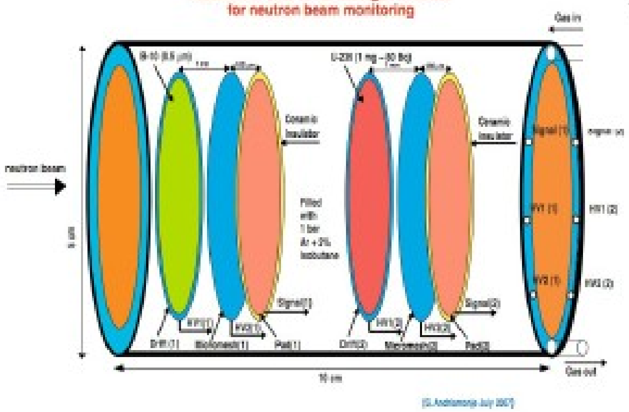
Micromegas applications

n_TOF

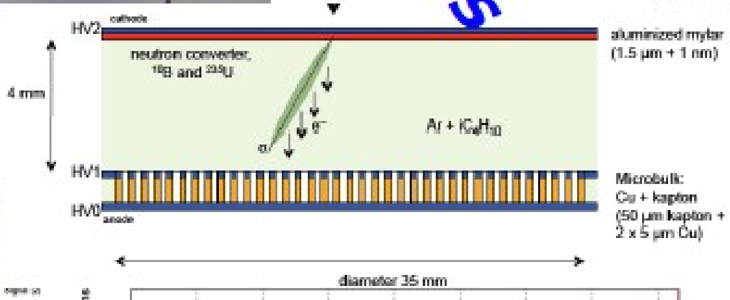
Low mass online neutron flux monitor:

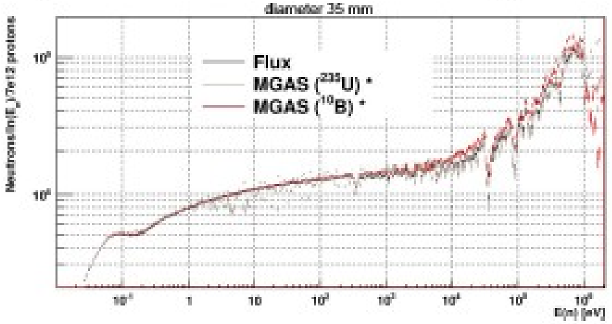
- ➢ Minimize beam perturbation and induced background
- ➢ Cover a wide energy range

Drift Cathode (1):
25 µm coppered (1 µm) Kapton
+ 1.5 µm of **B-10**
Drift Cathode (2) :
1.5 µm aluminised (~ nm) mylar
+ 1 mg **U-235** (99.94%)
Micromesh + Anode strip:
Micro-Bulk (5 µm Cu)
+ 50 µm Kapton (with 70500 holes)
+ 5 µm Cu)



Schematic view of Micromegas detector for neutron beam monitoring

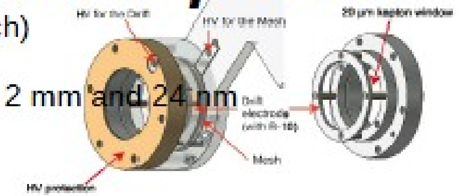


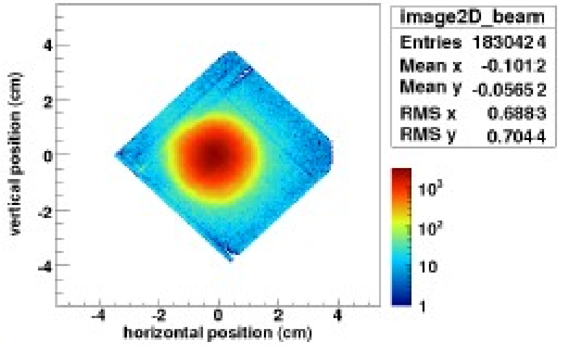


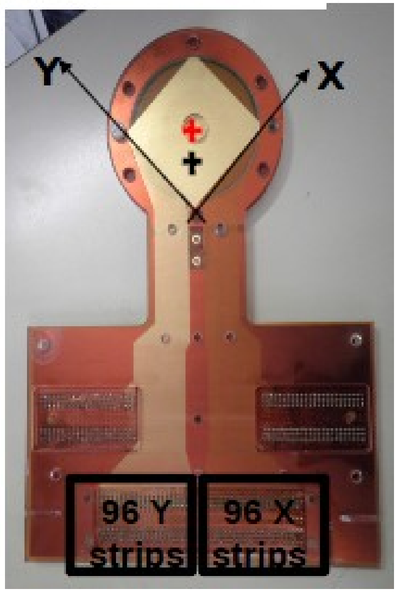
Nuclear physics

Neutron beam profiler

- 6x6 cm2 (2x106 strips, 0.5 mm pitch)
- drift gap = 4 mm
- converter: 10B4C enriched in 10B, 2 mm and 24 nm
- Ar + (10%)CF4 + (2%) iC4H10







Neutron detection with Micromegas

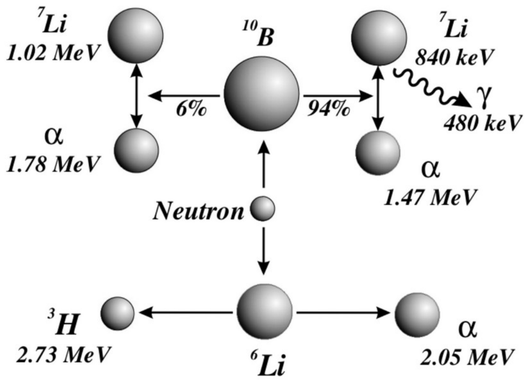
Due to the so-called 3He shortage crisis, many detection techniques used nowadays for thermal neutrons are based on alternative converters. Thin films of ^{10}B or $^{10}B_4C$ are used to convert neutrons into ionizing particles which are subsequently detected in gas proportional counters, but only for small or medium sensitive areas so far.

Neutron detection → neutron to charge converter

- *Solid converter: thin layers deposited on the drift or mesh electrode (**^{10}B, $^{10}B_4C$,** ^6Li, ^6LiF, U, actinides…)*
  - ✓ *Sample availability & handling*
  - ✓ *Efficiency estimation*
  - ✘ *Limitation on sample thickness from fragment range*
    ⏶ limited efficiency
  - ✘ *Not easy to record all fragments*

- *Detector gas (^3He, BF_3…)*
  - ✓ *Record all fragments*
  - ✓ *No energy loss for fragments ⏶ reaction kinematics*
  - ✓ *No limitation on the size ⏶ high efficiency*
  - ✘ *Gas availability*
  - ✘ *Handling (highly toxic or radioactive gasses)*

- *Neutron elastic scattering*
  - *gas (H, He)*
  - *solid (paraffin etc.)*
    - ✓ Availability
    - ✓ High energies
    - ✘ Efficiency estimation & reaction kinematics



Neutron detection with high efficiency (~50%):
- ^{3}He crisis
- Increased demand for neutron detectors
  - ➔ Science
  - ➔ Homeland security
  - ➔ Industry

Micromegas for neutrons
- *Micro-Pattern Gaseous Detector (gain, fast timing, high rate, granularity, radiation hardness, simplicity…)*
- *Low mass budget*
- *Transparent to neutrons*
- *Large area detectors cheap & robust*

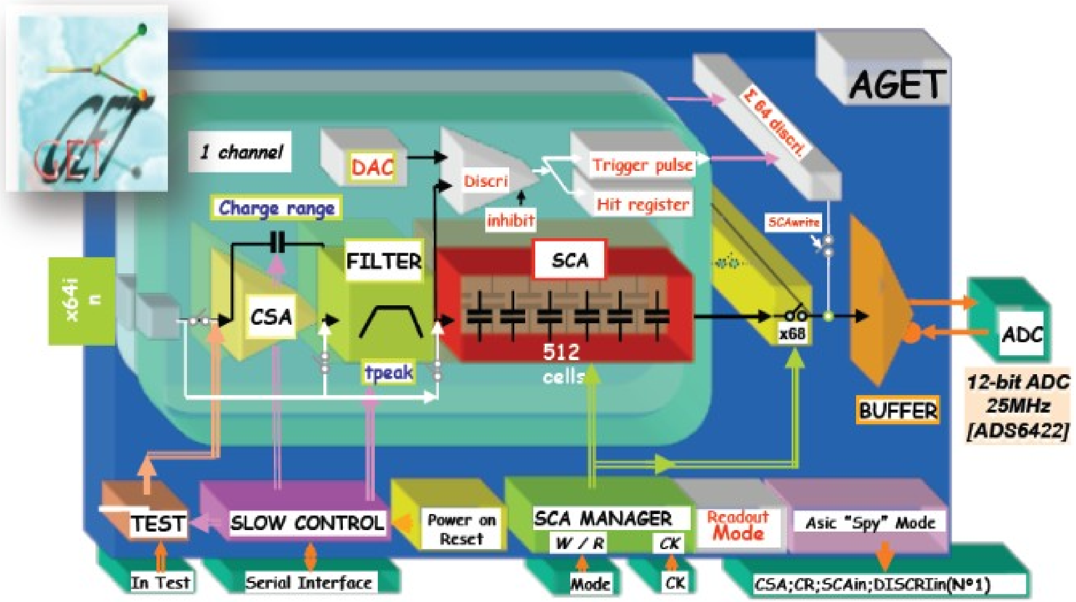
ELECTRONICS

Challenge:

No global trigger signal => **AGET electronics* + Reduced CoBo configuration**
Self triggering mode / timing difference between strips.

- 64 analog channels /chip.
- Auto trigger: discriminator and threshold
- Multiplicity signal: analog OR of 6discriminators
- Address of the hitted channels
- SCA readout mode (all/hitted/selected channels)

- Max sampling rate: 100 MHz.
- 16 peaking time values: 50 ns-1us.
- 4 charge ranges/channel: 120fC/ 240fC/ 1pC/ 10 pC.



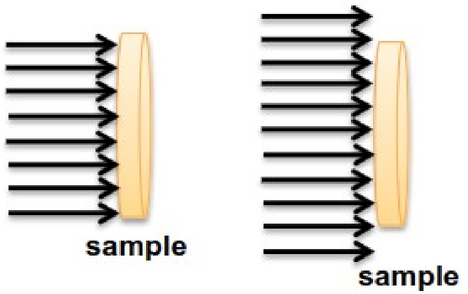
*GET, General electronics for TPC, ANR proposal / GET-QA-000-0005, AGET Data Sheet.

NEUTRON BEAM MONITOR + PROFILER

Accurate neutron cross section measurements require:

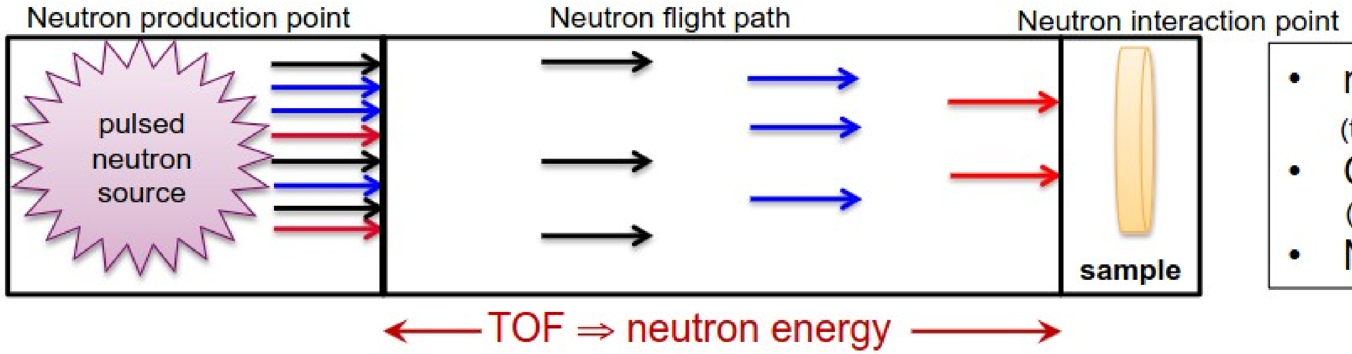
- **Neutron fluence/Beam interception factor**

Number/fraction of neutrons hitting the area covered by the sample.



- **Shape of the beam profile**

Beam optics misalignment => Beam fluence variations.
For **non-monoenergetic** neutron sources:



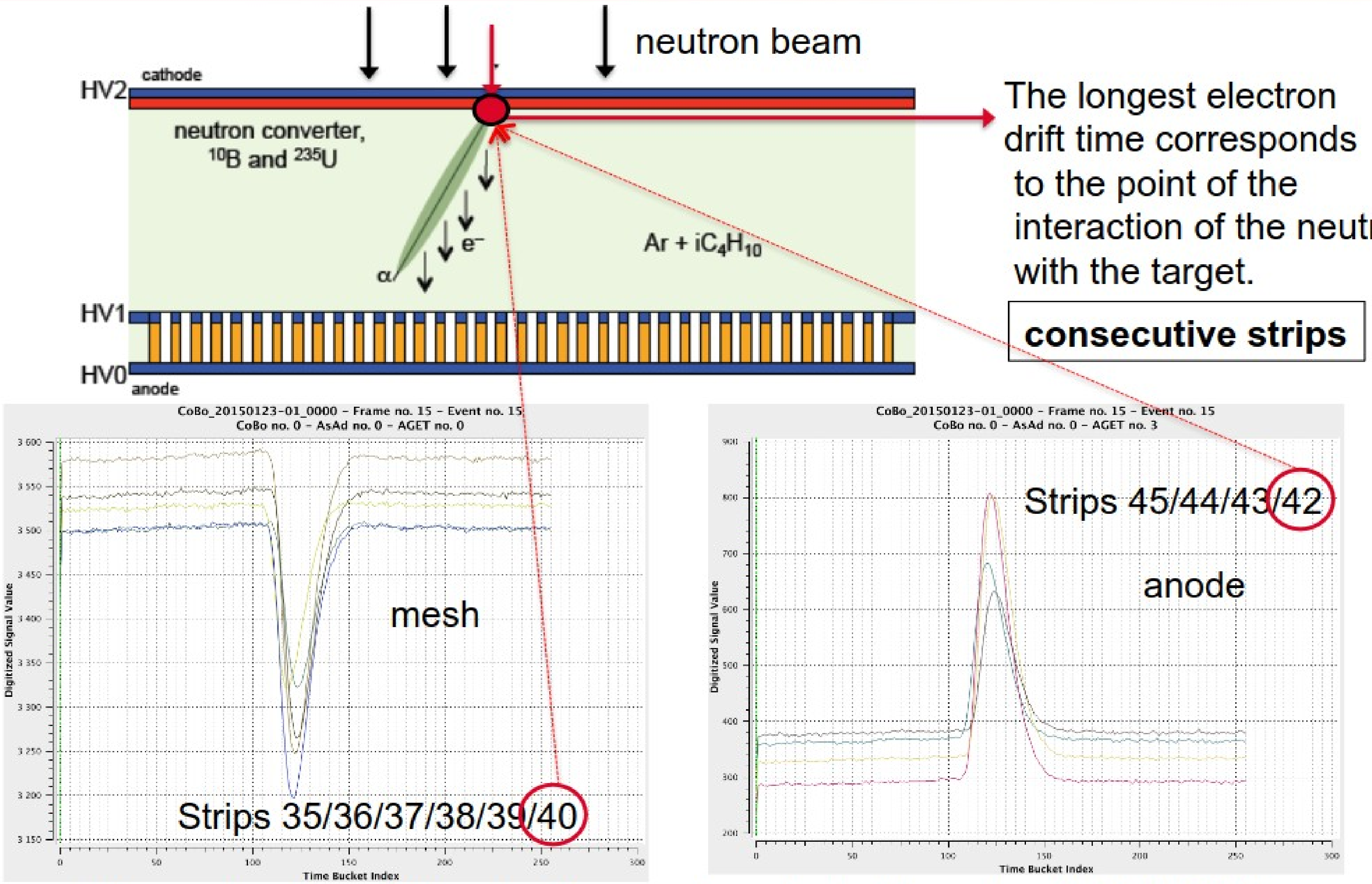
- n_TOF facility (CERN) (thermal-GeV)
- GELINA (IRMM) (1meV-20MeV)
- NFS (GANIL)

=>***Dependence of profile on the neutron energy***

Requirements:

- Quasi-online neutron flux + beam profiler as well
- Minimal perturbation of the neutron beam / Minimal induced background
- Stay permanently in the beam

PRINCIPLE OF NEUTRON BEAM PROFILER + MONITOR OPERATION



The longest electron drift time corresponds to the point of the interaction of the neutron with the target.

consecutive strips

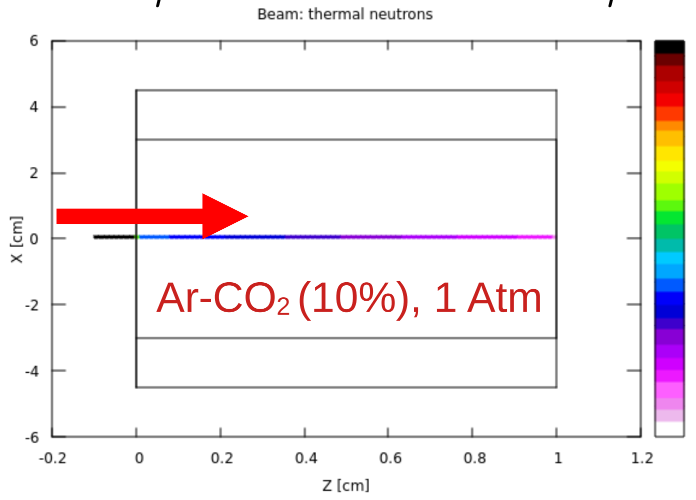
The neutron flux will be simultaneously extracted from the SUM SIGNAL.

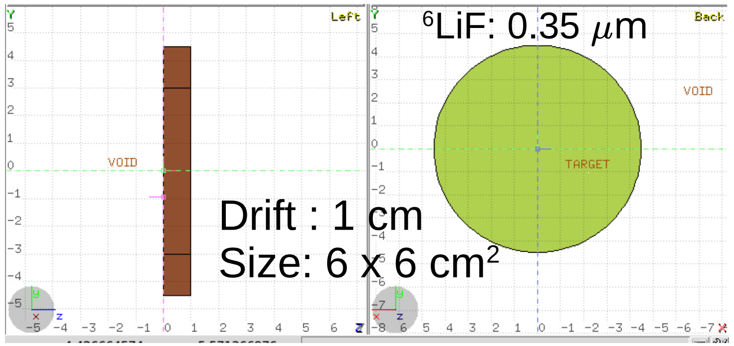
Basic set-up: approximation – alpha / triton yield FLUKA simulations

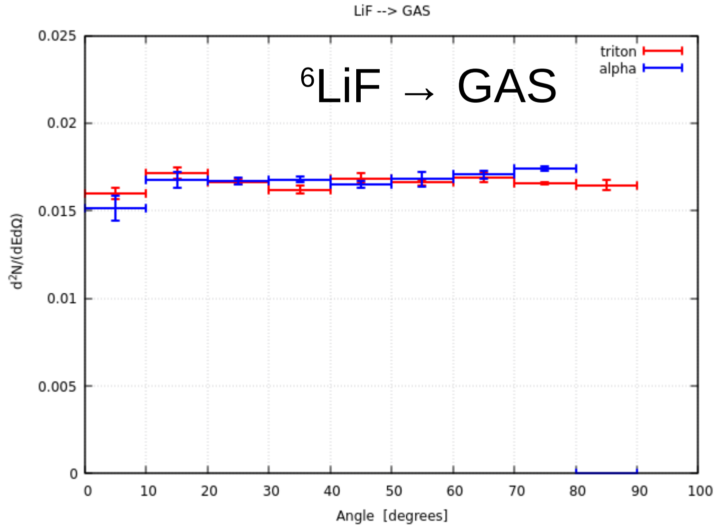
6 x 6 cm²

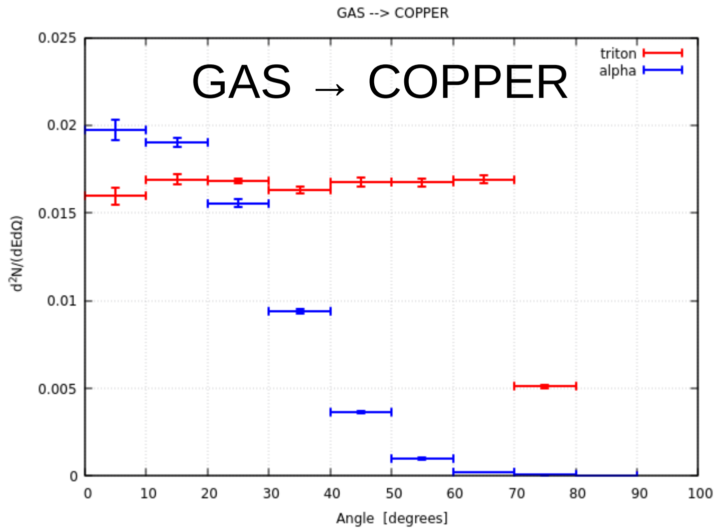
^{6}LiF: 0.35 μm

Cu: 5 μm









Frontiers in Physics 9, 788253 (2022).
Annals of Nuclear Energy 82, 10-18 (2015).
https://fluka.cern, https://flair.cern/

- Differential yield → solid angle in steradian
- Angles with respect of the beam direction (polar angles in degrees) and results normalized as double differential, expressed in [particles $GeV^{-1}sr^{-1}$/primary]

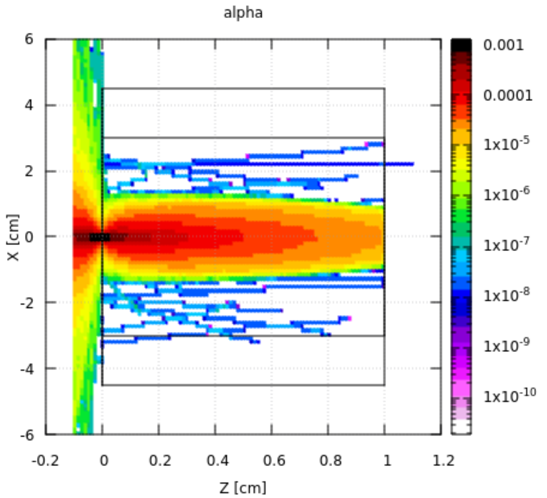
→ For a given neutron interaction point the direction the two capture fragments are emitted is isotropically distributed.
→ The detector response, depending on its geometry, will be different according to the particle ejection direction.
→ What is measured, when the detector is exposed to a point source, is an average over all the possibilities that results into a distribution with its own FWHM that defines the resolution due to the gas.

alpha / triton fluence FLUKA MC

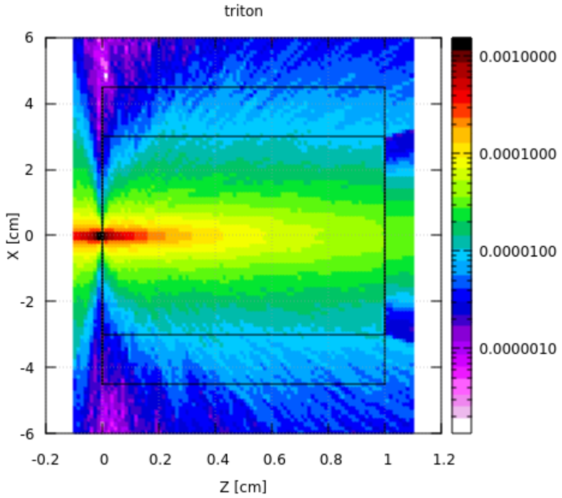
FLUKA vs GEANT4 : Energy deposition spectra

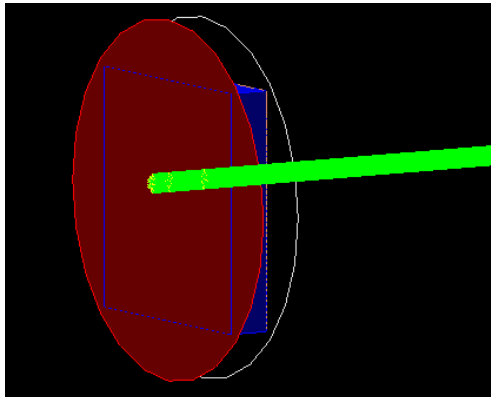
6 x 6 cm²

triton

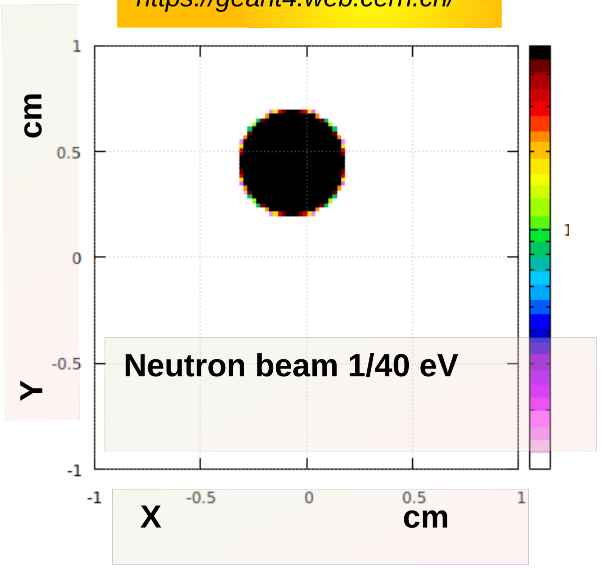


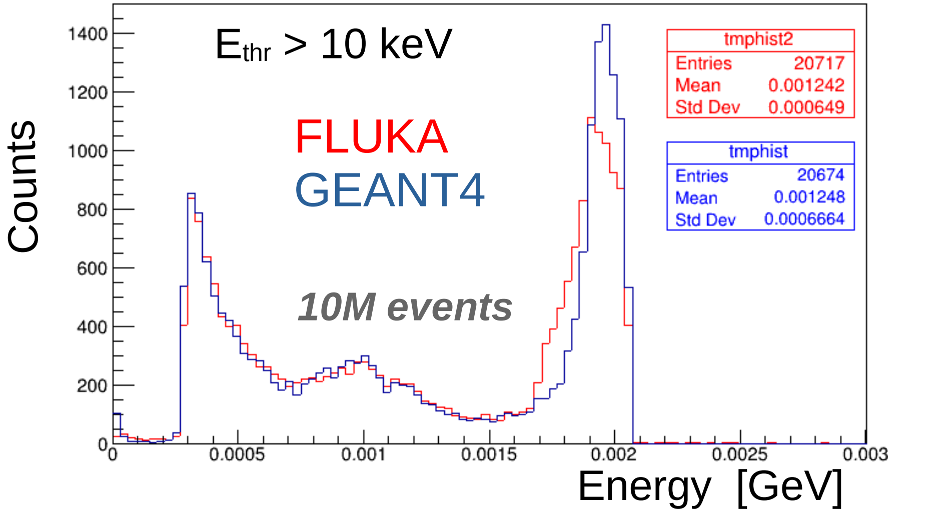
alpha

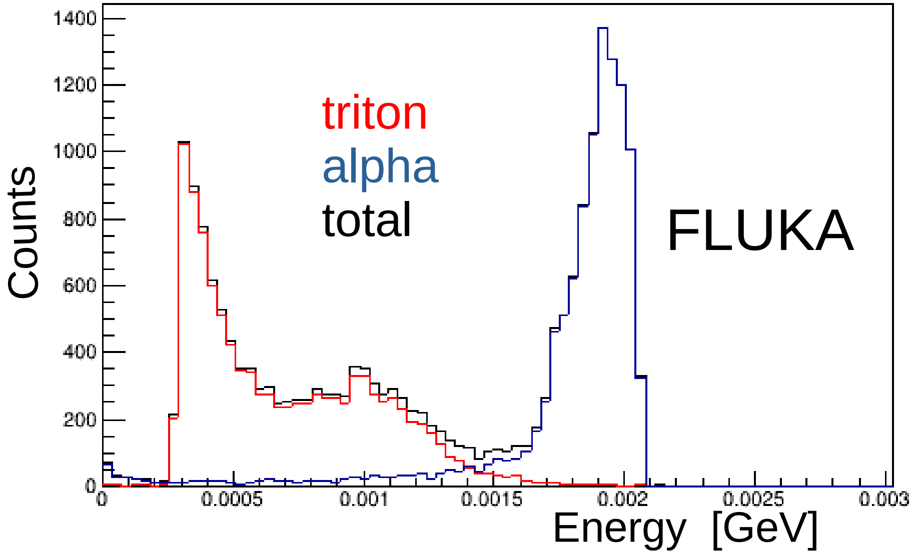




https://geant4.web.cern.ch/







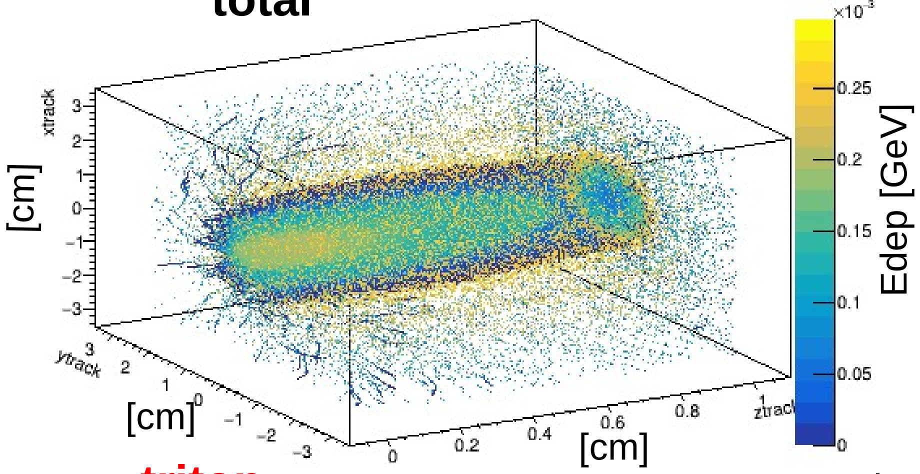
Energy deposition spectra

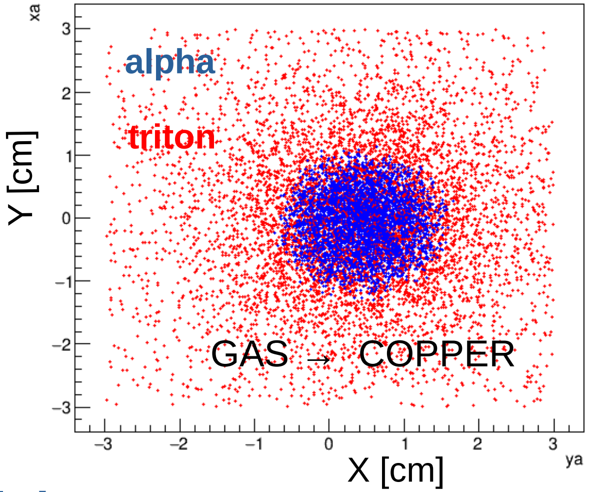
→ Track-length density in particles/cm² per primary

MGDRAW: Energy deposition hits – FLUKA simulations

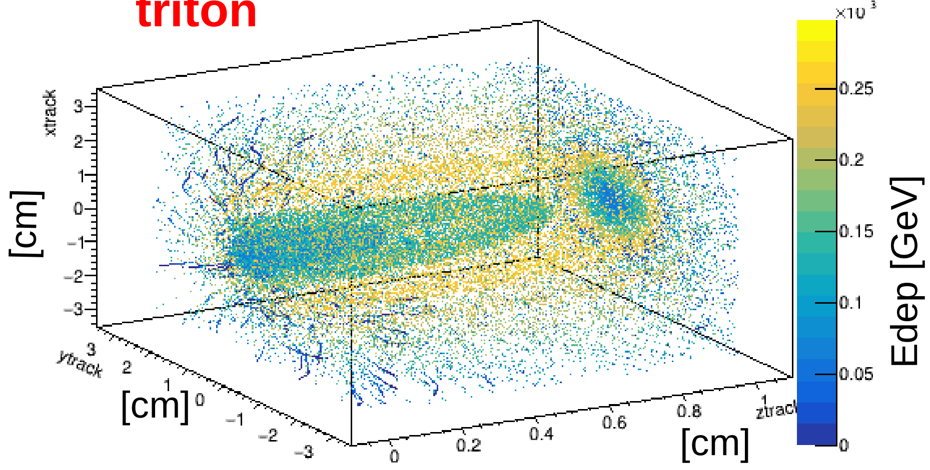
6 x 6 cm²

total

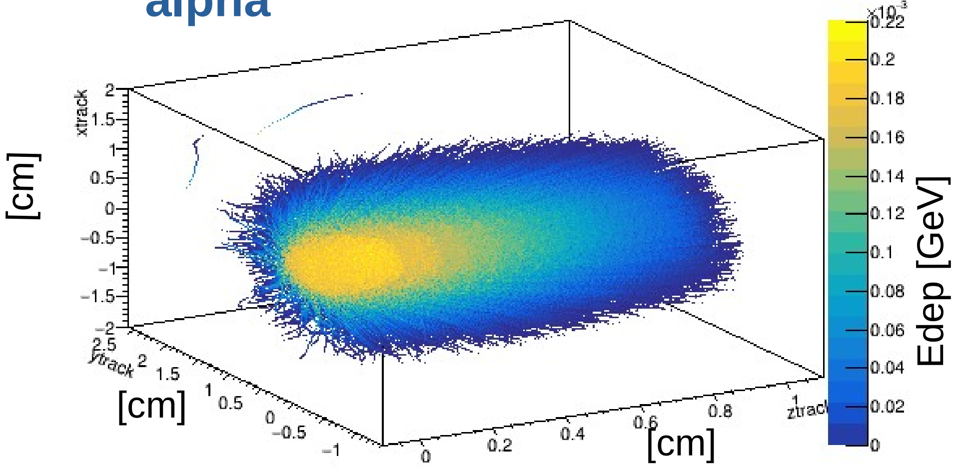




triton

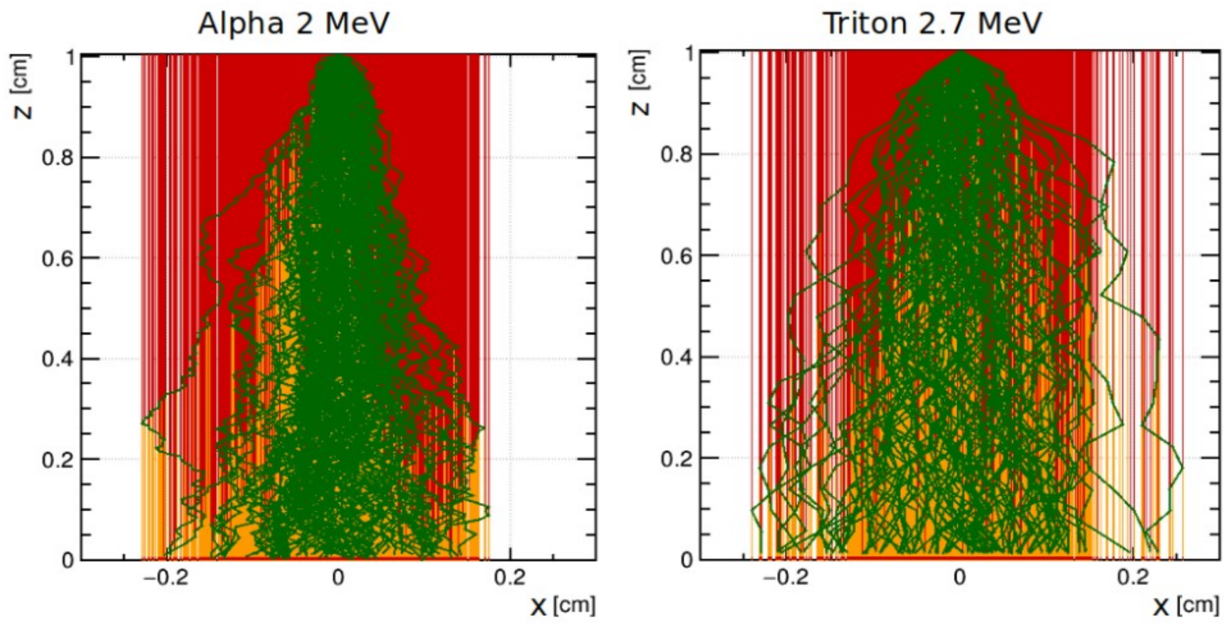


alpha



MC vs RKF in Garfield++

2D x-z projection of 100 tracks – RKF



- Generation of 200 vertical 2 MeV α-particles and 2.7 MeV tritons with Garfield++ with both methods
- Collection of simulated data for the deposited charge in the anode electrode (pad) using the RKF method
- The information for the energy loss for both ionizing particles is obtained by using the SRIM code (version: SRIM-2013.00)
- Load a file with the mobility of the ions in argon
- Then, retrieving the "clusters" along the track, the drift is simulated for each of the primary electrons
- The drift lines of the electrons released in the drift gap will stop once they hit the mesh plane
- Use of the MC method for evaluation of the spread of the arrival points of the electrons in the mesh and estimation of the magnitude of the diffusion

- 200 vertical tracks of 2 MeV α-particles and 2.7 MeV tritons were tested using both methods
- Both methods produce the same number of primary electrons that are ~ 152 / alpha track and ~ 24 / triton track, while The secondary electrons produced by the miscroscopic MC method are ~ 75.3 K / alpha track and ~ 11.6 K / triton track
- Are in perfect agreement with the expected quantities of electron—ion pair
- The standard deviations of the distributions of the arrival positions in the XY end plane of the primary electrons as well as of all electrons are almost equal
  → **Using the MC method but tracking only the primary electrons without the tracking of the secondaries**