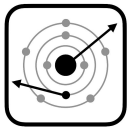


MIGDAL
Migdal In Galactic Dark mAtter expLoration

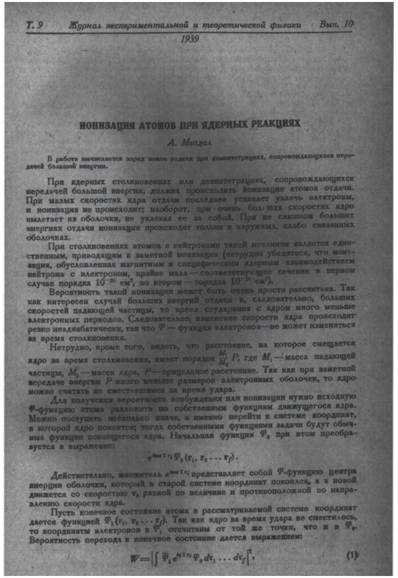
MIGDAL experiment at the NILE facility at RAL

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

July 2022

UNIVERSITY OF BIRMINGHAM
UAM Universidad Autónoma de Madrid
GDD Gas Detectors Development Group
HELSINKI INSTITUTE OF PHYSICS
Imperial College London
KING'S College LONDON
LIP
THE UNIVERSITY OF NEW MEXICO
UNIVERSITY OF OXFORD
ROYAL HOLLOWAY UNIVERSITY OF LONDON
Science & Technology Facilities Council
Rutherford Appleton Laboratory
The University Of Sheffield.

What do we already know about the Migdal effect ?



Т. 9 Журнал экспериментальной и теоретической физики Вып. 10

1939

ИОНИЗАЦИЯ АТОМОВ ПРИ ЯДЕРНЫХ РЕАКЦИЯХ

А. Мигдал

В работе вычисляется заряд ионов отдачи при дезинтеграциях, сопровождающихся передачей большой энергии.

При ядерных столкновениях или дезинтеграциях, сопровождающихся передачей большой энергии, должна происходить ионизация атомов отдачи. При малых скоростях ядра отдачи последнее успевает увлечь электроны, и ионизация не происходит; наоборот, при очень больших скоростях ядро вылетает из оболочки, не увлекая ее за собой. При не слишком больших энергиях отдачи ионизация происходит только в наружных, слабо связанных оболочках.

При столкновениях атомов с нейтронами такой механизм является единственным, приводящим к заметной ионизации (нетрудно убедиться, что ионизация, обусловленная магнитным и специфическим ядерным взаимодействием нейтрона с электроном, крайне мала — соответствующее сечение в первом случае порядка 10^{-28} см^2, во втором — порядка 10^{-30} см^2).

Вероятность такой ионизации может быть очень просто рассчитана. Так как интересен случай больших энергий отдачи и, следовательно, больших скоростей падающей частицы, то время соударения с ядром много меньше электронных периодов. Следовательно, изменение скорости ядра происходит резко неадиабатически, так что Ψ — функция электронов — не может измениться за время столкновения.

Нетрудно, кроме того, видеть, что расстояние, на которое смещается ядро за время столкновения, имеет порядок $\frac{M_1}{M_2}P$, где M_1 — масса падающей частицы, M_2 — масса ядра, P — прицельное расстояние. Так как при заметной передаче энергии P много меньше размеров электронных оболочек, то ядро можно считать не сместившимся за время удара.

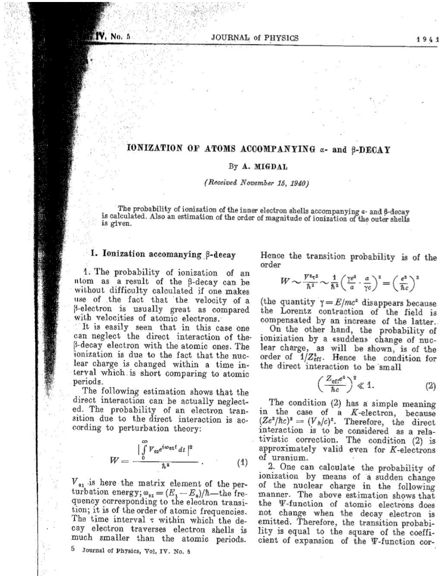
Для получения вероятности возбуждения или ионизации нужно исходную Ψ-функцию атома разложить по собственным функциям движущегося ядра. Можно поступить несколько иначе, а именно перейти к системе координат, в которой ядро покоится; тогда собственными функциями задачи будут обычные функции покоящегося ядра. Начальная функция Ψ_0 при этом преобразуется в выражение:

$$e^{imv\Sigma r_i}\Psi_0(\mathbf{r}_1, \mathbf{r}_2 \dots \mathbf{r}_f).$$

Действительно, множитель $e^{imv\Sigma r_i}$ представляет собой Ψ-функцию центра инерции оболочки, который в старой системе координат покоился, а в новой движется со скоростью $\mathbf{v}$, равной по величине и противоположной по направлению скорости ядра.

Пусть конечное состояние атома в рассматриваемой системе координат дается функцией $\Psi_1(\mathbf{r}_1, \mathbf{r}_2 \dots \mathbf{r}_f)$. Так как ядро за время удара не сместилось, то координаты электронов в Ψ_1 отсчитаны от той же точки, что и в Ψ_0. Вероятность перехода в конечное состояние дается выражением:

$$W = \left|\int \overline{\Psi}_1 e^{iq\Sigma r_i}\Psi_0 \, d\tau_1 \dots d\tau_f\right|^2, \quad (1)$$



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.

1. Ionization accomanying β-decay

1. The probability of ionization of an atom as a result of the β-decay can be without difficulty calculated if one makes use of the fact that the velocity of a β-electron is usually great as compared with velocities of atomic electrons.

It is easily seen that in this case one can neglect the direct interaction of the β-decay electron with the atomic ones. The ionization is due to the fact that the nuclear charge is changed within a time interval which is short comparing to atomic periods.

The following estimation shows that the direct interaction can be actually neglected. The probability of an electron transition due to the direct interaction is according to perturbation theory:

$$W = \frac{\left|\int_0^\infty V_{01} e^{i\omega_{01}t}\, dt\right|^2}{\hbar^2}. \quad (1)$$

V_{01} is here the matrix element of the perturbation energy; $\omega_{01} = (E_1 - E_0)/\hbar$—the frequency corresponding to the electron transition; it is of the order of atomic frequencies. The time interval τ within which the decay electron traverses electron shells is much smaller than the atomic periods. Hence the transition probability is of the order

$$W \sim \frac{V^2\tau^2}{\hbar^2} \sim \frac{1}{\hbar^2}\left(\frac{\gamma e^2}{a}\cdot\frac{a}{\gamma c}\right)^2 = \left(\frac{e^2}{\hbar c}\right)^2$$

(the quantity $\gamma = E/mc^2$ disappears because the Lorentz contraction of the field is compensated by an increase of the latter.

On the other hand, the probability of ioniziation by a «sudden» change of nuclear charge, as will be shown, is of the order of $1/Z_{eff}^2$. Hence the condition for the direct interaction to be small

$$\left(\frac{Z_{eff}e^2}{\hbar c}\right)^2 \ll 1. \quad (2)$$

The condition (2) has a simple meaning in the case of a K-electron, because $(Ze^2/\hbar c)^2 = (V_k/c)^2$. Therefore, the direct interaction is to be considered as a relativistic correction. The condition (2) is approximately valid even for K-electrons of uranium.

2. One can calculate the probability of ionization by means of a sudden change of the nuclear charge in the following manner. The above estimation shows that the Ψ-function of atomic electrons does not change when the decay electron is emitted. Therefore, the transition probability is equal to the square of the coefficient of expansion of the Ψ-function cor-

5 Journal of Physics, Vol, IV. No. 5

A. Migdal publications:

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

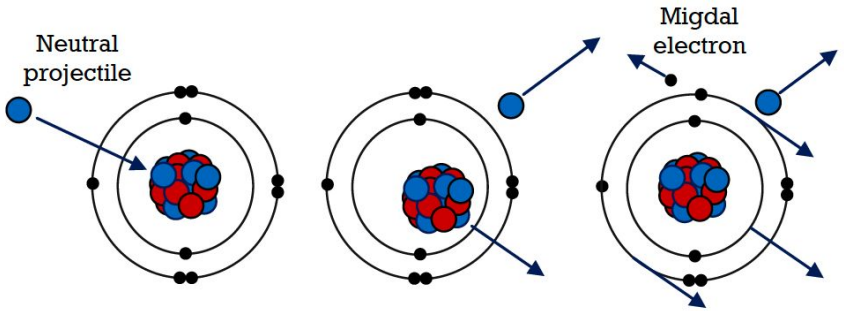
First observations of the Migdal effect in :

- 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 $^6He^+$ 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)*

Also in A.B. Migdal ”Qualitative Methods in Quantum Theory”
Advanced Book Classics CRC Press, 2000
L. Landau and E. Lifshitz ”Quantum Mechanics : Non-relativistic Theory”

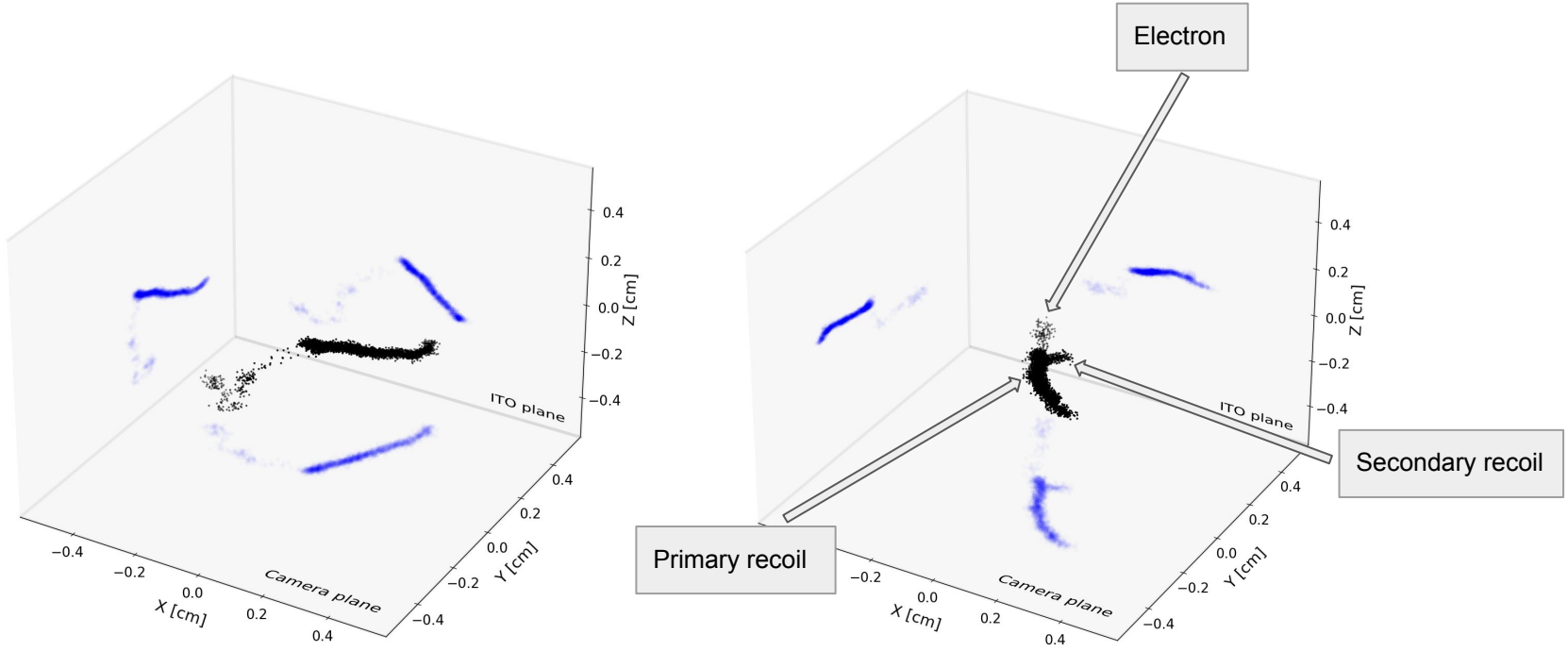
Migdal effect



Migdal event topology involves a nuclear recoil and electron recoil originating from the same vertex.

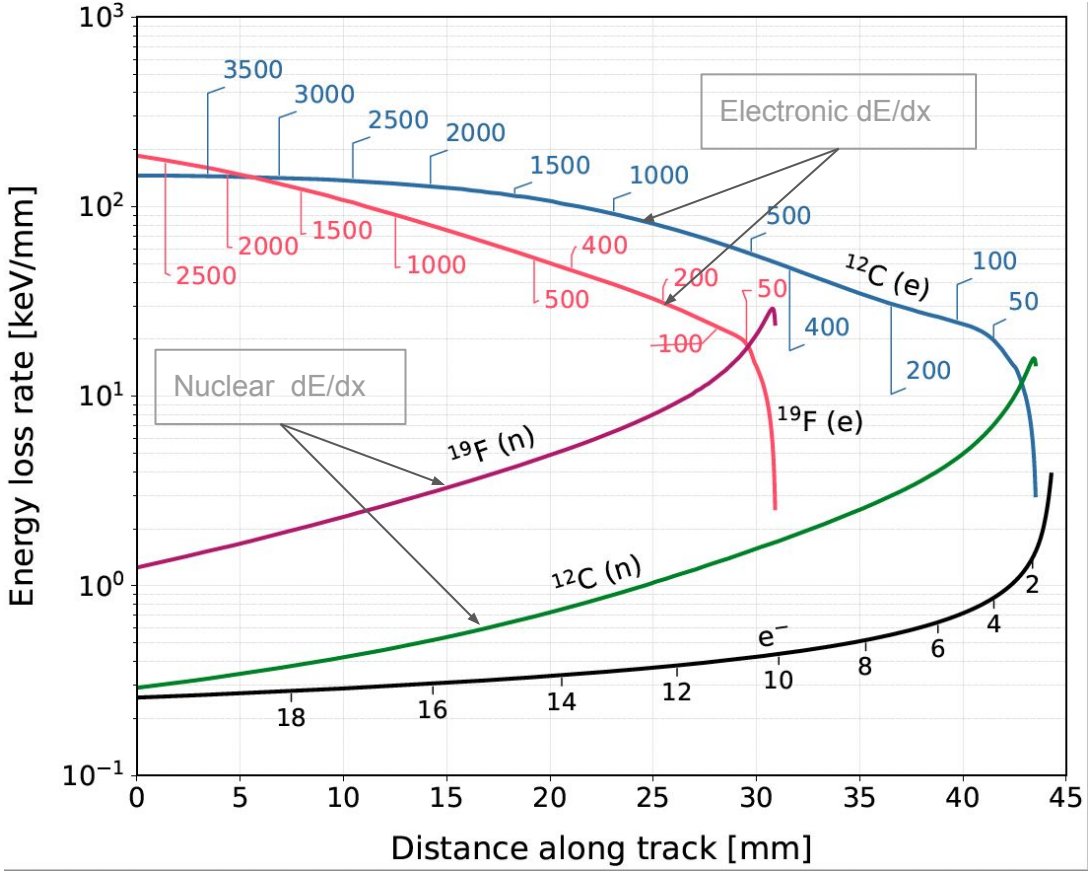
- Looking for a rare (10^{-5}) atomic phenomenon never before observed in the nuclear scattering
- Migdal effect increases sensitivity of DM experiments to low mass WIMPs
- Aim of the MIGDAL experiment - unambiguous observation and measurement of the Migdal effect using a low pressure Optical TPC
- Signal signature: “V-like” shaped event with two tracks from electron and NR with different dE/dx and sharing the same vertex

Simulated Migdal events in 100% CF_4 at 50 Torr



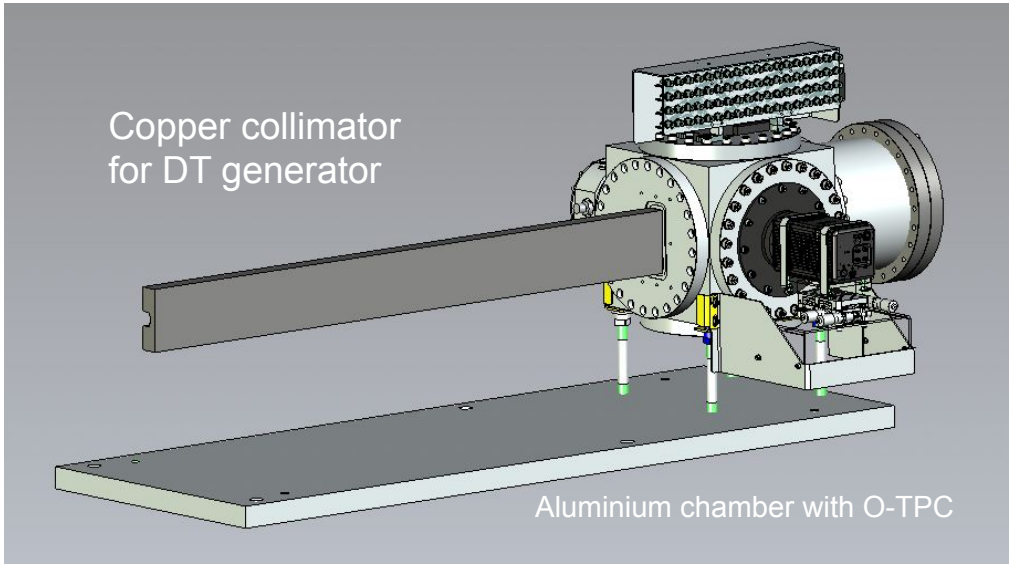
- Ionisation from electron using DEGRAD and full recoil cascade simulation using TRIM
- 150 keV Fluorine recoil and 7.5 keV electron
- 150 keV Fluorine recoils and 5 keV electron (secondary recoil clearly visible)

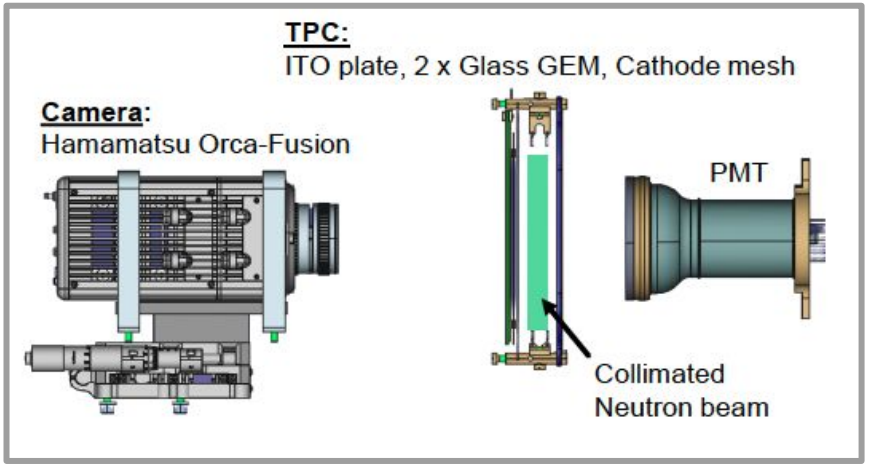
dE/dx and required dynamic range



- Distinctive difference in dE/dx between NRs and electrons
- Huge dynamic range required at vertex where dE/dx at maximum for NRs and at minimum for electrons
- With high gain to see low energy electrons can lead to approaching the Raether limit and unwanted gaseous discharges in the lower GEM
- Plan for testing different THGEMs structures for robustness with fission fragments (RD-51 2 year grant)

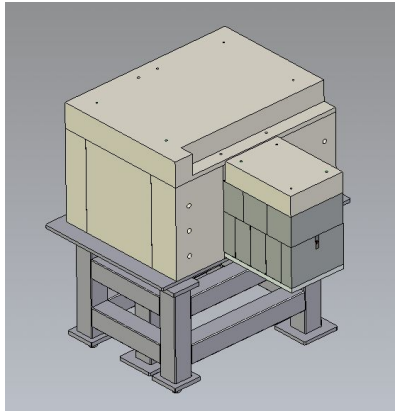
Detector

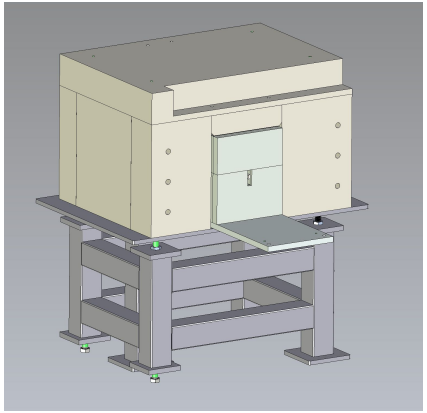


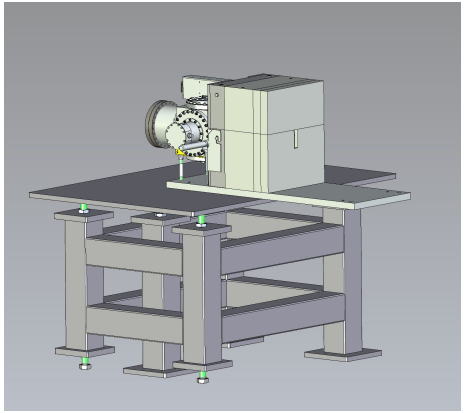


- Gas : 100% CF_4 at 50 Torr
  - (planned mixtures with all noble gases)
- Operating with low drift E-field for minimum diffusion
- Signal amplification with two glass-GEMs
- Light readout with fast CMOS camera; charge readout using ITO strips

Shield and collimator



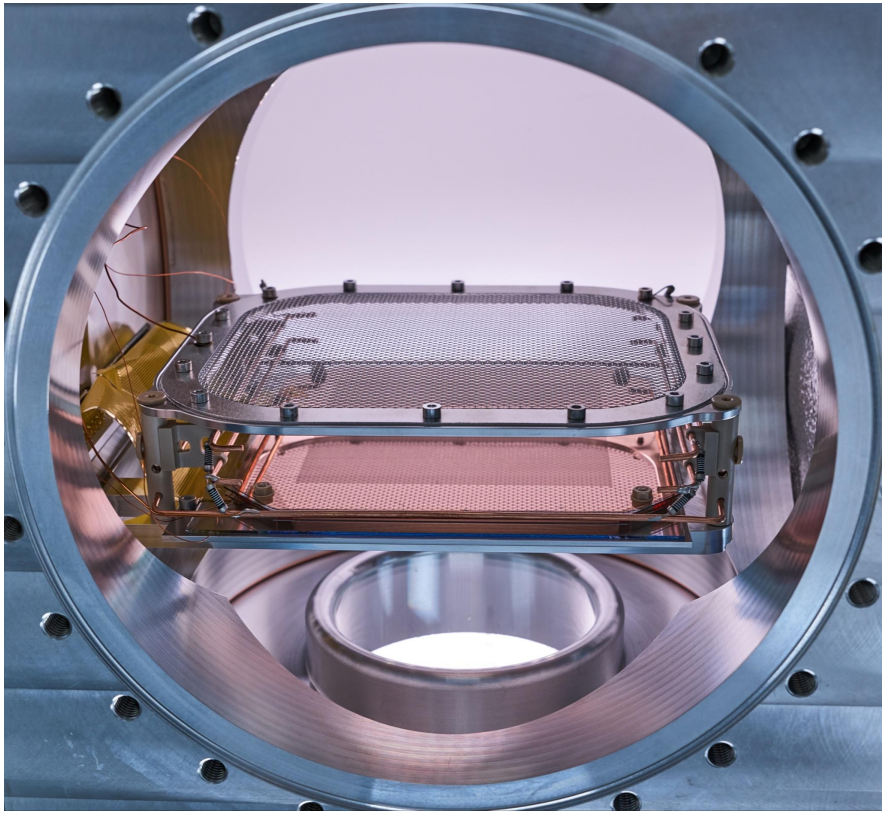


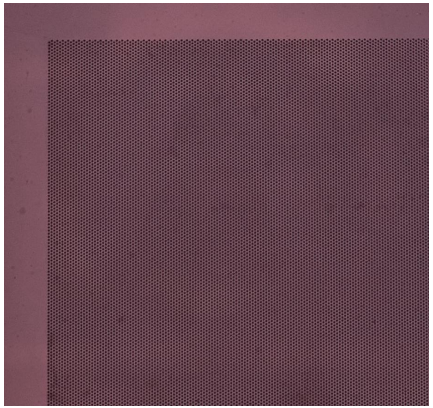


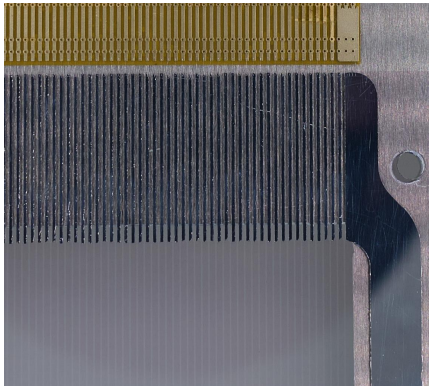
Copper 1 m long collimator

- Full shielding for the experiment with DT generator
  - Front shielding: Iron + borated HDPE + Pb
  - 1 m long copper collimator
- Full shielding for the experiment with DD generator
- Front shielding for the experiment with DD generator
  - borated HDPE + Pb
  - 35 cm long borated HDPE+Pb envelope collimator

TPC







<u>Two glass-GEMs:</u>

- 570 um thick
- OD /pitch: 180/280 um
- active area: 10x10 cm^2

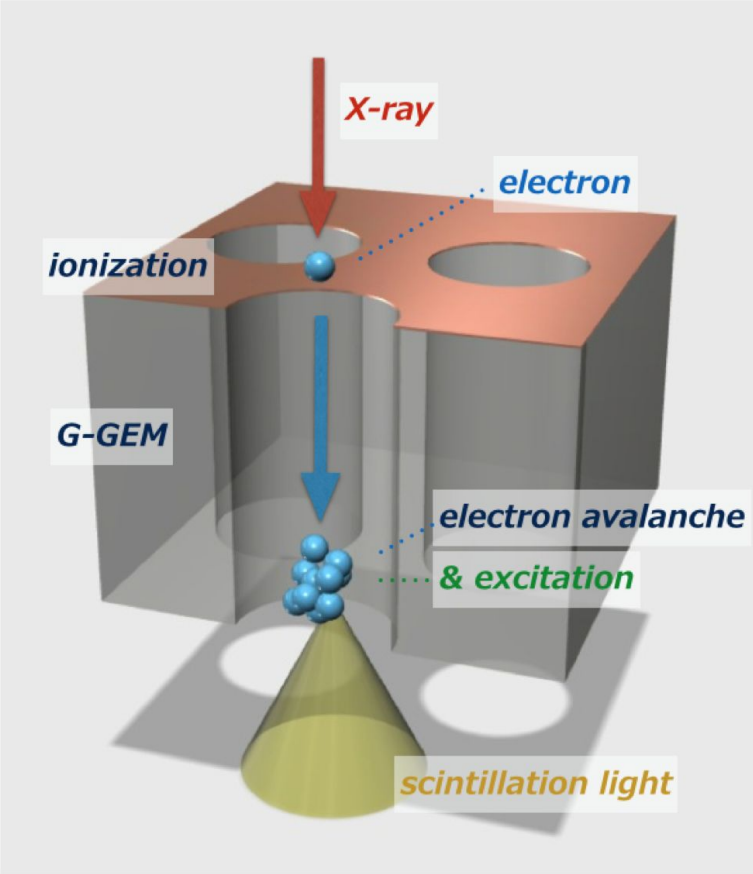
<u>ITO strips wire bonded to readout</u>

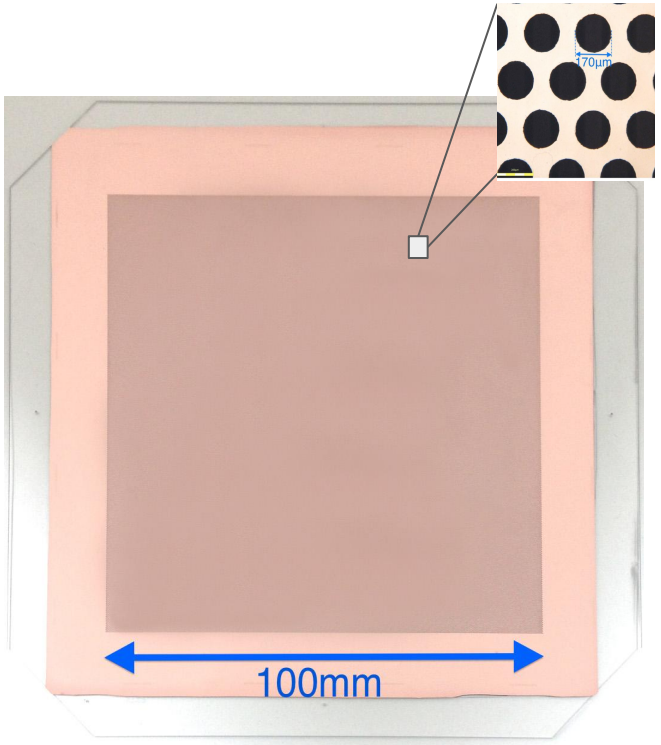
- 120 strips
- width/pitch: 0.65/0.83 mm

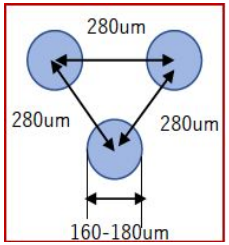
<u>Three field shaping copper wires</u>

- TPC inside of the central aluminium cube
- Drift gap: 3 cm between woven mesh and cascade of two glass-GEMs
- Transfer and signal induction gaps : 2 mm

Glass-GEMs

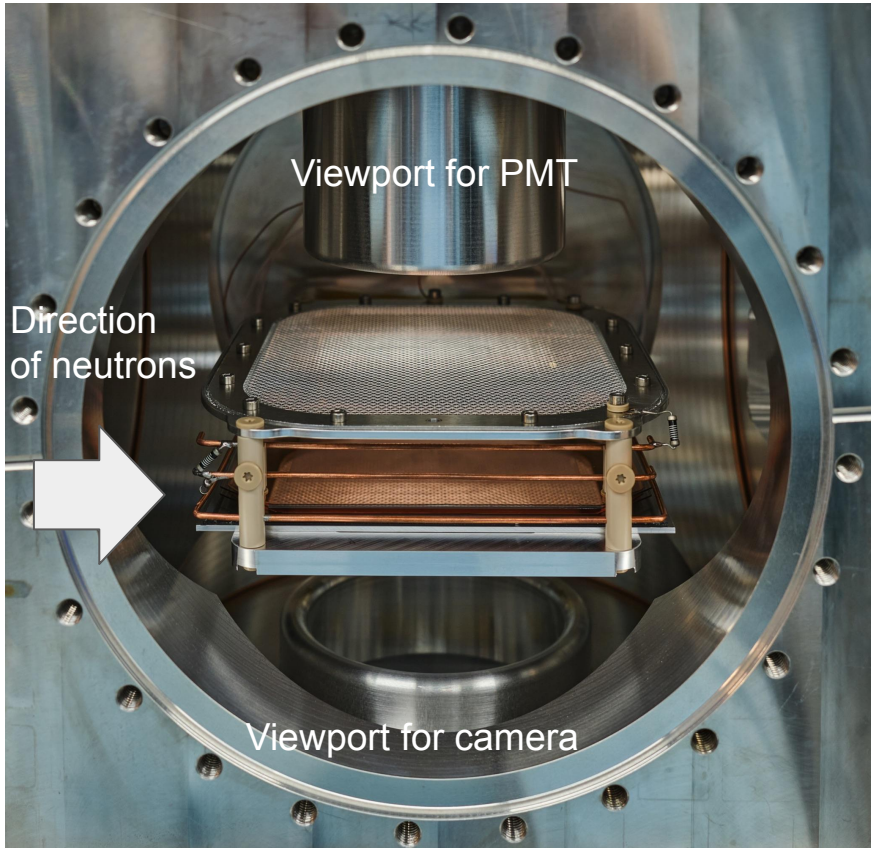


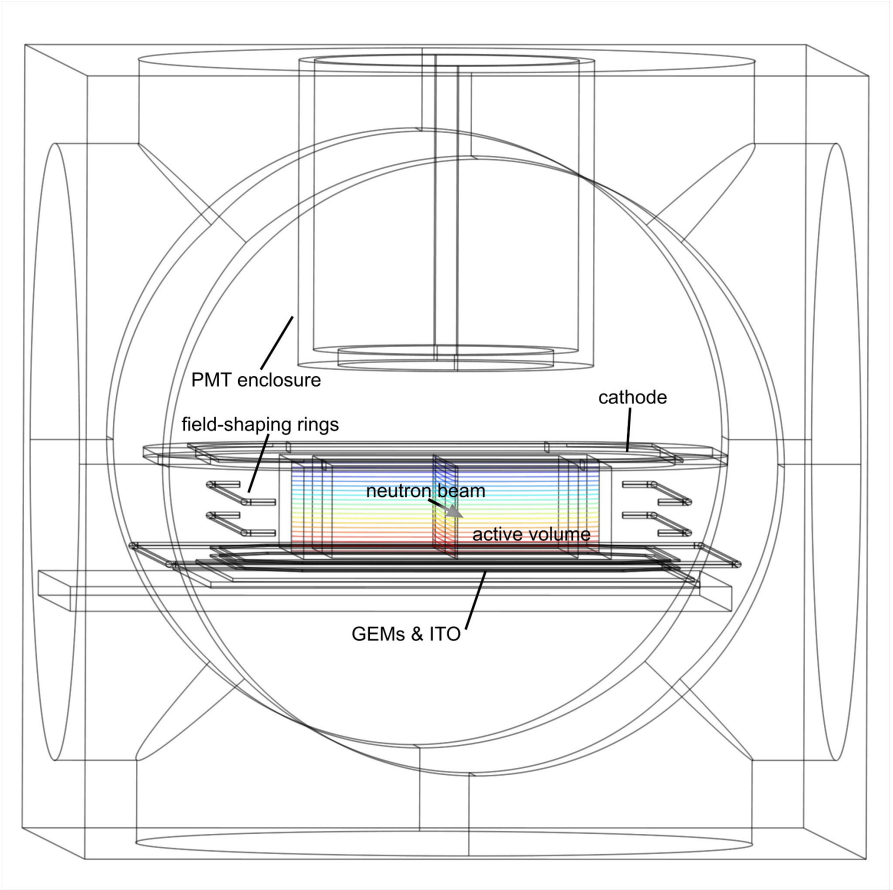




Glass thickness : 570 um

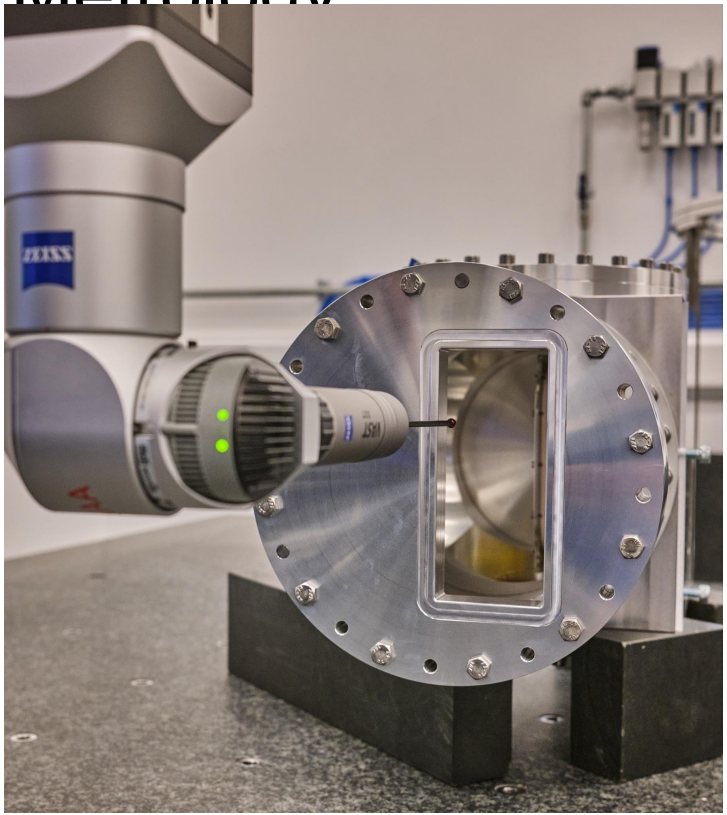
TPC





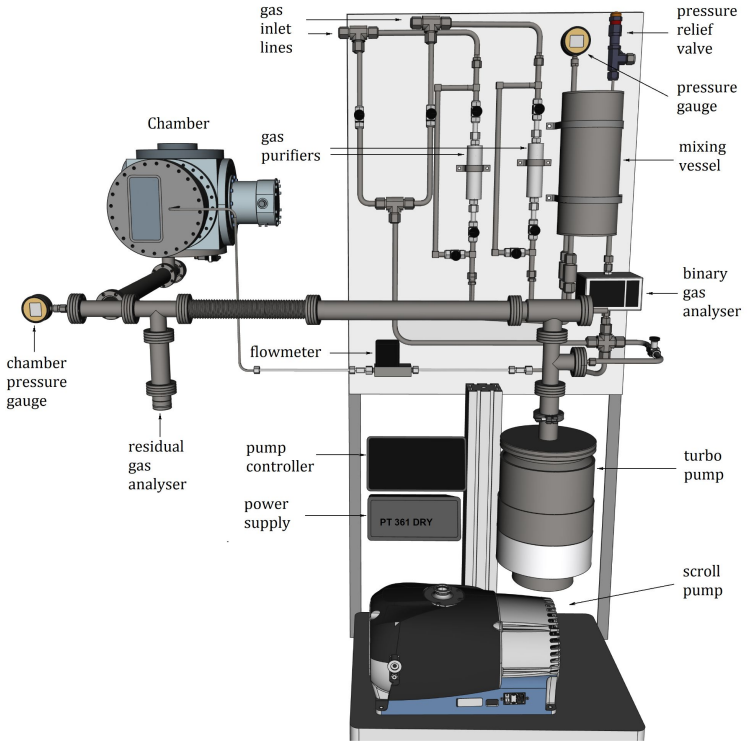
Electric field uniformity in the active volume simulated with COMSOL : fiducial area 8 cm x 8 cm

Detector Metrology



- Chamber with the O-TPC check for parallelism and alignment between all the elements
- Main focus on alignment between beam entrance/exit window and the drift gap of the TPC
- Largest deviation found - 0.5 mm

Gas system



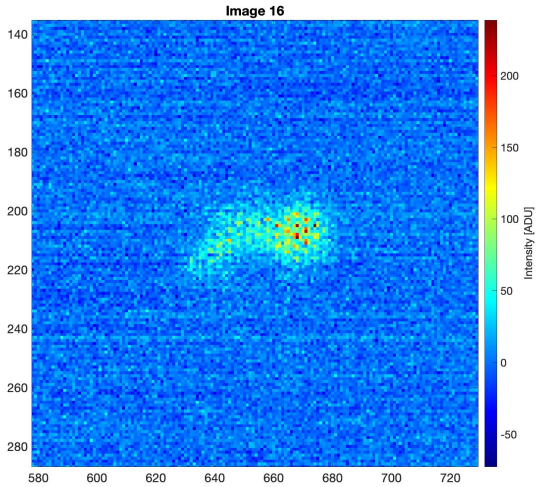
Gas system for single or two gases mixture operation almost ready.

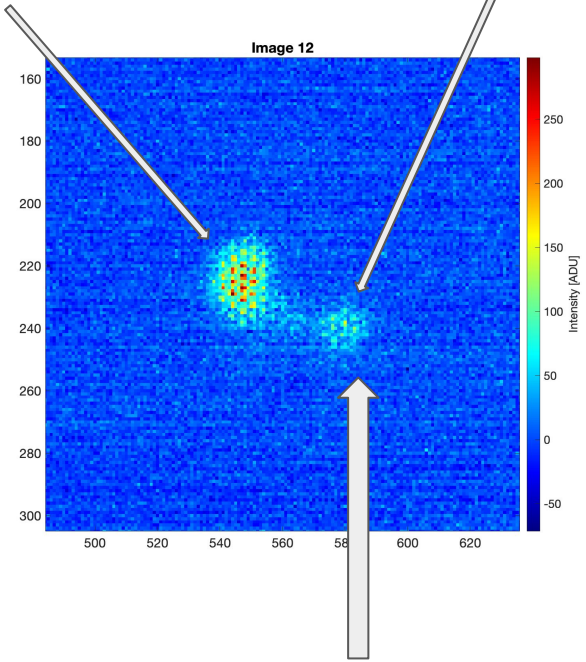
Acquiring images using Fe-55 source (5.9 keV X-ray)

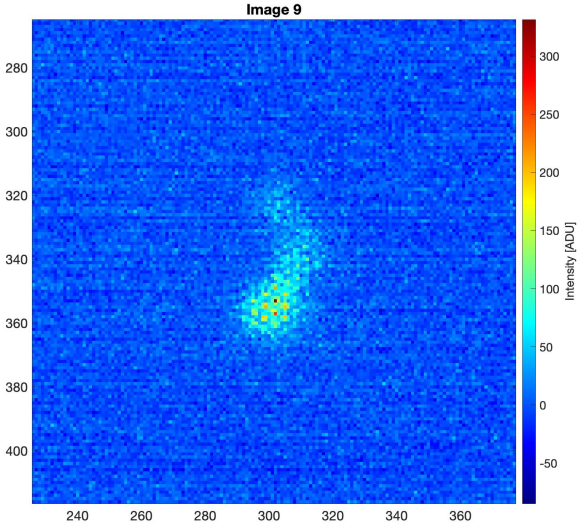
5.2 keV electrons

End

Start

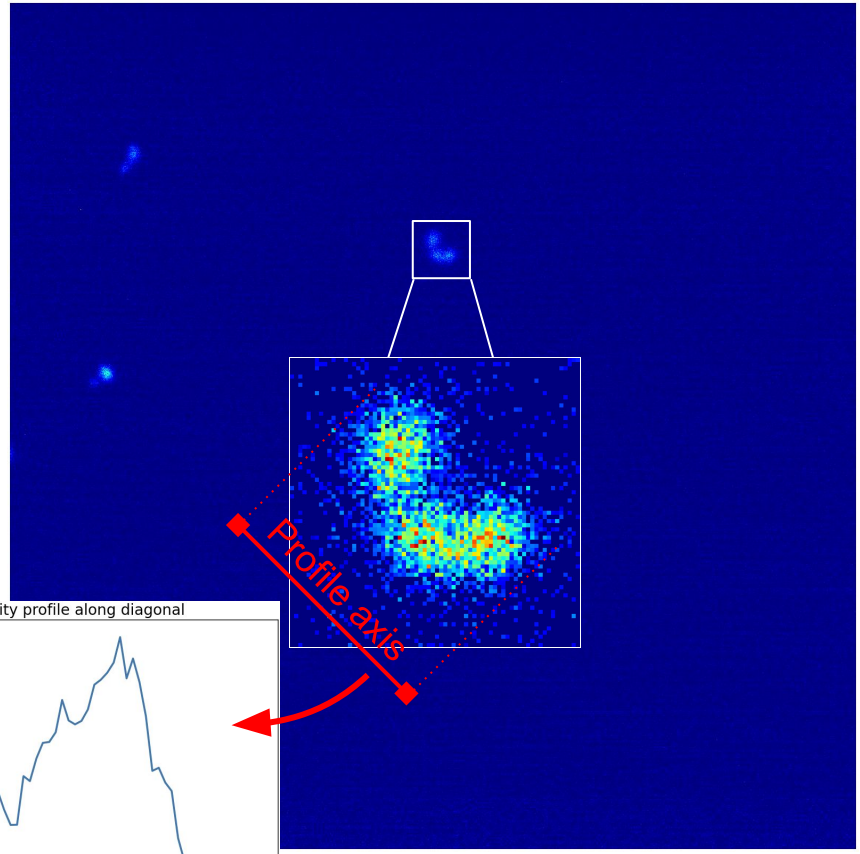


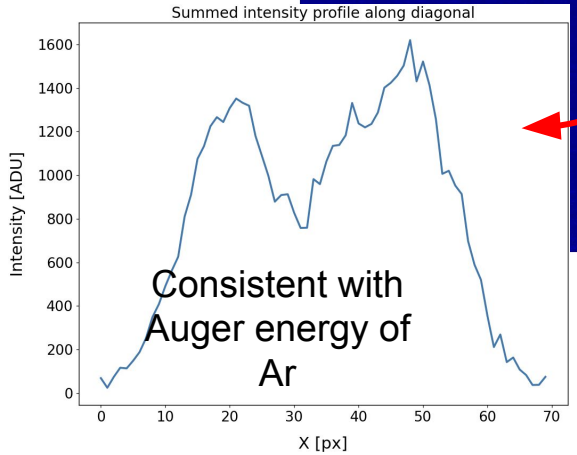




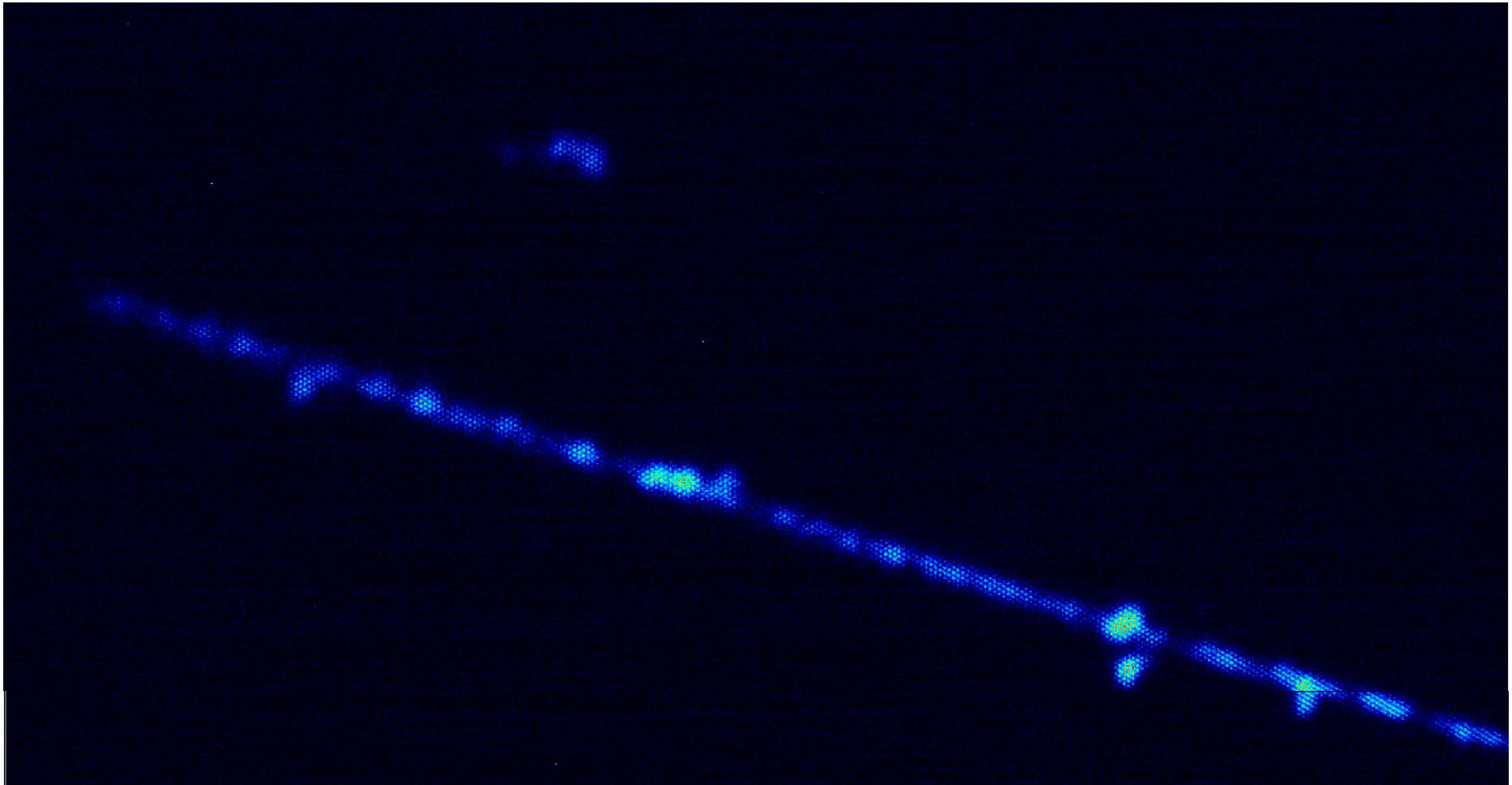
Extra charge at the start from
Fluorine 650 eV Auger Electron

We see 2.7 keV Auger electrons from argon !

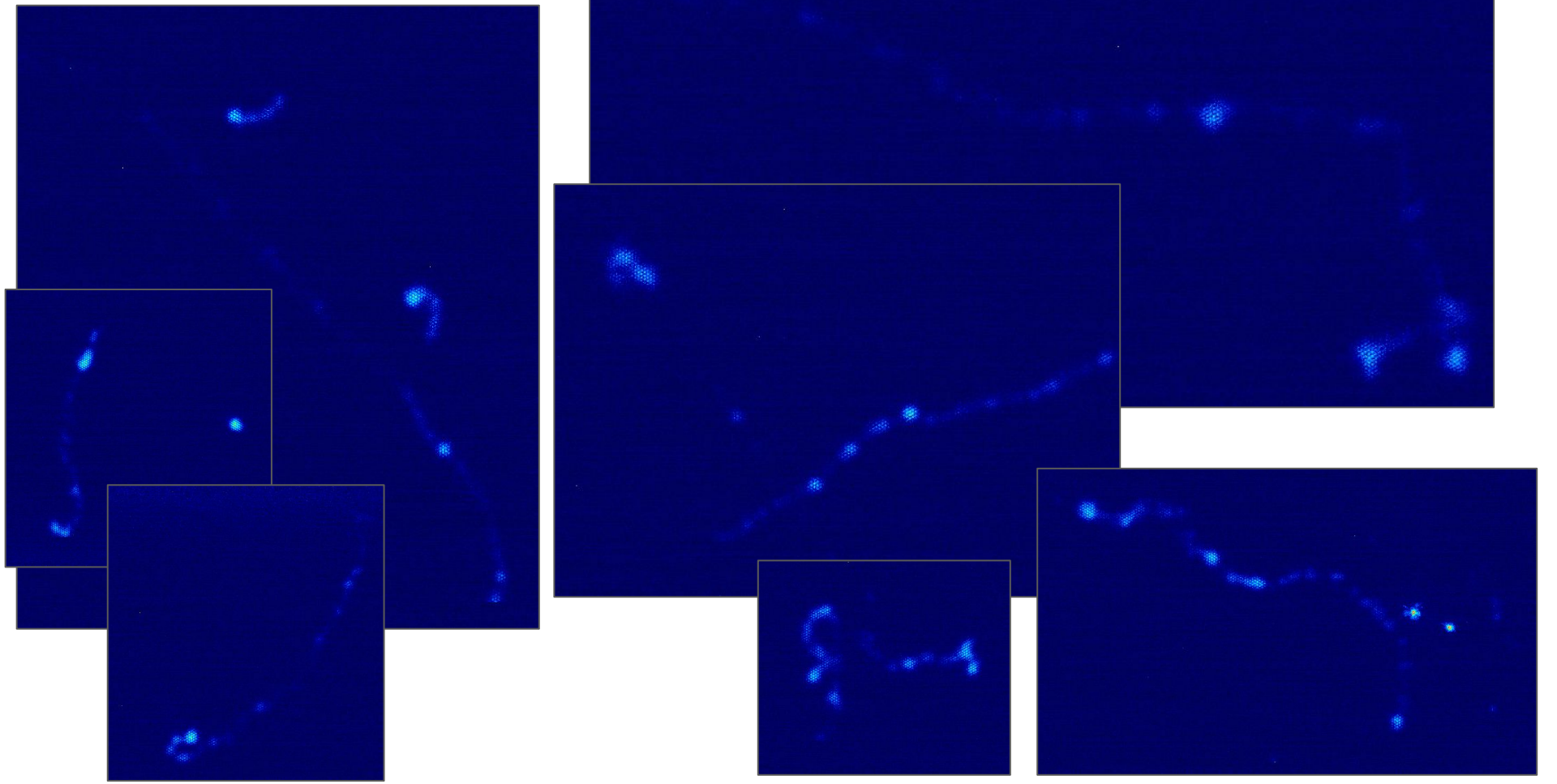




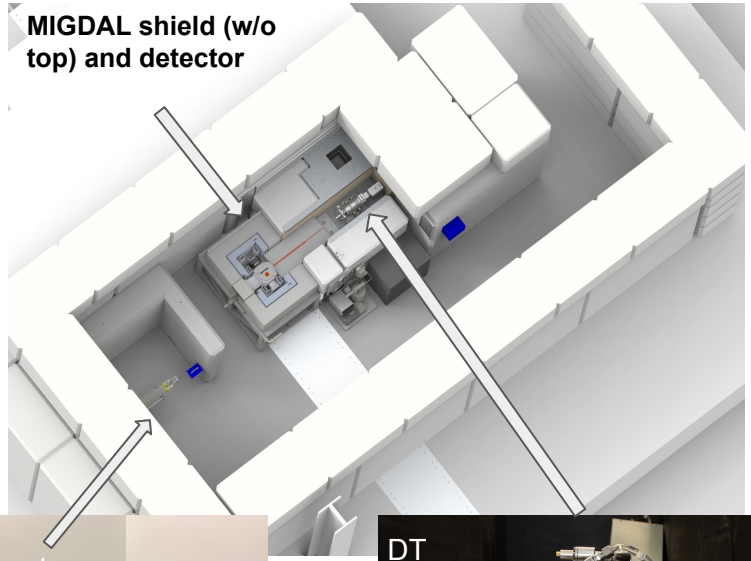
We see alphas too.

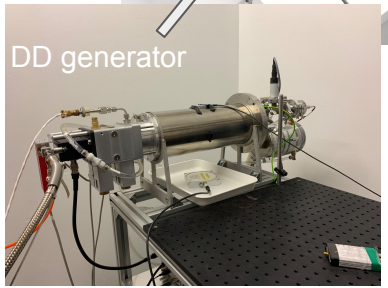


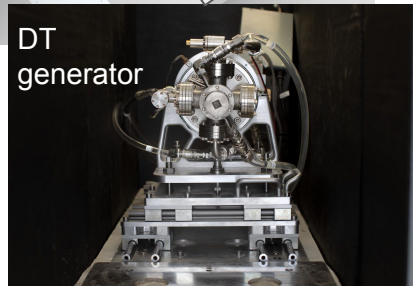
We see betas too



NILE facility and neutron generators







- Commissioning of both DD and DT neutron generators at the NILE facility at ISIS (RAL) is underway.
- MIGDAL experiment will start with DD (lower energy of neutrons) generator.

MIGDAL Experiment Paper

Experiment paper: https://arxiv.org/abs/2207.08284