OTPC for the observation of the Migdal effect in nuclear scattering

Pawel Majewski
(STFC/Rutherford Appleton Laboratory)
for the MIGDAL Collaboration

RD51 collaboration meeting and topical workshop on New Horizons in Time Projection Chambers, 5 - 9 October 2020

Presentation outline

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

Migdal In Galactic Dark mAtter Exploration

CERN (GDD) F. Brunbauer, F. Garcia (HIP), E. Oliveri, L. Ropelewski, L. Scharenberg, R. Veenhof

Coimbra-LIP E. Asamar, A. Lindote, I. Lopes, F. Neves, V. Solovov

Imperial College London H. Araujo, J. Borg, T. Marley, M. Nakhostin, T. Sumner,

King's College London C. McCabe

STFC (ISIS) C. Cazzaniga, C. Frost, M. Kastriotou ; **(PPD)** S. Balashov, C. Brew, M. Van der Grinten, A. Khazov, P. Majewski; **(TD)** Jason Tarrant

Royal Holloway University of London A. Kaboth

University of Birmingham I. Katsioulas, T. Neep, K. Nikolopoulos

University of New Mexico D. Loomba, A. Mills

University of Oxford H. Kraus

University of Sheffield V. Kudryavtsev

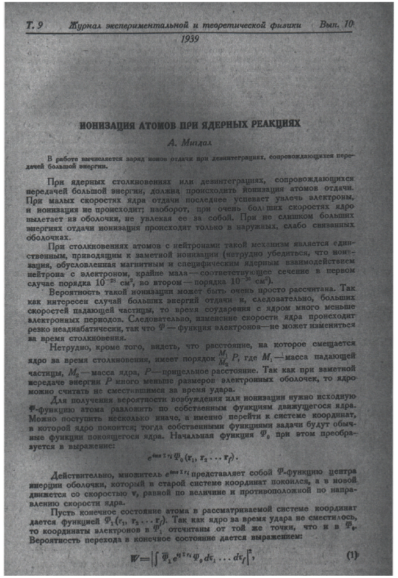
Migdal In Galactic Dark mAtter Exploration

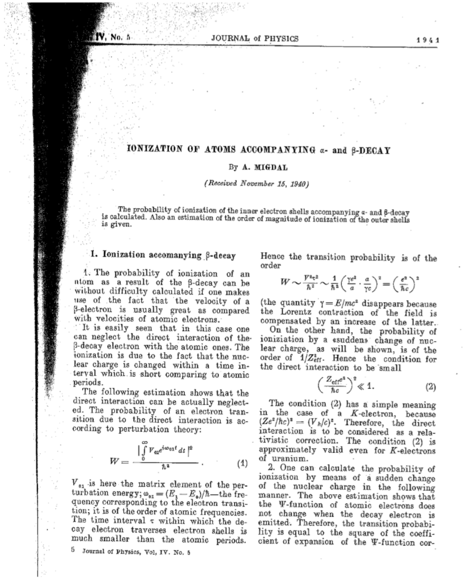
- Part of the STFC project for the Liquid Xenon R&D towards G3 DM future experiment
  - Phase I (18 months, funded):
    - Create a dedicated environment for an unambiguous first observation with a suppressed background
    - Clearly observe the effect with energies available from using a high flux DT 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 ?





A. Migdal publications:

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

First observations of the Migdal effect in :

- Alpha decay [3,4]
- Beta decay [5]
- Positron decay [6]
- 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] M.S. Rapaport, F. Asaro and I. Pearlman *K-shell electron shake-off accompanying alpha decay, PRC* ***11****, 1740-1745 (1975)*

[4] M.S. Rapaport, F. Asaro and I. Pearlman *L- and M-shell electron shake-off accompanying alpha decay, PRC* ***11****, 1746-1754 (1975)*

[5] C. Couratin et al. , *First Measurement of Pure Electron Shakeoff in the β Decay of Trapped $^{6}He^{+}$ Ions, PRL* ***108****, 243201 (2012)*

[6] 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

Huge attention of the DM community to the Migdal Effect

Papers in the past from: LUX, XENON1T, EDELWEISS, CDEX-1B SENSEI

Including targets:

Ge, Si, Xe and Ar

and claiming sensitivity to WIMPs with mass below 1 GeV

1. arXiv:2009.05939 [pdf, ps, other] physics.ins-det hep-ex
Detection capability of Migdal effect for argon and xenon nuclei with position sensitive gaseous detectors
Authors: Kiseki D. Nakamura, Kentaro Miuchi, Shingo Kazama, Yutaro Shoji, Masahiro Ibe, Wakutaka Nakano
Abstract: Migdal... ▽ More
Submitted 13 September, 2020; originally announced September 2020.
Comments: 13 pages, 13 figures

2. arXiv:2007.10965 [pdf, other] hep-ph hep-ex
Model-independent determination of the Migdal effect via photoabsorption
Authors: C. -P. Liu, Chih-Pan Wu, Hsin-Chang Chi, Jiunn-Wei Chen
Abstract: The Migdal... ▽ More
Submitted 21 July, 2020; originally announced July 2020.
Comments: 6 pages, 3 figures

3. arXiv:2006.12529 [pdf, other] hep-ph astro-ph.HE
Prospects of Migdal Effect in the Explanation of XENON1T Electron Recoil Excess
Authors: Ujjal Kumar Dey, Tarak Nath Maity, Tirtha Sankar Ray
Abstract: ...signal significance over the Standard Model prediction. In this paper we sketch the prospects of explaining such an excess from Migdal ionization events with below threshold nuclear recoil energies. Interestingly, these are expected to show signal events in the ballpark energy scale of the observed excess. We demonstrate that the observed signal can be repr... ▽ More
Submitted 8 July, 2020; v1 submitted 22 June, 2020; originally announced June 2020.
Comments: 9 pages, 2 figures; typos fixed, references added, plots & discussions updated

4. arXiv:2006.02453 [pdf, other] hep-ph astro-ph.CO hep-ex
Migdal effect and photon Bremsstrahlung: improving the sensitivity to light dark matter of liquid argon experiments
Authors: Giovanni Grilli di Cortona, Andrea Messina, Stefano Piacentini
Abstract: The search for dark... ▽ More
Submitted 3 June, 2020; originally announced June 2020.
Comments: 30 pages, 13 figures, 2 tables

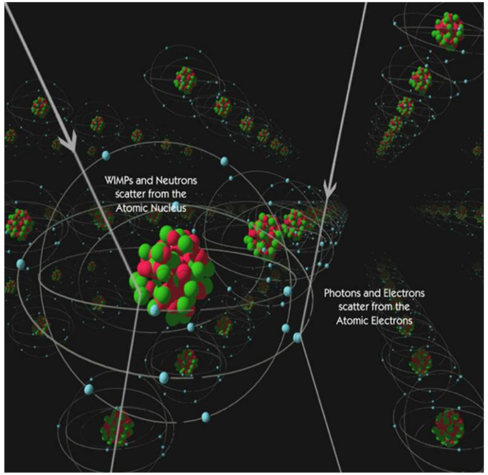
5. arXiv:1912.13484 [pdf, ps, other] cond-mat.mes-hall hep-ph nucl-th doi 10.1103/PhysRevD.102.043007
Describing Migdal effects in diamond crystal with atom-centered localized Wannier functions
Authors: Zheng-Liang Liang, Lin Zhang, Fawei Zheng, Ping Zhang
Abstract: Recent studies have theoretically investigated the atomic excitation and ionization induced by the dark... ▽ More
Submitted 26 August, 2020; v1 submitted 11 December, 2019; originally announced December 2019.
Comments: latest version
Journal ref: Phys. Rev. D 102, 043007 (2020)

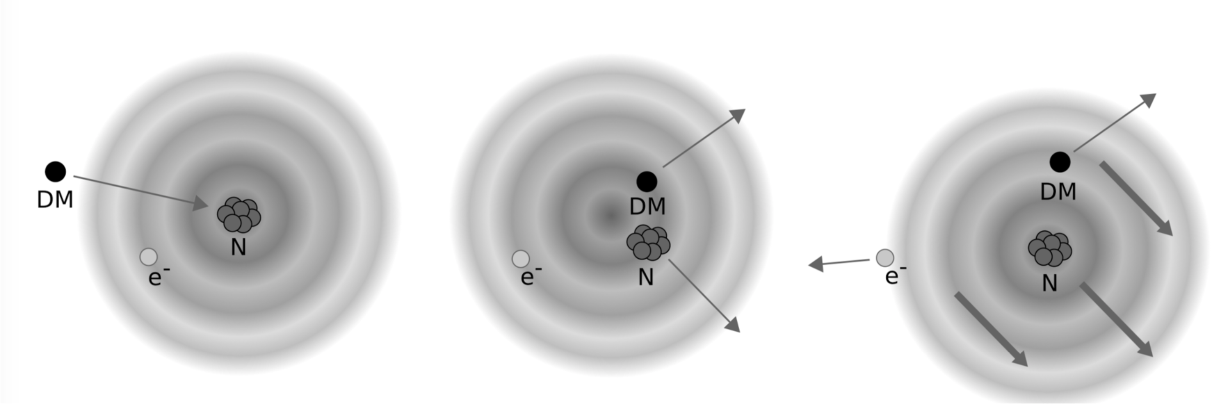
6. arXiv:1911.05249 [pdf] hep-ex physics.ins-det doi 10.1088/1742-6596/1468/1/012070
Results of direct dark matter detection with CDEX experiment at CJPL
Authors: Hao Ma, Ze She, Zhongzhi Liu, Litao Yang, Qian Yue, Zhi Zeng, Tao Xue
Abstract: The China Dark... ▽ More
Submitted 3 December, 2019; v1 submitted 12 November, 2019; originally announced November 2019.
Comments: for the TAUP2019 proceedings at Journal of Physics: Conference Series
Journal ref: J. Phys.: Conf. Ser. 1468 012070 (2020)

7. arXiv:1908.00012 [pdf, other] hep-ph astro-ph.CO hep-ex doi 10.1103/PhysRevD.101.076014
Electron Ionization via Dark Matter-Electron Scattering and the Migdal Effect
Authors: Daniel Baxter, Yonatan Kahn, Gordan Krnjaic
Abstract: There are currently several existing and proposed experiments designed to probe sub-GeV dark... ▽ More
Submitted 8 August, 2019; v1 submitted 31 July, 2019; originally announced August 2019.
Comments: v2: typos fixed, clarifications added, improved discussion of XENON1T effective exposure. v1: 11 pages, 5 figures, 1 table
Report number: FERMILAB-PUB-19-257-A
Journal ref: Phys. Rev. D 101, 076014 (2020)

Only last two months

What the Migdal effect is and why it matters in DM searches ?



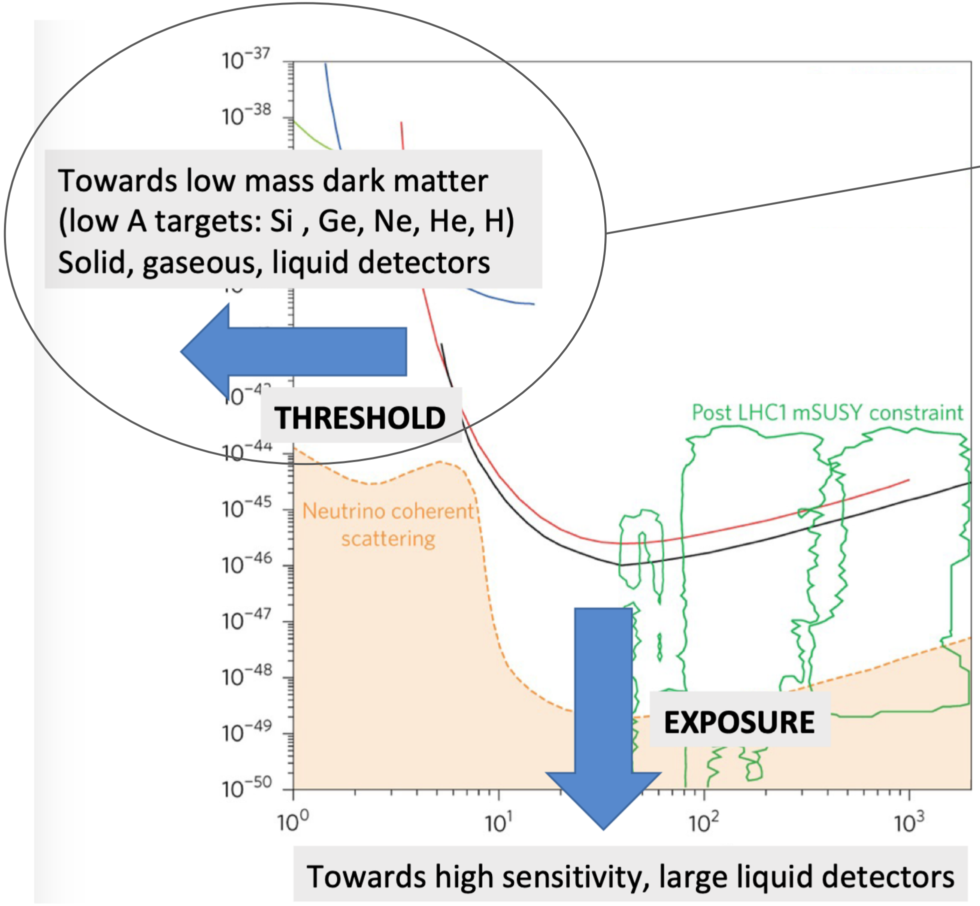


Migdal Effect - nucleus moves relative to the electron cloud. Individual electron might be left behind leading to ionisation.

- DM searches use signal from nuclear recoils as a signature of the DM interaction with the detector medium
- Targets with heavy elements such as Xe and Ar are immune to light WIMPs unless Migdal effect is experimentally confirmed

- M. J. Dolan et al., *Directly detecting sub-GeV dark matter with electrons from nuclear scattering;* *Phys. Rev. Lett. 121, 101801 (2018)*
- M. Ibe et al., *Migdal Effect in Dark Matter Direct Detection Experiments;* *J. High Energ. Phys. 2018, 194 (2018)*

What the Migdal effect is and why it matters in DM searches ?



Parameter space reachable exclusively by the detectors with a low mass target material

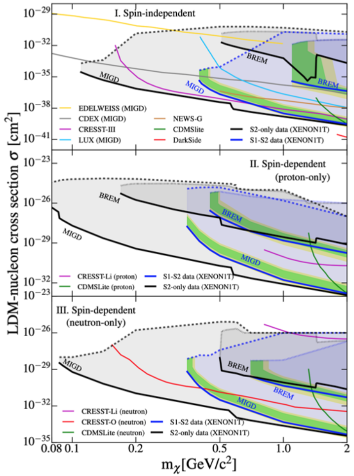
BUT not any longer

if the Migdal experimentally is confirmed in elements such as Xe and Ar

and as a bonus it comes for free !

Ionisation electrons treated so far as background can therefore become a signature of the signal from the low mass dark matter particles.

Dark Matter searches and Migdal Effect
-> sensitivity extension to low mass region

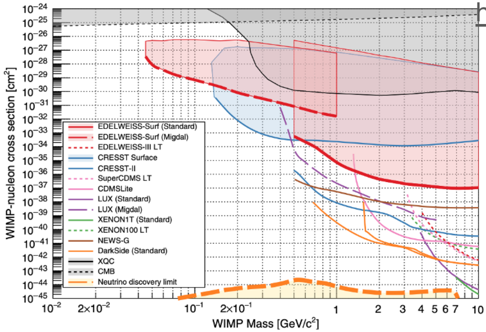


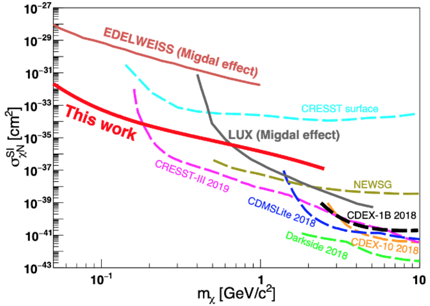
LUX (Xenon)
"Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data"
https://arxiv.org/pdf/1811.11241.pdf

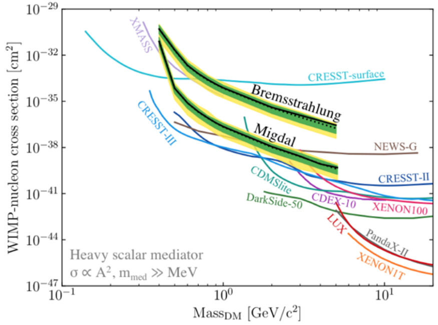
XENON1T (Xenon)
"A Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T"
https://arxiv.org/pdf/1907.12771.pdf

EDELWEISS (Germanium)
"Searching for low-mass dark matter particles with a massive Ge bolometer operated above-ground"
https://arxiv.org/abs/1901.03588

CDEX-1B (Germanium)
"Constraints on Spin-Independent Nucleus Scattering with sub-GeV Weakly Interacting Massive Particle Dark Matter from the CDEX-1B Experiment at the China Jin-Ping Laboratory"
https://arxiv.org/pdf/1905.00354.pdf

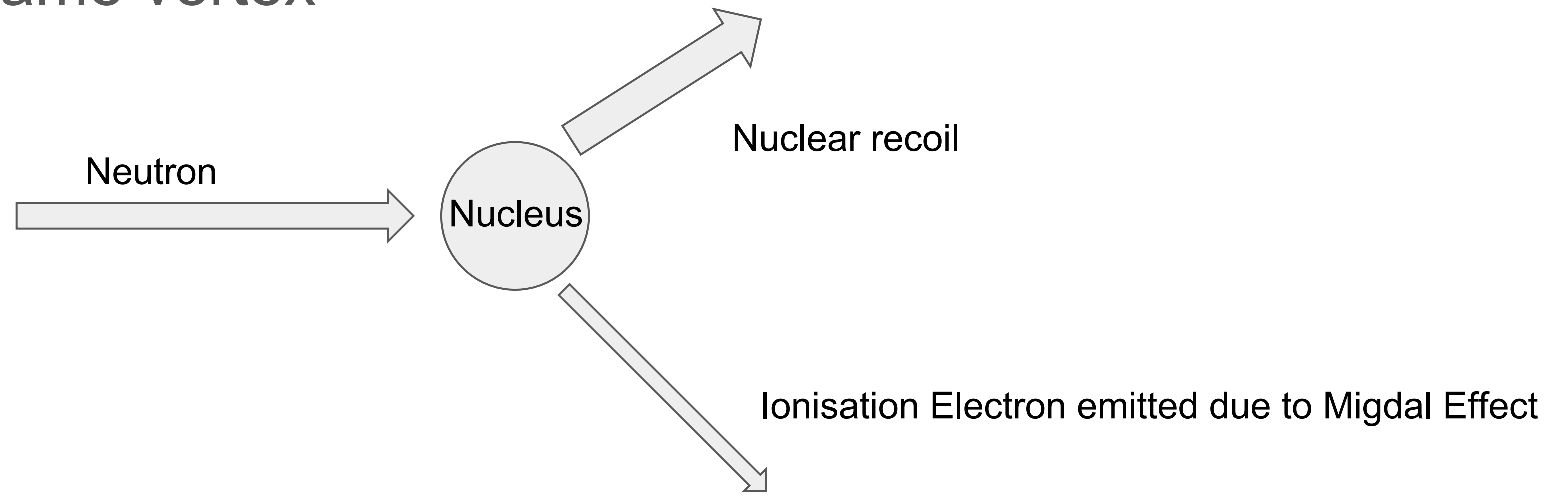






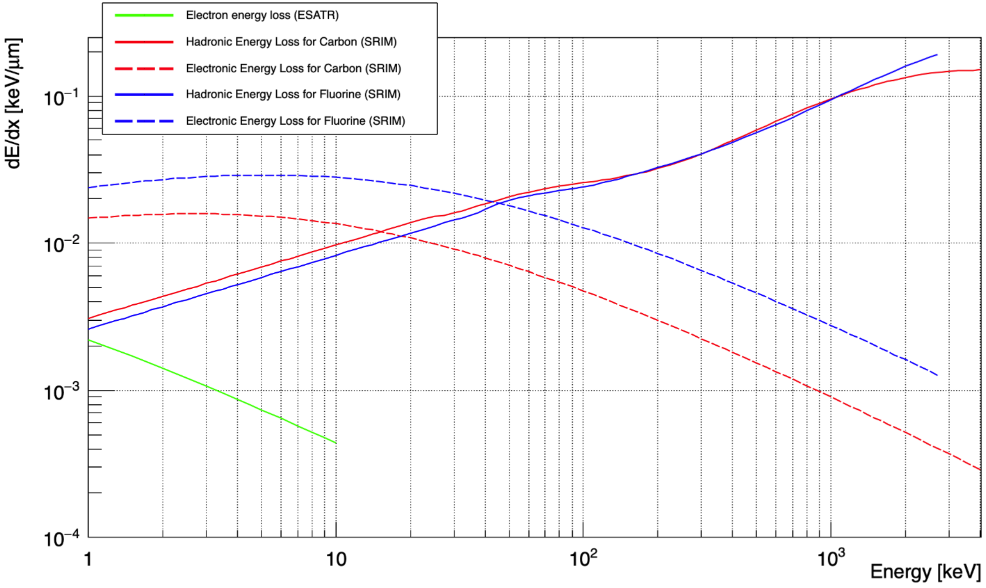
Experimental Goal

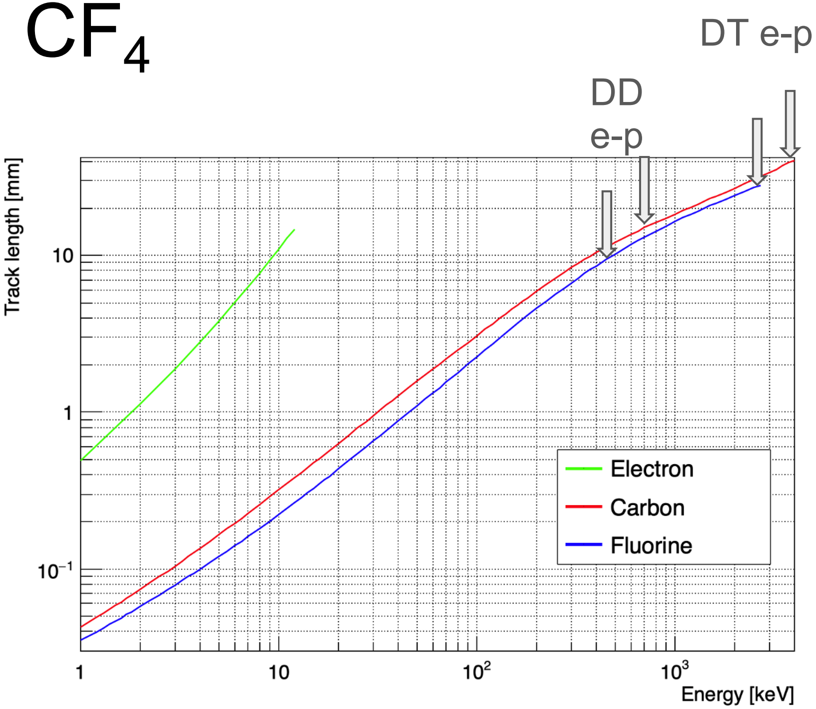
Observation of two simultaneously created tracks of the ionisation electron and the nuclear recoil originating from the same vertex



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

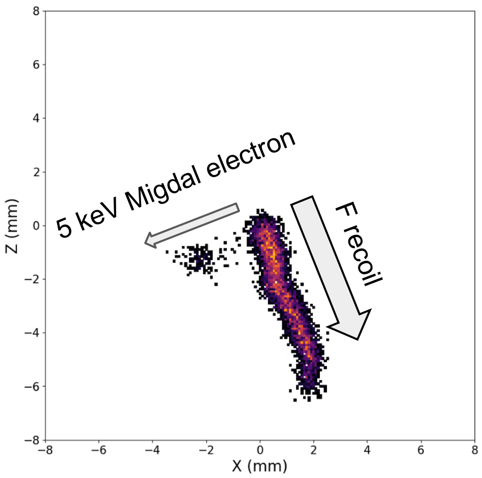
dE/dx distribution and track length for electrons and nuclear recoils in low pressure CF_4

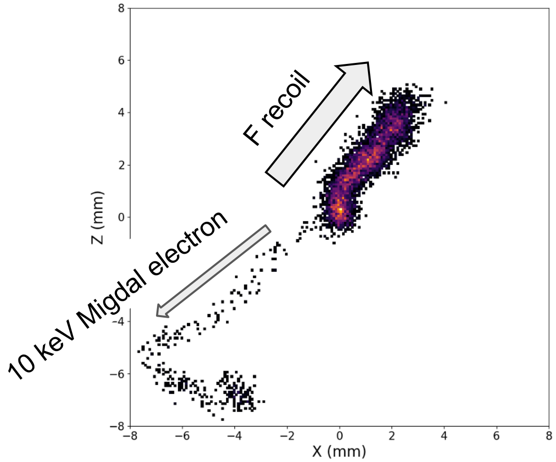




- dE/dx for the nuclear recoils decreases with the energy which is opposite for the electrons
- Electrons with energies 5 - 10 keV have track lengths between 4 - 10mm
- Nuclear recoils with energies E > 150 keV have track length > 4 mm

Detector operation and the signal signature

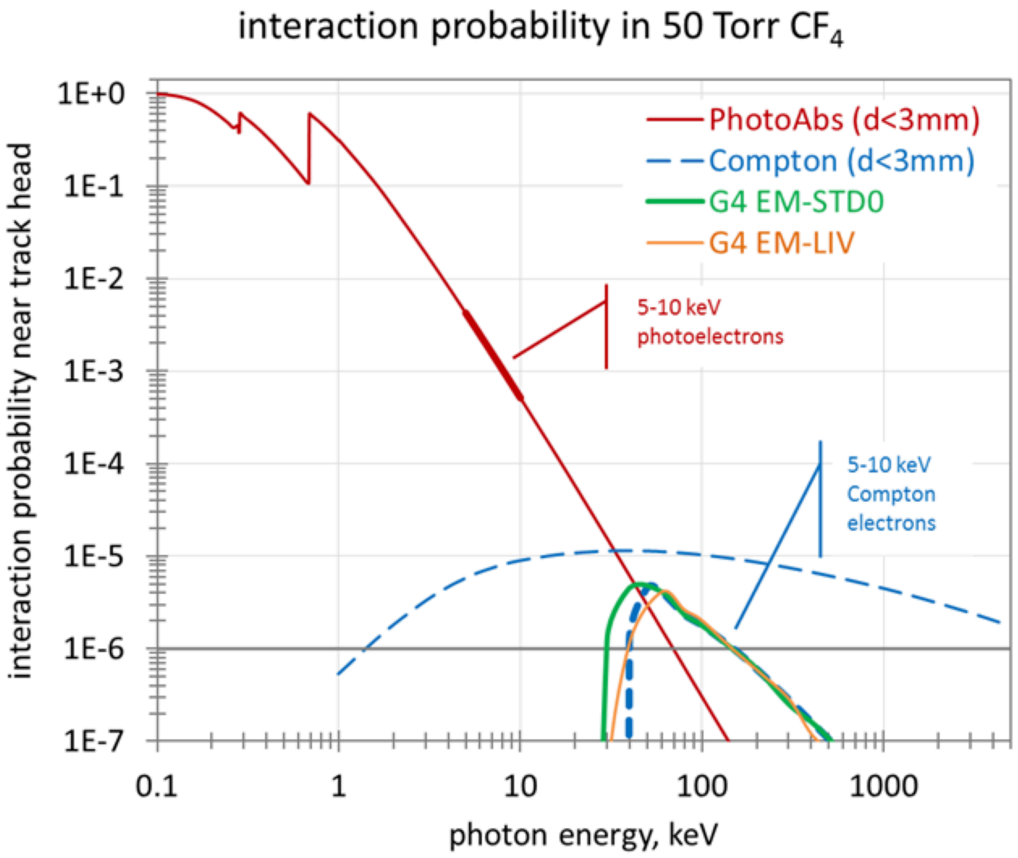




- Example of the Migdal effect with 250 keV Fluorine recoil & 5 (10) keV electron (after 10 mm of drift in CF_4 at 50 Torr)
- Simulated with SRIM and garf++ (recoil) and DEGRAD (electron)
- Clear “fork-like” topology
- Clear different dE/dx distribution for both tracks
  - Opposite head-and-tail ionisation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

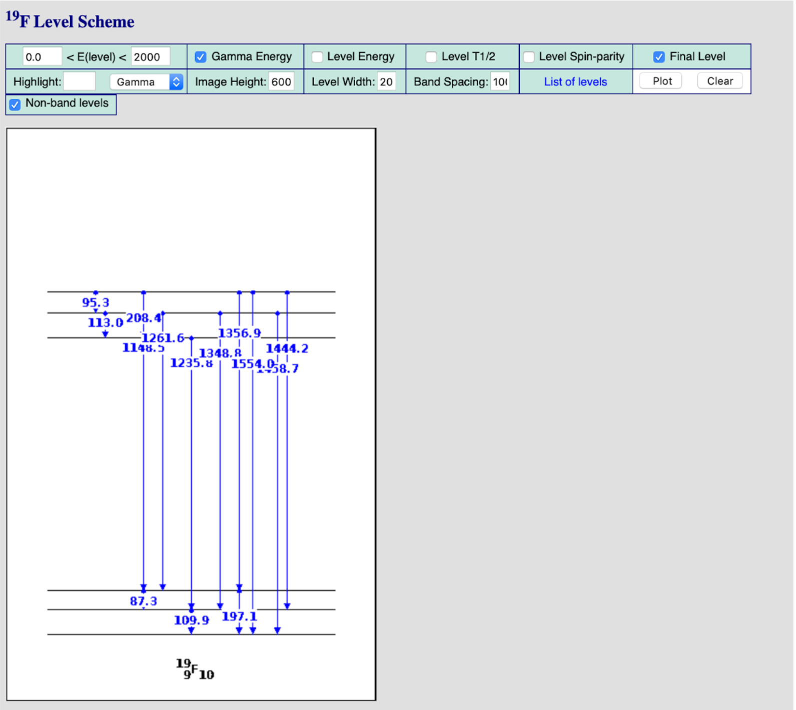
➔ At this moment we do not assume any specific angular distribution of the Migdal electron emission. We will have capability to measure it.

Signal background



Gamma-rays from inelastic scattering on :

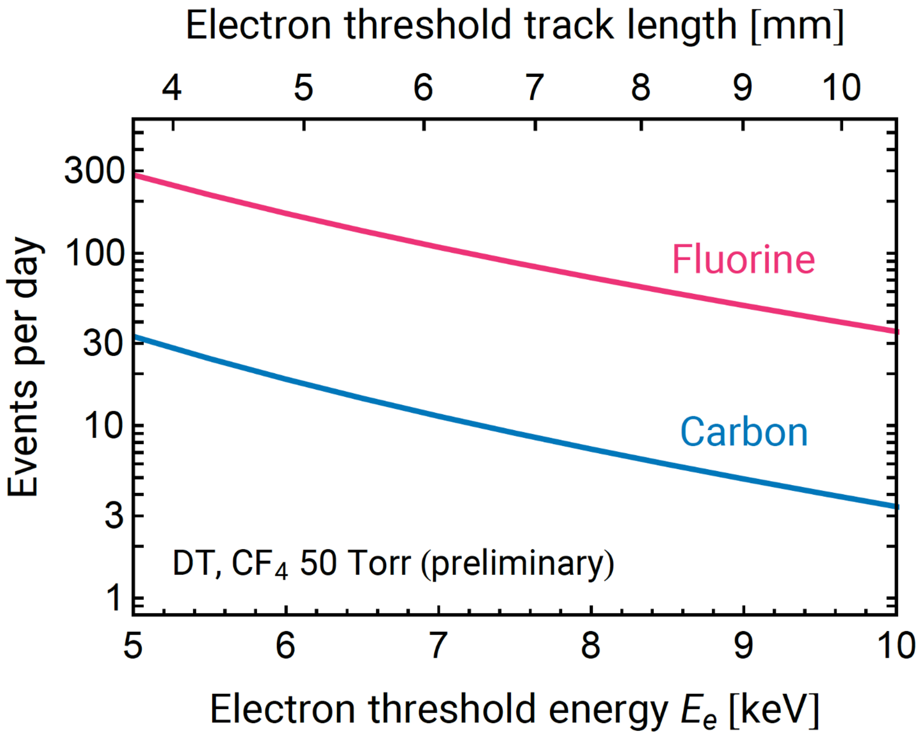
- Carbon : several lines E > 4.4 MeV
- Fluorine : Several low energy lines with most frequent - 109.9 and 197.1 keV



Sources of background

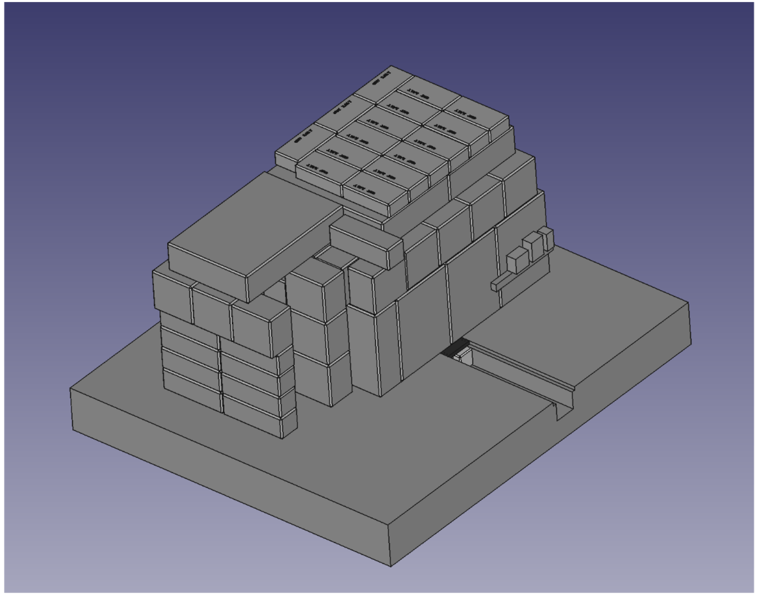
Recoil-induced δ-rays	δ electron from NR track head
Particle-induced X-ray Emission (PIXE)	
X-ray emission	Photoelectron near NR track head
Auger electrons	Auger electron near NR track head
Bremsstrahlung processes	
Quasi-Free Electron (QFEB)	Photoelectron near NR track head
Secondary Electron (SEB)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

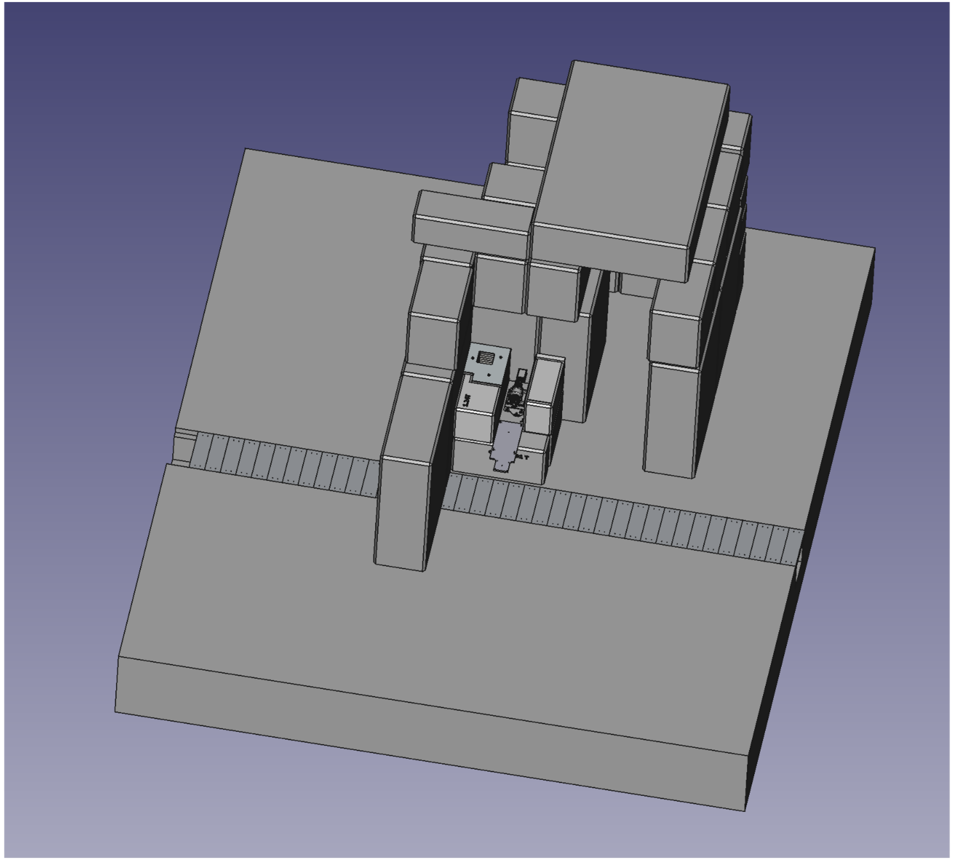
Expected number of Migdal events in CF_4 using DT generator



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.

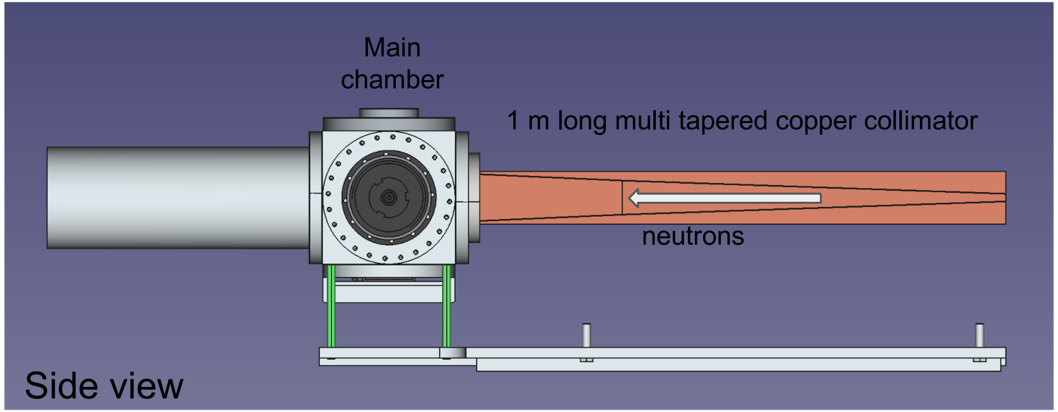
DT and DD neutron generators, beam collimation and shielding

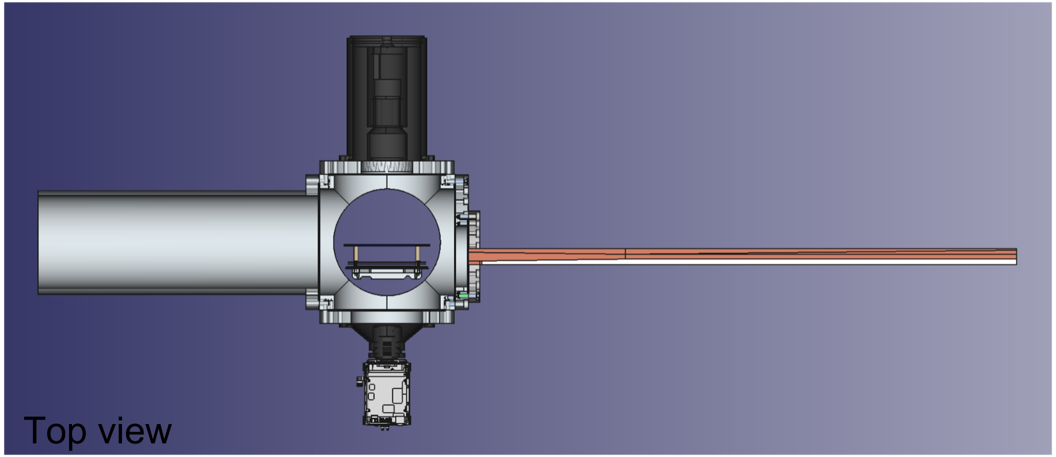




- DT neutron generator:
  E_n=14.1 MeV, flux 10^{10} n/s
- DD neutron generator:
  E_n=2.45 MeV, flux 10^9 n/s
- Both generators from Adelphi (USA)

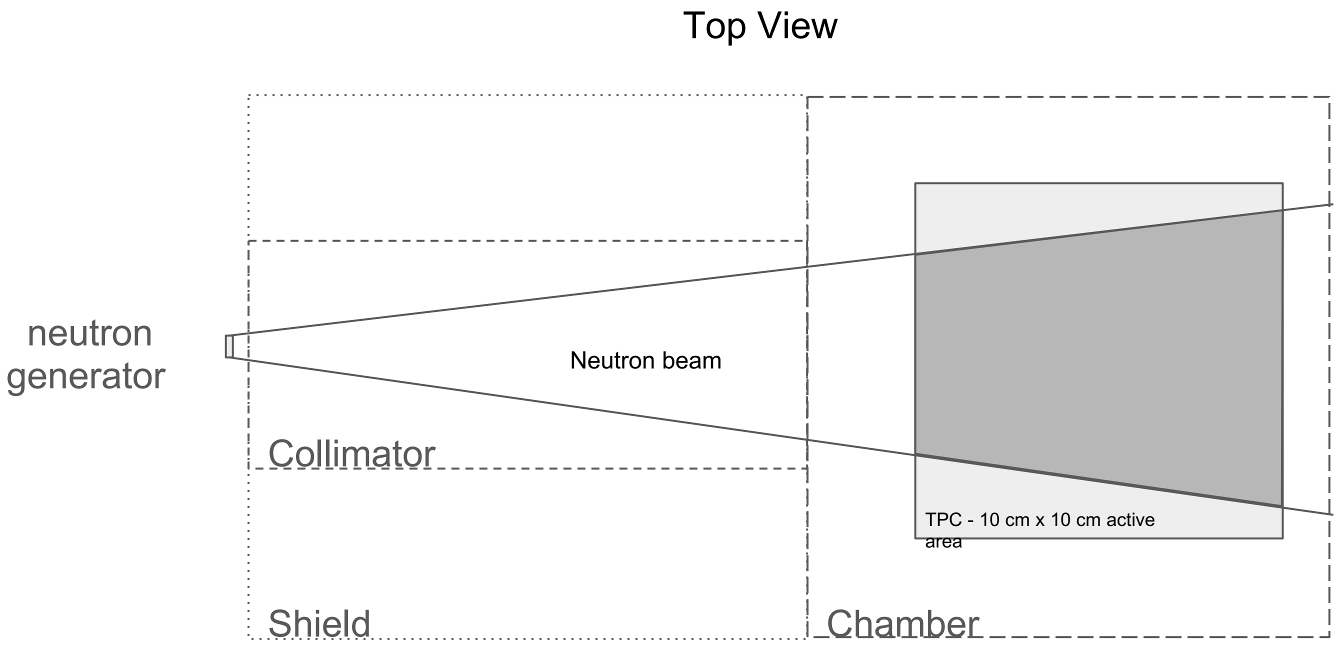
DT and DD neutron generators, beam collimation and shielding



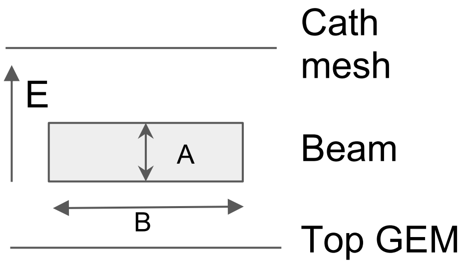


- Collimator length : 1 m
- Material : hard copper (brass)
- Rate of neutrons from DT generator at the front of the TPC: ~ 400 kHz
- Events rate ~ 60 Hz

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



Side view at the rear of sensitive volume



A - at the entrance : 1.8 cm

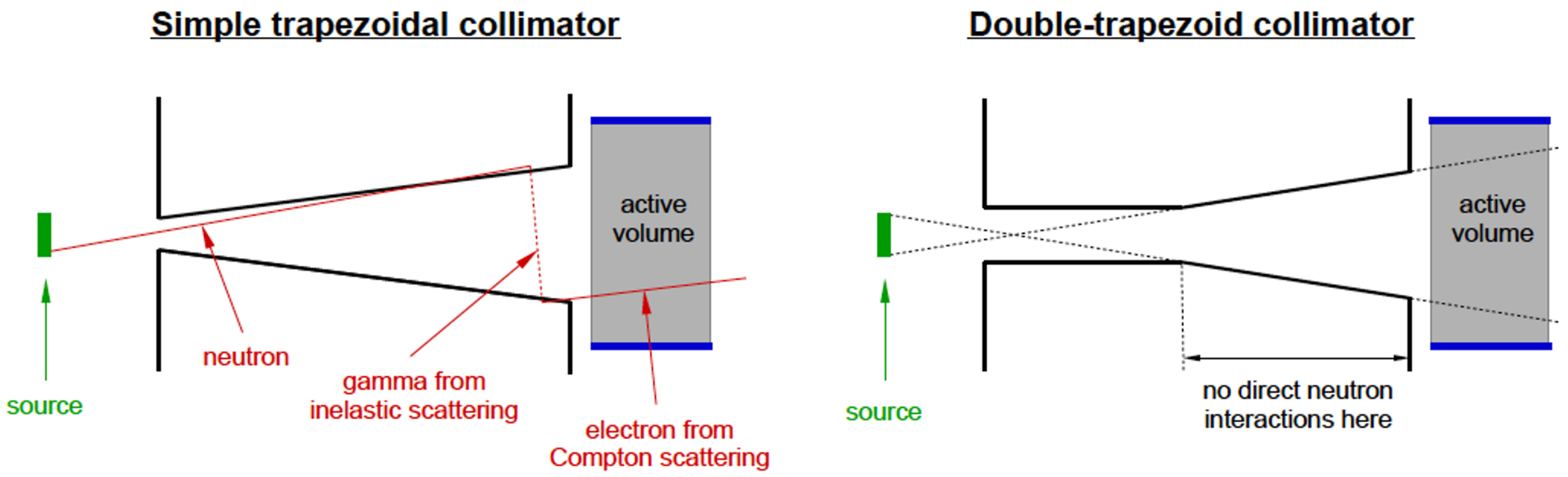
B - at entrance: 9.6 cm

A - at the exit : 2.1 cm

B - at exit : 10.5

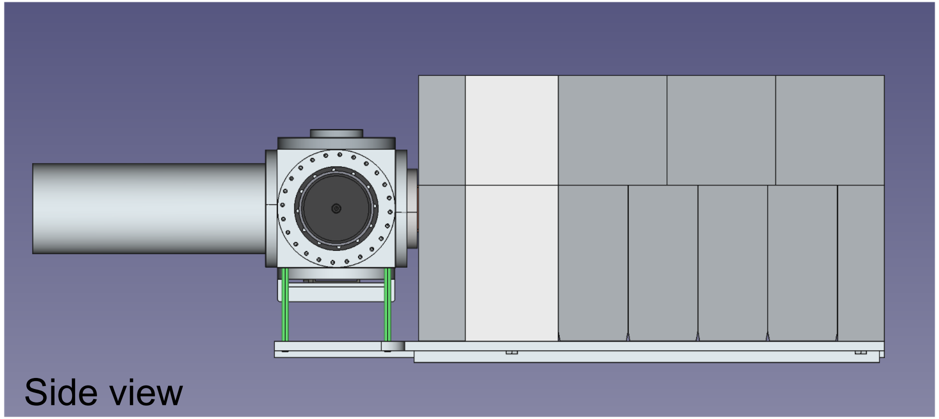
Collimator : solid block of copper with machined tunnel for neutrons
Shield : blocks of Fe, Borated Polyethylene and Pb
Chamber : Al

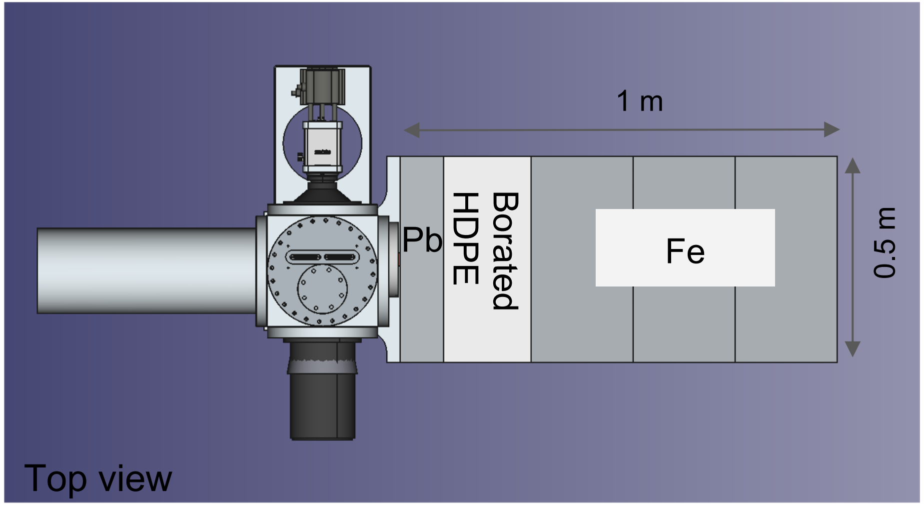
DT and DD neutron generators , beam collimation and shielding



- 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 %

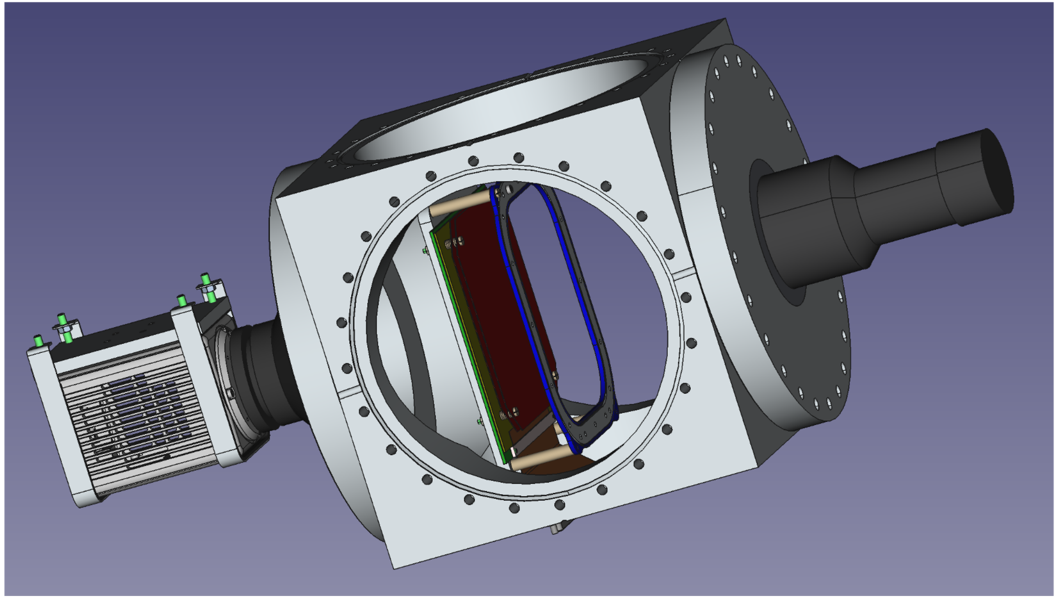
DT and DD neutron generators, beam collimation and shielding

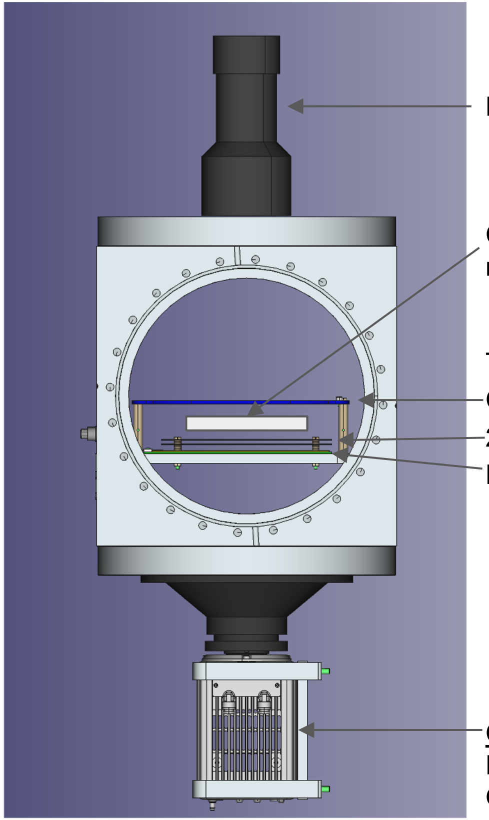




- Fe - slows down fast neutrons
- Borated HDPE - captures neutrons
- Pb - stops gamma rays
- Reduction of neutron flux : ~ 1E-6

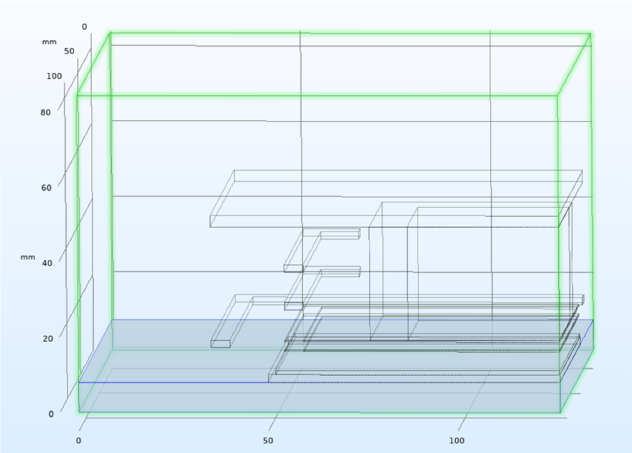
Optical Time Projection Chamber

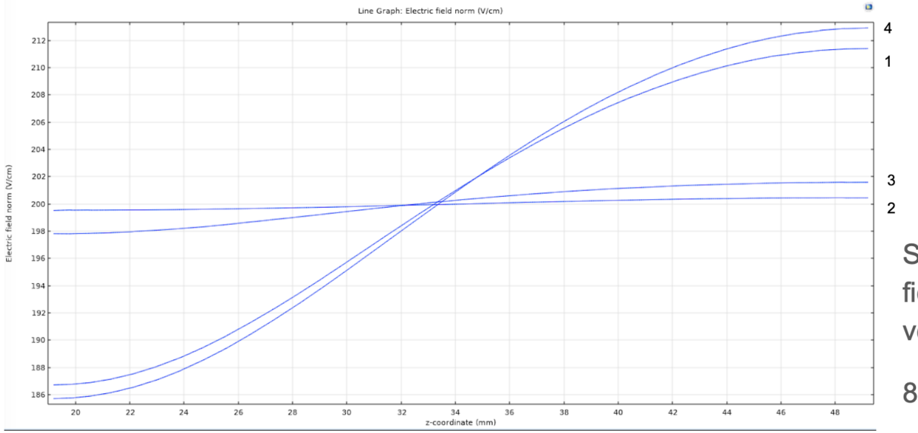




- Aluminium chamber : 25.4 cm^3
- TPC active area 10 cm x 10 cm
- Drift gap : 3 - 5 cm (yet to be optimised)
- Amplification with 2 x standard glass GEM
- ITO plate 15 cm x 15 cm with 120 readout strips

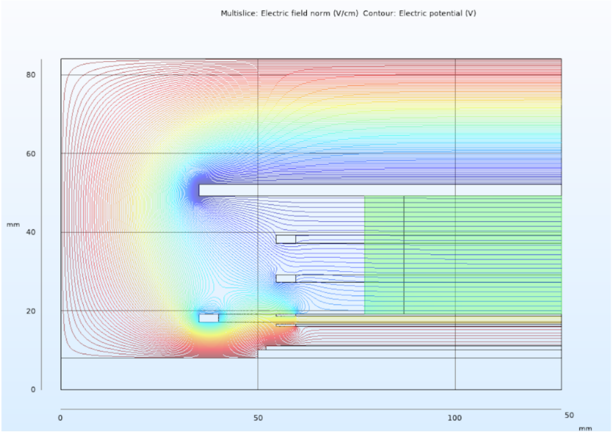
Optical Time Projection Chamber - Electric field in 3 cm drift gap

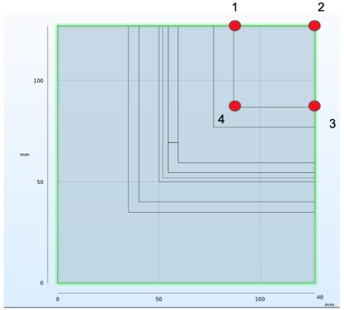




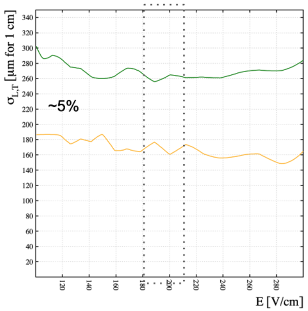
Smaller fiducial volume

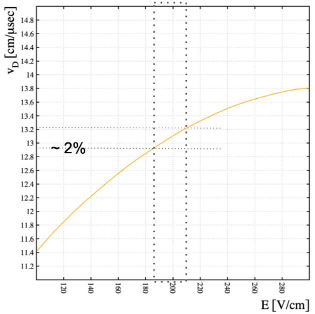
8 cm x 8 cm





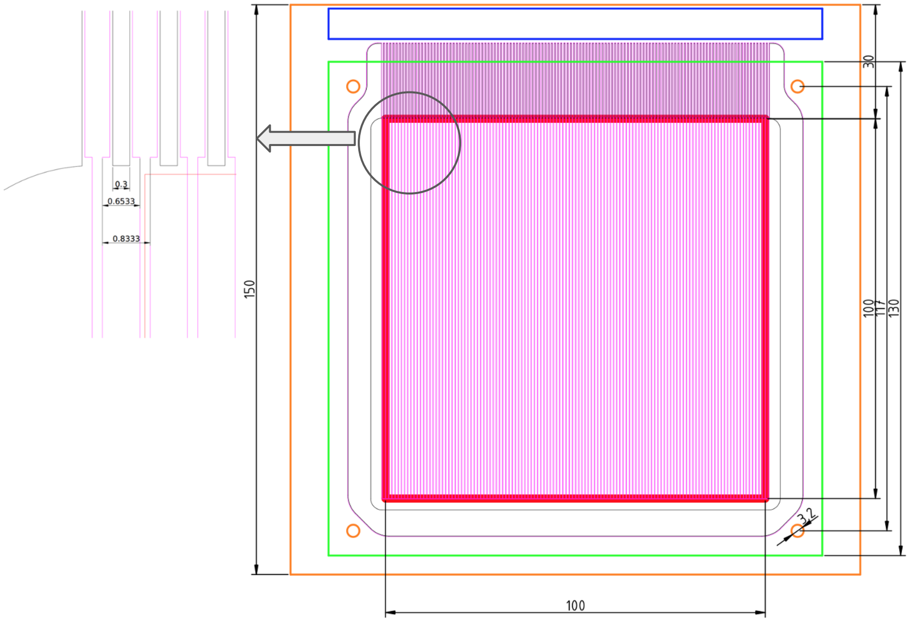
Electron transport in 50 Torr 100% CF4

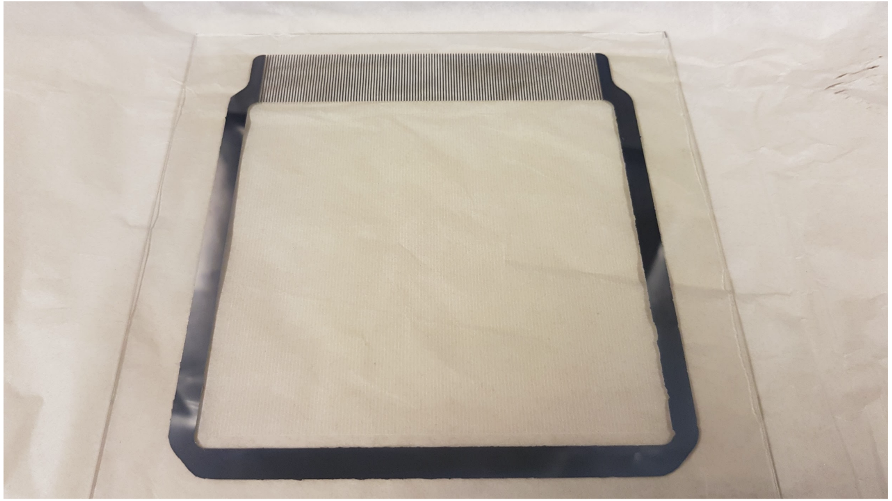


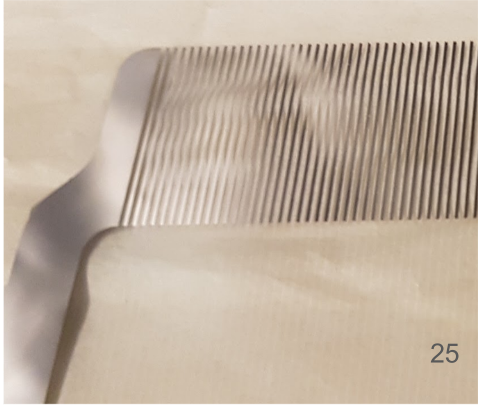


We want to use as little material as possible in the TPC and keep the electric field uniform.

Optical Time Projection Chamber - charge signal redout



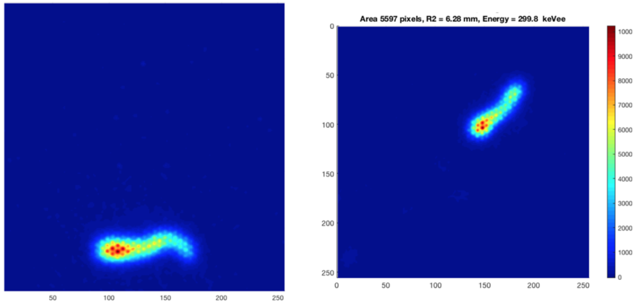




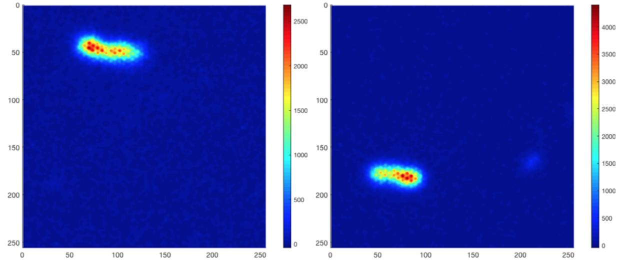
- 1.1 mm thick ITOGLASS 04, resistance 4 Ohm/square
- Metallised with Cr and Aluminium for wire bonding
- 120 strips connected to Acqiris 60 channel digitizer
- Digitisation of pulses with 2 ns sampling rate

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

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

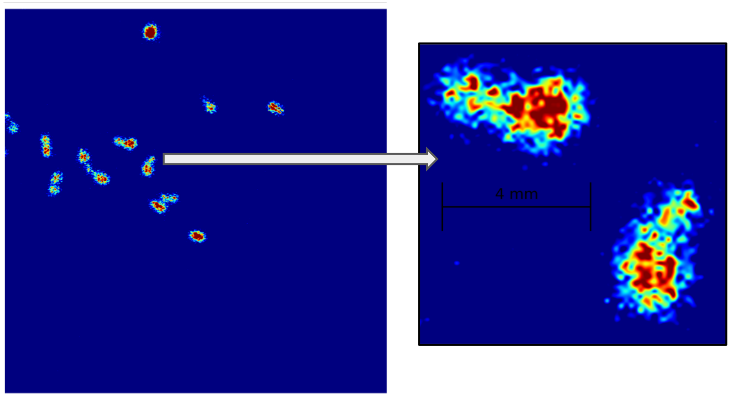
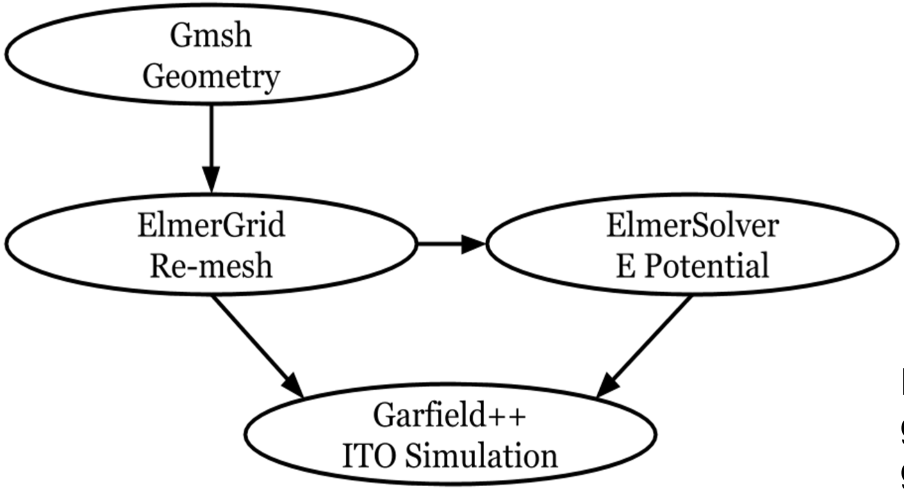
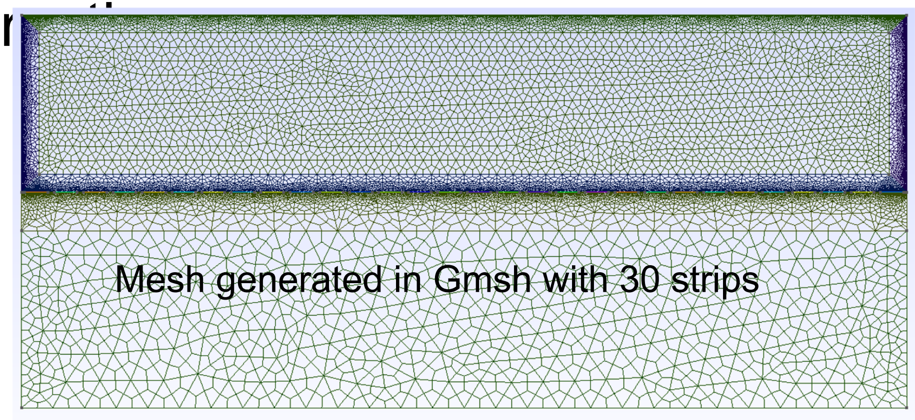


Image of low energy electron tracks from ^{55}Fe source in CF_4 at 50 Torr.
Tracks' head and tail structure is clearly resolved.

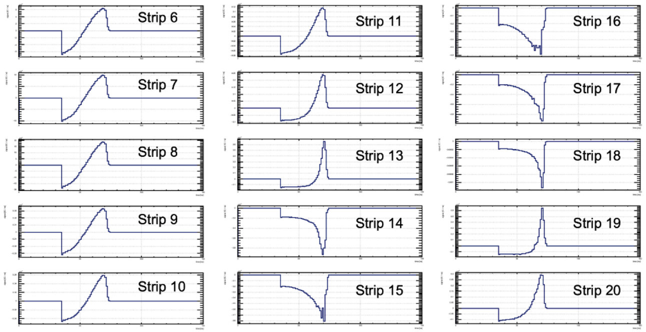
- 2D imaging with low noise CMOS camera

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



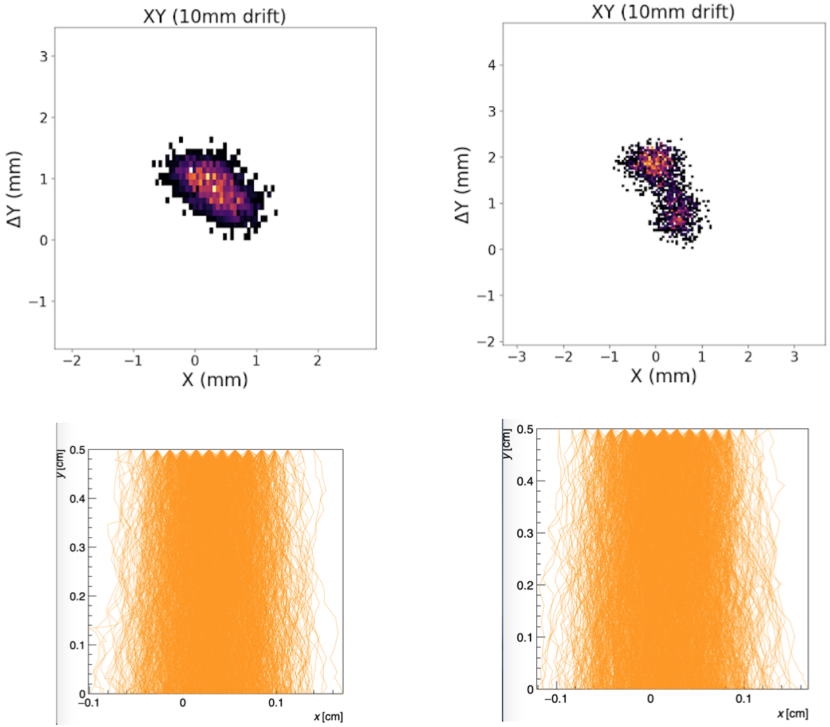


Raw pulses generated with garf ++

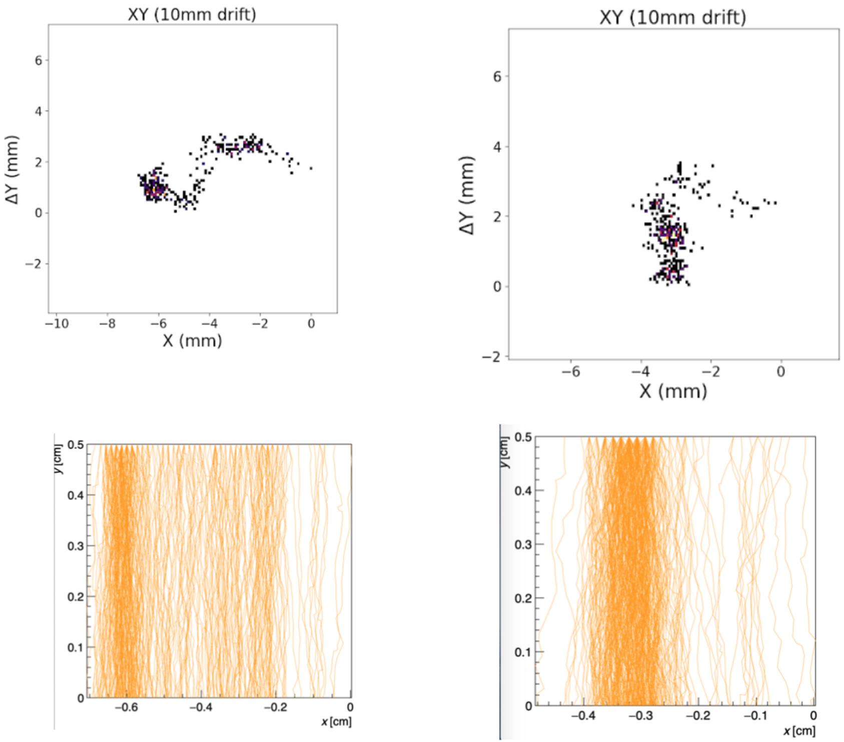


- Third coordinate reconstruction with charge readout using high granularity pattern of strips providing timing information

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

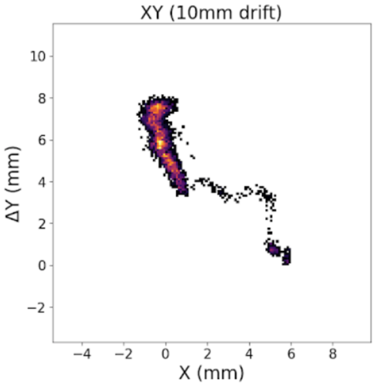


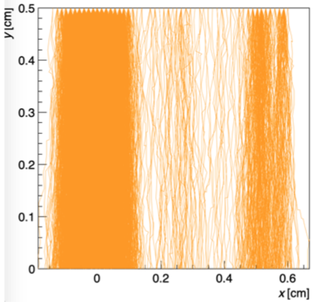
100 keV F recoils



10 keV electrons

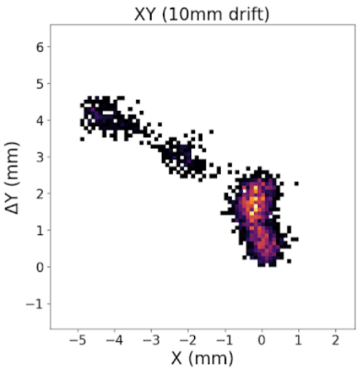
The Migdal effect in nuclear scattering: example of tracks - Migdal events

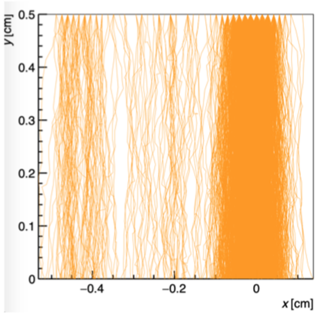




200 keV F &

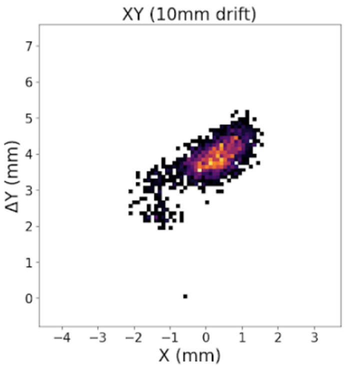
10 keV electron

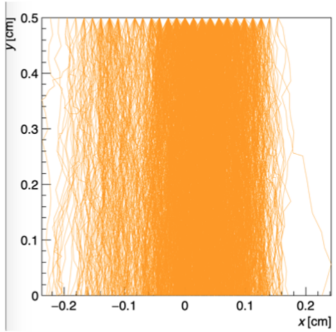




100 keV F &

10 keV electron

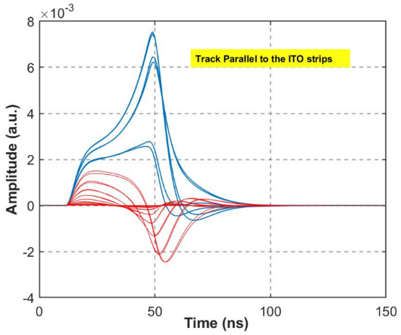


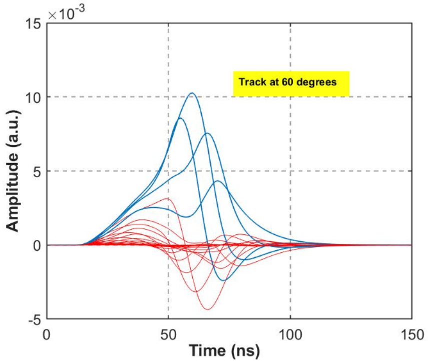


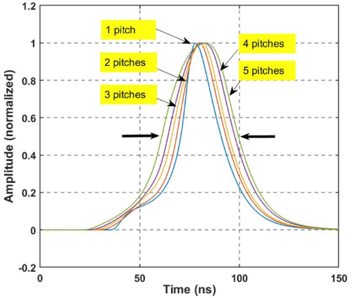
100 keV F &

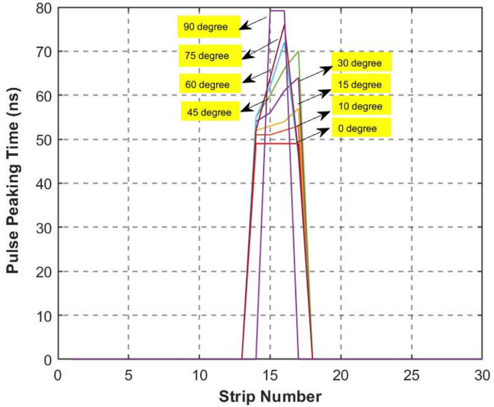
5 keV electron

Observation of the Migdal effect with 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 high granularity strips providing timing information

Proposal for a complementary observation of the Migdal effect in Ar and Xe - by K. D. Nakamura et al. (arXiv:2009.05939v1) -

- Neutron source : 565 keV neutrons from $^{7}Li(p,n)^{7}Be$ reaction using proton beam at the AIST facility in Japan
- Targets : 1 atm Ar and 8 atm Xe
- Signal : “Two-cluster” event topology
  - Detection of two signals from nuclear recoil and from characteristic X-ray associated with an atomic de-excitation following emission of the Migdal electron
- Detection technique : TPC using EL signal amplification stage with PMTs
- Background : Accidental coincidence, gamma-rays from inelastic scattering

Fixed energy expected for cluster B

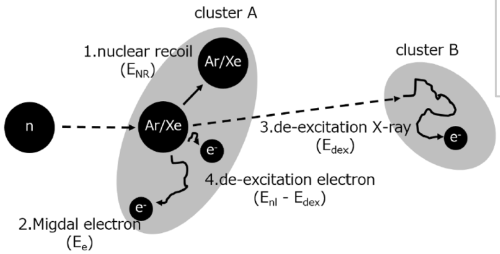


Fig. 1 Shcematis mechanism of the reactions related to the Migdal effect.

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.