MIMAC -35 cm: 3D-Directional Direct Detection for Dark Matter Search and Neutron Spectroscopy

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on behalf of the MIMAC collaboration

MIMAC (MIcro-tpc MAtrix of Chambers)

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- Data Acquisition: **T. Descombes**
- COMIMAC (quenching) **: J-F. Muraz**

CCPM (Marseille): C. Tao, J. Busto

IRSN- LMDN (Cadarache): M. Petit, T. Vinchon (neutron spectroscopy)

IHEP (Beijing-China): Wang Zhimin
USTC (University of Science and Technology of China, Hefei): Zhang Zhiyong
SJTU(Shanghai Jiao tong University): Wang Shaobo, Han Ke, Zhou Ning, Tao Yi
TSINGHUA University (Beijing-China): Yue Qian (China JinPing underground Laboratory (CJPL) director)
SHAO(Shanghai Astronomical Observatory): Shan Huan Yuan

Outline

- Introduction
- MIMAC detector and performance
  - Normal PCB to low background one
  - Towards MIMAC-35cm
- Next steps
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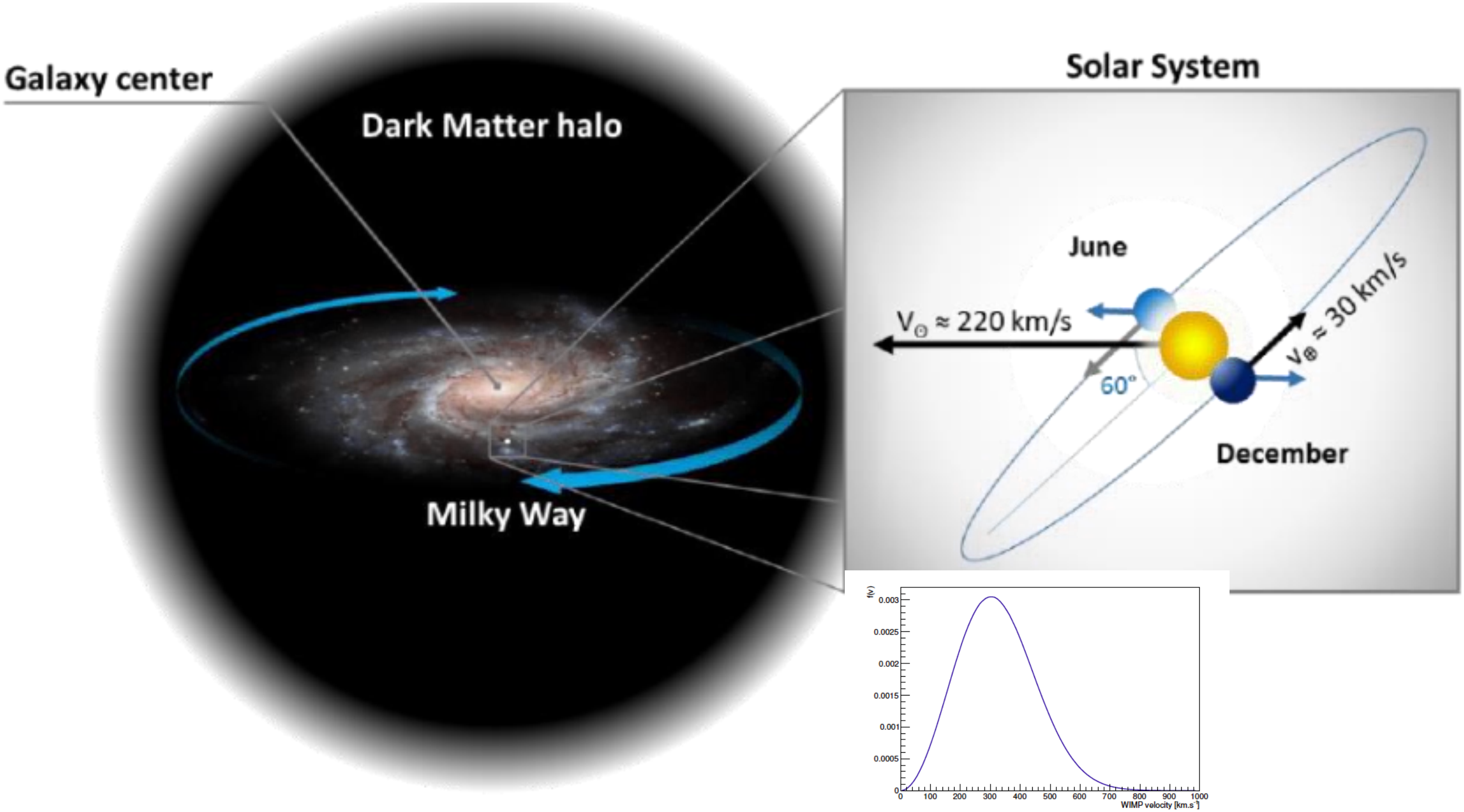
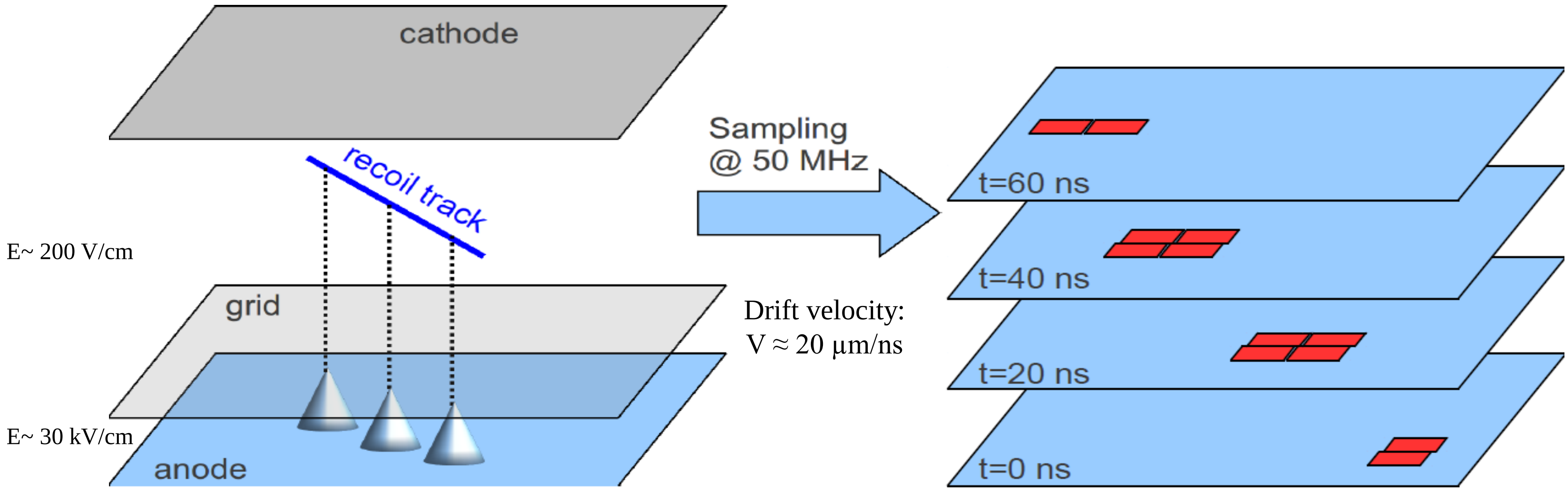
Dark Matter Directional detection principle



The only signature able to correlate the rare events in a detector to the DM galactic halo !!

MIMAC: Detection strategy

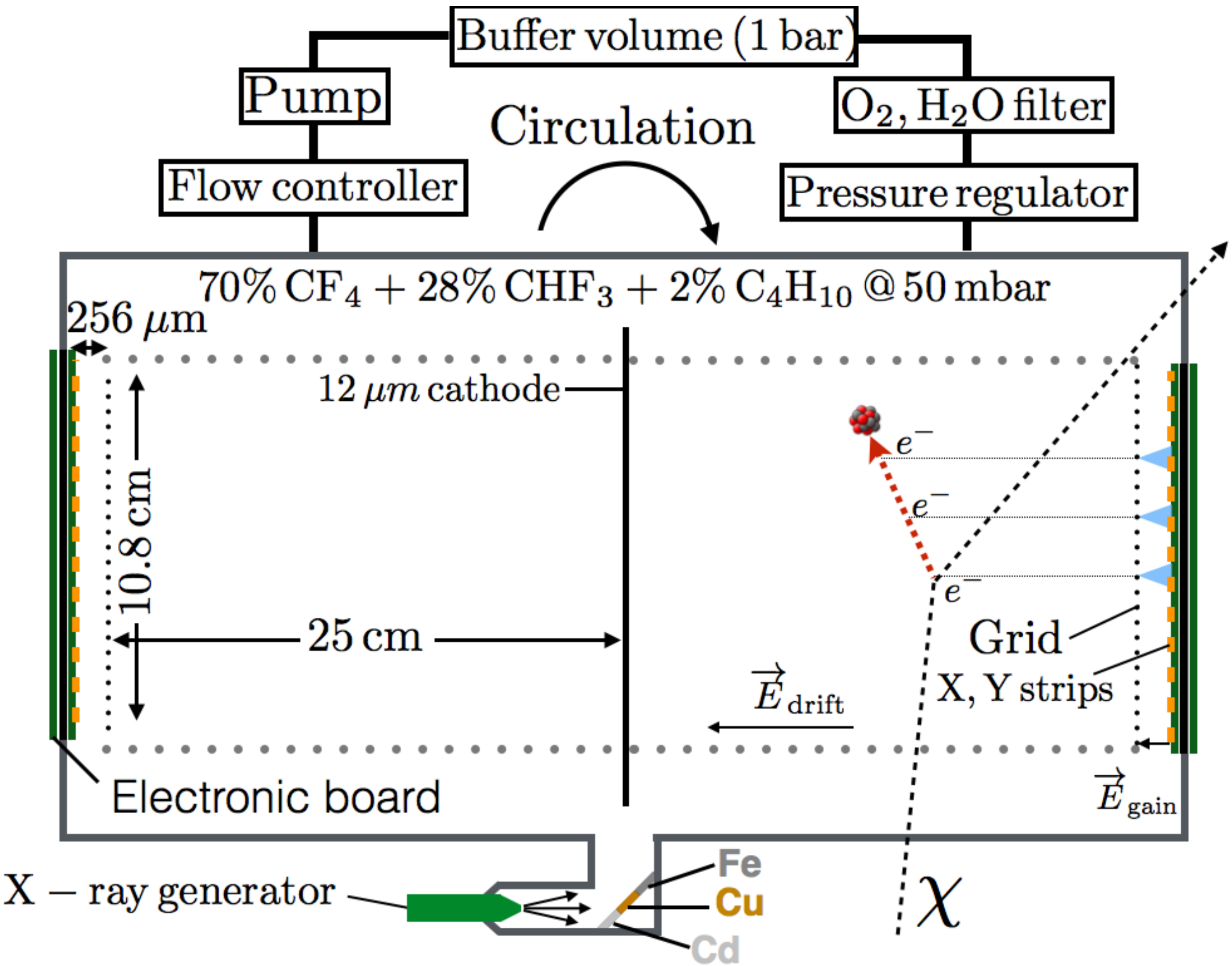


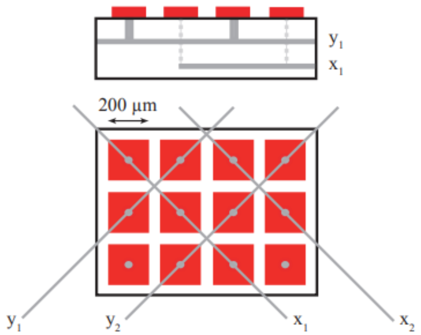
Scheme of a MIMAC µTPC

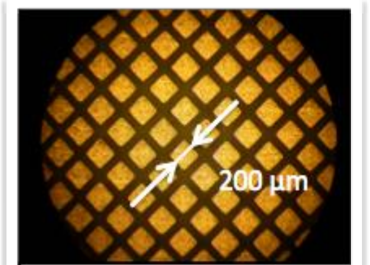
Evolution of the collected charges on the anode

Grid signal for deposit energy and pixelated anode for 3D track measurements

MIMAC-10cm-bi-chamber module prototype







Micromegas 10x10 cm², designed by IRFU- Saclay (France)

MIMAC Target: ^{19}F

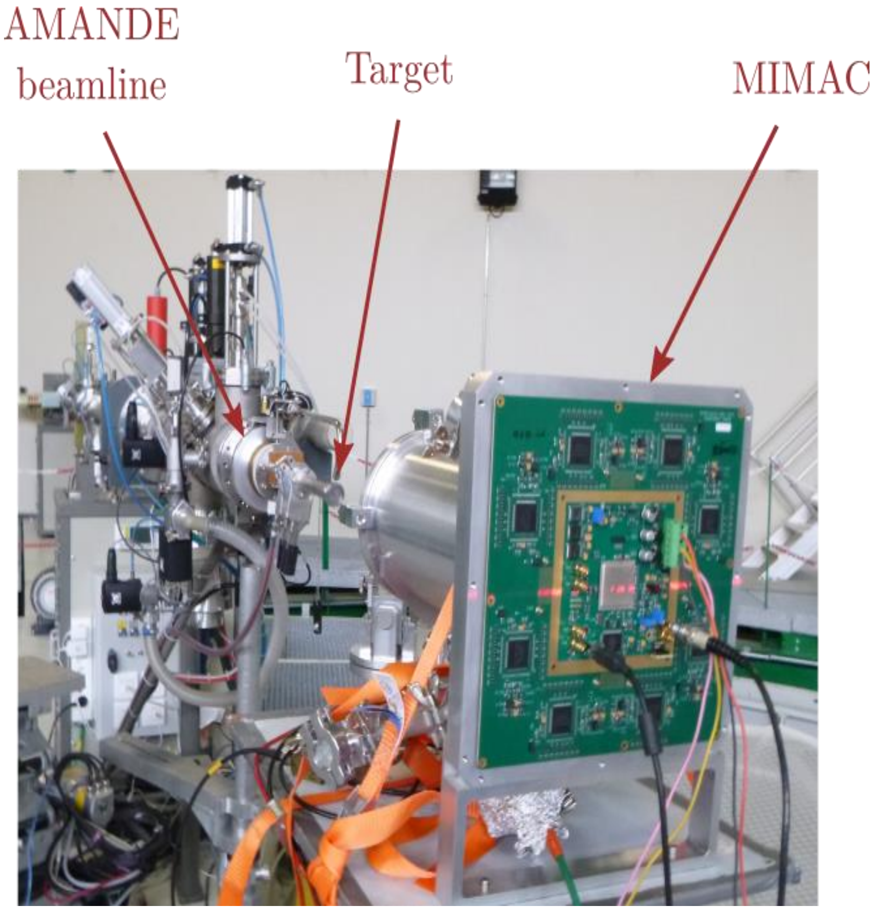
- Light WIMP mass
- Axial coupling

AMANDE facility

- The AMANDE facility (IRSN-Cadarache) provides mono-energetic neutron fields production between 2 keV and 20 MeV

- The energy of the mono-energetic neutron field is defined by the angle of **each nuclear recoil** track with respect to the neutron direction

V. Gressier et al., *AMANDE: a new facility for monoenergetic neutron fields production between 2 keV and 20 MeV*, Radiat. Prot. Dosimetry **110** (2004) 49.



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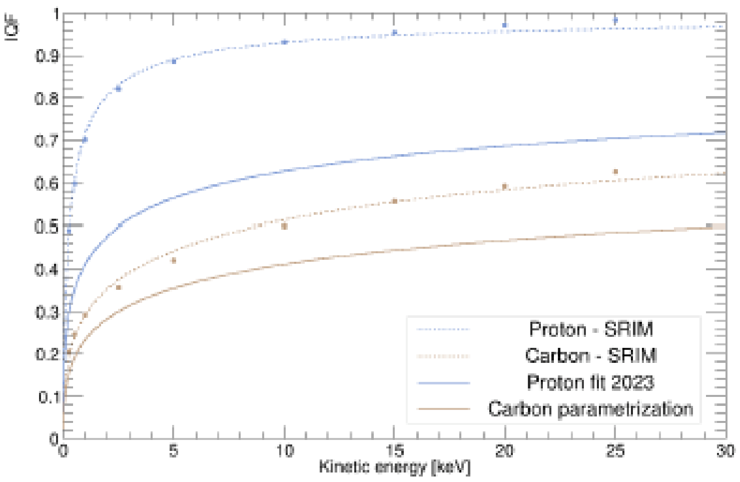
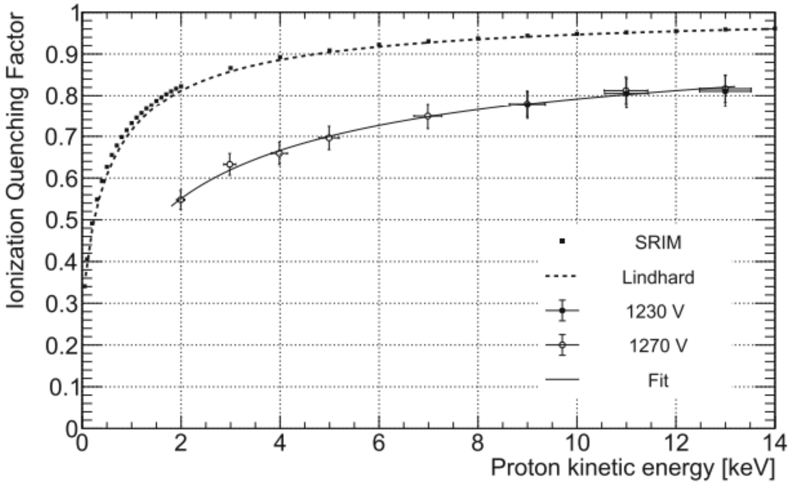
Quenching factor measurements





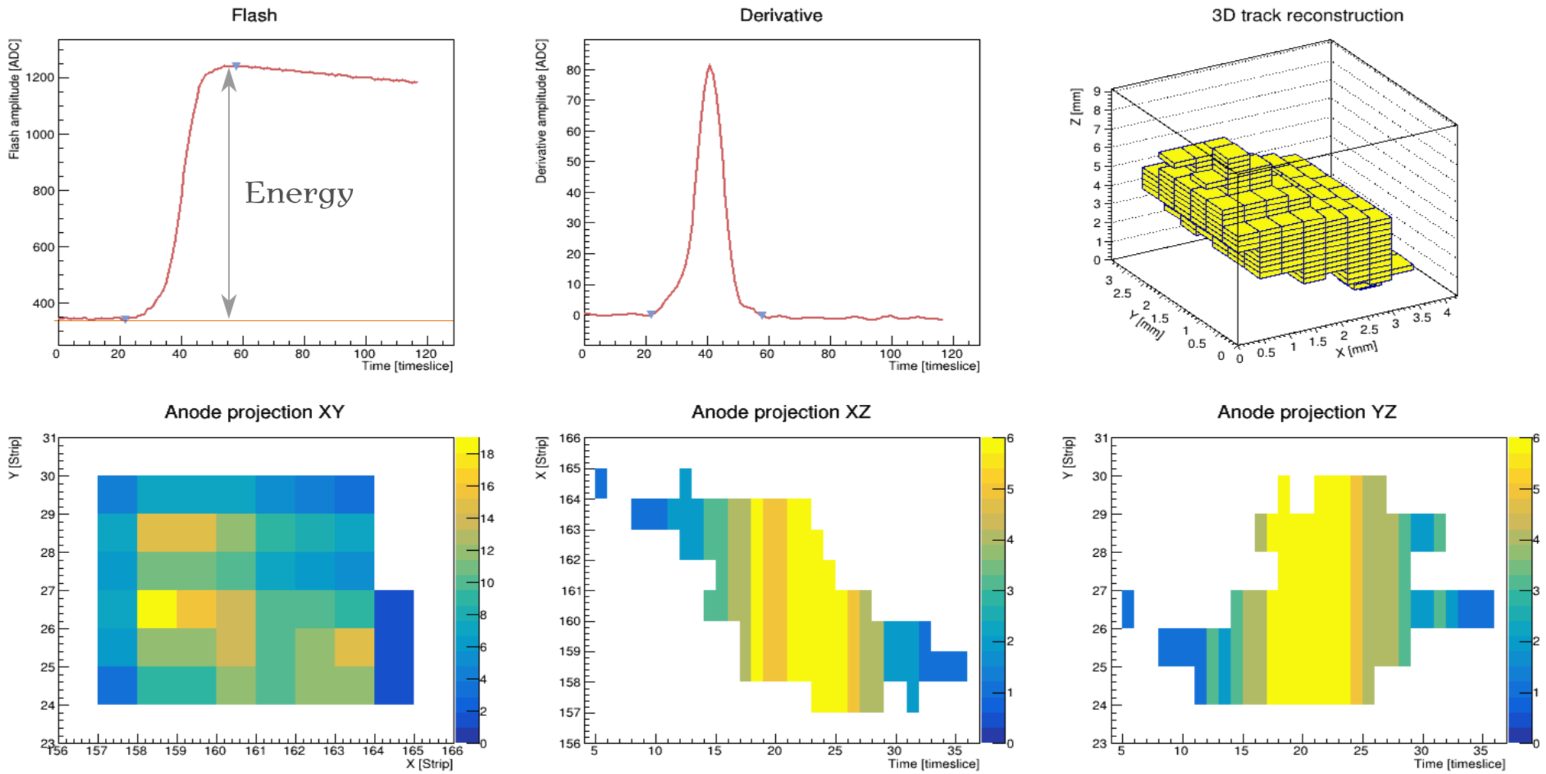
Ionization Quenching Factor for protons in 100 mbar of methane.

The IQF (Ionization Quenching Factor) Measurements performed with the COMIMAC facility (left picture)

An important paper showing these differences with respect to simulations is : arXiv:2201.09566. Measurements of the ionization efficiency of protons in methane (NEWS-G collaboration)

Example of a proton recoil of 6 keV_{ee} (8.6 keV_{nr})

$i\text{-}C_4H_{10}$ + 50% CHF_3 at 30 mbar – → Sampling at 50 MHz (20 ns)

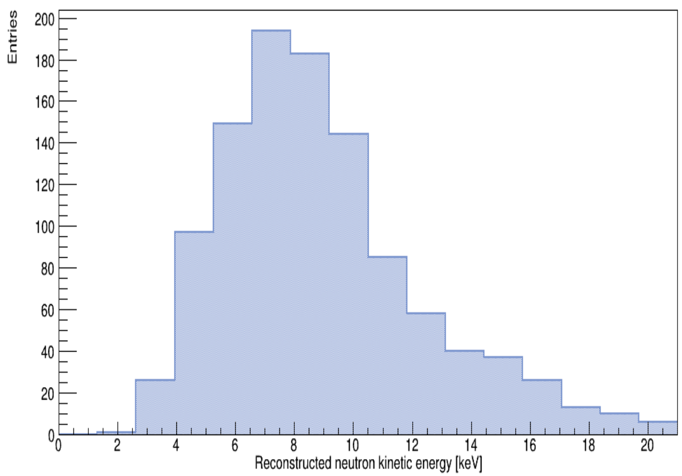


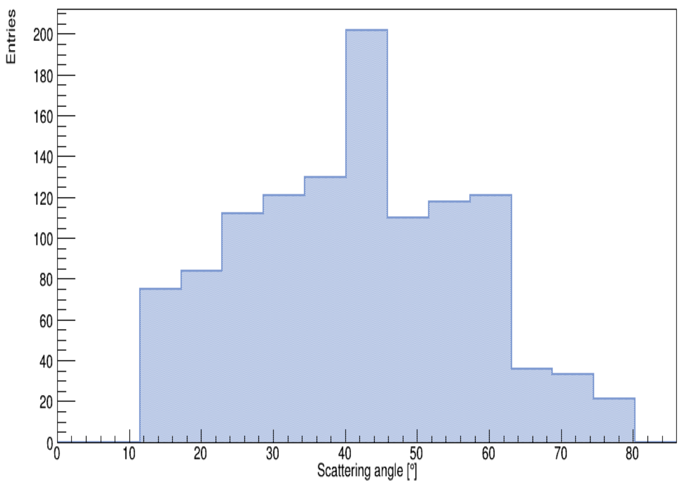
- A proton recoil of 8.6 keVnr obtained by elastic scattering from a 27 keV.
- The Flash mesh signal is presented in the upper left plot.
- The 3D track reconstruction on the upper right plot is obtained from the combination of the measurements on the pixelated anode presented in the lower panel of the figure.

Neutron spectroscopy

The kinetic energy is reconstructed with :

- the Ionization quenching factor measured by COMIMAC
- understanding the ion contribution to the signal





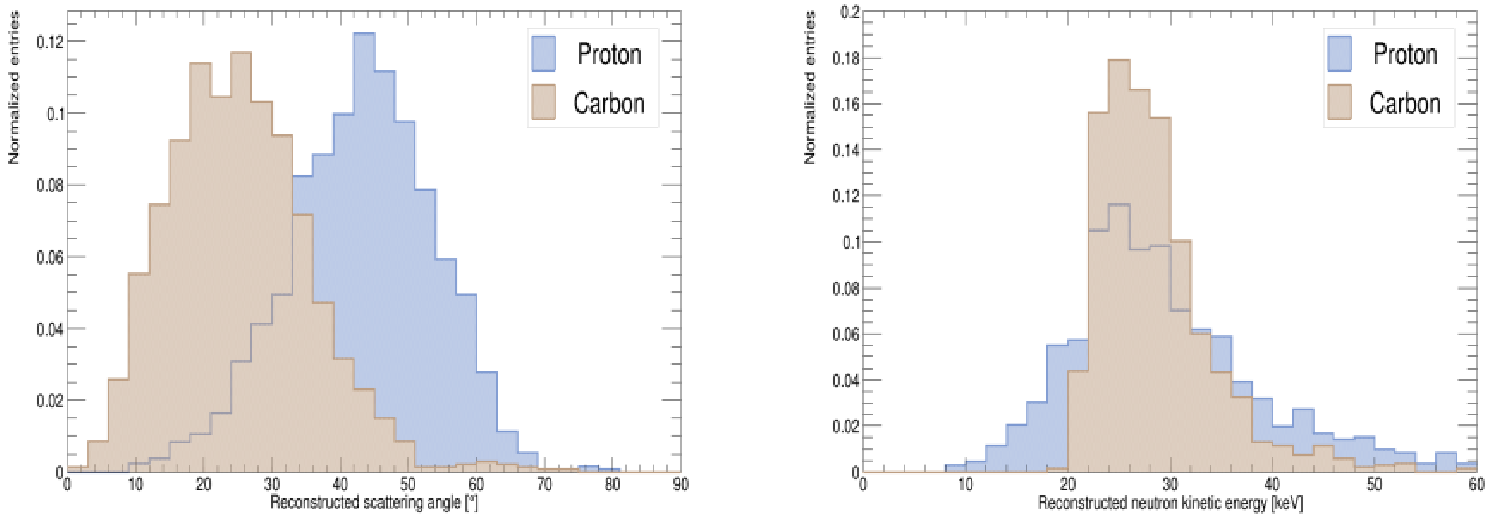
Mono-energetic neutron field (8 keV)， Neutron spectrum reconstruction from proton recoils
Energy reconstructed agrees within 4.0% and angular resolution better than 15◦

Cyprien Beaufort et al. JCAP08(2022)057

Neutron spectroscopy

At 27 keV neutron field

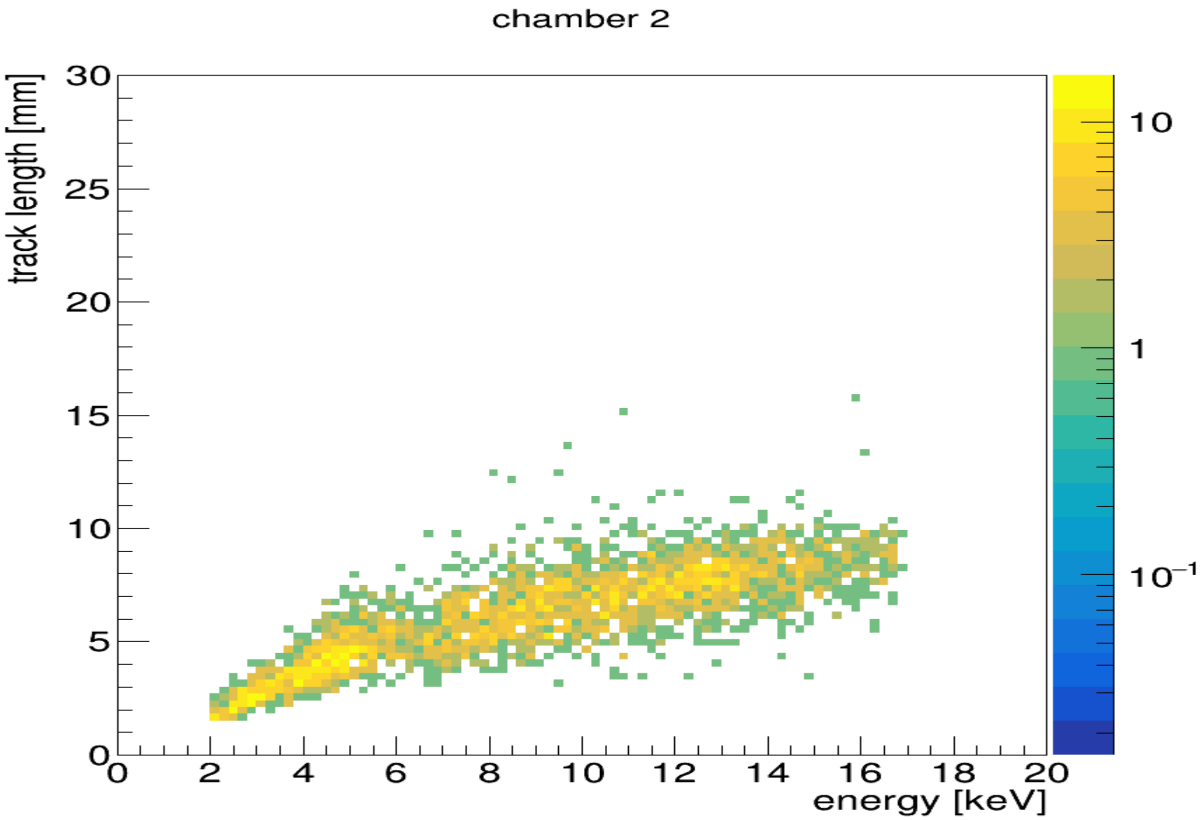
Proton and carbon recoils give the neutron spectra



C. Beaufort *et al* 2024 *JINST* **19** P05052

Proton recoil track lengths

Proton recoil track lengths (produced by a mono-energetic neutron field of 27 keV) as a function of their ionization energy



These H+ recoils are very useful in characterizing the nuclear recoils searched for DM detection

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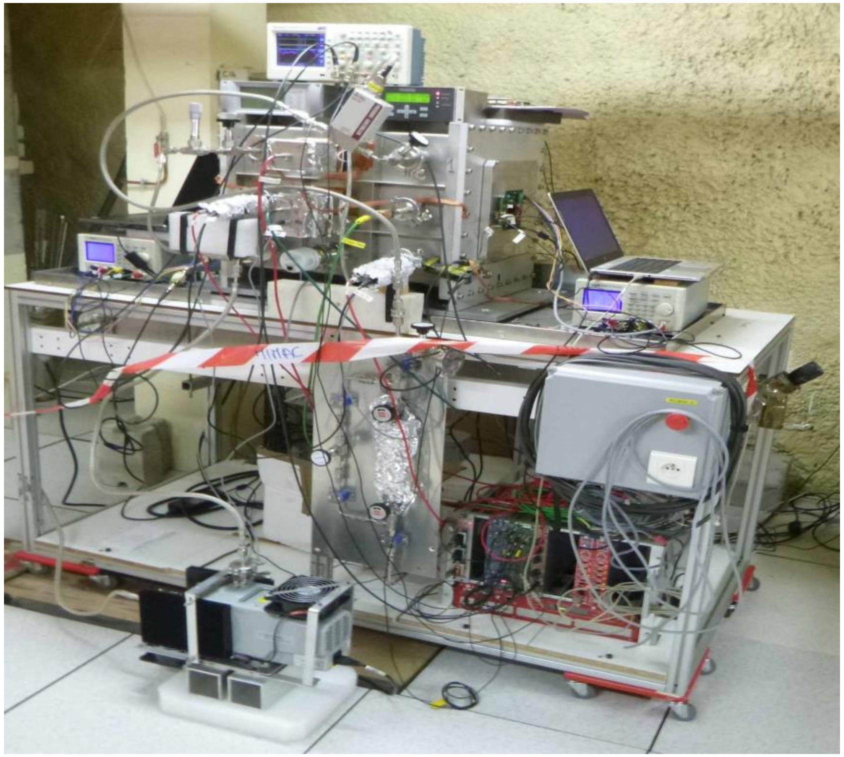
MIMAC-10cm low background prototype

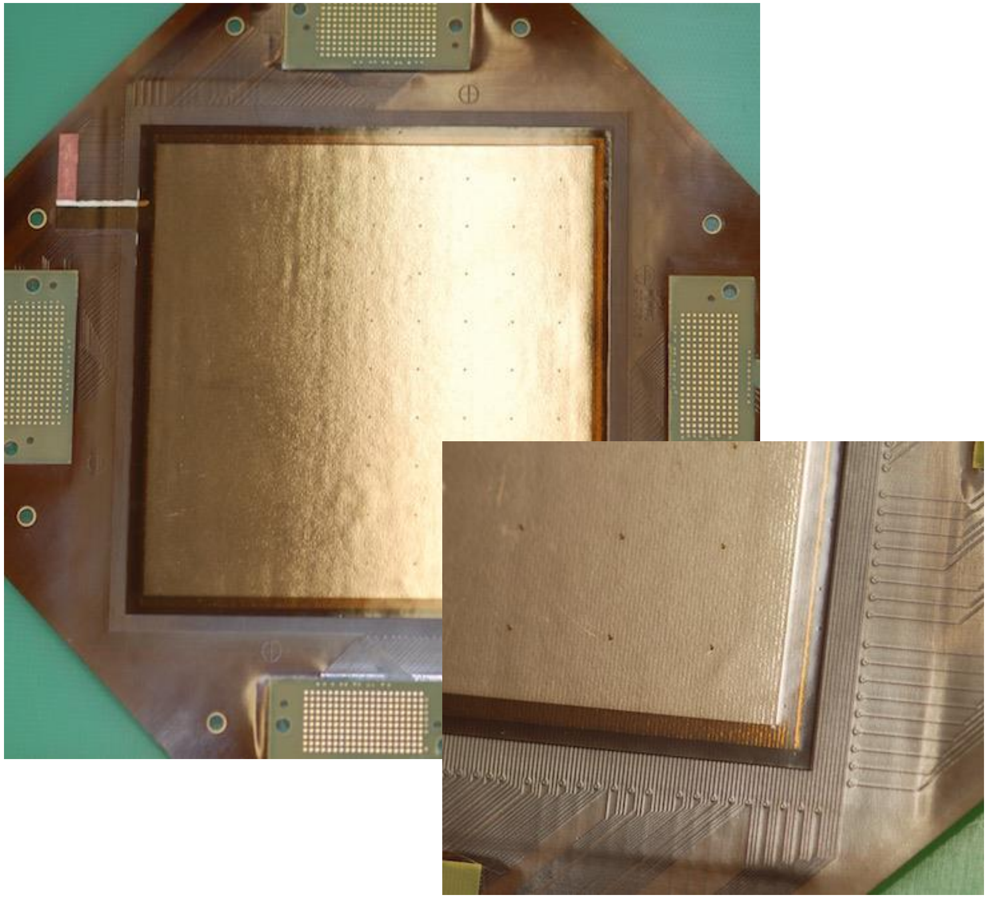
Bi-chamber-512 module
(with the Cathode Signal and
the new low background 10 cm detectors)

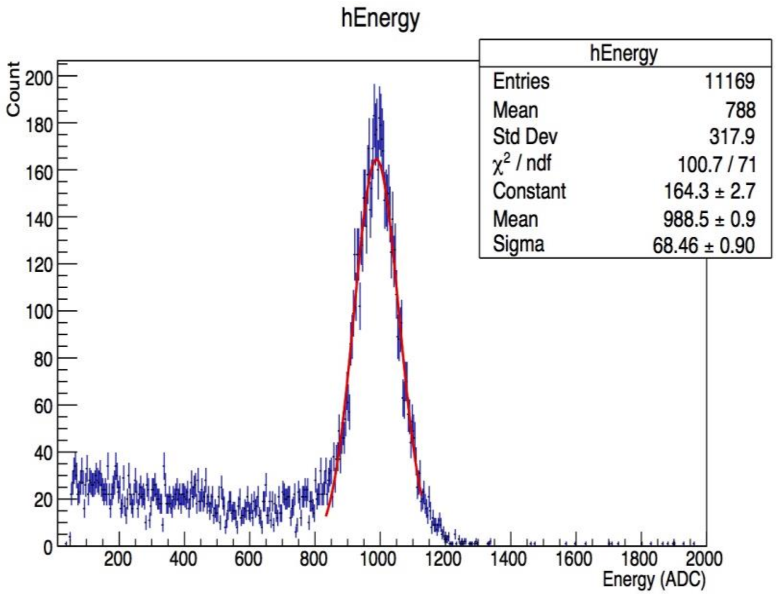
Installed in February 2023



- working at 30 mbar (i-C_4H_{10}+50% CHF_3)
-Permanent circulating mode
-Remote controlled and commanded
- A periodic calibration by an X-ray generator

Test with X-rays





Kapton micromegas readout
Piralux Pilar

Gaz : MIMAC 50 mbar
HT grille : -560 V
Drift field : -150 V/cm

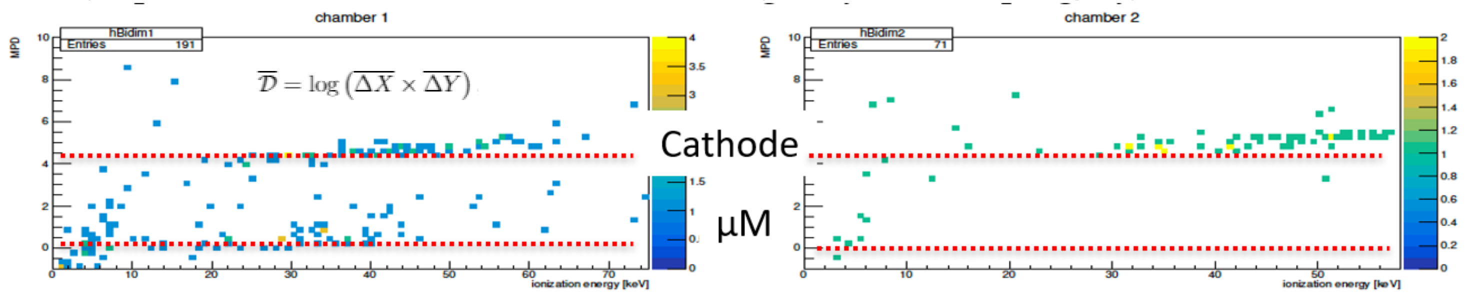
16,3 % FWHM (6 keV)
Gain ~25 000
Energy threshold <1 keV

First physics run and background rejection

The first physics run in february 2023 at Modane

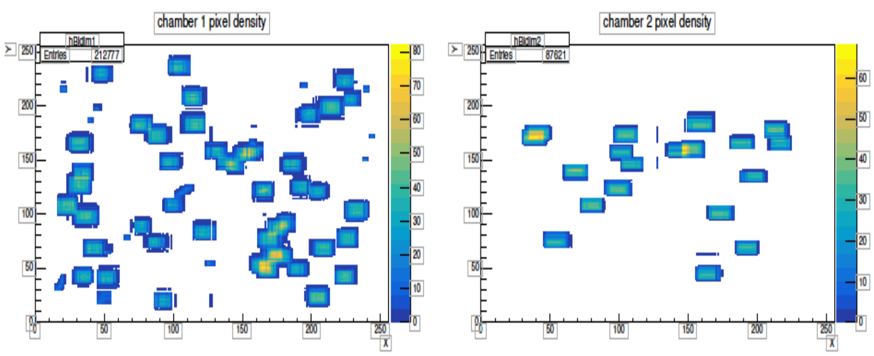
Chamber 1(nomal detector)- Chamber 2 (low background detector)

- 127 h analysed at moderate gain (470 V)
- Only recoils after the BDT selection, mainly from the Rn progeny.



(a) In chamber 1. (b) In chamber 2.

Mean Projected Diffusion (MPD) as a function of the energy in the background selection using the BDT at Modane



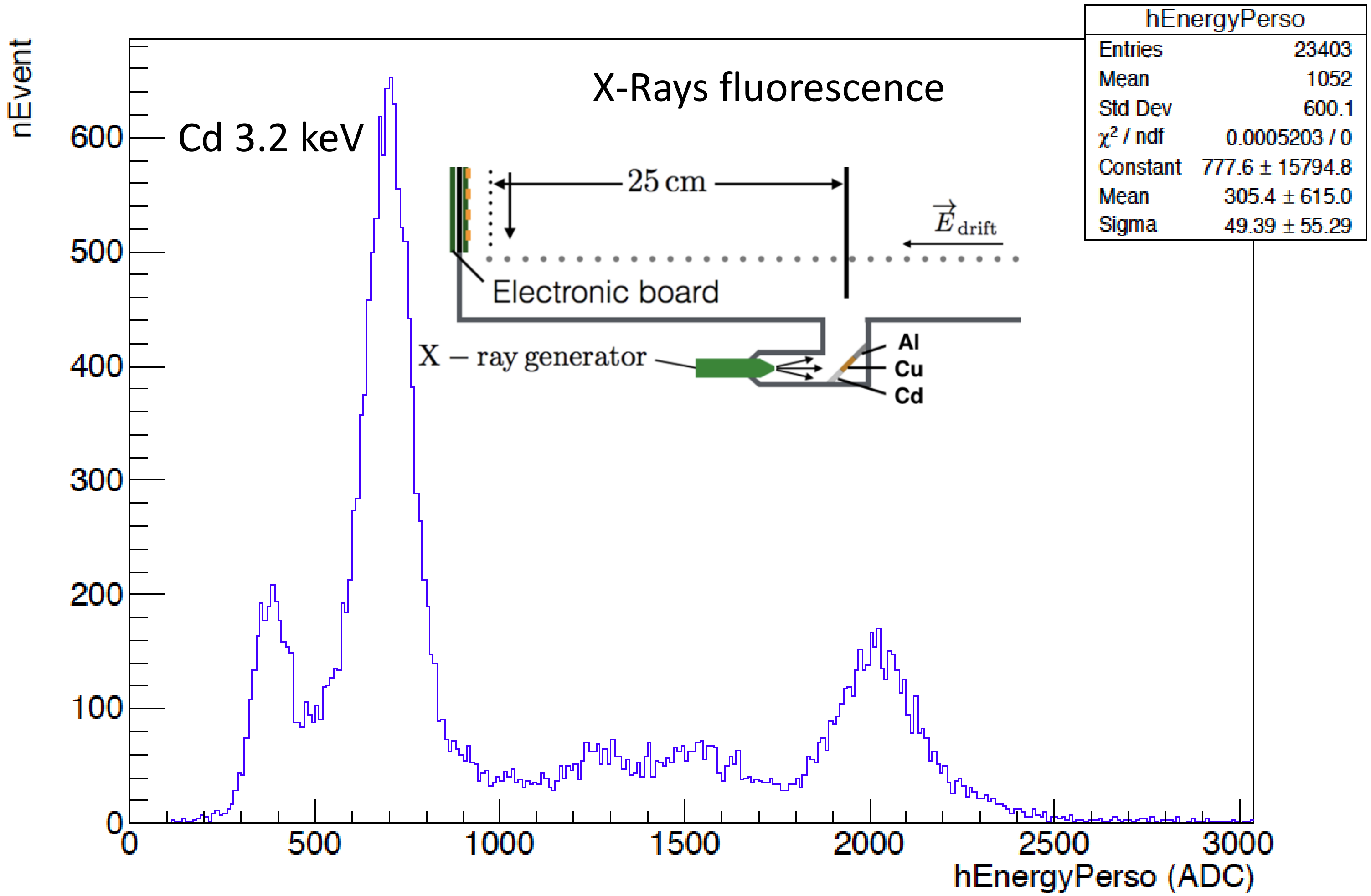
(a) In chamber 1. (b) In chamber 2.

X-Y projections of the 3D tracks

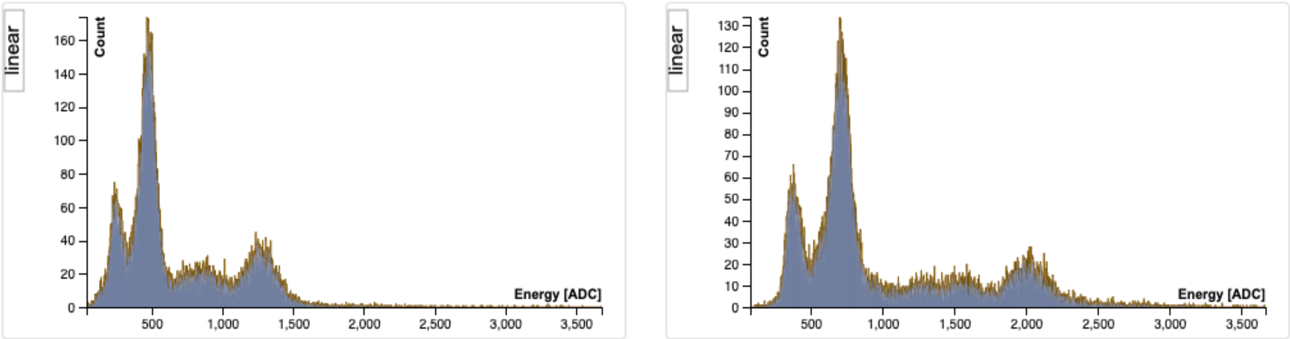
Improvement of the new detector showing very few Rn progeny contributions

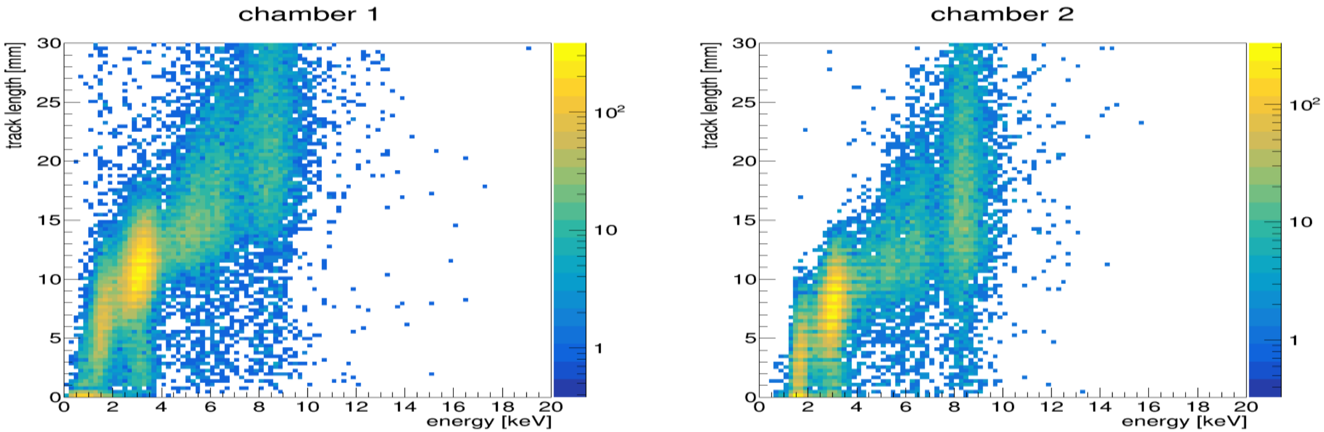
X-ray Calibration

X-ray Calibration of the new detector Bi-chamber Module at 500 V, 3000V drift



Electron track lengths





Track lengths as a function of their energy

These are very useful in the electron vs. nuclear recoil discrimination

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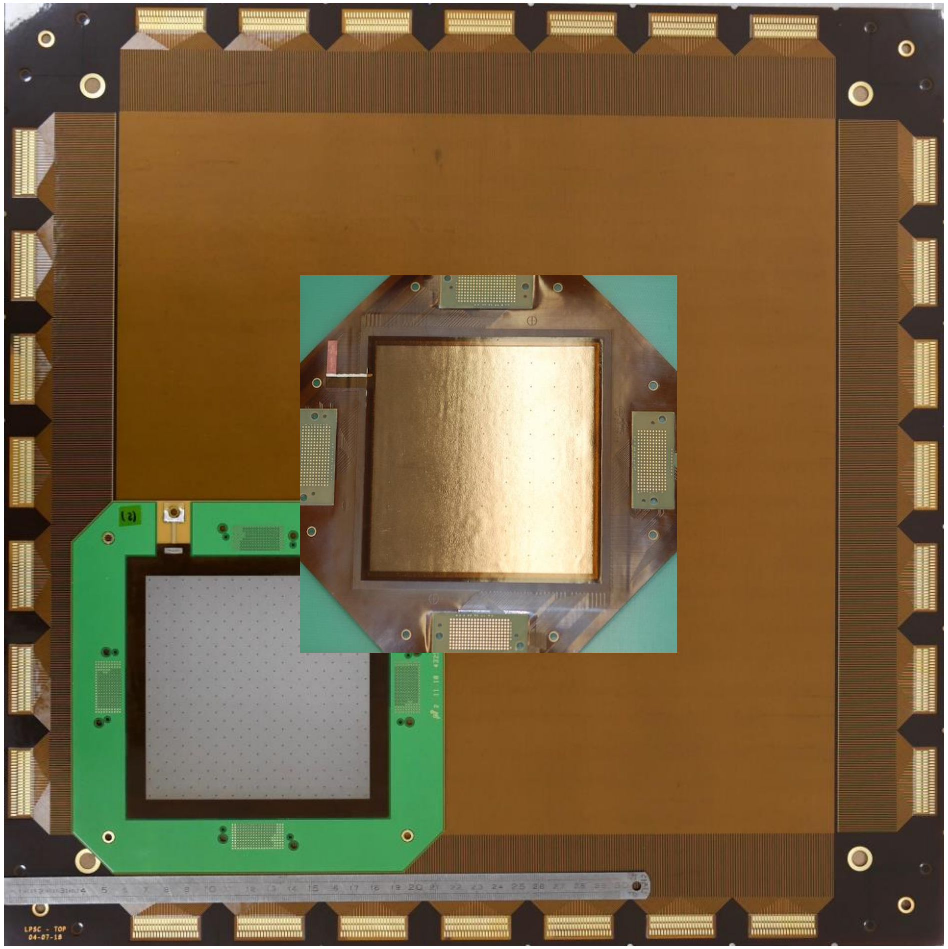
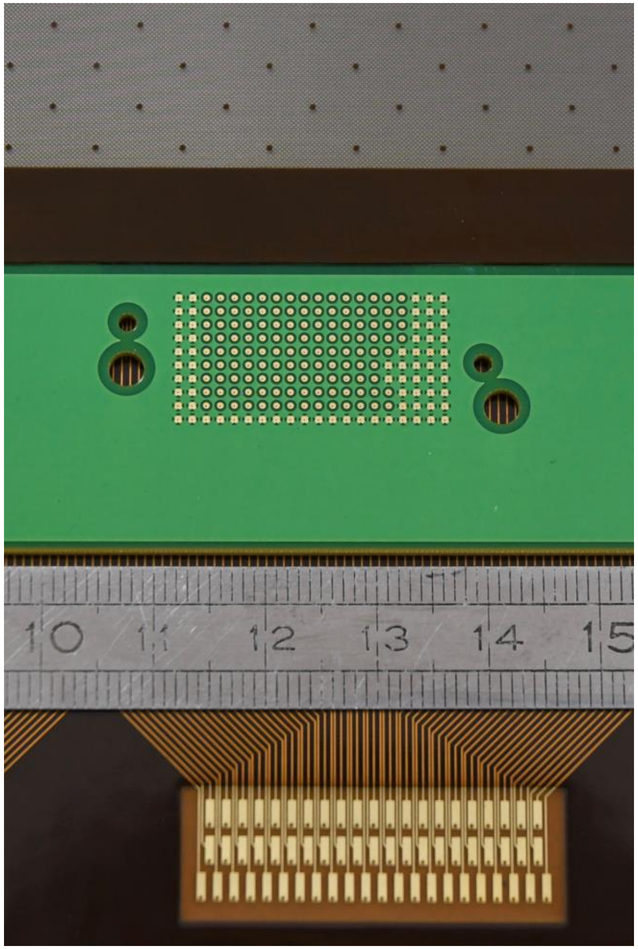
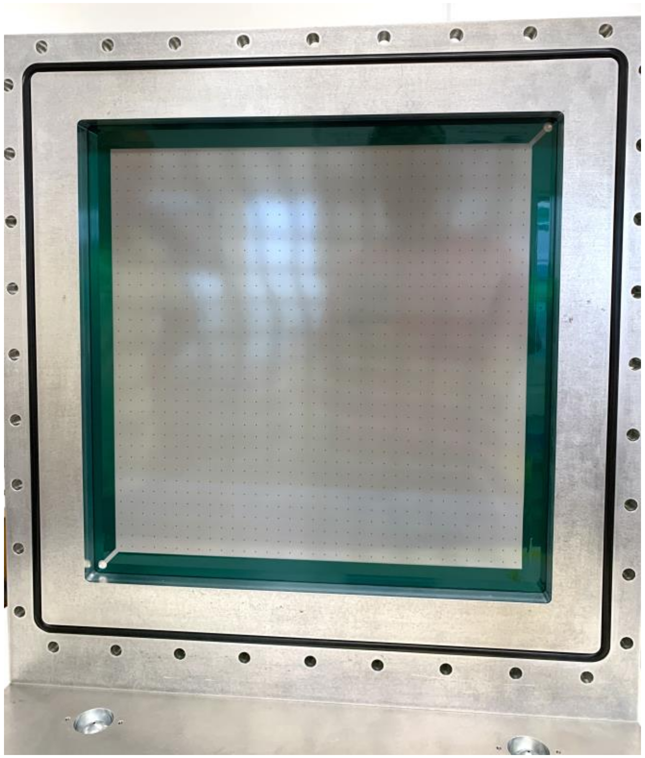
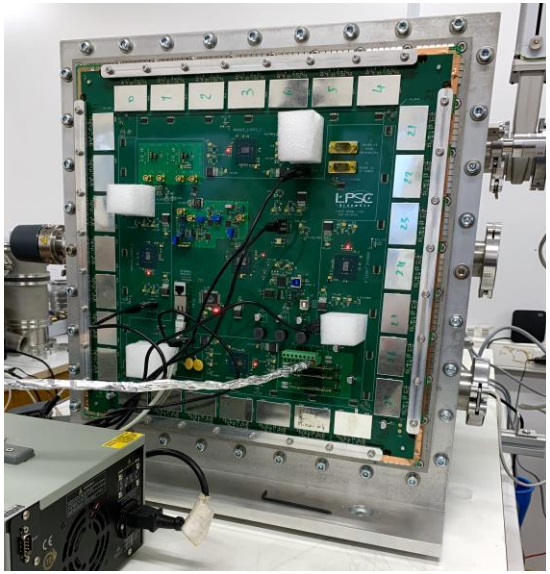
Toward large area detectors

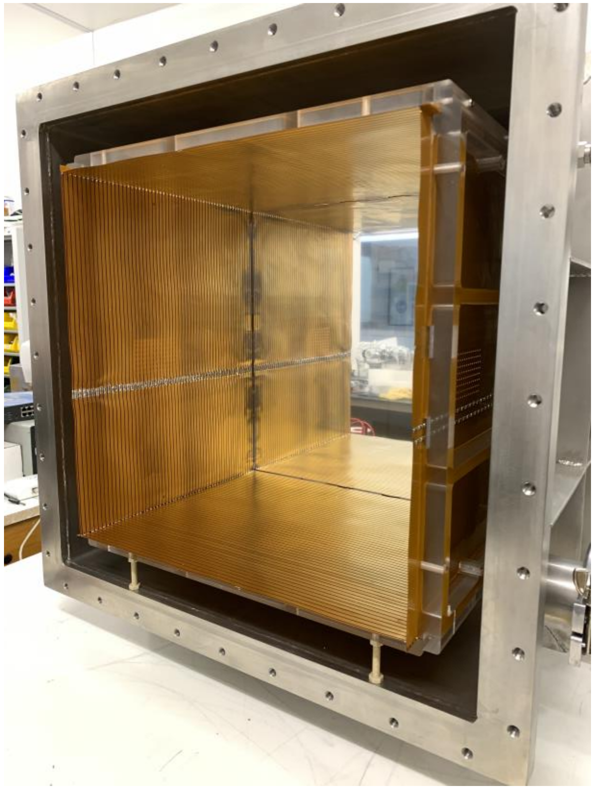




The 35cm detector (FR-4 normal PCB)





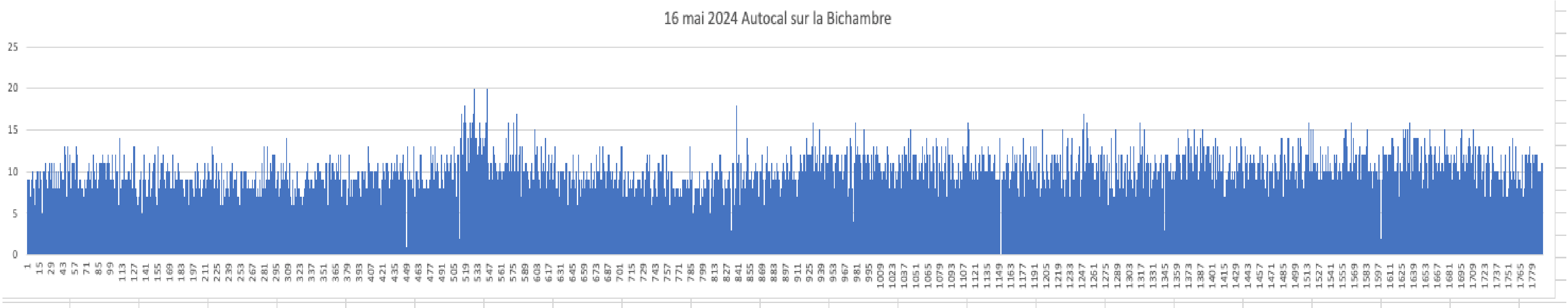


The MIMAC-35cm field cage

It is mounted in the bi-chamber at the LPSC-Grenoble

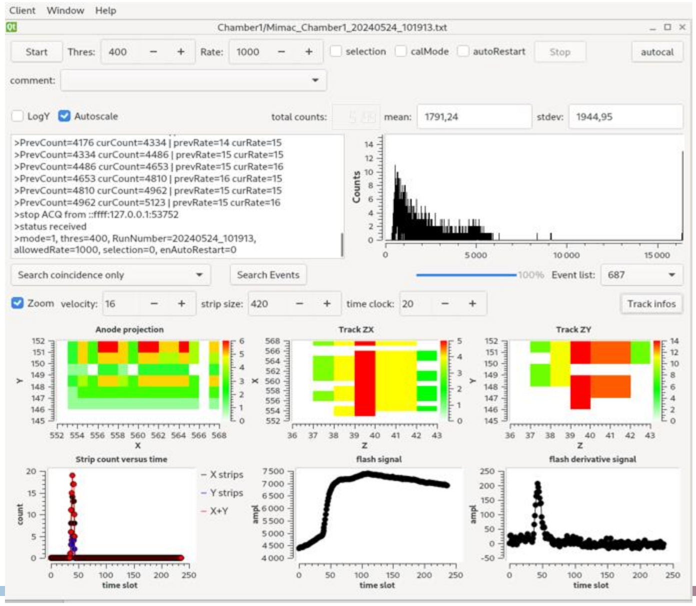
Channel calibration

AUTOCALIBRATION OF THE 1792 (896 + 896) CHANNELS



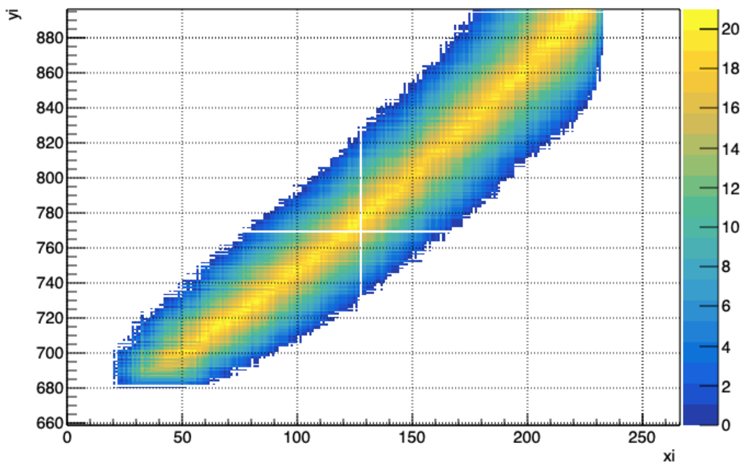
1792 threshold values from the autocalibration defined by the intrinsic electronic noise on each strip.

The first event with 3D track, of the background at Grenoble (May 24th 2024)



Trigger from the Mesh
~ 300 eV threshold

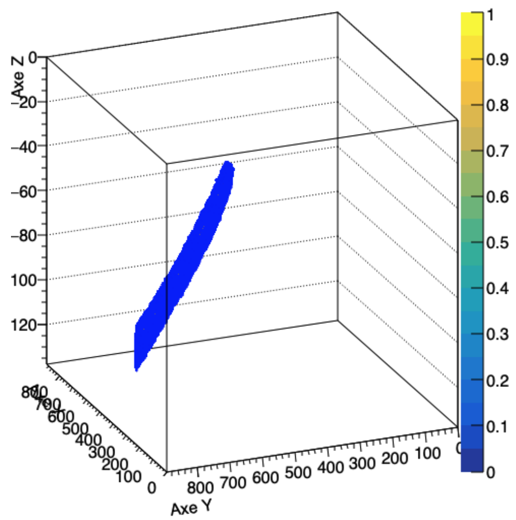
An alpha event from Rn…



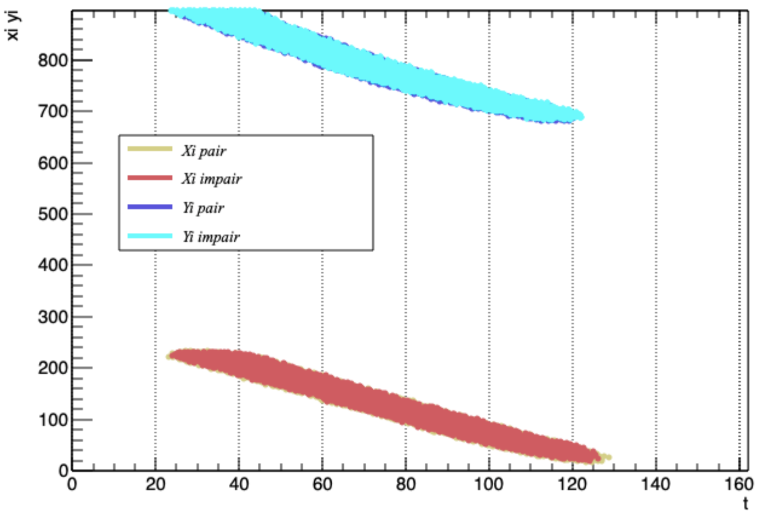
Exploring a large portion of the pixelated anode

Only 2 dead Channels over 1792

X-Y projection



X and Y as a function of time
Every 20 ns

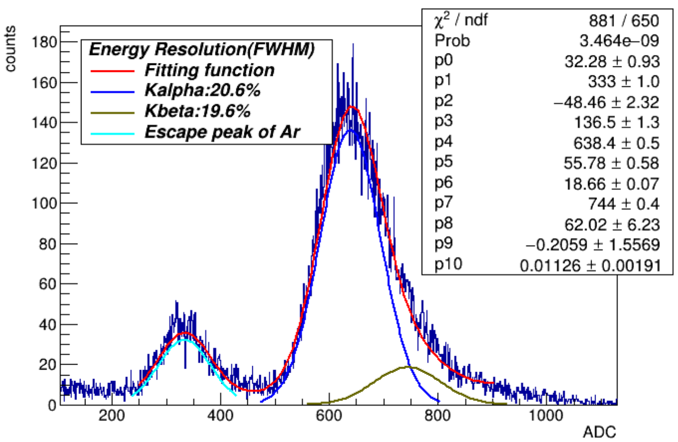


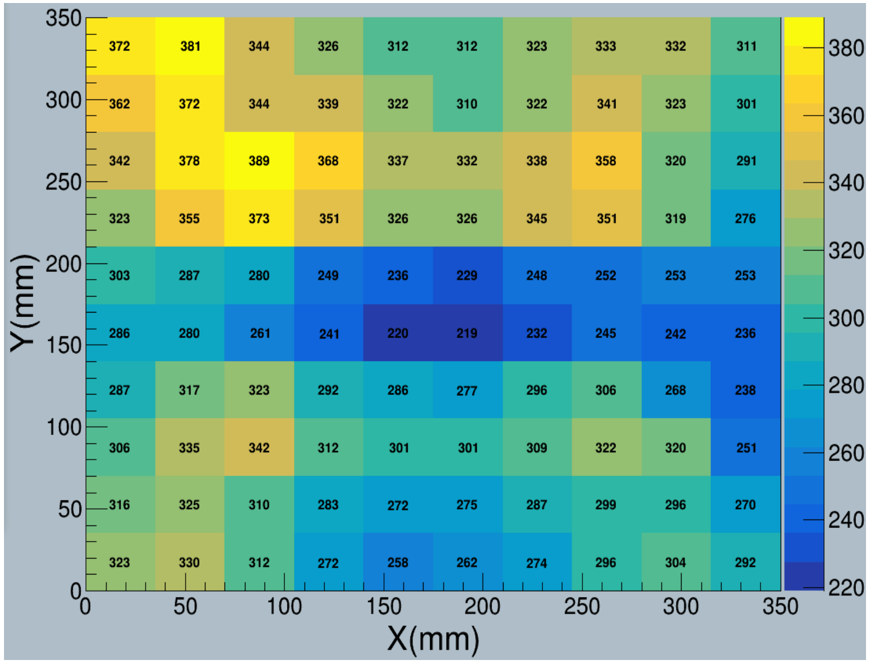
The 35cm detector (Kapton PCB)

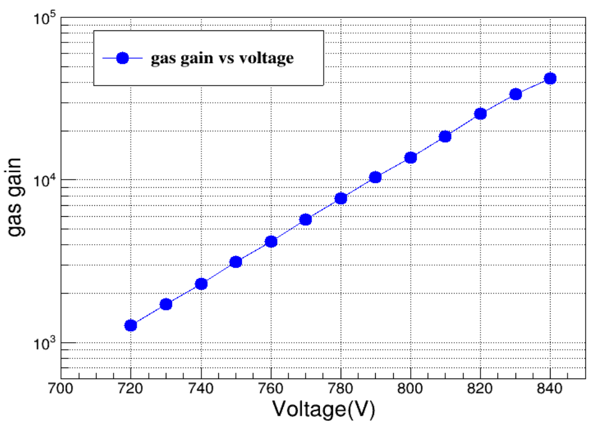
Thermal bonding Micromegas made at USTC

- Kapton PCB with coper substrate
- Ge coated resistive anode
- 500 µm avalanche gap

Test with x-rays in normal pressure







- 20.6%(FWHM) energy resolution
- >10^4 gas gain, and ~13.1 % (RMS/MEAN)

It is practical to improve by leveling the coper plate and polishing the anode surface of PCB

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New MIMAC Bi-chamber 35x35x25 cm^3

- Installation at Modane: December 2024 with the PCB version (1 chamber) and with the same gas system as the 10 cm Bi-chamber module

- Installation at Modane with the new low background (Kapton/Copper) micromegas in July 2025 （can be conducted earlier）

The future… MIMAC – 1m^3

16 bi-chamber modules (2x 35x35x25 cm^3)

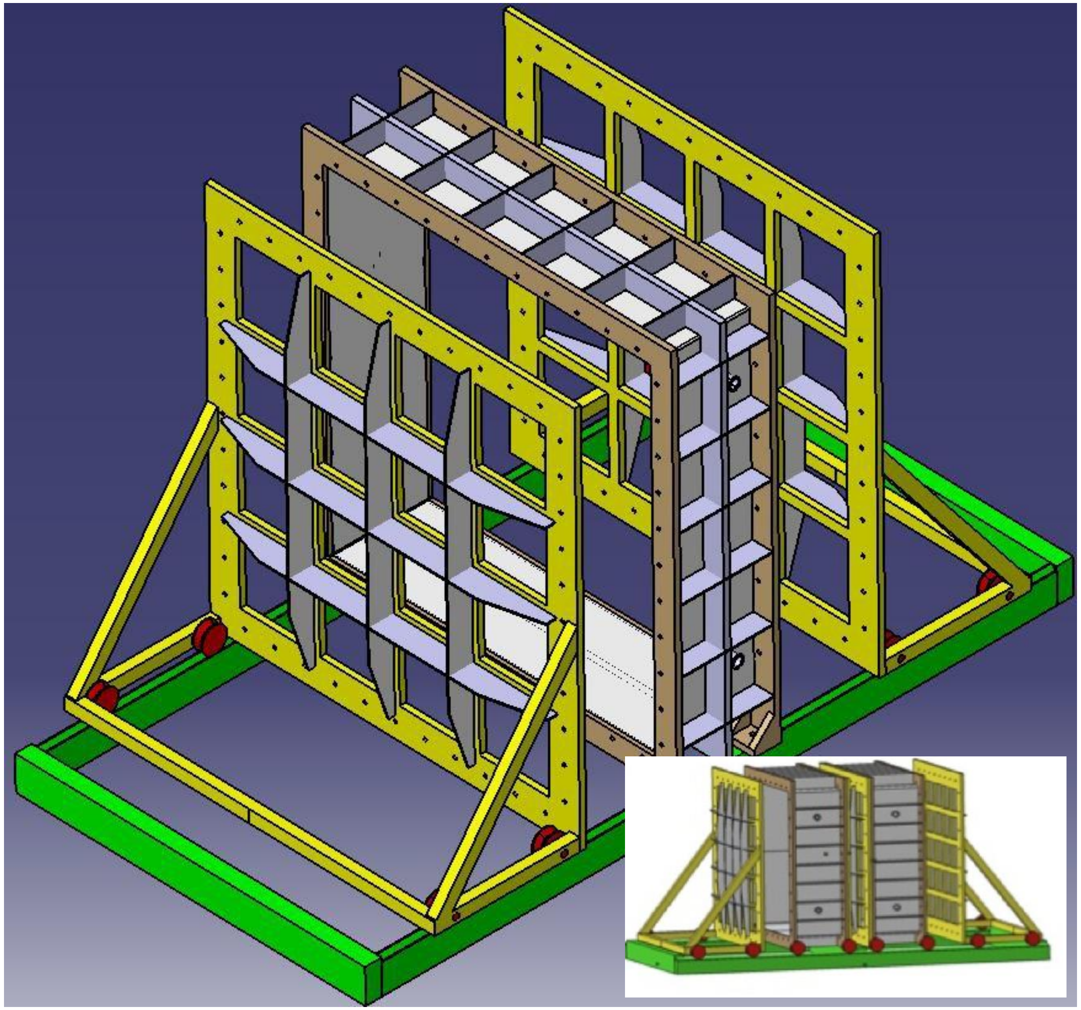
New technology anode
35cmx35cm

New electronic board
(1792 channels)

Only one big chamber with
4 field cages inside

First 1 m^3 at Modane
by the end of 2027

Second 1 m^3 at Jinping
by the end of 2028
financed by the Chinese partners



Conclusions

- MIMAC has developed a know-how on 3D nuclear recoil directional detection from 300 eV up to 15 MeV and even more…600 MeV
- The nuclear recoil directional detection is the observable needed to go beyond the neutrino floor for DM search
- The 35 x 35 cm^2 will be the elemental brick to build a big volume directional detector

Thank you for your attention!

Backup slides

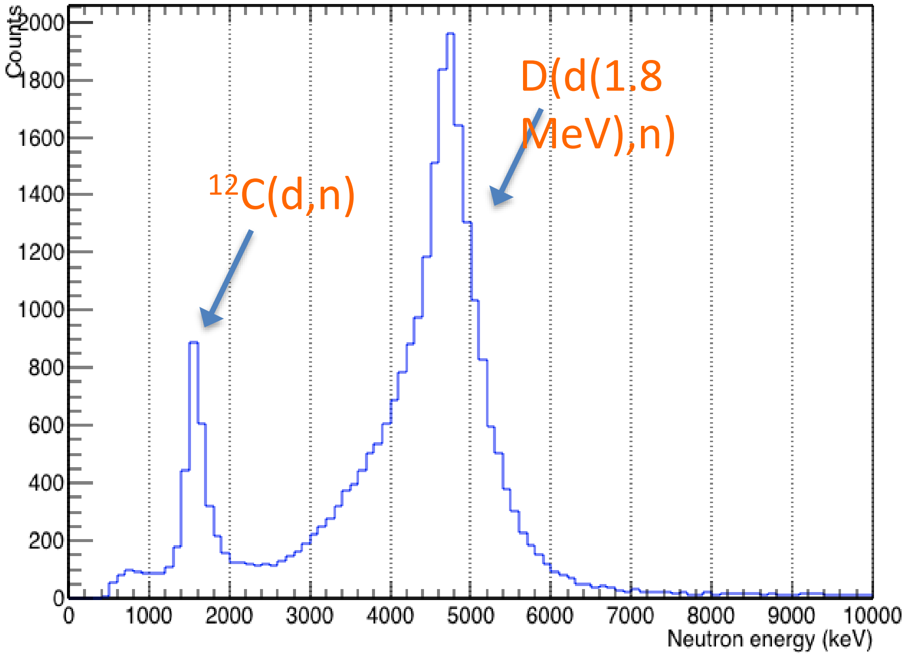
We measure an angular resolution better than 16◦ for proton recoils down to a kinetic energy of 4keV and for carbon recoils down to a kinetic energy of 5.5keV. For the first time, a detector achieves the directional measurement of proton and carbon recoils with kinetic energies in the keV range without any restriction on the direction of the incoming particle. This work demonstrates that directional detection is around the corner for probing DM with masses down to O(1GeV).

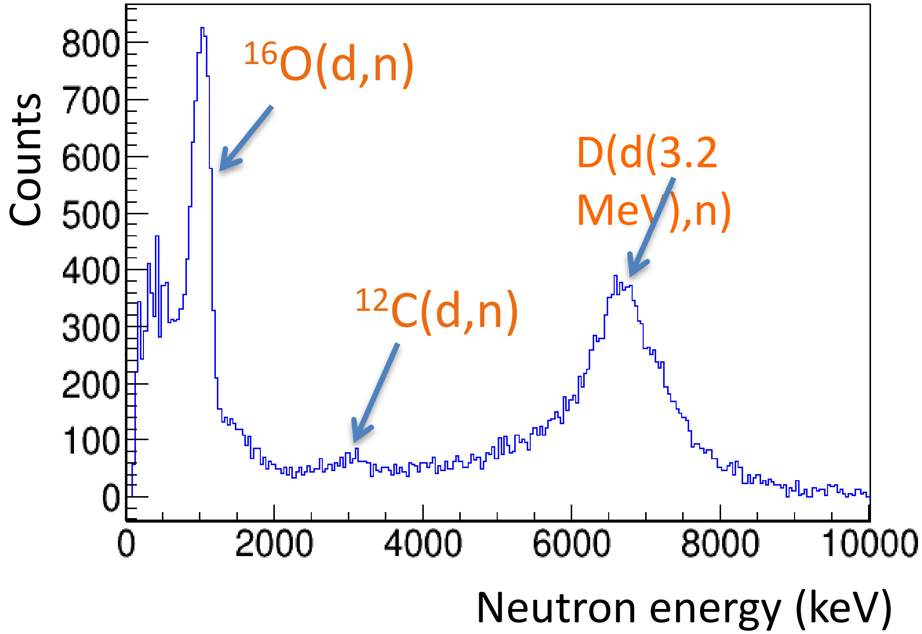
Monoenergetic measurements

Detection of target pollution

D(d(1.8 MeV,n) : neutrons of 5 MeV

D(d(3.2 MeV,n) : neutrons of 6.5 MeV





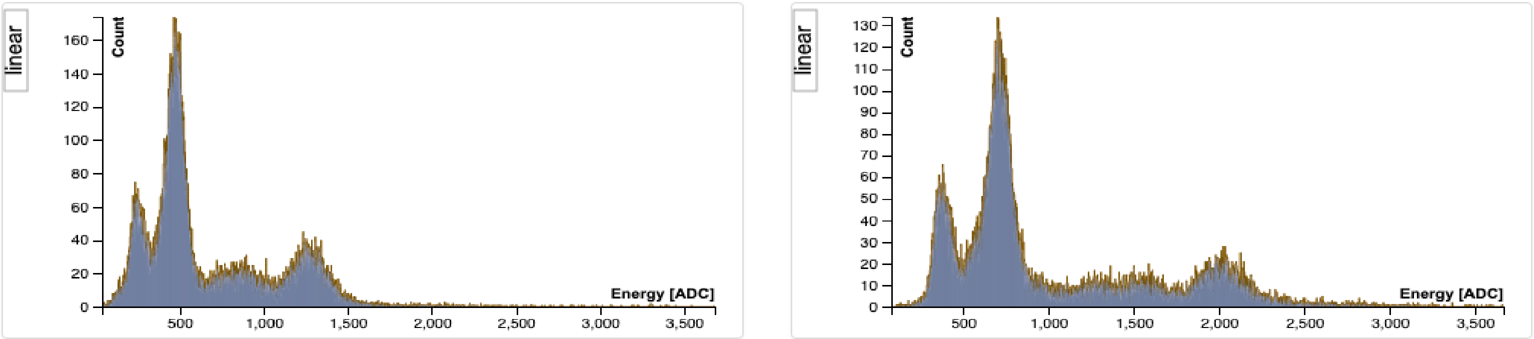
NPL /(UK)

700 mbar He/CO_2 (5%)

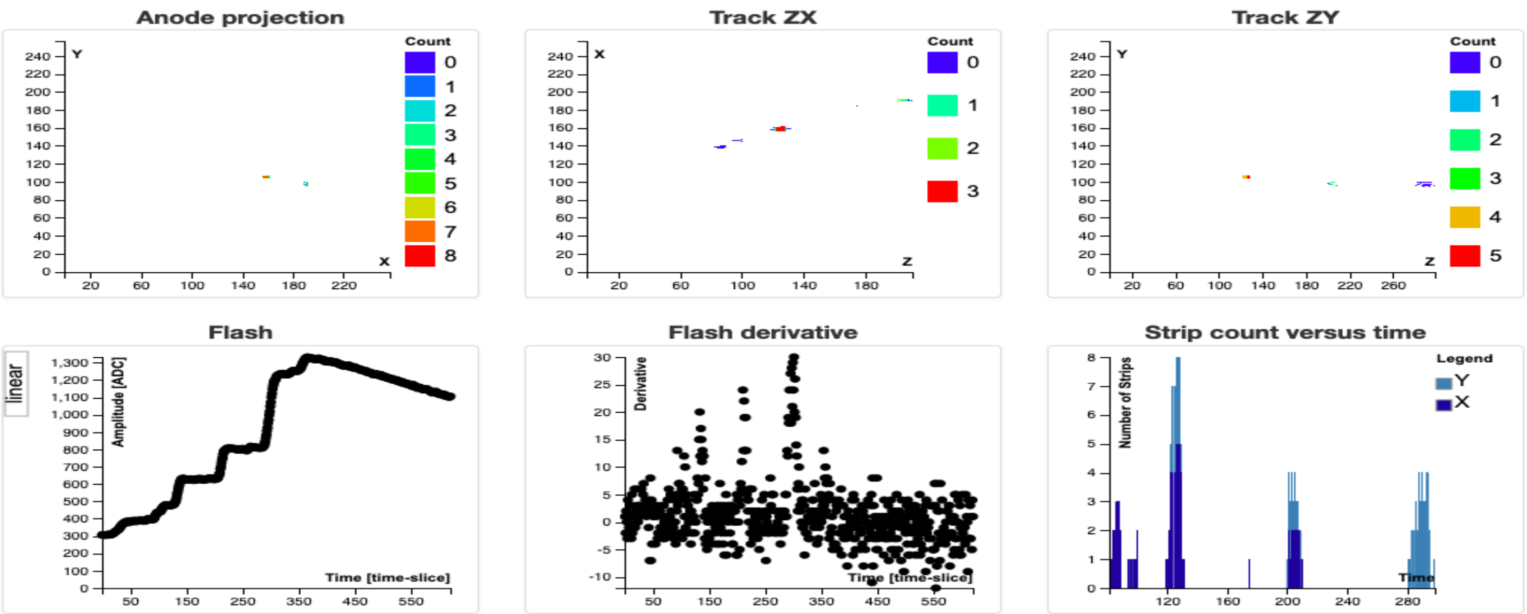
IRSN / AMANDE (Cadarache)

Fast neutron spectroscopy from 1 MeV up to 15 MeV with Mimac-FastN, a mobile and directional fast neutron spectrometer, N. Sauzet , D. Santos, O. Guillaudin, G. Bosson, J. Bouvier, T. Descombes, M. Marton, J.F. Muraz, NIM A 965 (2020) 163799

X-ray calibration of both chambers simultaneously

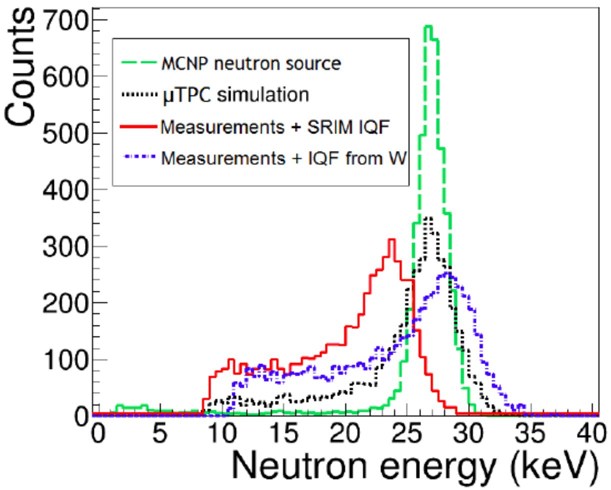


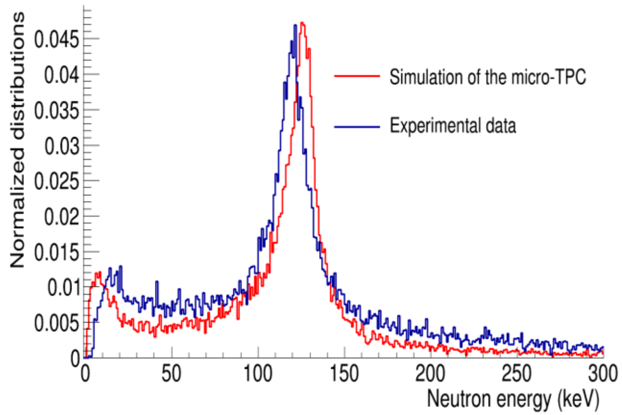
A typical electron event in the chamber 2

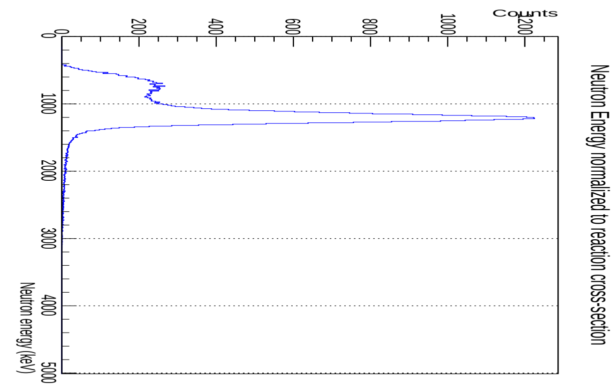


A large energy range of neutron fields

50% C_4H_{10} 50% CHF_3 30 mbar	60% C_4H_{10} 40% CHF_3 50 mbar	95% ^4He 5% CO_2 700 mbar
E_n=27 keV	***E_n=127 keV***	***E_n=1.2 MeV***







D. Maire *et al.*
« Neutron energy reconstruction and fluence determination at 27 keV with the LNE-IRSN-MIMAC µ-TPC recoil detector »
IEEE Transactions on Nuclear Science, 63(3) : 1934-1941, June 2016

D. Maire *et al.*
« First measurement of a 127 KeV neutron field with a µ-TPC spectrometer »
Nuclear Science, IEEE Transactions, 61(2014) 2090