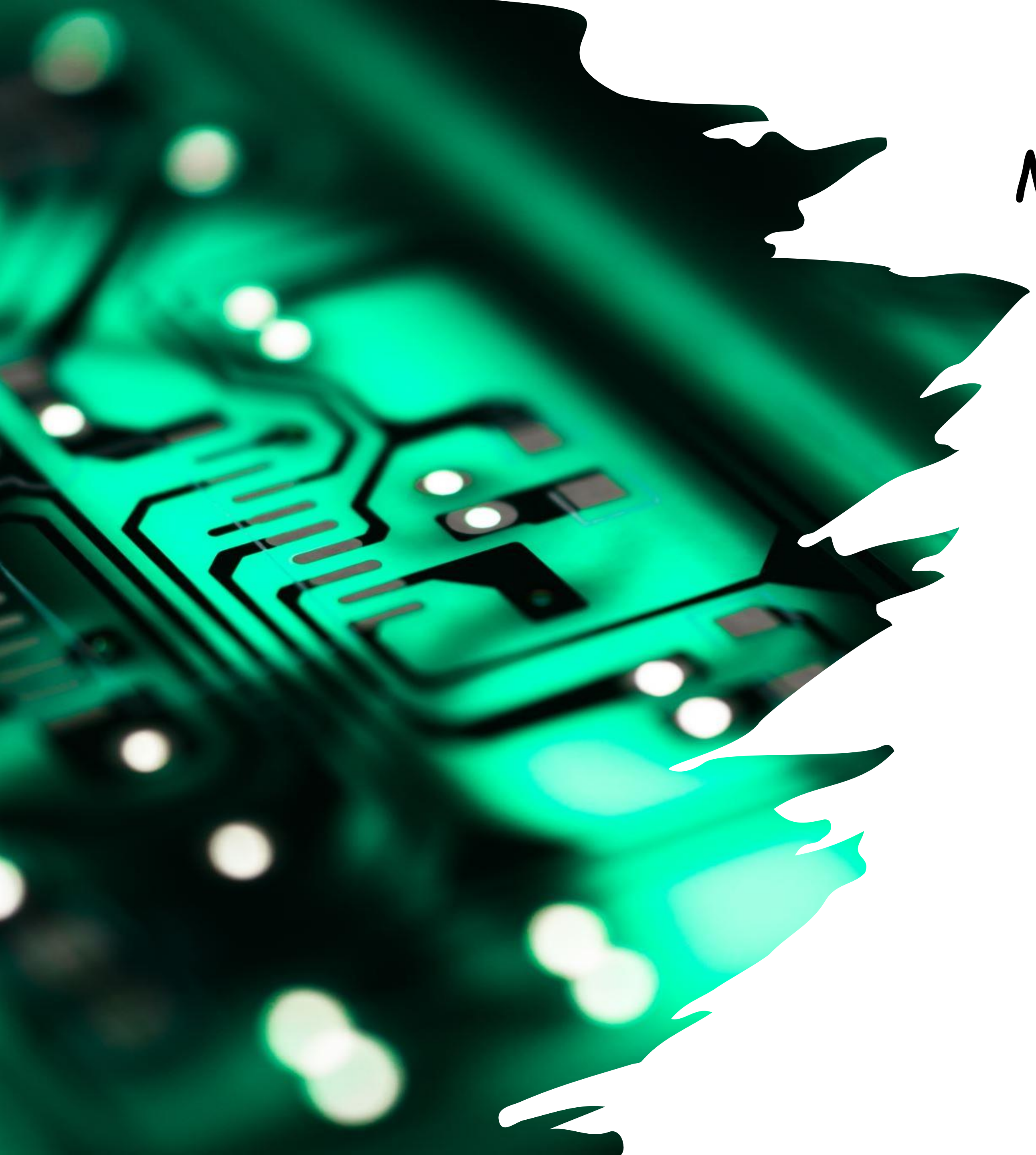


Micro Pattern Gas Detectors

- CERN workshop introduction
- Gaseous detector introduction
- First MPGD
- First evolution → more robust devices
- Second evolution → Introduction of resistive layers
- MPGD selection guide
- Future tasks

-21 persons

-14 persons from a contracting company

-7 CERN staff

-1400 square meters (new building operational in 2018)

-Making PCBs since 1965

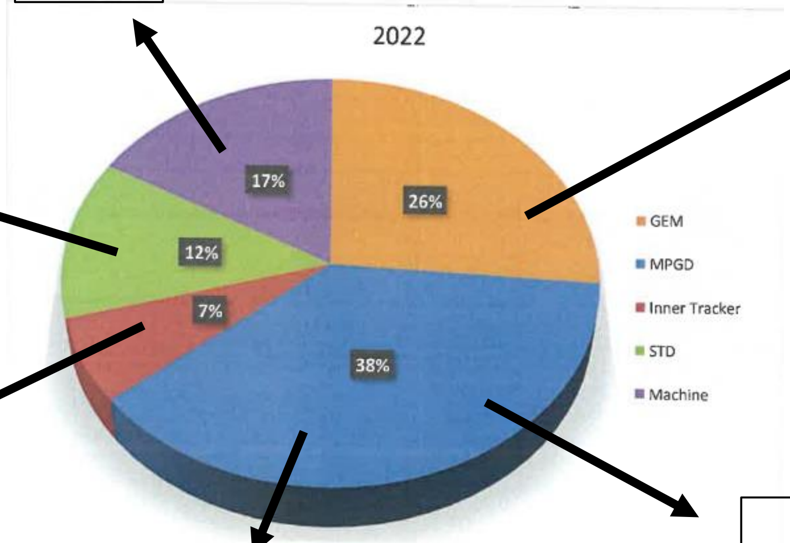
-Mandate:

- -produce parts difficult to find in industry
- -provide to CERN users expertise in the field
- -make some mass productions

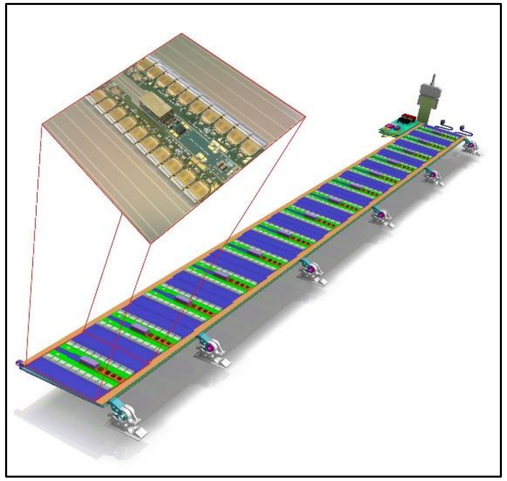
MPT activities

Component for LHC machine

STD PCB



GEM
4 technicians dedicated to GEM productions
-500 m2/ year capacity

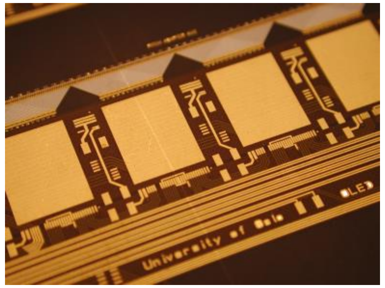


Components for Inner trackers detectors

Gas detectors production
Triple GEM
Resistive Micromegas
THGEM
uBulk
Etc..

R&D
- -PEP uRwell large size detectors
- -Capacitive sharing detectors
- -High rate detectors (MM & uRwell)
- -Resistive GEMs
- -Low IBF detectors
- -High dynamic range detectors
- -Fast timing detectors
- -Low mass

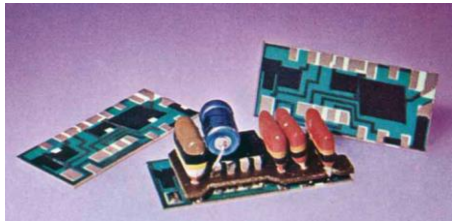
Interconnection technologies available at MPT



Minimum line and space

Minimum line and space	Technologies name
20um	MCM/D → vacuum depositon
25um	Thin film technology
50um	MCM/C → ceramic
75um	MCM/L or HDI → laminated
90um	Thick film technology
120um	PCB
200um	Screen printed circuits

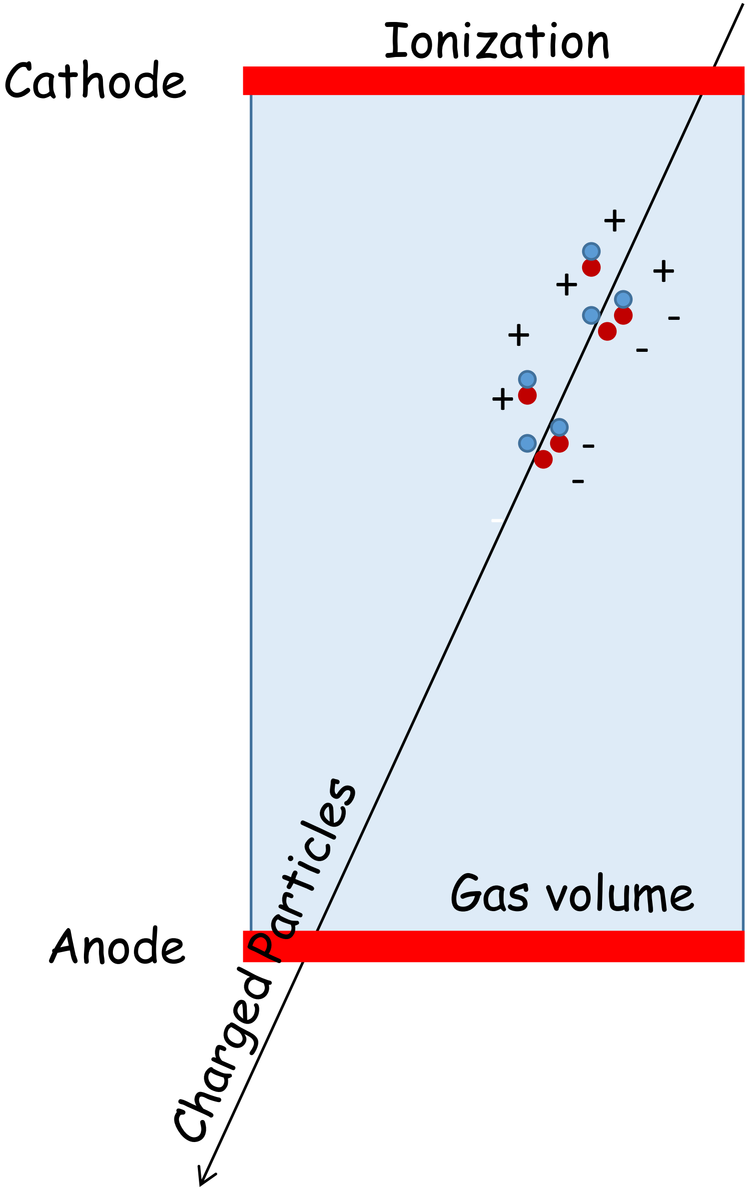
Technologies name



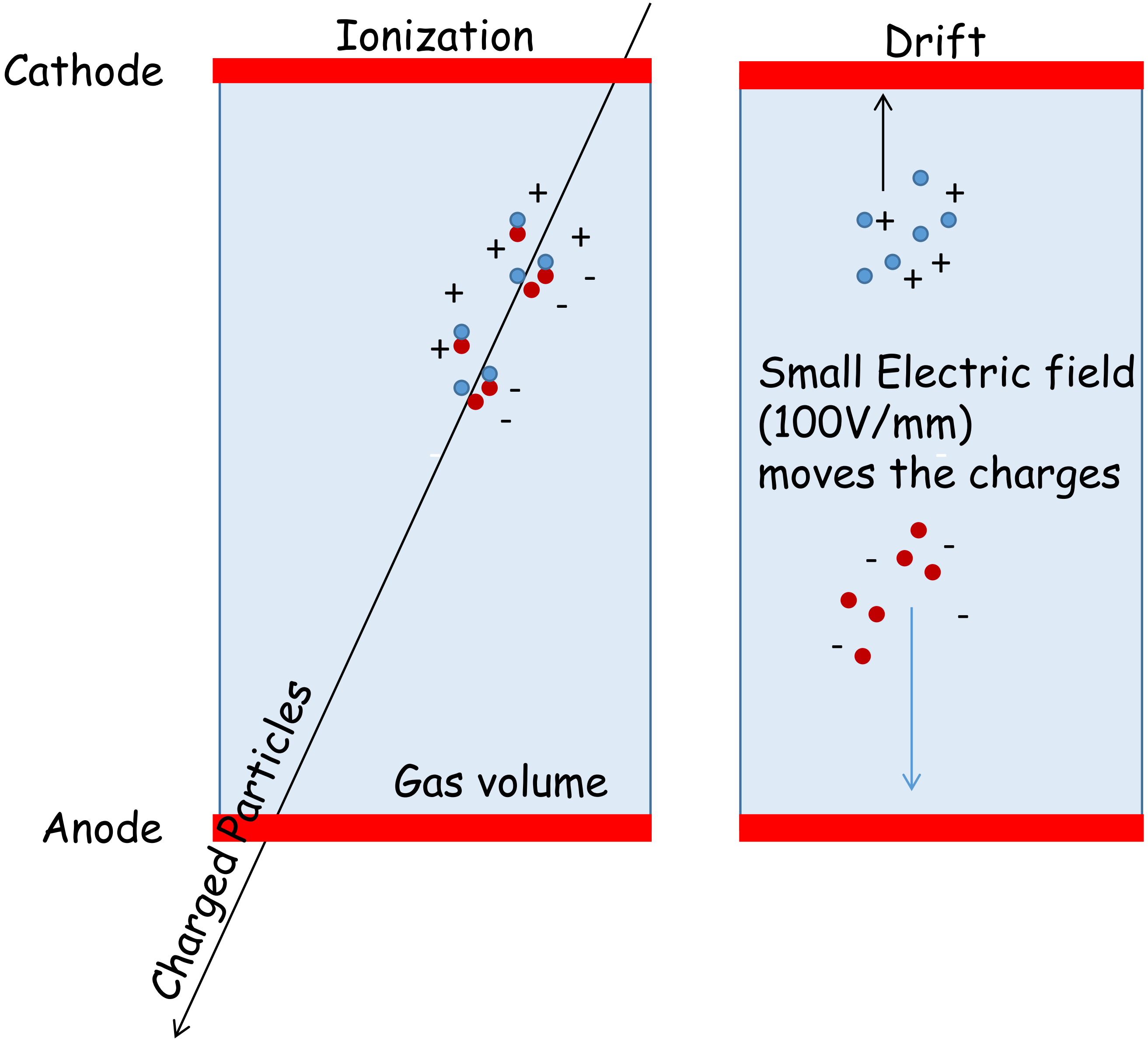
MCM → Multi Chip Module
PCB → Printed Circuit Board

Introduction to Micro Pattern Gas Detectors

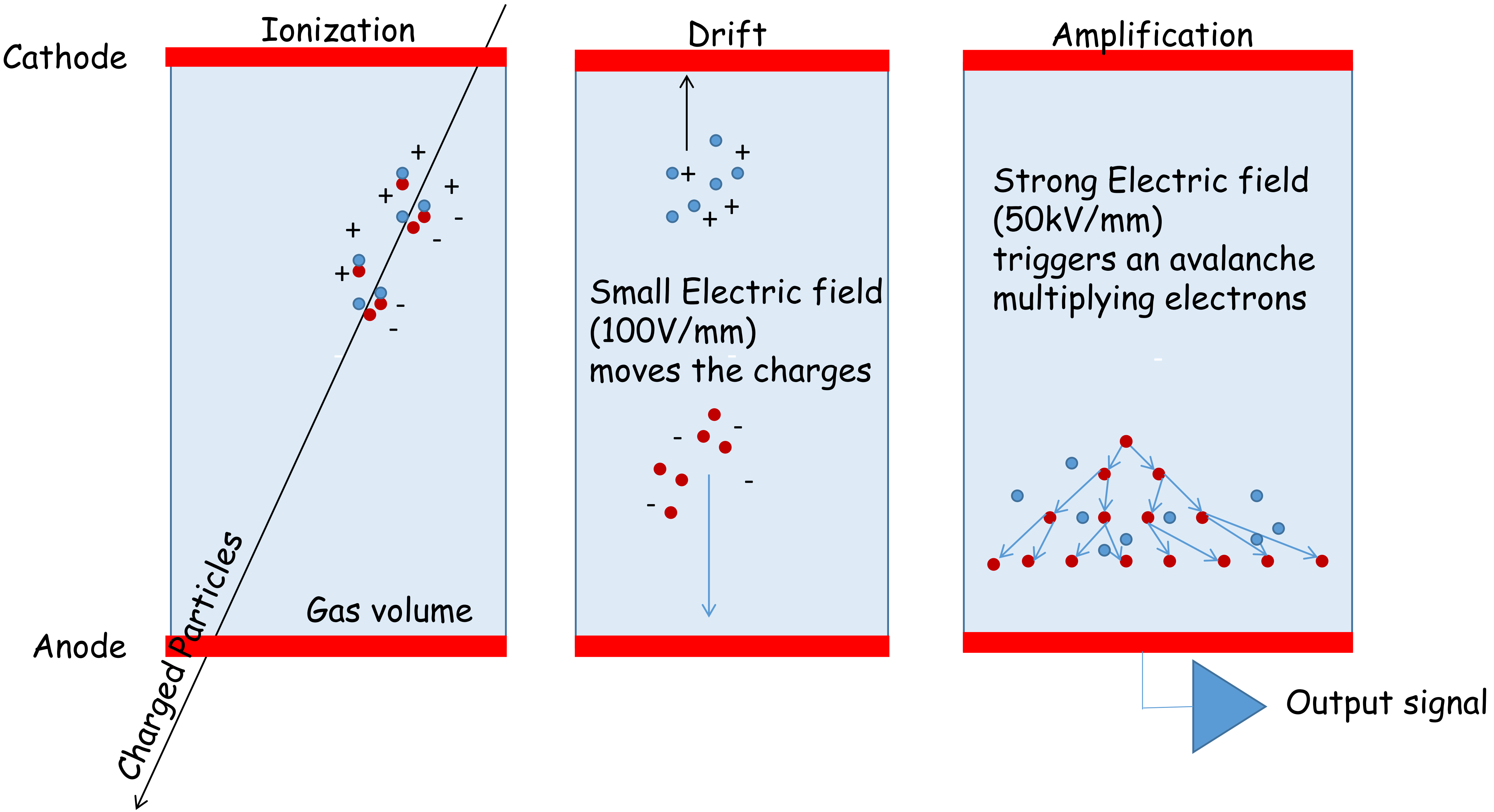
Gaseous detectors principle



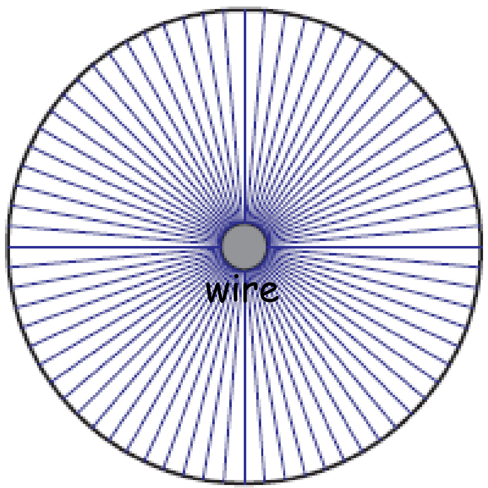
Gaseous detectors principle

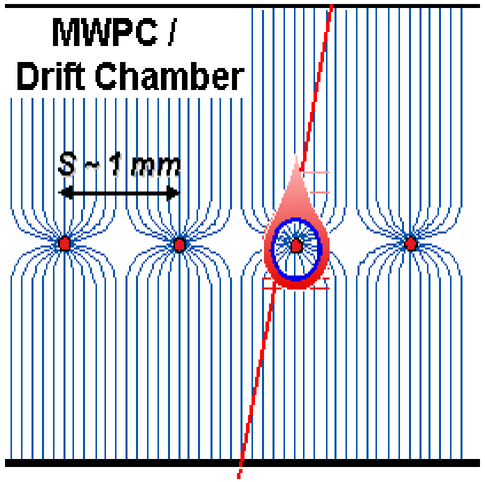


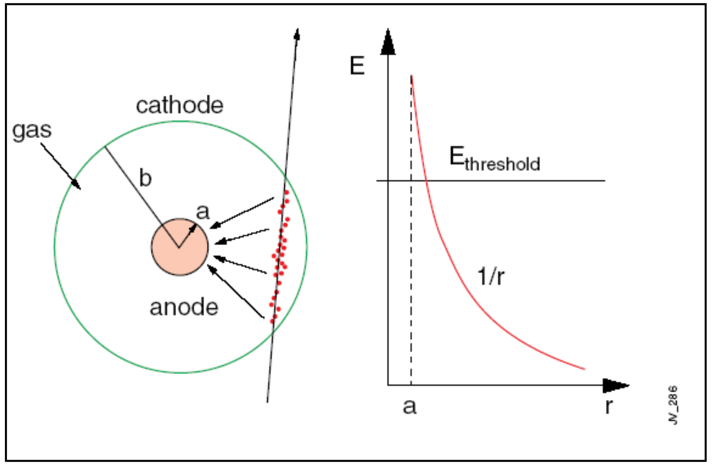
Gaseous detectors principle



Till 1988 Wire chambers







Wire chambers

- Slow ion evacuation.
- Pitch limited to 1 to 2mm causing limited R/O granularity.
- Classical mechanical production techniques.
- Exponential gain, most of the amplification is done in the last micro meters.
- Drift and amplification regions are defined by the field shape.
- Possibility of aging and polymerization.

- 1988 First MPGD

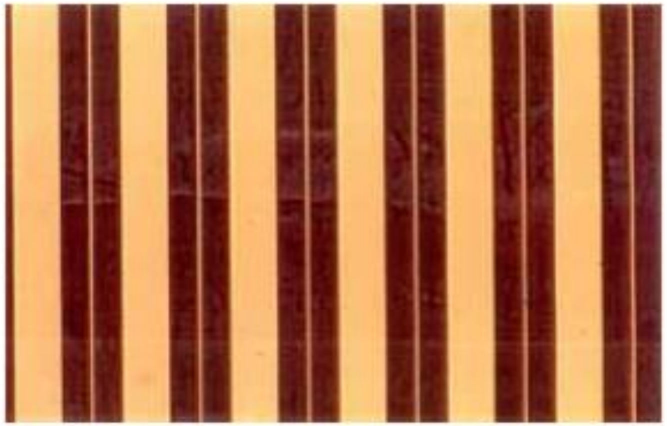
Micro Strip Gas Chamber (MSGC)

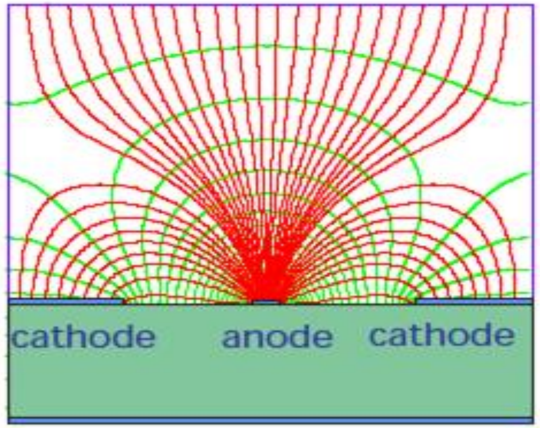
Anode strips of 10 um with a pitch of 200 µm on a glass substrate.

Spatial resolution ~50µm

Rate capability ~10^6 Hz/mm2

MSGC





A. Oed
Nucl. Instr. and Meth. A263 (1988) 351.

- Faster ion evacuation
- Higher spatial resolution
- 100um scale structures
- Photolithographic techniques
- Still exponential gain close to the thin anode
- Drift and amplification field are separated

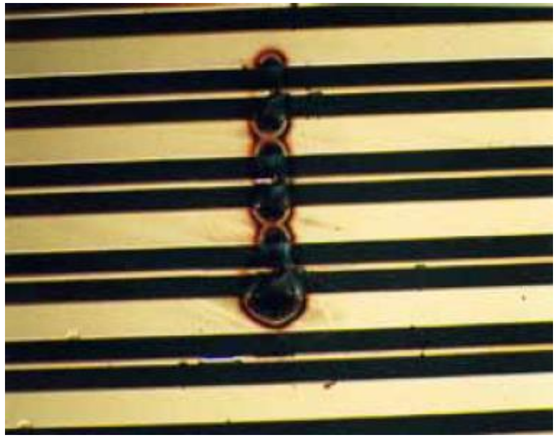
But this device shown some problems in HEP environment

Structure

-less than 1um thick metal

-Mandatory thickness to keep the sub-micrometer precision at the Strips edges

Spark damages



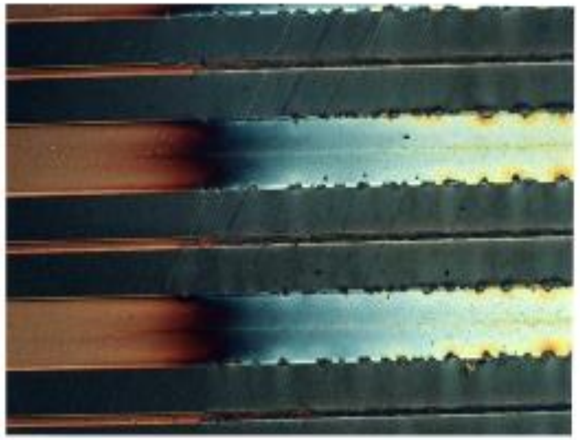
-Triggered by heavy ionizing particles.

-Unstoppable erosion of electrodes.

-Spark energy above the materials capabilities to evacuate it .

-This triggers : evaporation, metal melting, carbonization. Sign of really high temperature processes

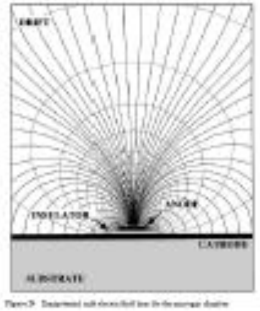
Aging/polymerization



-Creation of surface or dendritic deposits due to complex gas molecules in presence of exponential fields.

- Nineties → First evolution
- Explosion of ideas to solve these 2 defects

Micro Gap Chambers



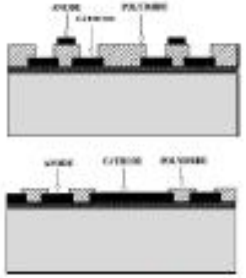


Figure 28 Two variants of small-gap chambers, using thick polyimide ridges to prevent the onset of discharges.

Angelini F, et al. Nucl. Instrum. Methods A335:69 (1993)

Micro Gap Wire Chamber

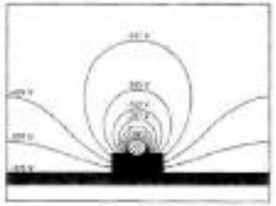
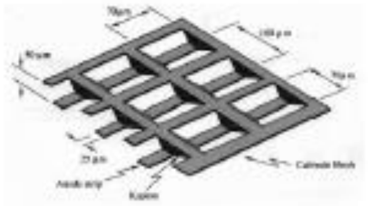


Figure 2.27 Scheme of a MGWC with equipotential and field lines. The circle filled with lines is the section of an anode wire [CHRISTOPHEL1997].

E. Christophel et al, Nucl. Instr. and Meth, vol 398 (1997) 195

Micro Wire Chamber



B. Adeva et al., Nucl. Instr. And Meth. A435 (1999) 402

MicroDot

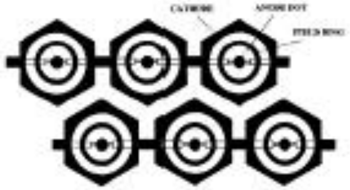
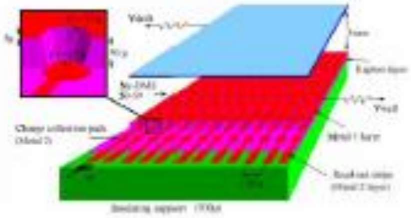


Figure 26 Schematics of the microdot chamber. A pattern of metallic anode dots surrounded by field and cathode electrodes is implemented on an insulating substrate, using microelectronics technology. Anodes are interconnected for readout.

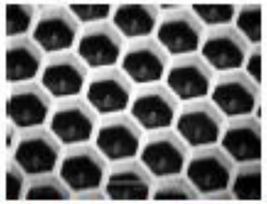
Biagi SF, Jones TJ. Nucl. Instrum. Methods A361:72 (1995)

MicroWELL



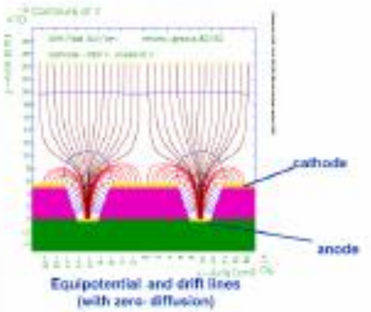
R. Bellazziniet al Nucl. Instr. and Meth. A423(1999)125

MicroPin



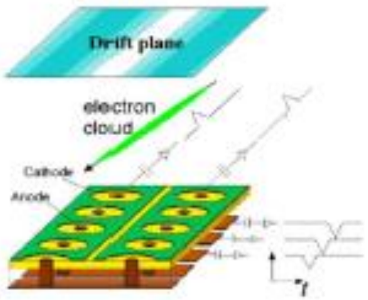
P. Rehak et al., IEEE Nucl. Sci. Symposium seattle 1999

MicroGroove



R. Bellazzini et al Nucl. Instr. and Meth. A424(1999)444

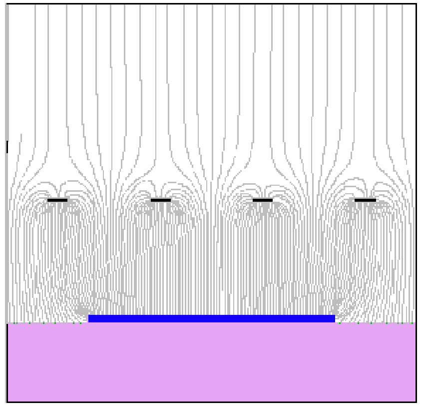
μPIC

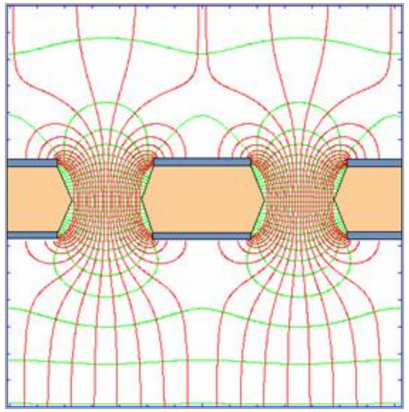


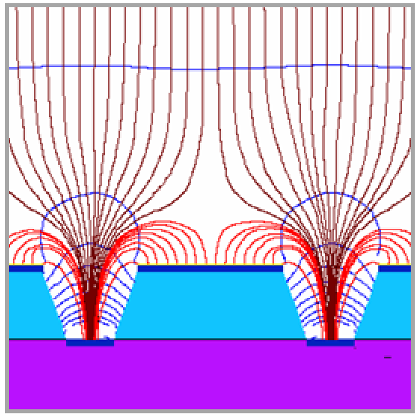
Ochi et al NIMA471(2001)264

AND MANY OTHERS ….

It took a decade, but at the end , 3 structures have emerged !


Mesh with spacers


Holes in Polyimide


Wells in polyimide

The problem of aging and polymerization have been solved by removing exponential fields, in addition to a precise materials and gas selection. Such problems have not been seen anymore.

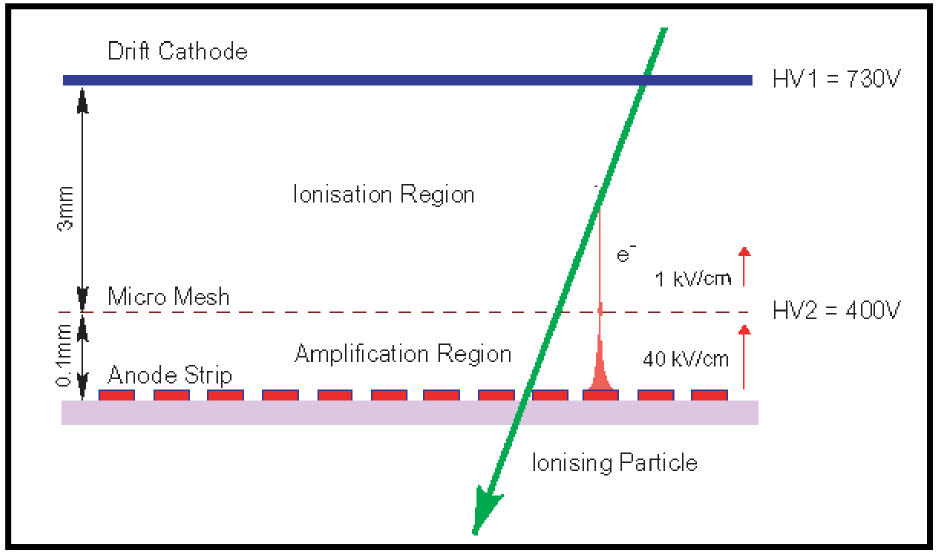
The detectors were more robust against sparks thanks to thicker conductors, but not completely immune.

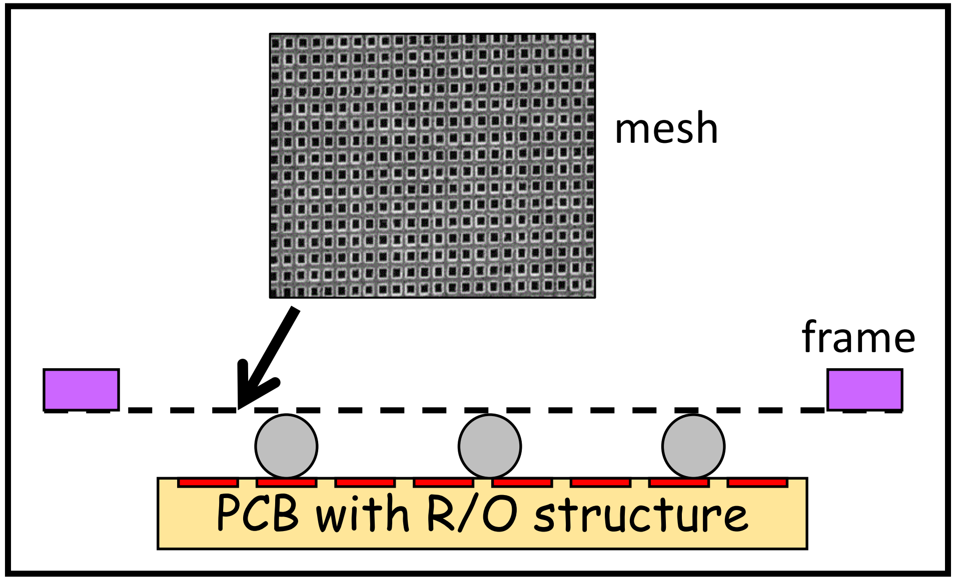
It is interesting to observe that in these 3 options the amplification gaps are precisely defined by industrial materials, not by photolithography:

-Polyimide 50um +/-0.1um

-Photo-imageable coverlay spacer 128um +/-2um

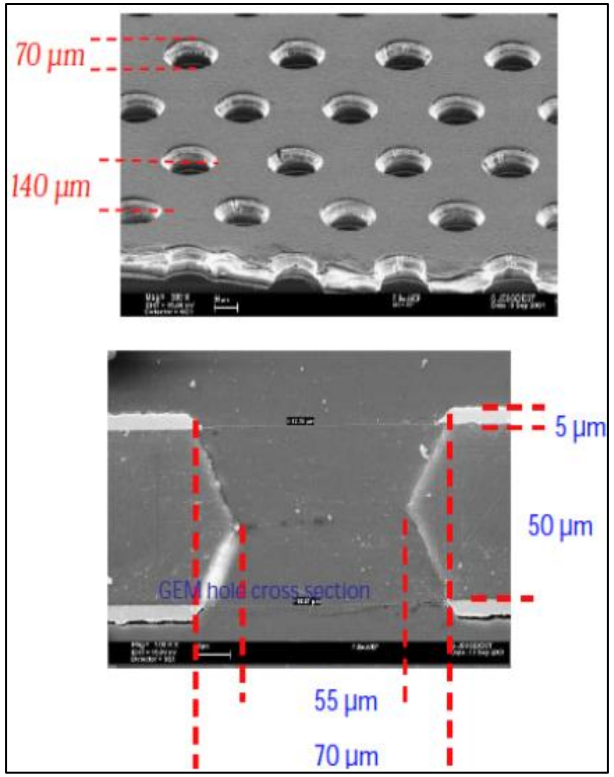
1997→Micromegas (Ioannis Giomataris)

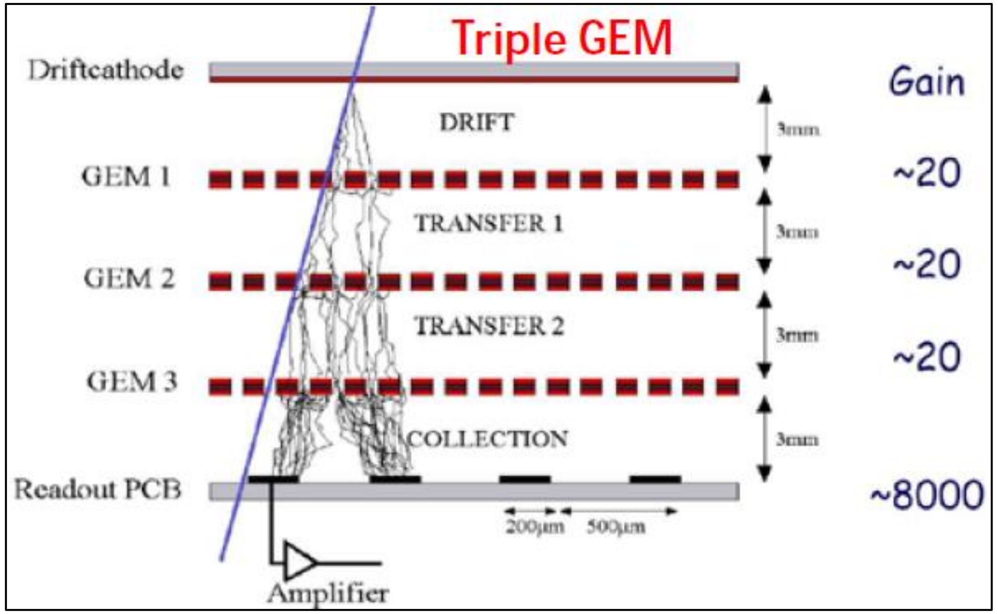




-Electroformed meshes, mechanically fragile.
-Spacers made with fishing wires.
-Delicate artisanal production.
-Special anode strip connection to FE to minimize sparks damages.
-The use of this structure stayed quite confidential till 2007 due to production difficulties.

1998→GEM foil and then triple GEM detector (Fabio Sauli)





Spark problem solved:
→triple GEM structure

Aging problem solved:
→no exponential A-field
→Specific gases
→Specific materials

The amplification gaps are not affected by the detector size.

A GEM is only made with Photolithographic processes. Industrial by nature.

The technology grow was fast.

GEM

•Base material : Polyimide 50um + 5um on both sides

•Double mask

•Single mask

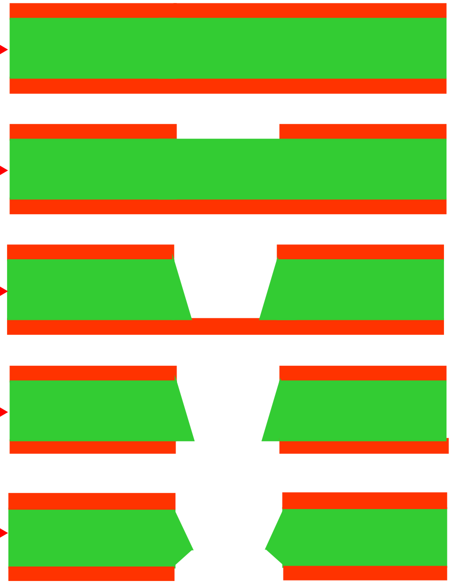
•Same base material

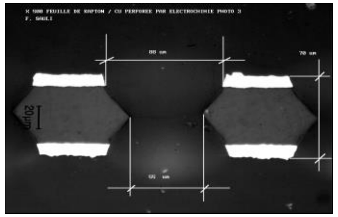
•Hole patterning in Cu

•Polyimide etch

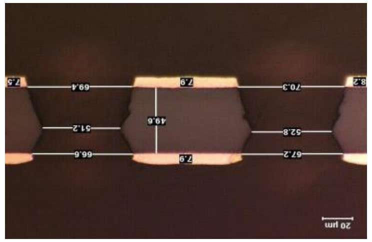
•Bottom electro etch

•Second Polyimide Etch



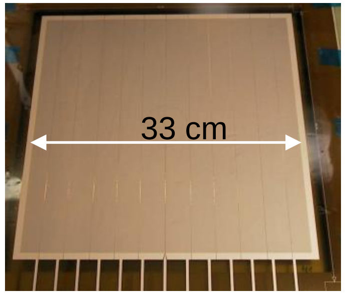


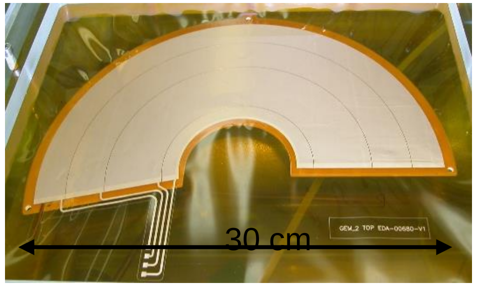
•Limited to 40cm x 40cm due to:
- •The 2 masks alignment precision
- •And Glass mask cost

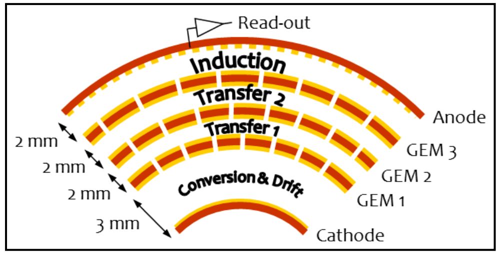


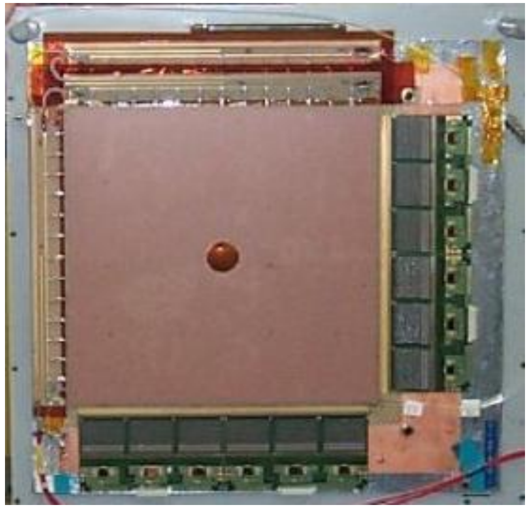
•Limited to 2m x 60cm due to:
- •Base material
- •Equipment

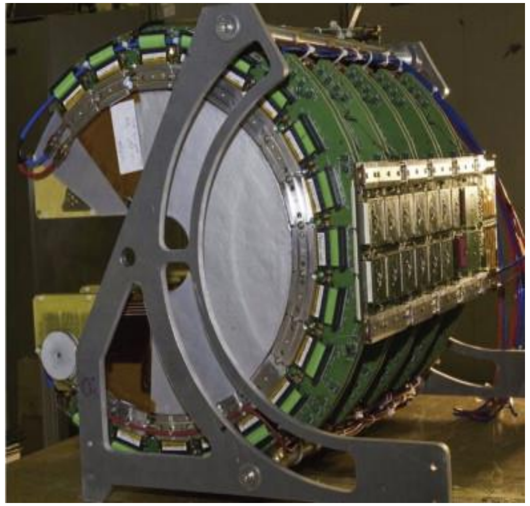
Double mask triple GEM detector

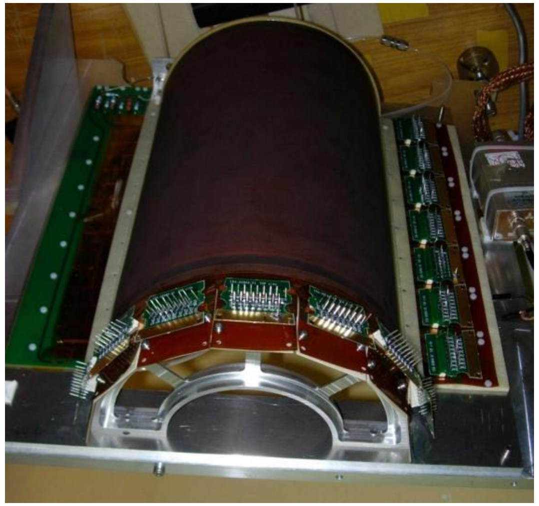


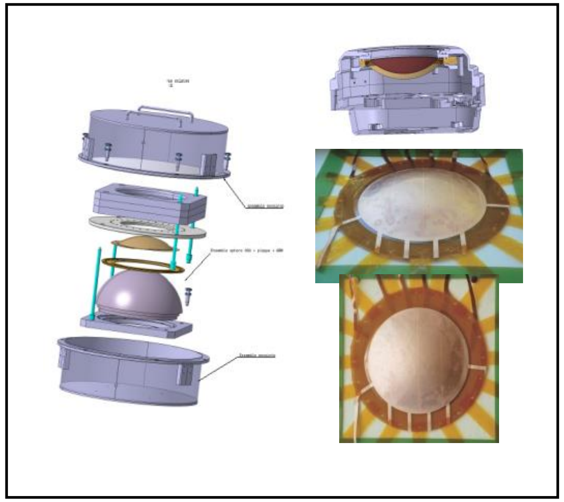












COMPASS
Settled all the parameters:
- GEM Segmentation
- HV distribution
- X/Y Read out board
- FE electronics

TOTEM
30cm diameter

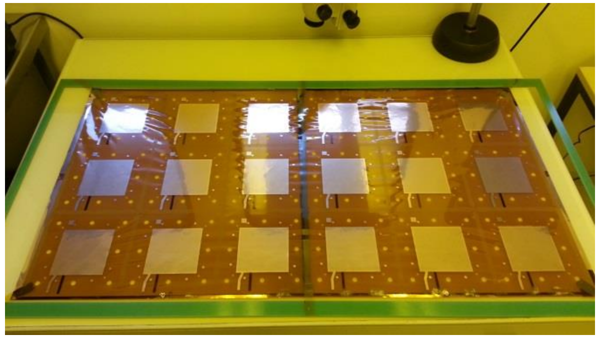
Cylindrical R&D
40cm x 40cm

Spherical GEM R&D
for X-Ray diffraction
application

“Single mask” was introduced to make larger detectors and reduce the cost

0.6m

1.8m



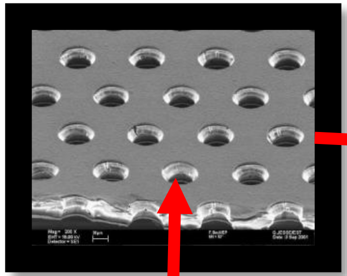
A 10cm x 10cm double mask GEM costs 300 $/piece.

For 100 single mask GEM the cost drops to 100 $/piece.

For 10 000 pieces , less than 50 $.

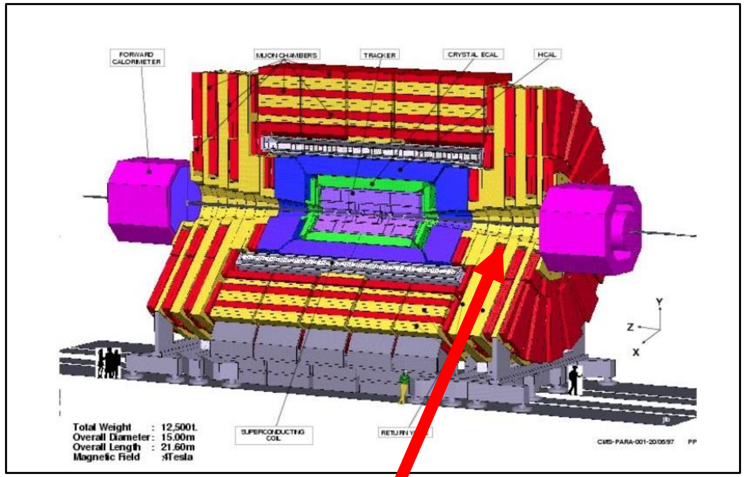
There is ways to even go below for Larger quantities!

CMS upgrade with single Mask

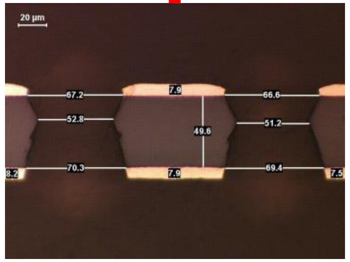


Microscopic view

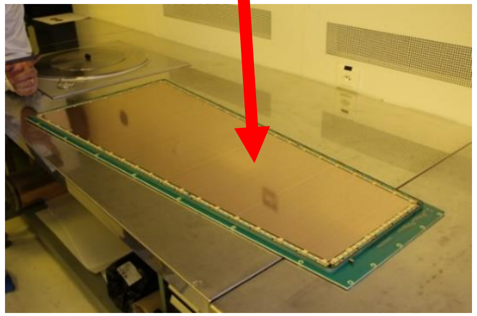
Single mask GEM



CMS experiment

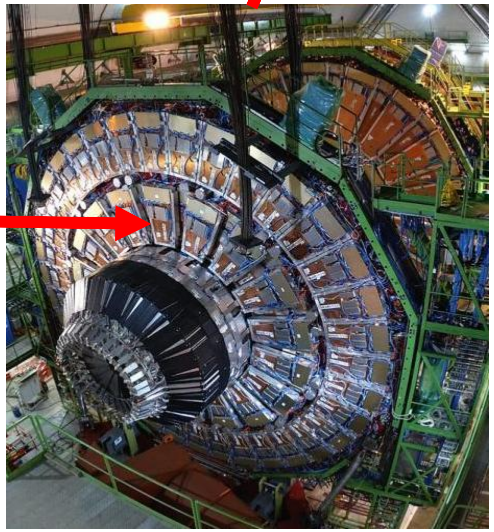


Cross section



Triple GEM stack

GE1/1 Muon detector



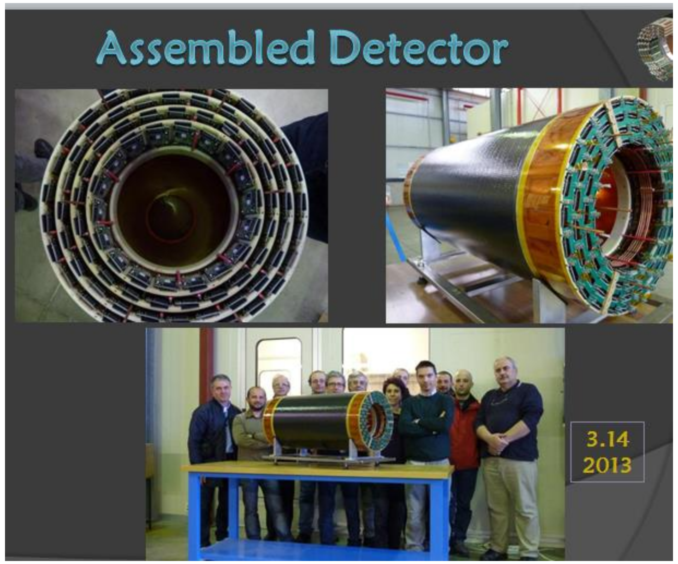
CMS nose

GE1/1 → 400 GEM (1.3m x 0.5m) made at CERN
GE2/1→ 1000 GEM (1.3m x 0.5m) CERN/Korea

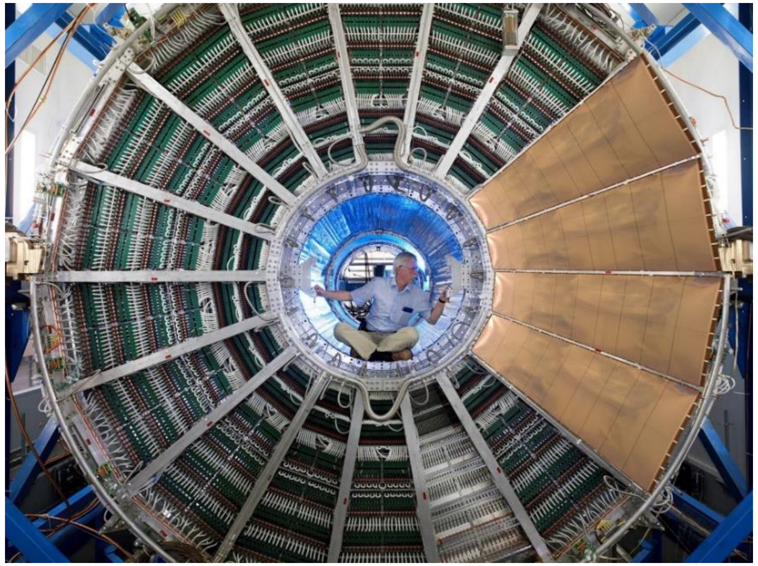
GEM producers' capabilities:
-CERN MPT : 500m2/year
-Mecaro Korea : 250m2/year

Other detectors with single mask technique

Future CMS ME0 → 1000 GEMs



KLOE – Cylindrical Detector



ALICE TPC → 700 GEM

And many more

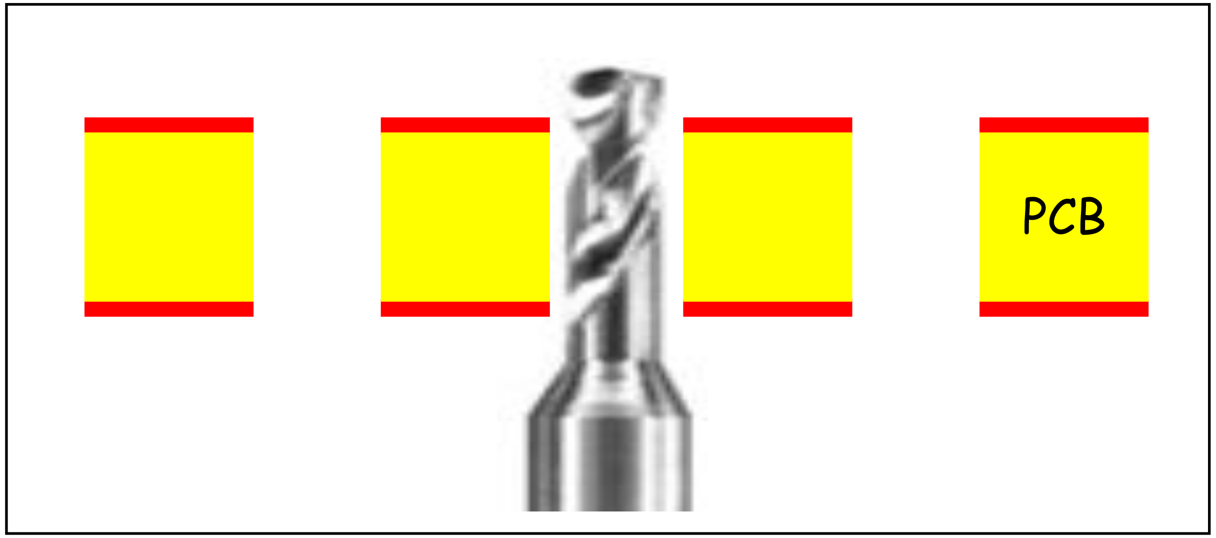
-BM@N in Dubna (1.6m x 0.5m)
-SBS tracker Jefferson lab
-CBM at Fair
-BESIII China

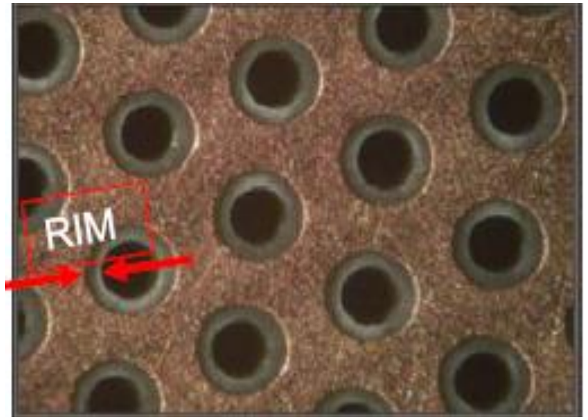
-SOLID
-BONUS 12
-P-RAD
-S-Phenix TPC

-COMPASS upgrade
-GEM for nuclear physics TPCs
-ESS for neutron detectors
-and lot of small GEMs for academic purpose

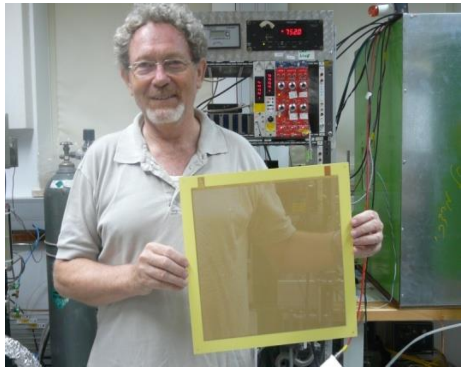
1998→first LEM or THGEM (Pio Picchi)

Mechanical Drilling : FR4, PMMA etc..
More recently:
Sand blasting on glass
Photo imaged glass





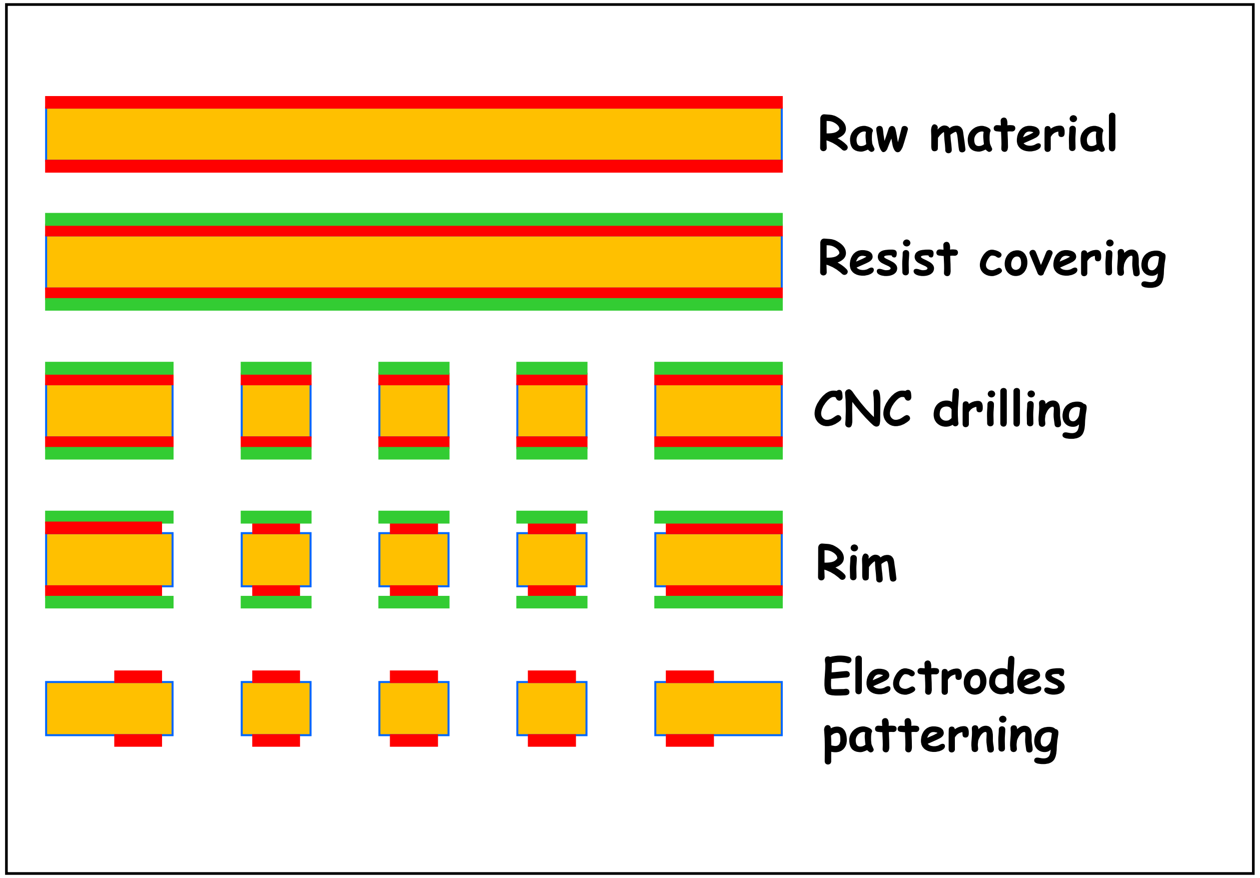
Eltos (IT)
Hold by
Fulvio Tessarotto



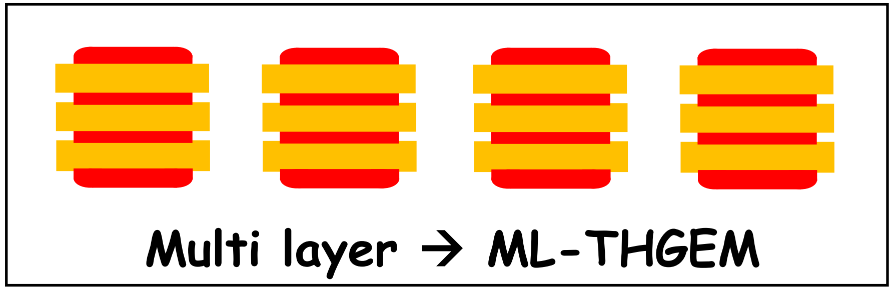
Print electronics (IS)
Hold by
Amos Breskin

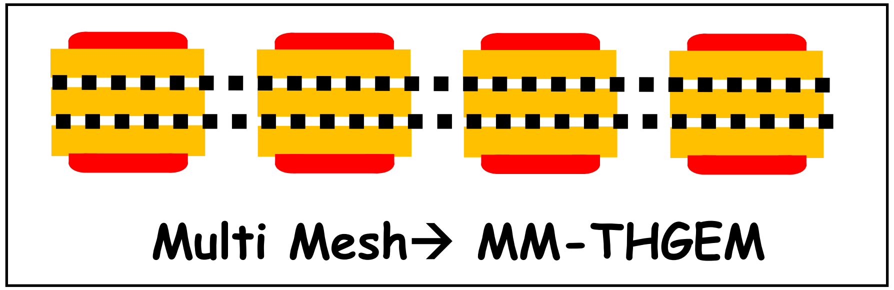
CERN
Hold by
Serge Ferry

RIM creation

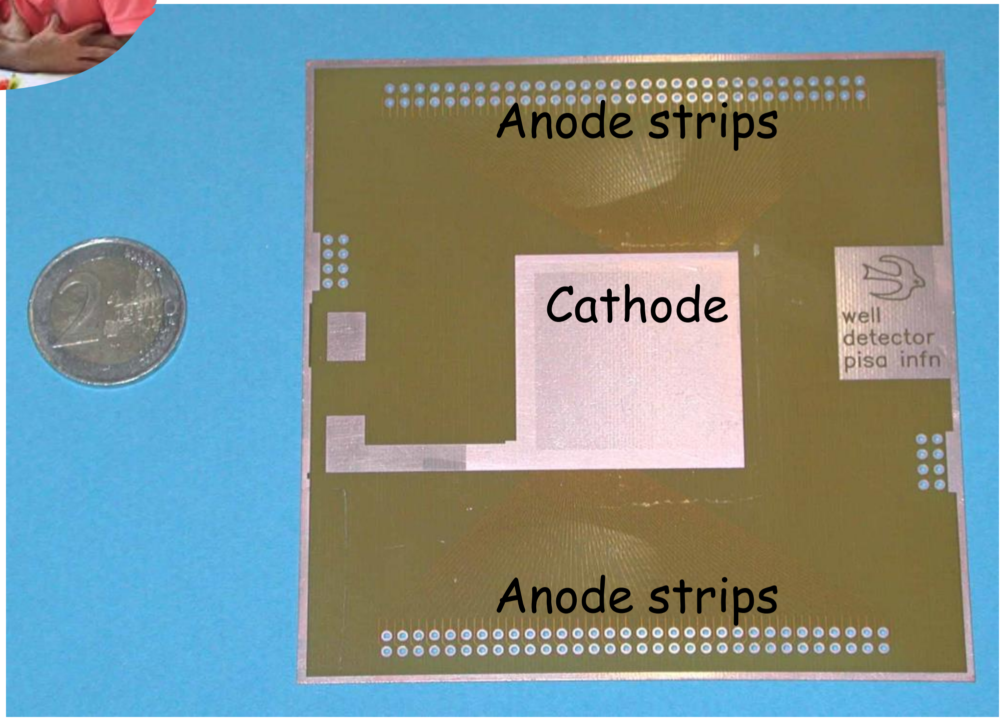


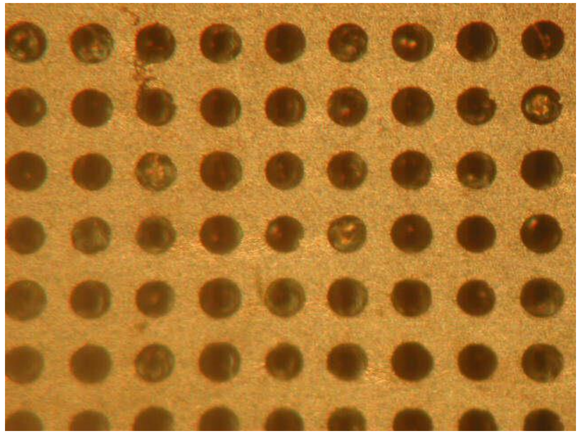
Other types of THGEMs

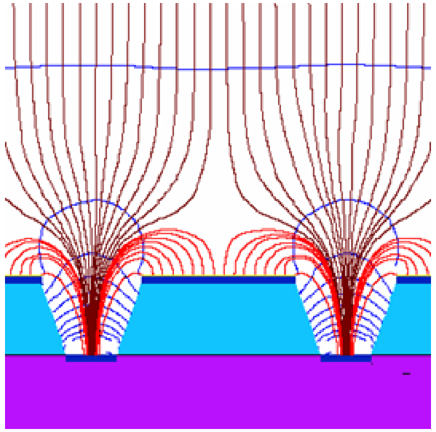




1999→Micro-Well (Ronaldo Bellazzini)

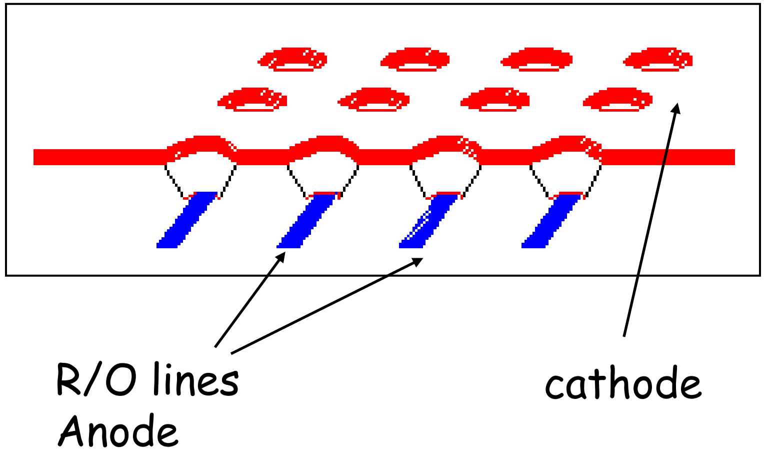




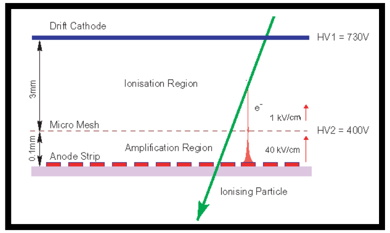


Close-up view
Square pattern used
in the early days

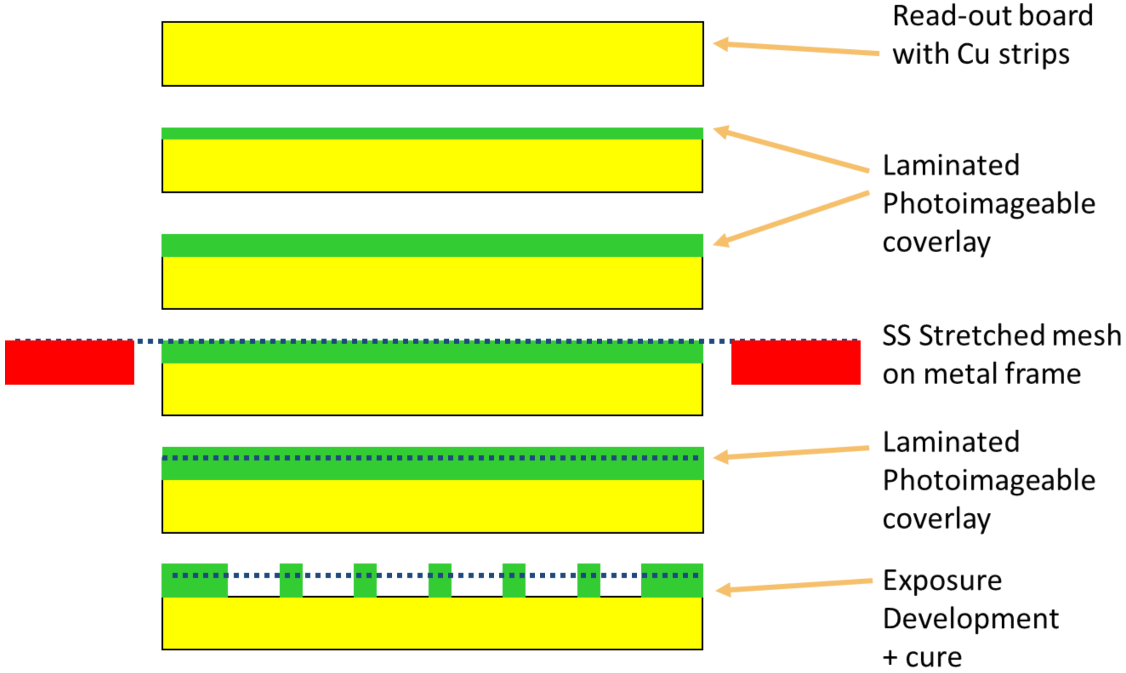
- -3 x 3 cm Micro-well detector
- -Produced at MPT with GEM processes
- -Really simple but abandoned due to the difficulty to mitigate sparks

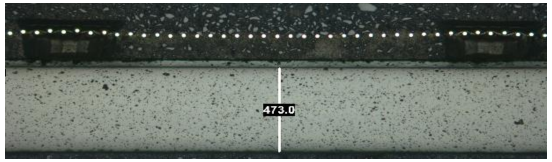


2007→A better process was found to produce MM

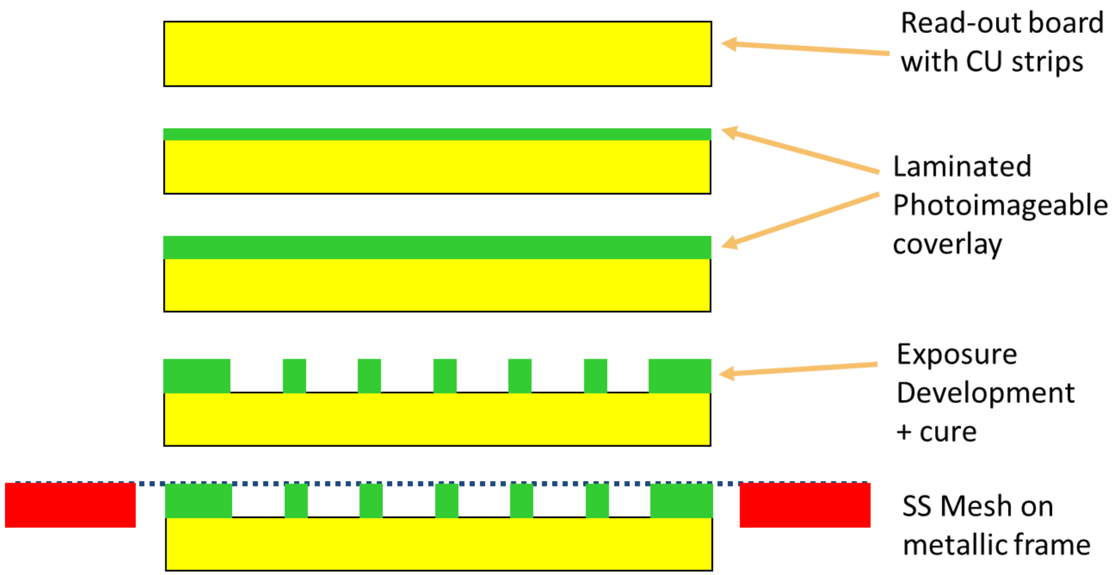


BULK Micromegas

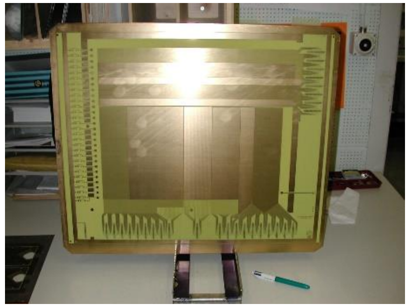




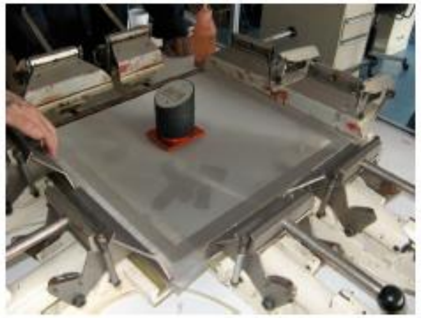
Floating mesh Micromegas

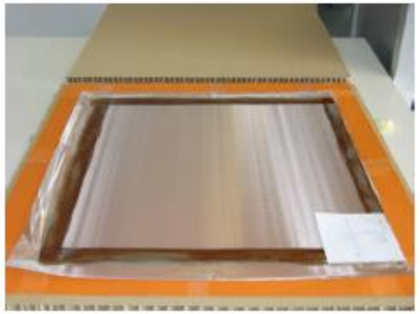


The detector behavior was really good !
The production was easier, repeatable and using industrial processes.
The technology spread was then rapid.



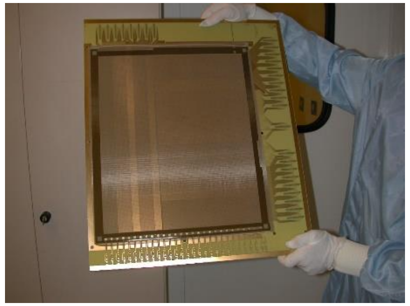
Read-out board





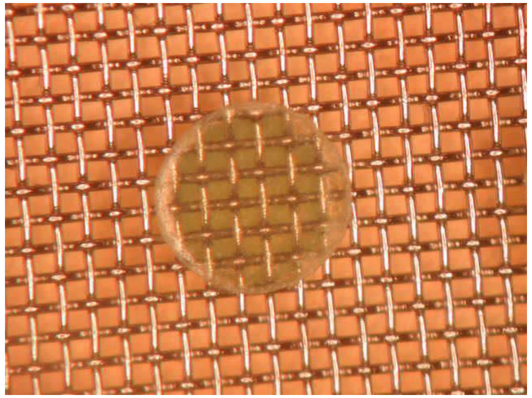
Mesh stretching
& gluing on frame

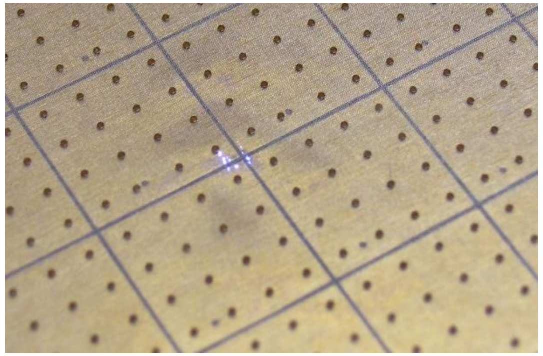
Coverlay lamination



Detector developed / cured / tested

400um pillar

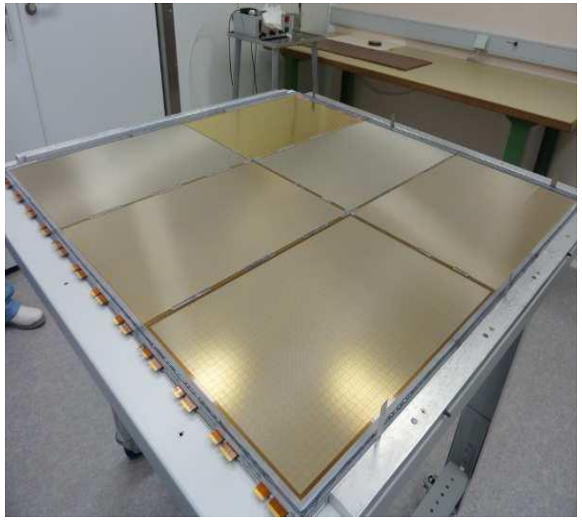




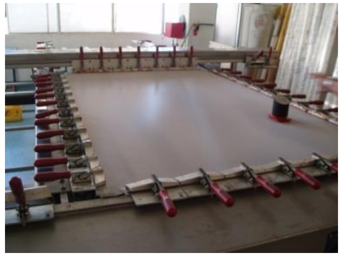
Pillar matrix
on 1cm x 1cm pads

BULK Micromegas detectors

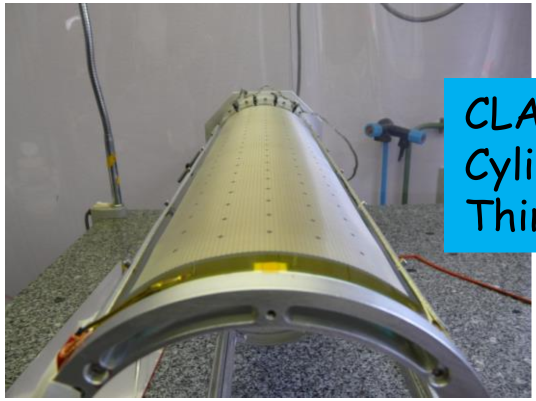
T2K TPC ,J.Beucher
1.8m x 0.8m plane
With 12 detectors



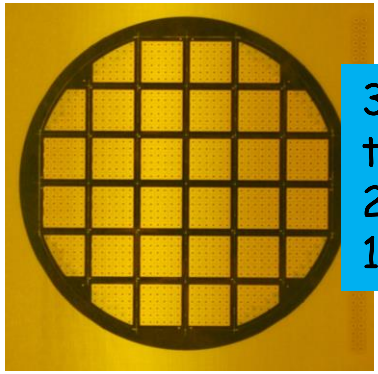
ILC DHCAL , M.Chefdeville
1m x 1m plane
With 6 detectors



Early ATLAS NSW R&D
Joerg Wotschack
1.5m x 0.5m plane
Single panel



CLAS 12
Cylindrical Micromegas bulk
Thin substrate



33 sectors , 12cm diameter
test detector
2.5mm dead space for sectorization
1mm hole for HV connection

- 2012 Second evolution
- Resistive layer introduction.

  A long path, I think not yet fully explored !

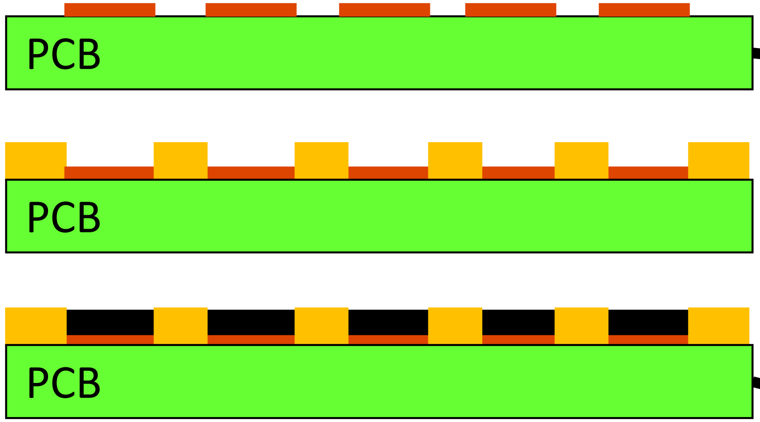
In 2012 during the early phase of ATLAS NSW R&D we faced a new problem.

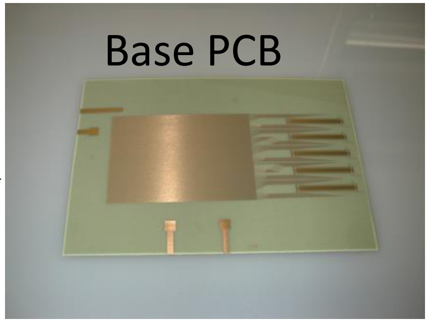
With LHC background the single amplification stage large MPGD's were continuously sparking, they were not damaged but simply constantly stopped due to the spark rate

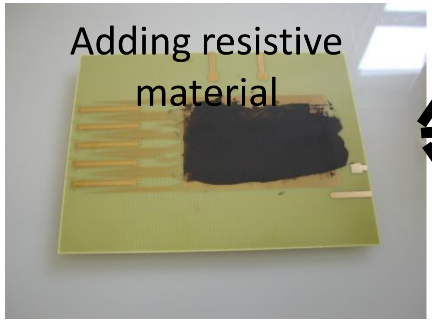
In close collaboration with Joerg Wotschack we decided to introduce resistive layers.

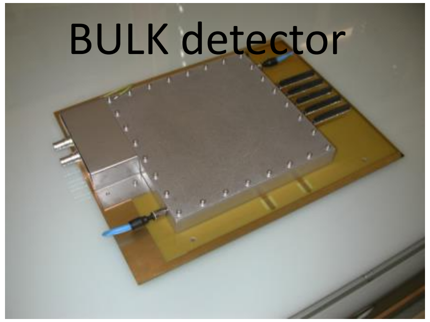
It took us 12 iterations to understand how to solve the problem adding resistive layers

First but bad idea : Cover the R/O lines with Resistive material

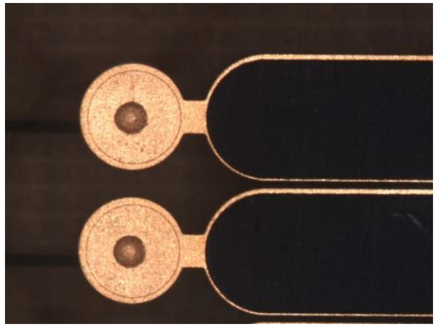


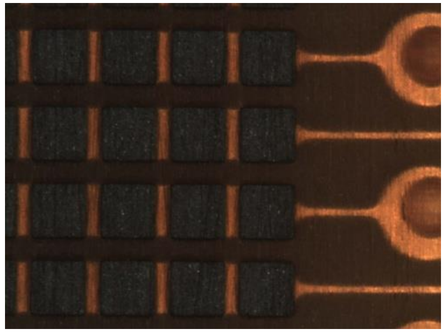


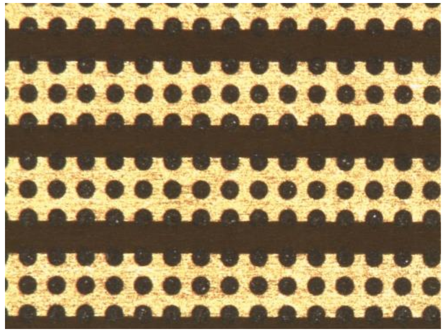




8 configurations tested !



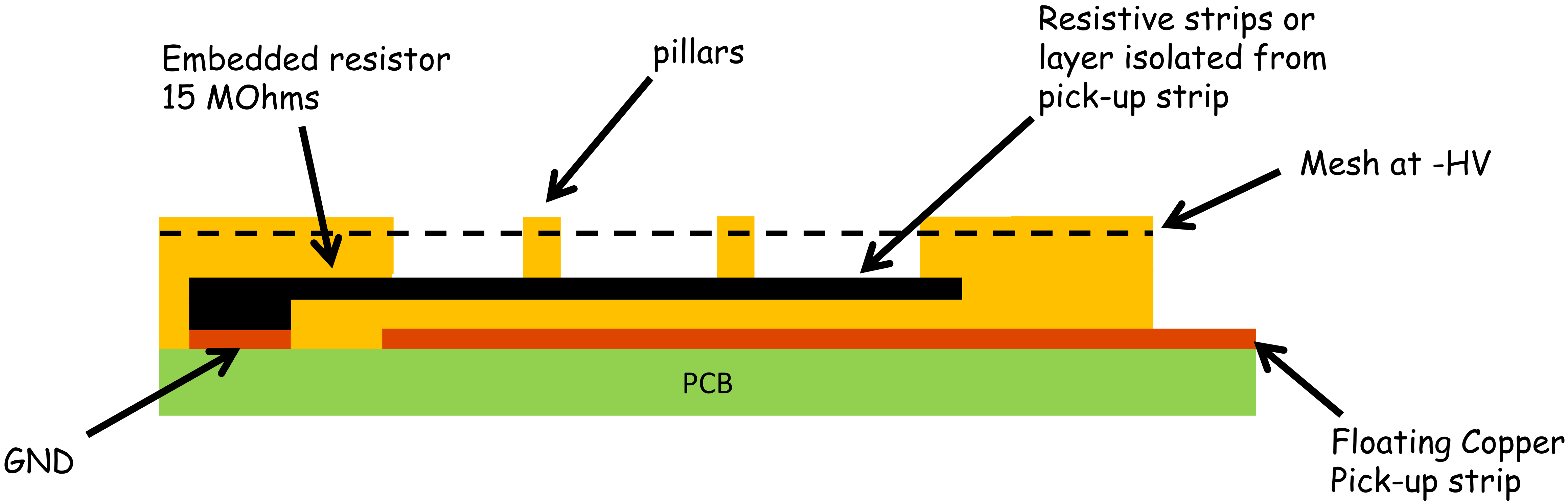




Test : apply a voltage above the breakdown voltage of the Air, with a really high current limitation of 10mA and see if the detector can quench the spark on its own.

All detectors died within a sec !
- Vertical resistive layer breakdown
- Massive mesh melting

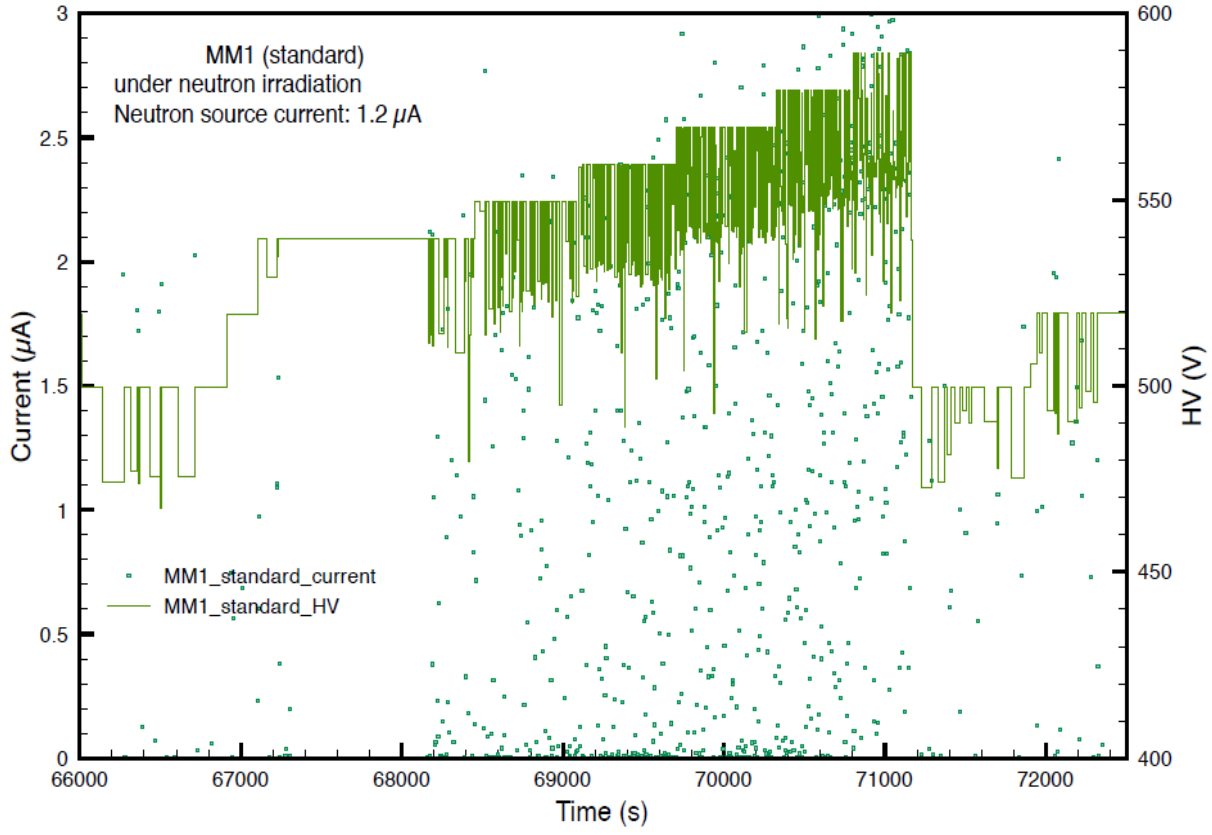
And finally, after 4 more trials!



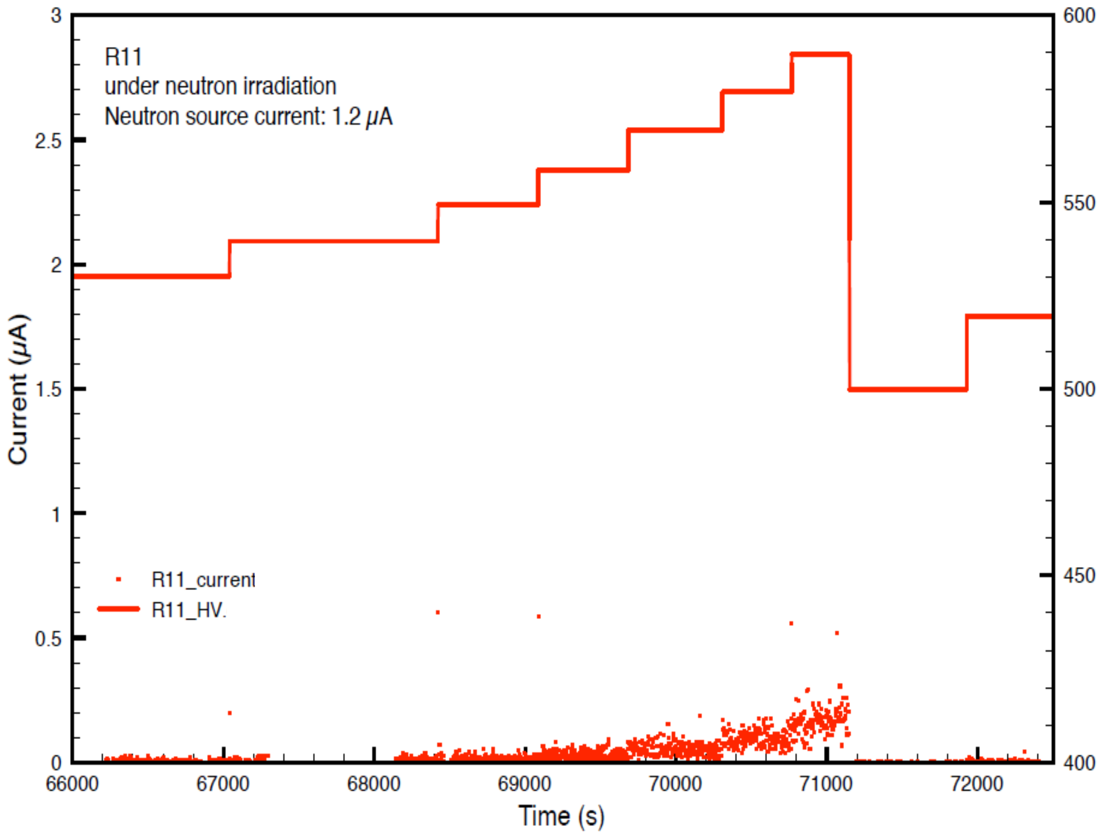
Perfect behavior, the structure is quenching the sparks on its own.
This helped us to validate our electrical model and
understand precisely how to control the spark energy

Validation with Neutron irradiation

Without resistive layer

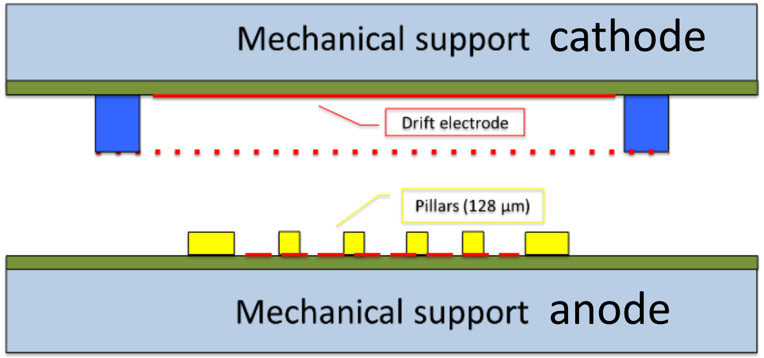


With resistive

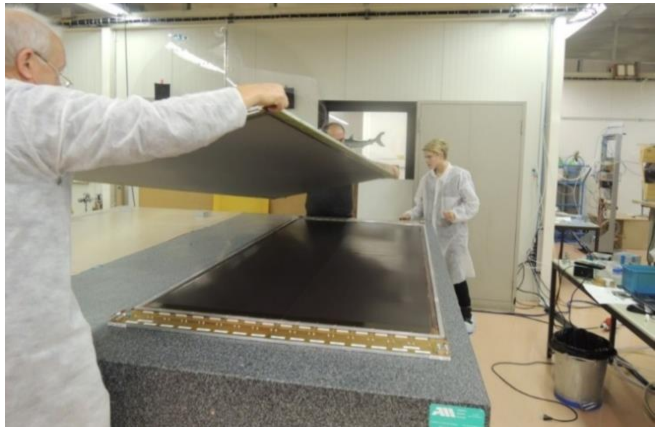


ATLAS NSW prototype 1m x 2m → Floating mesh

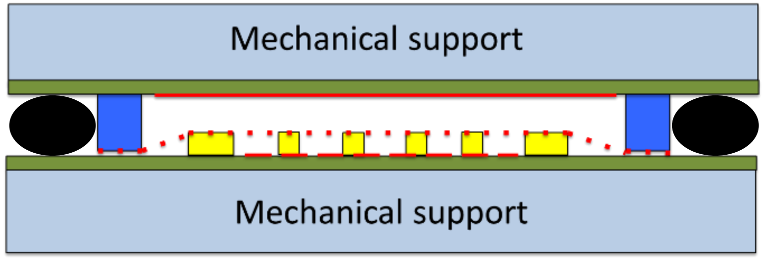
Open



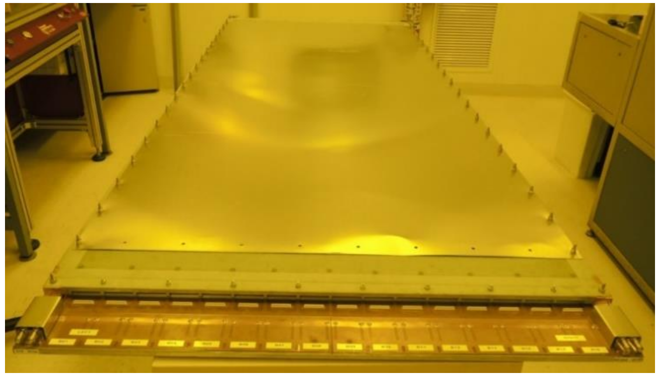
Open



Closed

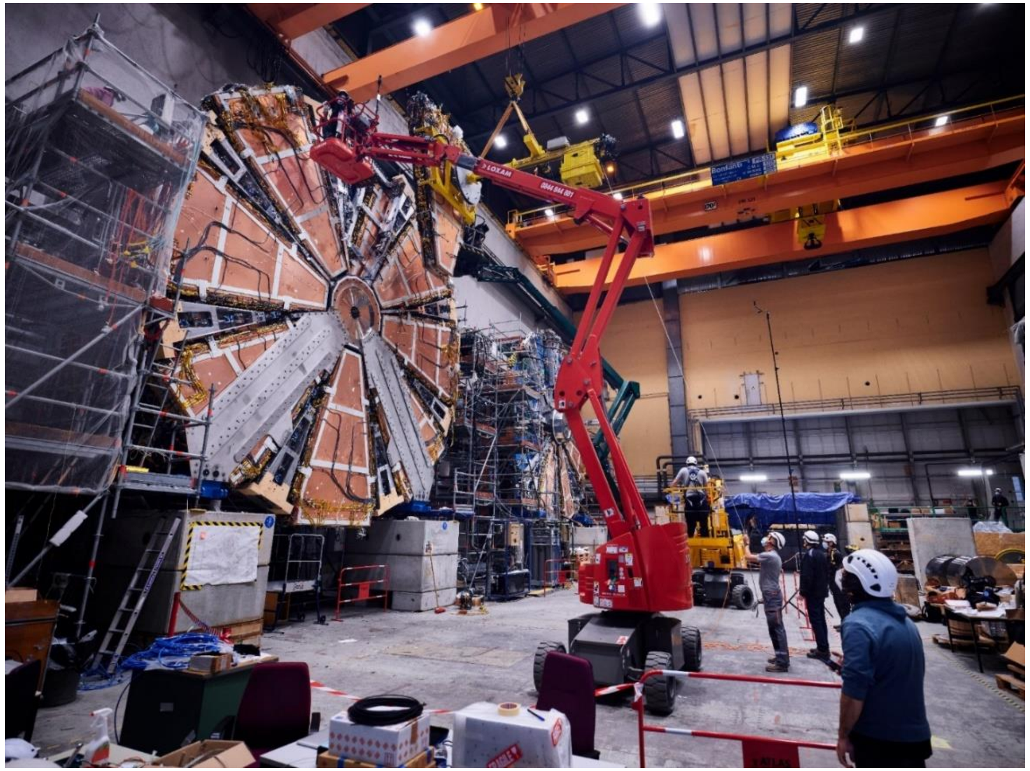


Closed



Atlas NSW

Joerg Wotschack



Close to 2000 Micromegas detectors produced with modules sizes up to 2m x 0.5m

PCBs with pillars built at ELTOS (IT) and ELVIA (FR)
Panels construction and detector Assy :

- Dubna
- INFN Frascati
- CEA Saclay
- LMU Munich

MPT participated to the R&D and was also involved in the mass production with industry

- Specification
- Companies selection
- Technology transfer

Right after we did a Survey on existing resistive layers to take a direction for the future

Polymer paste 10Kohms to 100K/Square	Too low values (but strips can artificially increase the value)
RuO Thick film paste 10K to 100M/square	Perfect range , but a ceramic substrate is mandatory
Resistive ceramics or glass	Limitation on resistive values and size
Resistive Kapton	Limitation on resistive values
Dissipative films	Too high values
DLC: Diamond Like Carbon	Perfect range 100K to 1T→ chosen direction

A Large collaboration inside RD51 was raised :

USTC

INFN Frascati

Lanzhou institute

Study:

DLC deposition

Detectors production

Detectors characterization

Aging

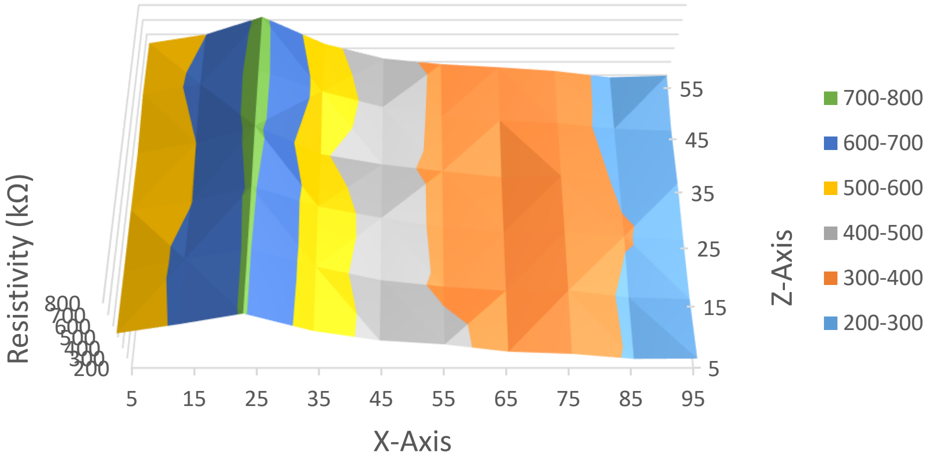
DLC producers

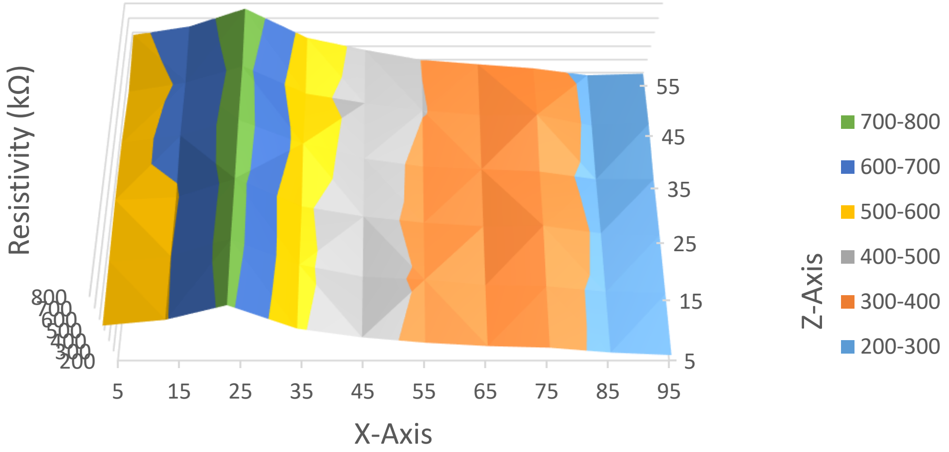
Kobe

ESS

Lanzhou institute

And now
CERN





Initial results: example of 1m x 0.6m foils 500Kohms/square +/-60%
The error dropped today to values around +/- 30%

First benefit coming with resistive layers : Spark protection

- Spark energy : ½ CV2
  - 600 uJ in a 10cm x 10cm GEM.
  - 30 uJ with a classical MM 10cm x10cm.
  - 0.06 uJ (10M resistive layer).

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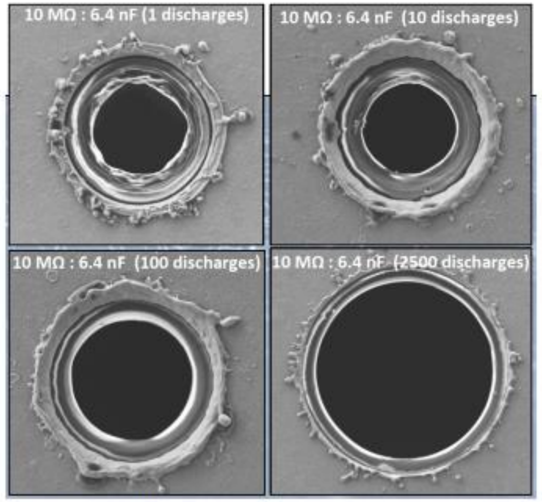
No structural defect
No process above 100deg
No effect on metals or Polymers



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https://indico.cern.ch/event/709670/contributions/3008626/

Massive structural effects
Metal melting
Kapton evaporation
Processes happening above 1000 deg

But thanks to Triple GEM structure
This is not happening

First benefit coming with resistive layers : Spark protection

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No process above 100deg
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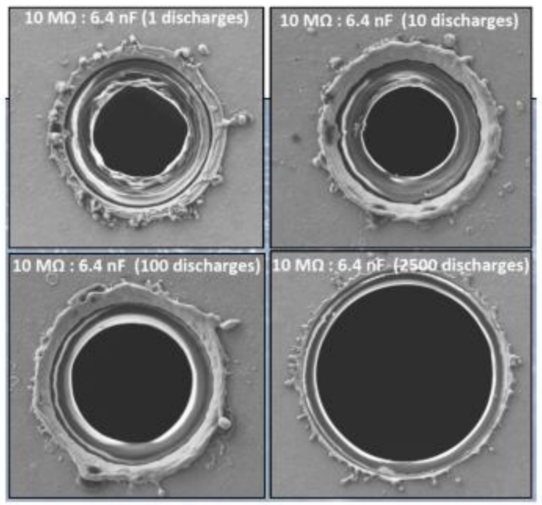

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https://indico.cern.ch/event/709670/contributions/3008626/

- Below 10M/square.
  - We can still create some visible compounds.
  - There is still enough energy to slightly deteriorate dielectrics.

Massive structural effects
Metal melting
Kapton evaporation
Processes happening above 1000 deg

But thanks to Triple GEM structure
This is not happening

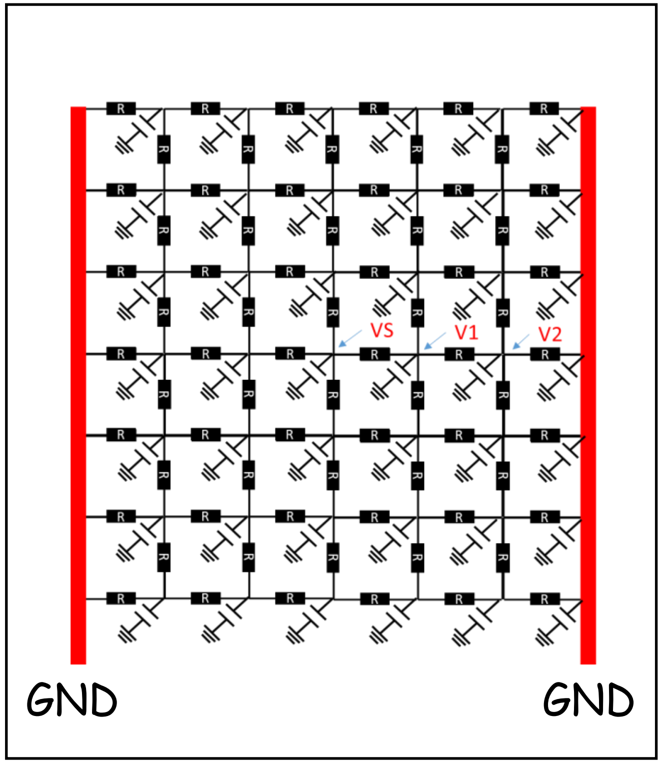
- Above 10M/square
  - No visible compounds.
  - The structure is never damage.
  - Low Humidity and High cleanliness is mandatory !

- FE electronics input protections are not needed anymore

second benefit : Resistive spreading

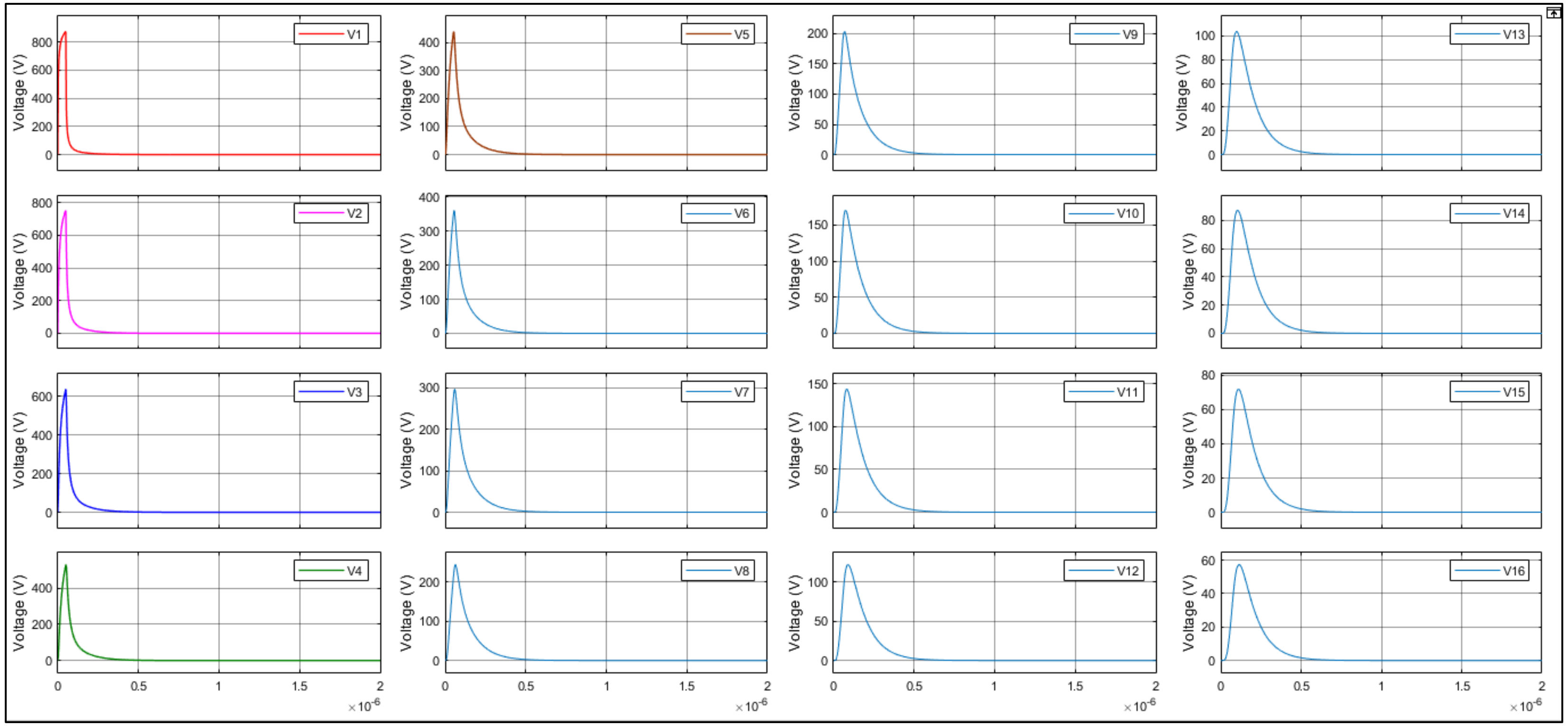
spice simulation Virginia university collaboration

Resistive layer model

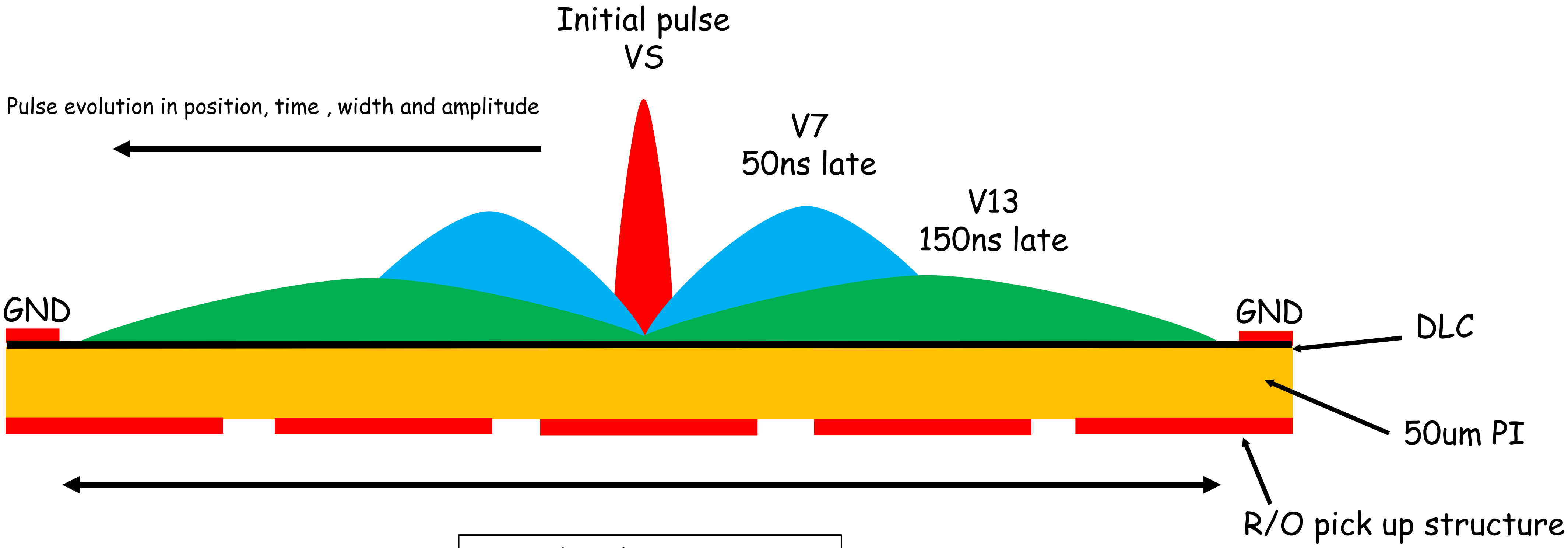


1600 cells
0.125mm x 0.125mm

Pulse amplitude and time shift with a 1MOhms/SQR layer

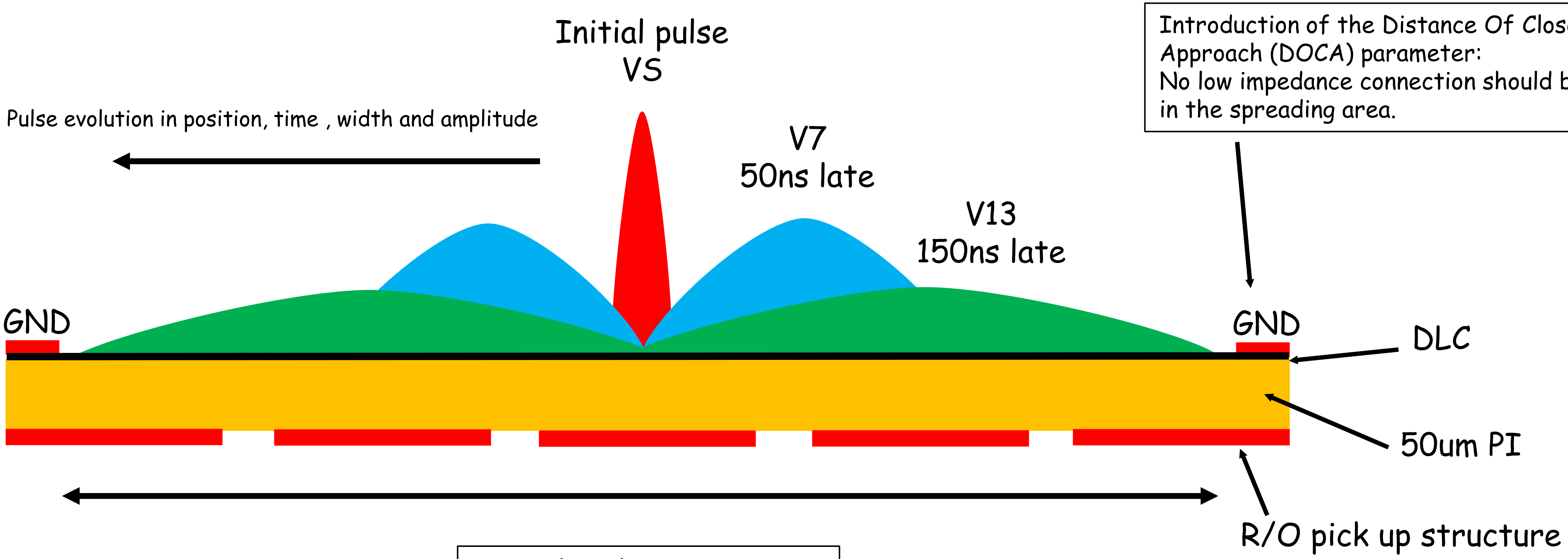


Resistive spreading



Spreading diameter
- -3mm for 1M
- -1.25mm for 10M
- -0.25mm for 100M
- -less than 0.1mm for 1G

Resistive spreading



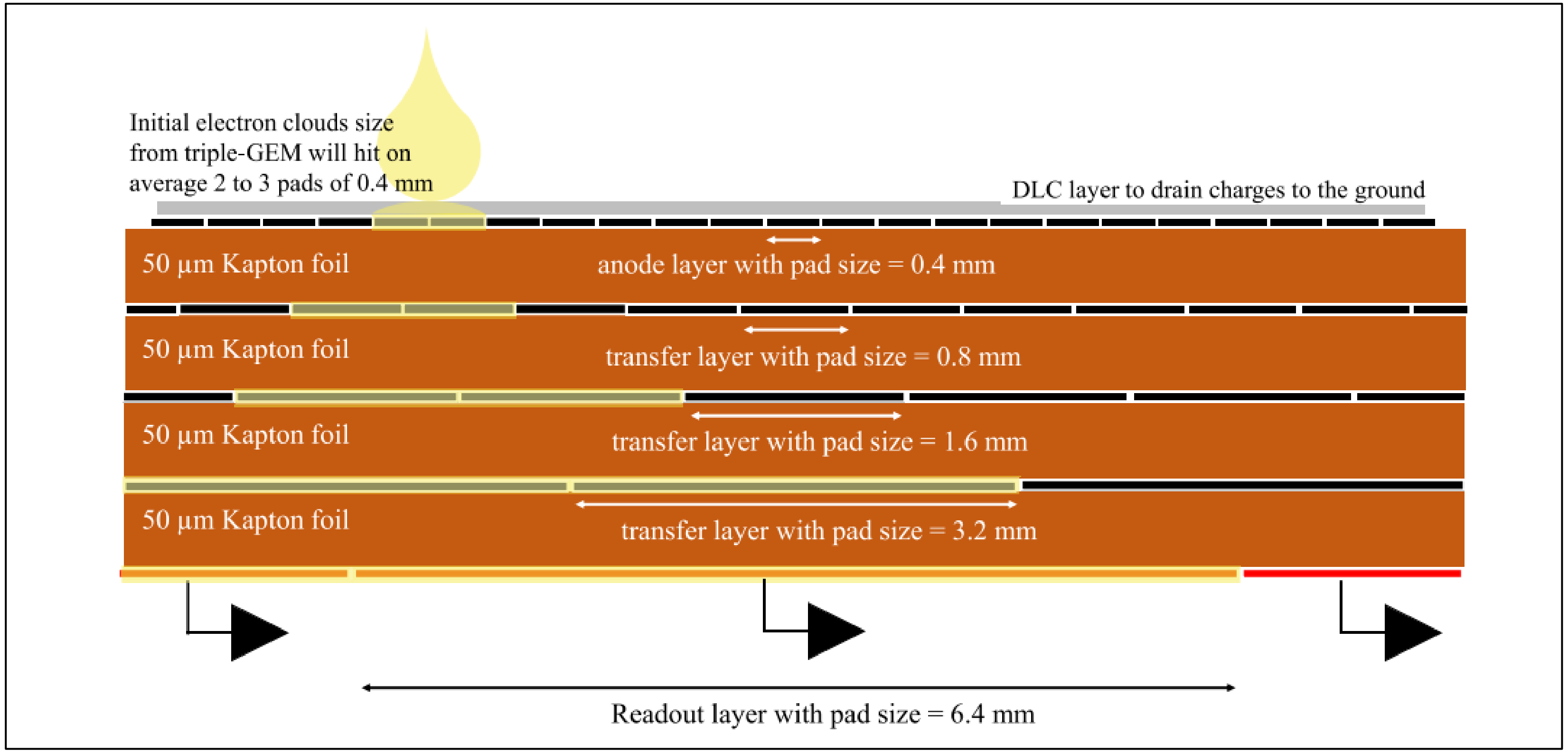
Introduction of the Distance Of Closest Approach (DOCA) parameter:
No low impedance connection should be done in the spreading area.

Problem if you want to have a large spreading and good protection !

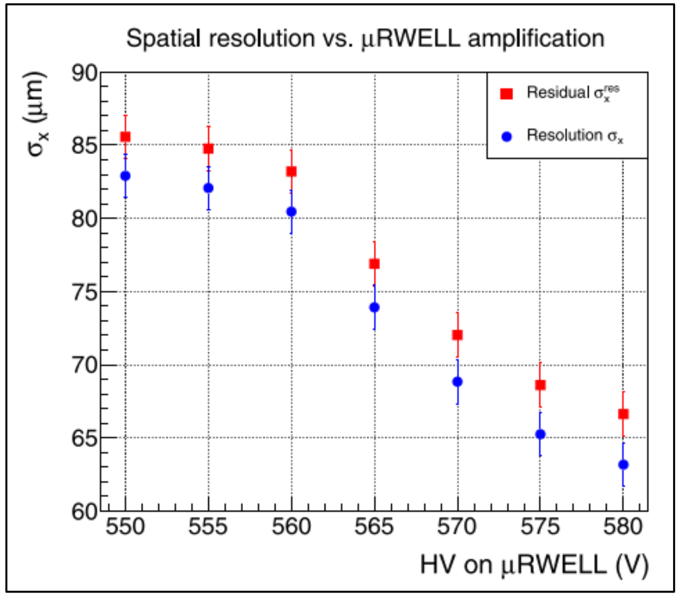
Spreading diameter
- -3mm for 1M
- -1.25mm for 10M
- -0.25mm for 100M
- -less than 0.1mm for 1G

Third benefit : Possibility to do capacitive sharing

- This is the solution to keep a large spreading keeping high resistive value !
- The pulse is transmitted without delay.



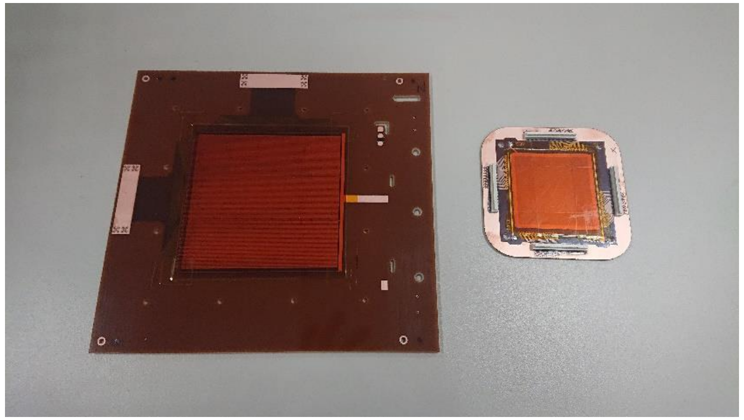
uRwell with CS sharing layer
0.8mm pitch X/Y R/O



Performance of a resistive micro-well detector with capacitive-sharing strip anode readout

Kondo Gnanvo [a,*], Nilanga Liyanage [a], Bertrand Mehl [b], Rui de Oliveira [b]
[a] University of Virginia, Department Of Physics, Charlottesville VA 22903, USA
[b] CERN Esplanade des Particules 1 P.O. Box 1211 Geneva 23, Switzerland

Fourth benefit : E-cleaning



Detectors with Kapton foils protecting the active area

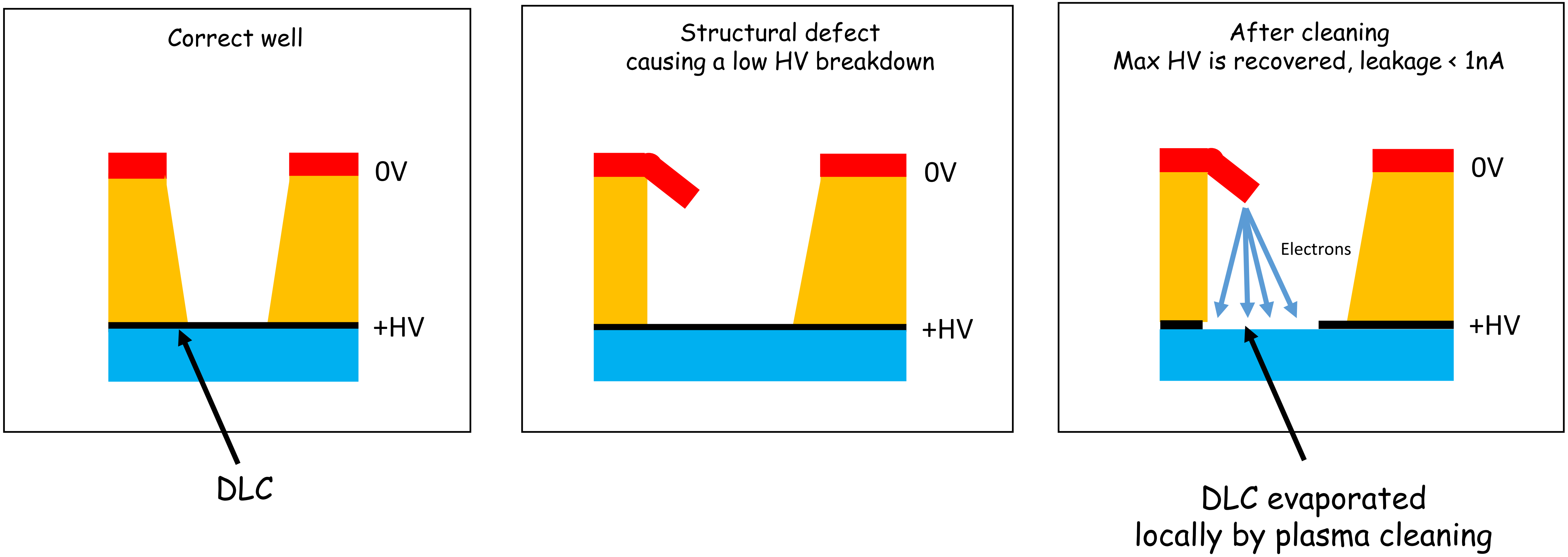
Oven set at 90 deg

HV Power supply

1/Minimum requirement → the detector should hold 1/3 of final voltage in open air, leakage current <100nA.
2/The active area should be covered with a Kapton foil to avoid dust dropping on.
3/The detector is put in the oven at 90 to 100deg Celsius.
4/A precise sequence is then applied to reach HV max (can be fully automatized).

Depending on the detector size and the type of defect the E-cleaning can takes few days.

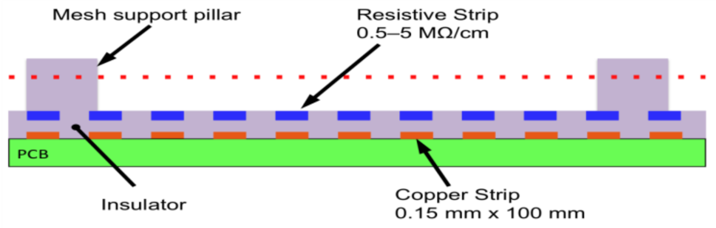
Cleaning process



To avoid any re-deposition or nasty compound creation
an extremely low level of humidity is required during this process.

2013→Resistive layer applied to MM structures

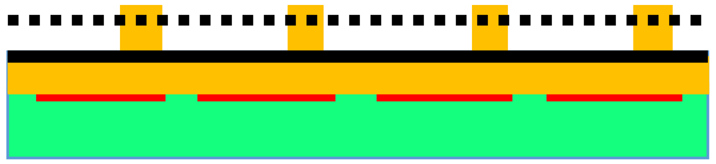
<u>Medium-rate detectors 100kHz/cm2</u>
Side evacuation of the charges



Screen printed resistive strips (ATLAS NSW)

2013

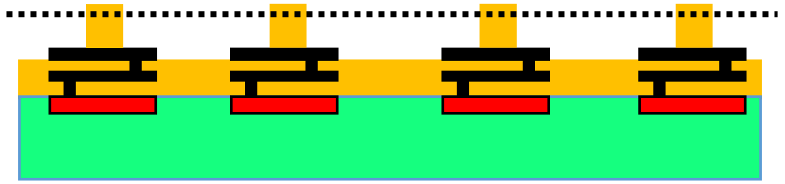
or



1 full DLC layer

2015

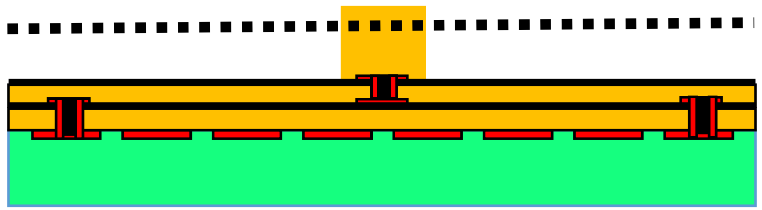
<u>High-rate detectors 10Mhz/cm2</u>
Charge evacuation inside active area



2 layers with screen printed pads

2015

or

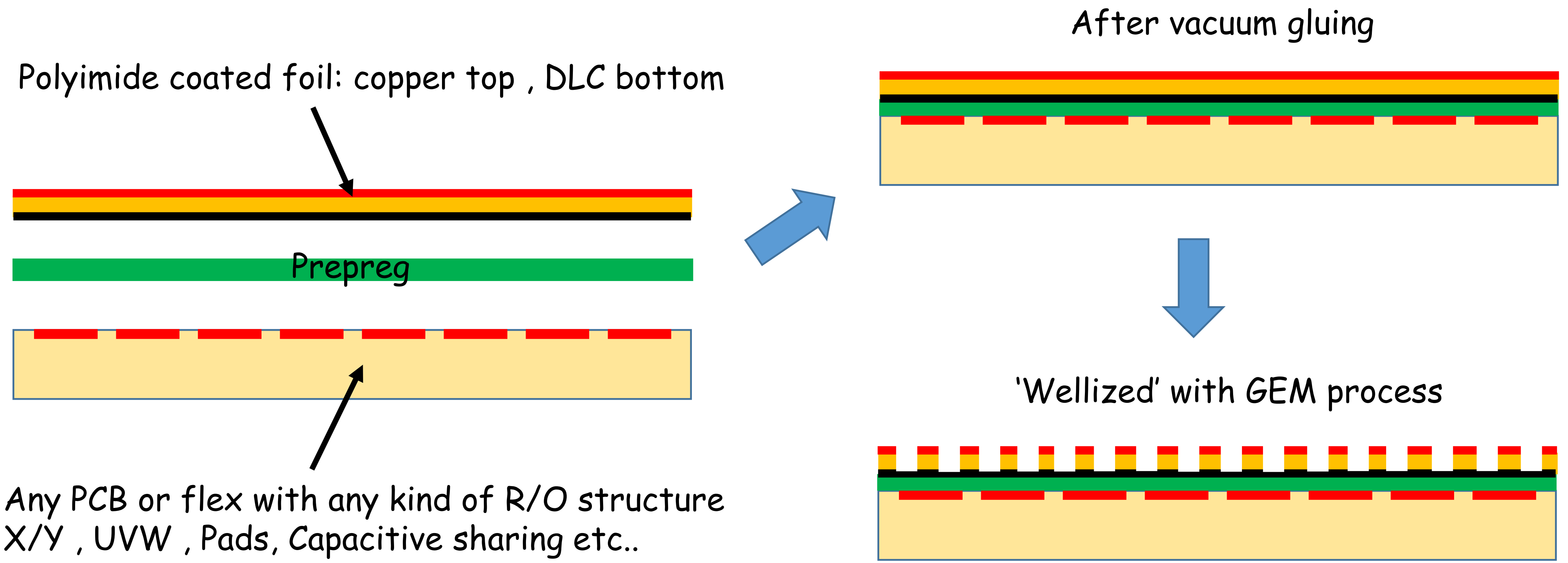


2 DLC layers without patterns

2020

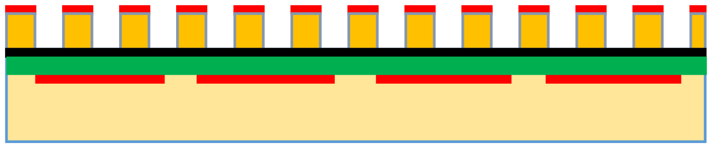
Damien Neyret	Saclay
Max Chefdeville	Lapp Annecy
Renaud Gaglionne	Lapp Annecy
Mauro Iodice	INFN Roma

2015→Resistive layer applied to Micro-Well (Giovanni Bencivenni) → uRwell

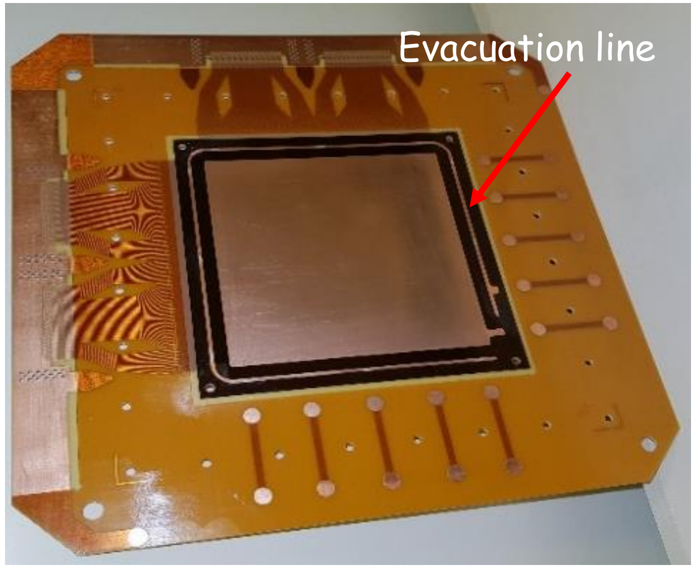


Medium rate µRwell

Lateral evacuation of charges



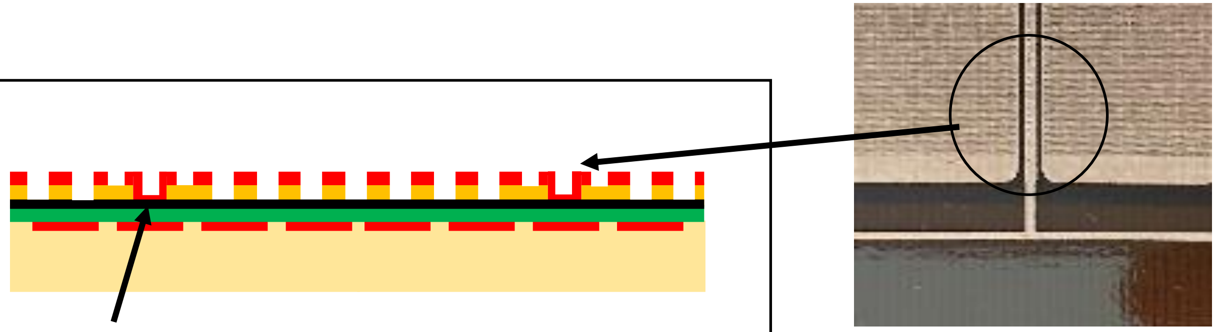
- 1 DLC layer



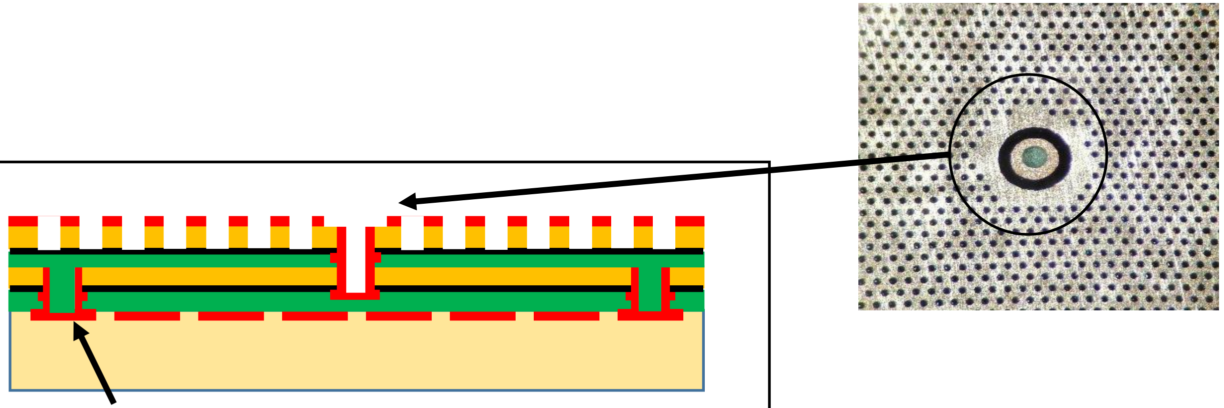
10cm x 10cm µRwell detector
"STD kit"

High rate uRwell

Charge evacuation in the active area

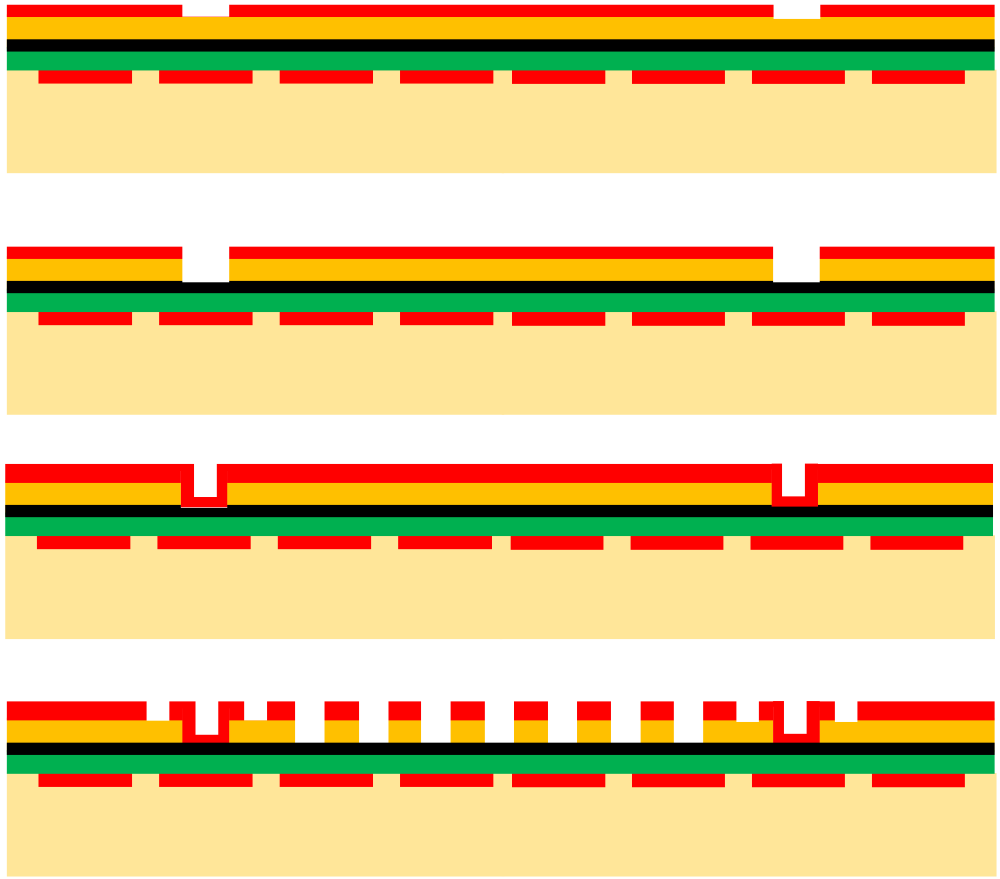


- DLC connected by plated grooves or holes



- 2 DLC layers connected by plated holes

Best compromise between performances & cost → PEP uRwell



P→ Pattern top copper

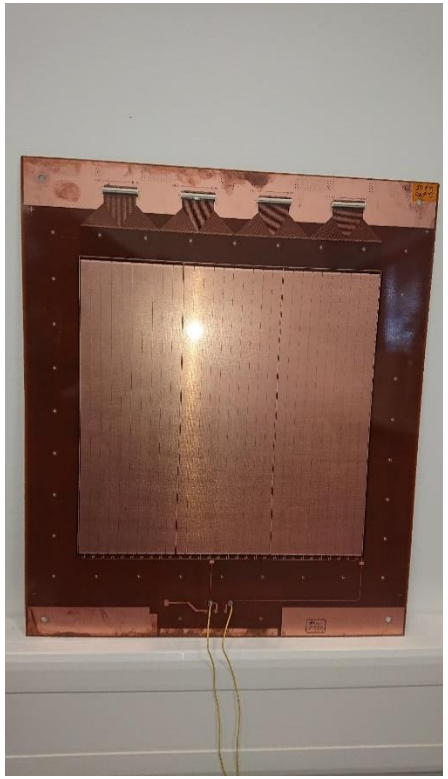
E→ Etch the kapton

P→ Plate

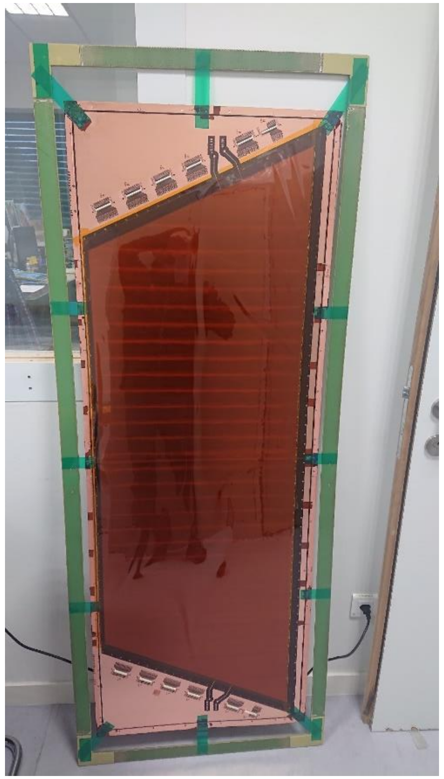
Wellize

PEP uRwell examples

Frascati R&D
1D PEP uRwell
Active area:
40cm x 5cm



Frascati R&D
1D PEP uRwell
Active area:
30cm x 30cm



CLAS12 R&D
2D PEP uRwell
Active area:
150cm x 50cm

CLAS12 uRwell
rolled in an oven
for E-cleaning

2023

2016→PicoSec precise timing with Micromegas

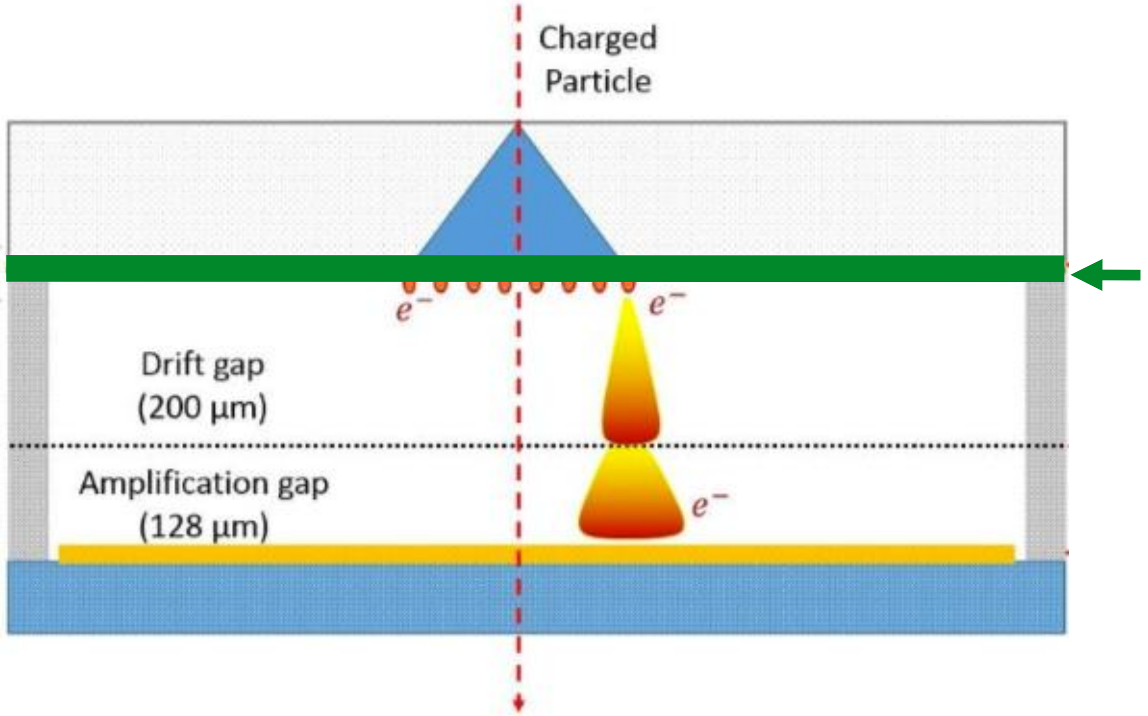
PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector
J. Bortfeldt et. al. (RD51-PICOSEC collaboration), NIM A (903), 2018, https://doi.org/10.1016/j.nima.2018.04.033

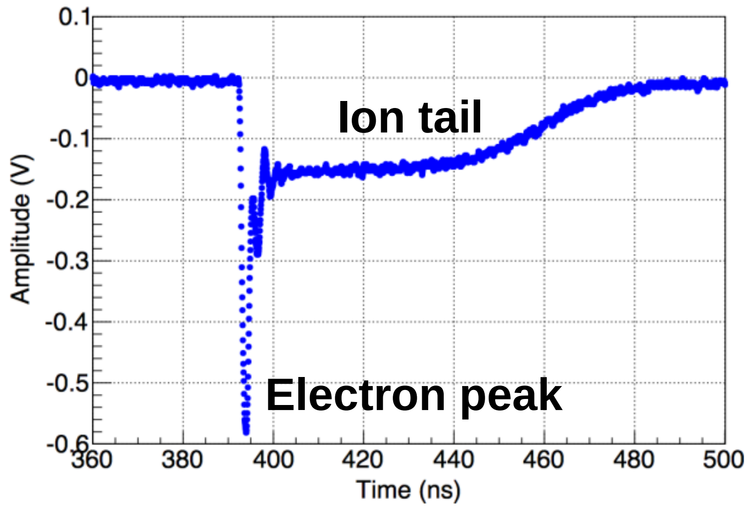
Cherenkov radiator
(3 mm MgF_2)

Photocathode
(3 nm Cr + 18 nm CsI)

Drift gap
(Pre-amplification)

Micromegas
(Amplification)





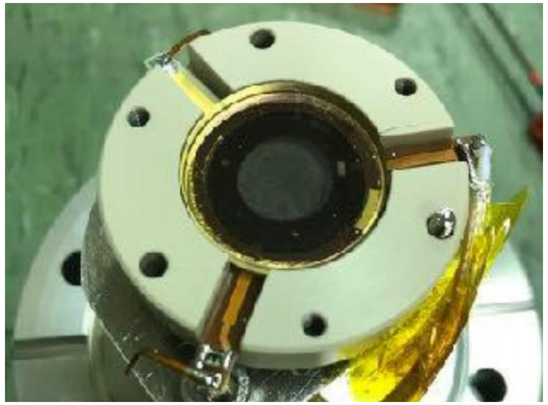
- **Signal with two distinct components:**
  Electron peak: fast (≈0.5 ns)
- Ion tail: slow (≈100 ns)

Gas mixture: 80% Ne + 10% C_2H_6 + 10% CF_4 (COMPASS gas)

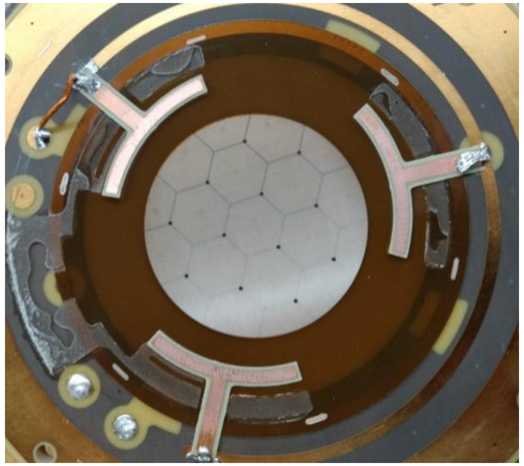
Schematic not drawn to scale

X. Wang et al., Study of DLC photocathode for PICOSEC detector, RD51 collaboration meeting, October 2018

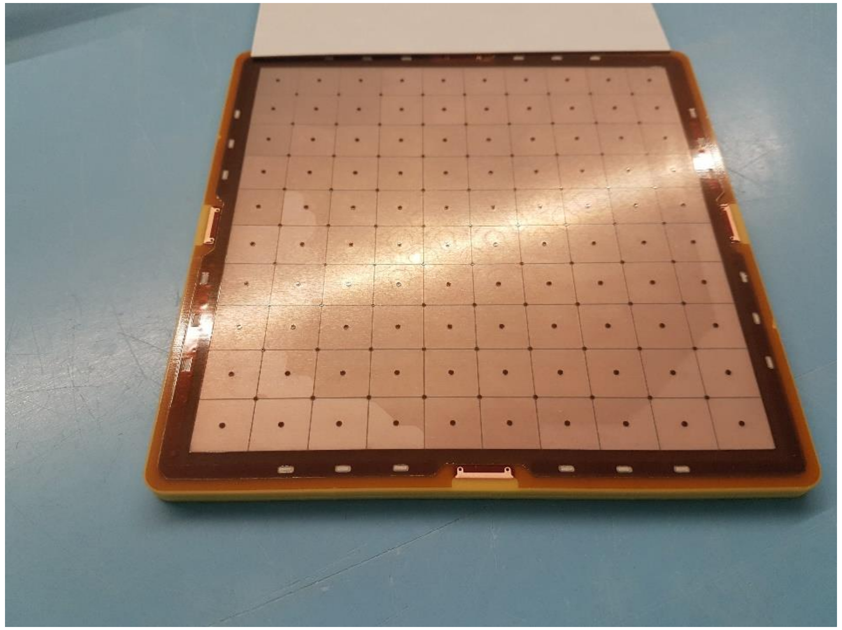
PicoSec detector modules



Single pad (2016)
⌀1 cm



Multi pad (2017)
⬡ 1 cm



10x10 module (2022)
□ 1 cm

Other types of MPGD not presented

Rwell → Weizmann :

uRwell with THGEM well

Rpwell → Weizmann :

RPC with THGEM well

High-rate RPCs → INFN & Kobe :

RPC with DLC electrodes

MHSP →Coimbra (Pt) :

MSGC with 2 amplification stages

Double mesh MM→ USTC China

Micro-PIC→ Kobe :

The only dot detector

MPGD selection Table

Space resolution : Micromegas or GEM with capacitive sharing →below 50um	Energy resolution: uBULK MM →11% FWHM	Ion back flow: multi devices stack → 0.1%	Rate : GEMs up to 1Mhz/mm2 resistive MM and uRwell 10Mhz/cm2	Time resolution : PicoSec down to 15ps* GEM 4ns RPCs with DLC*
Cryogenic temperatures: THGEMs , Rwell* , Rpwells*	Low background : Micro Bulk MM , uRwell	Low mass : uRwell, uBulk MM	Large size : GEM , floating mesh MM, uRwell	Cylindrical detector: uRwell , GEM and MM (but semi flexible)
	Spherical detectors: GEM	Lower Cost : uRwell → below 10 000 $/m2 (material and labor cost included)	Mass production: uRwell , GEM , MM	

*Still in R&D

Future tasks

-Mass production of vacuum deposited DLC layers

-DLC/Cr/Cu vacuum deposition : needed for high rate Micromegas detectors , resistive GEM and also to simplify uRwell detector production.

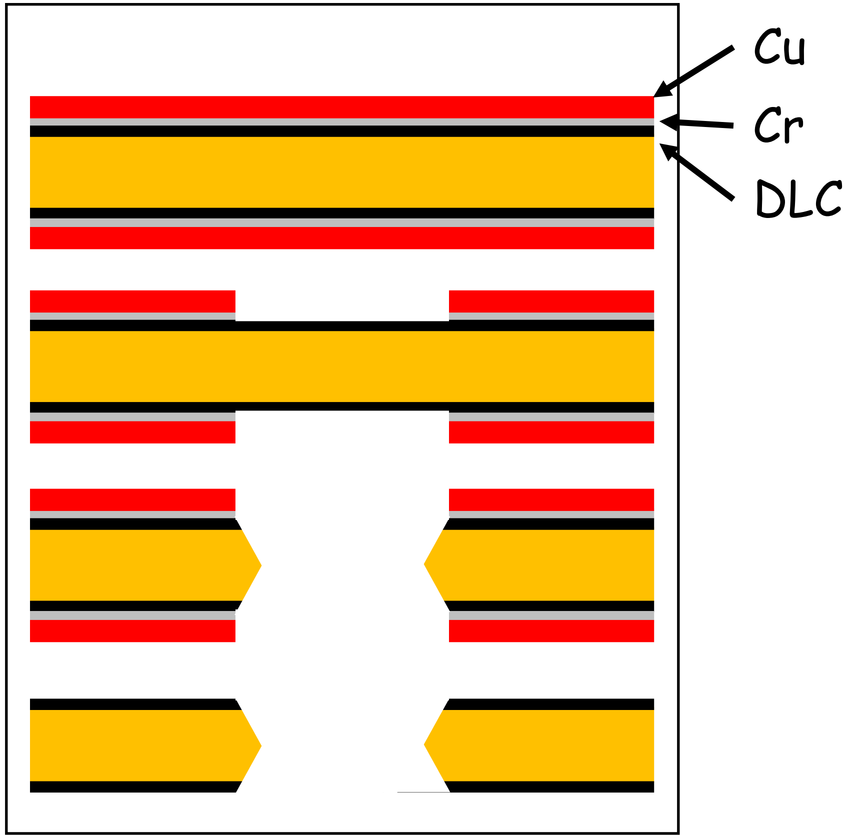
-Stronger vacuum deposited photocathodes for PICOSEC detectors.

-Neutron converter layers : vacuum deposited B4C

-Transparent conductors : vacuum deposited ITO

-Other vacuum deposited resistive or converting materials.

Example of resistive GEM production steps



Conclusion

After millimetric wire Gas chamber

came the Micro Pattern Gas Chambers.

With nanometric resistive and converting layers

we are probably already in the era of NLGCs (Nano layers Gas Chambers) .