UNIVERSITÀ
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Tesi di Laurea Magistrale in Fisica

# Development and characterization of the Fast Timing Micro-pattern gaseous detector

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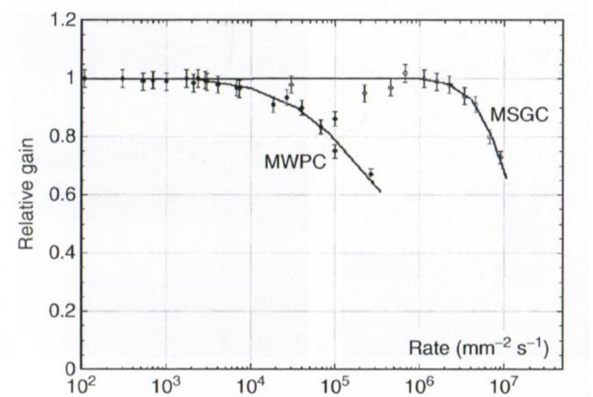
# Micro-Pattern Gaseous Detectors

**Large group of different detectors:**

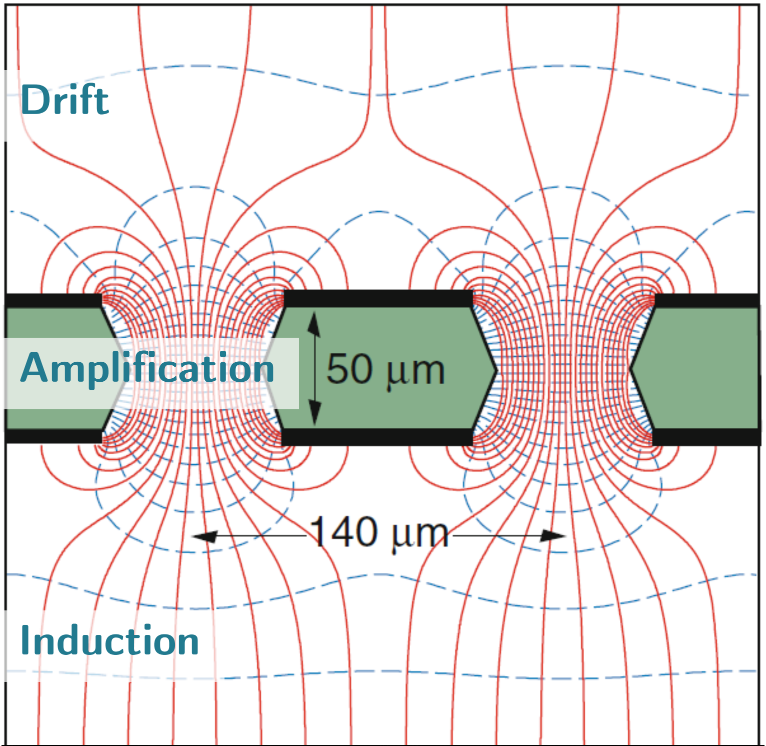
- No wires but micro-metric amplification structures (use of photolithography) → **high spatial resolution**
- Full decoupling of amplification and readout → **versatility**
- **High rate capability**

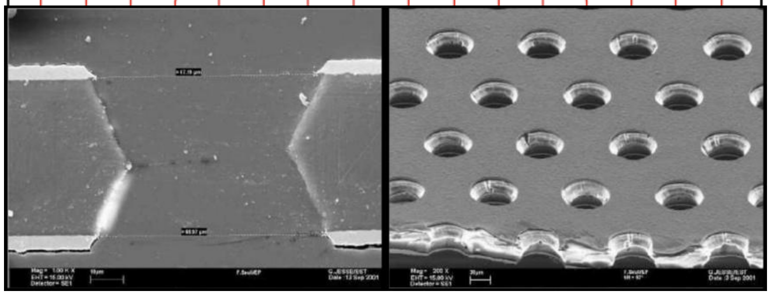



(MWPC) A. Breskin et al., Nucl. Instr. Meth. A **124 (1975)** - (MSGC) A. Barr et al., Nucl. Phys. B **61B (1998)**

## Examples:

- Micro Strip Gas Counter **MSGC**
- Gas Electron Multiplier **GEM**
- Micro-MEsh Gaseous Structure **Micromegas**



F. Sauli, Nucl. Instr. and Meth., A805:2-24, 2016.

# Why Fast Timing detectors?

## Future challenges:

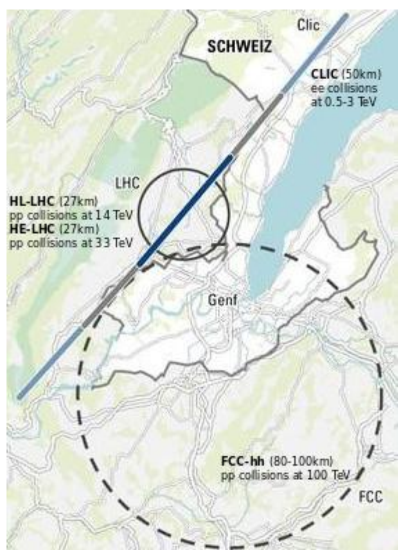
### High-Luminosity Collider detectors

Future Circular Collider (FCC) at CERN:

- Higher $\sqrt{s}$ ($\rightarrow$ 100 TeV)
  - High B field, <u>Large instrumented area</u>
- Higher Luminosity
  - <u>High rate</u> capability needed
  - $\geq$ 200 collisions will overlap with the interesting collision (<u>Pile-Up</u>)

**Gaseous detectors** can cover large areas, have high rate capability and good spatial resolution.

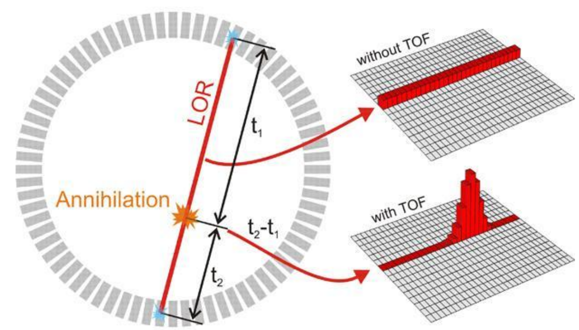
**Fast Timing**
($\sigma \approx$ 100 ps) will enable to identify the correct interaction in a high rate environment.




### Time-of-Flight PET

Positron Emission Tomography:

- positron-emitting radionuclide concentrates at regions of high metabolic activity (tracer)
- 2γ (511 keV) emitted back-to-back
- Coincident detection determines the **Line of Response (LOR)**
  - w/o TOF: equal probability assigned to each point along the LOR
  - **w/ TOF**: few **100 ps** measurement will lead to ⇠ 5 cm precision along the LOR
    - **High contrast images**




PET principle, w/ & w/o TOF. [source: sublima-pet-mr.eu/]

# MPGDs: time resolution

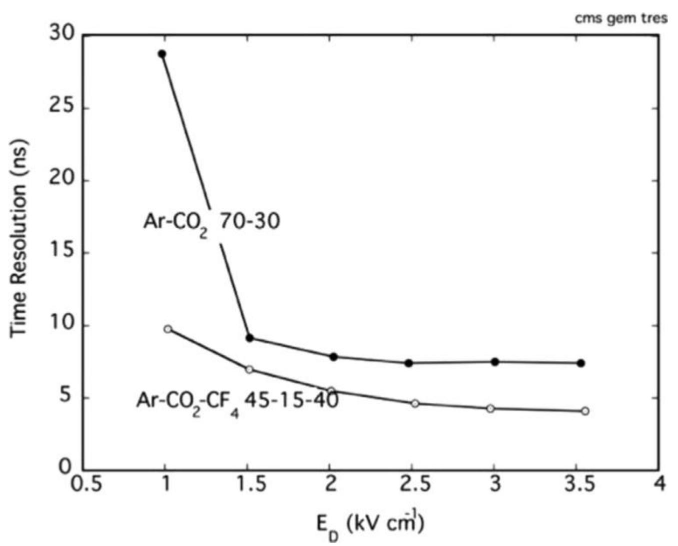
In all MPGDs, $\sigma_t$ determined by:

- Statistics of ion-pairs production
- Diffusion in the gas medium
- Gain fluctuations

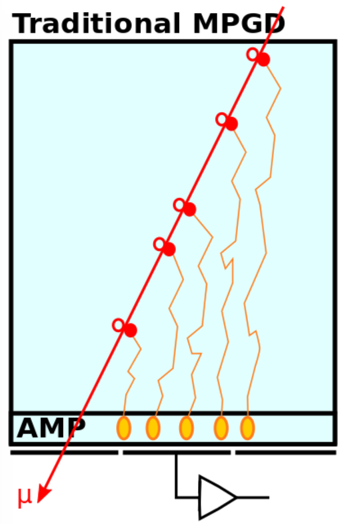
The contribution of the statistics is dominant.

$$\sigma_t = 1/v\lambda$$

- $\lambda$ number of primary electrons per unit lenght
- v drift velocity of electrons in the gas




F. Sauli, Nucl. Instr. and Meth., A805:2-24, 2016.




- $\lambda \approx 31\ cm^{-1}$ for a MIP in Ar/CO2 70/30
- $v \approx 7$ cm/μs drift velocity of $e^-$ in Ar/CO2 70/30 with 3 kV/cm drift field

$\sigma_t \geq 5$ ns

Intrinsic time resolution → lower limit

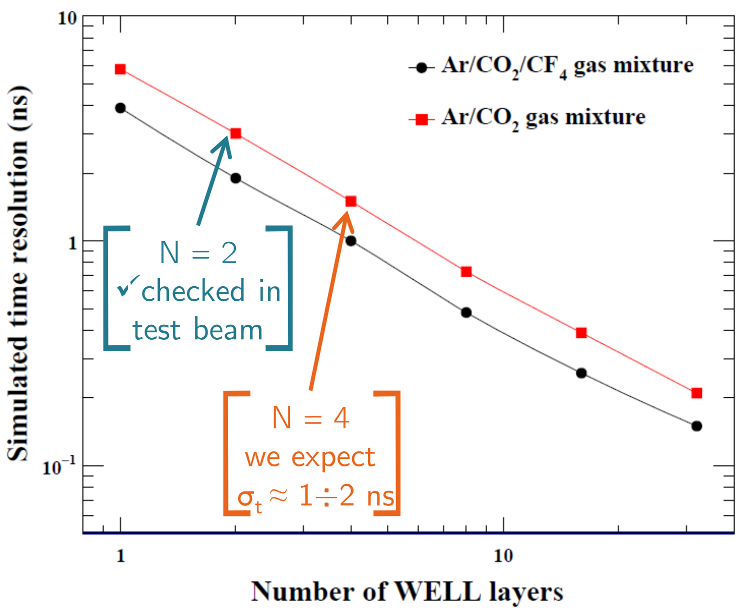
# Fast Timing MPGD: working principle

## Basic idea:

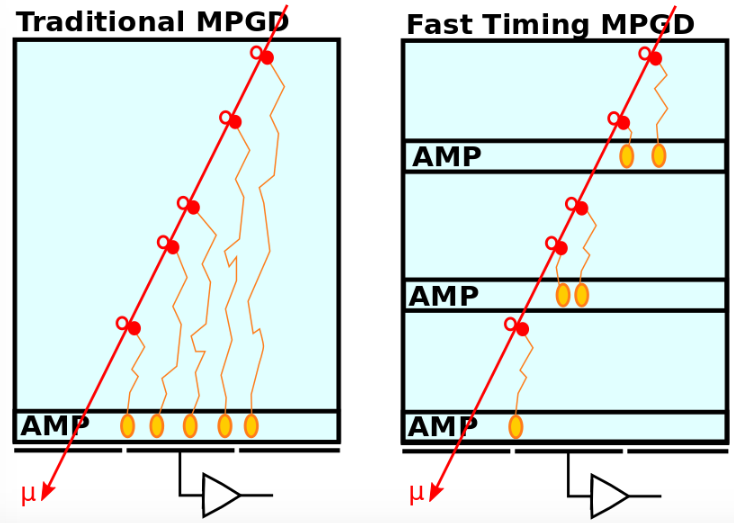
segmentation of the drift gap into **N** independent drift + amp. layers.

$$\sigma_t = 1/N v \lambda$$

- **λ** number of primary electrons per unit lenght
- **N** number of layers
- **v** drift velocity of electrons in the gas



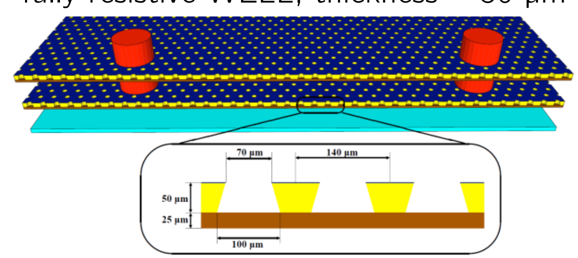

R. De Oliveira et al., A novel fast timing micropattern gaseous detector: FTM, arXiv:1503.05330, 2015.




**First FTM:**
- N = 2 layers
- $\sigma_t$ = 2.4 ns with muon beam

**New FTM prototype:**
- N = 4 layers
- Test beam planned in August 2018

Amplification structure:
fully resistive WELL, thickness = 50 μm

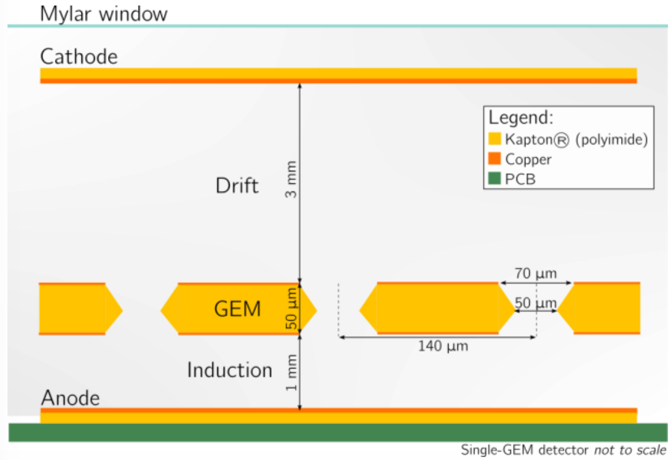


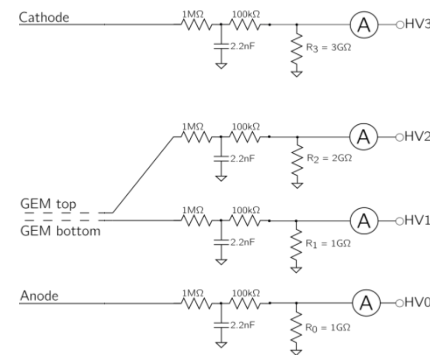
# Experimental setup

## CAEN N1471H **Power Supply**

- **4 independent channels**
- **Output ranges:**
  5.5 kV / 20 μA
  (IMonRange = High)
  5.5 kV / 2 μA
  (IMonRange = Low)
- **Imon Resolution:**
  1 nA (IMonRange = High)
  50 pA (IMonRange = Low)

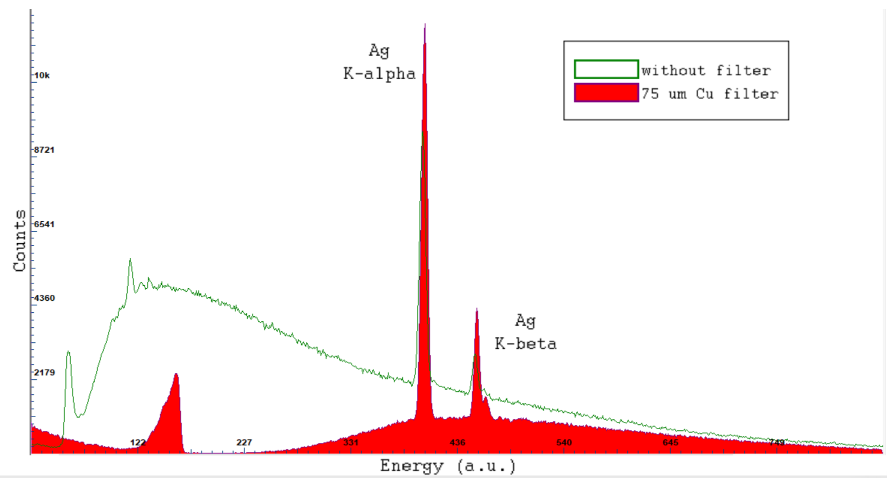
## **Single-GEM detector** as a benchmark



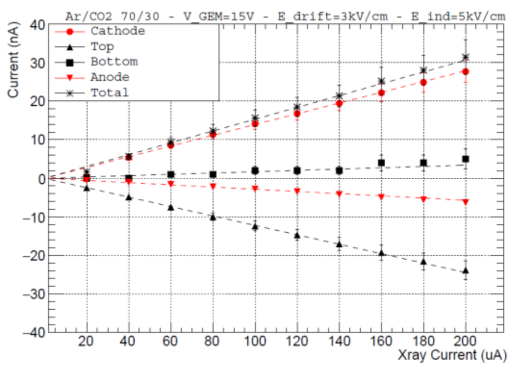

## Amptek Mini-X **X-ray tube**

- **Ag target:** 20 keV and 22 keV emission peaks
- **4 W maximum power**
  $I_{xray} = [5; 200]$ μA  $\Delta I_{xray} = 0.1$ μA
  $V_{xray} = [10; 50]$ kV  $\Delta V_{xray} = 0.1$ kV
- **Nominal flux:** $10^6$ Hz mm$^{-2}$ on the axis
  @ 30 cm @ maximum power

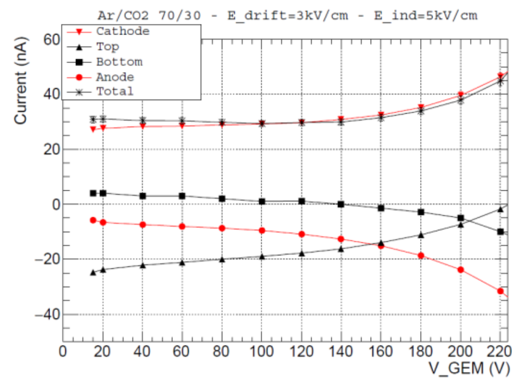


# Benchmark tests on a Single-GEM

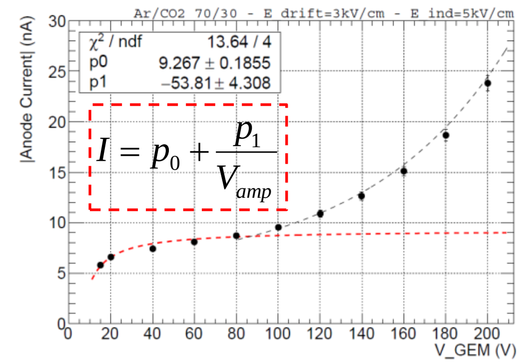
## Linearity with x-ray flux



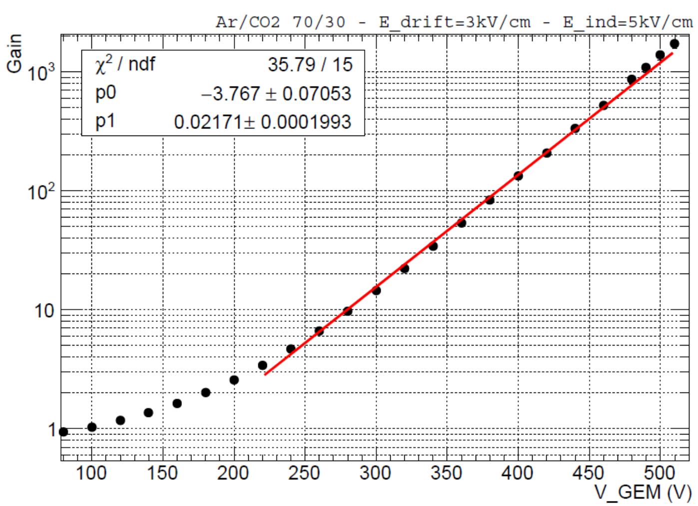

## All currents at low $V_{amp}$




## Estimation of the **ionization current** ($p_0$)




## Gain




**Gas Mixture:** Ar/$CO_2$ 70/30

Max $V_{GEM}$ = 510 V → **Max $E_{amp}$** = 102 kV/cm

**$E_{drift}$** = 3 kV/cm

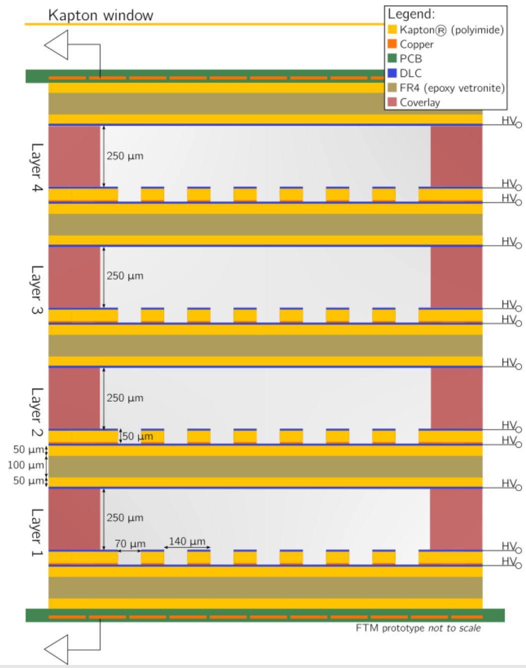
**$E_{ind.}$** = 5 kV/cm

$$\langle I \rangle = \langle I_{\text{GEM ON, source ON}} \rangle - \langle I_{\text{GEM ON, source OFF}} \rangle$$

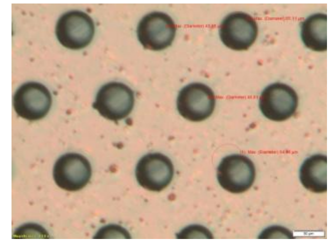
$$G = \frac{I_{\text{anode, amp}}(V_{\text{GEM}})}{I_{\text{anode, ionization}}} \cdot \frac{I_{\text{xray, max}}}{I_{\text{xray}}(V_{\text{GEM}})}$$

# FTM v.4: design & assembly

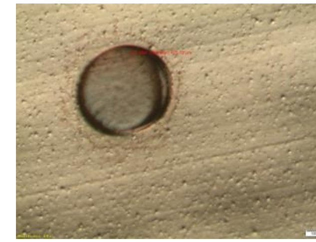
## Schematic view of the detector



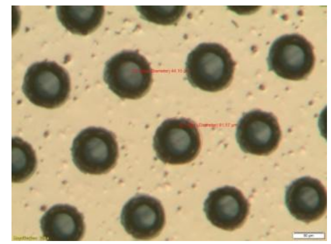

- **N = 4** independent drift and amp. layers
- **250 µm** drift gaps
- **50 µm**-thick "GEM-like" amplification structures
- **Forced gas circulation** through all layers
- **Top & bottom readout:** 2 X 200 strips (500 µm pitch)
- **Preserve fast pulse:** SAMTEC connectors
- **Reduce noise pick-up:** Connectors directly on middle of strips, no long vias
- **Modular design:** readout pcb can hold up to 12 layers



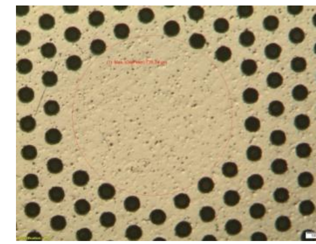
Bottom side of the amplication foil, Cu coated.



Coverlay pillar placed on the DLC coating of the drift electrode.

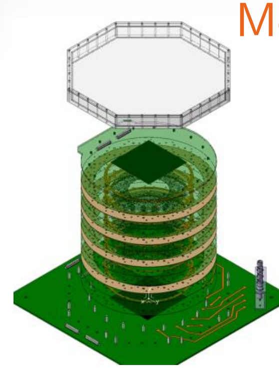


Top side of the amplication foil, DLC coated



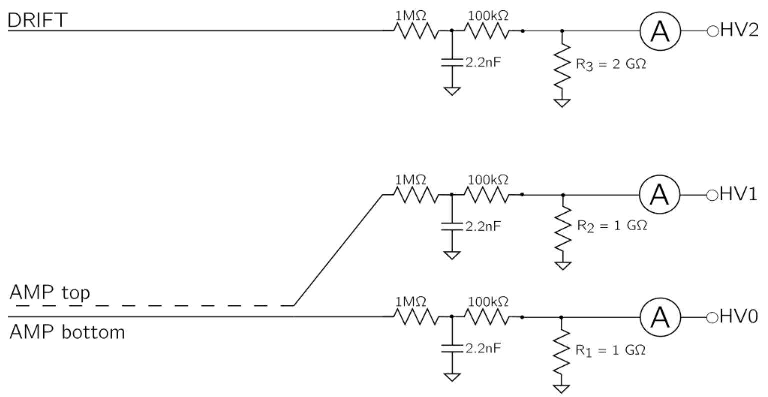
Detail of the amplication layer, showing a zone without holes to support the pillars.

## Modular design



# FTM v.4: HV stability

## Single channel powering schematic:



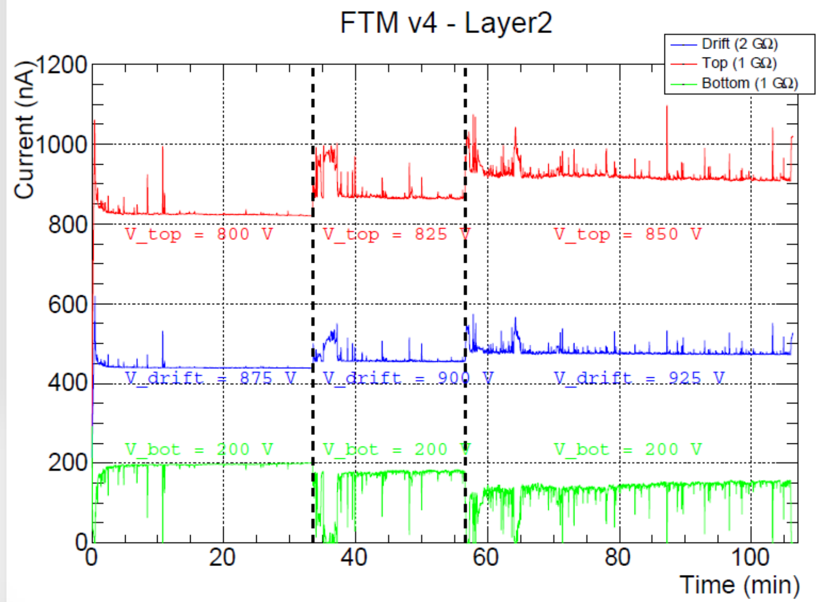

**Gas Mixture:** $Ar/CO_2$ 70/30
$E_{drift} = 3$ kV/cm

## Summary:

- **Layer 1:** stable @ $V_{AMP} = 550$ V
- **Layer 2:** stable @ $V_{AMP} = 600$ V
- **Layer 3:** stable @ $V_{AMP} = 600$ V
- **Layer 4:** stable @ $V_{AMP} = 550$ V

("stable" → $\Delta I << 5$ nA)

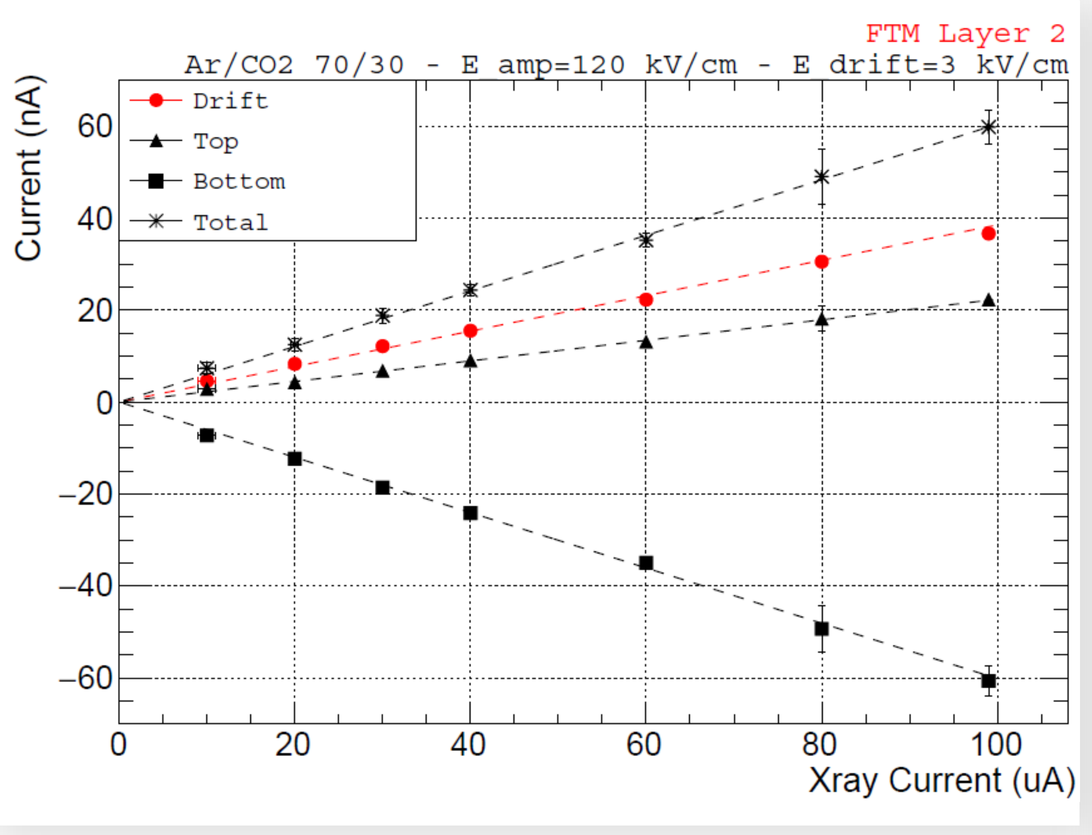
## HV stability test:

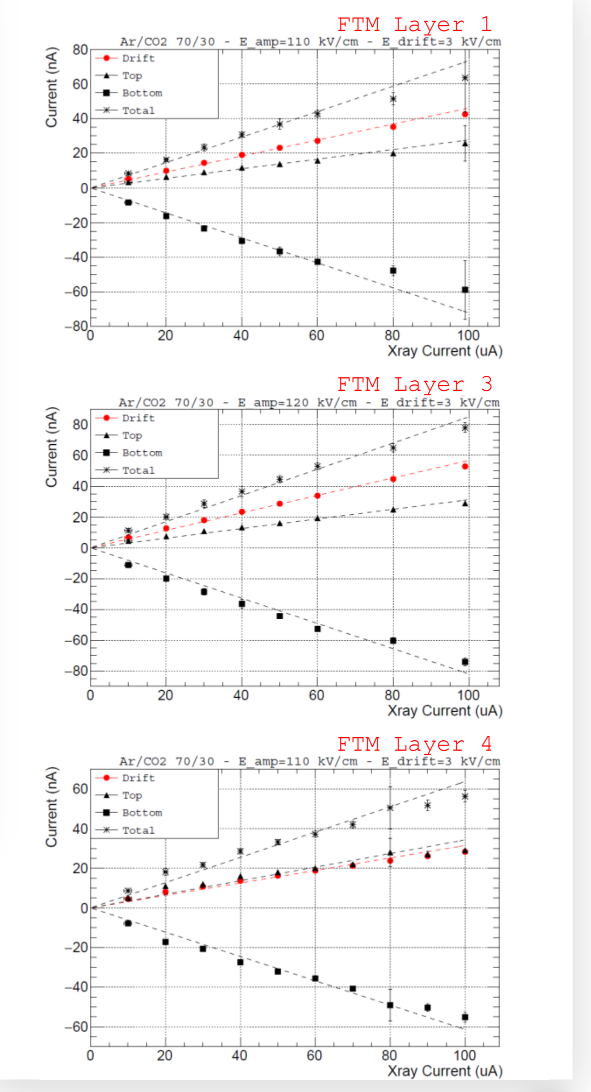



**Example: Layer 2**

- $V_{AMP} = V_{TOP} - V_{BOT} = 675$ V
  - Stabilized after ≈ 30 min
  - Current fluctuations ≈ 10 nA
- $V_{AMP} = 700$ V
  - Unstable, with ≈ 200 nA peaks

# FTM v.4: linearity with the X-ray flux

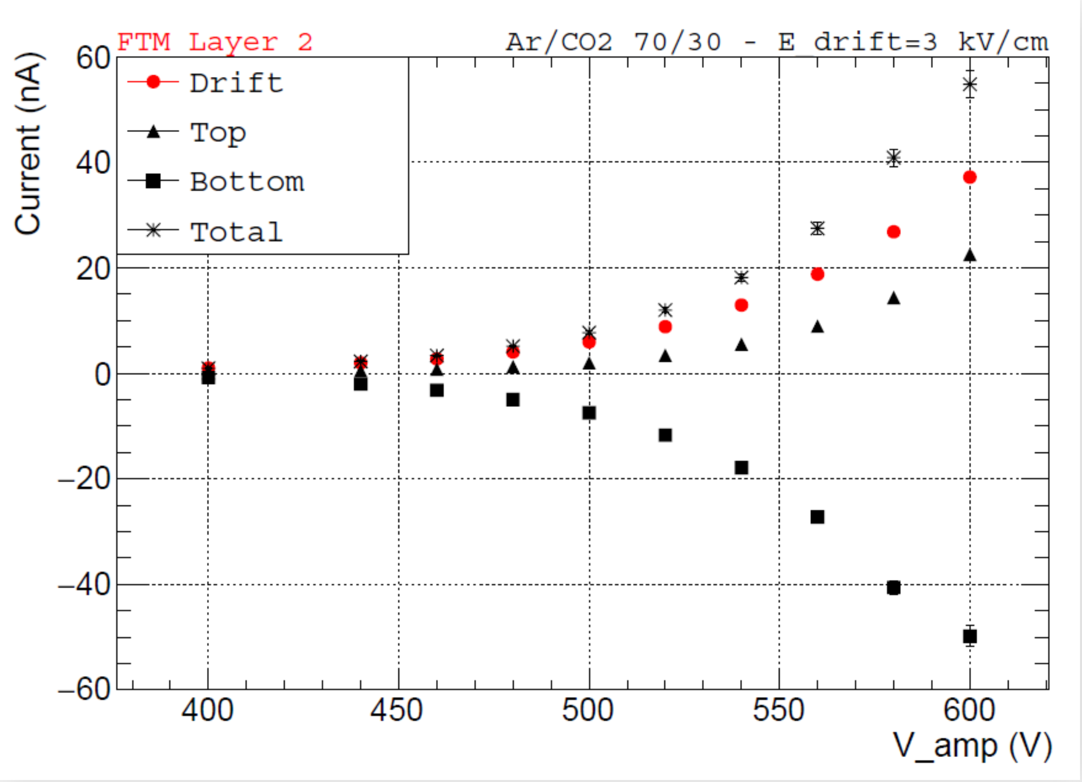


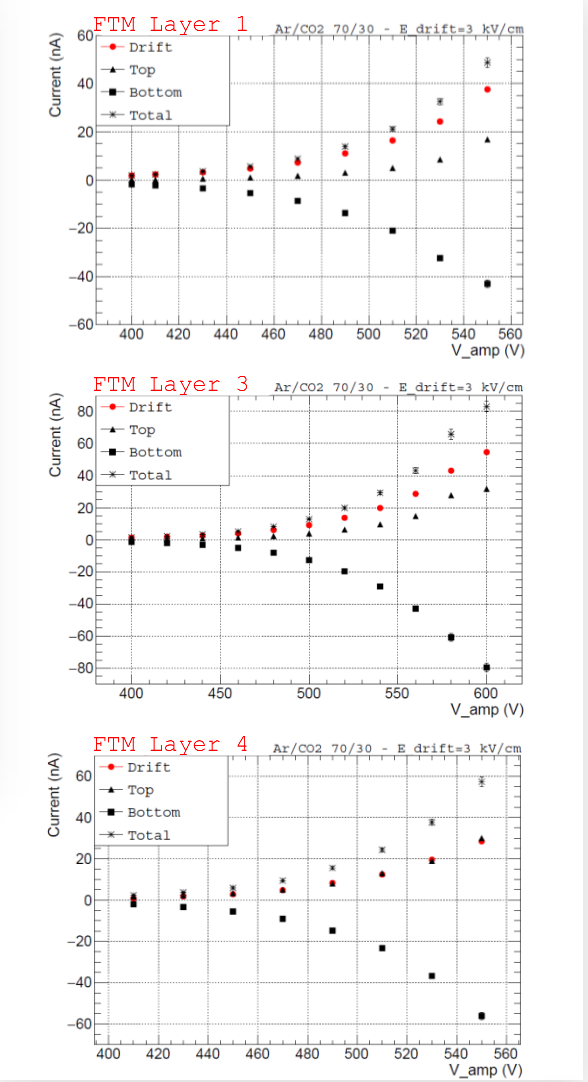




$$\langle I \rangle = \langle I_{\text{FTM ON, source ON}} \rangle - \langle I_{\text{FTM ON, source OFF}} \rangle$$

$$I_{\text{tot}} = (|I_{\text{drift}}| + |I_{\text{top}}| + |I_{\text{bottom}}|)/2$$

# FTM v.4: avalanche



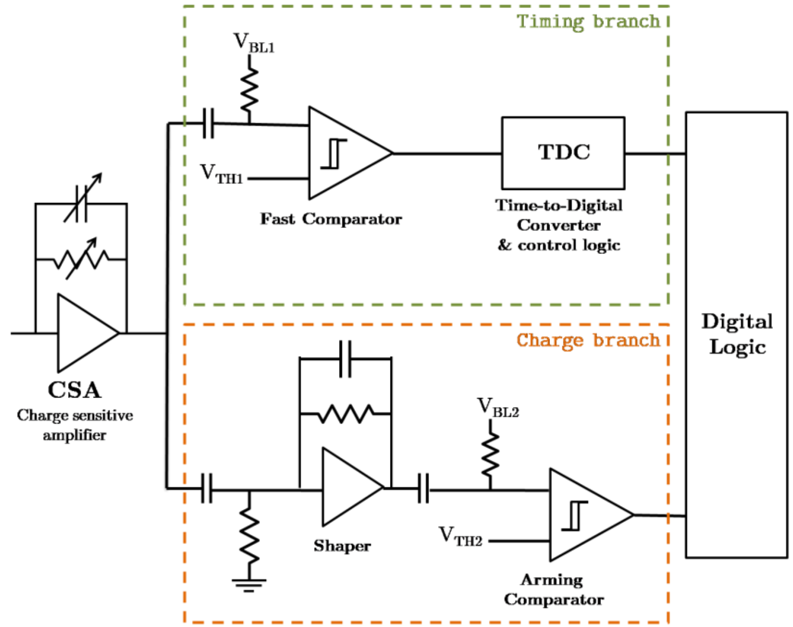




$V_{AMP} < 400$ V → $I_{anode} < 1$ nA
Comparable with fluctuations

**Simulated gain** @ $E_{AMP}$ =120 kV/cm → $10^4$ (**1.6 fC**)
→ dedicated readout electronics needed

# Fast Timing Readout Electronics

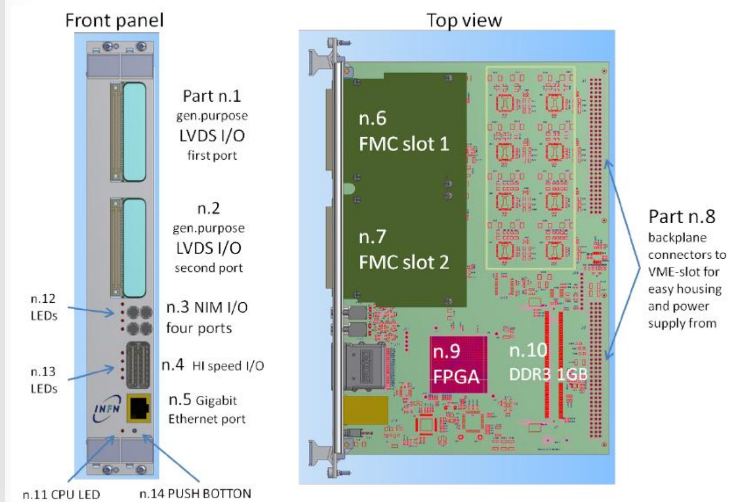
## Fast Timing Integrated Circuit (FATIC)

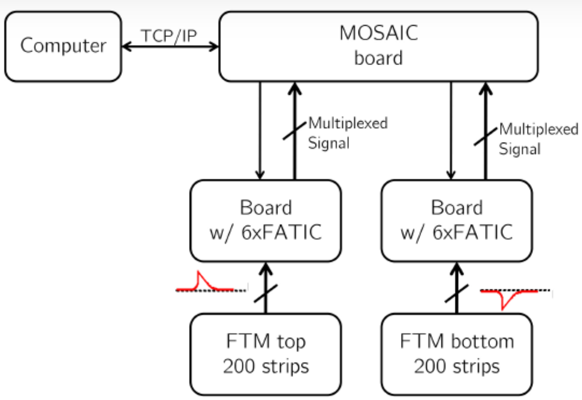



| CSA | | | TDC | |
|---|---|---|---|---|
| Peaking time* | | 7.3ns | Resolution | 5-bit fine / 16-bit coarse |
| Time jitter* | | 300ps@1fC input charge | Ref. Clock | 320 MHz |
| ENC* | | $18.2e^{-}/pF \cdot C_{in}(pF) + 235.5e^{-}$ | Time res. | 100 ps |
| Current/Ch* | | 1.3mA | **Fast Comparator** | |
| Signal Polarity | | positive & negative | Global Th. | 8-bit DAC, LSB = 2.5 mV |
| Gain | High | 50mV/fC | Local Th. | 6-bit DAC, LSB = 2 mV |
| | Low | 10mV/fC | **Arming Comparator** | |
| **Shaper** | | | Global Th. | 8-bit DAC, LSB = 2.3 mV |
| Peaking time | | 100 ns | Local Th. | 6-bit DAC, LSB = 1.725 mV |

*simulation in high gain mode with $C_{in} = 15pF$

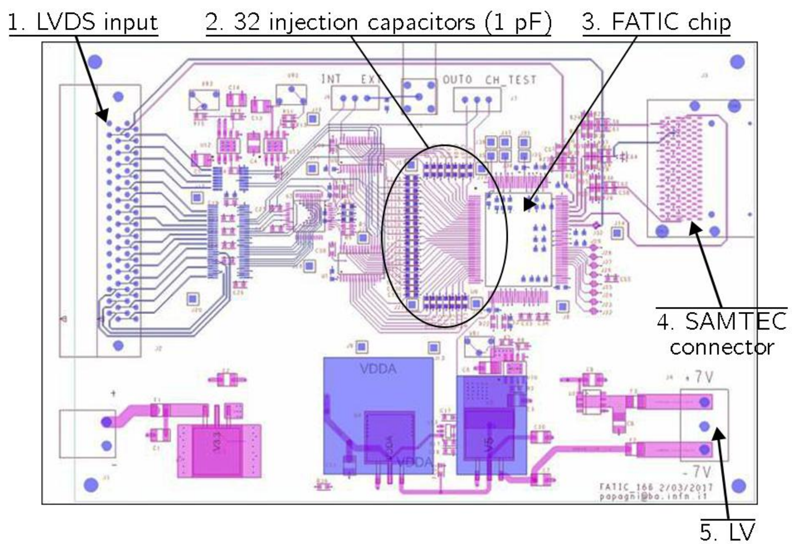
## MOdular System for Acquisition, Interface and Control (MOSAIC)



# FATIC v.1: test setup

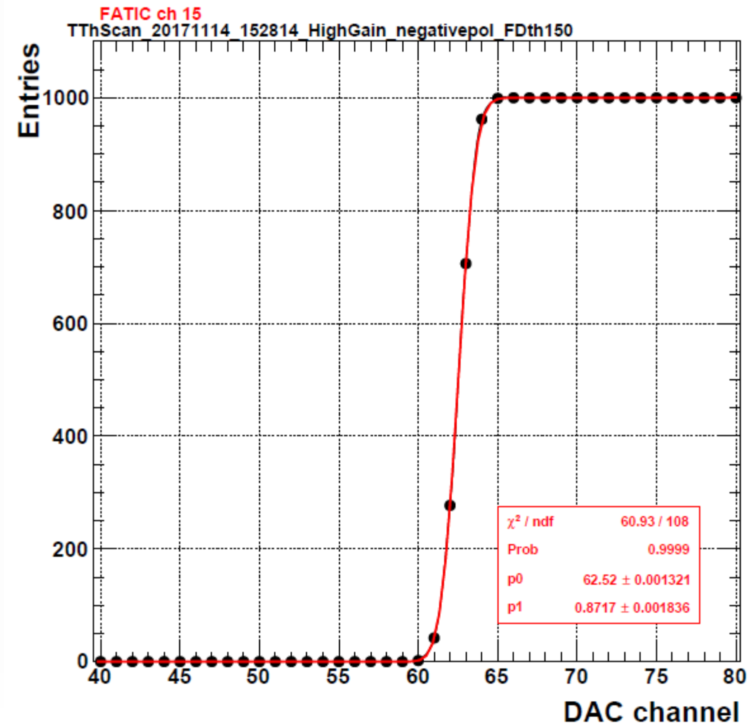
## Test Board




Injected charge : Q = 0.1 mV/unit * C * DAC_units
C = (1 ± 0.25) pF

$$\Phi = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-(z-\mu)^2}{2\sigma^2}} \, dz = $$

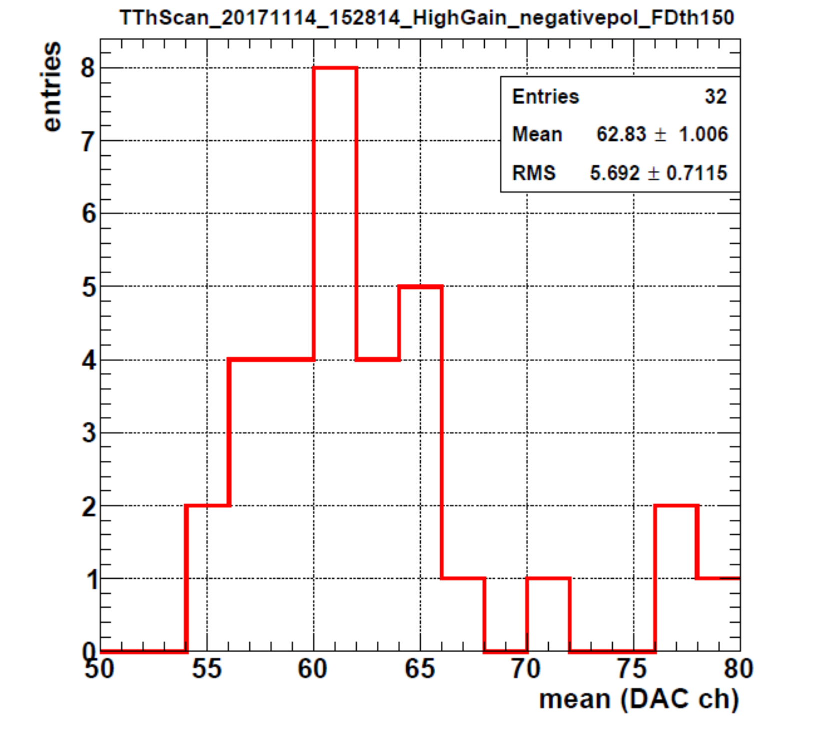
$$= \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right]$$

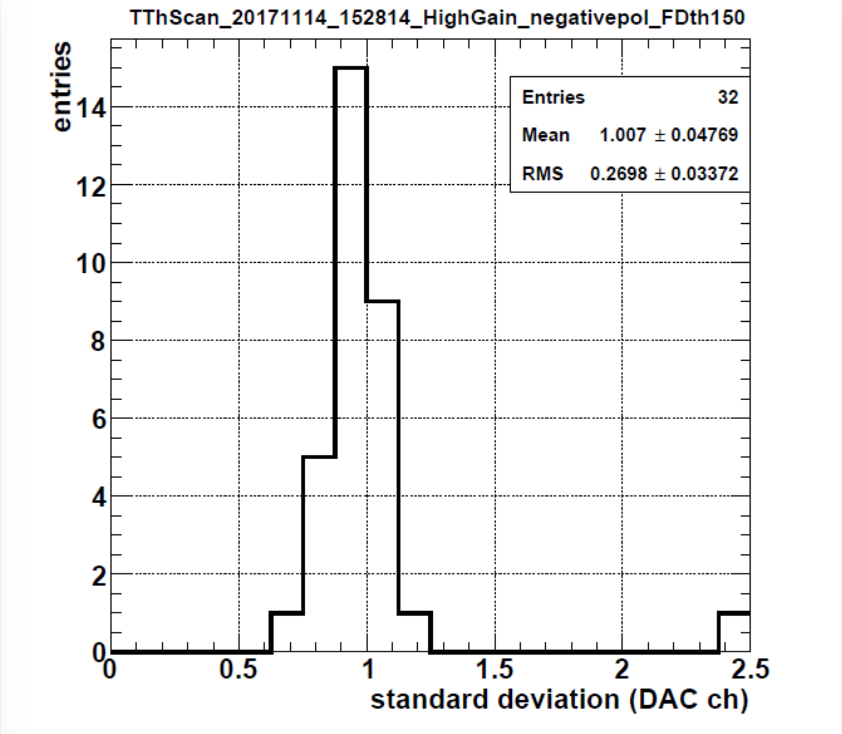



Single channel response fitted with function Φ.
CSA in High Gain Mode.
Arming comparator disabled.

σ → Equivalent Noise Charge (ENC)

# FATIC v.1: CSA response



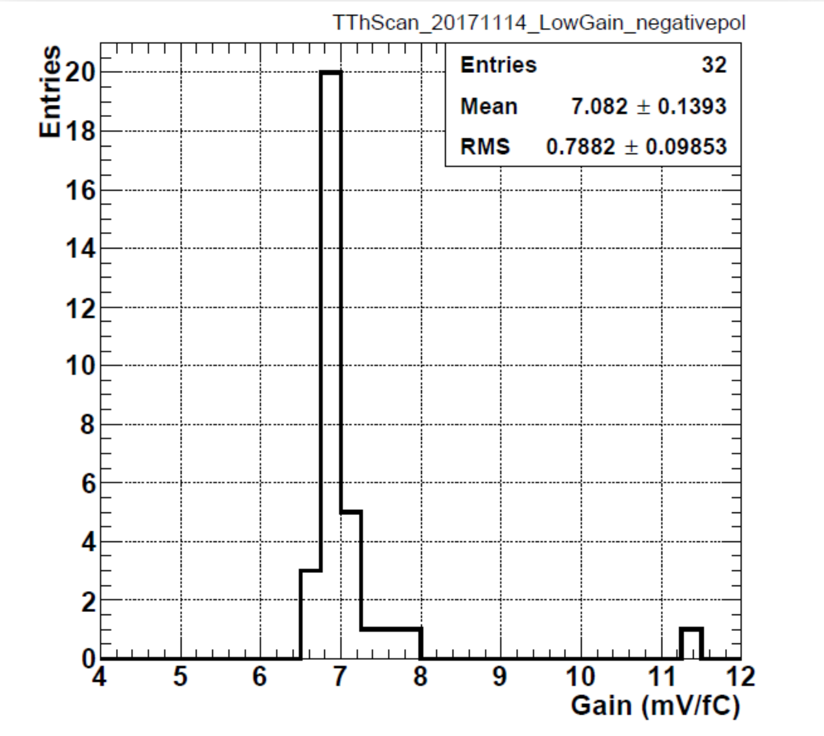

Distribution of mean μ and standard deviation σ of sigmoid fits for all 32 FATIC channels. (Global FC threshold = 150, High Gain mode, Arming comparator disabled)

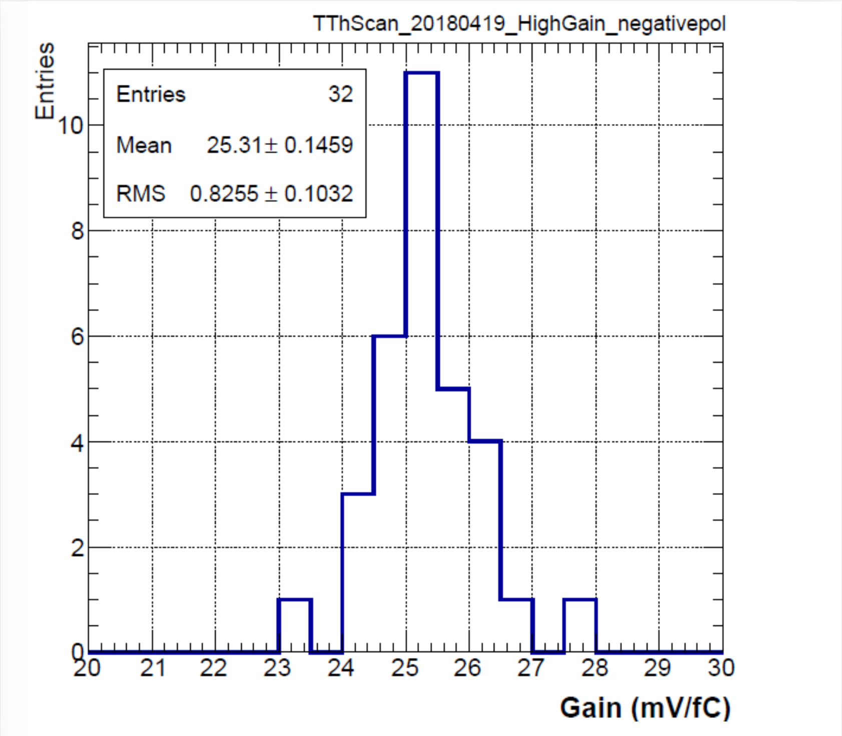
$$Th_{FC} = (DAC\ units - 220) * 2.5\frac{mV}{unit}$$

average $\mathrm{ENC}_{\mathrm{timing}}$ ≈ 1.043 DAC units ≈ 652 $e^-$

Note: Distribution of the μ values due to local threshold mismatch

# FATIC v.1: CSA gain



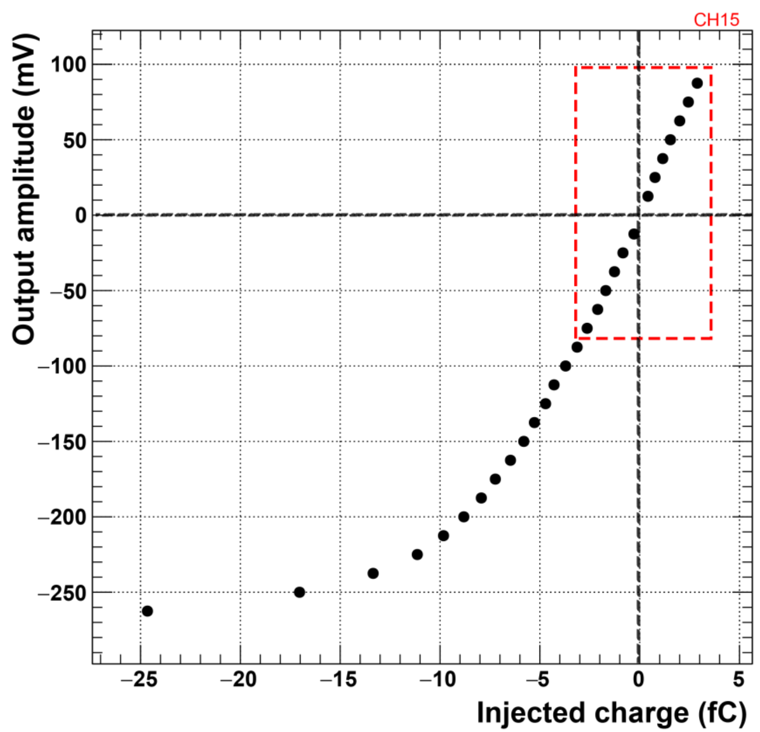

$$G = \frac{Th_1 - Th_2}{\mu_1 - \mu_2} \left(\frac{mV}{fC}\right)$$

$$\langle G \rangle_{\text{high gain}} = [25.35 \pm 0.146\ (\text{stat}) \pm 1.03\ (\text{syst})]\ \text{mV/fC}$$

$$\langle G \rangle_{\text{low gain}} = [7.082 \pm 0.139\ (\text{stat}) \pm 0.36\ (\text{syst})]\ \text{mV/fC}$$

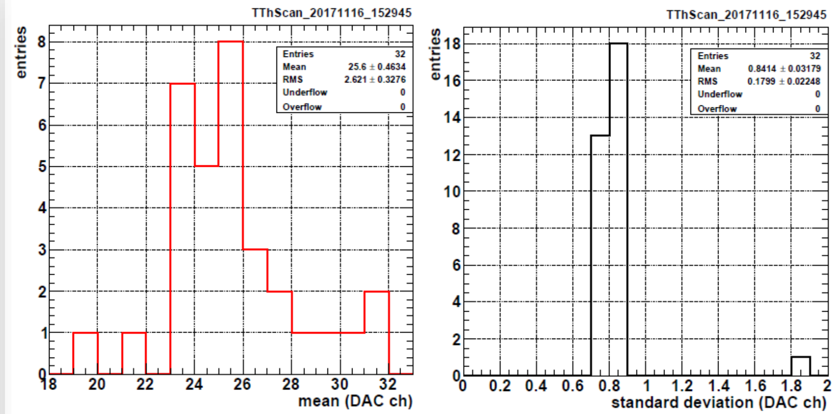
[Note: systematic errors from C = $(1 \pm 0.25)$ pF]

# FATIC v.1: CSA linearity & Arming comparator




**CSA linearity** (channel 15)
(High Gain mode, Arming comp. disabled)
Note: baseline ≈ 220 DAC units.

Injected charge : Q = 0.1 mV/unit · C · DAC units
C = (1 ± 0.25) pF



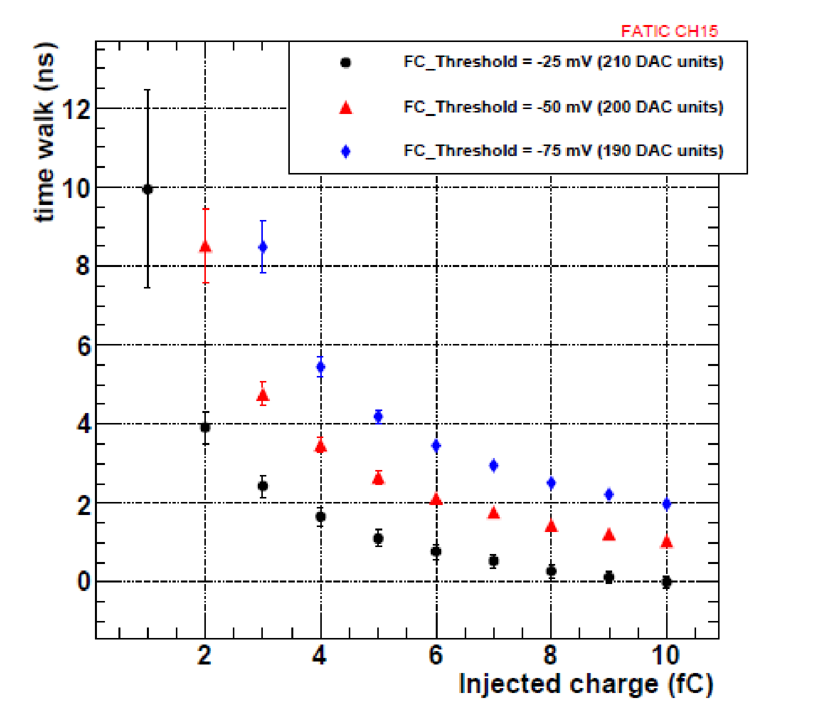

Distribution of mean μ and standard deviation σ of sigmoid fits for all 32 FATIC channels.
(Global FC th. = 200, Global AC th. = 40,
High Gain mode, Arming comparator enabled)

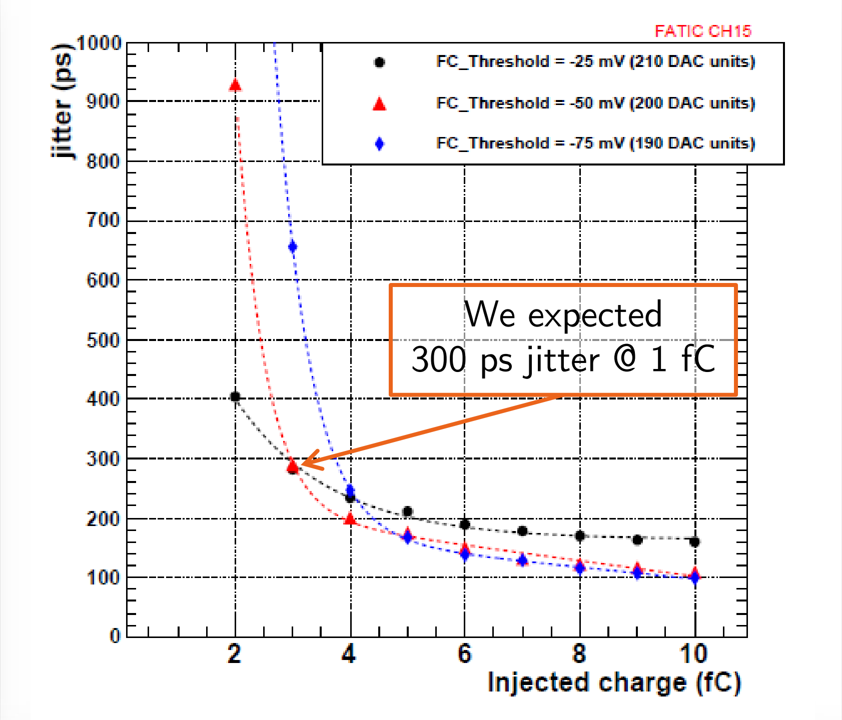
$$\mathrm{ENC_{timing}} \approx 1.04 \text{ DAC units}$$
$$\mathrm{ENC_{arming}} \approx 0.84 \text{ DAC units}$$

**Effect of the shaper:**

$$\%\mathrm{ENC_{reduction}} = [\mathrm{ENC_{timing}} - \mathrm{ENC_{arming}}] \,/\, \mathrm{ENC_{timing}} \approx 19\%$$

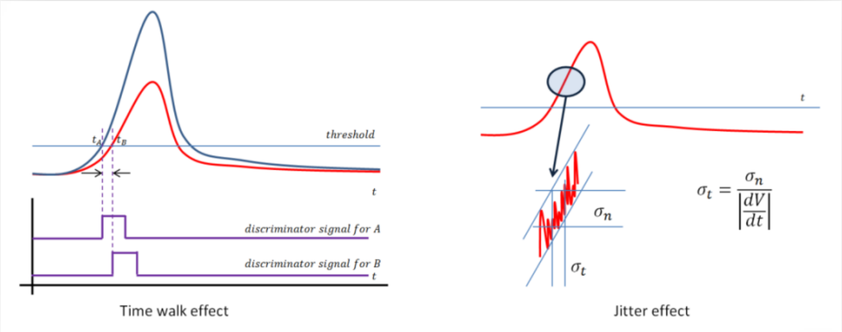
# FATIC v.1: time walk & jitter




Input trigger and the fast-OR signal sent to the scope:

- Average delay = time walk
- Delay std deviation = time jitter



# Conclusions & future perspectives

## FTM v.4: Limitations of the actual test setup

- X-rays absorbed before entering the active region
- No copper electrode facing the gas volume → no 8 keV conversion by fluorescence
- Optimization of the gas mixture needed
- Small drift gap → low efficiency

## FATIC v1:

- CSA gain lower than expected
- Test board needed to calibrate the local thresholds

**Summary of the FATIV v.1 characterization results**

| | | |
|---|---|---|
| Time jitter | 300ps@3fC input charge | |
| Gain | High | 2520 mV/fC |
| | Low | $\simeq$ 7.1 mV/fC |
| ENC | Fast Comparator | 0.1043 fC $\simeq 652e^-$ |
| | Arming Comparator | 0.084 fC $\simeq 525e^-$ |

## FTM v.4: Upgrade of the test setup

- Window for X-rays in the top PCB to reduce the absorption
- UV Laser facility to test the prototypes
- From N = 4 to N = 12 layers

## FATIC v.2:

- Internal charge injection to correct the threshold mismatch
- Gain at its nominal value (50 mV/fC in High Gain Mode)

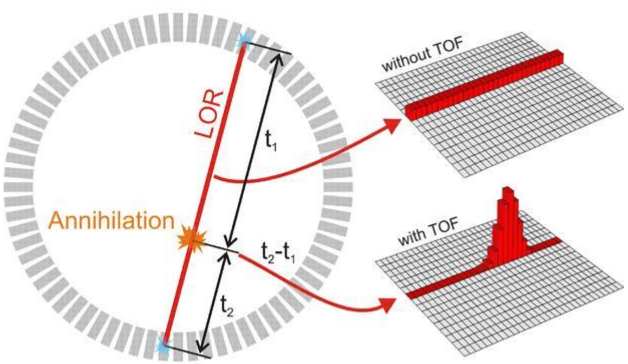
# Why Fast Timing detectors?

## Time-of-Flight Positron Emission Tomography

**Positron Emission Tomography:**

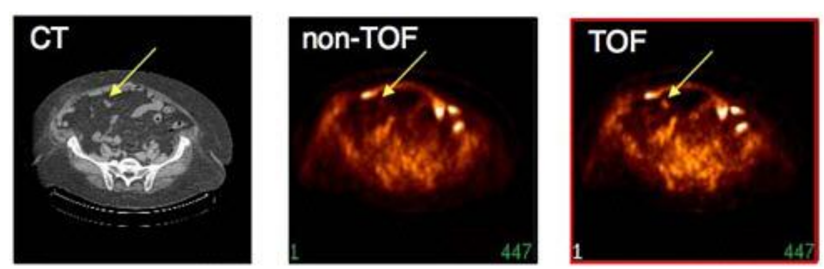
• positron-emitting radionuclide concentrates at regions of high metabolic activity (tracer)
• 2γ (511 keV) emitted back to back
• Coincident detection determines the **Line of Response (LOR)**

- w/o TOF: equal probability assigned to each point along the LOR
- **w/ TOF**: few **100 ps** measurement will lead to 5 cm precision along the LOR → **High contrast images**



PET principle, w/ & w/o TOF. [source: sublima-pet-mr.eu/]

An ideal TOF-PET detector should
• have high detection **efficiency** for γ
• have **high spatial resolution** to determine precisely the LOR
• have good **energy resolution** to reject scattered γ's
• have high **time resolution** to increase the sensitivity / image contrast
• be **inexpensive** to produce (instrument larger area, instrument more hospitals) and safe to operate



PET scans of a patient with colon cancer. The use of TOF improves the lesion detectability (arrow). [source: J. Karp, U. Pennsylvania.]

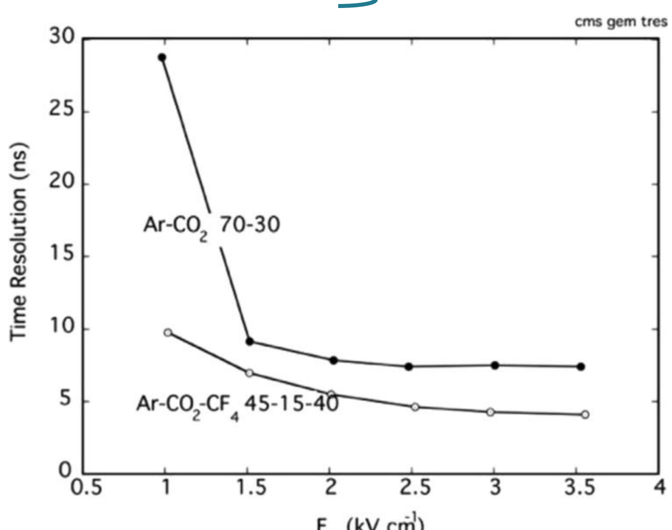
# GEMs: time resolution with CF4

$\sigma_t = 1/v\lambda$

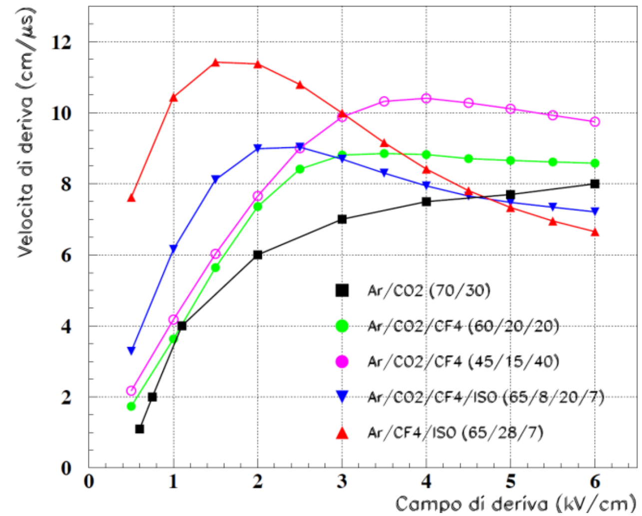
- **λ** number of primary electrons per unit lenght
- **v** drift velocity of electrons in the gas

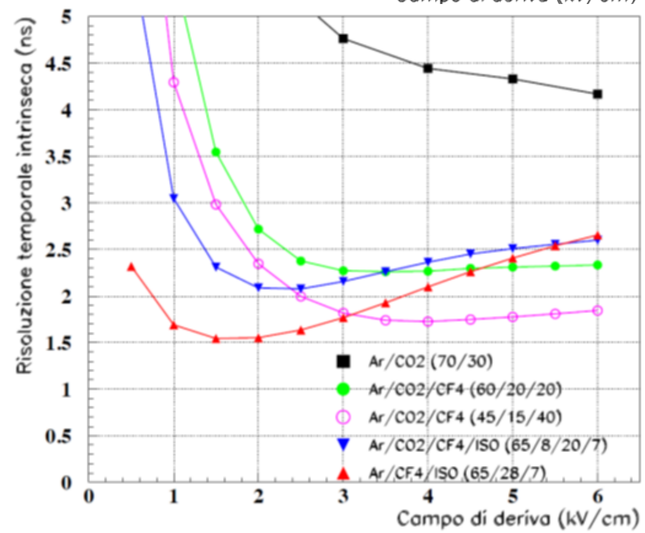
- **λ ≈ 39 cm$^{-1}$** for a MIP in Ar/CO2/CF4 45/15/40
- **v ≈ 10 cm/μs** drift velocity of e$^-$ in Ar/CO2/CF4 45/15/40 with 3 kV/cm drift field

} $\sigma_t \geq 2.5$ **ns**



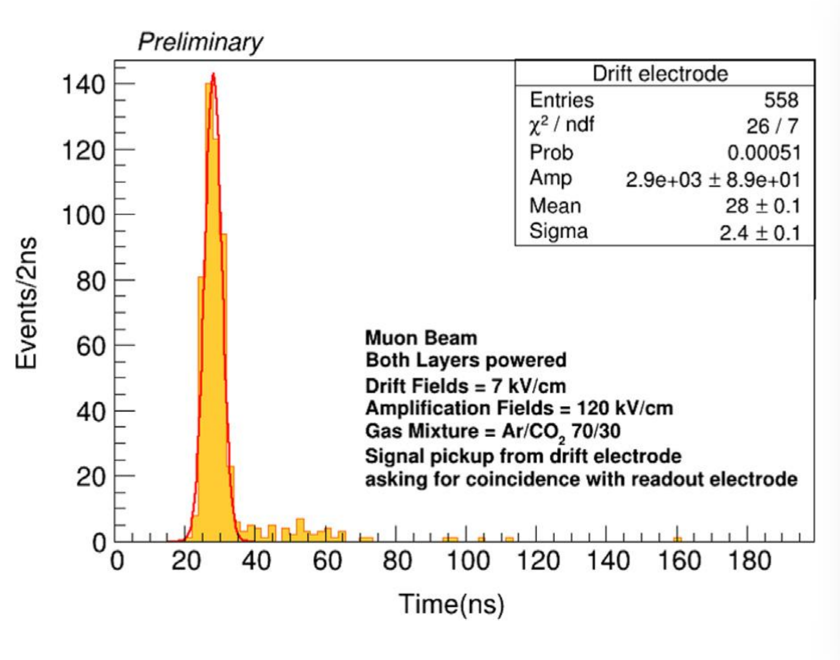

F. Sauli, Nucl. Instr. and Meth., A805:2-24, 2016.

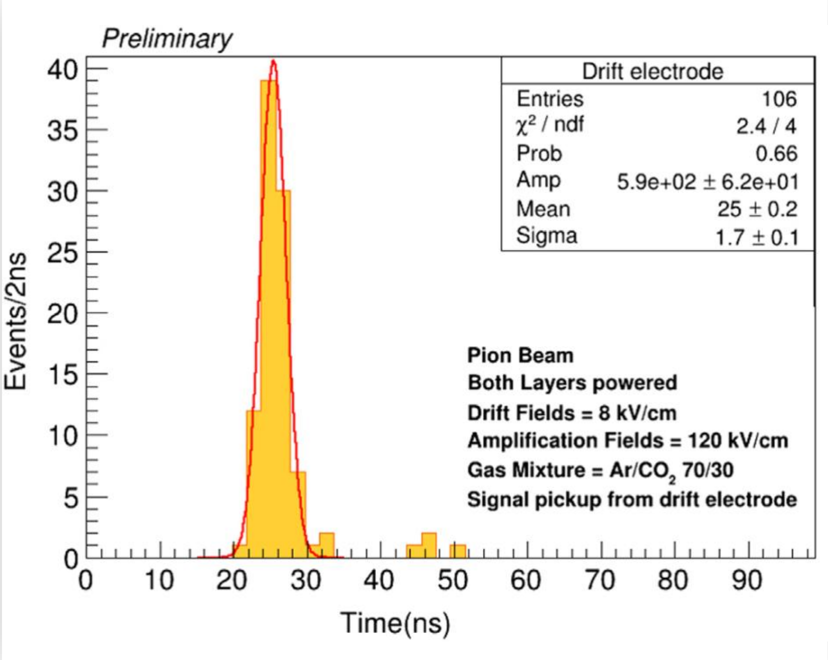


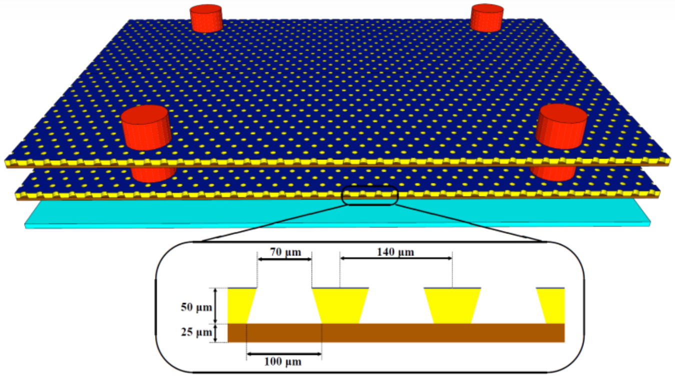

GARFIELD Simulations [F.Murtas (LNF-INFN), 2002]

# FTM v.1: design & results



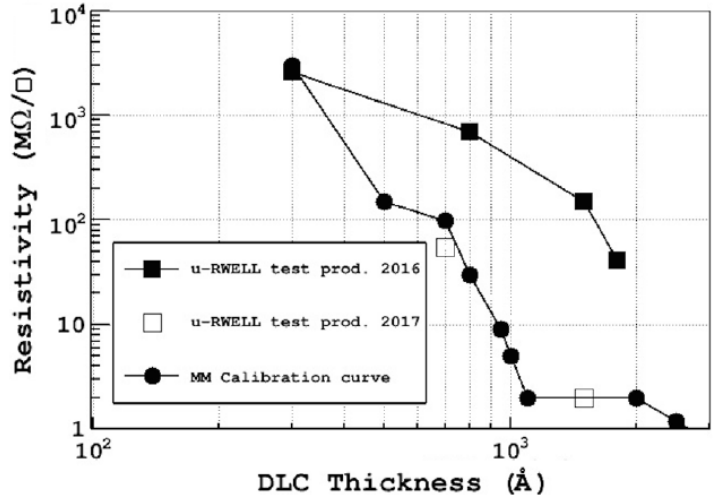

- **N = 2** independent drift and amp. layers
- **250 μm** drift gaps
- **50 μm**-thick "GEM-like" amplification structures
- **Holes:** bottom base diameter: 100 μm, top base diameter: 70 μm, pitch: 140 μm
- **Top & bottom readout:** 2 X 200 strips (500 μm pitch)
- Panasonic connectors
- Active area ≈ 20 $cm^2$
- Glued structure



# FTM v.4: DLC Resistivity

| | Layer 1 | Layer 2 | Layer 3 | Layer 4 |
|---|---|---|---|---|
| Drift | 30 MΩ | 35 MΩ | 40 MΩ | 50 MΩ |
| Amp. top | 360 MΩ | 450 MΩ | 1.1 GΩ | 450 MΩ |
| Amp. bottom | 40 MΩ | 35 MΩ | 37 MΩ | 30 MΩ |

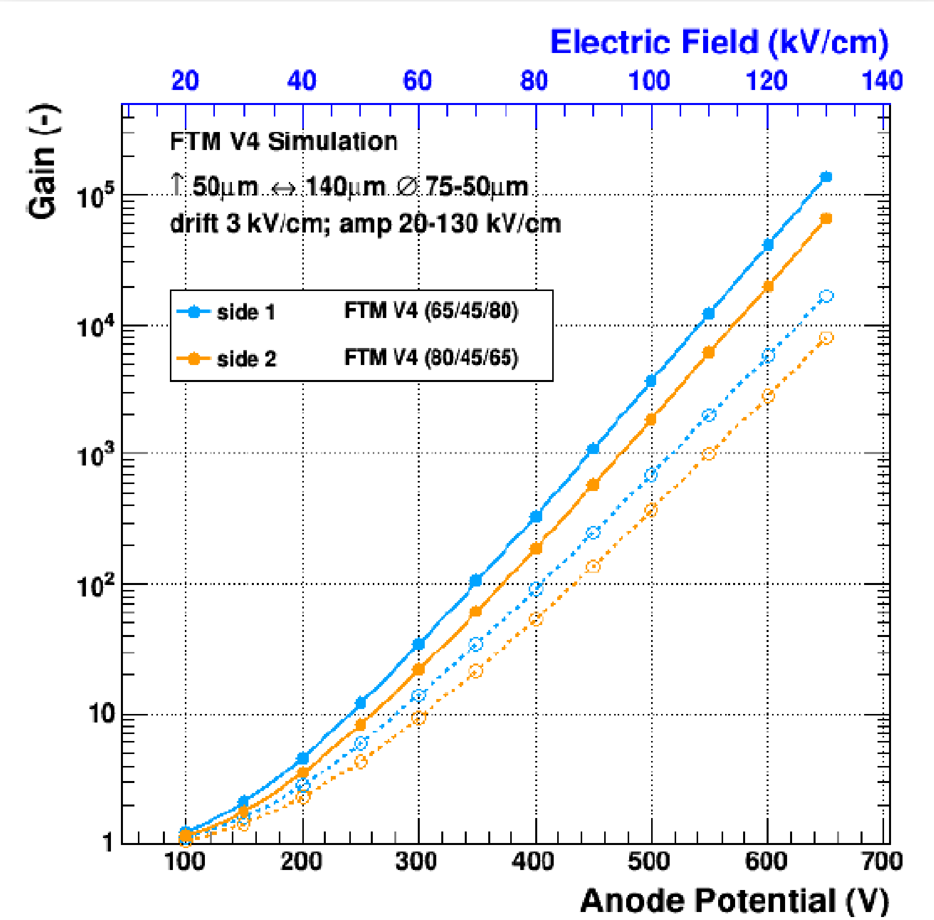
**Resistivity** of the DLC layers for the FTM v.4 prototype, measured with Megger insulation tester.

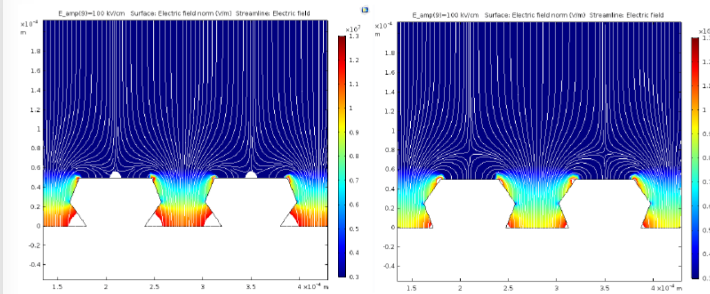



G. Bencivenni et al., Nucl. Instr. and Meth., A 886 (2018) 36–39

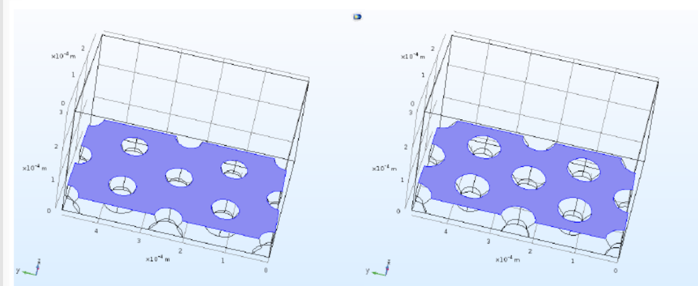
Resistivity as a function of the sputtered DLC **thickness** for different sputtering batches.

# FTM v.4: gain simulation



Electric field lines in the FTM v.4 amplification foils, for two different orientations of the holes, simulated with COMSOL Multiphysics

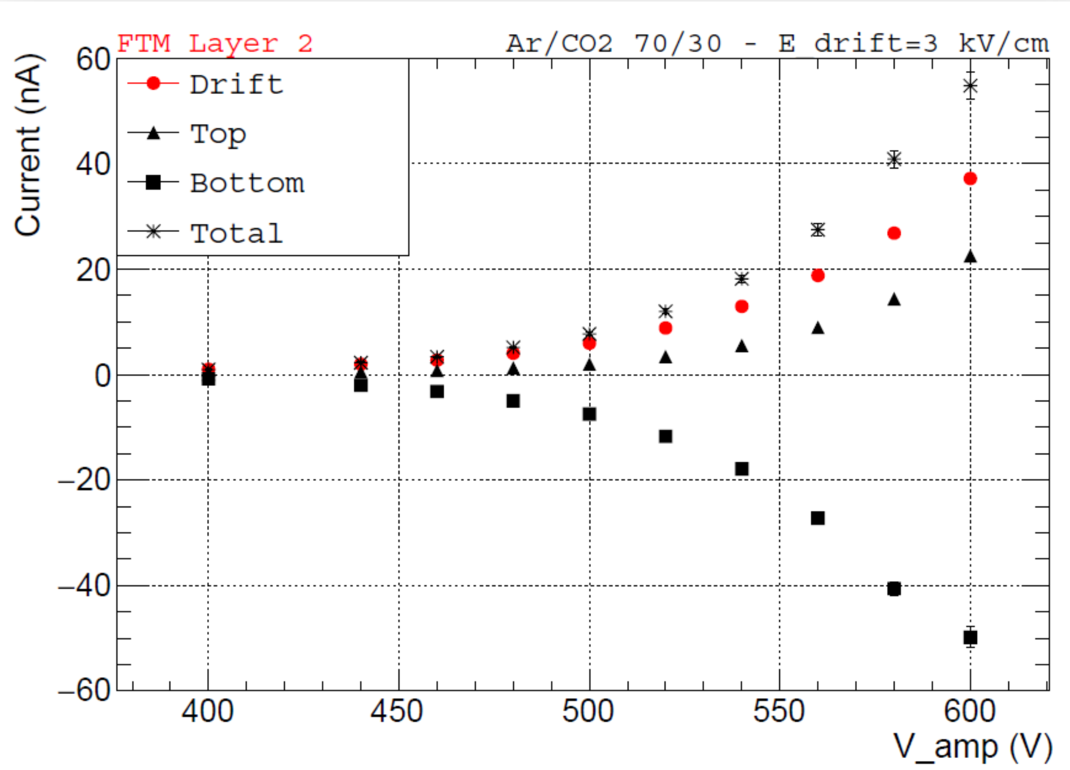


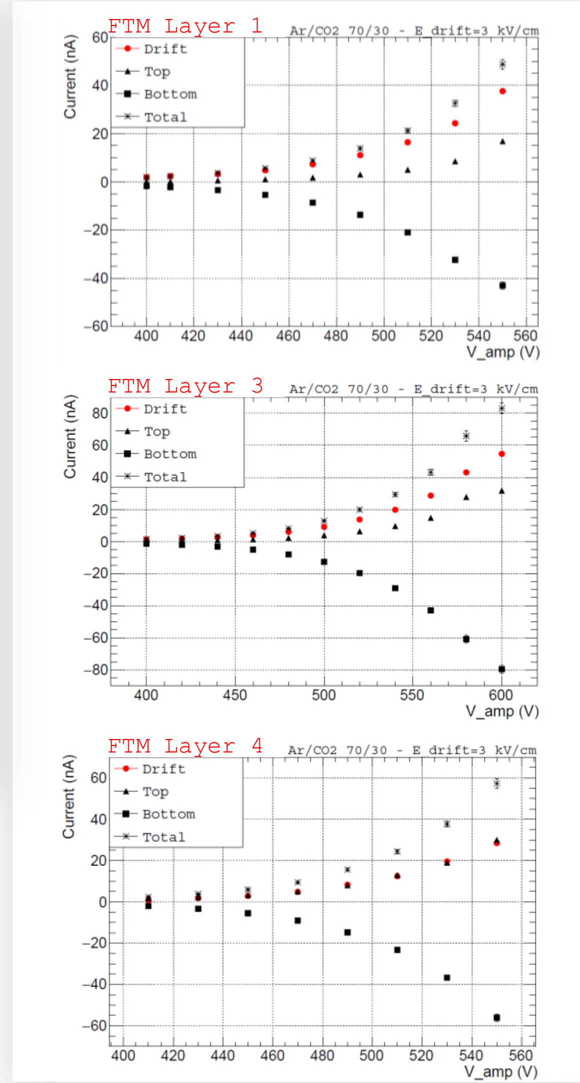
Geometry of the holes used for the COMSOL simulation.

Nominal gain of the biconical holes of the FTM v.4 detector, as a function of the amplification field, at constant drift field (3 kV/cm), simulated for two different orientations of the holes.

[P. Verwilligen, Progress Report on the new prototype for the fast timing mpgd (FTM), RD-51 Collaboration Meeting, CERN, September 26th 2017]

# FTM v.4: avalanche




$V_{AMP} < 400$ V $\rightarrow$ $I_{anode} < 1$ nA

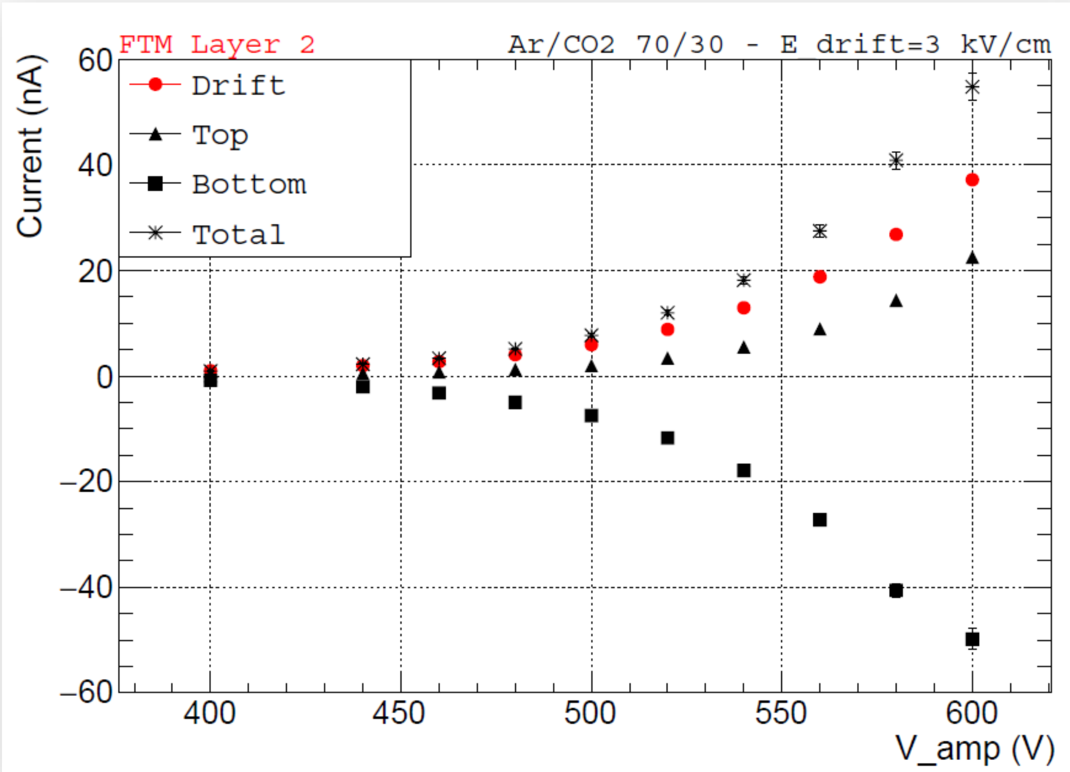
<u>Comparable with fluctuations</u>

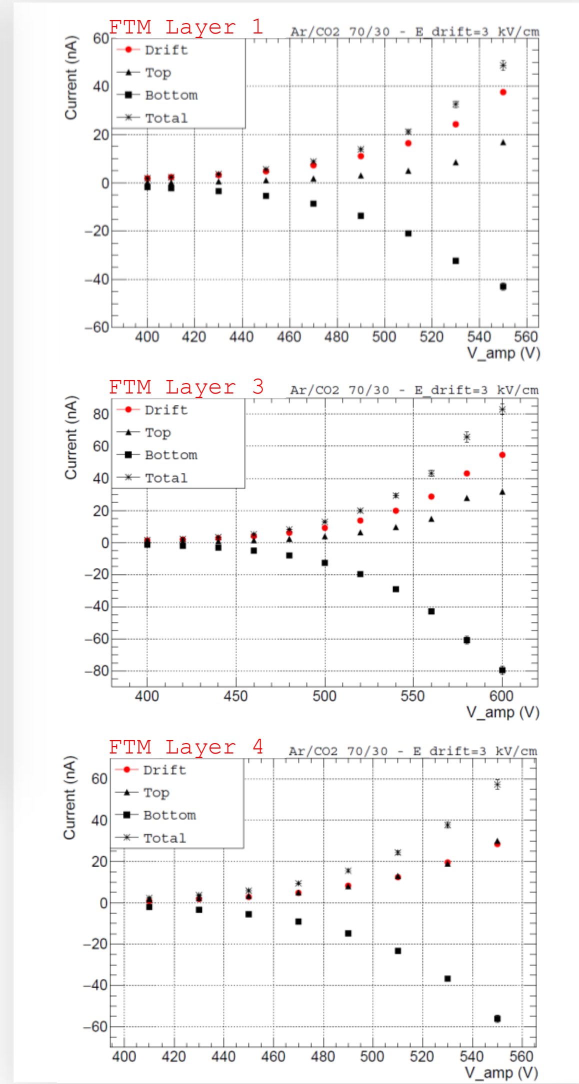
**Upper limit for $I_{ioniz}$ $\rightarrow$ lower limit for the gain:**

$\sigma_I = 0.1$ nA $\rightarrow$ $I_{ioniz} < 0.1$ nA

$\rightarrow$ @ $V_{AMP} = 600$ V **$G > 50$ nA/0.1 nA $= 500$**

# FTM v.4: avalanche



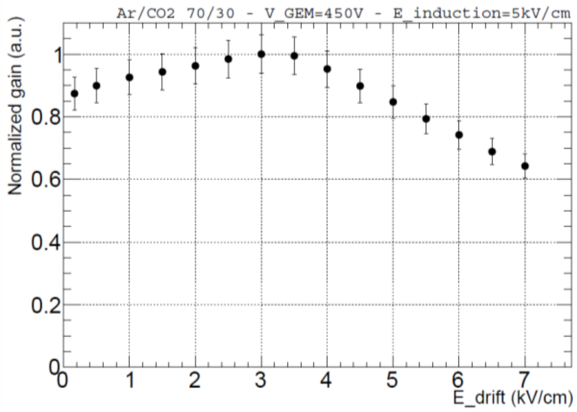

**Simulated gain** @ $E_{AMP}$ =120 kV/cm → G ≈ $10^4$

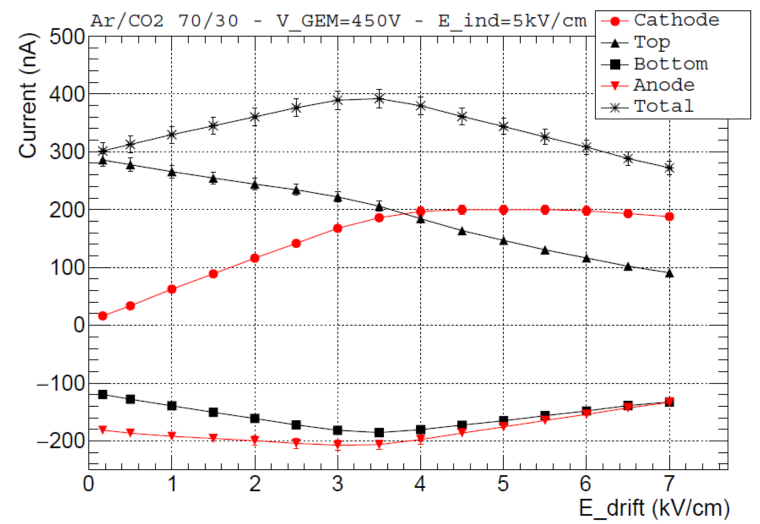
**Estimation of the ioniz. current**

**G ≈ $10^4$** → $I_{ioniz} \approx I_{AMP}/10^4 = 50\ nA/10^4 =$ **5 pA**

# Tests on the Single-GEM detector

## Effect of the drift field




## Effect of the induction field