Development of novel tracking concepts at NSCL

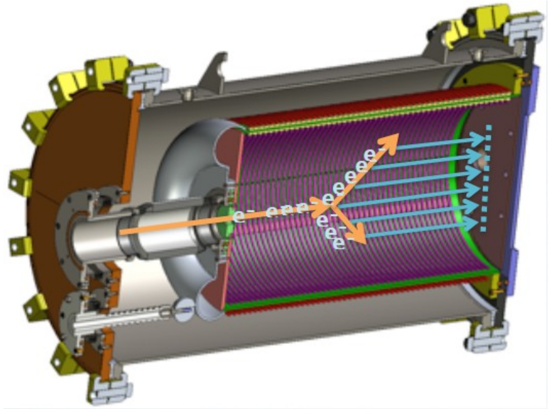
Marco Cortesi
National Superconducting Cyclotron Laboratory,
Michigan State University
East Lansing, Michigan 48824, U.S.A

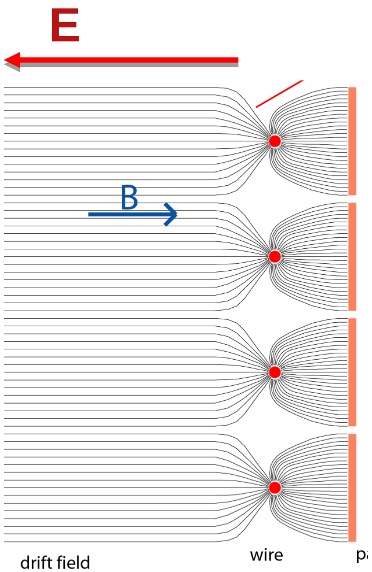
Outlines:

-) New MPGD structures for tracking applications
-) The Optical-PPAC
-) Summary and Conclusions

AT-TPC @ NSCL

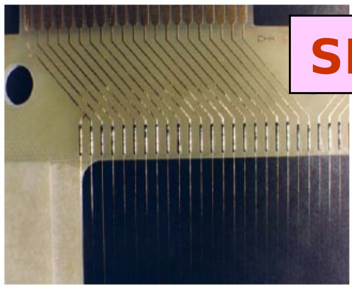
Operational mechanism of gaseous tracking devices: collection of ionization formed along the charged particle tracks & amplifying that ionization to create a detectable signal.





Wire-Based Detector:

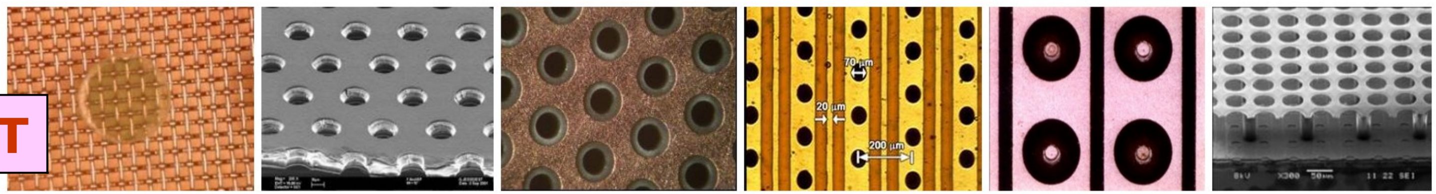
"Mechanics", Economic but
Secondary effects ➔ Gain limits
Space charge ➔ Counting-rate limits
Aging ➔ Damage after long-term



SLOW

MPGD: move down in size & add cathodes very close to anodes to evacuate ions produced during the avalanche process

FAST

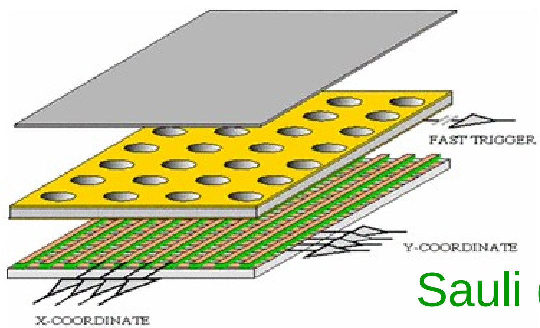


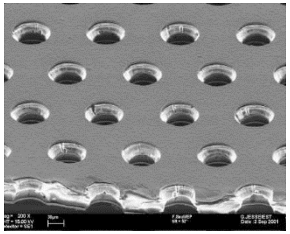
MicroMegas | GEM | THGEM | MHSP | microPIC | Ingrid

Rate Capability Limits due to space charge overcome by increasing the amplifying cell granularity

Micro-Pattern Gas Detectors

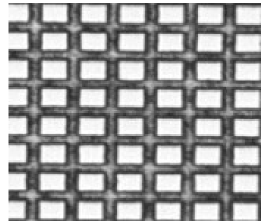
GEM : Gas Electron Multiplier

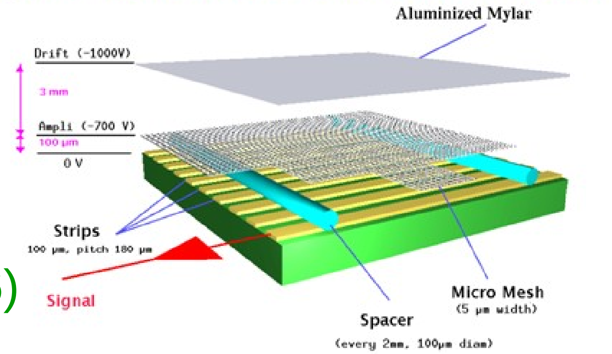




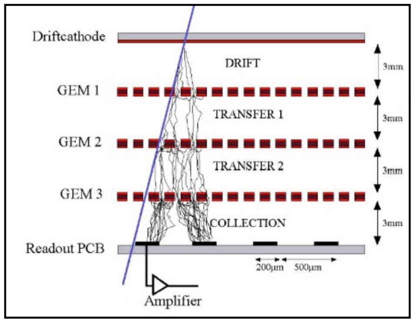
Sauli (1997)

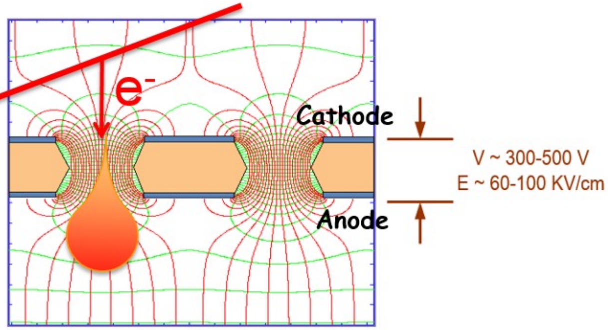
Micromegas : Micro Mesh Gaseous Detector

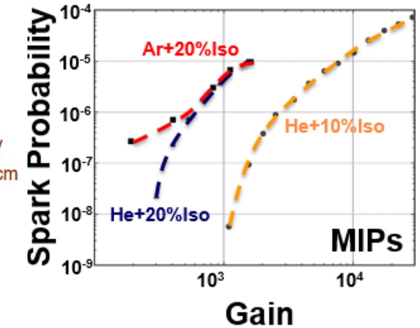


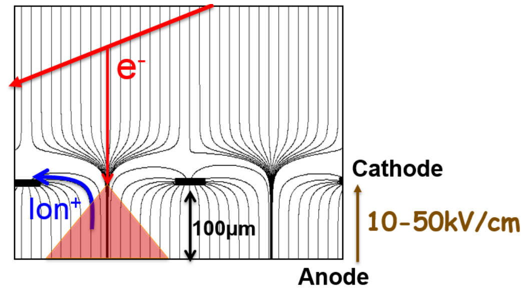


Giomataris (1996)





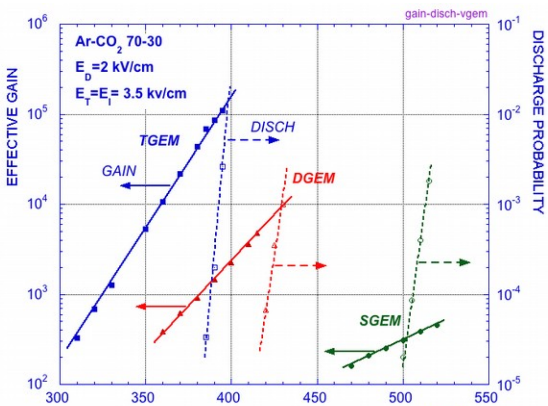


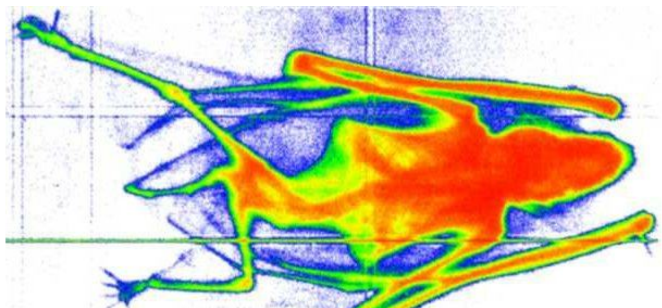


https://gdd.web.cern.ch/GDD/

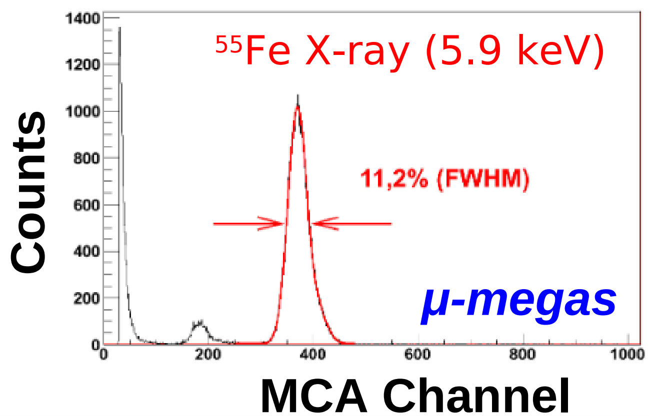
High Spatial Resolution (≈40 µm)

Iguaz et al. 2009 J. Phys. 179





Triple GEM



"Pure" elemental gas for low-energy nuclear physics applications

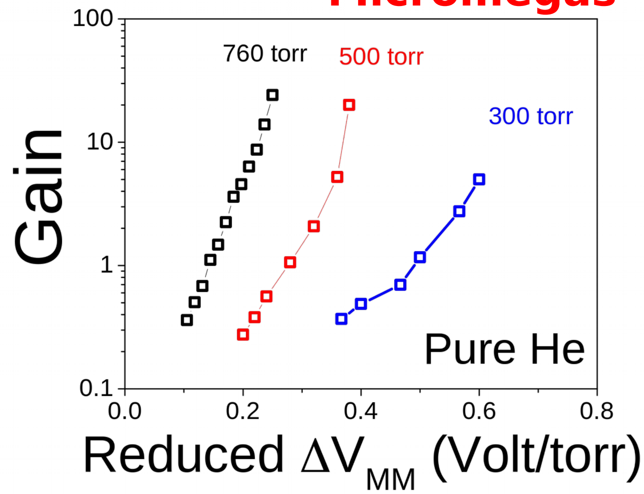
Active-Target Gases for Studying Inverse Kinematic Reactions

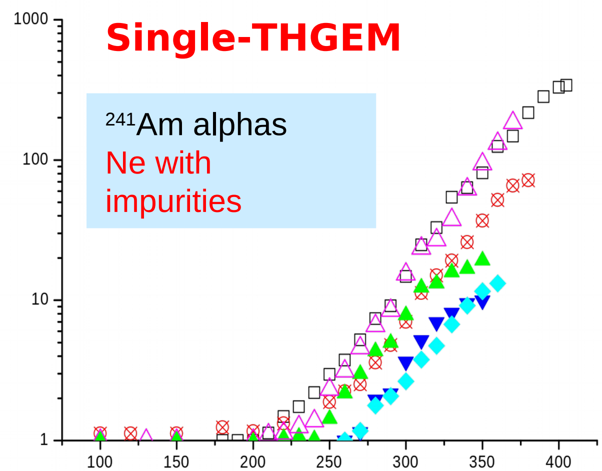
- **H_2 (alternatively iC_4H_{10}) as proton target**
  1 neutron pickup (p,d)
  2 neutron pickup (p,t)
  p-scattering
- **D_2 as deuteron target**
  1 neutron transfer (d,p)
  1 proton pickup (d,^{3}He)
  Inelastic scattering (d,d')
- **^{3}He**
  1 proton transfer (^{3}He,d)
- **^{4}He as alpha target**
  Inelastic scattering (^{4}He, ^{4}He'),
  Isoscalar Giant Resonances excitations …
  Alpha-induced reactions for astrophysical p-process

-) Purity (no quencher) → High Reaction Yield
-) Low-Pressure Operation → Large Dynamic Range

Endcap Detector Performance:
Gas Gain, Energy Resolution, Spatial Resolution, Counting Rate Capability, Stability etc…

Micromegas

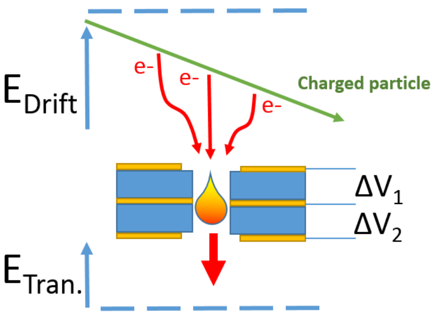




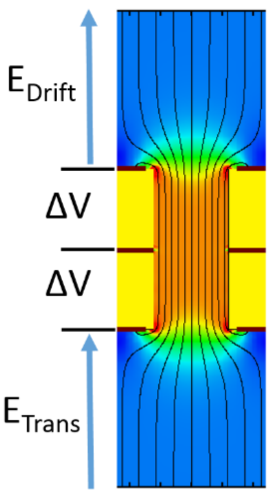
Miyamoto et al. 2010 JINST 5 P05008

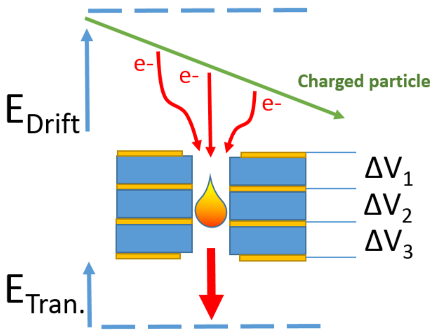
Multi-layer THGEM (M-THGEM)

Manufactured by multi-layer PCB techniques out of FR4/G-10/ceramic substrate

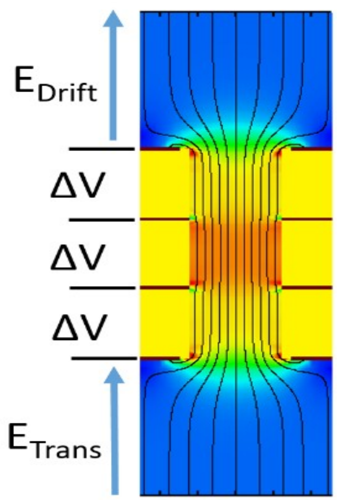


2-Layer M-THGEM



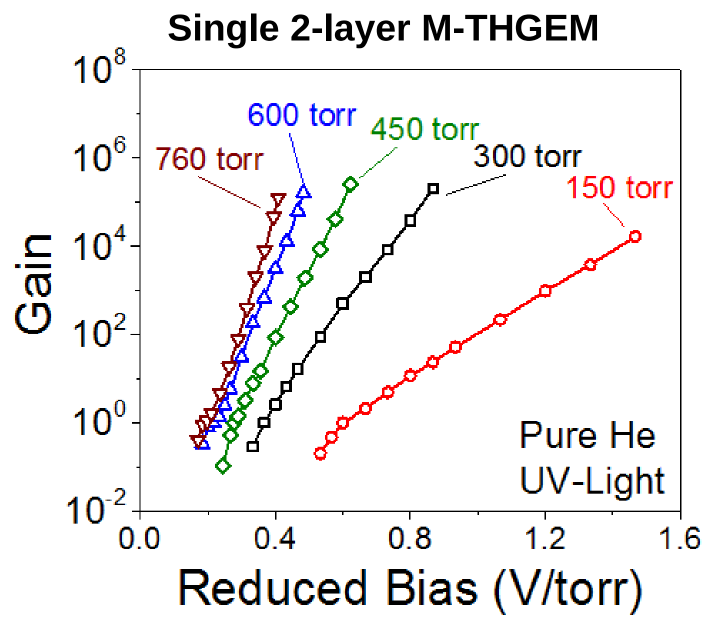


3-Layer M-THGEM

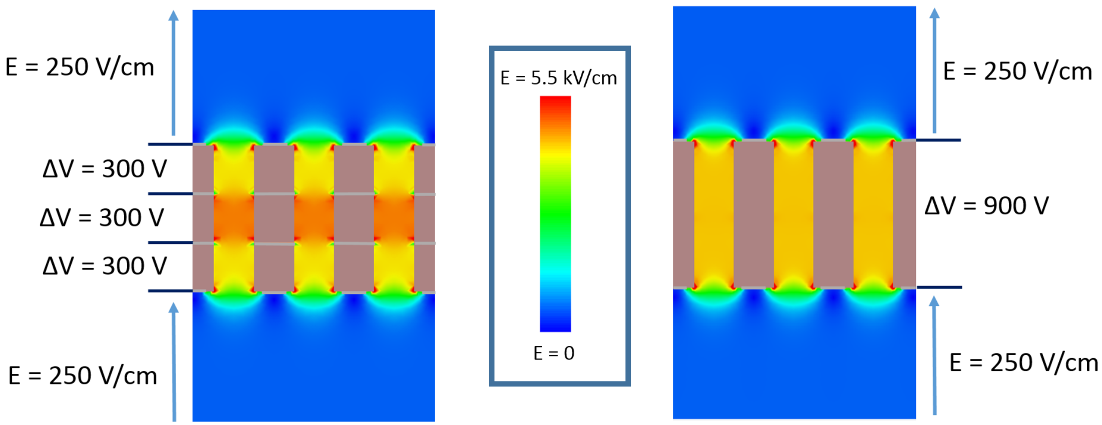


- -) No loss of charge
  - ➔ high gain @ low voltage
- -) Robust avalanche confinement
  - ➔ lower secondary effects
- -) Long avalanche region
  - ➔ high gain @ low pressure
- -) Field geometry stabilized by inner electrodes
  - ➔ reduced charging up

Cortesi et al. *RSI* **88**, 013303 (2017)



Three-Layer M-THGEM vs Single-layer THGEM

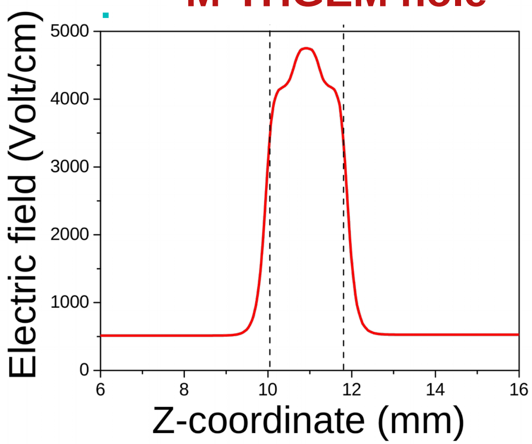


-) Lower voltage applied to each stage
→ low energy released during discharges
→ low probability to damages

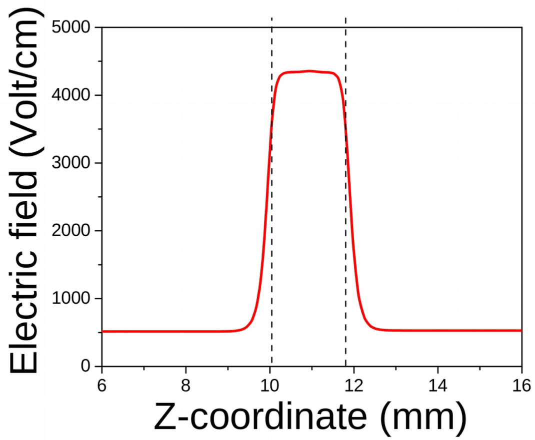
-) True confinement of the electron avalanche inside the THGEM hole
➔ higher gain

Lower photon-mediated secondary effects in pure noble gas at low pressure

M-THGEM hole



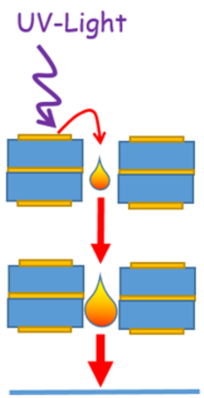
THGEM hole

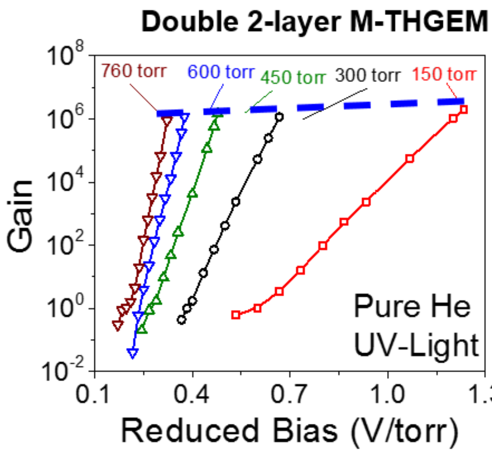


Multi-layer THGEM (M-THGEM): performance

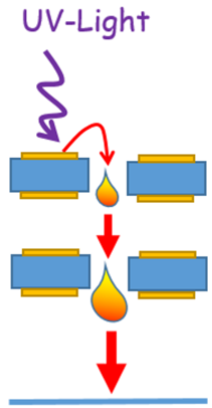
Cortesi et al. *RSI* **88**, 013303 (2017)

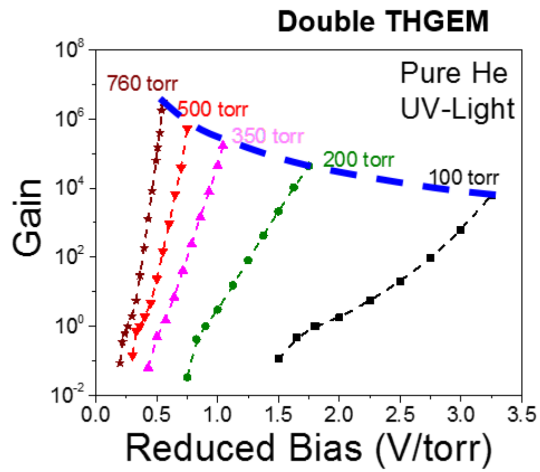
10x10cm² M-THGEM
(thickness = 1.2 mm, hole = 0.5 mm, pitch = 1 mm)



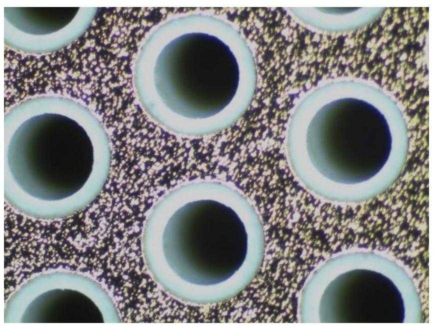


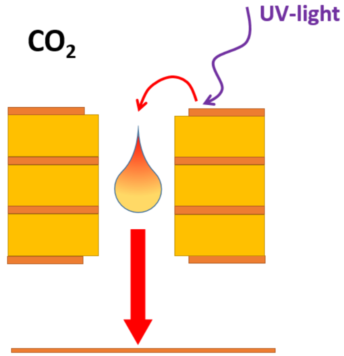
10x10cm² THGEM
(thickness = 0.6 mm, hole = 0.5 mm, pitch = 1 mm)

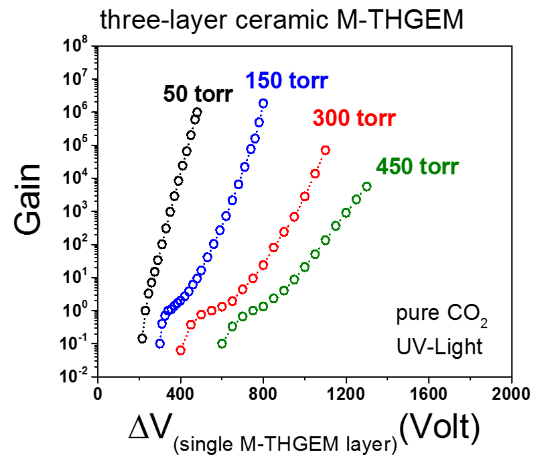




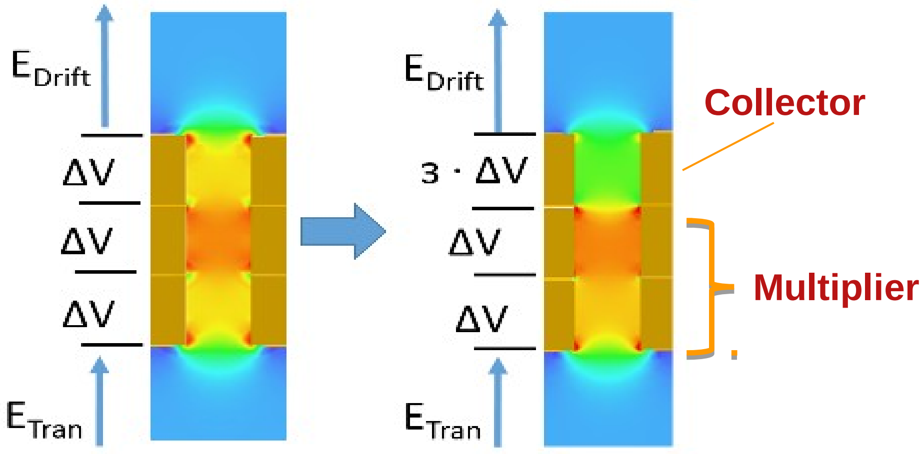
Ceramic M-THGEM
10x10 cm²







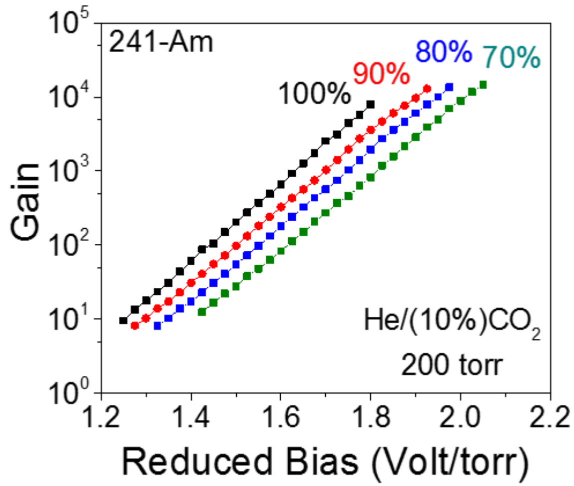
M-THGEM: photo-feedback suppression

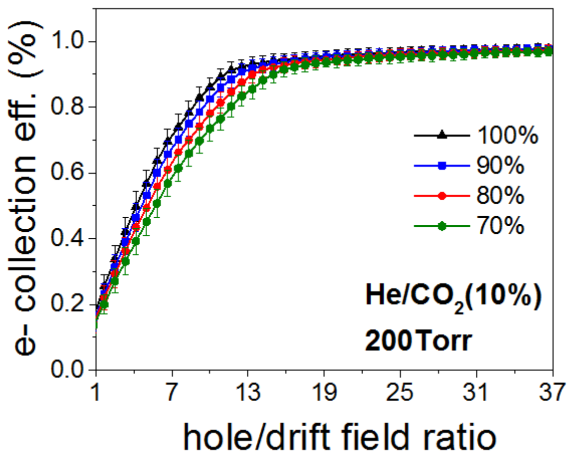


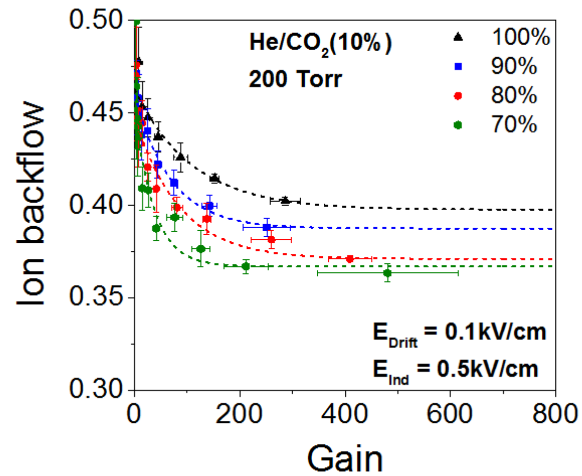
"Collection" operation mode:
-) The first THGEM acts as a "collector" – no multiplication
-) Avalanche multiplication occurs in the lower THGEM elements

Cortesi et al. *RSI* **88**, 013303 (2017)

Maxwell-Garfield Simulations







Constant Maximum Achievable Gain!

No significant loss of e- collection efficiency

Low ion backflow!
Double 3layer → few %

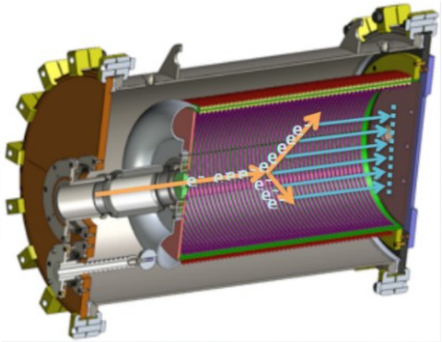
M-THGEM: Applications at NSCL (1)

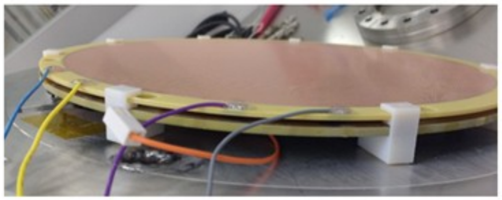
AT-TPC readout

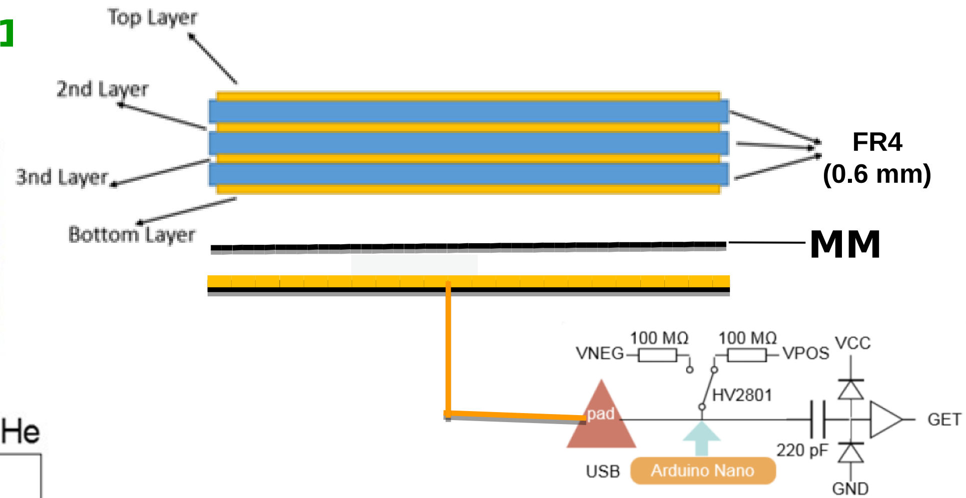
Hybrid MM + M-THGEM gas amplifier

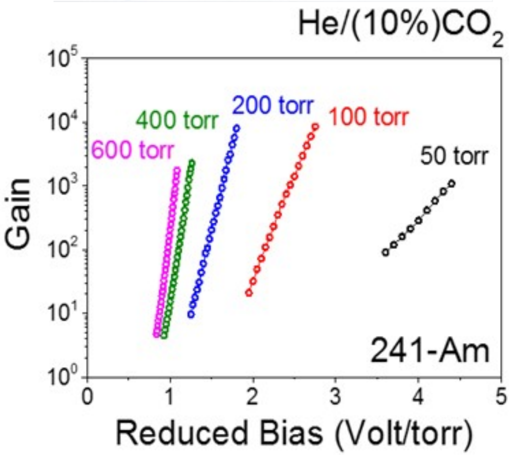
- -) M-THGEM as pre-amplification in pure elemental gas
- -) Gas gain variation by biasing the Micromegas pads
- -) Larger versatility
- -) Good ion-back flow reduction

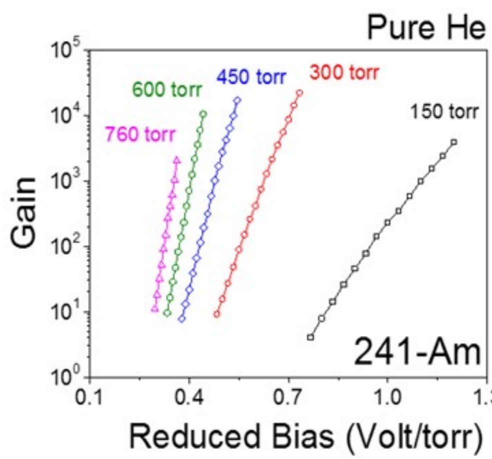
Cortesi et al., Rev. Sci. Ins. 88, 013303 (201

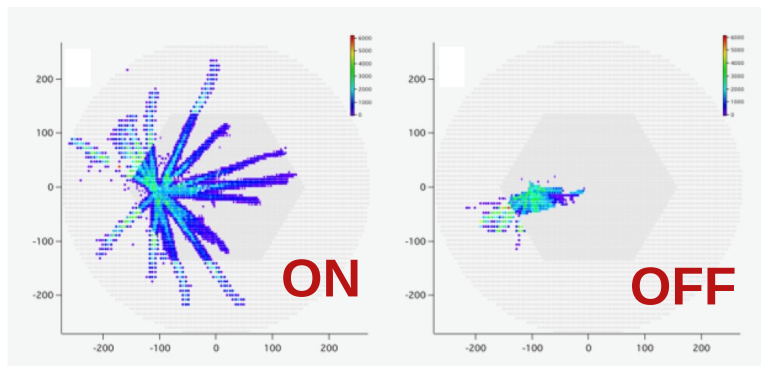






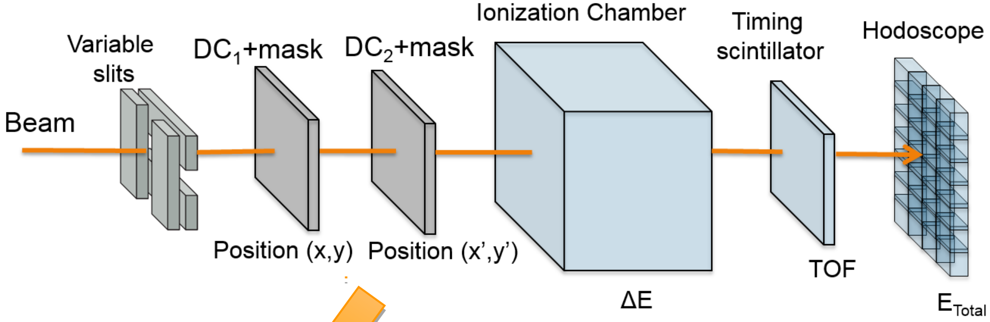


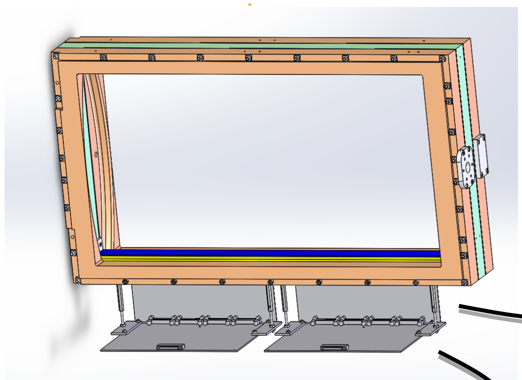




M-THGEM: Applications at NSCL (2)

Tracking for the S800 Focal Plane Detectors System





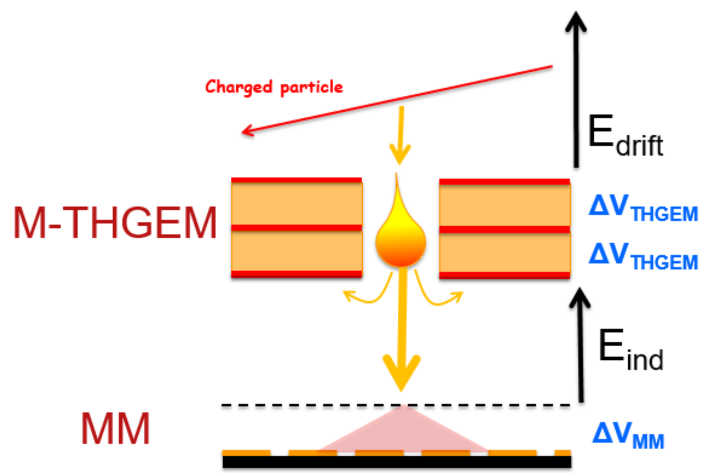
Intermediate Zap board (includes protection circuitries for the GET electronics and 16X2 channels reserved for the Ionization chamber signals)

Front end AsAd board
-) 4 AGET per board, 64 channel each ➔ 512 channels
-) 480 channels for the MM-readout
-) 16 channels for the ionization chamber
-) 16 spare channels

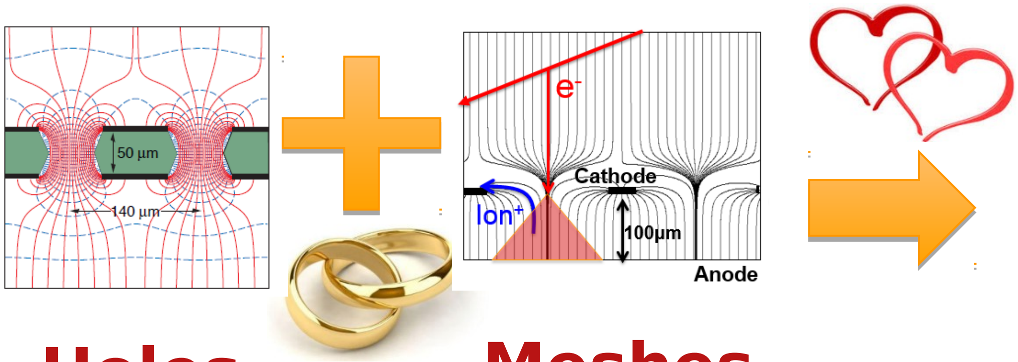
Features of new DC readout:

-) Simple (construction) and robust
-) Good ion-backflow suppression
-) High detector gain at low pressure (MM+THGEM)
-) Counting rate capability (~ a few tens kHz)
-) Moderate dynamic range
-) Pulse-Mode Gating
-) High granularity (all pad are readout individually)
➔ Good (sub-mm) position resolution

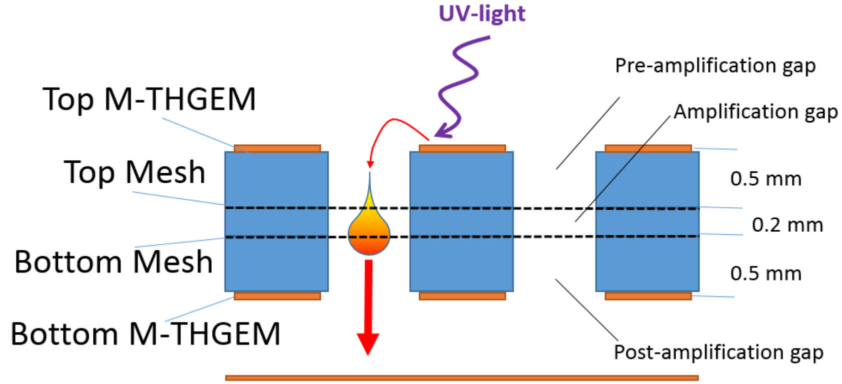
Position-sensitive Micromegas readout + 2L M-THGEM-based pre-amplification stage + GET front-end electronics



Multi-Mesh THGEM-type multiplier (MM-THGEM)

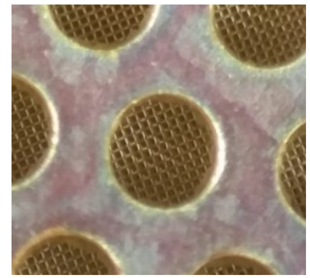


Holes **Meshes**

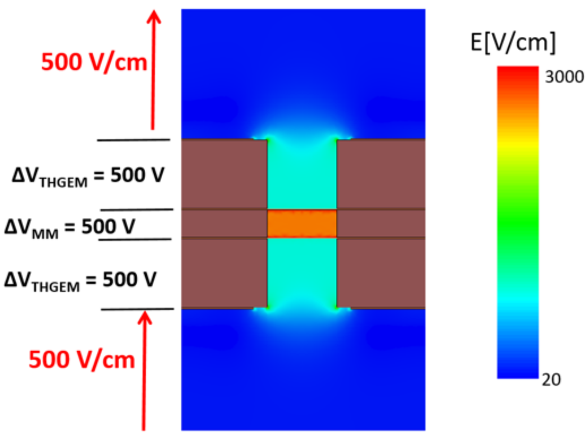


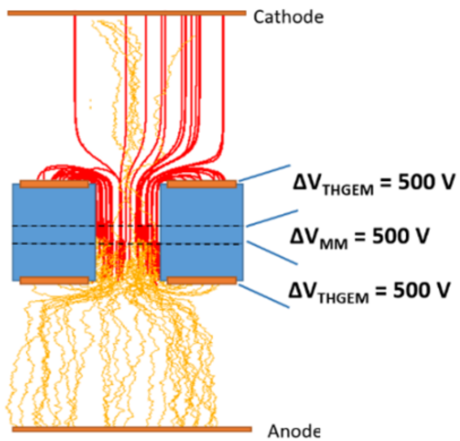
R. de Olivera & M. Cortesi 2018 *JINST* 13 P06019

MM-THGEM



Maxwell-Garfield Simulations





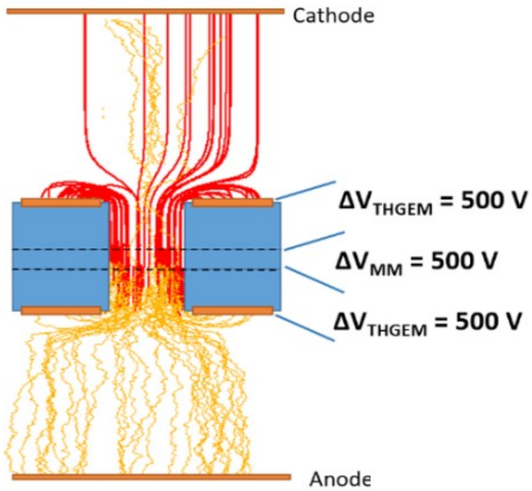
Advantages:
- -) Uniform avalanche field
- -) Lower Ion backflow
- -) Double/Replaceable MM over large area

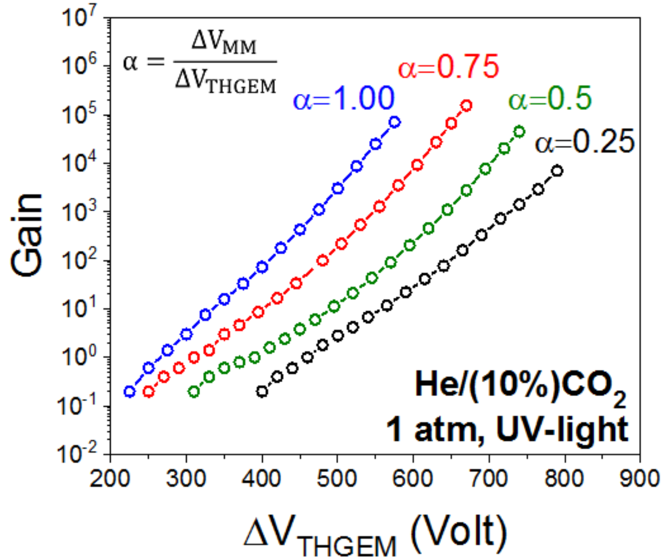
Disadvantages:
- -) Lower e- transparency

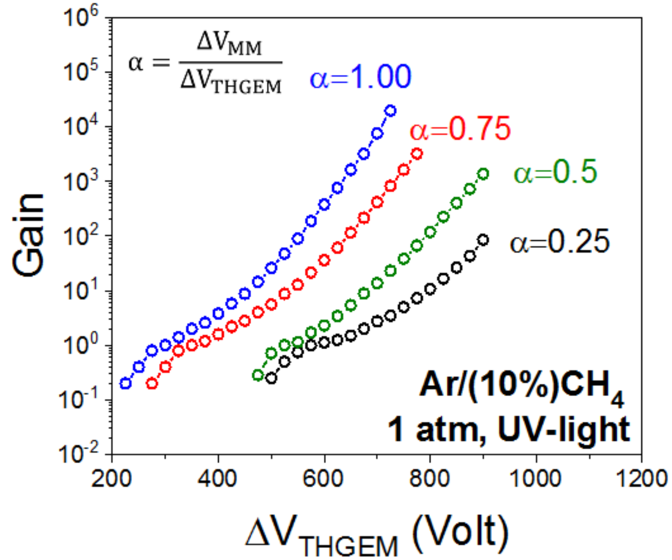
MM-THGEM: effective gain

R. de Olivera & M. Cortesi 2018 *JINST* 13 P06019

Single MM-THGEM





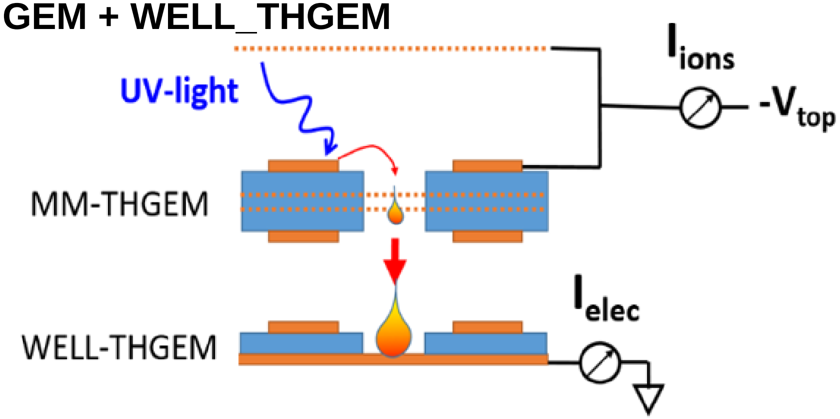


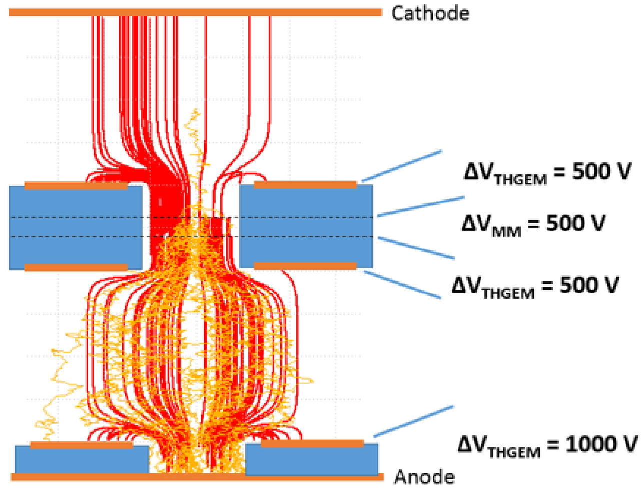
- -) High effective (single photo-electron) gain (> 10^5) with single element
- -) Higher gain when the amplification is confined inside the meshes (α=1)
- -) High stability and high max achievable gain at low operational voltage

MM-THGEM: reduction of Ion BackFlow (IBF)

R. de Olivera & M. Cortesi 2018 *JINST* 13 P06019

Two cascade elements
MM-THGEM + WELL_THGEM

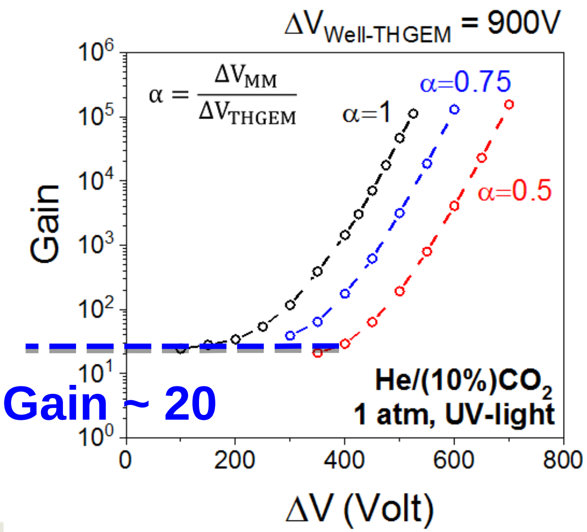


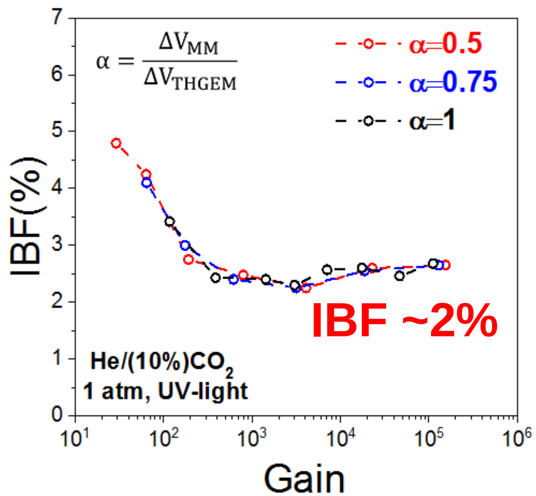


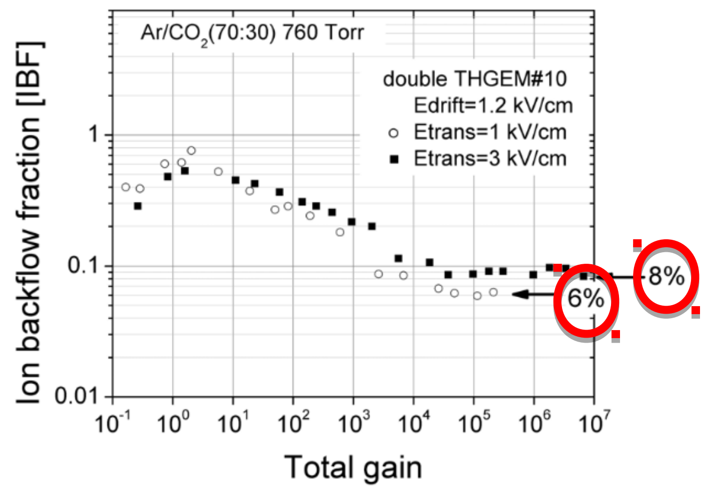
MM-THGEM ➔ Electron multiplication & stop the ions
WELL-THGEM ➔ Extra gain

Double-THGEM

C. Shalem et al. NIM A558 (2006) 475-489

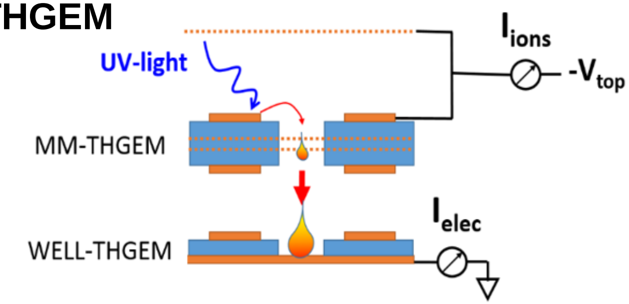


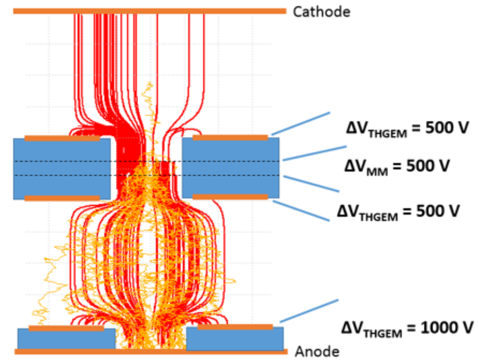




MM-THGEM/WELL-THGEM: IBF

Two cascade elements
MM-THGEM + WELL-THGEM





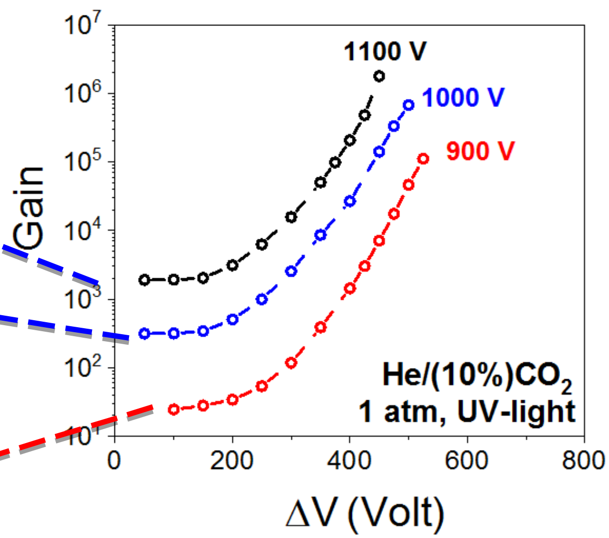
R. de Olivera & M. Cortesi 2018 *JINST* 13 P06019

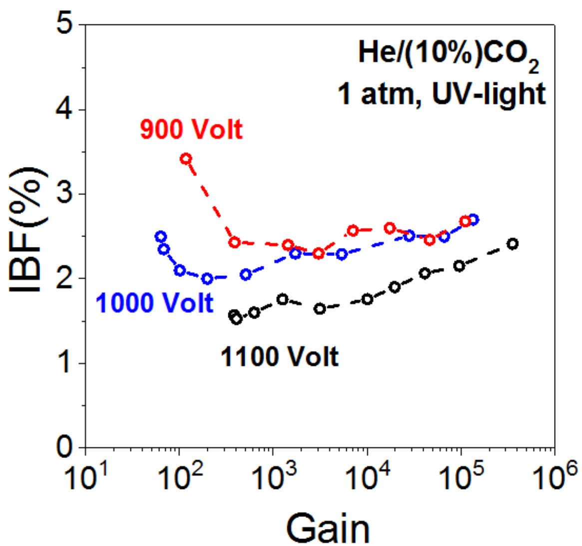
IBF smaller than with conventional double THGEMs

Gain ~ 3000

Gain ~ 500

Gain ~ 20

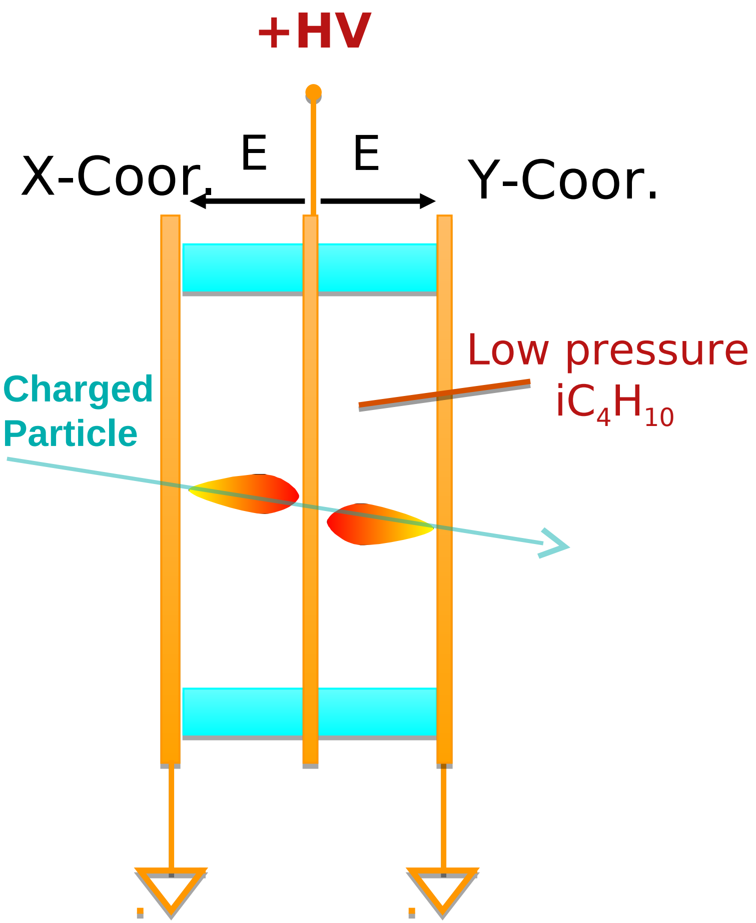




Optical Parallel-Plate Avalanche Counter

Conventional Parallel-Plate Avalanche Counter (PPAC)

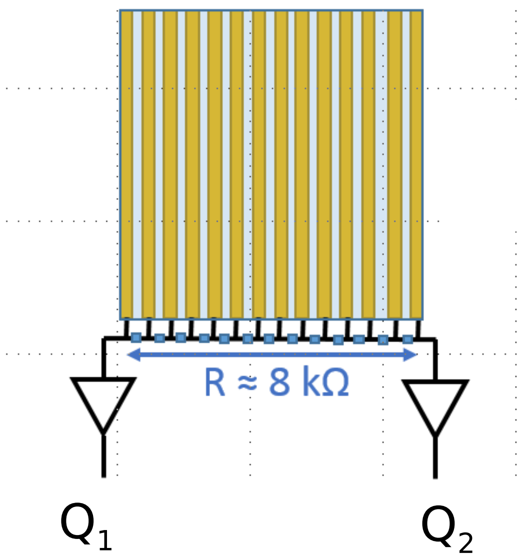
2D imaging with double-PPAC



PPAC

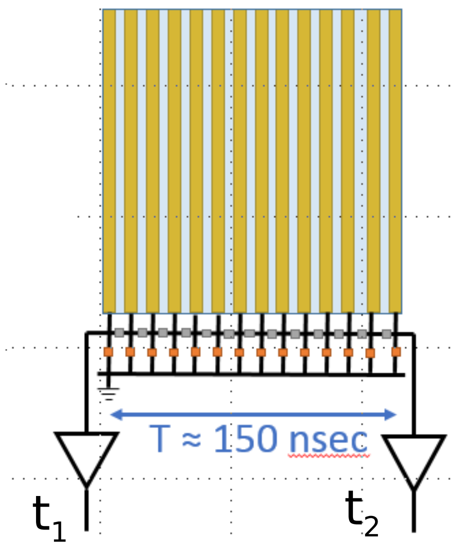
-) Three flat electrode plates separated by 2-3 mm
-) Middle plate (Anode) at high voltage
-) X-Y localization via segmented (strips) cathodes
-) Gap filled with suitable gas (i.e. iC_4H_{10}) at low pressure (5-50 torr)

Charge Division Method



$$X = f(Q_1,Q_2)$$

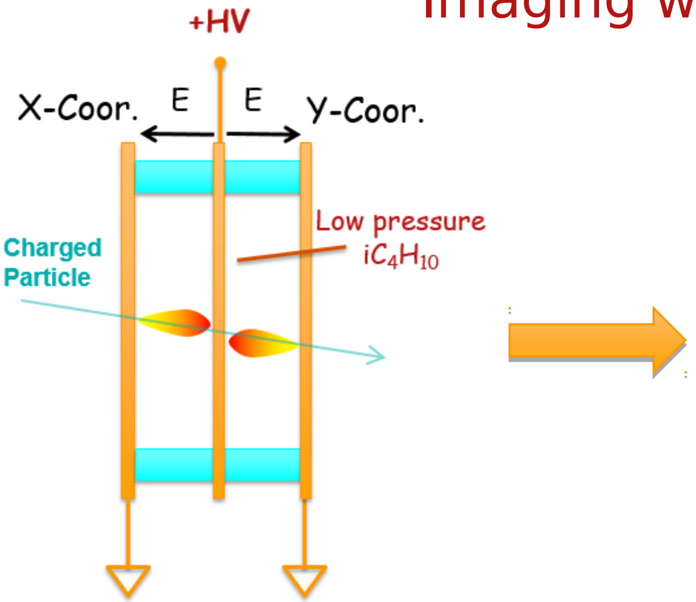
Delay-Line Method



$$X = f(t_1,t_2)$$

Let there be "scintillation" light

Imaging with Conventional double PPAC



- -) Time resolution ➔ ~200 psec
- -) Position resolution ➔ ~1-2 mm
- -) Counting rate capability
  - Charge division Meth. ➔ few tens kHz
  - Delay-line Meth. ➔ few hundreds kHz
- -) Moderate gas gain ➔ heavy charged particle
- -) Simple and low cost
- -) low-mass detector but not uniform

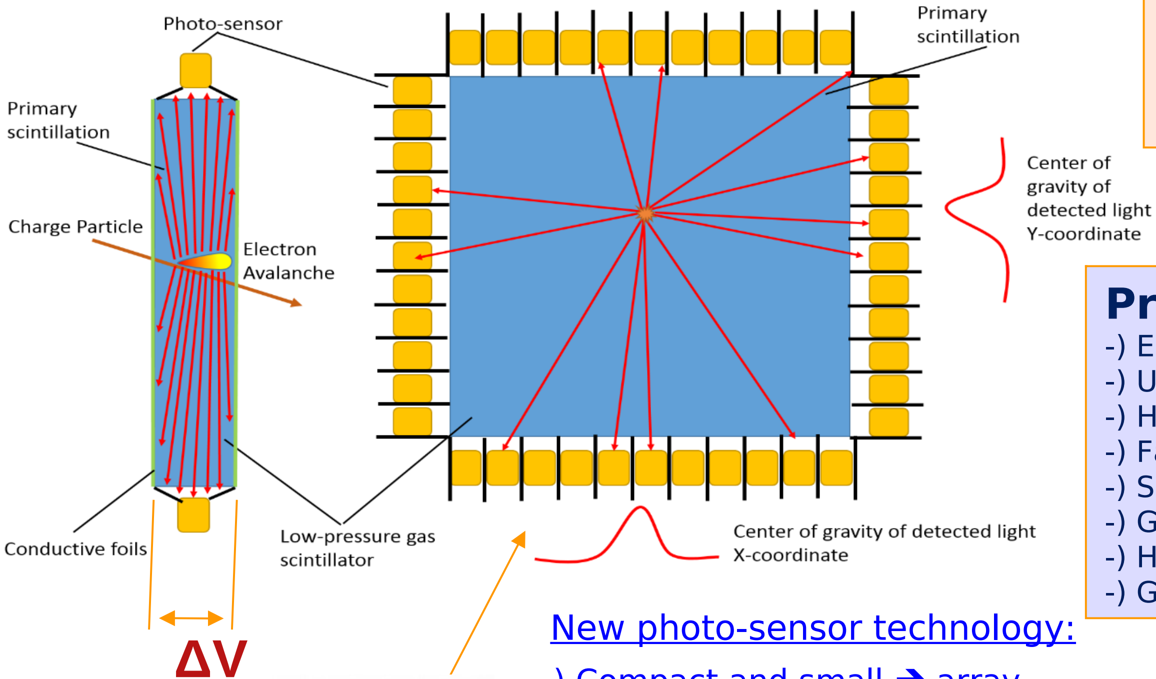
Idea: localization based on recording electroluminescence light instead of charge

Advantages:

- -) New semiconductor technologies (APD, SiPM ...)
- -) High SNR
- -) No limits on photon-production (Charge ➔ Raether limit)
- -) Compact and high granularity
- -) Versatile- large area
- -) Better energy resolution

Optical Parallel-Plate Avalanche Counter (O-PPAC)

Motivation:
- Uniform, low-mass detector
- High spatial resolution, good time resolution
- High counting rate



Concept:
- Volume filled with scintillating gas
  ➔ (CF_4, TEA/TMAE mixture, etc.)
- Ionizing particle that crosses the PPAC, trigger *avalanche/streamer* process
- Secondary scintillation photons are generated
- 2D position of the particle is sensed by arrays of photo-sensors

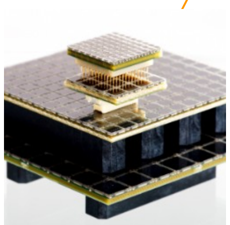
Properties

-) Easy construction/ maintenance
-) Uniform, low-mass detector
-) High spatial resolution (limited by the SiPM granularity)
-) Fast signal (sub-n rise time) → Good time resolution
-) SiPM: single-pe sensitivity -> high sensitivity
-) Good SNR → high detection efficiency
-) High Counting rate (limited by PPAC operation)
-) Geiger mode → infinity dynamic range

New photo-sensor technology:

-) Compact and small ➔ array
-) Low bias
-) Single pe sensitivity (SiPM)
-) Insensitive to magnetic field
-) High PDE
over large wavelength range
(including VUV range)

Producers:
SensL*
Hamamtsu*
Excelitas
Optoi
AdvancedSid
etc. etc.



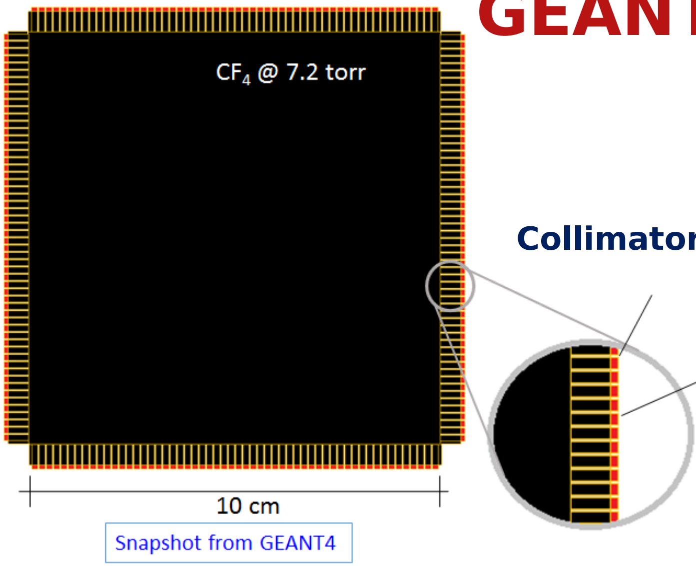
20-40 individual photo-sensors per array

DAQ based on GET

O-PPAC: Simulations

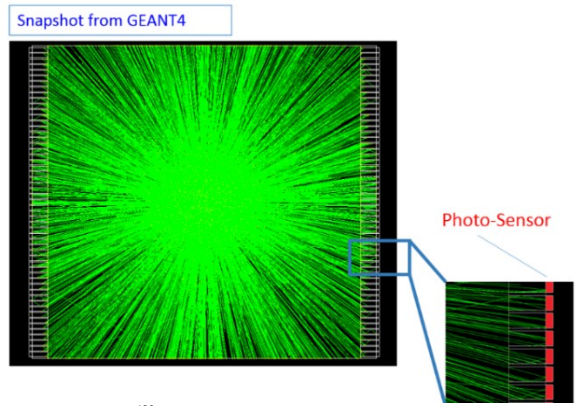
GEANT4

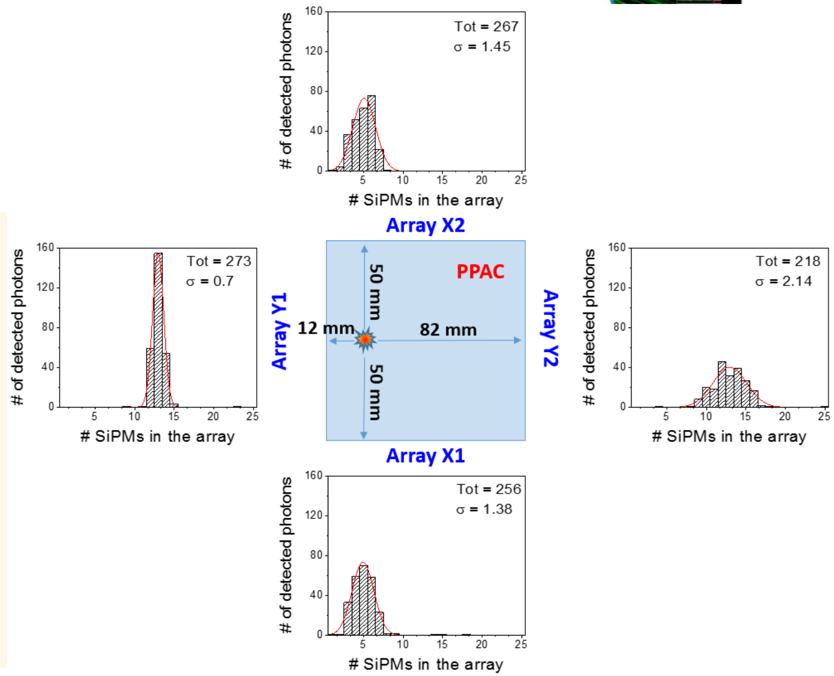
M. Cortesi et al. 2018 *JINST* 13 P10006



Collimators (10 mm)

Photo-sensor
area = 1x3 mm^2
Pitch = 2 mm
50 sensor/array

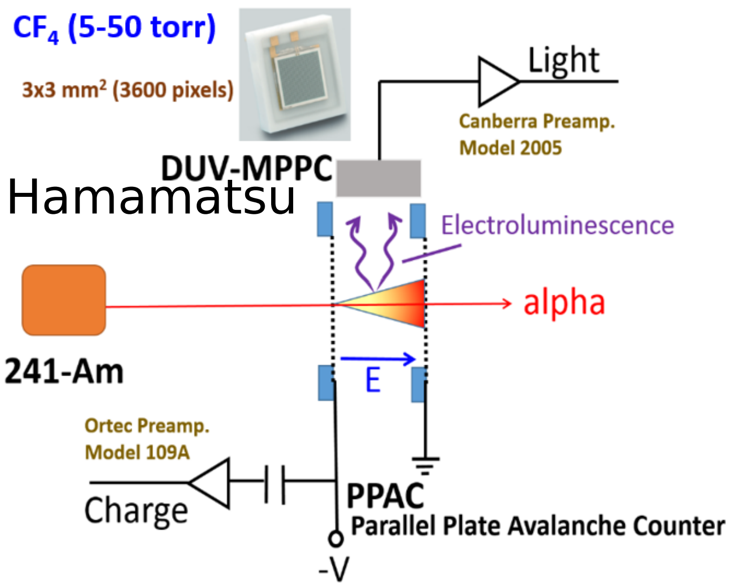




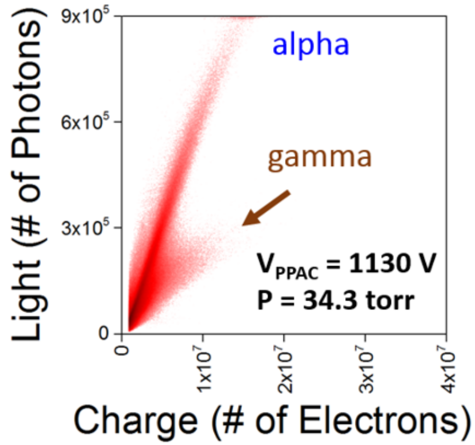
Parameters:

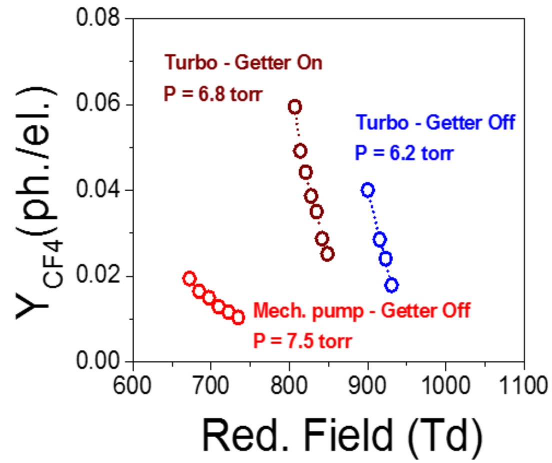
- Scintillating Gas: Type (i.e. CF_4), pressure and thickness of the active area
  - ➔ Luminescence spectrum and photon yield
  - ➔Deposited energy
  - ➔Primary beam energy straggling and angular dispersion
- Dimension of the photo-sensor
  - ➔ Photon collection efficiency
  - ➔ Spatial resolution
  - ➔ Complexity and cost
- Collimation of the Photo-sensors
  - ➔ Photon collection efficiency
  - ➔ Spatial resolution

O-PPAC Feasibility Study: experimental setup

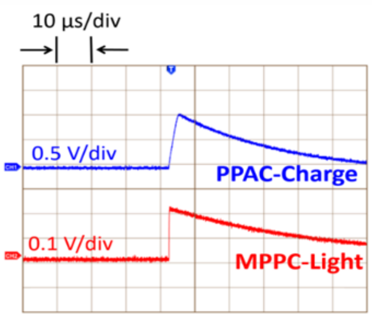


Cortesi, Yurkon and Stolz, 2016 *JINST 11 P04017*

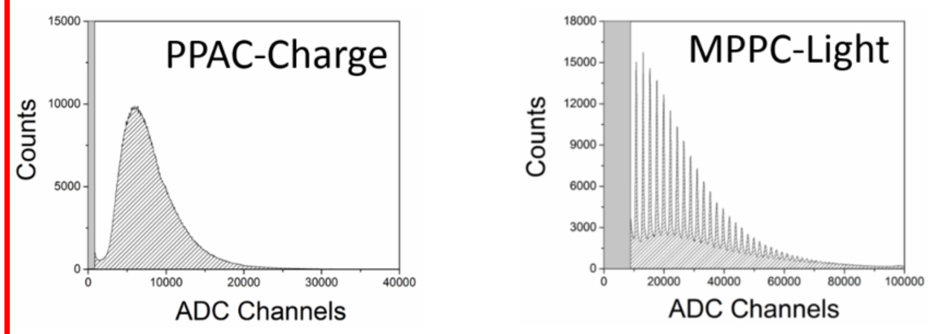




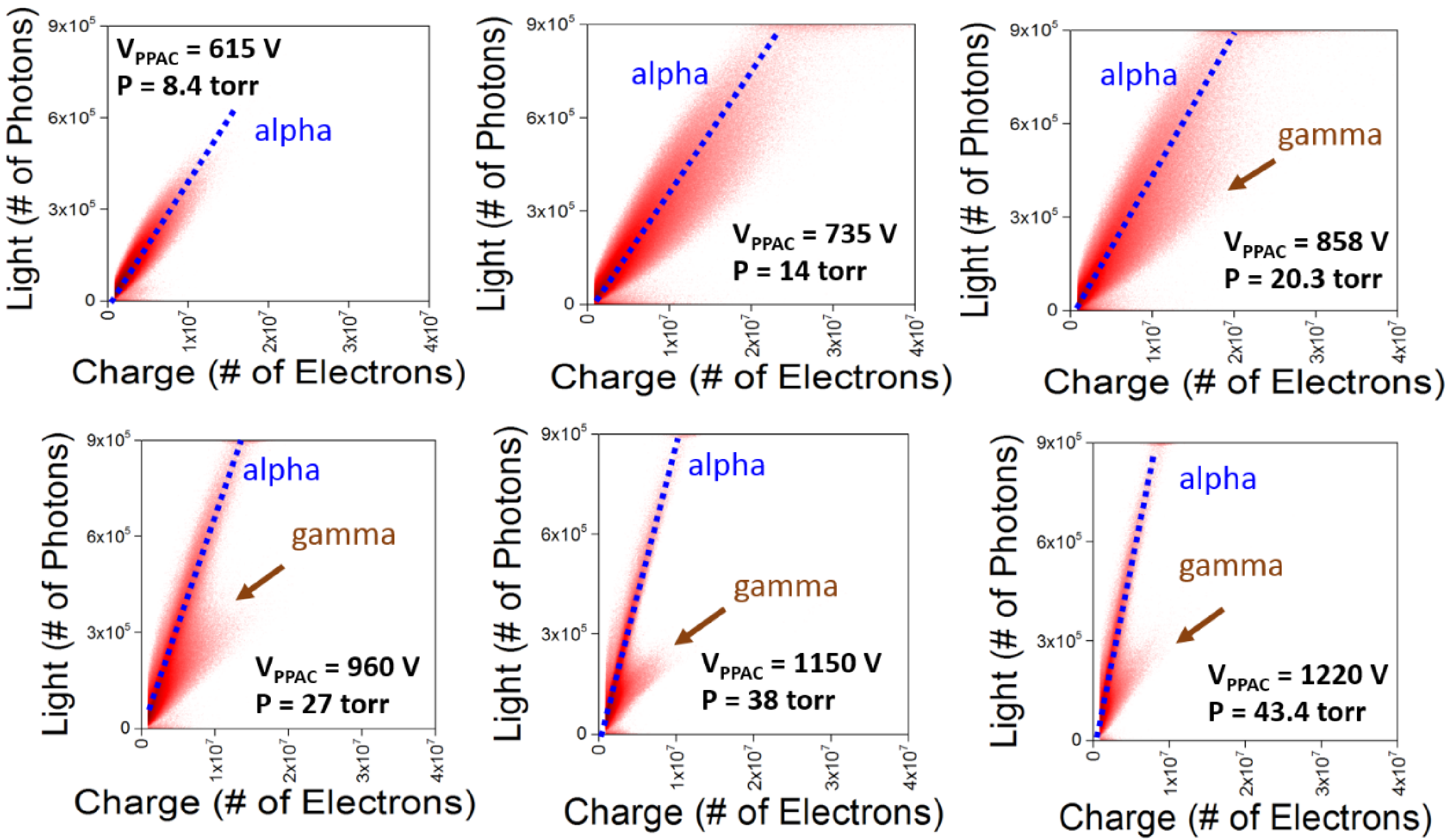
Good Charge-Light Correlation



Pulse-height Signals

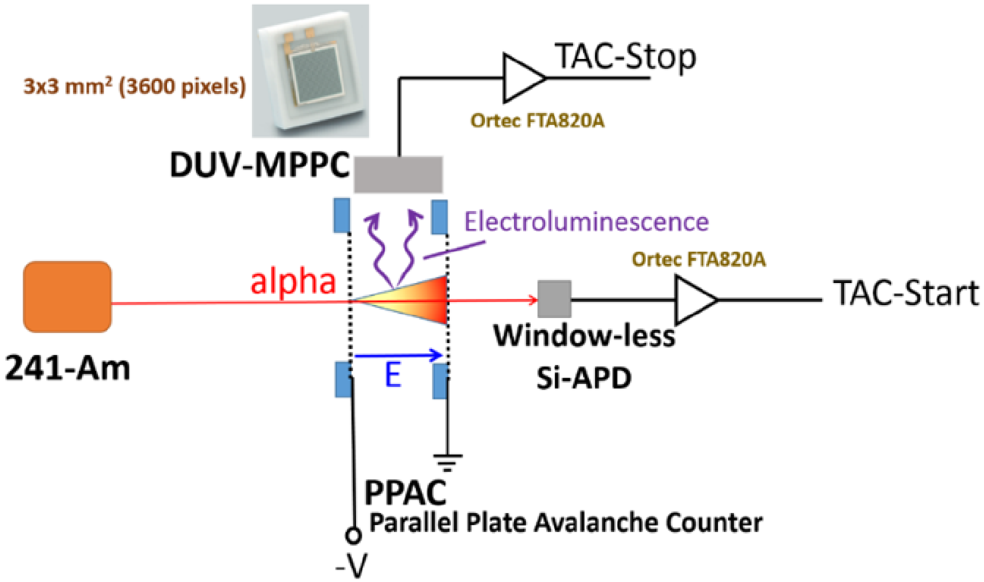


Charge-Light Correlation

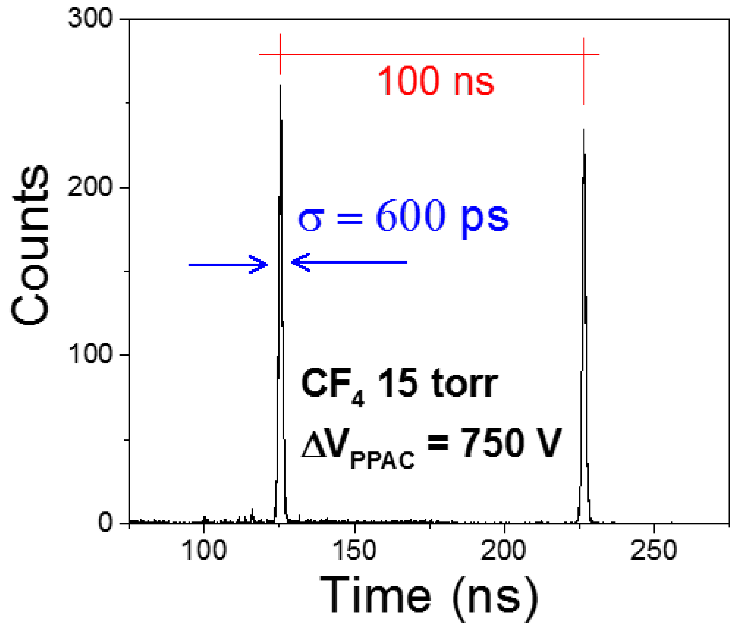


O-PPAC: Time resolution

Single SiPM ➔ Ω/4π ≈ 1.8%



Cortesi, Yurkon and Stolz, 2016 *JINST 11 P04017*



Time resolution = 600 ps (pressure range 5-50 torr) for 3.2 mm gap, limited by low statistics (small solid angle)
➔ lower limit imposed by the decay-time of scintillation process: 2 ns (UV) & 15 ns (visible) in CF_4

Goal for the future experiments ➔ σ < **100 ps**

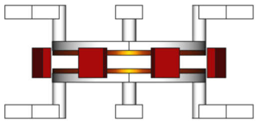
- Time resolution measurements with 10 SiPM (VUV-sensitive MPPC) ➔ higher statistics
- Measurement with heavy charge particle (252-Cl Fission source) ➔ higher scintillation yield

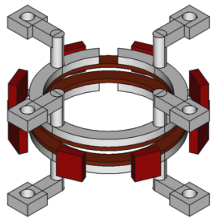
New O-PPAC prototypes

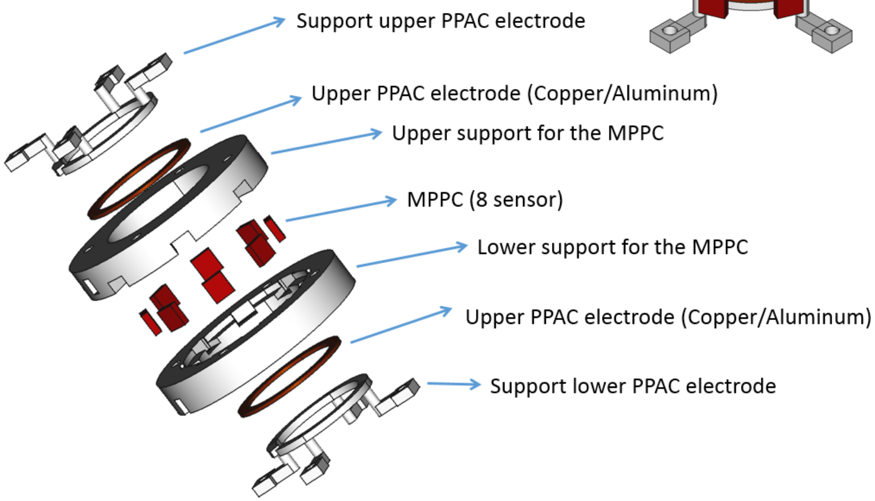
Timing

8 DUV-MPPC in parallel
Test beam with
heavy ions beams

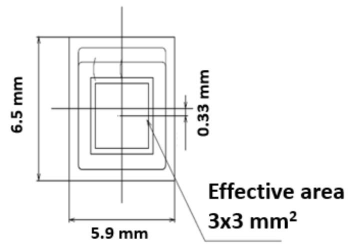
Goal → < 100 ps

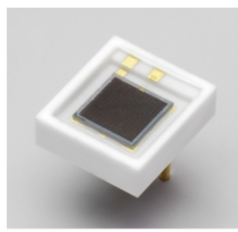

PPAC + 8 MPPC sensor





Hamamatsu VUV3-MPPC
-) Ceramic package, 50 um pixel pitch
-) Quartz window
-) Crosstalk, afterpulse suppression

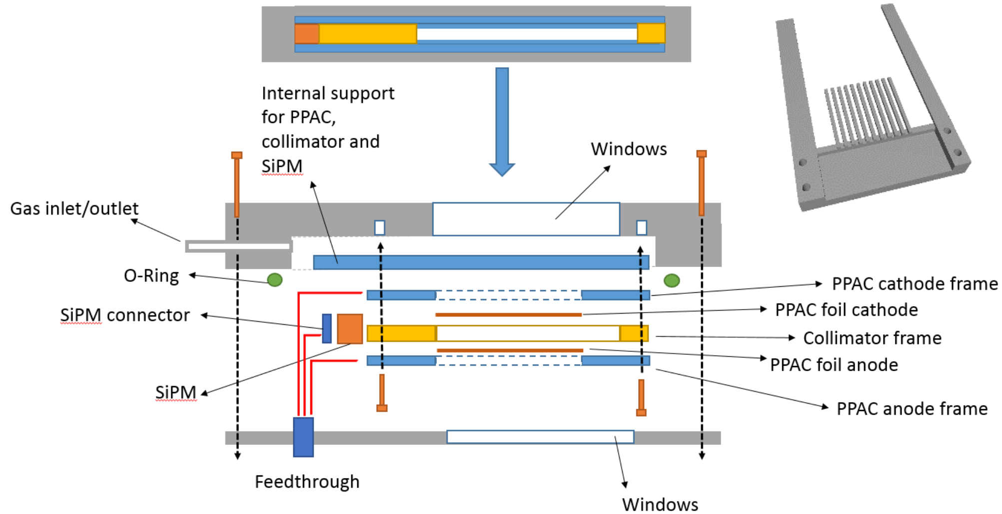


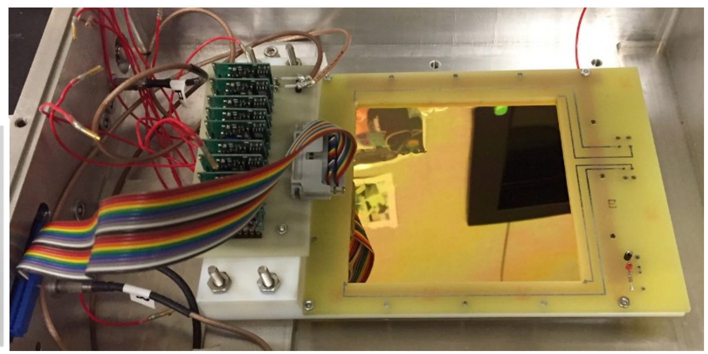


Tracking

M. Cortesi et al. 2018 *JINST* 13 P10006

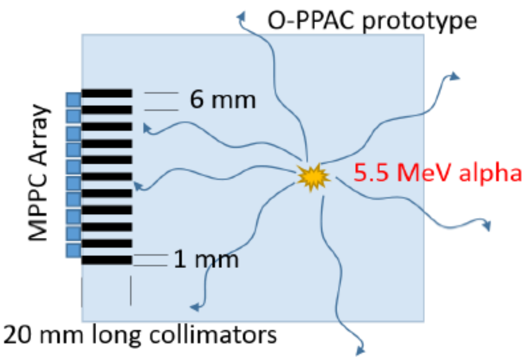
Position sensitive array of 10 DUV-MPPCs

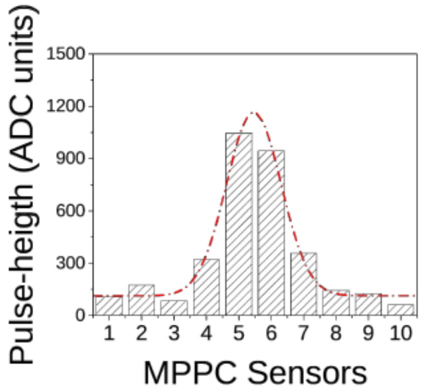


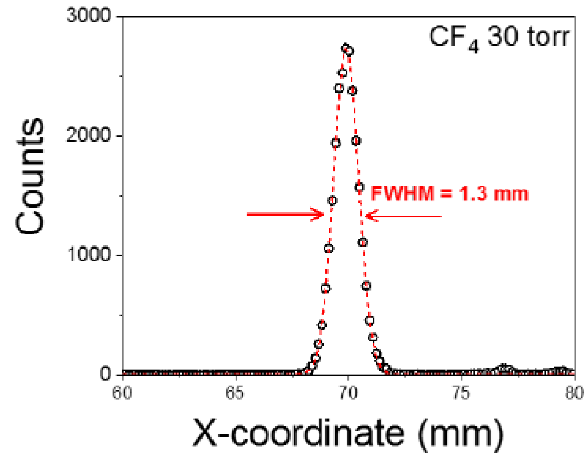


Test of the 1D OPPAC

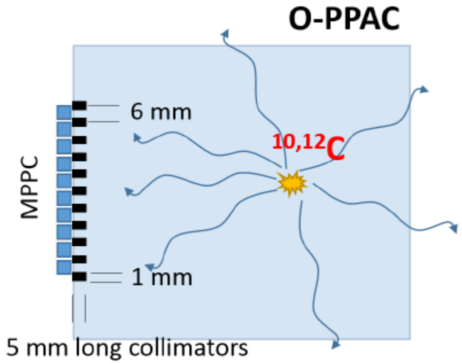
Test beam with 5.5 MeV alpha-particle ---

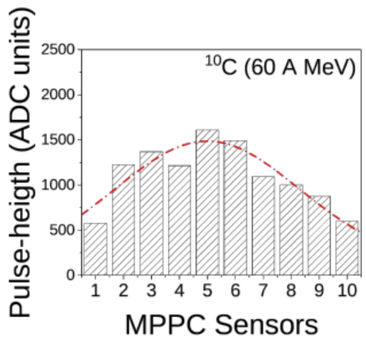


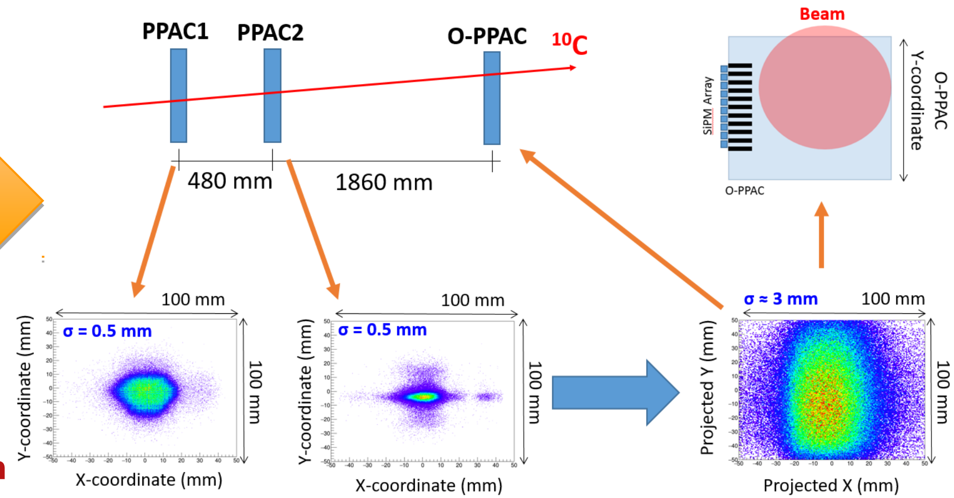




Test beam with ^{10,12}C in RCNP (Japan) ---





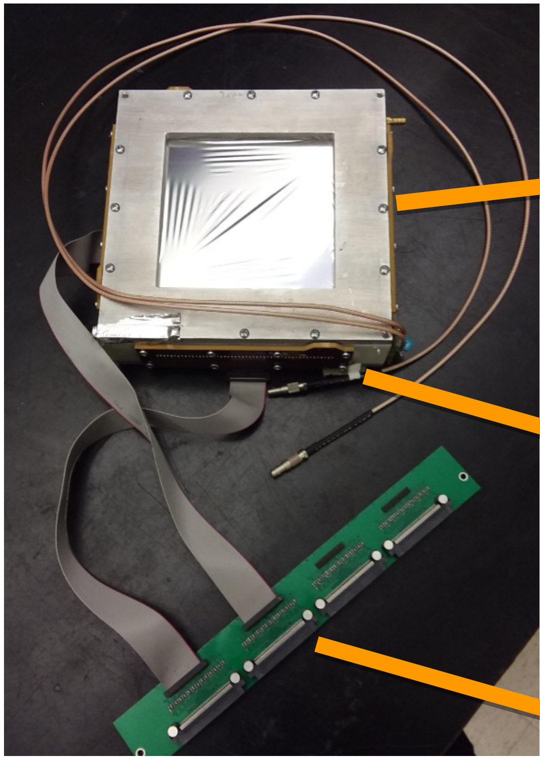


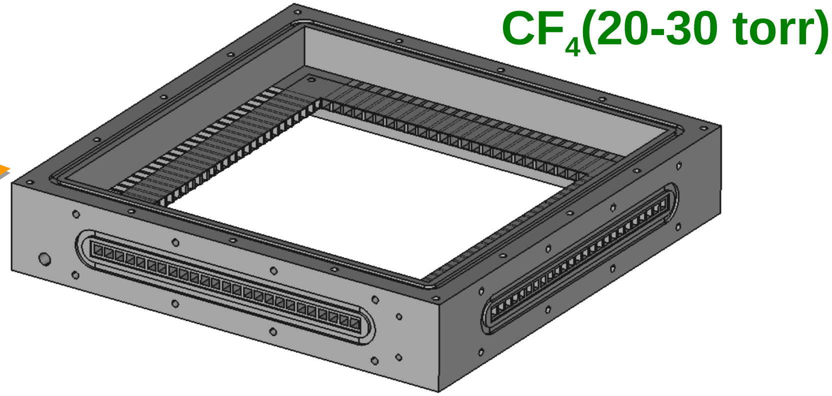
Good detection efficiency (~ 100%)
Spatial resolution (~3 mm) limited by the soft collimation

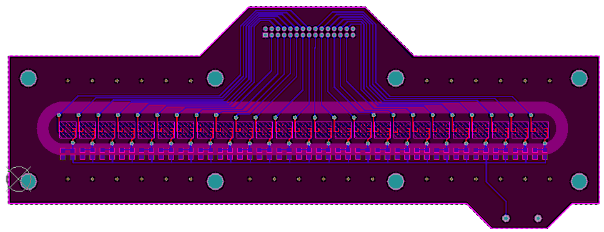
2D OPPAC prototype

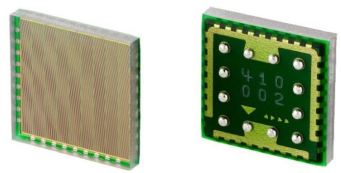
Goal: new concept for application as heavy-ion tracking capable of good position resolution (< 1 mm), high rate capability (1 MHz) good homogeneity & high dynamic range

Collimator frame:
-) 3D printing production
-) OPPAC effective area = 10x10 cm²









KETEK PM33-WB

25 SiPMs on each side (100 channles)

DAQ based on GET electronics

Summary

New MPGD architectures:

Goals: operation of TPC in pure element gas operation (AT mode) and higher counting rate capability

1) Multi-layer THick Gas Electron Multiplier (M-THGEM)

-) confinement of the avalanche in a small volume within the holes

→ lesser photo-mediated secondary effect

-) most stable high gain in pure elemental gases

-) lower operation voltage applied between different electrode

→ lower probability to damages

2) Multi-Mesh THGEM-type multiplier (MM-THGEM)

-) multi-mesh avalanche structure over large area

-) uniform electric field in the avalanche gap

→ better energy resolution (?)

-) significant reduction of the IBF

(lower IBF compared to other hole-type multiplier)

O-PPAC: Expected Performance

-) Uniform, low-mass detector (transmission detector for heavy ions) ➔ low angular/energy straggling
-) Imaging/tracking of charged particles
-) Good time resolution (as low as few hundred pico-second)
-) Good energy resolution
High scintillation yield and light readout decouple form charge/light avalanche process ➔ high SNR
-) Position resolution (<1 mm based on light CG)
could be improved by dedicated algorithm that includes other factors (light dispersion, etc.)
-) Wide dynamic range in Geiger-mode operation
(in proportional avalanche mode, pressure of the filling gas can be adjusted depending on application)

O-PPAC: Potential Applications

- ✓ Applications of conventional PPAC:
  - -) Detection of fast-particle (i.e. time-of-flight measurement)
  - -) Transmission Imaging/tracking of heavy ions (i.e. as focal plane detector in magnetic spectrometer or in mass separator)
- ✓ Medical Applications:
  Beam diagnostic (hadron-therapy applications as position/profile online beam monitor, online treatment plan optimization and fast-interlock, proton range radiography for dosimetry study)
- ✓ Heavy-ions radiography/tomography