

First images with the Optical Micromegas detectors

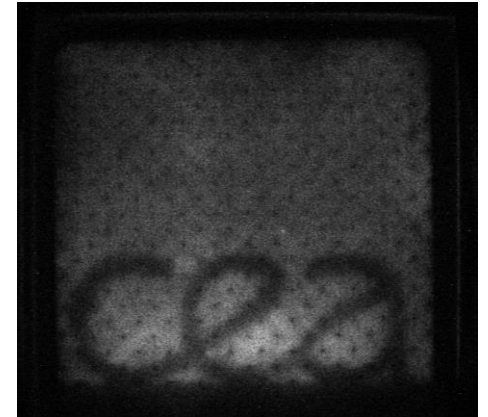
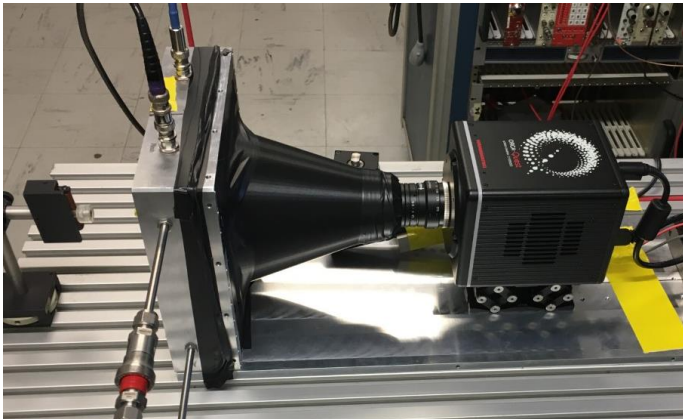
RD51 – 14/06/2022

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CONTEXT

LIGHT PRODUCTION MECHANISMS

OPTICAL READOUT OF MPGDs

OPTIMED-BETA

OMNIS

LIGHT DETECTION DEVICES

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

DETECTOR CHARACTERIZATION WITH ^{55}Fe SOURCE

PRELIMINARY RESULTS WITH TRITIUM SAMPLES

CONCLUSION AND PERSPECTIVES

LIGHT PRODUCTION MECHANISMS

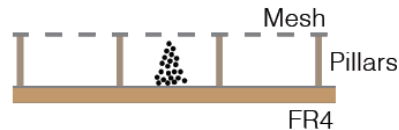
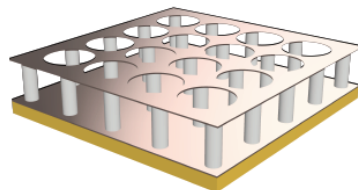
OPTICAL READOUT OF MPGDS

OPTIMED-BETA

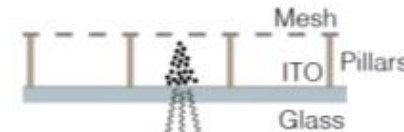
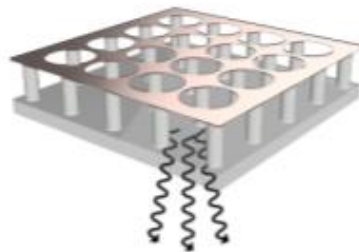
OMNIS

LIGHT DETECTION DEVICES

Charge readout



Optical readout



CCD camera

F. Brunbauer



Radiation imaging with glass Microgases
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ABSTRACT

Optically readout scintillation light emitted by MicroPattern Gaseous Detectors (MPGDs) with imaging sensors is a versatile and powerful readout modality using advantage of modern high granularity imaging sensors. To allow scintillation light readout of detectors based on MicroMesh Gaseous Structures (MicroMesh) technology, we have integrated a Microgase on a glass substrate with a transparent anode. In addition to optical detection of scintillation light emitted during electron avalanche multiplication between the micro-mesh and the anode, this setup also achieves a good energy resolution. A glass Microgase detector was operated in an Ar-CF₄ gas mixture and showed a response comparable to conventional Microgase detectors. The spectrum of the scintillation light was recorded and shown to be equivalent to the one obtained with other gaseous detectors in the same gas mixture. Optically read out images were recorded with CCD camera and integrated X-ray radiographic imaging with good spatial resolution was demonstrated. A spatial resolution of 480 μm (FWHM) was found. High X-ray fluxes detectors with a high sensitivity sensor was achieved, which potentially permits energy-resolved X-ray fluorescence imaging.

1. Introduction

Optical readout of MicroPattern Gaseous Detectors (MPGDs) takes advantage of combining the high gain factors achieved by MPGD technologies with the high granularity pixel readout permitted by modern imaging sensors. This allows for the realisation of radiation detectors with spatial resolution and sensitivity to a wide range of radiation ranging from Minimum Ionising Particles (MIPs) to low-energy X-rays, as well as highly ionising radiation such as alpha particles. Detector concepts based on optically read out MPGD-based detectors have been previously developed for applications such as radiation imaging [1,2], 3D track reconstruction in optically read out Time Projection Chambers (TPCs) [3,4] or dose imaging in hadron therapy [5].

Detector MPGD-based detector concepts employ optical readout with imaging sensors were predominantly based on Gaseous Electron Multiplier (GEM), a variety of MPGDs consisting of perforated multiplier foils. This geometry makes GEM well-suited for optical readout as scintillation light emitted during electron avalanche multiplication can be easily recorded by a camera placed behind the detector. In contrast, most other MPGD technologies are integrated on substrates such as Printed Circuit Board (PCB) which are opaque and thus inhibit scintillation light recording. This is also true for MicroMesh Gaseous Structures (MicroMesh), which employ a micro-mesh supported by

insulating pillars to create a uniform amplification region with an electric field strength sufficient for electron avalanche amplification between the micro-mesh and an anode [7]. However, MicroMesh are typically integrated on PCBs, which has previously inhibited the optical readout of such detectors.

We have developed a Microgase detector on a glass substrate with a transparent anode made of Indium Tin Oxide (ITO) to enable the optical readout of Microgase based detectors. This is possible to take advantage of the superior energy resolution reached by this MPGD technology as well as profit from the high spatial resolution and sensitive 2D imaging capabilities associated with optical readout with state-of-the-art imaging sensors.

This enables the readout of secondary scintillation light emitted during electron avalanche multiplication in the amplification gap between the micro-mesh and the anode. As with the optical readout of GEM-based detectors, the glass Microgases were operated in an Ar-CF₄ gas mixture. Gas mixture contains CF₄ because wide scintillation light emission bands in the ultraviolet (UV) and visible (VIS) wavelength ranges [8], which are compatible with the wavelength-dependent quantum efficiency (QE) of common CCD and CMOS imaging sensors. Optical readout of GEM-based detectors operated in Ar-CF₄ gas mixture has been reported and used for X-ray radiography [1,2] as well as 3D track reconstruction [3,4].

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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 μ s)

Electroluminescence

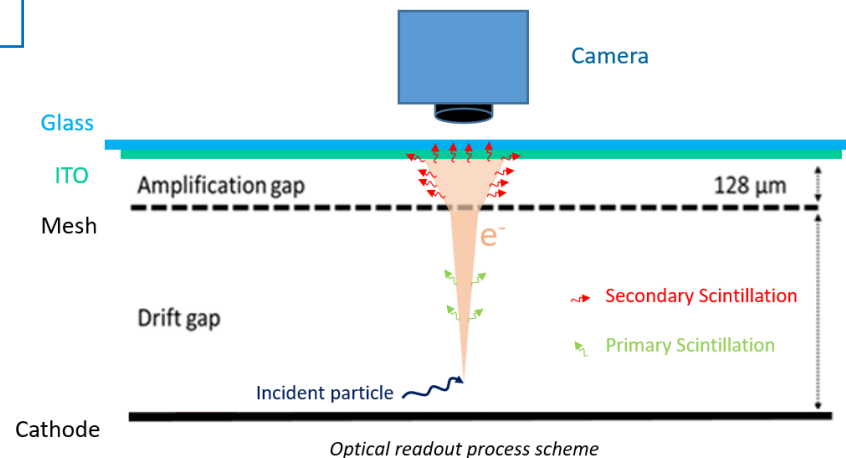
Electrons with energy lower than ionization threshold just excite atoms or molecules.

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.



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

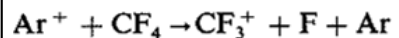
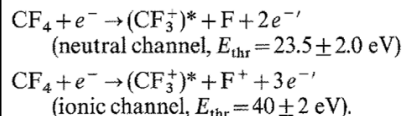
CF₄ : Carbon tetrafluoride

- 0.1 to 0.3 secondary scintillation photons per secondary electron in avalanche.
- High charge gain > 10⁴
- Emits in wavelength regions compatible with readout device : visible wavelengths

Argon + CF₄ scintillation wavelengths

- **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⁺.

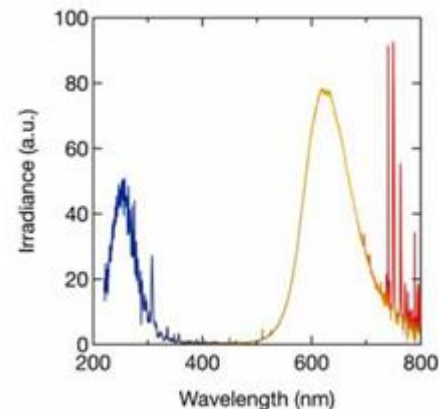


- **VIS : Electron impact** : excited CF₄^{*} dissociates to CF₃^{*} which emits in VIS.

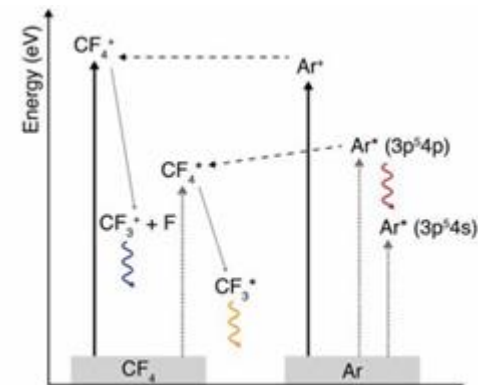
Dissociation of CF₄^{*} is not the only way to get CF₃^{*} :

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

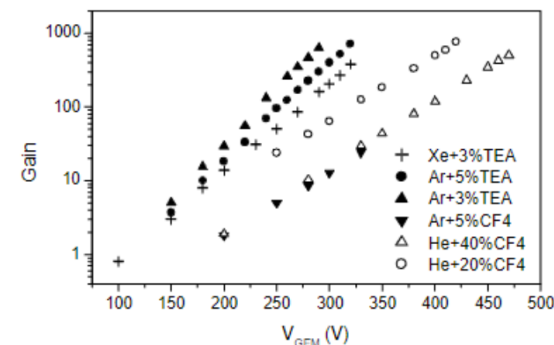
- **NIR : Transitions** between excited state of Ar emits in NIR.



Adapted from Seravalli, E., PhD thesis, 2008



Scintillation spectrum and mechanisms of Ar/CF₄ gas



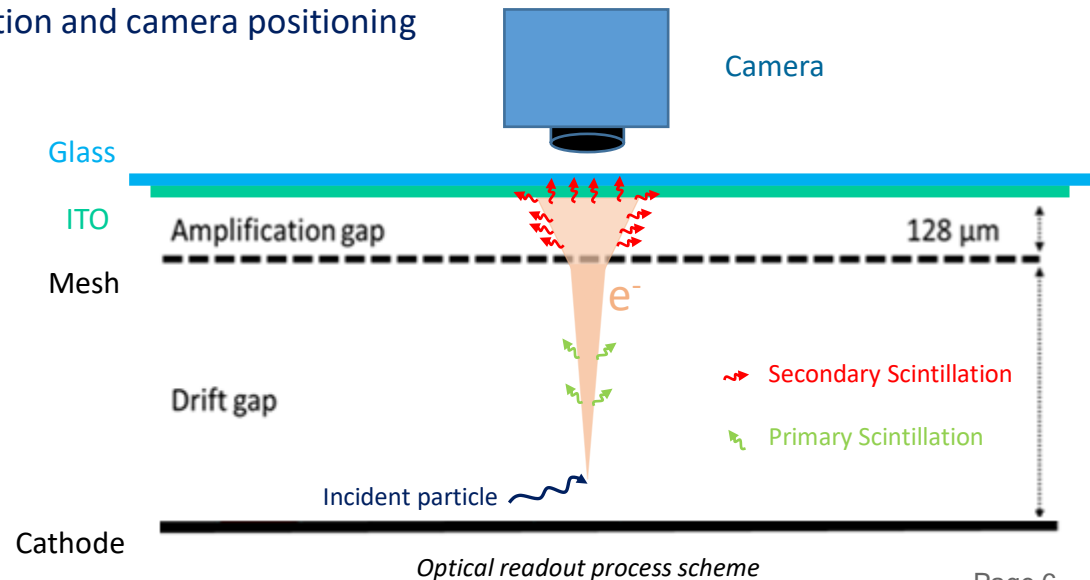
Gain versus applied voltage for several gas mixtures.

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

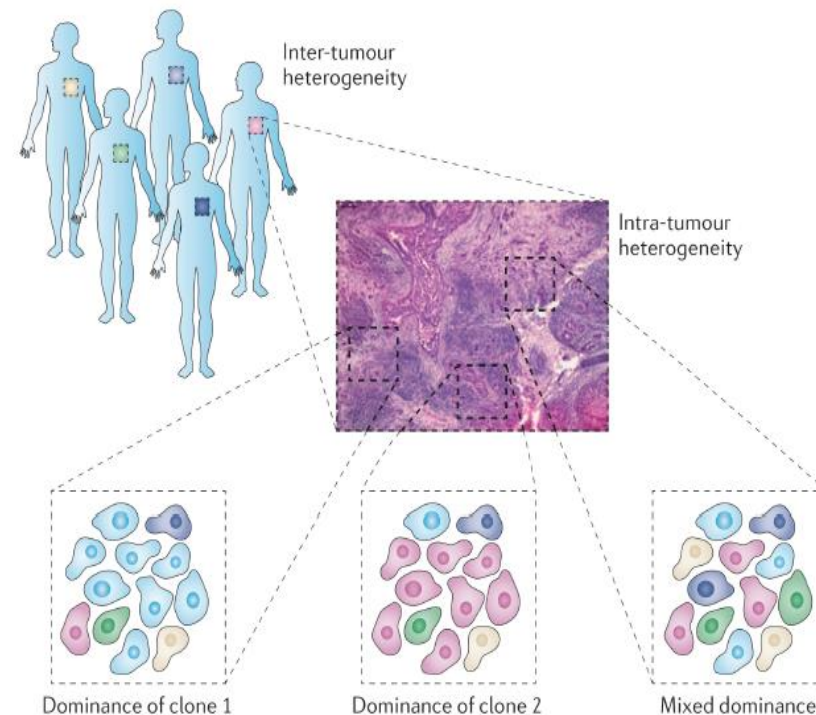
Disadvantages

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



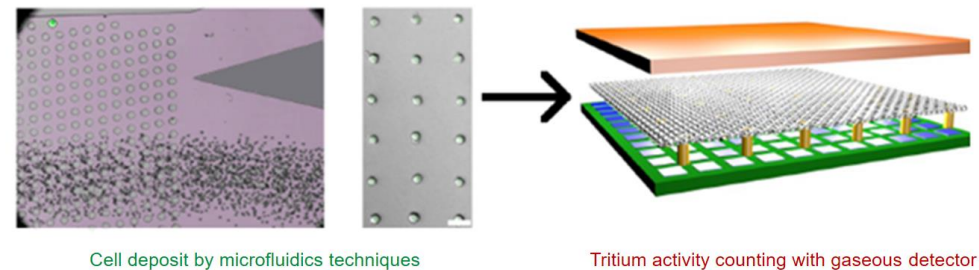
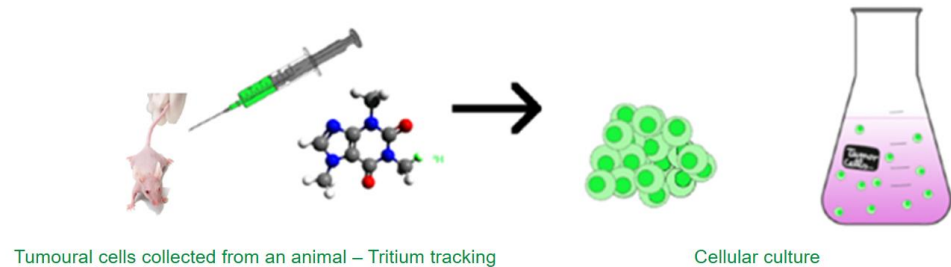
➤ Tumoral heterogeneity : different cell types inside a tumor

- 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



Molecule labelling and tracking with tritium

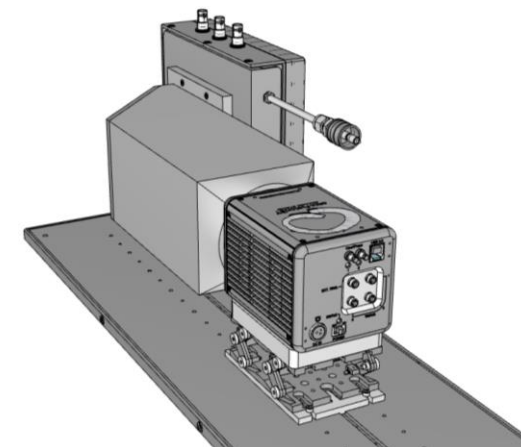
- Pharmaceutical needs at the cell level for drug development :
 - Assess the **drug distribution** among cells
 - Evaluate the impact of the cell heterogeneity on drug biodistribution
 - At the cell level : Quantification of ^3H concentration in **single cell** samples

Micromegas-based neutron imager

- Real-time neutron radiography for high-radiation environments
- Two major applications :
 - Jules Horowitz 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 γ -to-n suppression of the Micromegas : $>10^6$
 - Spatial resolution on the order of **100 μm** : camera high granularity
 - Scalable to larger areas : $50 \times 50 \text{ cm}^2$
 - Highly contrasted images
 - Real time measurement



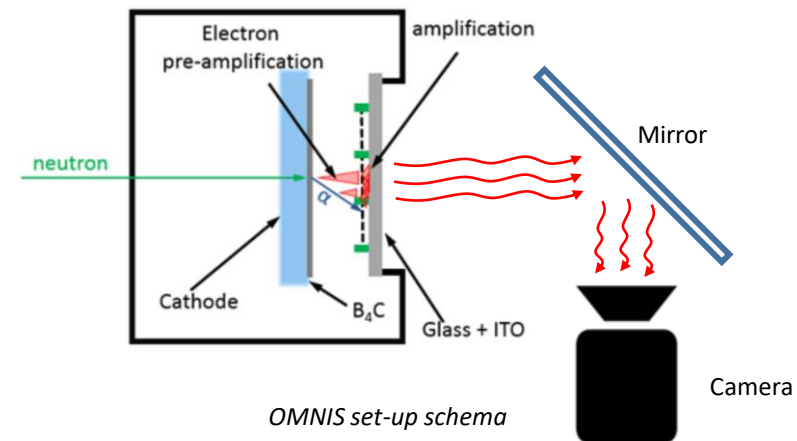
SAPHIR Linatron (X-ray from 6 MeV to 9 MeV)



OMNIS 3D representation

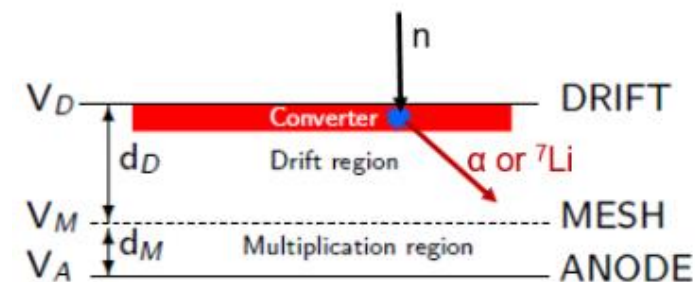
Micromegas-based neutron imager

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



OMNIS set-up schema

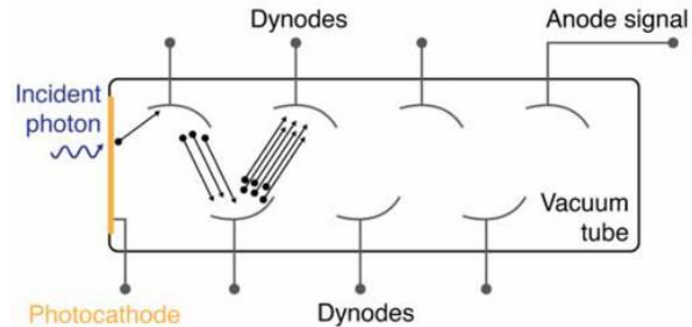
- ¹⁰B₄C neutron-to-charge converter
 - **Thermal neutrons** created by 2 μm thin ¹⁰B₄C layer
 - Conversion efficiency : 5%
 - (α or Li) fragments causes strong ionisation compared to electrons
 - Drawback : fragments long range in the gas (10mm)



Boron converter principle

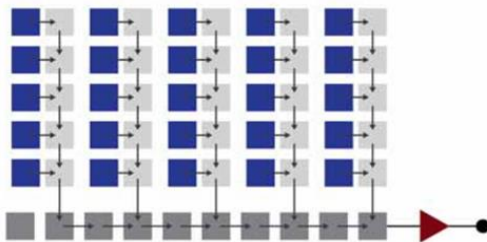
Photon detection devices

PMT : High gain, fast response.



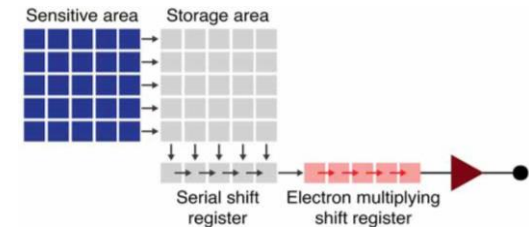
CCD (Charges-Coupled Devices) camera :

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



EMCCD (Electron Multiplying CCD) camera :

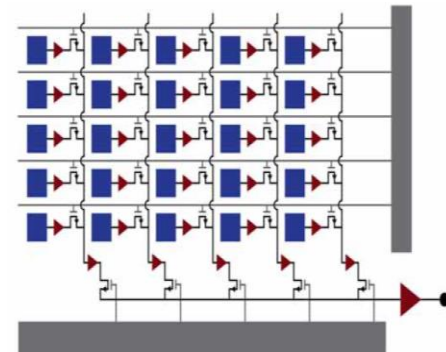
- High signal-to-noise ratio in low-light conditions.
- Charge multiplication through impact ionisation.
- Limited image resolution due to larger pixels.



CMOS (Complementary Metal-Oxide semiconductors) :

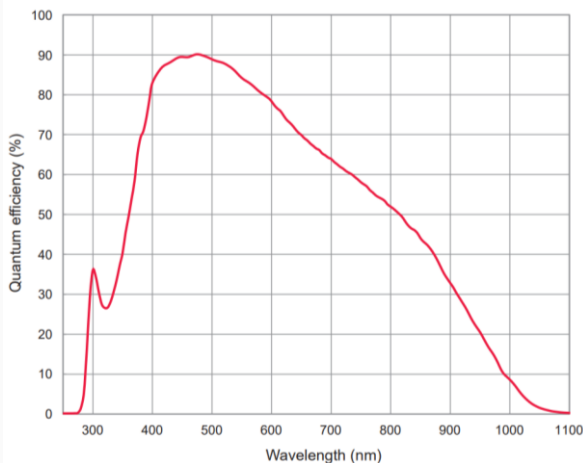
Very low noise : each pixel has a photosensitive region and an active amplifier.

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



Hamamatsu CMOS camera

Quantum efficiency



Readout noise

Standard scan	0.43 electrons rms
Ultra quiet scan	0.27 electrons rms

Dark current

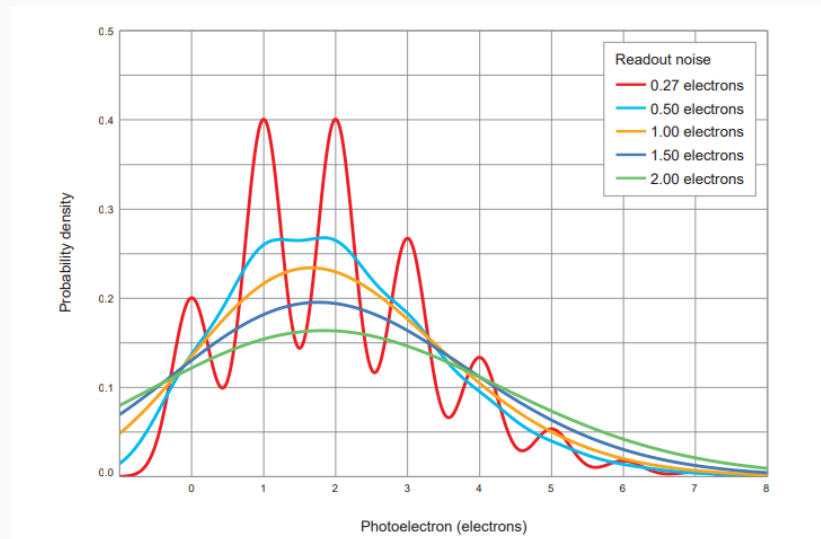
Cooling	Sensor temperature
Air	- 20 °C
Water	- 35 °C

Dark current
0.016 e ⁻ /pixels/s
0.006 e ⁻ /pixels/s

ORCA[®]-Quest



Photon number resolving



Rate

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

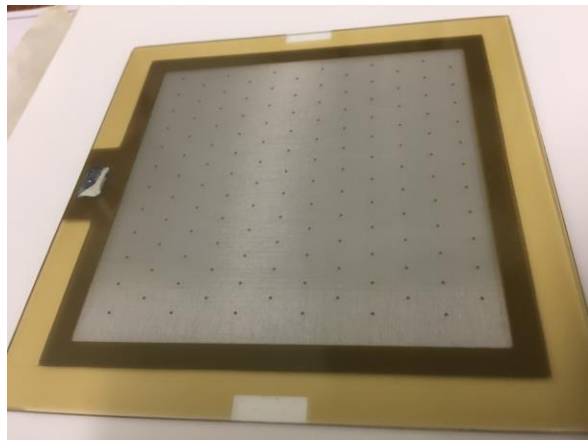
Pixels

Number
4096 x 2304

Size
4.6 μm x 4.6 μm

DETECTOR CHARACTERIZATION WITH ^{55}Fe SOURCE

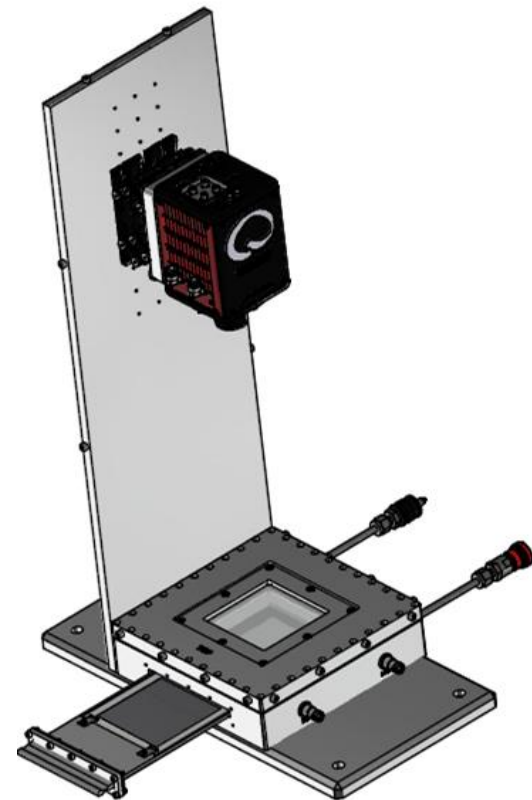
PRELIMINARY RESULTS WITH TRITIUM SAMPLES



Glass Micromegas



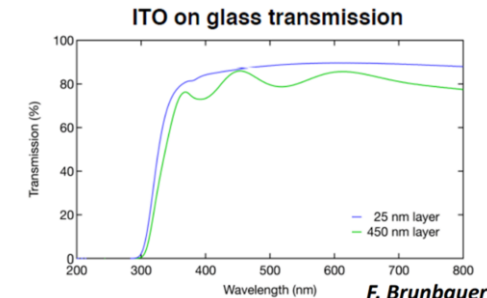
OPTIMED-BETA set-up



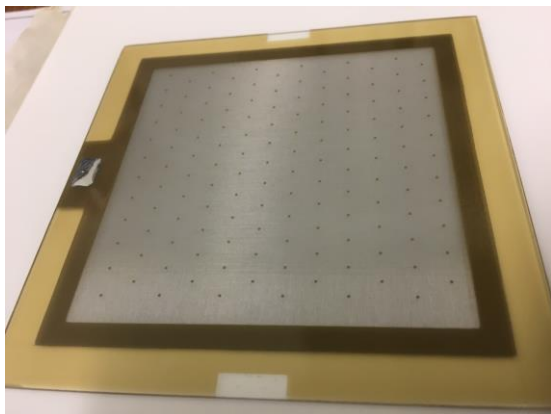
OPTIMED-BETA 3D representation

Experimental set-up

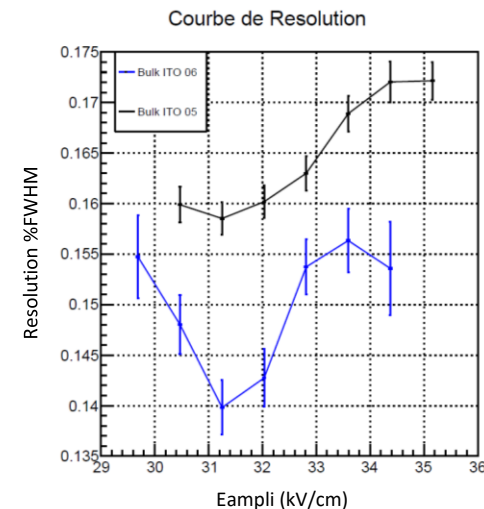
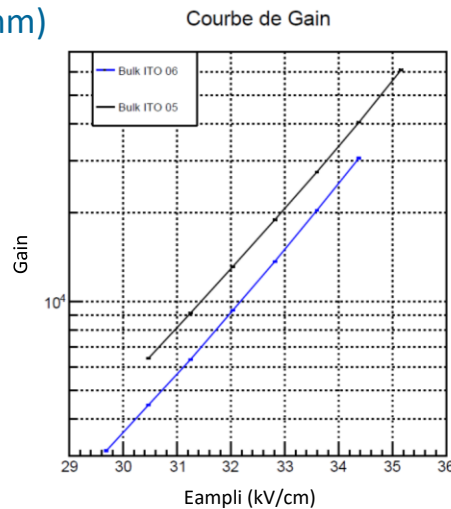
- Bulk on glass from DEDIP
 - Charge readout test in Argon+5%Iso : gain above 10^4 and FWHM reaches 14%
 - The glass is coated with 100 nm of ITO (Indium Thin Oxide) : 80% light transmission above 400 nm wavelength
 - Pillars with hexagonal pattern and large pitch (6 mm)



S. Aune, T. Benoit, M. Kebbiri



Glass Micromegas



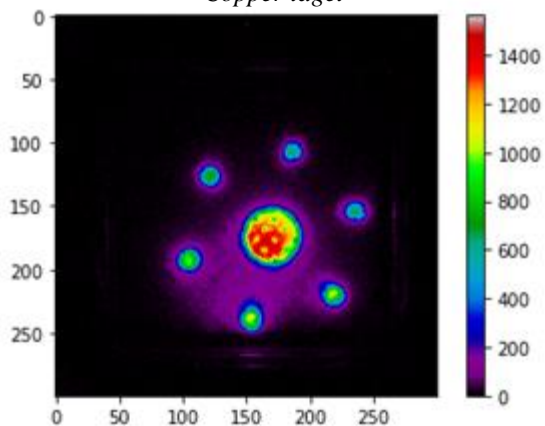
Gain and resolution curves in **charge readout** mode - ITO bulks

Experimental set-up

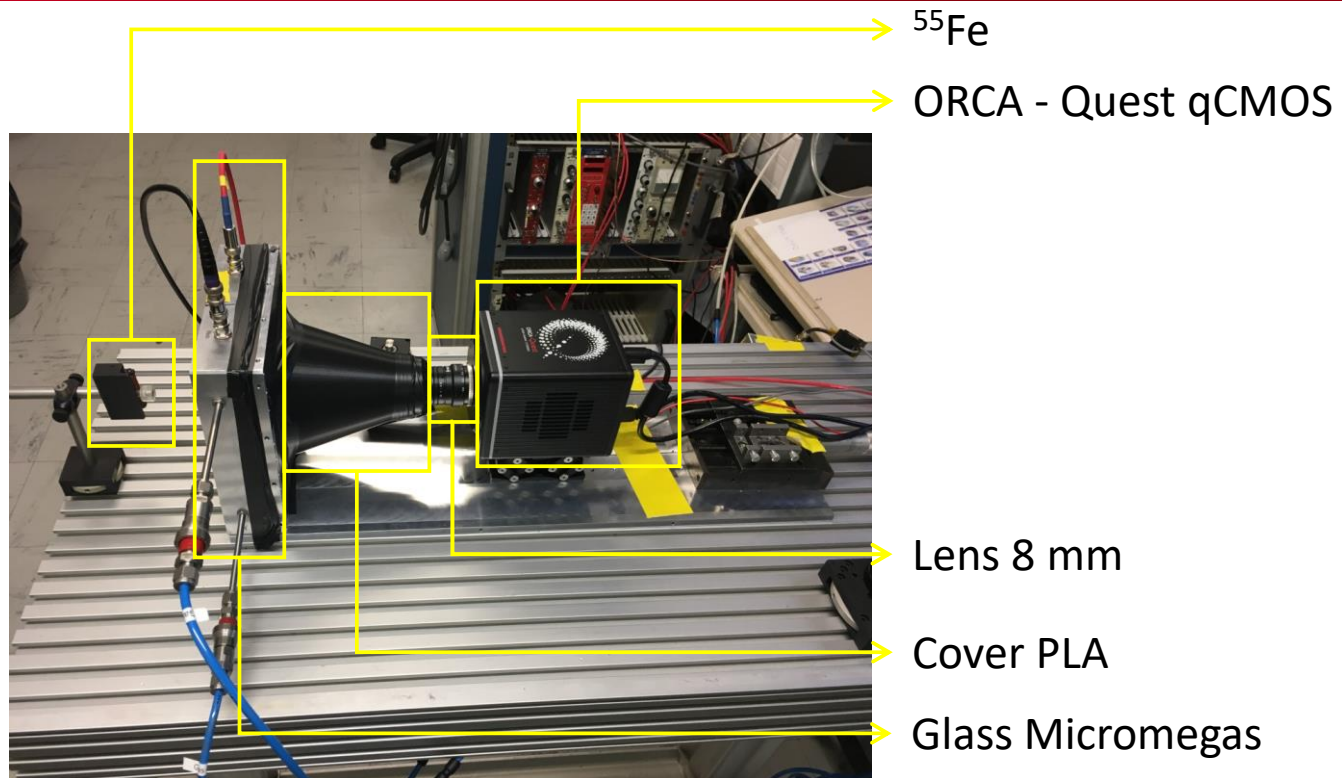
X-ray detection



Copper target



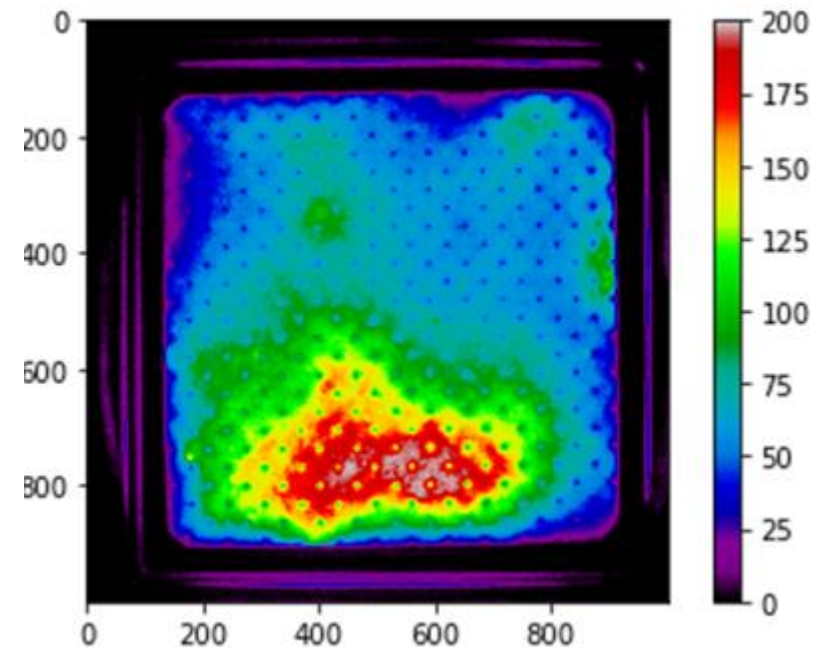
60 sec target image with simple background suppression



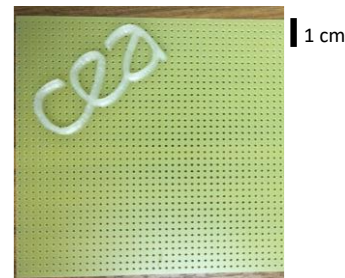
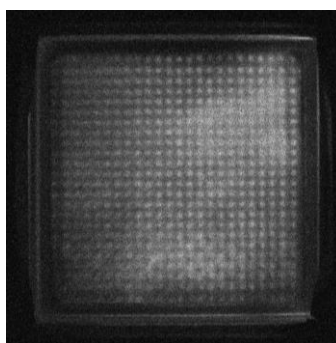
Experimental set-up for x-rays

X-ray radiography

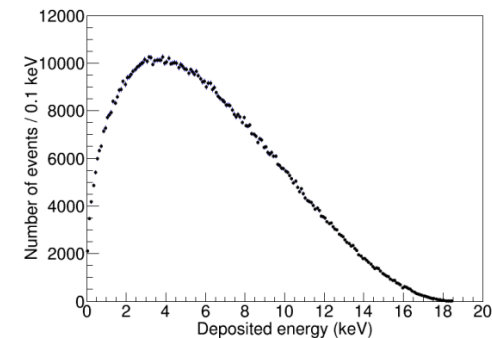
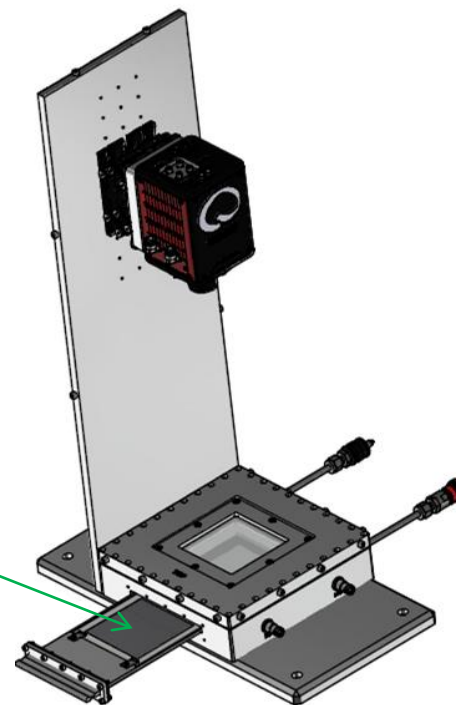
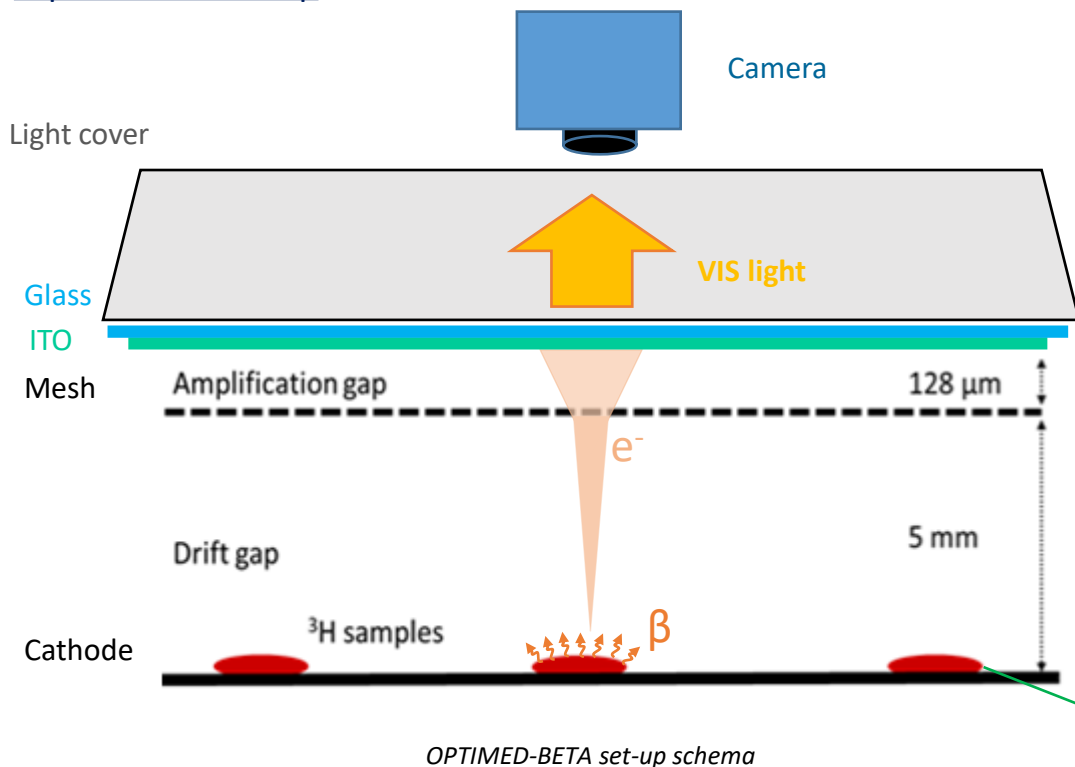
- Good spatial resolution
- High gain : 1 min exposure time gives images with good contrast
- Optimisation :
 - New bulk with more uniform gain
 - Suitable lens (greater magnification)
 - Mechanics without light leak at single photon level



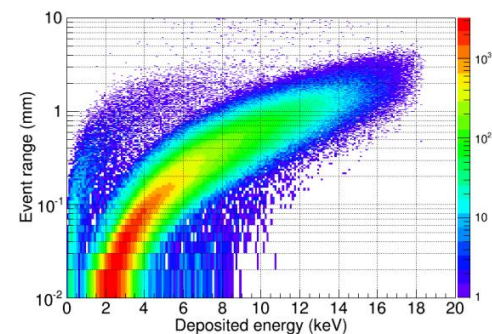
60 sec full detector image with simple background suppression



Experimental set-up

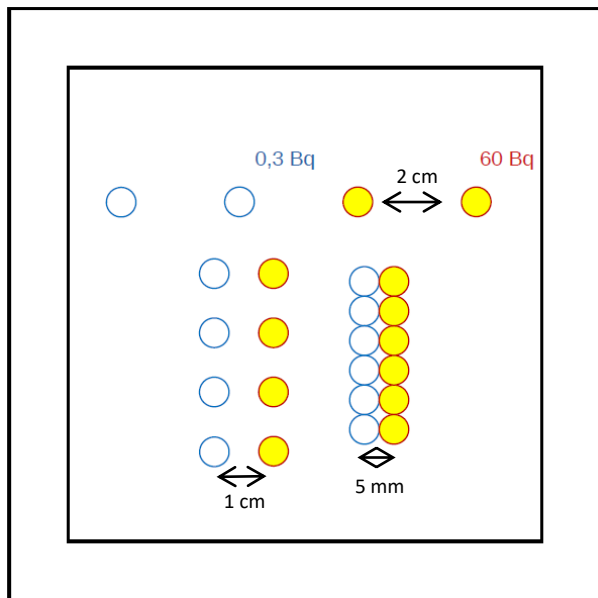


Tritium beta ray spectrum

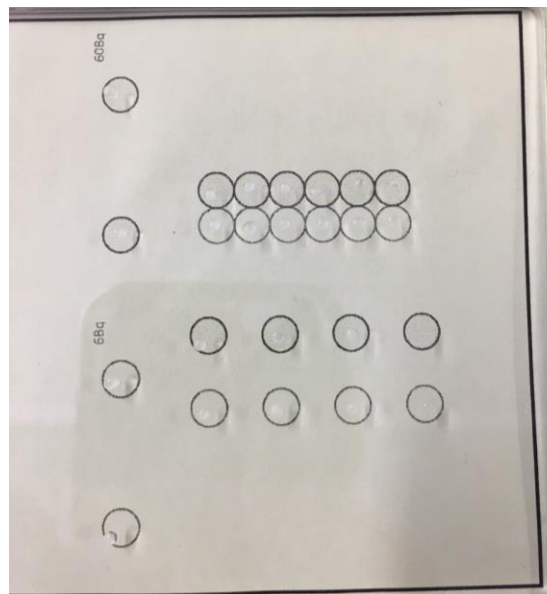


Tritium beta ray range

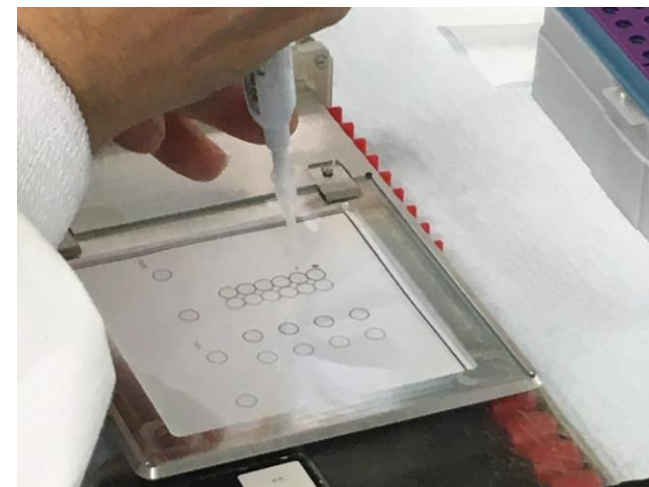
First deposit : tritiated glucose



Tritium deposits scheme



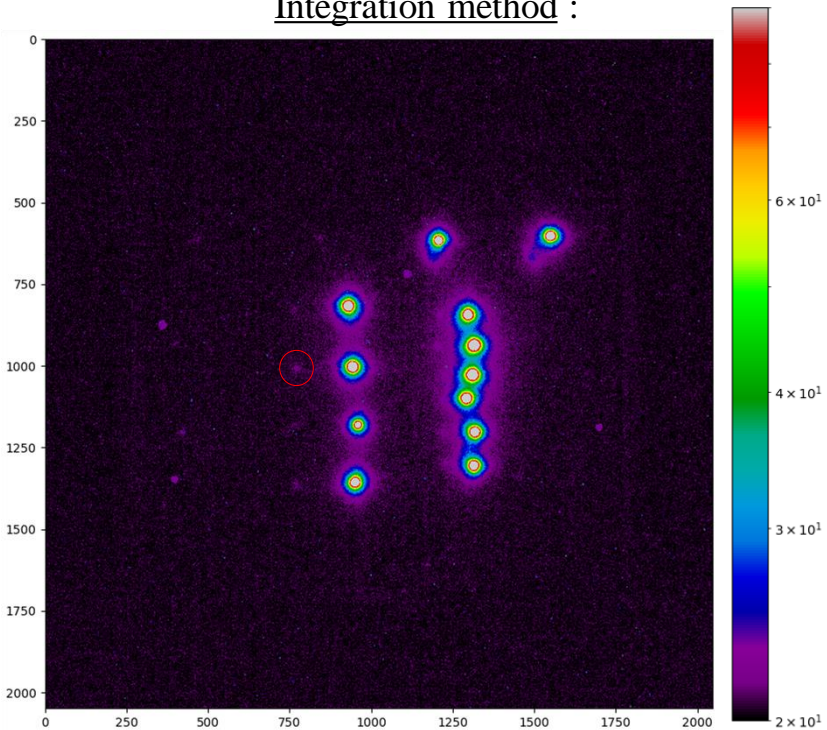
Tritium deposits pictures



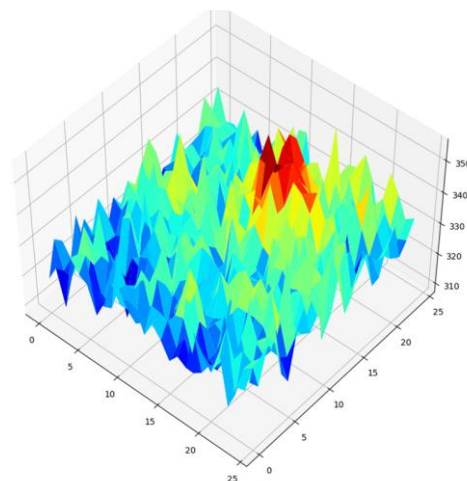
➤ Activity measurement limits and dynamic range → Activities : 0.3 Bq and 60 Bq

➤ Spatial resolution → gap between drops : 2 cm – 1 cm – 5 mm

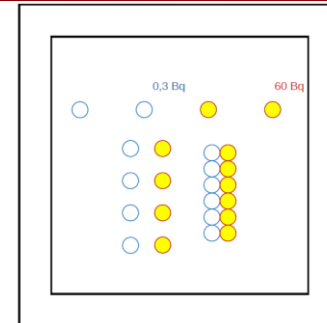
Integration method :



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



3D representation of a 0.3 Bq sample



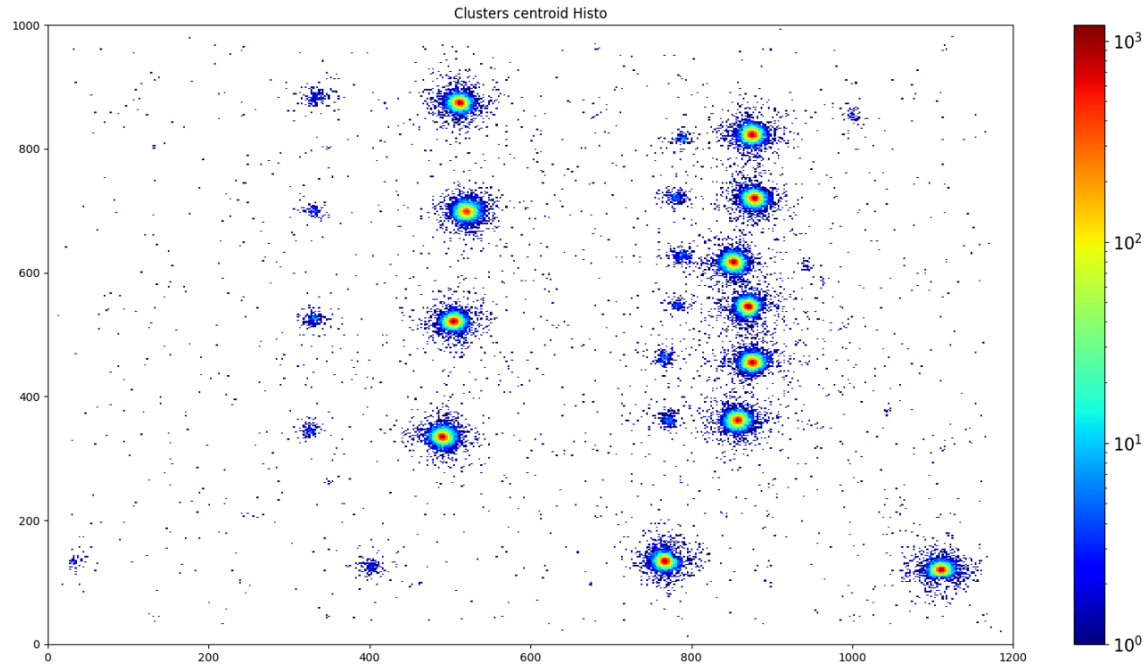
Tritium deposits scheme



Schneider lens :
25mm, f/0,95

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

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

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

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).

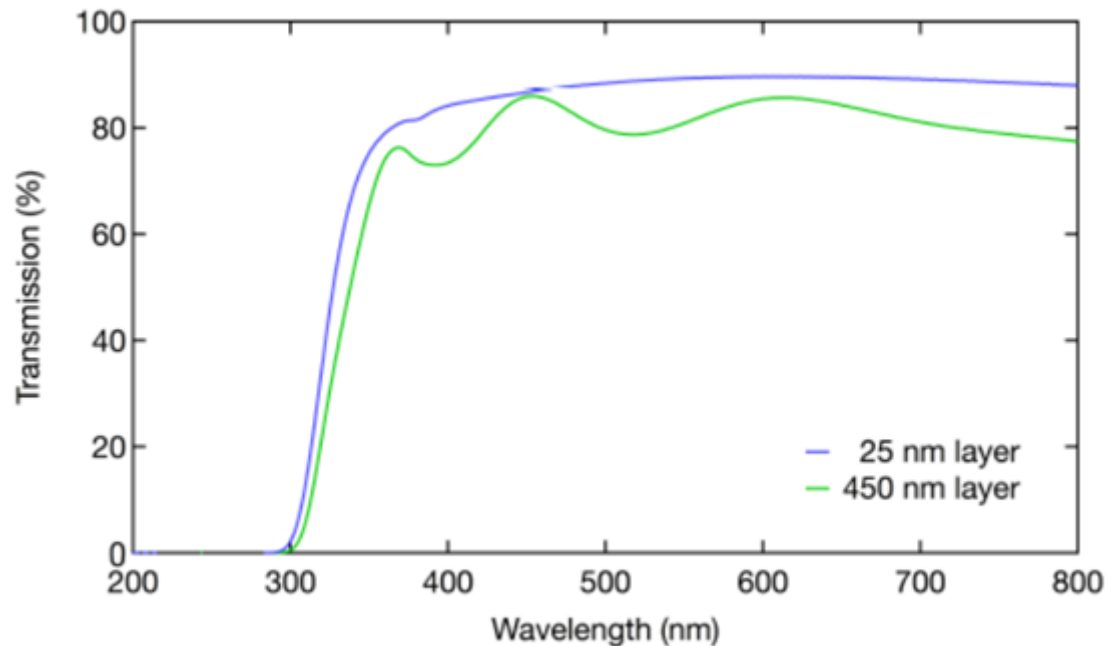
Readout noise

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.

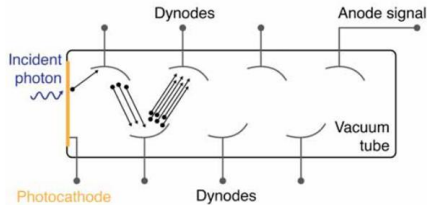
ITO on glass transmission



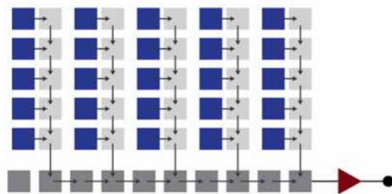
F. Brunbauer

Photon detection devices

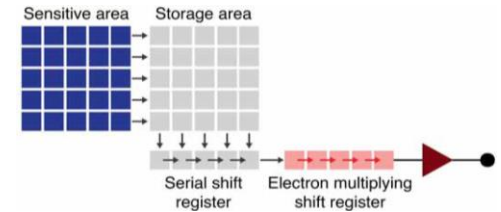
PMT : High gain, fast response. Conversion of incident photon by photoelectric effect at a photo-cathode. Multiplication of primary electron at dynodes to secondary electron emission



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-Oxide 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

