First images with the Optical Micromegas detectors

RD51 – 14/06/2022

S. Aune, M. Benali, F. Benedeti, T. Benoit, A. Cools, D. Desforge, E. Ferrer Ribas, M. Kebbiri, T. Papaevangelou, E. Pollacco

CEA-Saclay/IRFU/DEPHYS

F. Brunbauer

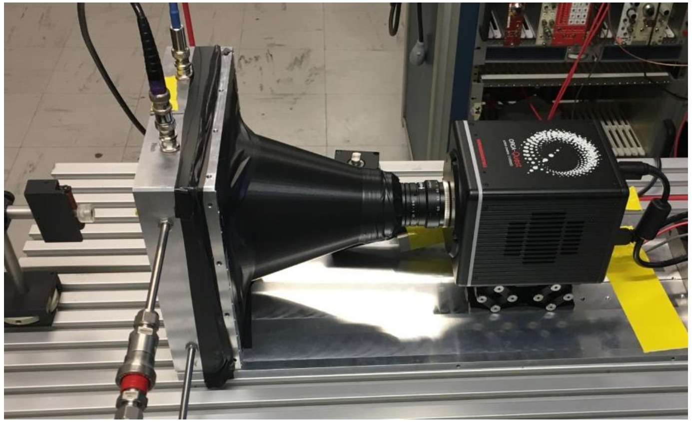
CERN

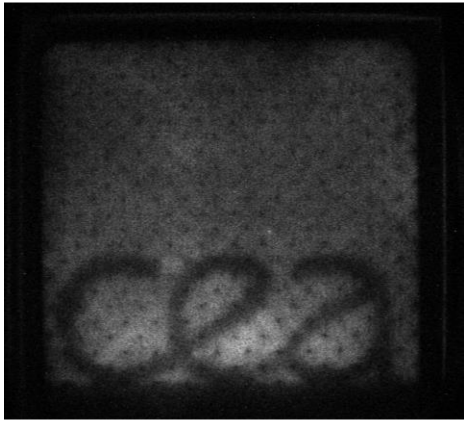
F. Beau, C. Malgorn

CEA Saclay/JOLIOT/DMTS/SIMOS/LBC

A. Sari

CEA Saclay/DRT-List





PLAN

CONTEXT

LIGHT PRODUCTION MECHANISMS

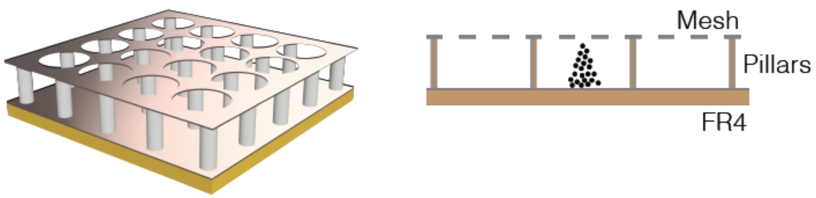
OPTICAL READOUT OF MPGDs

OPTIMED-BETA

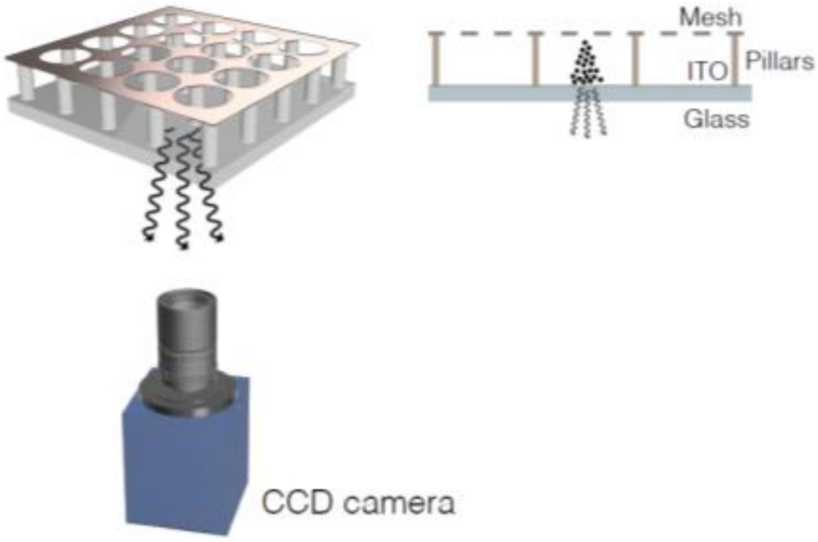
OMNIS

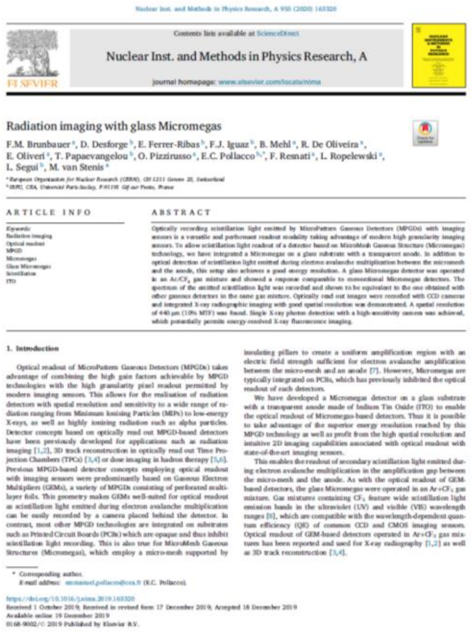
LIGHT DETECTION DEVICES

Charge readout



Optical readout




Nuclear Inst. and Methods in Physics Research, A 958 (2020) 163320

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Radiation imaging with glass Micromegas

F.M. Brunbauer [a], D. Desforge [b], E. Ferrer-Ribas [b], F.J. Iguaz [b], B. Mehl [a], R. De Oliveira [a], E. Oliveri [a], T. Papaevangelou [b], O. Pizzirusso [a], E.C. Pollacco [b,*], F. Resnati [a], L. Ropelewski [a], L. Segui [b], M. van Stenis [a]

ARTICLE INFO

ABSTRACT

F. Brunbauer

LIGHT PRODUCTION MECHANISMS

Scintillation : excited atoms or molecules emit photons during de-excitation transitions from an excited state to an energetic ground state.

Scintillation

Phosphorescence

Delayed emission of photons after absorption. (1 ms to 100 s)

Fluorescence

Prompt emission of photon after absorption of incident radiation. (1 ns to 1 µs)

Primary scintillation

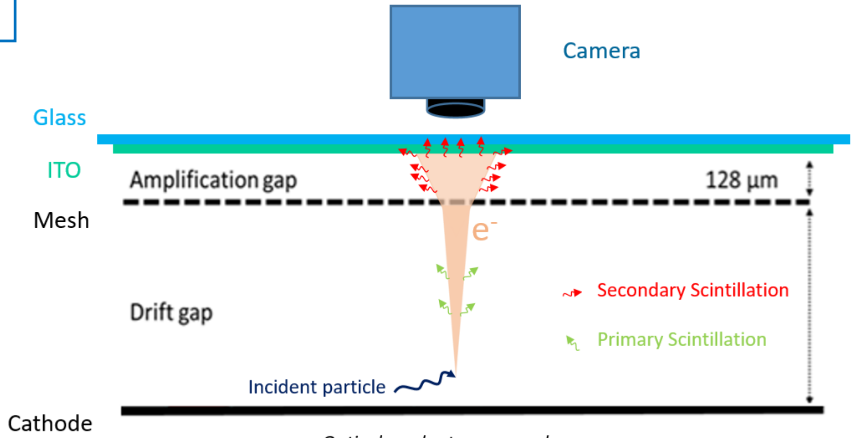
From the creation of primary electron coming from the excitation of gaz due to incident particles.

Secondary scintillation

From the creation of secondary electrons taking place during avalanche amplification.

Electroluminescence

Electrons with energy lower than ionization threshold just excite atoms or molecules.



Optical readout process scheme

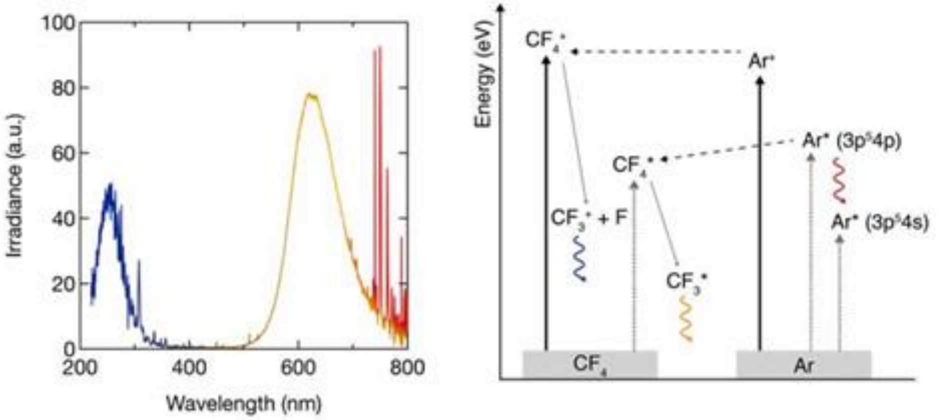
Light yield : amount of light determines the signal to noise ratio. It depends on electric field, pressure and gas mixture.

CF4 : Carbon tetrafluoride

- 0.1 to 0.3 secondary scintillation photons per secondary electron in avalanche.
- High charge gain > 10^4
- Emits in wavelength regions compatible with readout device : visible wavelengths

Argon + CF4 scintillation wavelengths

Adapted from Seravalli, E., PhD thesis, 2008



Scintillation spectrum and mechanisms of Ar/CF4 gas

- UV : **Ionisation**, $CF4^+$ dissociates to $CF3^+$ + F with short half life

and high probability, $CF3^+$ emits in UV.

Charge transfer processes : ionised Ar^+ contributes to production of $CF3^+$.

$$CF_4 + e^- \rightarrow (CF_3^+)^* + F + 2e^{-\prime}$$
(neutral channel, $E_{thr} = 23.5 \pm 2.0$ eV)
$$CF_4 + e^- \rightarrow (CF_3^+)^* + F^+ + 3e^{-\prime}$$
(ionic channel, $E_{thr} = 40 \pm 2$ eV).

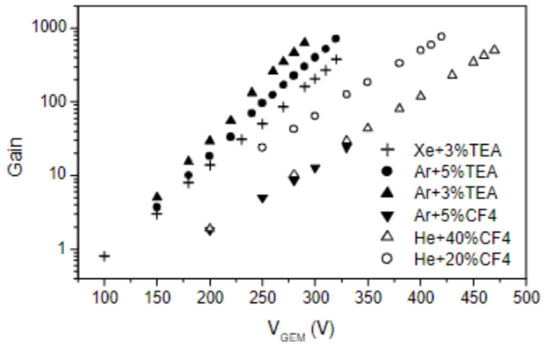
$$Ar^+ + CF_4 \rightarrow CF_3^+ + F + Ar$$

- VIS : **Electron impact :** excited $CF4^*$ dissociates to $CF3^*$ which emits in VIS.

Dissociation of $CF4^*$ is not the only way to get $CF3^*$:

Charge transfer processes : ionised Ar^+ contributes to production of $CF4^+$ towards $CF3^*$ production.

- NIR : **Transitions** between excited state of Ar emits in NIR.



Gain versus applied voltage for several gas mixtures.

M.M.F.R. fraga et al. ISSN 0168-9002 (2003)

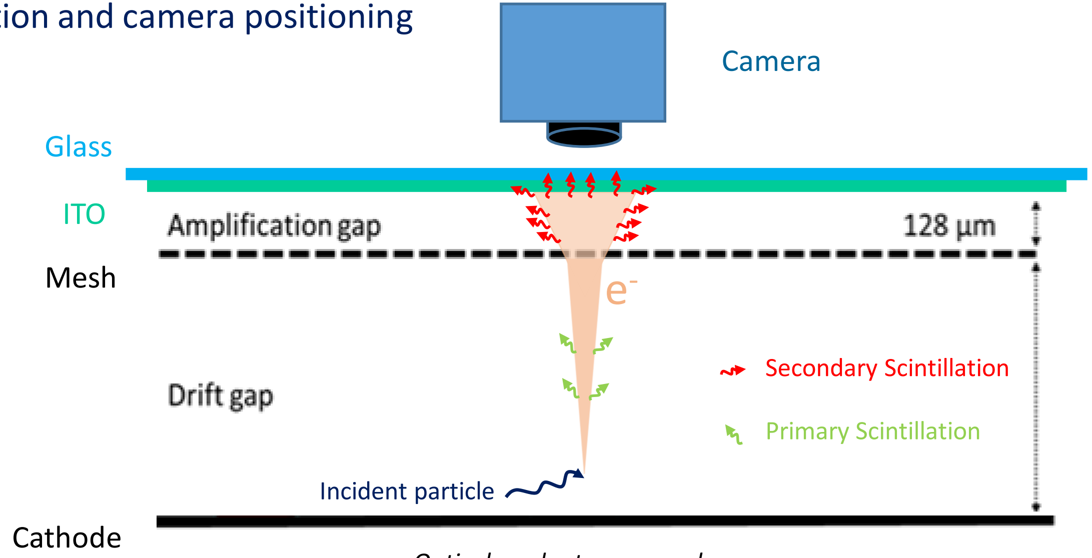
OPTICAL READOUT OF MPGDs

Advantages

- Full 2D pixelized readout for high spatial resolution
- Availability of commercial suitable cameras with megapixel resolution
- Integrated imaging approach
- Flexibility with lenses and mirrors for adjustable magnification and camera positioning

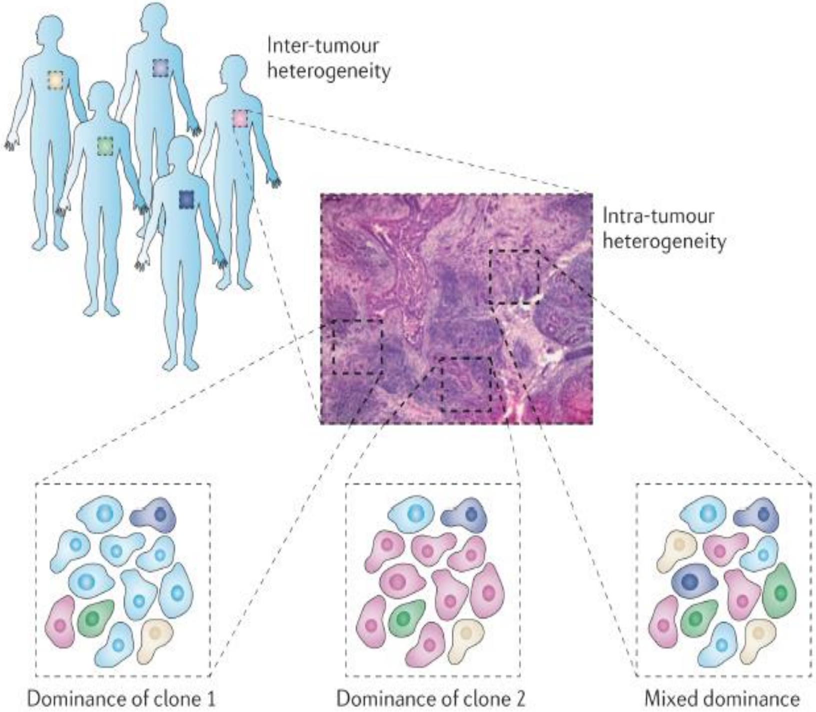
Disadvantages

- Limited frame rate / time resolution
- TPC mode not possible
- Need of CF_4 based gas mixtures or other specific gases



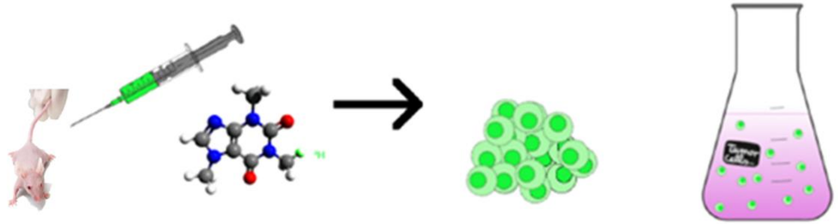
Optical readout process scheme

- Tumoral heterogeneity : different cell types inside a tumor
  - Heterogeneity effect on drug targeting?
  - Might decrease targeting drug efficiency
  - Requires better detection sensibilities

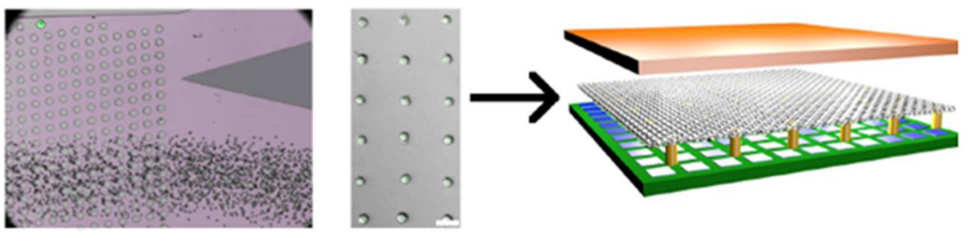


Marusyk, Nature Reviews Cancer 12(5) (2012) 323-34

- Tumoral heterogeneity : different cell types inside a tumor
  - Heterogeneity effect on drug targeting?
  - Might decrease targeting drug efficiency
  - Requires better detection sensibilities



Tumoural cells collected from an animal – Tritium tracking   Cellular culture



Cell deposit by microfluidics techniques   Tritium activity counting with gaseous detector

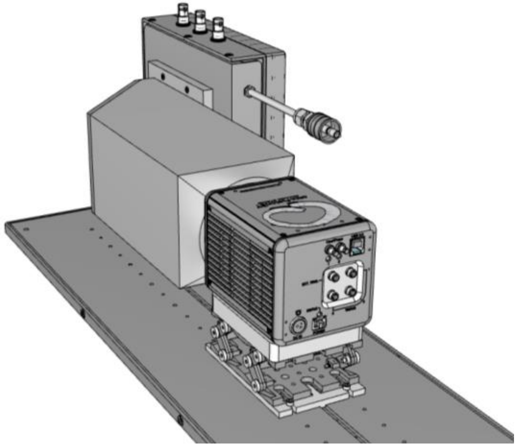
<u>Molecule labelling and tracking with tritium</u>

- Pharmaceutical needs at the cell level for drug development :
  - Assess the **drug distribution** among cells
  - Evaluate the impact of the cell heterogeneity on drug biodistribution
  - At the cell level : Quantification of ^{3}H concentration in **single cell** samples

<u>Micromegas-based neutron imager</u>

- Real-time neutron radiography for high-radiation environments
- Two major applications :
  - Jules Horrowitz Reactor : Real-time neutron imaging in material testing reactors for non-destructive examination of fresh irradiated fuel
  - SAPHIR platform : characterization of radioactive waste through active neutron
- Objectives of the detector :
  - Strong ɣ-to-n suppression of the Micromegas : **>10^6**
  - Spatial resolution on the order of **100 µm** : camera high granularity
  - Scalable to larger areas : 50x50 cm^2
  - Highly contrasted images
  - Real time measurement

SAPHIR Linatron (X-ray from 6 MeV to 9 MeV)



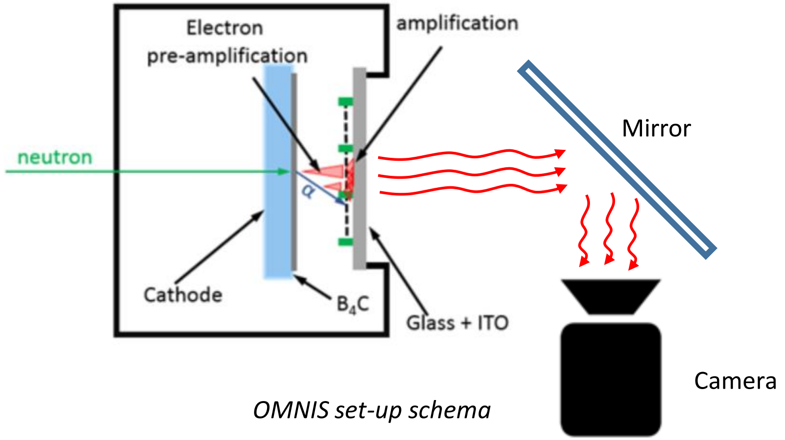
OMNIS 3D representation

OMNIS

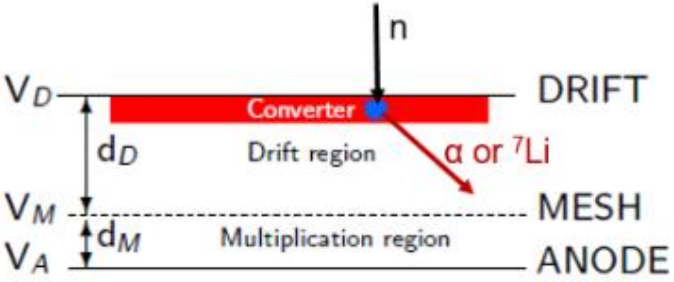
Micromegas-based neutron imager

- Acquisition modes :
  - **Event-by-event** : track reconstruction :
    potentially higher resolution (100 µm), better ɣ-to-n suppression
  - **Integrated** : real-time radiography :
    best camera operation mode, ɣ-to-n suppression less efficient

- $^{10}B_4C$ neutron-to-charge converter
  - **Thermal neutrons** created by 2 µm thin $^{10}B_4C$ layer
  - Conversion efficiency : 5%
  - (α or Li) fragments causes strong ionisation compared to electrons
  - Drawback : fragments long range in the gas (10mm)



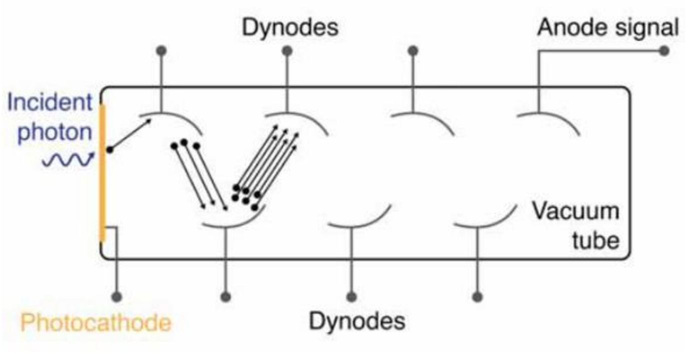
OMNIS set-up schema



Boron converter principle

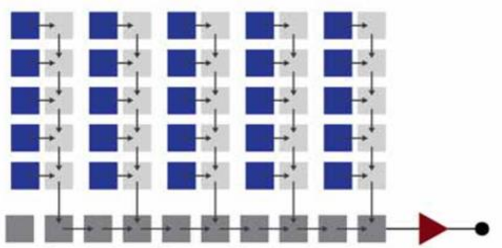
Photon detection devices

PMT : **High gain, fast response**.



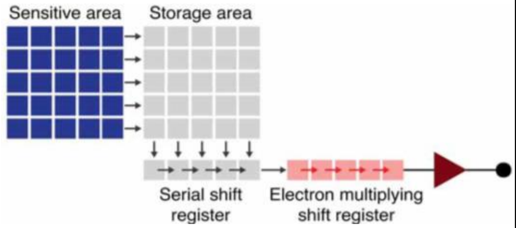
CCD (Charges-Coupled Devices) camera :

- Large number of pixels
- Significant readout time (tens of Hz).



EMCCD (Electron Multiplying CCD) camera :

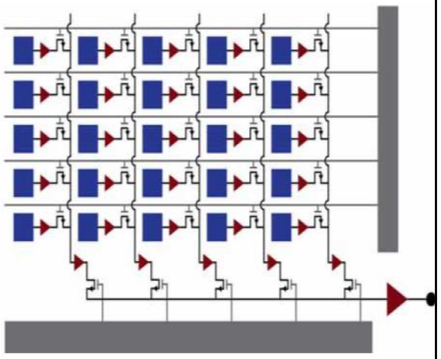
- High signal-to-noise ratio in low-light conditions.
- Charge multiplication through impact ionisation.
- Limited image resolution due to larger pixels.



CMOS (Complementary Metal-Oxyde semiconductors) :

Very low noise : each pixel has a photosensitive region and an active amplifier.

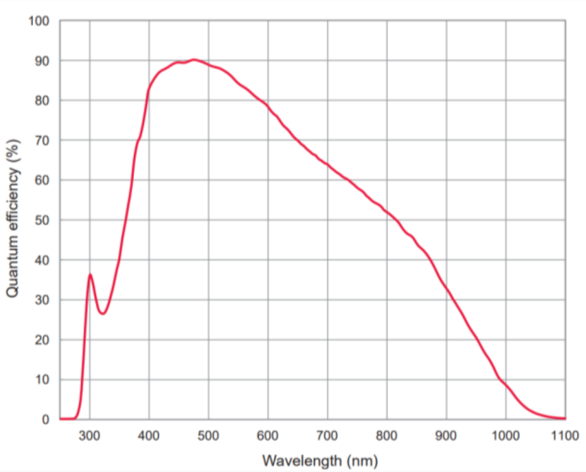
- Shorter readout time.
- Lower manufacturing cost than CCD sensors
- Rolling shutter effect : pixels are exposed alternatively



Hamamatsu CMOS camera

ORCA®-Quest

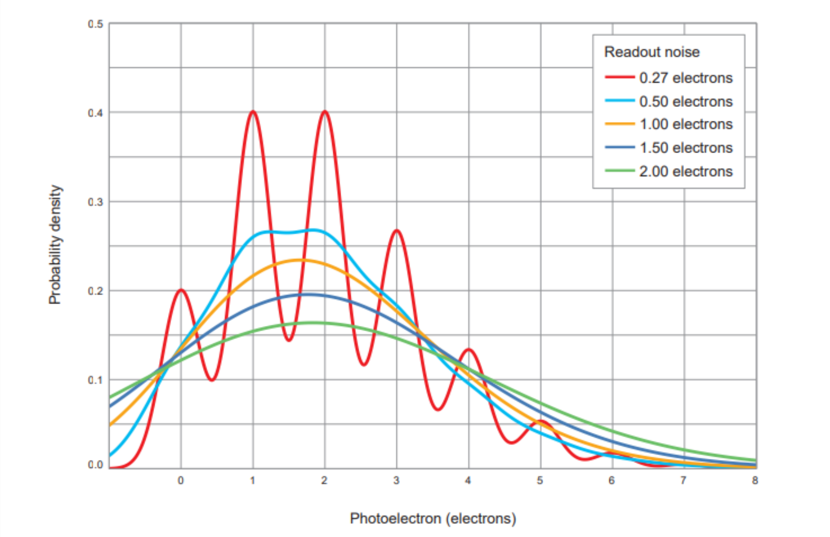
Quantum efficiency



Readout noise

Standard scan	0.43 electrons rms
Ultra quiet scan	0.27 electrons rms

Photon number resolving



Rate

Mode	**Rate**
Standard	120 frames/s
Ultra quiet	10 frames/s

Pixels

Number
4096 x 2304

Size
4.6 µm x 4.6 µm

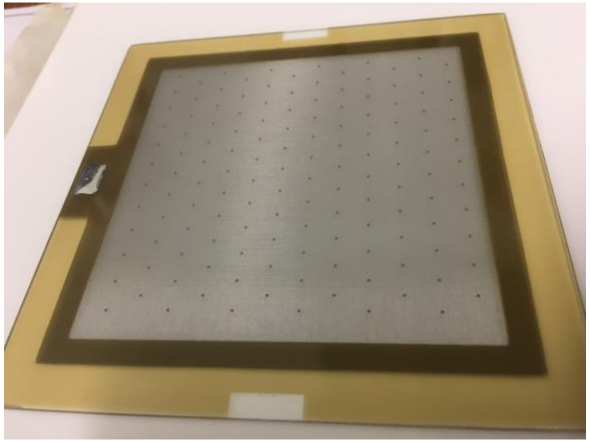
Dark current

Cooling	**Sensor temperature**	**Dark current**
Air	- 20 °C	0.016 e^- /pixels/s
Watter	- 35 °C	0.006 e^- /pixels/s

X-RAY AND B-RAY DETECTION WITH A CMOS CAMERA

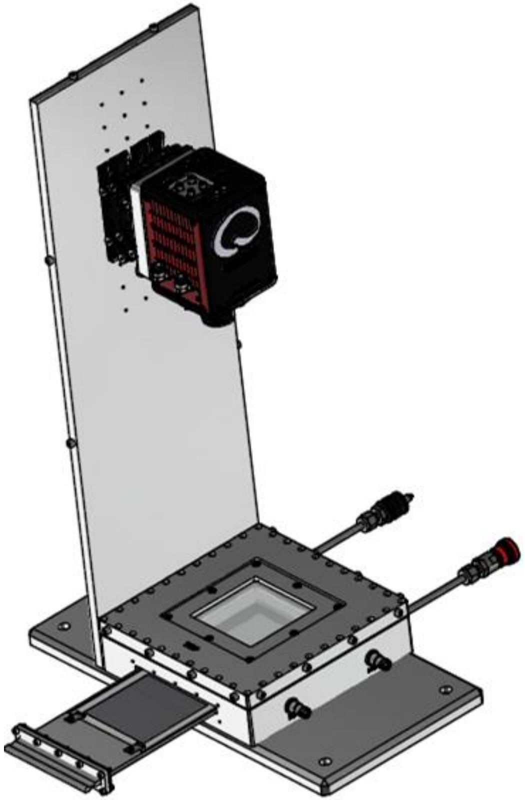
DETECTOR CHARACTERIZATION WITH ^{55}FE SOURCE

PRELIMINARY RESULTS WITH TRITIUM SAMPLES

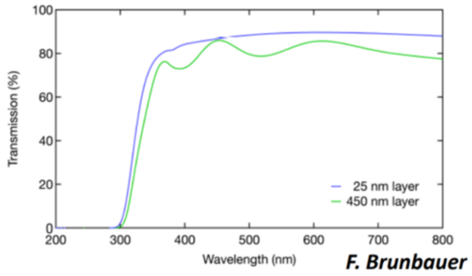


Glass Micromegas

OPTIMED-BETA set-up



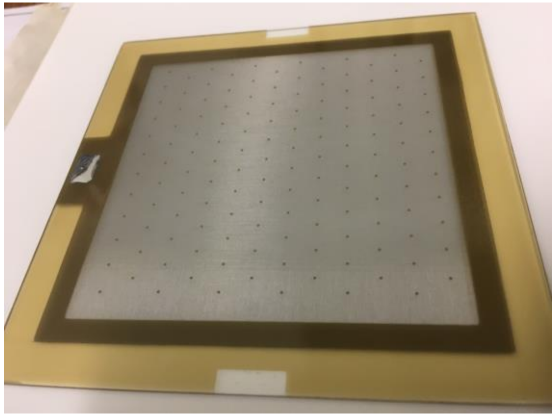
OPTIMED-BETA 3D representation



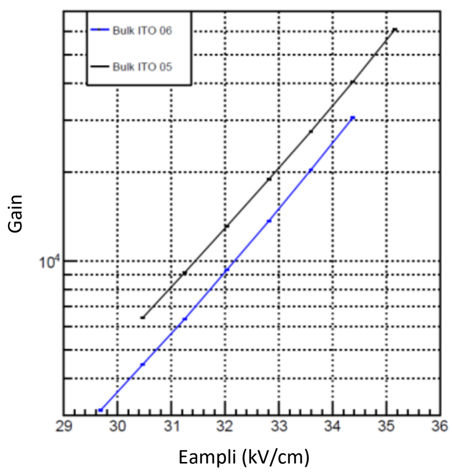
Experimental set-up

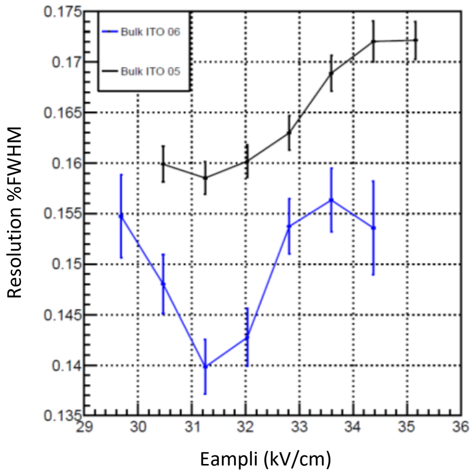
- Bulk on glass from DEDIP
  - Charge readout test in Argon+5%Iso : gain above 10^4 and FWHM reaches 14%
  - The glass is coated with 100 nm of ITO (Indium Thin Oxide) : 80% light transmission above 400 nm wavelength
  - Pillars with hexagonal pattern and large pitch (6 mm)

S. Aune, T. Benoit, M. Kebbiri



Glass Micromegas



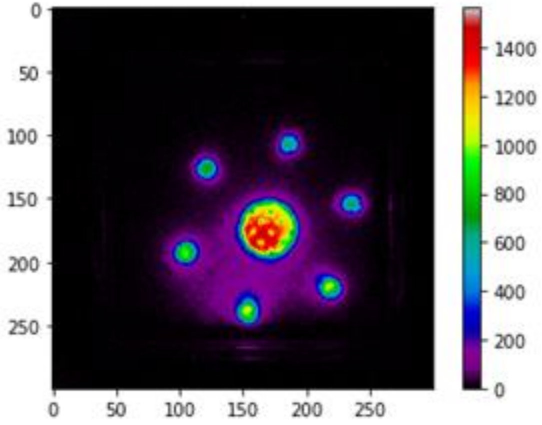


Gain and resolution curves in ***charge readout*** *mode - ITO bulks*

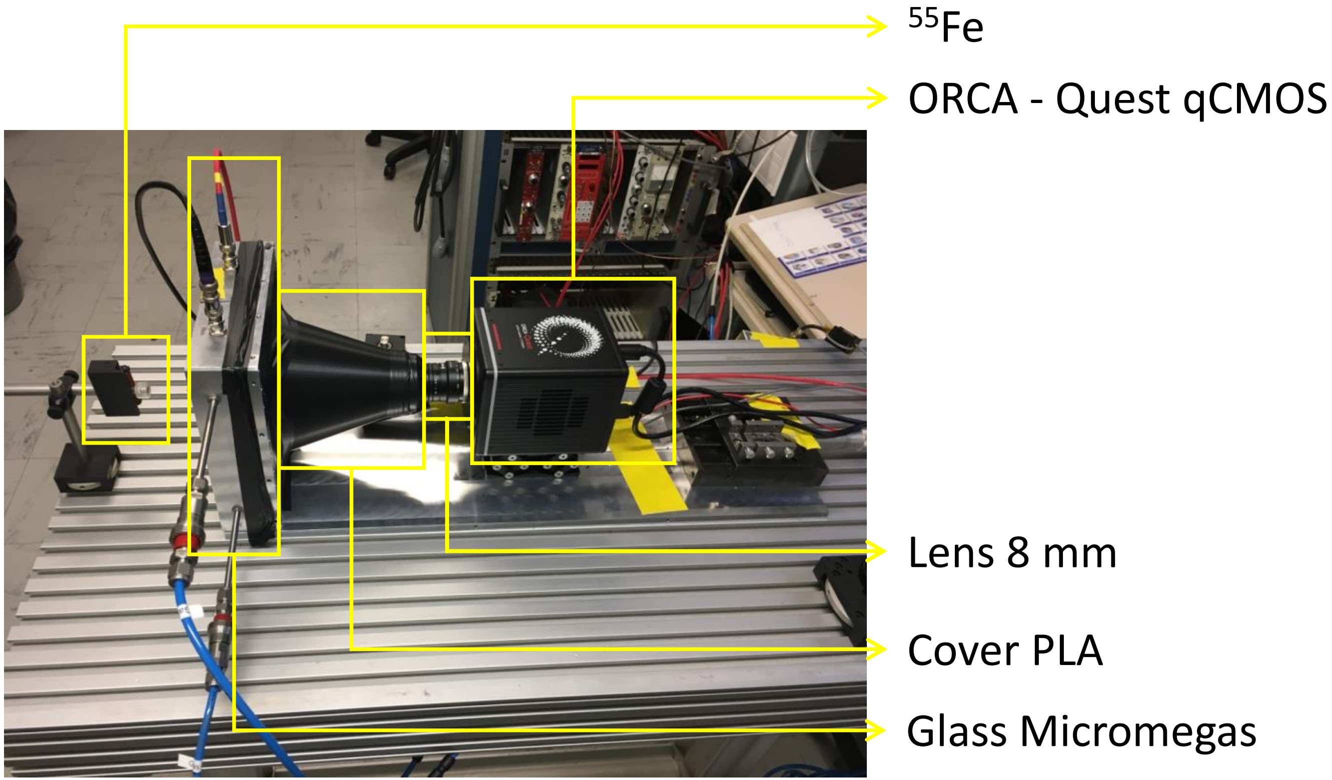
Experimental set-up

- X-ray detection

Copper taget



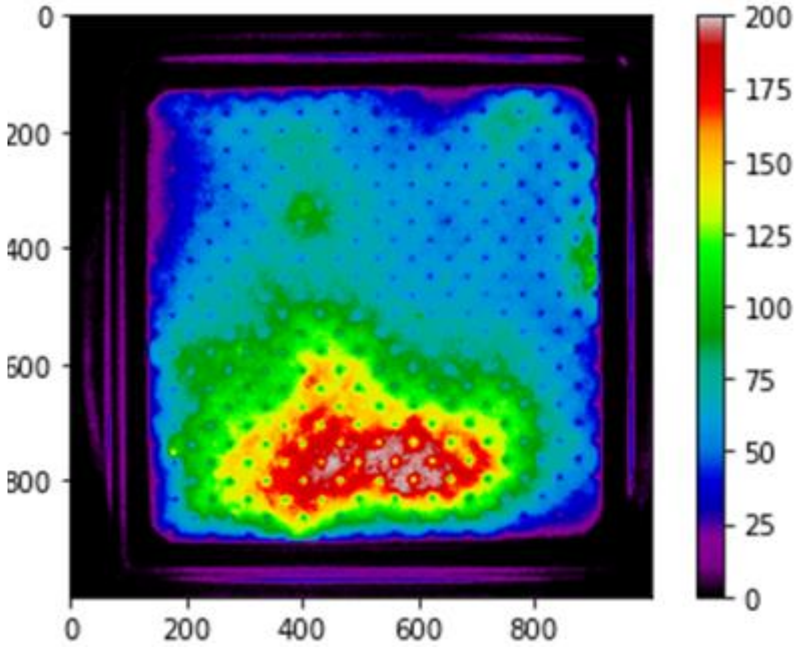
60 sec target image with simple background suppression



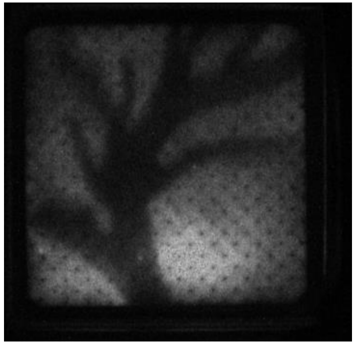
Experimental set-up for x-rays

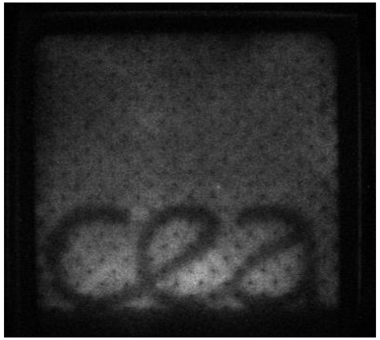
X-ray radiography

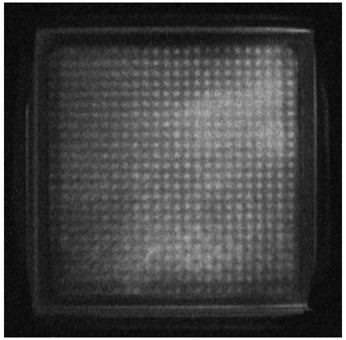
- Good spatial resolution
- High gain : 1 min exposure time gives images with good contrast
- Optimisation :
  - New bulk with more uniform gain
  - Suitable lens (greater magnification)
  - Mechanics without light leak at single photon level

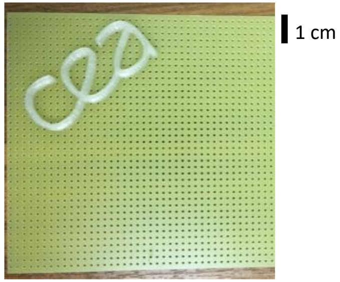


60 sec full detector image with simple background suppression

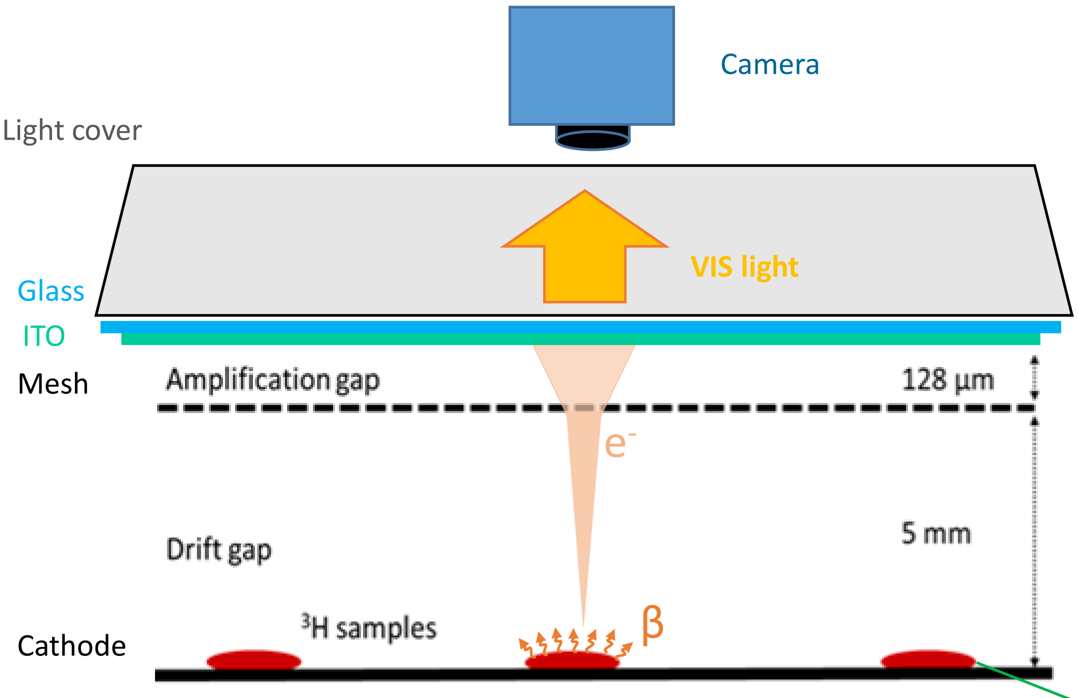




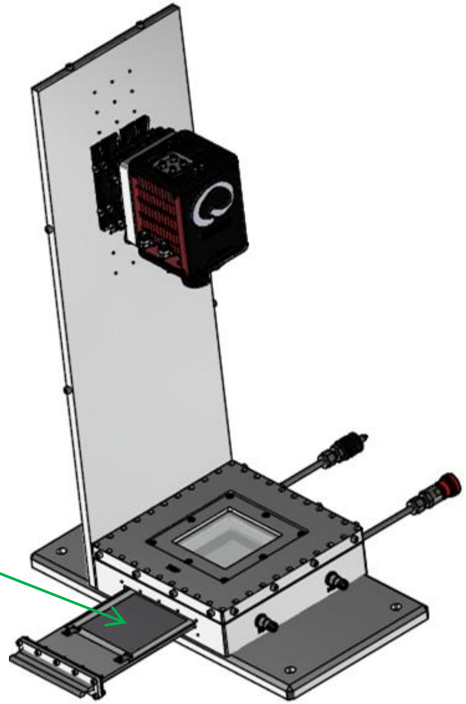




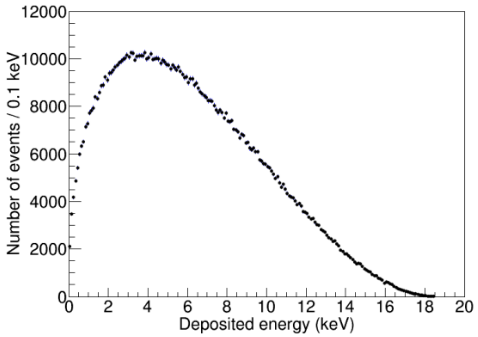
Experimental set-up



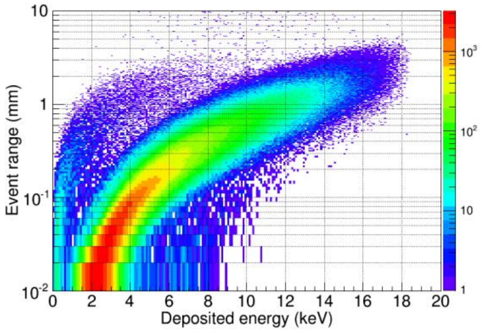
OPTIMED-BETA set-up schema



OPTIMED-BETA 3D representation

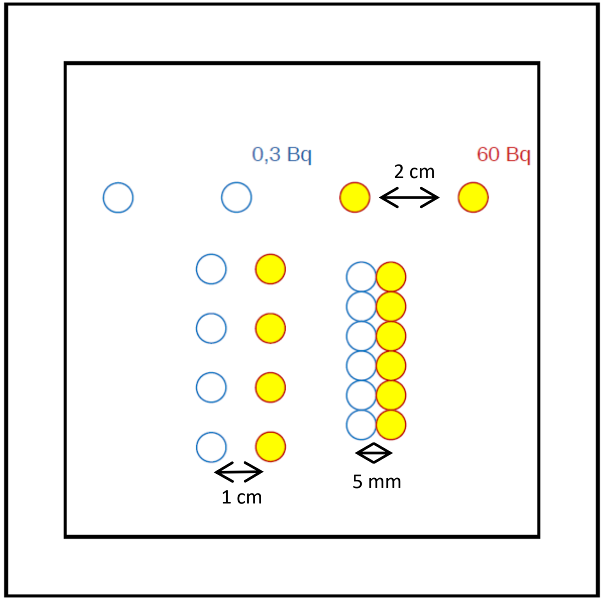


Tritium beta ray spectrum

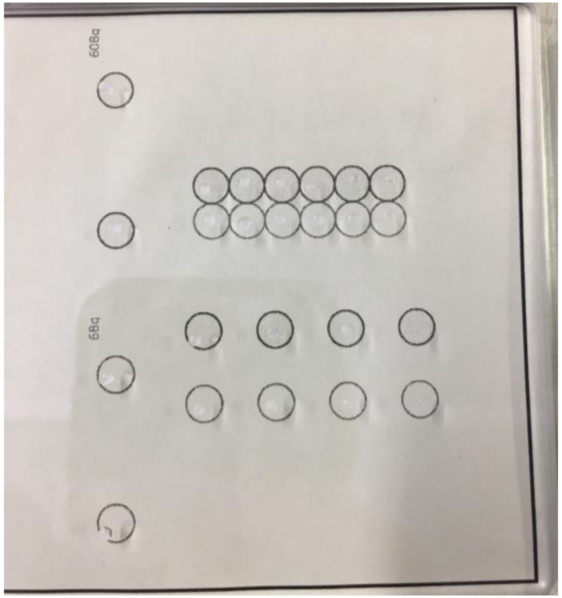


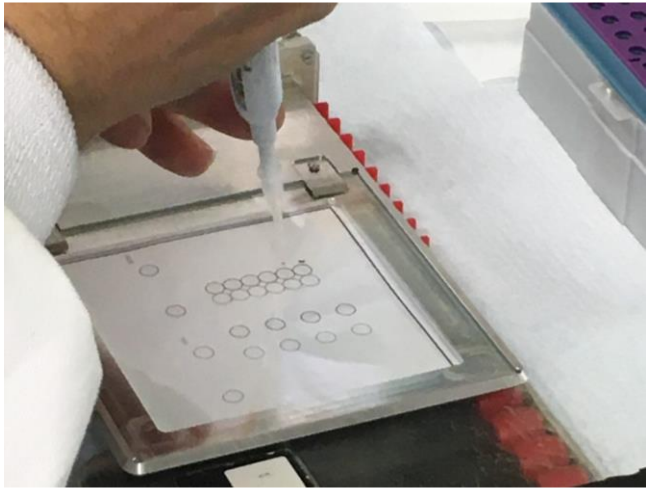
Tritium beta ray range

First deposit : tritiated glucose



Tritium deposits scheme



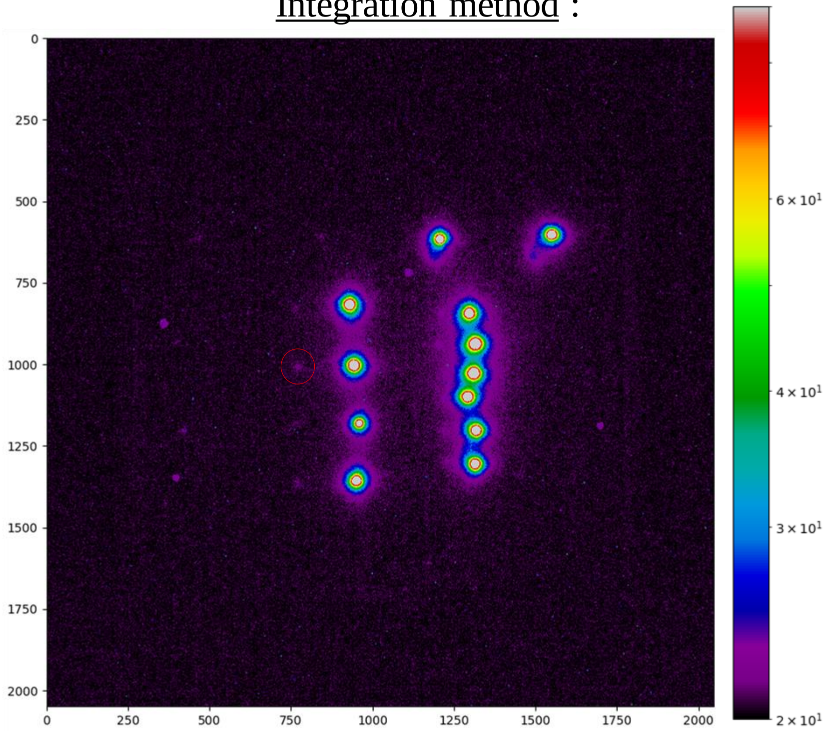


Tritium deposits pictures

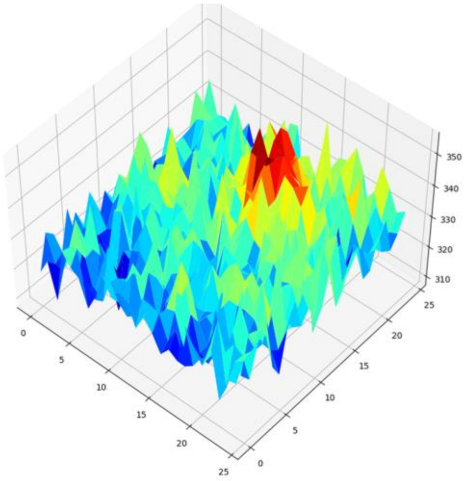
- Activity measurement limits and dynamic range → Activities : 0.3 Bq and 60 Bq
- Spatial resolution → gap between drops : 2 cm – 1 cm – 5 mm

Preliminary results with tritium samples

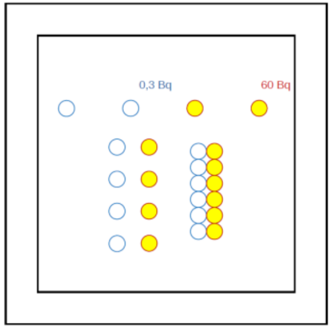
Integration method :



180 frames of 10 sec (30 min) added with simple background suppression 20% of CF4



3D representation of a 0.3 Bq sample



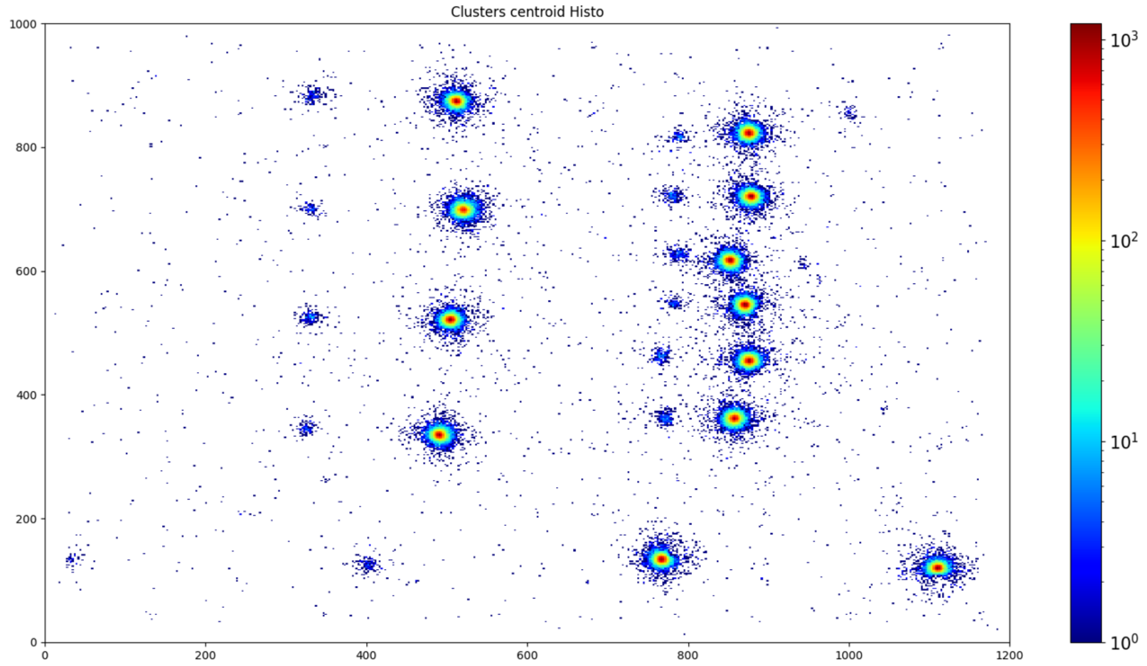
Tritium deposits scheme

Schneider lens :
25mm, f/0,95

- 60 Bq drops positions are well assessed
- 0.3 Bq drops hardly visible

Preliminary results with tritium samples

Clustering method :



20000 frames of 100 msec (33 min), individual pixel background thresholding, 20% of CF4

- Both 60 Bq and 0.3 Bq drops positions are well assessed
- Better signal-to-noise ratio and counting events capability

CONCLUSION

Ongoing work : Single photon calibration with a PMT

- Measure single photon response of PMT
- Measure the number of photons per event (X-ray, Beta, neutron)
- Establish a correlation between sample activity and integrated image intensity

CONCLUSION

What we have done

- Fabrication and test of several Micromegas bulks in glass
- Design and mounting of optical readout detectors for neutron and beta detection
- PM data analysis and camera images analysis from x-rays and beta-rays

Outlook

- Beam test at Soleil accelerator : spatial resolution measurement
- Set-up amelioration : light tightening, water cooling : to lower dark current, more uniform gain on glass Micromegas, explore more image treatment methods
- Optimed-beta : next tests on tumoral cells and with isolated single tumoral cells in the future
- OMNIS : first images with neutrons soon

Back up

Some definitions

Quantum efficiency

Rate between created photoelectrons and incident photon, in terms of photon wavelength.

Gain

Ratio between the output charge signal of the photon detector and the charge directly produced by incident photons.

Signal-to-noise ratio

Ratio of amplitude of the produced signal and the sum of all contributions to the noise level : dark current and readout noise.

Dark current

Depends on exposure time. The dark current is a certain current flowing even in the absence of light mainly due to thermally produced charge carriers (e^- /pixel/sec).

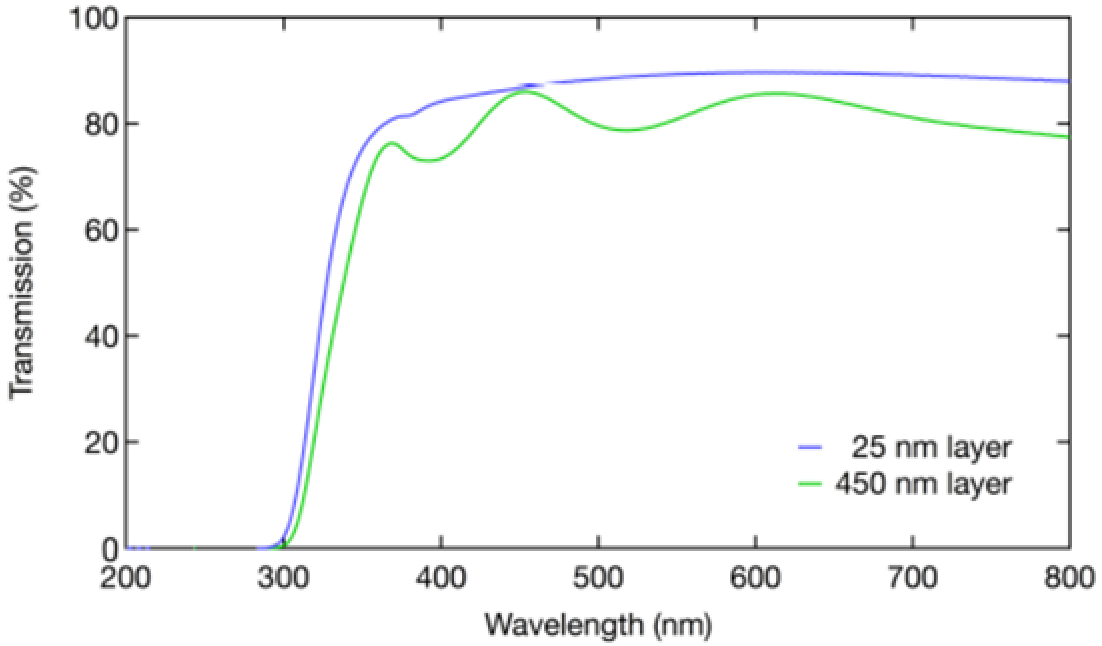
Readout noise

Random contribution to each readout cycle of a pixel. It depends on the readout speed of pixels.

Pixel

Layer of Silicon : photosensitive region.
Photon creates electron-hole pair in this region. Electric field accumulates electrons or holes at the surface of the pixel. Charges are accumulated during exposure time and read out by a charge amplifier and digitised.

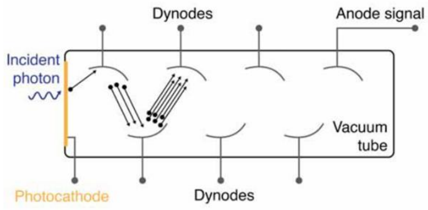
ITO on glass transmission



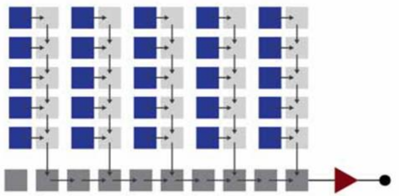
F. Brunbauer

Photon detection devices

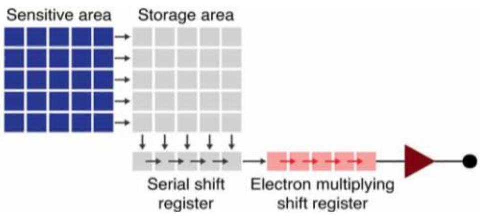
PMT : **High gain, fast response**. Conversion of incident photon by photoelectric effect at a photo-cathode. Multiplication of primary electron at dynodes to secondary electron emission



CCD (Charges-Coupled Devices) camera : Reads out a large number of pixels with few digitisers and **unique amplifier** by reading pixels by rows. Less amplifier involves significant readout time (tens of Hz).



EMCCD (Electron Multiplying CCD) camera : Achieves high signal-to-noise ratio in low-light conditions. Similar to CCD camera with an additional shift register which multiplies charges through **impact ionisation**. Limited image resolution due to larger pixels.



CMOS (Complementary Metal-Oxyde semiconductors) :

Each pixel has a photosensitive region and an active amplifier. Achieves low noise : each pixel amplifies charges before being moved through shift registers.

- Active pixel implies much shorter readout time.
- Lower manufacturing cost than CDD sensors
- Rows of pixels are read out sequentially : not all pixels are exposed simultaneously :

rolling shutter effect