Observation of the Migdal effect from nuclear scattering using a low pressure Optical-TPC

Pawel Majewski

Rutherford Appleton Laboratory

RD51 mini-week, CERN, 10-15 Jan 2020

Outline

1. Migdal Effect and its relevance to Dark Matter searches
2. Migdal project : organisation and goals
3. Current status and plans for this year

Publications by Arkady Migdal : http://www.itp.ac.ru/en/persons/migdal-arkady-beinusovich/

136. A. Migdal, *Ionizatsiya atomov pri α- i β-raspade*, ZhETF, 11, 207-212 (1941) [A. Migdal, *Ionization of atoms accompanying α- and β-decay*, J. Phys. Acad. Sci. USSR 4(1-6), 449-453 (1941)].

137. A. Migdal, J. Pomeranchuk, *Note on the Ends of the Mesotron Tracks Observed in an Expansion Chamber*, Phys. Rev. 57(10), 934-934 (1940), Scopus: 2-s2.0-36149008739.

138. A. Migdal, I. Pomeranchuk, *O kontse treka mezotrona v kamere Vil'sona*, Dokl. AN SSSR, 27, 652-653 (1940) [A. Migdal, J. Pomeranchuk, *Note on the ends of the mesotron tracks observed in an expansion chamber*, C. R. (Dokl.) Acad. Sci. URSS, n. Ser. 27, 652-653 (1940)].

139. A. Migdal, *Rasseyanie ionov v paramagnetikakh*, ZhETF, 10, 5 (1940).

140. A. Migdal, *Ionizatsiya atomov pri yadernykh reaktsiyakh*, ZhETF, 9, 1163-1165 (1939).

Migdal Effect

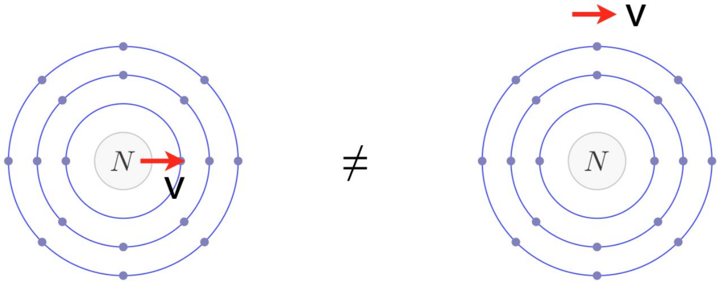
Ionization of an Atom in Nuclear Reactions

In nuclear collisions involving large energy transfer there must occur ionization of the recoil atoms. If the velocity acquired by the nucleus is not too large, then it can carry its electrons off with it, and ionization takes place only in the outer, weakly bound shells. For large velocities, on the other hand, the nucleus recoils right out of its electronic shells instead of carrying them with it.

We shall calculate the probability of ionization when a neutron collides with the nucleus (Migdal 1939). The duration of the neutron-nucleus collision is of order $\tau \sim R/v$, where R is the nuclear radius and v the neutron velocity. This time is much less than the electronic periods $\tau_{e\ell}$, so that the electron wave function is practically unchanged over the duration of the collision.

A.B. Migdal
"Qualitative Methods in Quantum Theory"
Advanced Book Classics CRC Press, 2000

Conventionally the recoiling nucleus is treated as a recoiling neutral atom however as described by Migdal in reality it takes some time for the electrons to catch up … and this may lead to atomic ionisation !



A long time ago, Migdal (1941, 1977) gave a rather simple formula for this ionisation probability. The transition probability P_i from an initial electron state i to a final electron state f is given by

$$P_i = |\langle \varphi_f(\boldsymbol{r})| \exp[\mathrm{i}(m_e/\hbar)\boldsymbol{v}_f \cdot \boldsymbol{r}]|\varphi_i(\boldsymbol{r})\rangle|^2$$

G. Baur, F. Rosel and D. Trautmann
"Ionisation induced by neutrons"
J. Phys. B: At Mol. Phys. 16 (1983) L419-L423

PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under the influence of such a "jolt" (A. B. MIGDAL 1939).

L. Landau and E. Lifshitz
"Quantum Mechanics : Non-relativistic Theory"
Volume 3

Migdal effect and Dark Matter

Migdal effect calculations reformulated by M. Ibe et al. with ionisation probabilities for atoms and recoil energies relevant to Dark Matter searches:

JHEP

PUBLISHED FOR SISSA BY SPRINGER

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Migdal effect in dark matter direct detection experiments

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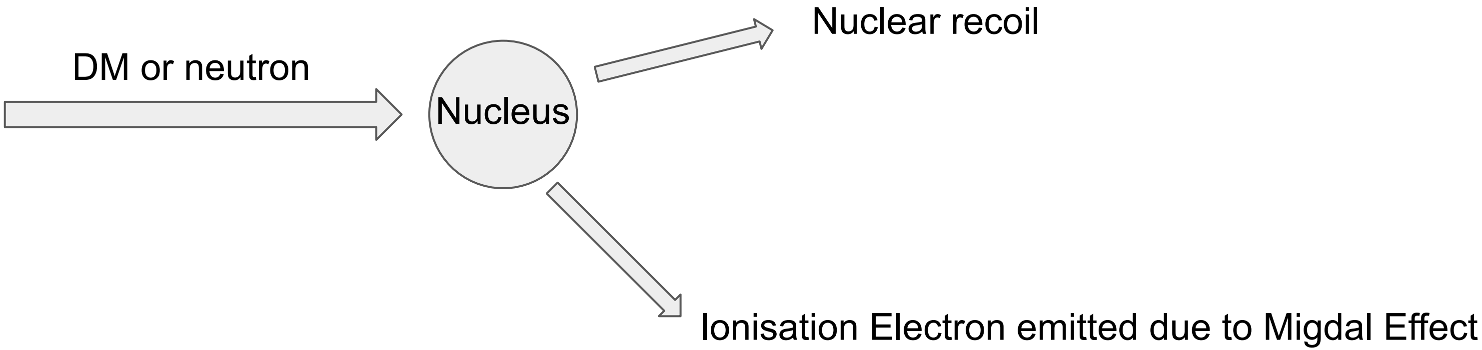
Also : M. Dolan et al. “ Directly detecting sub-GeV dark matter with electrons from nuclear scattering”; arXiv: 1711.09906v2

Migdal effect kinematics with DM and neutrons



It should be noted that the atomic recoil energy, E_R, and the electron transition energy, ΔE, are correlated through the energy-momentum conservation;

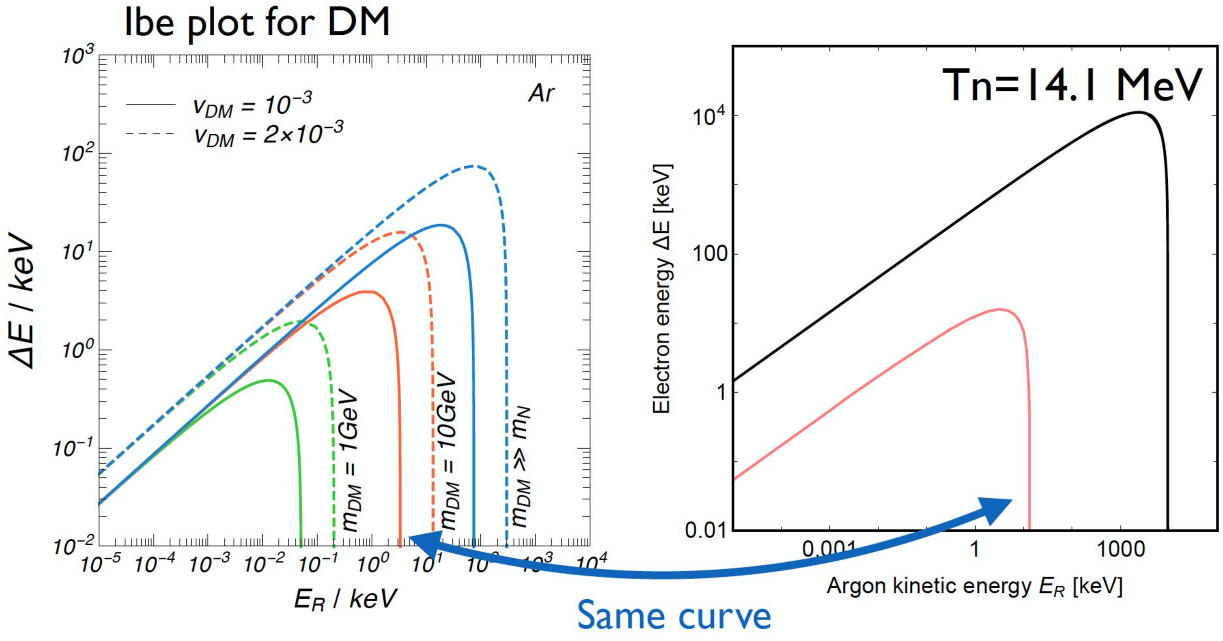
$$E_R = \frac{\mu_N^2}{2m_N} v_{DM}^2 \left(\left(1 - \sqrt{1 - \frac{2\Delta E}{\mu_N v_{DM}^2}} \right)^2 + 2(1 - \cos\theta_{CM}) \sqrt{1 - \frac{2\Delta E}{\mu_N v_{DM}^2}} \right) , \quad (94)$$

where

$$\Delta E = E_e + E_{n\ell} \, , \quad (95)$$

ΔE - electron transition energy including ionisation and de-excitation .

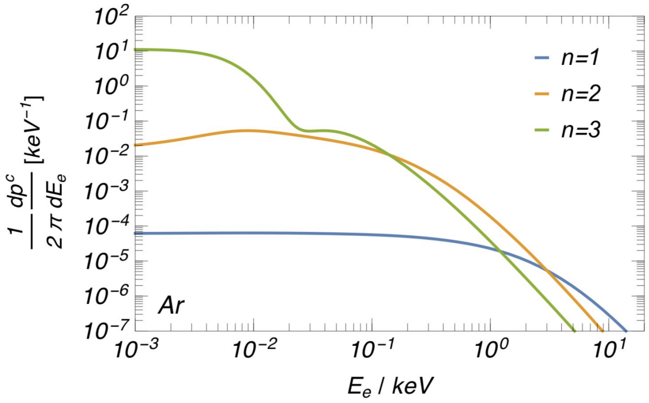
Migdal effect kinematics with DM and neutrons from DT generator

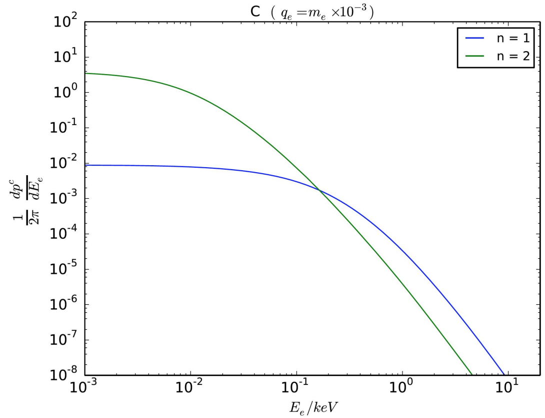


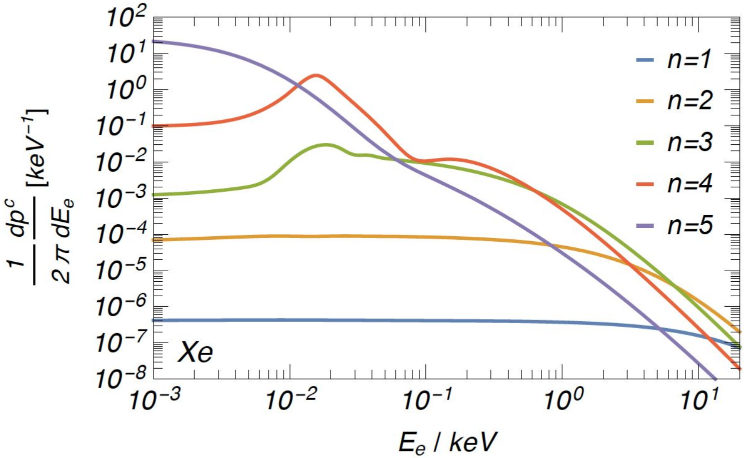
From C. McCabe

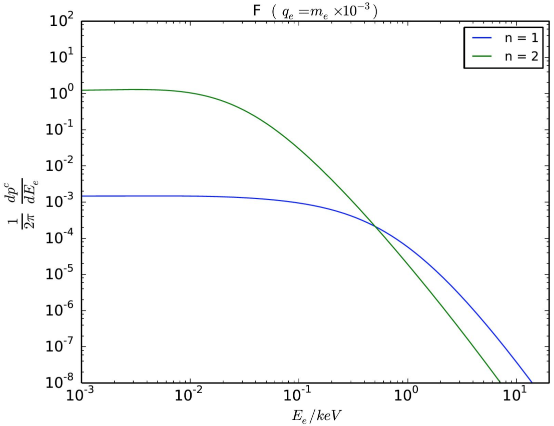
Nucleus recoil and electron energies much larger for DT neutrons

Migdal Effect probabilities calculation from M. Ibe et al.



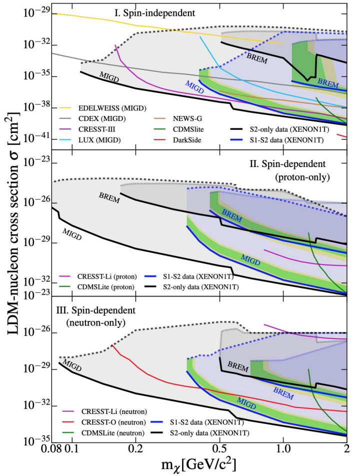






Rare event with probabilities 10^{-5} - 10^{-7} depending on the electron energy

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

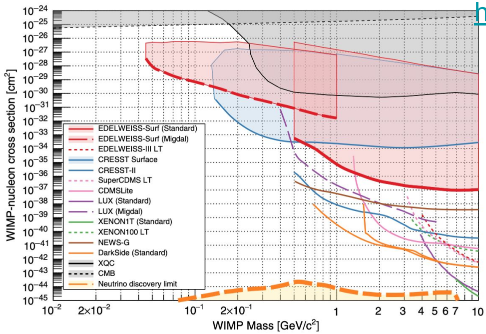


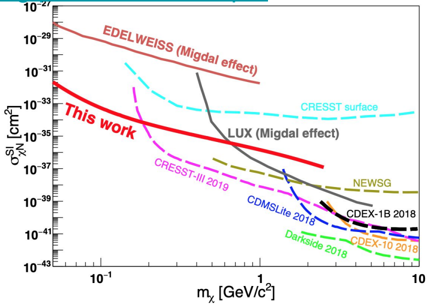
LUX (Xenon)
”Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data”
https://arxiv.org/pdf/1811.11241.pdf

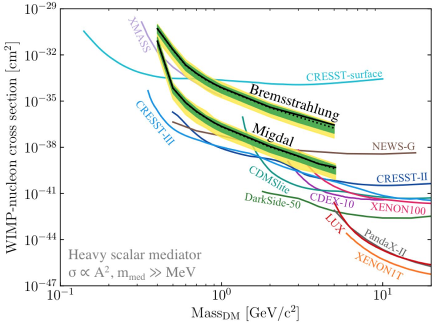
XENON1T (Xenon)
”A Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T”
https://arxiv.org/pdf/1907.12771.pdf

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



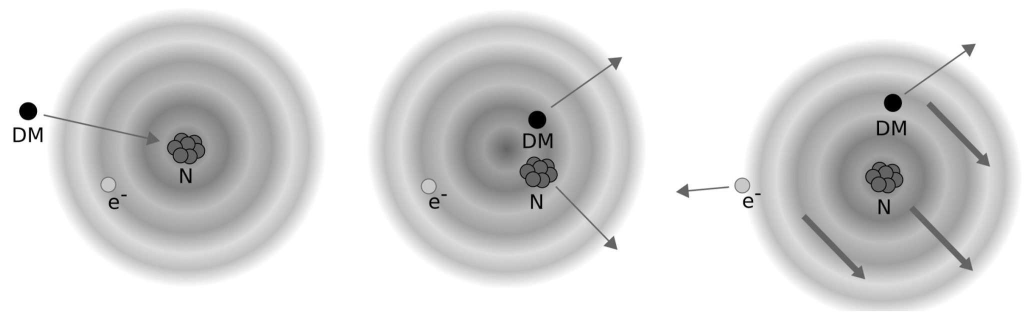




Observation of the Migdal Effect

- Create a dedicated environment for an unambiguous observation with suppress background
- Detect clearly the effect with energies available from using high flux n-generators creating high energy nuclear recoils

How ?



Experimental goal - observation of two simultaneously created tracks of the ionisation electron and the nuclear recoil originating from the same vertex

Collaboration

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

Coimbra-LIP E. Asamar, 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)** Project Engineer

Royal Holloway University of London A. Kaboth

University of New Mexico D. Loomba

University of Oxford H. Kraus

University of Sheffield V. Kudryavtsev

Observation of Migdal from Nuclear Scattering

Ambitious plan for phase I and phase II:

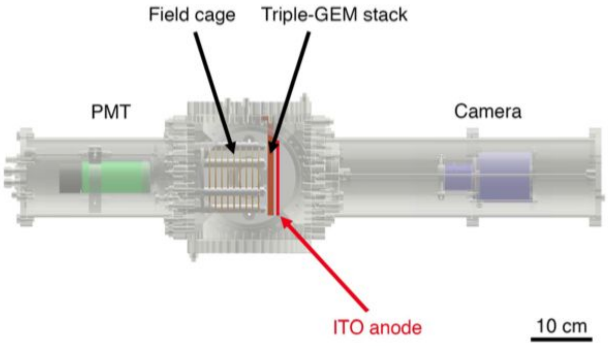
Phase I (High profile with clear high-impact deliverables)

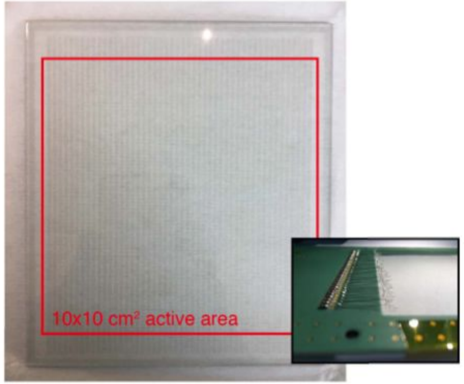
- Proof of principle of detecting low-energy NR and ER in low-pressure O-TPC
- Exposure to high intensity beam of neutrons and **first ever observation** of the effect

Phase II

- Study of the effect in various elements (gaseous mixtures) relevant to DM
- Study towards a first observation of the effect in LXe

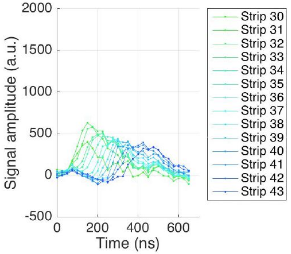
O-TPC at CERN (from F. Brunbauer)



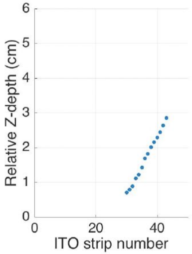


3D track reconstruction
in Ar/CF4 (80/20)
at 100 Torr

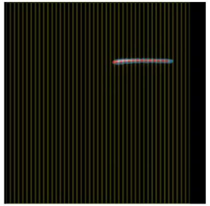
ITO strip signals



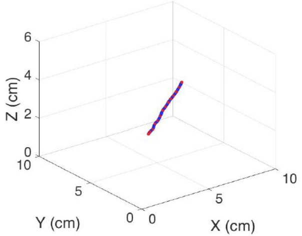
Depth information



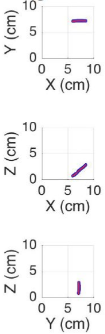
Camera image



3D track visualisation



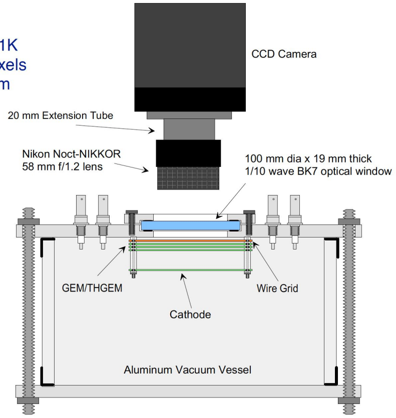
Projections



O-TPC at UNM (from D. Loomba) 2D reconstruction

UNM setup:

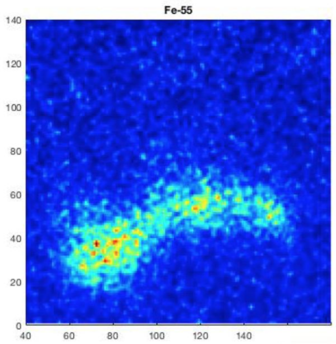
- Finger Lakes CCD with 1Kx1K E2V chip, with 13x13 μm² pixels
- lens to imaging plane ~20 cm

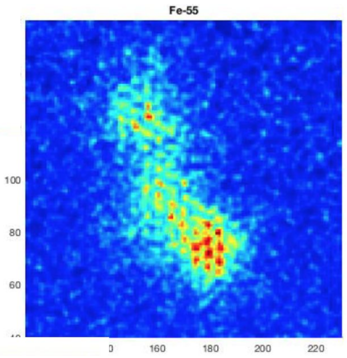


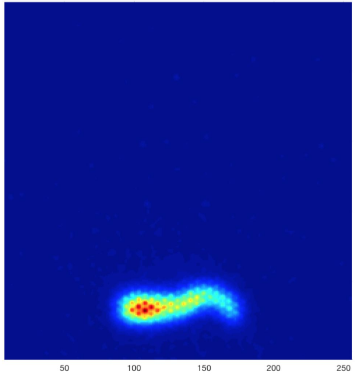
- 25-35 Torr CF4
- 2THGEMs (**σ > 0.7 mm**)
- Imaging area ~1.9cm x 1.9cm
- 4x4 on-chip binning

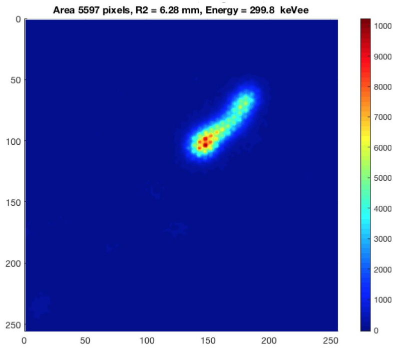
Data acquired using following sources:

- Fe-55 (5.9 keV x-rays)
- Co-60 (γ's)
- DD neutron generator (~2.2 MeV n's + γ's)

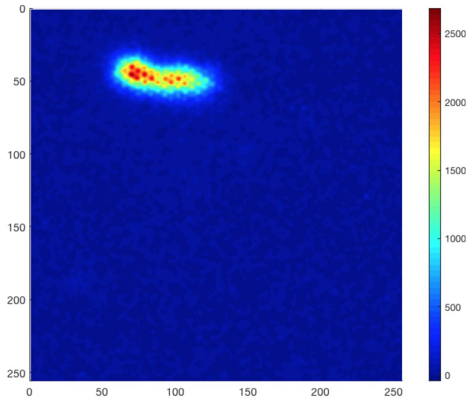


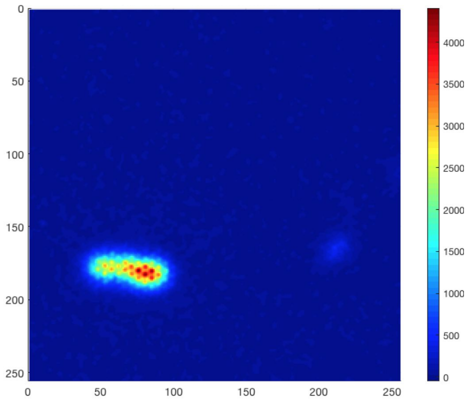






E ~ 270-300 keVee





E ~ 100-120 keVee

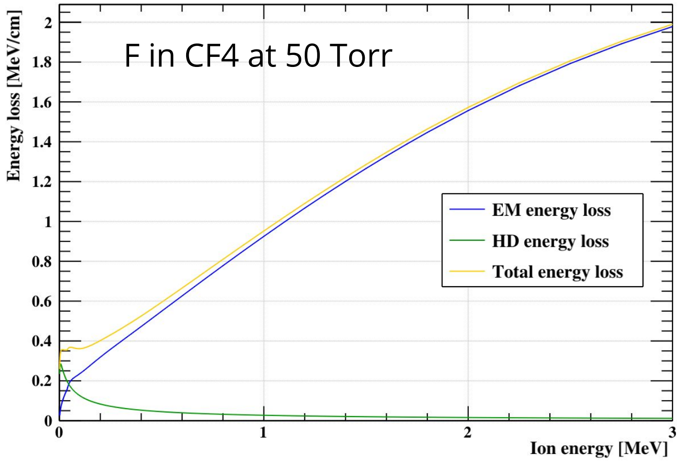
Simulations

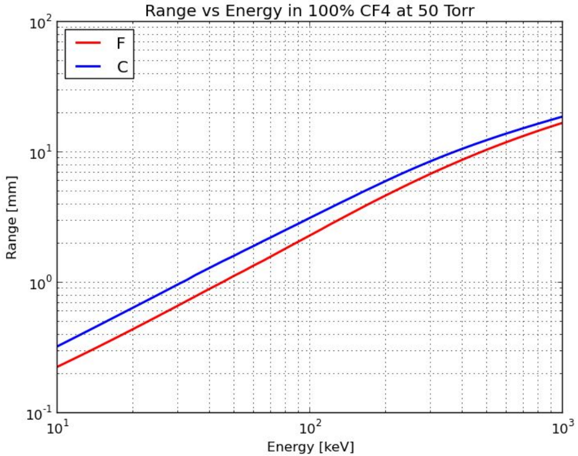
Nuclear Recoil Tracks:

- GARF++ with stopping power and straggling from SRIM (Stopping and Range for Ions in Matter)
- Simulation of the primary ionisation electrons produced along the track
- 200 keV Fluorine ions in pure CF4
- Initial direction was in positive x
- Produced 500 tracks

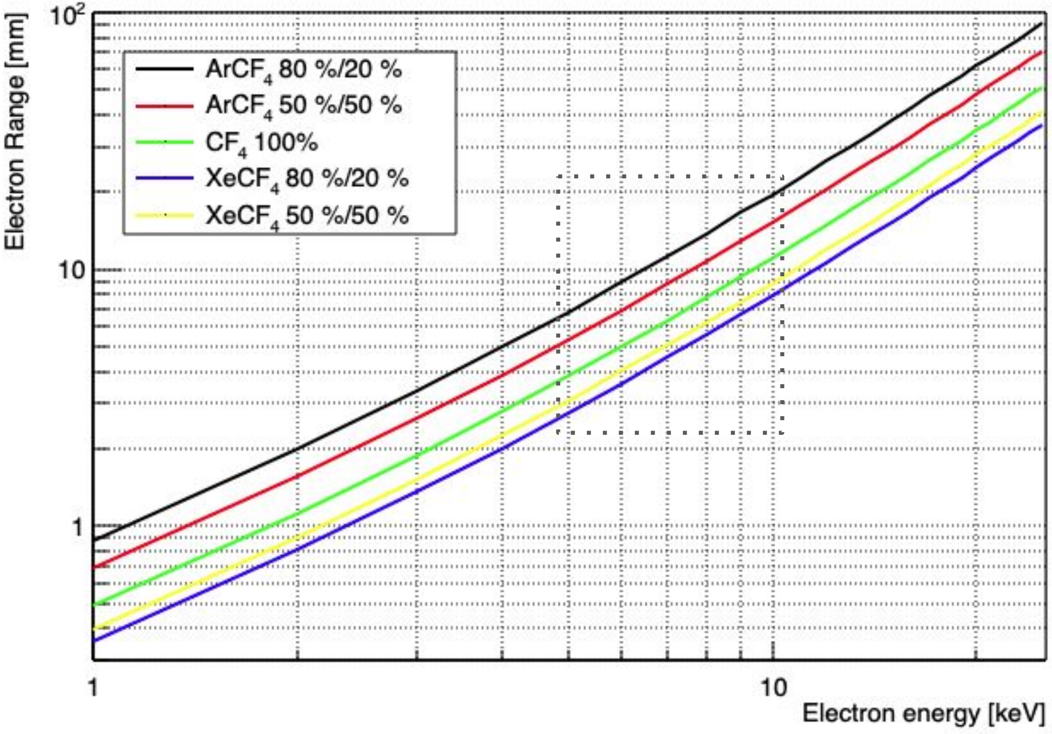
Electron Tracks:

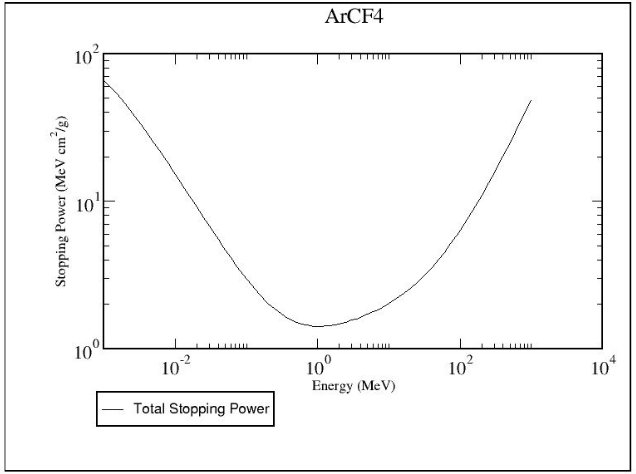
- Degrad v 3.7 (2019) by Steve Biagi
- Creates the ionisation electrons along the track
- 3 keV - 10 keV electrons in pure CF4
- Initial direction : random
- Produced 500 tracks

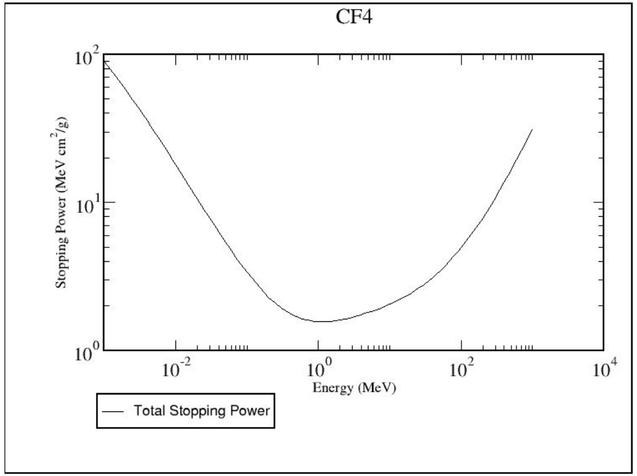




dE/dx and ranges of electrons

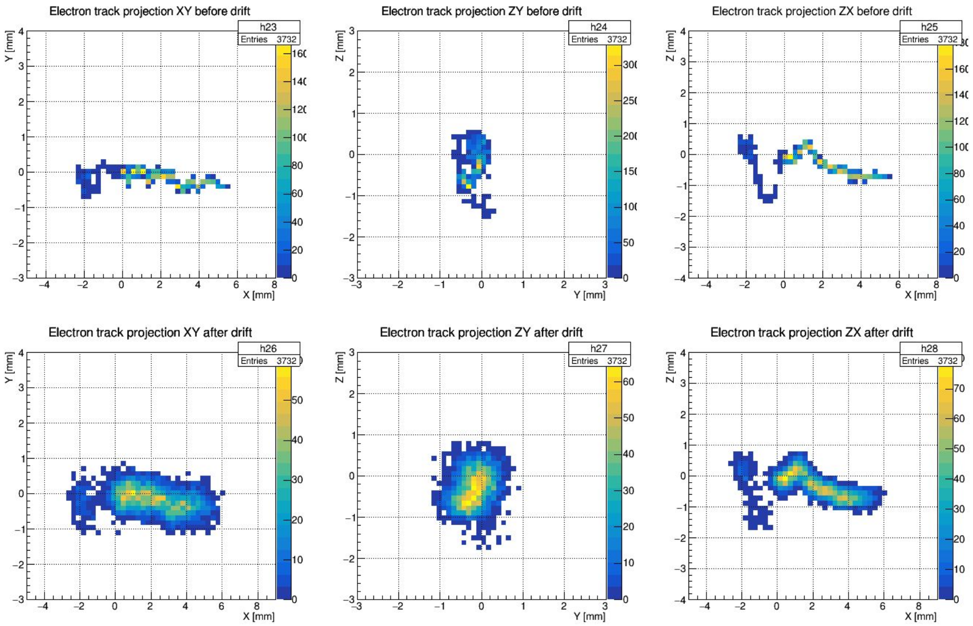


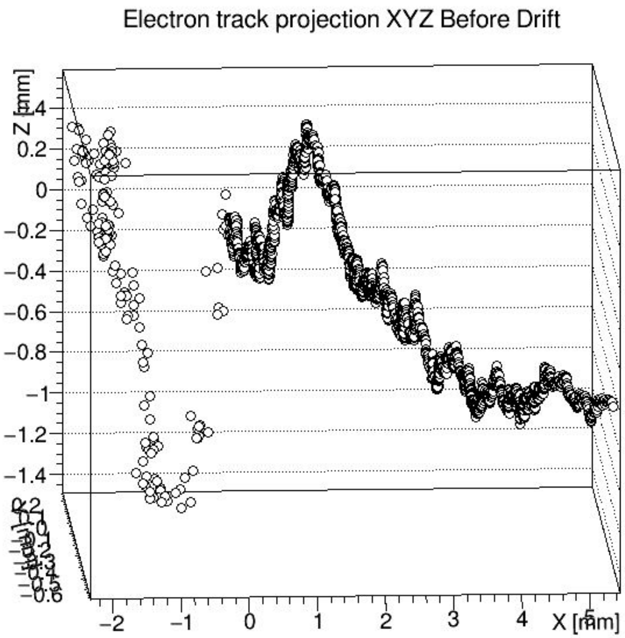




From: Energy Deposition by Electron Beams and δ Rays

Low energy electron and nuclear recoil simulations

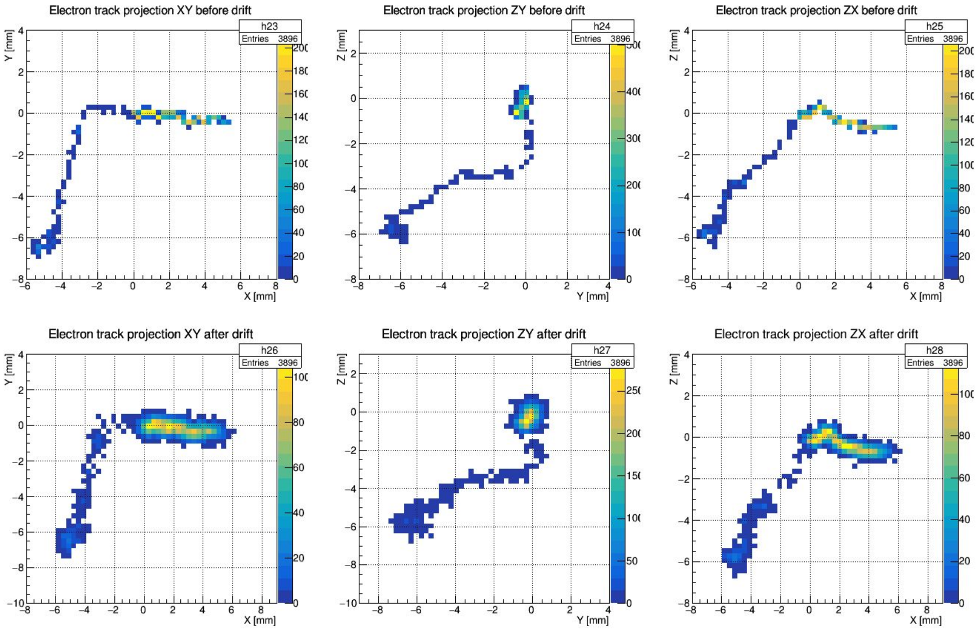


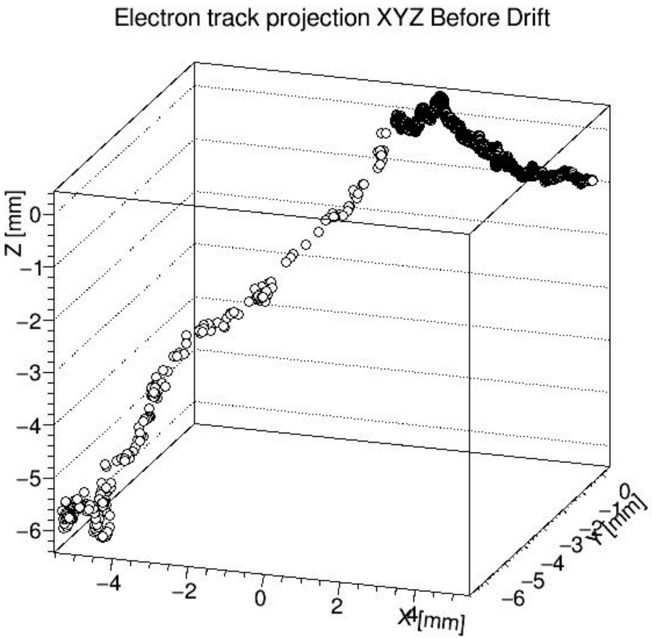


No.Electrons from electron track: 172
No.Electrons from nuclear recoil track: 3560

5 keV electron and 200 keV F ion in pure CF_4

Low energy electron and nuclear recoil simulations

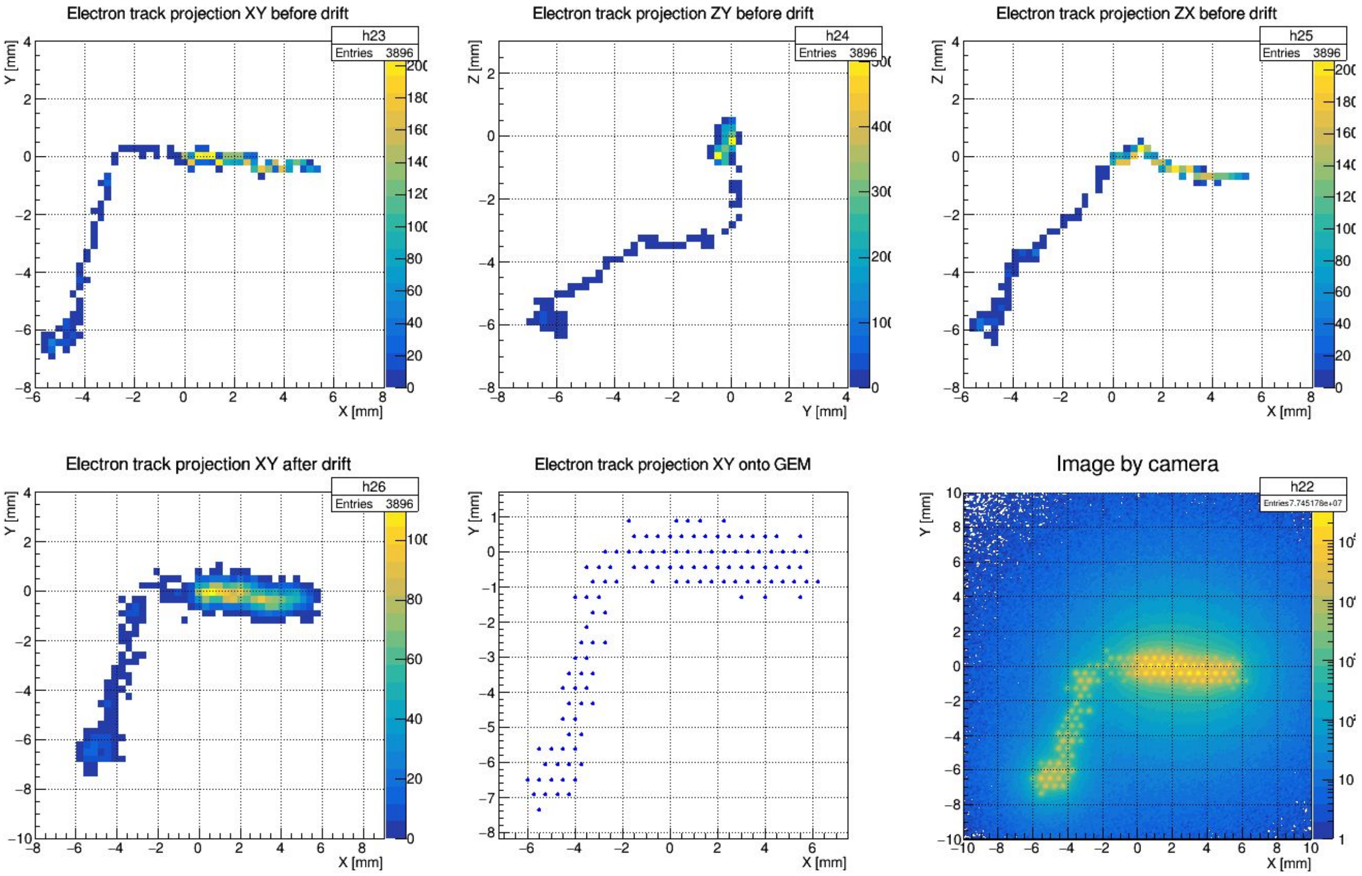




5 keV electron and 200 keV F ion in pure CF4

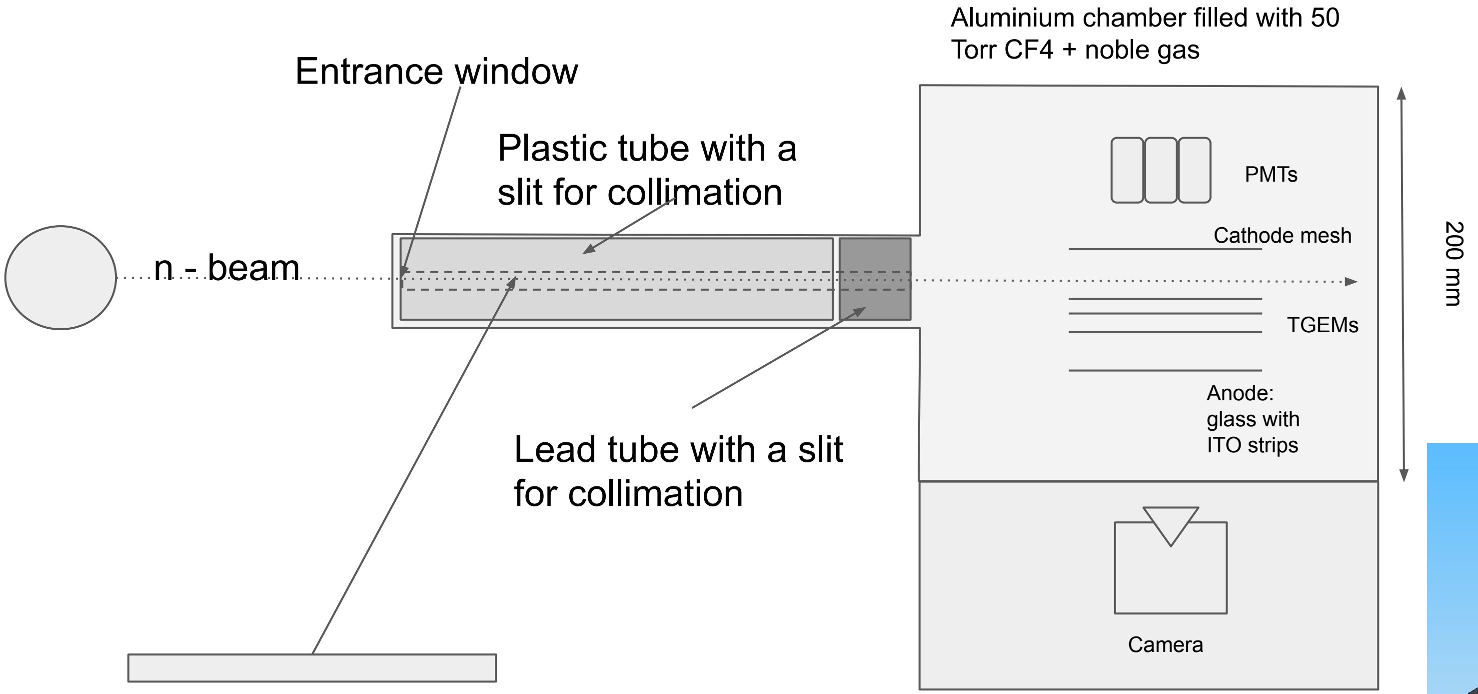
No.Electrons from electron track: 336
No.Electrons from nuclear recoil track: 3560

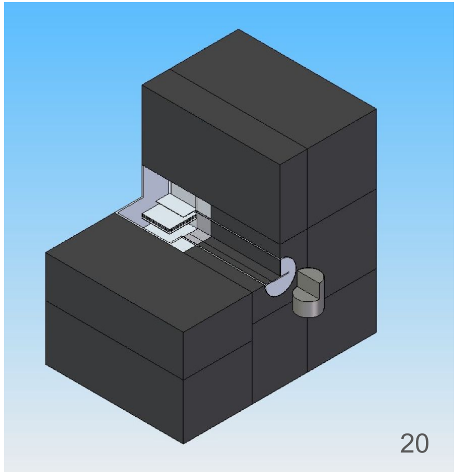
Low energy electron and nuclear recoil simulations



10 keV electron and 200 keV F ion in pure CF4

Detector conceptual design





Slit in plastic and lead: 60 mm x 3 mm

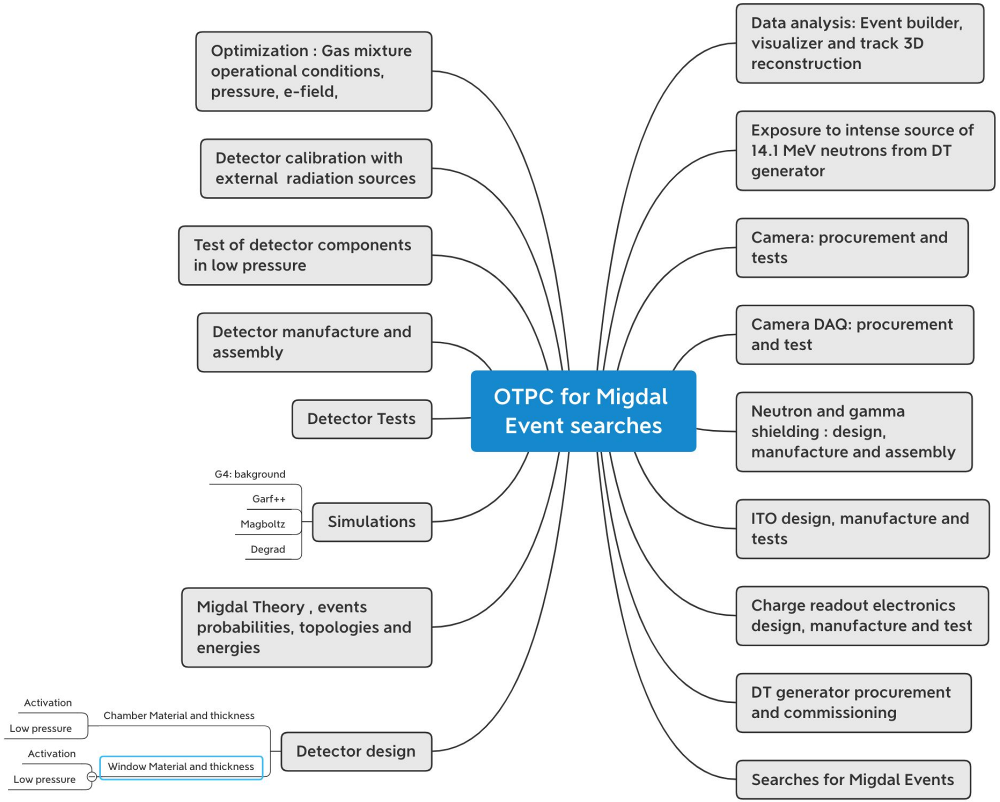
TGEM size: 100 mm x 100 mm

Number of stages to be optimised

Observation of the Migdal Effect challenges

Challenging in every aspect:

- **Looking for rare event** - *understanding of background and event topologies*
- **Background from high rate of neutrons** - *shielding and material choice*
- **O-TPC operation at low pressure** - *use of selected TGEMs and charge readout, operate at low diffusion and high light yield for accurate 3D track reconstruction*
- **High event rate** - *low noise camera with high rate readout capability*
- **Data storage** - *data transfer, temporary and permanent storage*



Request to join RD51 collaboration

Dark Matter Group at Rutherford Appleton Laboratory

Sergey Balashov (staff physicist, mechanical engineering support)

Maurits Van der Grinten (staff senior physicist)

Asher Kaboth (senior physicist, joint post with RHUL)

Andrei Khazov (staff physicist, electrical engineering support)

Pawel Majewski (staff senior physicist, group leader)

Tim Marley (project PhD student, joint post with Imperial College London)

Mohammad Nakhostin (project PDRA, joint post with Imperial College)

Experience and expertise :

Single and double-phase noble gas liquid detectors for Dark Matter (DEAP-3600, ZEPLIN-II/III, LUX-ZEPLIN)

Ultra-low temperature cryogenics, ultra-cold neutrons, magnetic shielding (nEDM)

Simulations and modelling of gaseous detectors including low pressure negative ion TPC (DRIFT)

Summary

- Project started in October 2019. It is funded by the STFC as part of the G3 LXe R&D programme
- A strong international collaboration has been formed
- Detailed simulations are underway
- Detector design already started
- New personnel hiring process is complete
- Plan for the first exposure to neutrons at ISIS : autumn 2020