Migdal **I**n **G**alactic **D**ark m**A**tter exp**L**oration

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(STFC/Rutherford Appleton Laboratory)
for the MIGDAL Collaboration

Presentation outline

1. MIGDAL collaboration and its programme
2. What do we already know about the Migdal effect ?
3. The Migdal effect in nuclear scattering - signal and potential backgrounds
4. DT and DD generators, beam collimation and shielding
5. Observation of the Migdal effect with the Optical Time Projection Chamber
6. Conclusions

Collaboration

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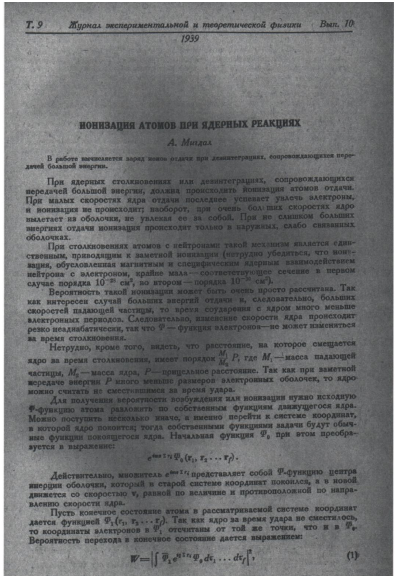
Migdal In Galactic Dark mAtter expLoration

- Part of the STFC project for the Liquid Xenon R&D towards G3 DM future experiment
  - Phase I (18 months, funded):
    - Create a dedicated environment for an unambiguous first observation with a suppressed background
    - Clearly observe the effect with energies available from using a high flux DT n-generator creating high energy nuclear recoils
  - Phase II (24 months, under peer review):
    - Based on results from Phase I measure the Migdal effect in gases such as CF_4 and CF_4 + noble gases using high flux DD and DT n-generators

Detector operation and the signal signature

- Use of CF_4 scintillating gas as a base gas for the experiment operating at low pressure
  - Advantages :
    - Well known gas for gaseous detectors
    - A lot of expertise exists in the O-TPCs operating with pure CF_4 and CF_4+ noble gases
    - Start with light atoms producing only low energy characteristic X-rays (below threshold)
    - Few mm long tracks of electrons and nuclear recoils can be captured by digital camera
    - Long gamma absorption mean free path minimising the background
  - Disadvantages in rare event searches :
    - Low mass of the target which requires operation in very high neutron flux environment
- Use of high energy neutrons from DT generator
  - Advantages :
    - Long track of the recoils - easier to image
    - Increased yield of the Migdal Effect - easier to observe the effect
  - Disadvantages
    - Increased background rate

What do we already know about the Migdal effect ?


Т. 9 Журнал экспериментальной и теоретической физики Вып. 10
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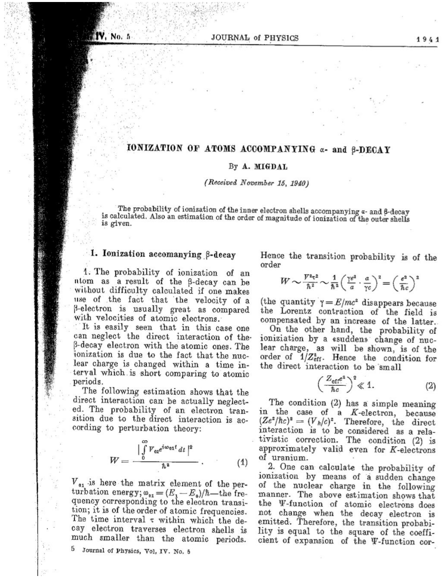
ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

А. Мигдал


Vol. IV, No. 5 JOURNAL of PHYSICS 1941

IONIZATION OF ATOMS ACCOMPANYING α- and β-DECAY

By A. MIGDAL

(Received November 15, 1940)

The probability of ionization of the inner electron shells accompanying α- and β-decay is calculated. Also an estimation of the order of magnitude of ionization of the outer shells is given.

I. Ionization accompanying β-decay

A. Migdal publications:

- Ionisation in nuclear reactions [1]
- Ionisation in radioactive decays [2]

First observations of the Migdal effect in :

- Alpha decay [3,4,5]
- Beta decay [6,7]
- Positron decay [8]
- Nuclear scattering [ ]

- [1] A. Migdal *Ionizatsiya atomov pri yadernykh reaktsiyakh, ZhETF, 9, 1163-1165 (1939)*
- [2] A. Migdal *Ionizatsiya atomov pri α- i β- raspade, ZhETF, 11, 207-212 (1941)*
- [3] E. E. Berlovich et al., *Investigation of the “jolting” of electron shells of oriented molecules containing ^{32}P, Sov. Phys. JETP, Vol. 21 , 675 (1965)*
- [4] M.S. Rapaport, F. Asaro and I. Pearlman *K-shell electron shake-off accompanying alpha decay, PRC* ***11****, 1740-1745 (1975)*
- [5] M.S. Rapaport, F. Asaro and I. Pearlman *L- and M-shell electron shake-off accompanying alpha decay, PRC* ***11****, 1746-1754 (1975)*
- [6] F. Boehm and C. S. Wu *Internal Bremsstrahlung and Ionization Accompanying Beta Decay, Phys. Rev.* ***93****, Number 3, 518 (1954)*
- [7] C. Couratin et al. , *First Measurement of Pure Electron Shakeoff in the β Decay of Trapped $^{6}He^{+}$ Ions, PRL* ***108****, 243201 (2012)*
- [8] X. Fabian et al., *Electron Shakeoff following the $β^{+}$ decay of Trapped $^{19}Ne^{+}$ and $^{35}Ar^{+}$ trapped ions, PRA,* ***97****, 023402 (2018)*

What do we already know about the Migdal effect ?

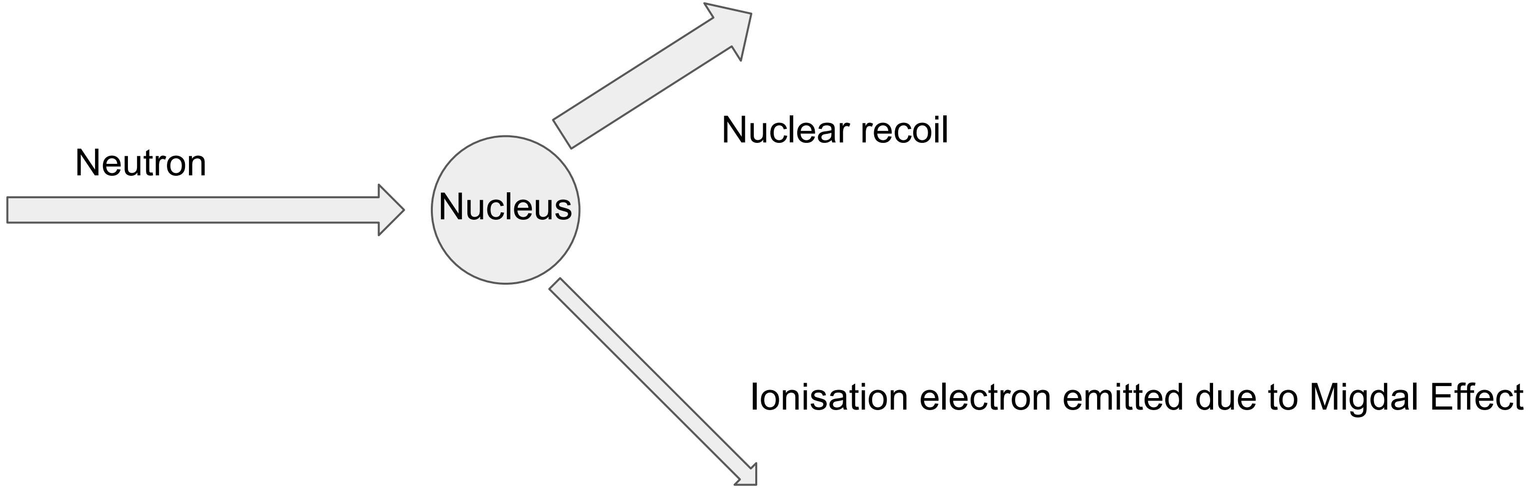
- Observation of the Migdal effect in α decay
  - Measured in ^{210}Po and ^{238}Pu decays measuring α particles in coincidence with X-rays emitted from K, $L_{I,II,III}$ and M-shell due to electron shake-off effect (emission of Migdal electron)
- Observation of the Migdal effect in β and β+ decay
  - Measured in $^{6}He^{+}$ (β- decay) and also in $^{19}Ne^{+}$ and $^{35}Ar^{+}$ (β+ decay) using an ion trap coupled to a TOF recoil-ion spectrometer detecting recoils of $^{6}Li^{2+}$ and also $^{19}F^{q+}$ and $^{35}Cl^{q+}$

None of the experiments was actually observing Migdal electrons.

- Migdal effect in nuclear scattering
  - Extremely challenging and awaiting for its first observation

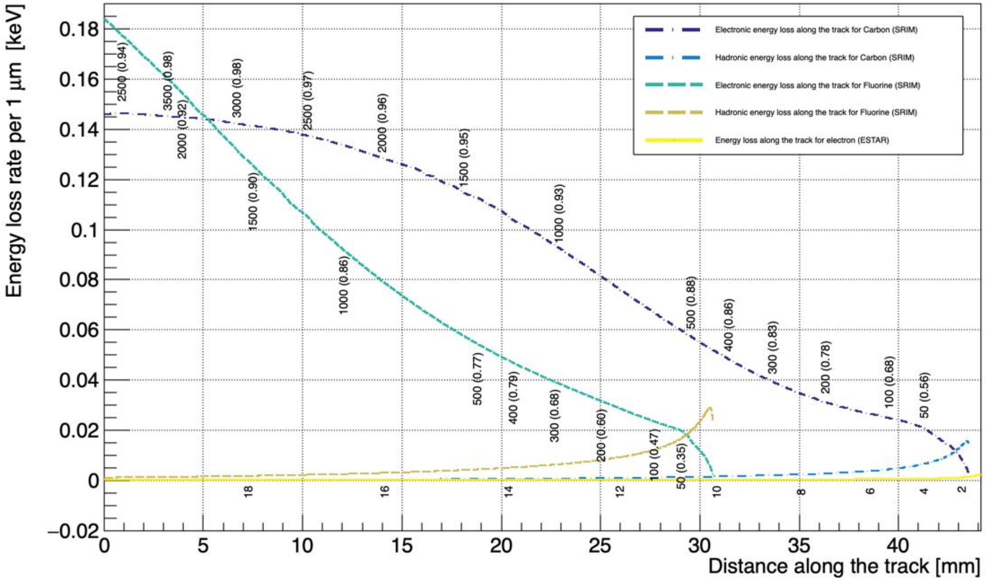
Experimental Goal

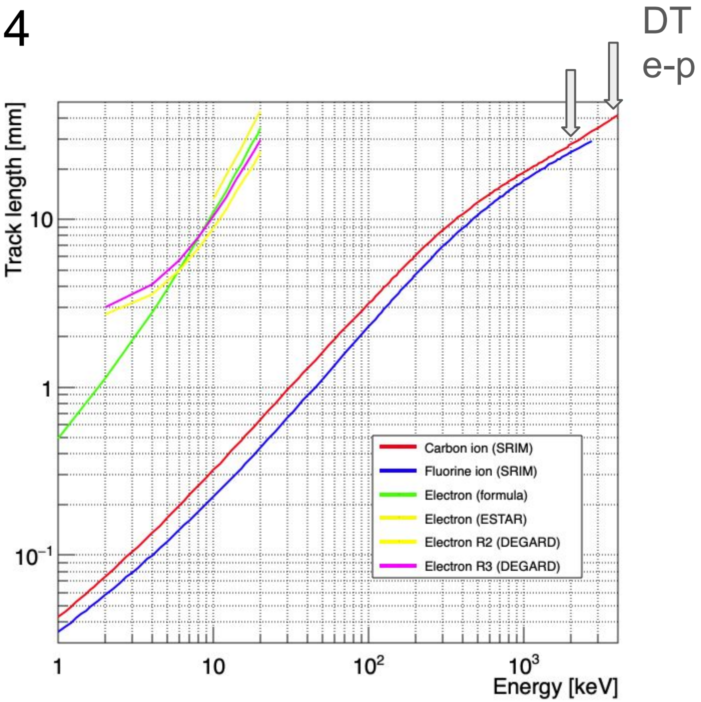
Observation of two simultaneously created tracks of the ionisation electron and the nuclear recoil originating from the same vertex



We propose first observation of the Migdal effect with detection of the Migdal electrons.

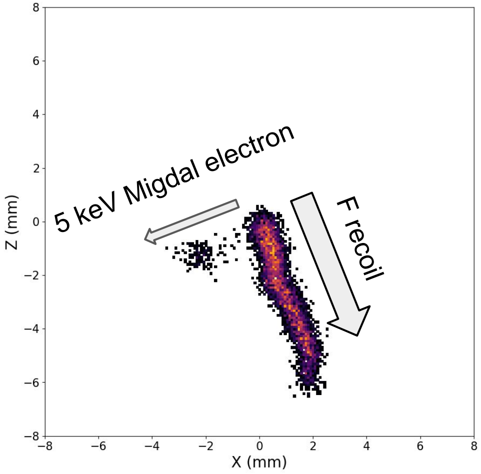
dE/dx distribution and track length for electrons and nuclear recoils in low pressure CF_4

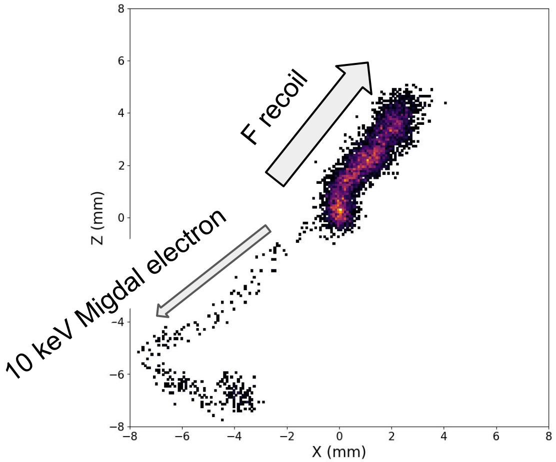




- dE/dx for the nuclear recoils decreases with the energy which is opposite for the electrons
- Electrons with energies 5 - 10 keV have track lengths between 4 - 10mm
- Nuclear recoils with energies E > 150 keV have track length > 4 mm

Detector operation and the signal signature

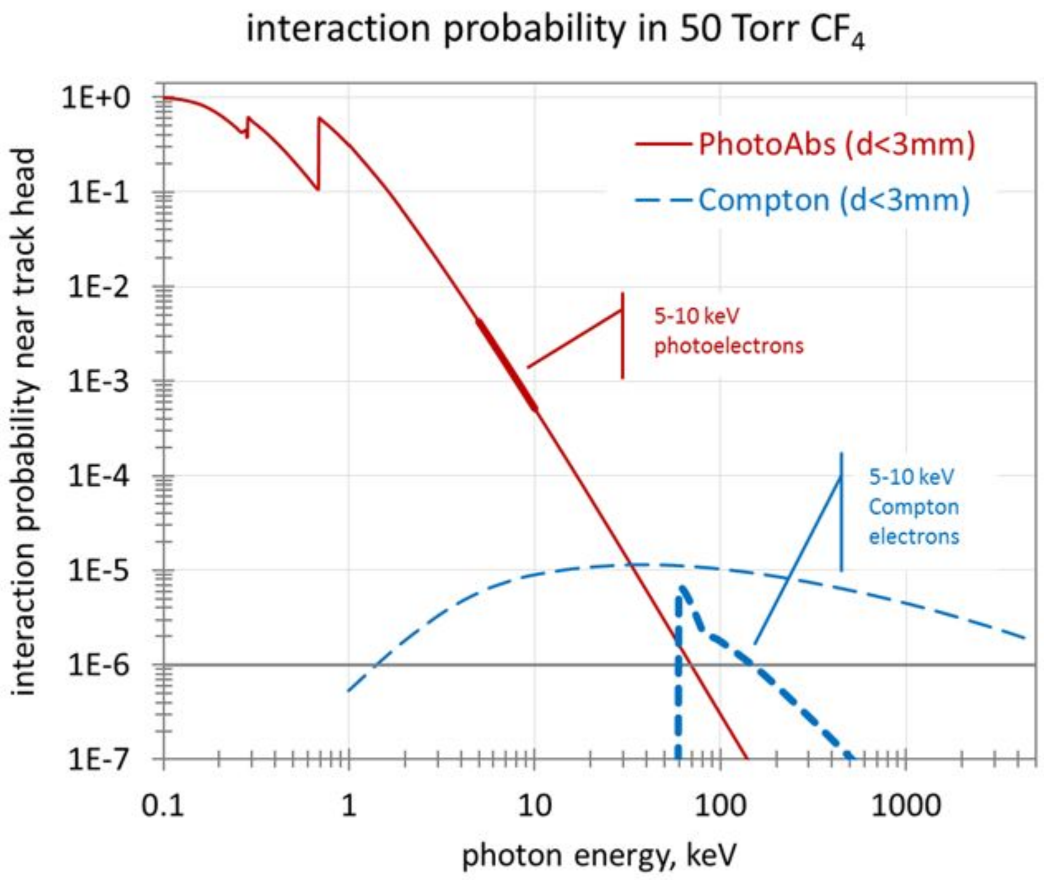




- Example of the Migdal effect with 250 keV Fluorine recoil & 5 (10) keV electron (after 10 mm of drift in CF_4 at 50 Torr)
- Simulated with SRIM and garf++ (recoil) and DEGRAD (electron)
- Clear “fork-like” topology
- Clear different dE/dx distribution for both tracks
  - Opposite head-and-tail ionisation distribution
- Clear different ionisation density for both tracks

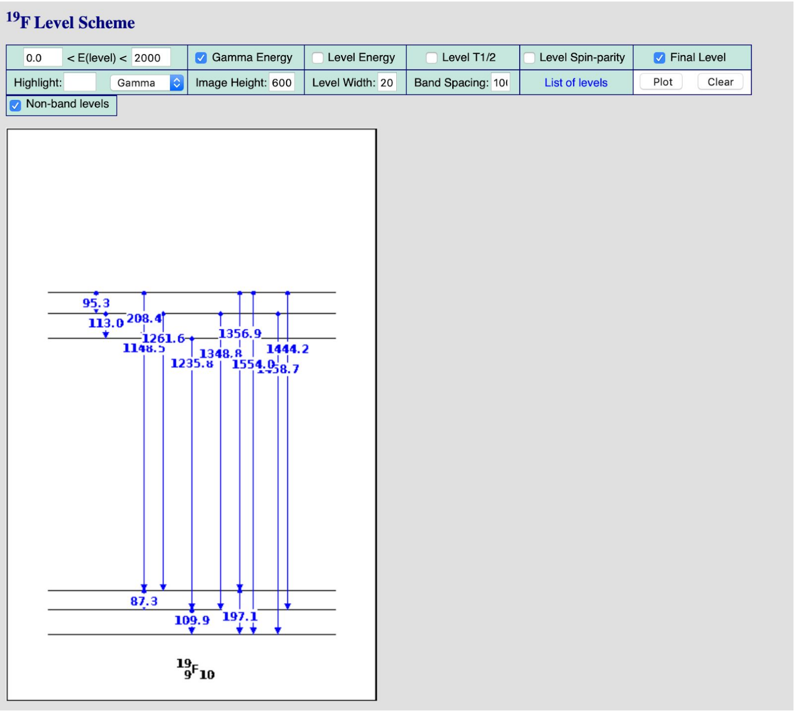
➔ At this moment we do not assume any specific angular distribution of the Migdal electron emission. We will have capability to measure it.

Signal background



Gamma-rays from inelastic scattering on :

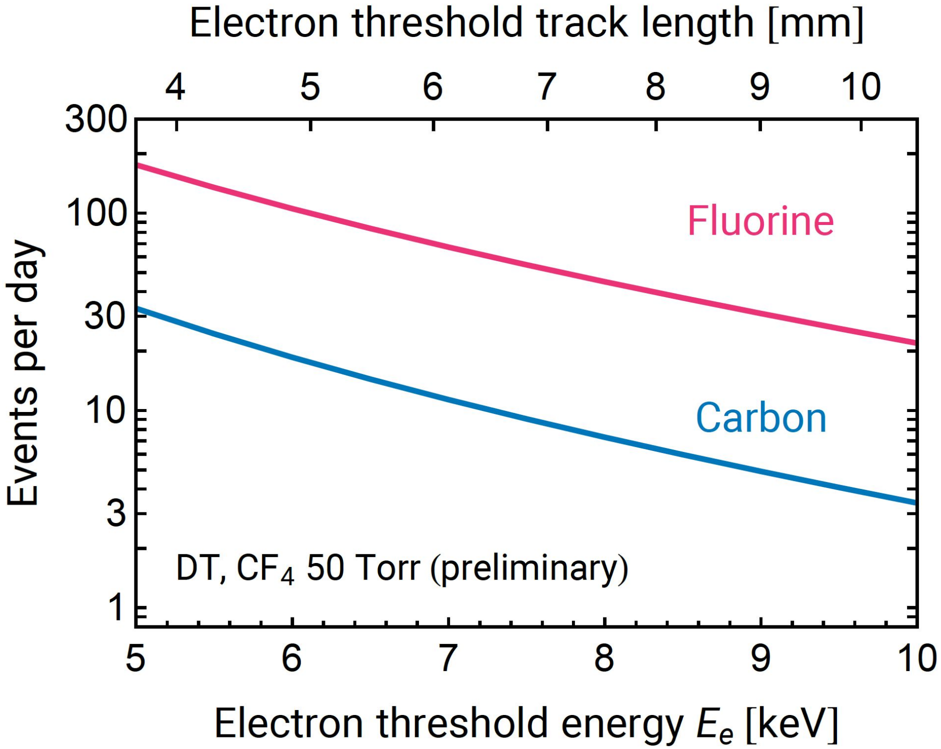
- Carbon : several lines E > 4.4 MeV
- Fluorine : Several low energy lines with most frequent - 109.9 and 197.1 keV



Sources of background

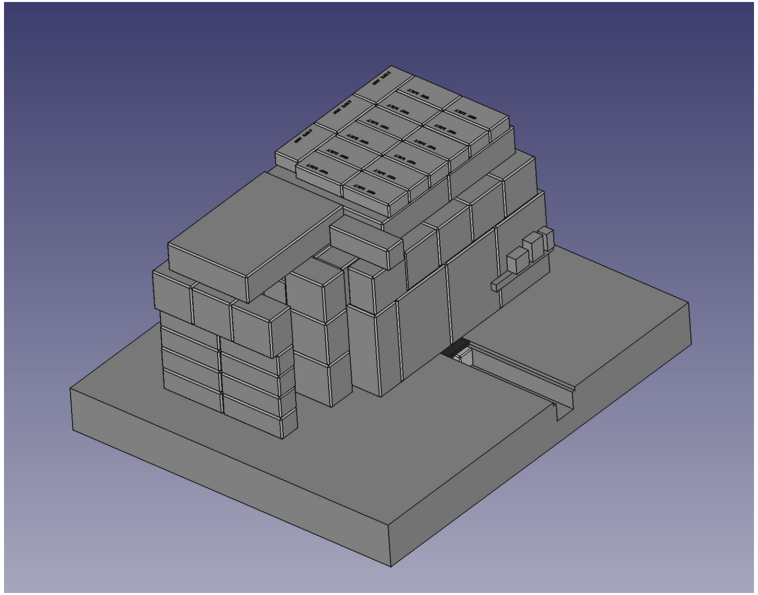
Recoil-induced δ-rays	δ electron from NR track head
Particle-induced X-ray Emission (PIXE) X-ray emission Auger electrons	 Photoelectron near NR track head Auger electron near NR track head
Bremsstrahlung processes Quasi-Free Electron (QFEB) Secondary Electron (SEB) Atomic (AB) Nuclear (NB)	 Photoelectron near NR track head Photoelectron near NR track head Photoelectron near NR track head Photoelectron near NR track head
Coincidences of track ejecta	Coincidences of the above topologies
Photon interactions Neutron inelastic γ-rays External X-/γ-rays	 Compton electron near NR track head Photo-/Compton electron near NR track
Decay of residual nucleus	Electron from radioactive decay of NR
Decay of gas contaminant	Electron from decay near NR track head
Nuclear recoil cascades NR tracks head cascade NR tracks tail cascade	 NR track fork due to cascade near head NR track fork due to cascade near head

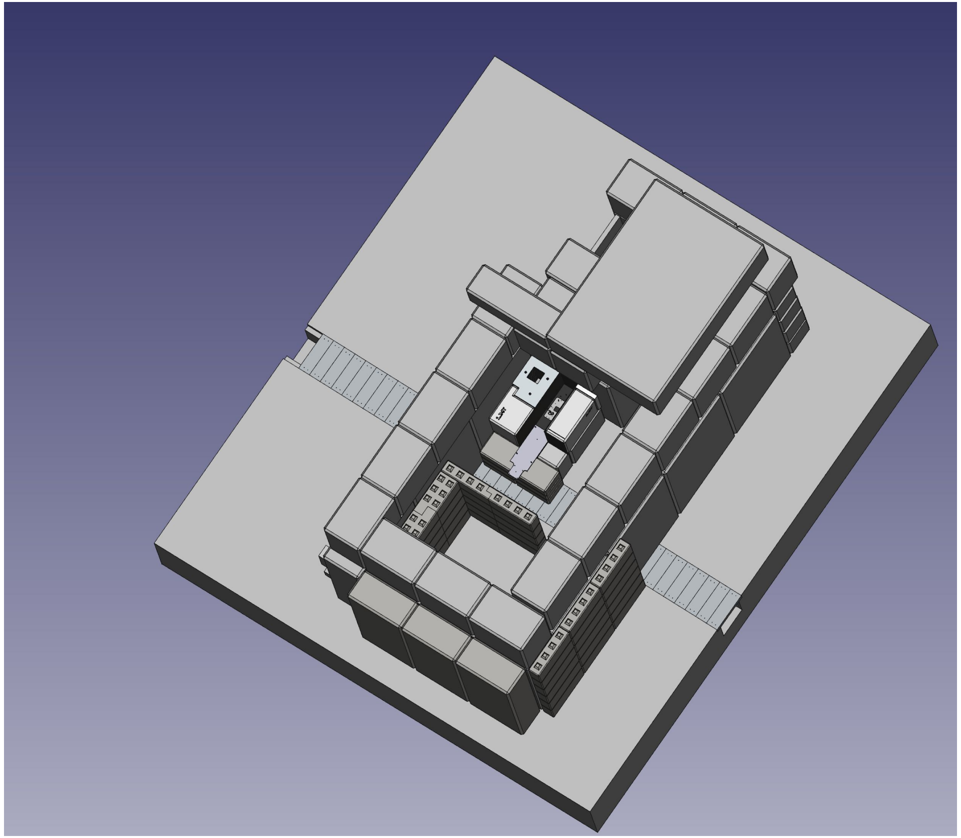
Expected number of Migdal events in CF_4 using DT generator



Taking into account energy distribution and rates of the events with C and F recoils in the fiducial region over one day of exposure to neutron from DT generator.

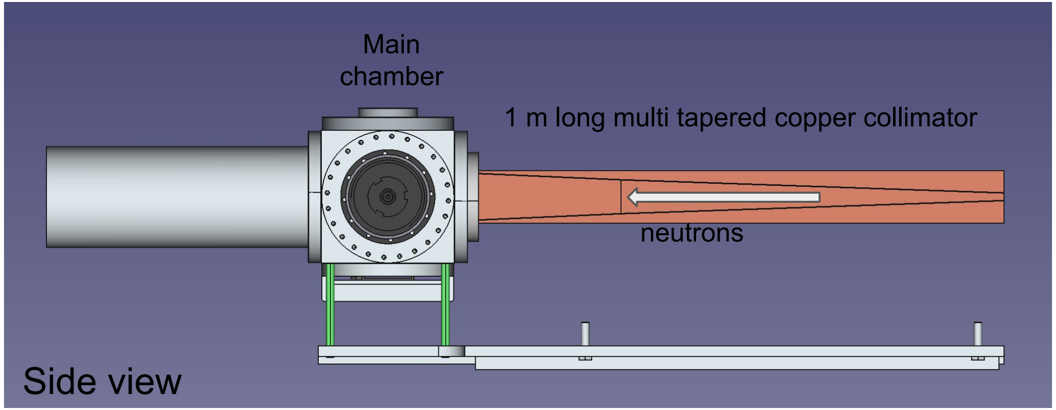
DT and DD neutron generators, beam collimation and shielding

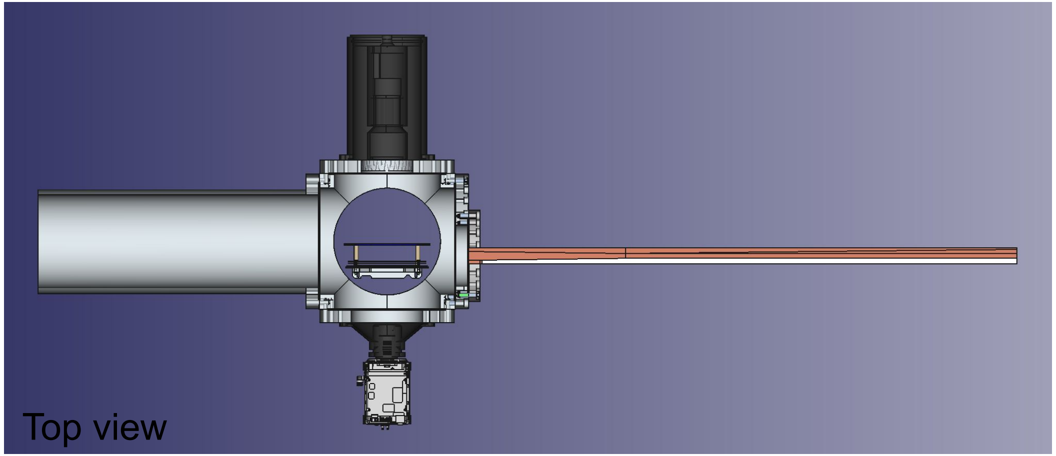




- DT neutron generator:
  E_n=14.1 MeV, flux 10^{10} n/s
- DD neutron generator:
  E_n=2.45 MeV, flux 10^{9} n/s
- Both generators from Adelphi (USA)

DT and DD neutron generators, beam collimation and shielding

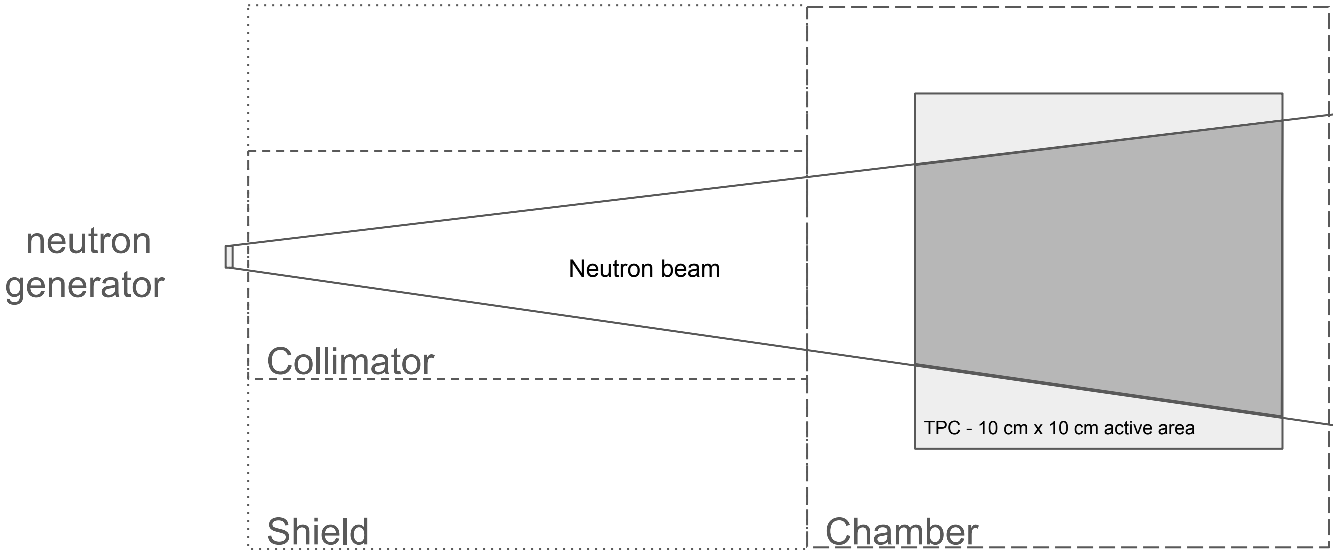




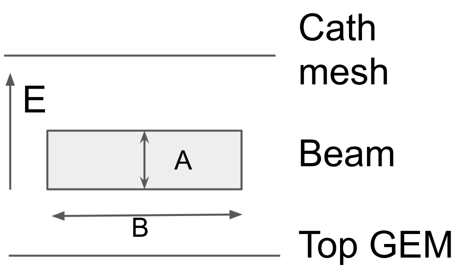
- Collimator length : 1 m
- Material : hard copper (brass)
- Rate of neutrons from DT generator at the front of the TPC: ~ 400 kHz
- Events rate in the TPC ~ 60 Hz

DT and DD neutron generators , <u>beam collimation</u> and shielding

Top View



Side view at the rear of sensitive volume



A - at the entrance : 1.8 cm

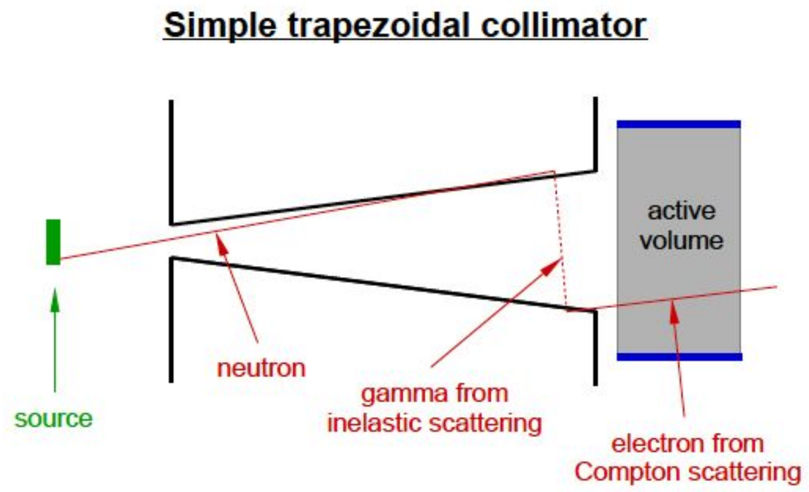
B - at entrance: 9.6 cm

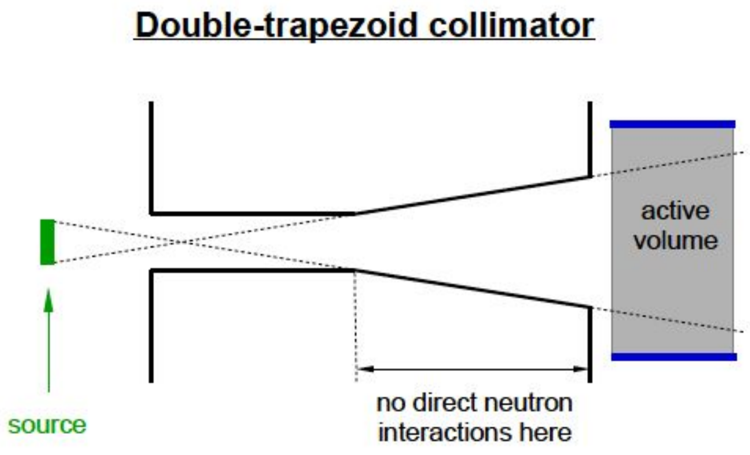
A - at the exit : 2.1 cm

B - at exit : 10.5

Collimator : solid block of copper with machined tunnel for neutrons
Shield : blocks of Fe, Borated Polyethylene and Pb
Chamber : Al

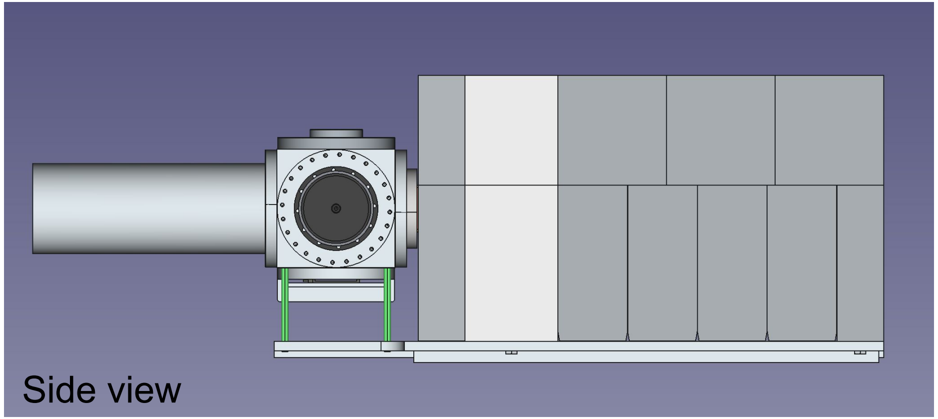
DT and DD neutron generators , <u>beam collimation</u> and shielding

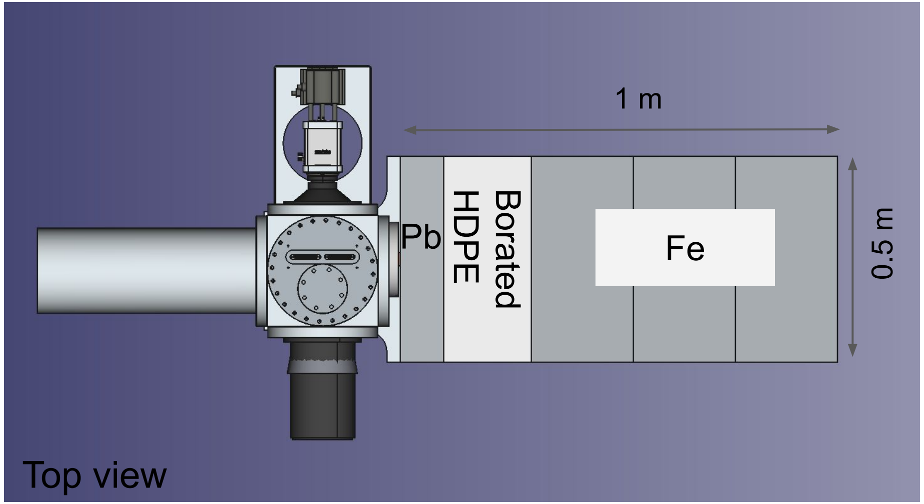




- Extended neutron source - 1.36 x 1.36 cm T target in the DT generator - simple trapezoidal collimator leads to electrons produced near active volume : NR/all events ~ 35 %
- Double-trapezoidal shape has been design with an extensive Geant4 simulations achieving NR/all events ~ 84 %

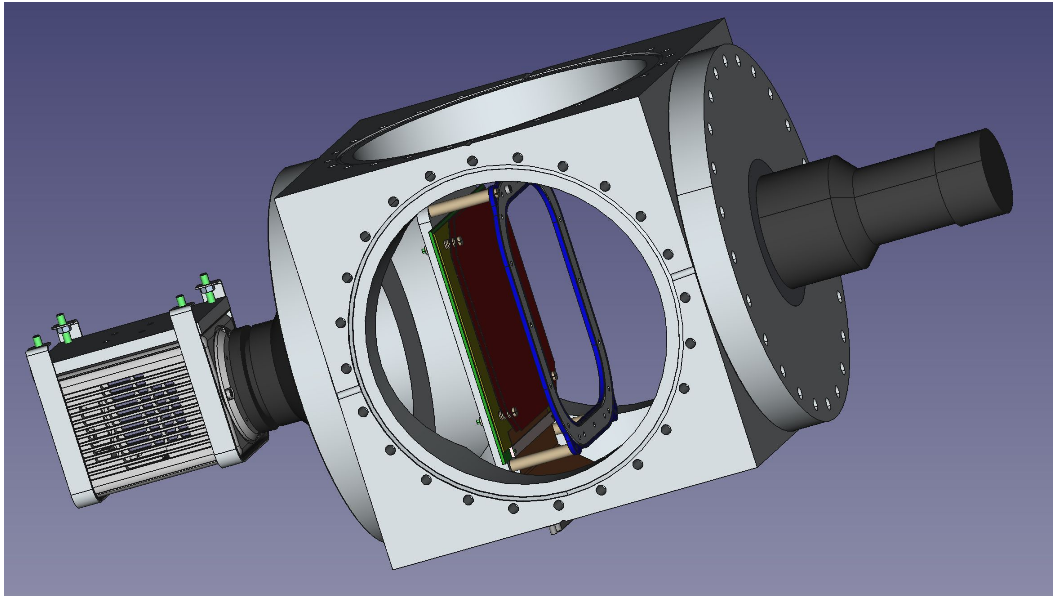
DT and DD neutron generators, beam collimation and shielding

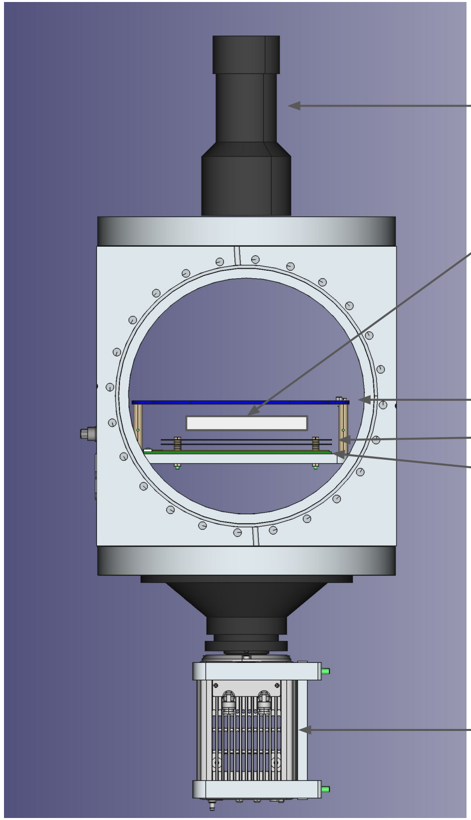




- Fe - slows down fast neutrons
- Borated HDPE - captures neutrons
- Pb - stops gamma rays
- Reduction of neutron flux : ~ 1E-6

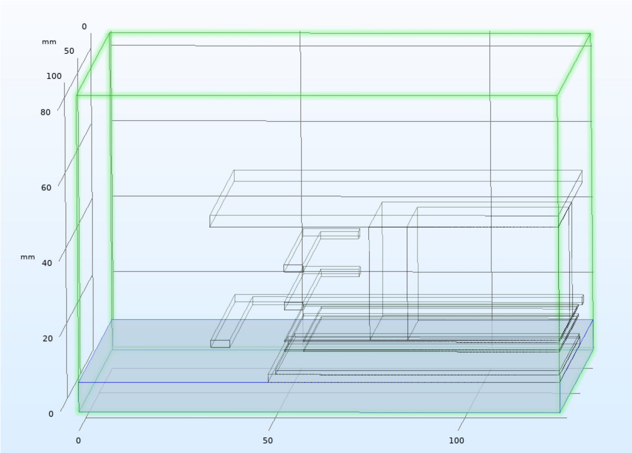
Optical Time Projection Chamber

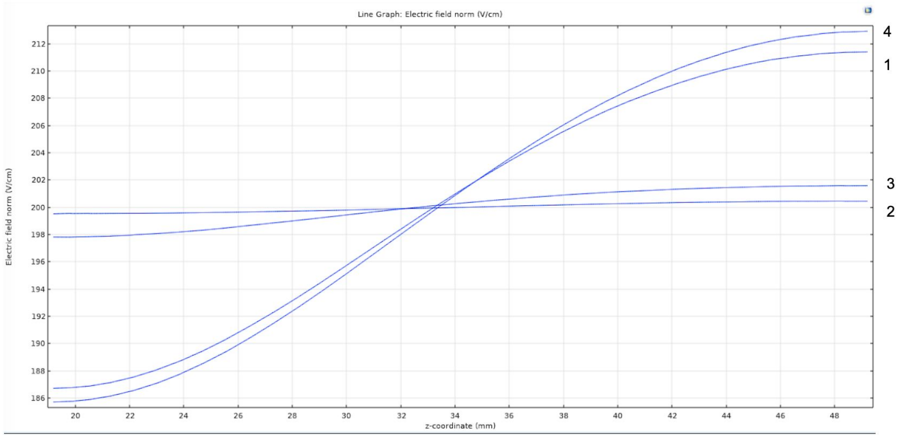




- Aluminium chamber : 25.4 cm^3
- TPC active area 10 cm x 10 cm
- Drift gap : 3 - 5 cm (to be optimised)
- Amplification with 2 x standard glass GEM (2 mm gap)
- ITO plate 15 cm x 15 cm with 120 readout strips (5 mm induction gap)

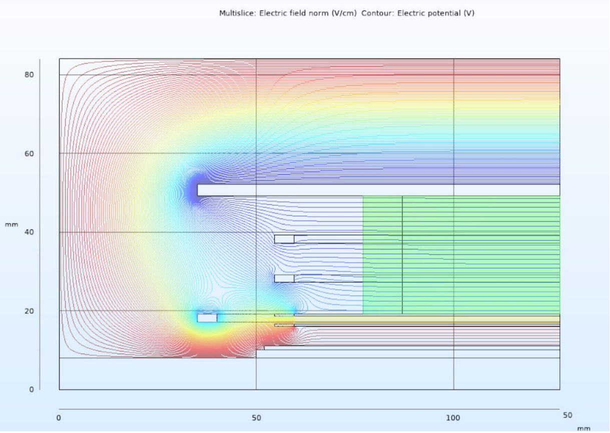
Optical Time Projection Chamber - Electric field in 3 cm drift gap

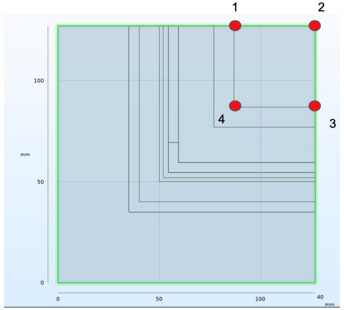




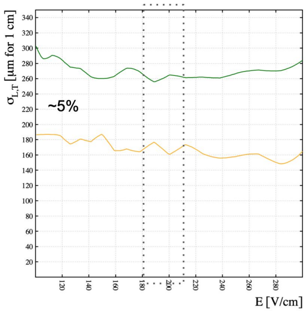
Smaller fiducial volume

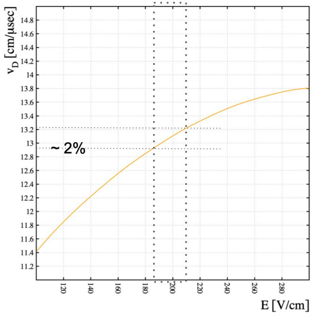
8 cm x 8 cm





Electron transport in 50 Torr 100% CF_4

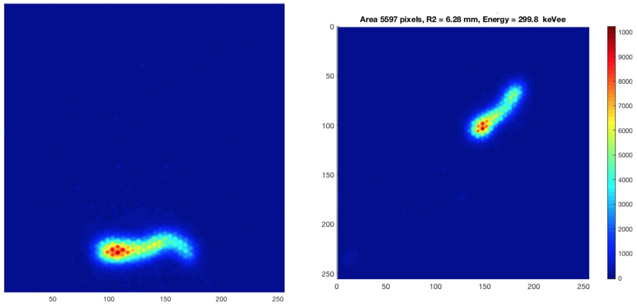




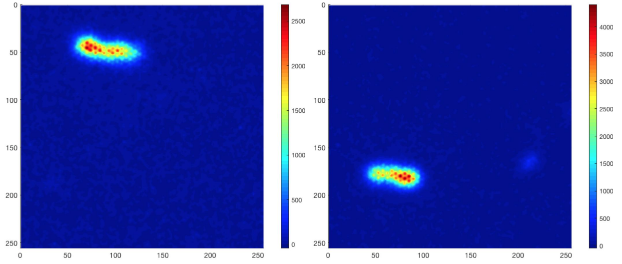
We want to use as little material as possible in the TPC and at the same time keep the electric field uniform.

Observation of the Migdal effect with Optical TPC
- 3D track reconstruction -

NR captured in the OTPC system at UNM by D. Loomba et al.



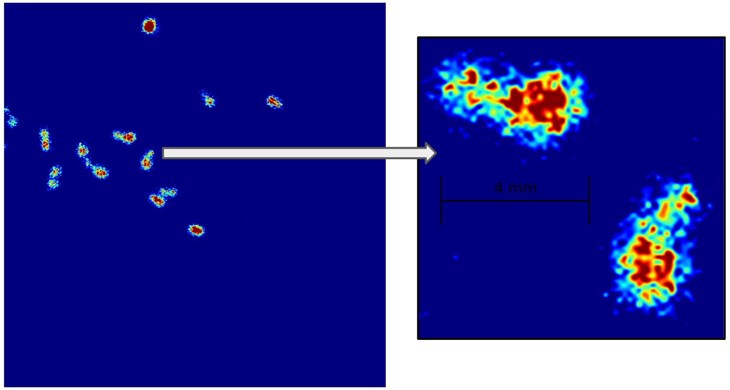
E ~ 270-300 keVee



E ~ 100-120 keVee

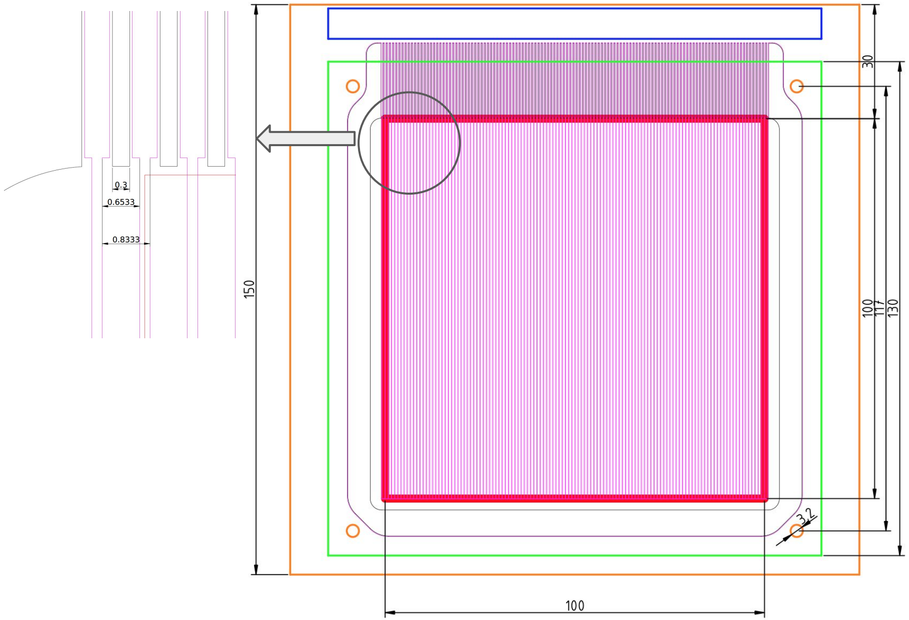
- 2D imaging with low noise CMOS camera

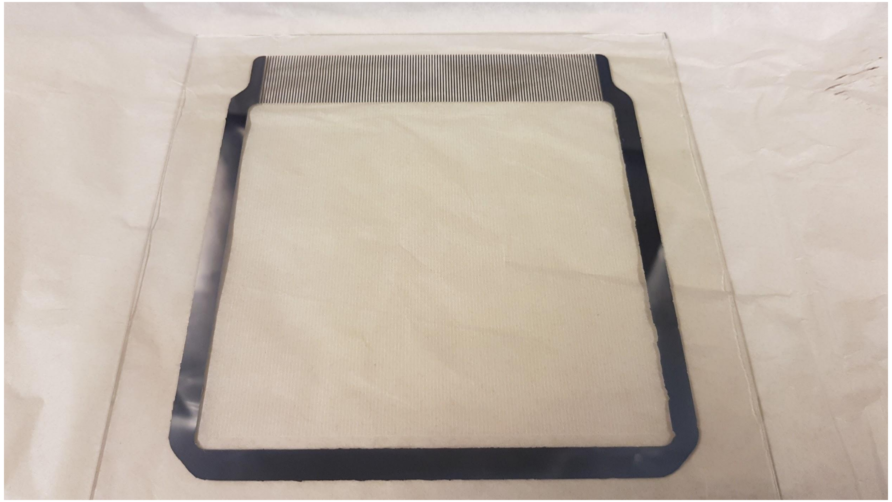
Thick GEM tests at CERN led by F. Brunbauer, (March 2020)

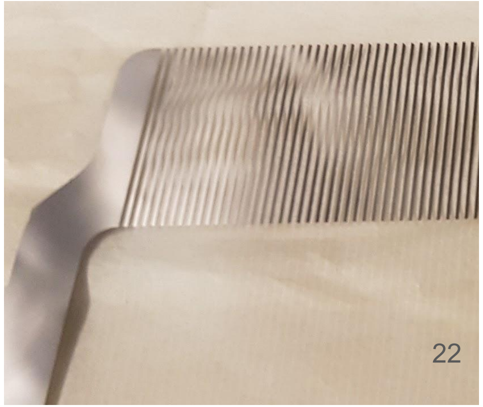


- Image of low energy electron tracks from ^{55}Fe source in CF_4 at 50 Torr.
- Tracks' head and tail structure is clearly resolved.

Optical Time Projection Chamber - charge signal redout

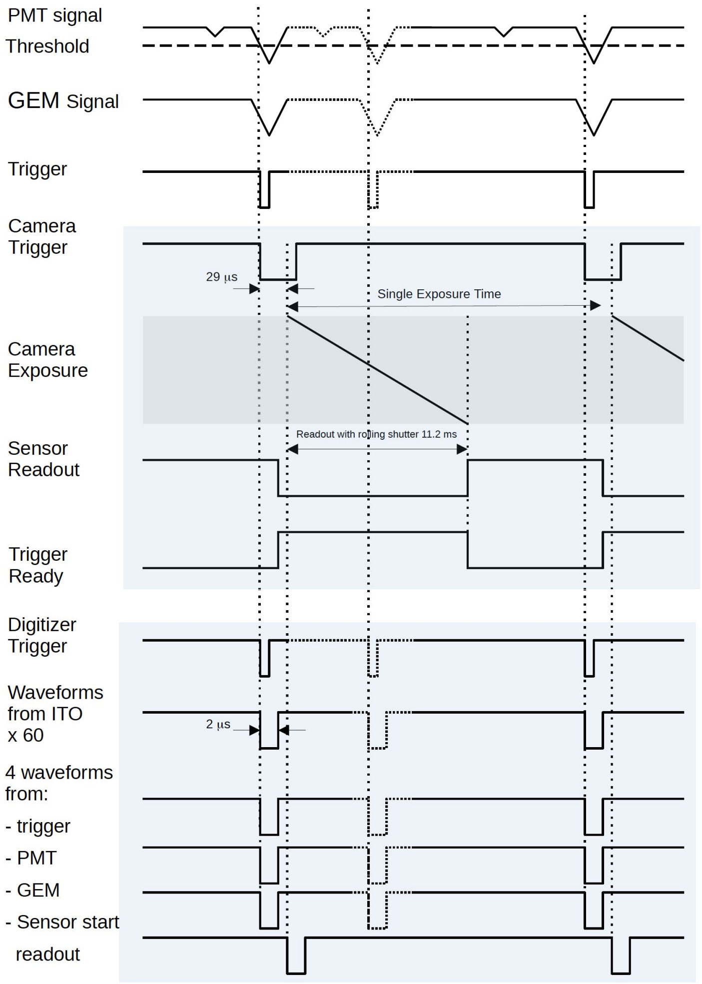






- 1.1 mm thick ITOGLASS 04, resistance 4 Ohm/square
- Metallised with Cr and Aluminium for wire bonding
- 120 strips connected to Acqiris 60 channel digitizer
- Digitisation of pulses with 2 ns sampling rate

DAQ



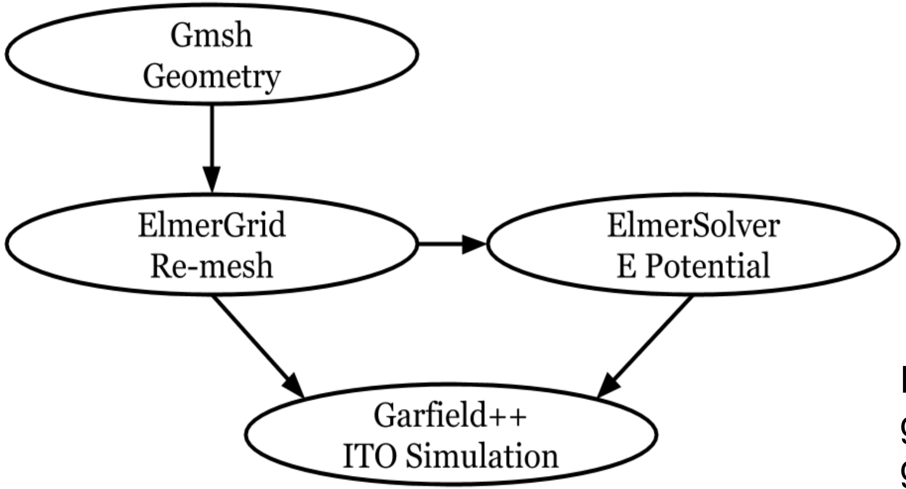
Signal readout from:

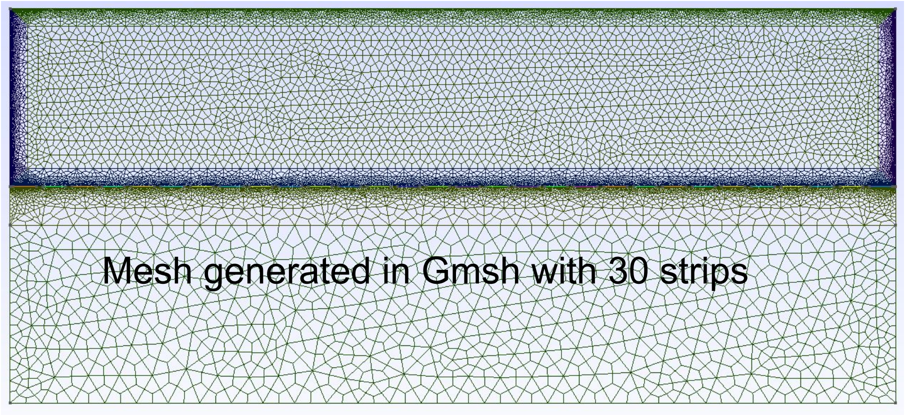
- High QE large PMT (light)
- Camera: Hamamatsu Orca-Fusion (light)
- Lower glass GEM (charge)
- 120 ITO strips (charge)

Digitization:

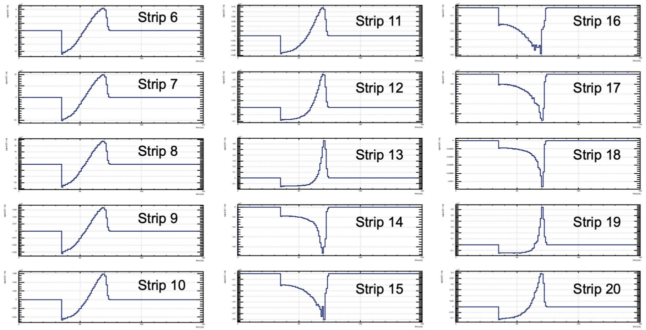
- Acqiris 66 channels, 8-bit, 2 ns sam. rate
- High speed PC with spec for fast data transfer from the camera operating at 90 frames/s
- 2 us long waveforms including pre- and post- trigger pulses

Observation of the Migdal effect with Optical TPC
- 3D track reconstruction -



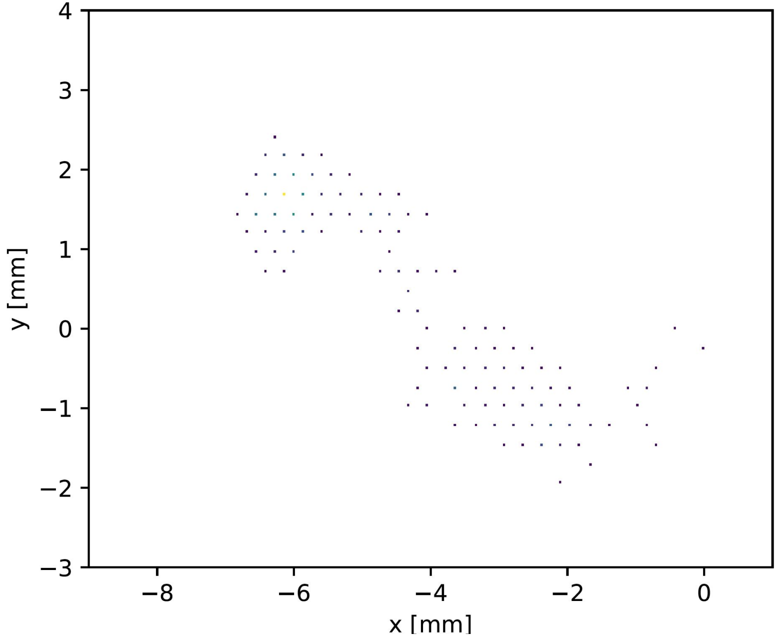


Raw pulses generated with garf ++

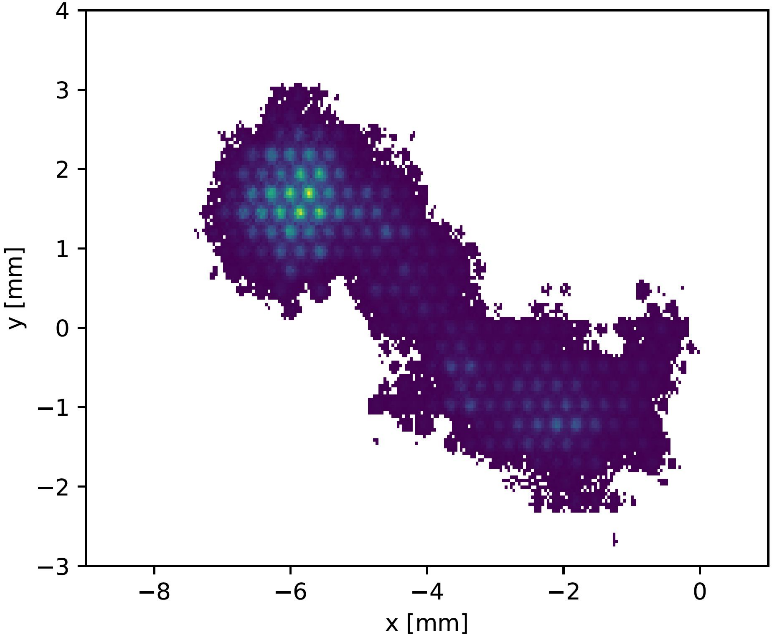


- Third coordinate reconstruction with charge readout using high granularity pattern of strips providing timing information

GEM simulation (gain + diffusion between two GEMs)
10 keV electron

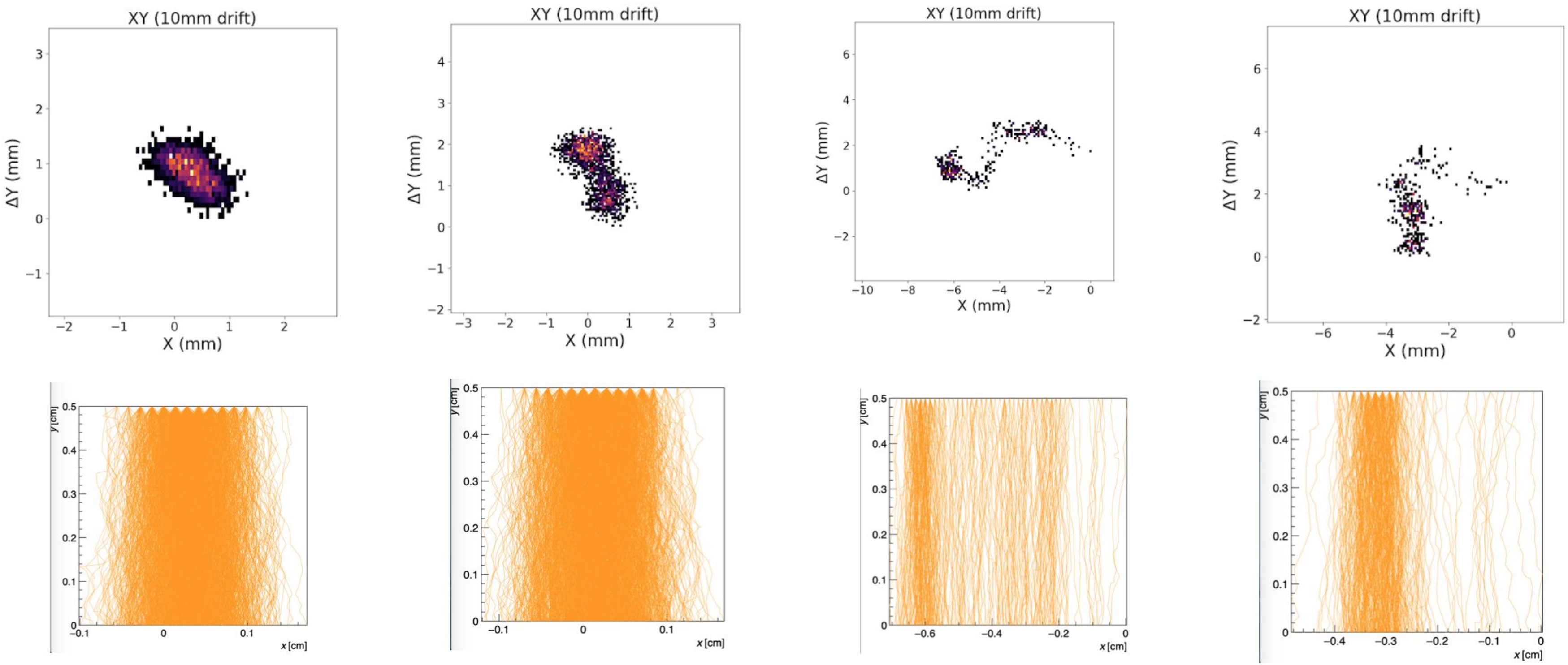


Primary charge at the entrance to the top GEM



After 2 GEMs 2 mm apart

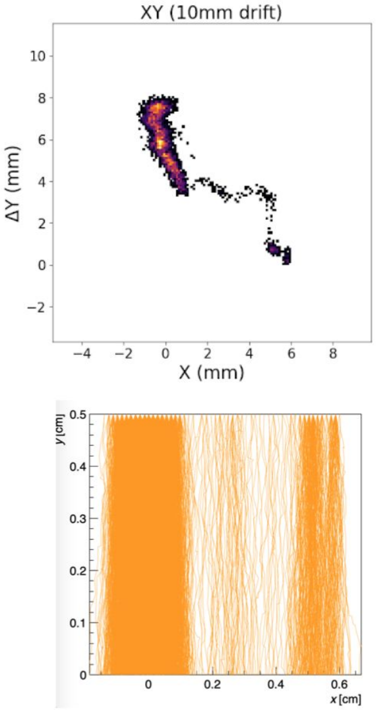
The Migdal effect in nuclear scattering: example of isolated NR and electron tracks



100 keV F recoils

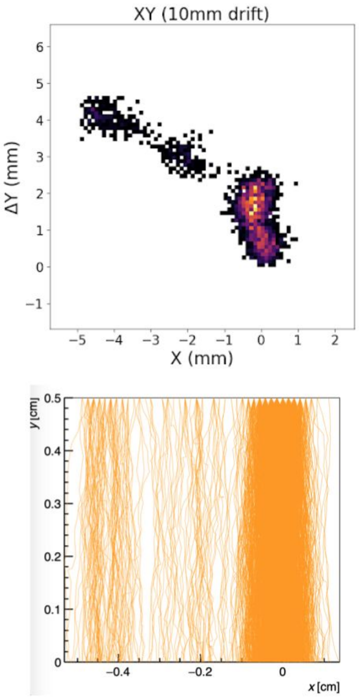
10 keV electrons

The Migdal effect in nuclear scattering: example of tracks - Migdal events



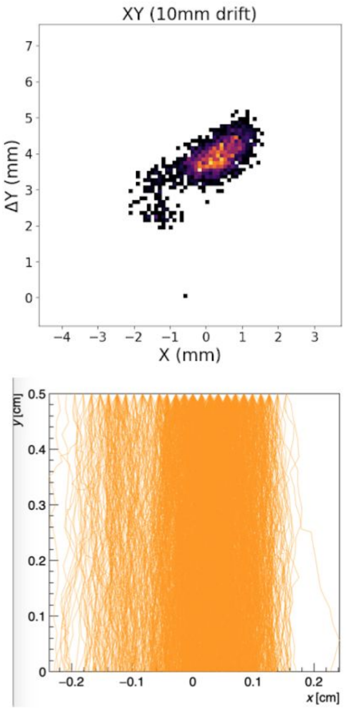
200 keV F &

10 keV electron



100 keV F &

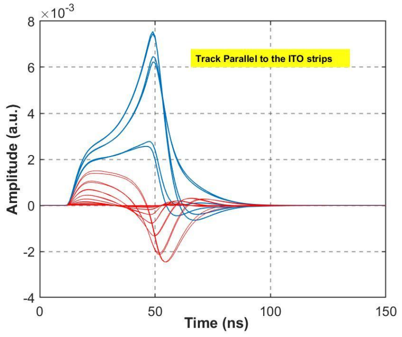
10 keV electron

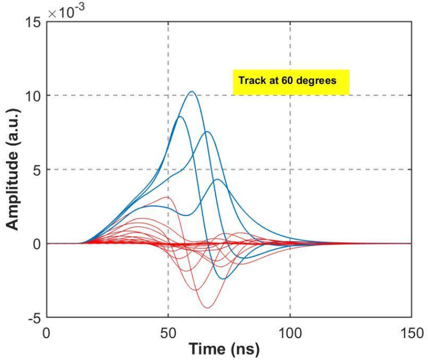


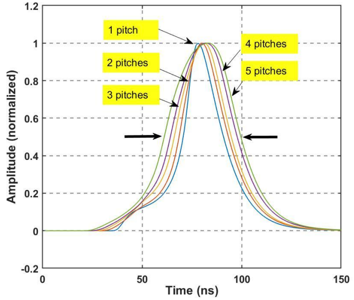
100 keV F &

5 keV electron

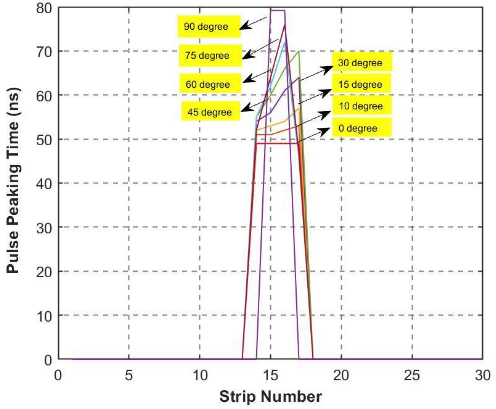
Observation of the Migdal effect with the Optical TPC
- 3D track reconstruction -





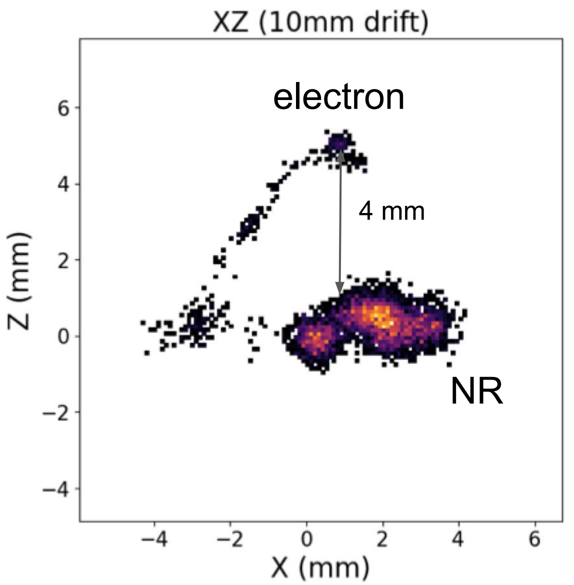


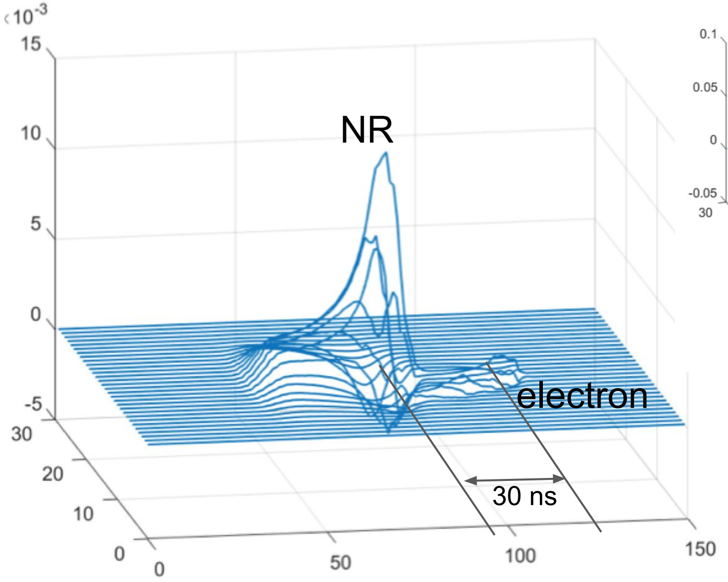
Track's extension in Z direction and the angle reconstruction come from timing and the width of the pulses.



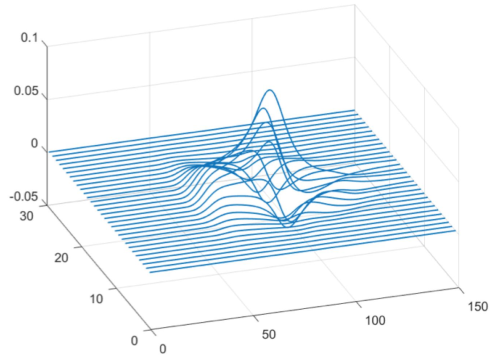
- Third coordinate reconstruction with charge readout using 120 strips (with pitch 0.83 mm) providing timing information

Observation of the Migdal effect with the Optical TPC
- Pulses from ITO strips from Migdal event (10 keV electron)





Raw signal



Including amplifier's response function

Drift velocity in the drift gap at 200 V/cm
in pure CF_4 at 50 Torr : 13 cm / 1 us

Expected time difference for two clusters 4 mm apart : 31 ns

Conclusions

- Theoretical calculations of the Migdal Effect well established. Yields of the effect are well known for all the elements relevant to dark matter searches.
- Migdal Effect has been already observed in radioactive decays in both light and heavy elements.
- We propose first observation of the effect in nuclear scattering using OTPC allowing a full 3D reconstruction of the event's topology which is a key feature of our experiment. Our goal is to capture events with both recoil and electron tracks emerging from the same vertex.
- We have made a lot of design progress and tests of GEMs over the last 6 months. We are moving now towards construction of the experiment.