PSD and Micro Pattern Gas Detector technologies

Eraldo Oliveri, CERN, EP-DT-DD, Gas Detector Development (GDD) team

Outline

- **Micro Pattern Gas Detector (MPGD) technologies**
- **Strategies for Position Sensitive Detectors**
  - **1st part… General (and short) intro**
  - **2nd part… Focused on the readout stage and aspects not necessarily exclusive of gaseous detector**
    - **Readout layouts and resistive elements (charge induced signals)**
    - **Modelling & Simulation and new FE electronics**
    - **Pixel (charge & photon) sensors**

"The conference has a strong multidisciplinary bias and encourages cross-fertilisation and transfer of ideas between researchers working in many different fields."

12th International Conference on
POSITION SENSITIVE DETECTORS

Hosted by
UNIVERSITY OF BIRMINGHAM

Disclaimers

- **Biased by my research activities and community (CERN GDD & EP RD, RD51) …**
- **Focused on Micro Pattern Gas Detector …**
- **Impossible to be exhaustive or complete…**
- **Main goal is to highlight what are the possibilities in the context of position sensitive detectors…**
- **Some of the shown concepts/ideas are/looks old.. but they are today revised thanks to new technological developments in manufacturing, material, electronics…**
- **I apologize with colleagues if their work will not be not presented properly…**

Contributions linked to gas detector @ PSD12

Apologize if I missed someone

Talks

1. Micromegas sectors for the ATLAS Muon Upgrade, towards the installation of the New Small Wheel in 2021 , Luca Martinelli
2. High rate capability studies of triple-GEM detectors for the ME0 upgrade of the CMS muon spectrometer , Luis Felipe Ramirez Garcia
3. High-granularity optical and hybrid readout of gaseous detectors: developments and perspectives , Florian Maximilian Brunbauer
4. Studies on tetrafluoropropene-CO2 based gas mixtures for the Resistive Plate Chambers of the ALICE Muon Identifier, Alessandro Ferretti
5. Detectors for Neutron Facilities , Richard Hall-Wilton
6. GridPix: the ultimate electron detector for TPCs, Harry Van Der Graaf
7. High Granularity Resistive Micromegas for high particle rates environment, Massimo Della Pietra
8. Towards the first observation of the Migdal effect in nuclear scattering I. Design and construction of the MIGDAL experiment, Mohammad Nakhostin
9. Precise timing and recent advancements with segmented anode PICOSEC Micromegas prototypes, Dr Ioannis Manthos

Posters

1. A programmable readout system for 3He/BF3 neutron detectors, Mr Yuri Venturini
2. The Hyperbolic drift chamber for ALERT, Gabriel Charles
3. Background in the CMS Drift Tubes: measurements with LHC collision data and implications for detector longevity at HL-LH, Lisa Borgonovi
4. Precision Antihydrogen Annihilation Reconstructions using the ALPHA-g Apparatus, Ms Pooja Woosaree
5. Timing techniques with picosecond-order accuracy for novel gaseous detectors, Aggelos Tsiamis
6. Upgrade of the ATLAS Muon Spectrometer with high-resolution Drift Tube Chambers (sMDT) for LHC Run-3, Elena Voevodina
7. Precision tracking micro-pattern gaseous detectors at Budker INP, Timofei Maltsev
8. Small-Strip Thin Gap Chambers for the Muon Spectrometer Upgrade of the ATLAS Experiment , Xinfei Huang
9. CMS Improved Resistive Plate Chamber Studies in Preparation for the High Luminosity Phase of the LHC, Cecilia Uribe Estrada
10. Position reconstruction studies with GEM detectors and the charge-sensitive VMM3a ASIC, Lucian Scharenberg
11. A slice-test demonstrator for the upgrade of the CMS Drift Tubes at High-Luminosity LHC, Carlo Battilana
12. The Topmetal-CEE Prototype, a Direct Charge Sensor for the Beam Monitor of the CSR External-target Experiment, Dr Chaosong Gao
13. A Novel Front-End Amplifier for Gain-less Charge Readout in High-Pressure Gas TPC, Dr Chaosong Gao
14. A congestion awareness and Fault-tolerance Readout Network ASIC for High-Density Electrode Array Targeting Neutrinoless Double-Beta Decay Search in TPC, bihui you
15. ACHINOS: A multi-anode read-out for position reconstruction and tracking with spherical proportional counters, Dr Patrick Ryan Knights
16. Cylindrical GEM Inner Tracker for the BESIII experiment, Sara Morgante
17. Gas electron tracking detector for beta decay experiments, Dagmara Rozpedzik
18. Longevity Study on the CMS Resistive Plate Chambers for HL-LHCC, Reham Aly
19. Novel zigzag and diamond pattern for Micromegas and Gas-based detector, Maxence Revolle
20. The ATLAS Muon spectrometer upgrade for the High Luminosity LHC using a new generation of Resistive Plate Chambers, Mauro Iodice

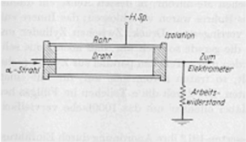
MPGD, RPC, WIRES, ELECTRONICS, SphPC

MPGD: Micro Pattern Gas Detector technologies

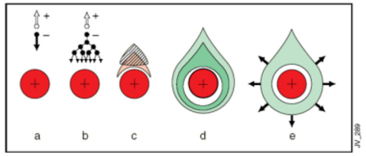
Short historical intro and overview of current situation…

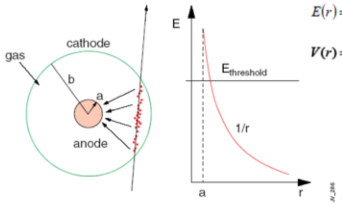
(Simplified) Historical flow

Single Wire Proportional Counter (SWPC) [Rutherford, E. and Geiger, H. (1908)]



Signal proportional to the original ionization (large collection volume – small amplification volume)

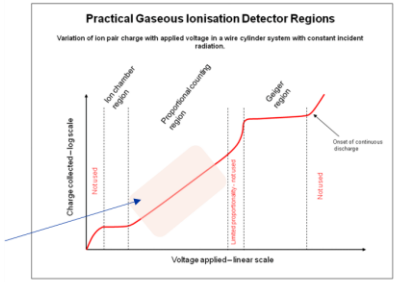




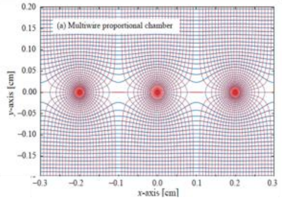
$$E(r)=\frac{CV_0}{2\pi\varepsilon_0}\cdot\frac{1}{r}$$

$$V(r)=\frac{CV_0}{2\pi\varepsilon_0}\cdot\ln\frac{r}{a}$$

Today we will focus on detectors working in proportional counting region



Multi Wire Proportional Counter(MWPC) [Charpak, G. et al. (1968)]



De gauche à droite, Georges Charpak, Fabio Sauli et Jean-Claude Santiard en train de travailler sur une chamber multifils en 1970. (Image : CERN)

Noble Prize in 1992

First time (If I'm not wrong, I can be biased) signals (electronics) are recorded (statistics) in HEP experiments opening the today scenario (well presented by Petra yesterday)…

Fast position-sensitive detectors (1968)

Continuously active,

Efficient at particle fluxes up to several MHz/cm2

Sub-mm position accuracy

In the 80's…

Limited multi-track separation: mechanical instabilities due to electrostatic repulsion - critical length of about 25cm for 10μm wires and 1mm spacing]

Fast gain drop at high fluxes: field-distorting space charge accumulation due to the long time taken by the ions produced in the avalanches to clear the region of multiplication.

Aging: permanent damage of the structures after long-term exposure to radiation due to the formation of solid deposits on electrodes.

1st

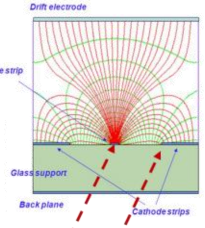
The first Micro Pattern Gas Detector

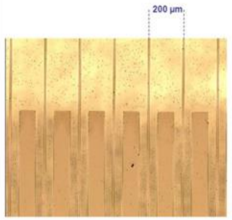
Micro Strip Gas Chamber (MSGC) [A.Oed (1988)]

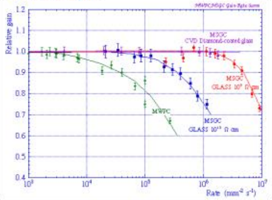
90's

Novel **photolithographic techniques**

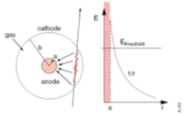
Photolithography: down in size from millimeters to tens of microns.. reducing the gas volume "used" by single events (improving resolution, multitrack separation, occupancy,..) and offering a faster evacuation of ions (reduced space charge).



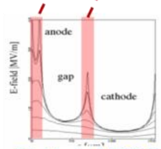




Impressive results t that time…



Fields in SWPC



Fields in MSGC

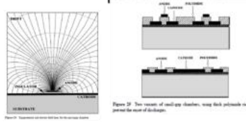
Two comments (potentially useful or to keep in mind)

- **High Fields at both electrodes** (again compare with wire field)
- **Dielectric** between electrodes and facing the active volume (just compare with wires/all metals).

(On Fields… interesting developments in RPC community.. RCC Resistive Cylindrical Chamber See pag. 14 of https://indico.cern.ch/event/999799/contributions/4204006/attachments/2235619/3790575/Aielli_ECFA_2021.pdf)

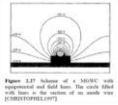
Micro Patterns

Micro Gap Chambers



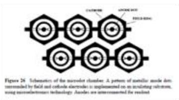
Angelini F, et al. Nucl. Instrum. Methods A335:69 (1993)

Micro Gap Wire Chamber



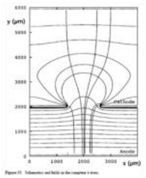
E. Christophel et al, Nucl. Instr. and Meth, vol 398 (1997) 195

MicroDot



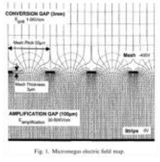
Biagi SF, Jones TJ. Nucl. Instrum. Methods A361:72 (1995)

CAT



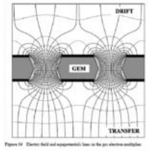
A. Sarvestani et al., Nucl. Instr. And Meth. A410 (1998) 238

MICROMEGAS



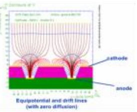
Y. Giomataris et al, Nucl. Instr. and Meth. A376(1996)29

GEM



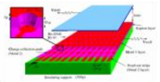
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

MicroGroove



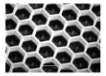
R. Bellazzini et al Nucl. Instr. and Meth. A424(1999)444

MicroWELL



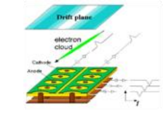
R. Bellazziniet al Nucl. Instr. and Meth. A423(1999)125

MicroPin



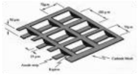
P. Rehak et al., IEEE Nucl. Sci. Symposium seattle 1999

μPIC



Ochi et al NIMA471(2001)264

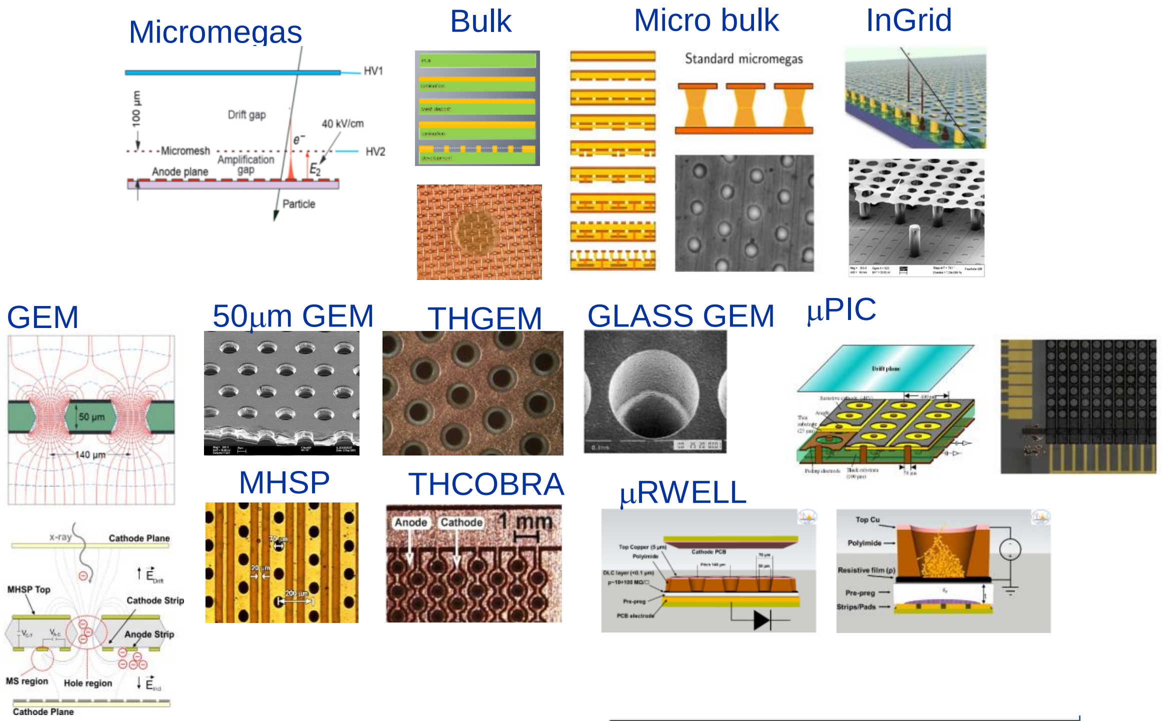
Micro Wire Chamber



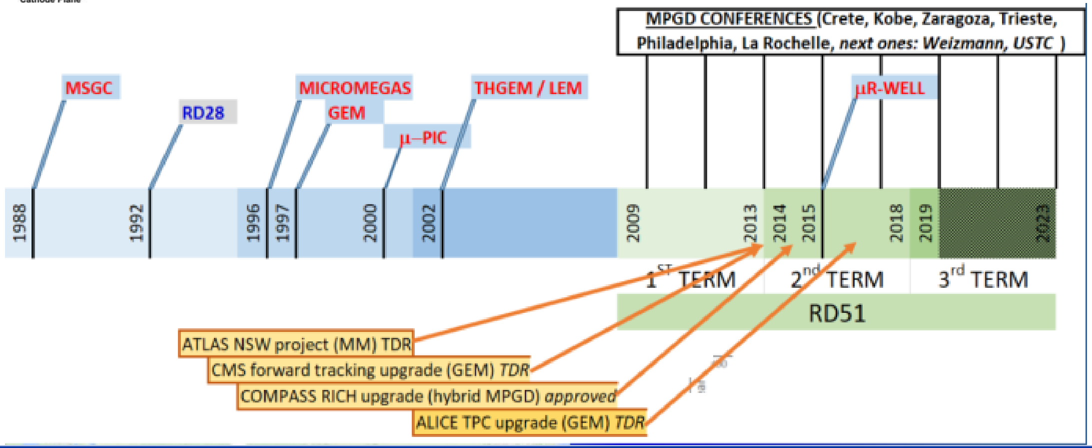
B. Adeva et al., Nucl. Instr. And Meth. A435 (1999) 402

+ surely several missing ones…

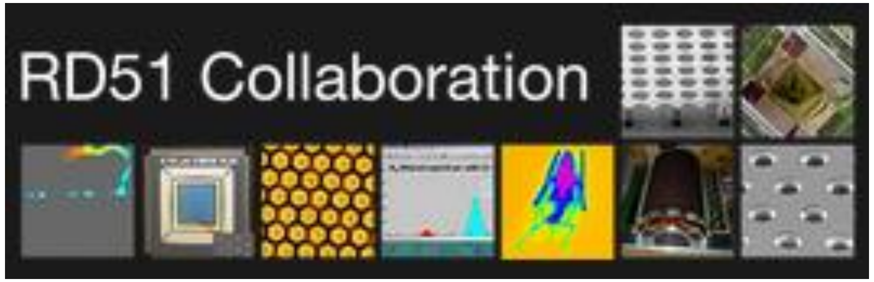
Today



- High Rate Capability — Up to MHz/mm^2 (MIP)
- High Gain — Up to 10^5 -10^6
- High Space Resolution — <100μm
- Good Time Resolution — In general few ns , sub-ns in specific configuration
- Good Energy Resolution — 10-20% FWHM @ soft X-Ray (6KeV)
- Excellent Radiation Hardness
- Good aging Properties
- Ion Backflow Reduction — % level sort of easy, below % in particular configuration
- Photon Feedback Reduction
- Large size — m^2
- Low material budget
- Low cost
- …



Technology share-point RD51 (**Development of Micro-Pattern Gas Detectors Technologies**)

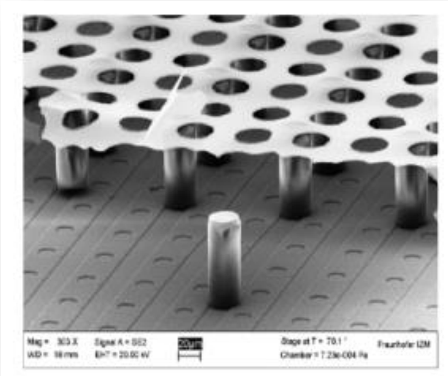


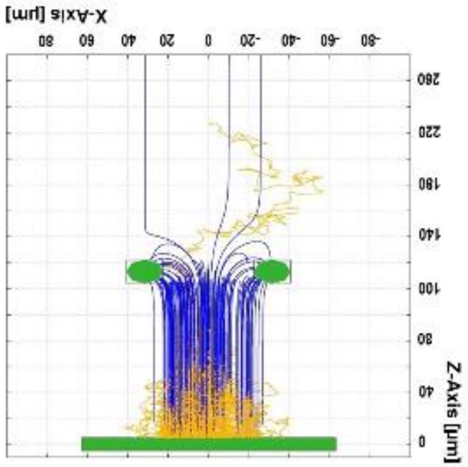
https://rd51-public.web.cern.ch/

Avalanches in …

Down to tens/hundreds of microns scale (good from PSD perspective)

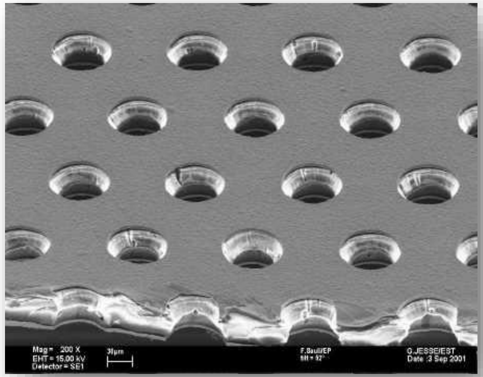
Meshes (MM)

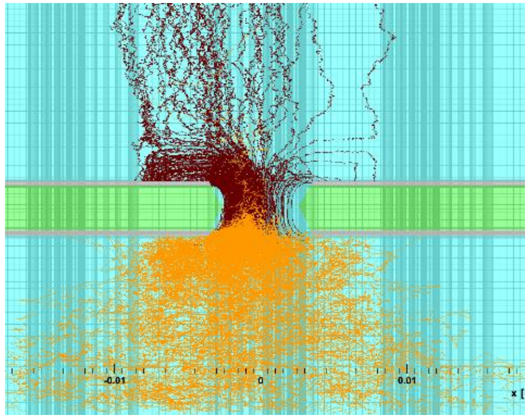




https://cds.cern.ch/record/2152254/files/arXiv:1605.02896.pdf

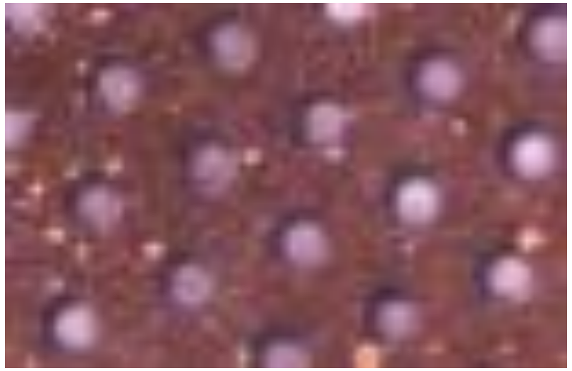
Holes (GEM)

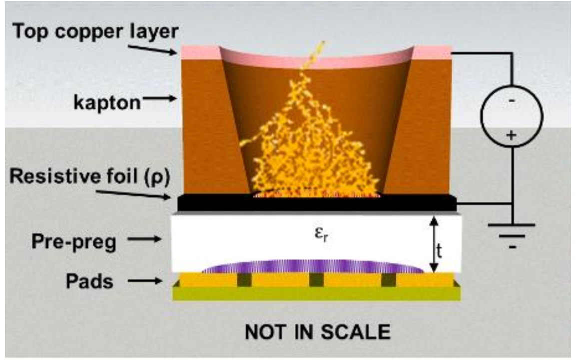




http://www-flc.desy.de/tpc/projects/GEM_simulation/

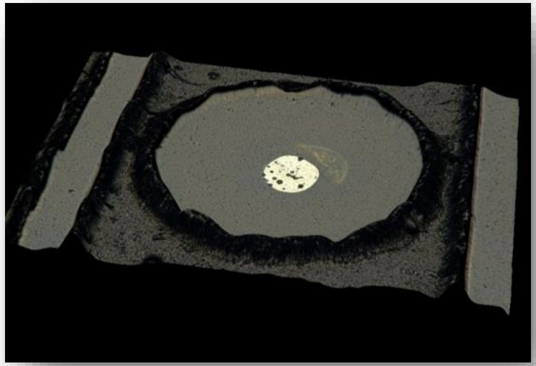
Blind holes (WELL)

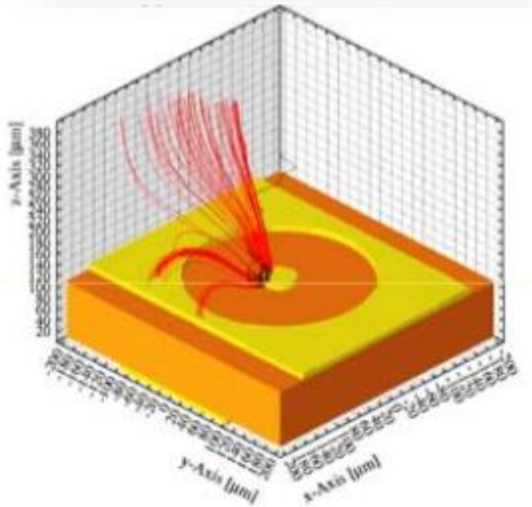




https://cds.cern.ch/record/2238861/files/10.1088_1748-0221_10_02_P02008.pdf

Dots (PIC)





Development and tests of μPIC Resistive Cathode, A. Ochi

MPGD for LHC (LS2 Upgrades) / Important milestone in the context of instrumenting large area systems

https://indico.cern.ch/event/1038992/contributions/4363702/attachments/2256312/3829107/LHCC_146th_ALICE_Status_Mesut_Arslandok_comp.pdf

ALICE

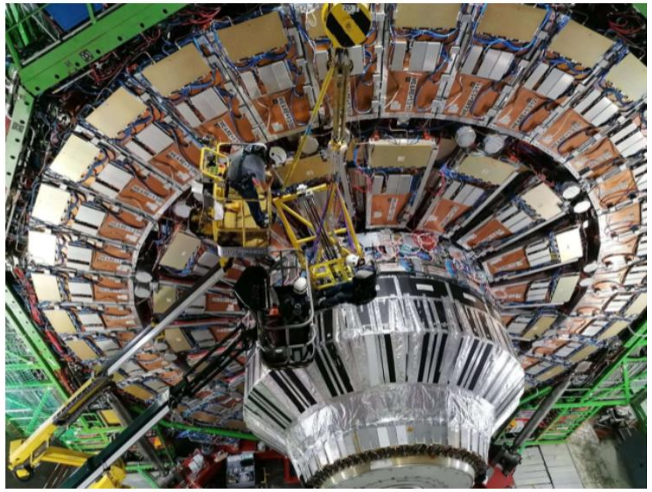
TPC GEM

ATLAS EXPERIMENT

NSW Muon System micromegas

https://indico.cern.ch/event/1038992/contributions/4363710/attachments/2256387/3828801/LHCC_ATLAS_OpenSession_June2nd.pdf

! ***@PSD12*** *Micromegas sectors for the ATLAS Muon Upgrade, towards the installation of the New Small Wheel in 2021 , Luca Martinelli*



https://ep-news.web.cern.ch/cms-gems-are-changing-gear

Muon System (GE1/1) GEM

CMS

! ***@PSD12*** *High rate capability studies of triple-GEM detectors for the ME0 upgrade of the CMS muon spectrometer , Luis Felipe Ramirez Garcia*

Possibilities and Strategies for MPGD based PSD

Going through examples of current research lines…

Followed approach: How to improve position resolution

Each stage plays a role in the achievable position resolution.

Most of the time, stages are decoupled and optimization of each stage can be done independently from the others.

Despite the fact that probably the first one is the one that can be more innovative …

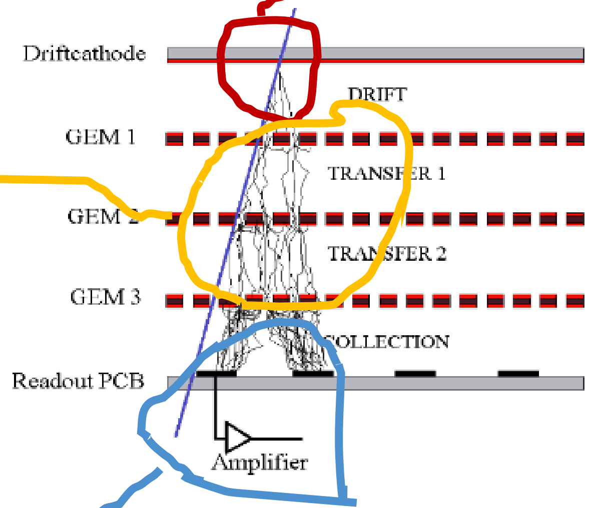
Today I will focus mostly on the last one..

It refers to aspects that are of interest of other technologies as well and it is therefore more in the spirit of the conference of encouraging cross-fertilisation and transfer of ideas between researchers working in many different fields

Primary charge (primary ionization in gas or via converters)

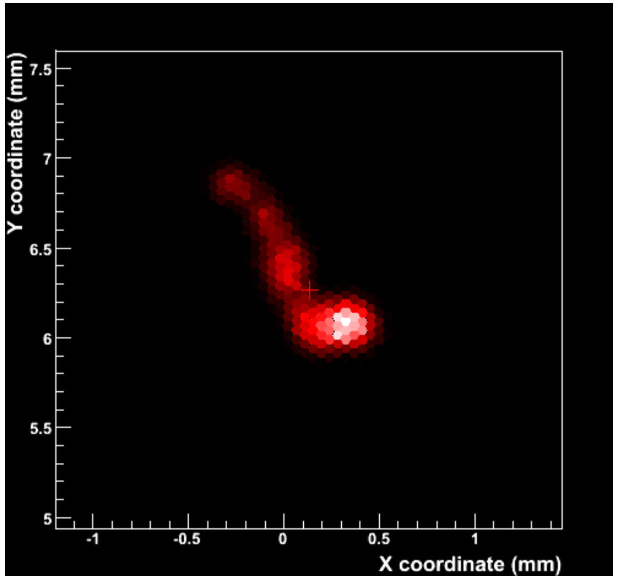
Amplification and Transfer stages (gas and micro pattern structures)

Readout stage (coupled to charge/photons sensitive electronics)



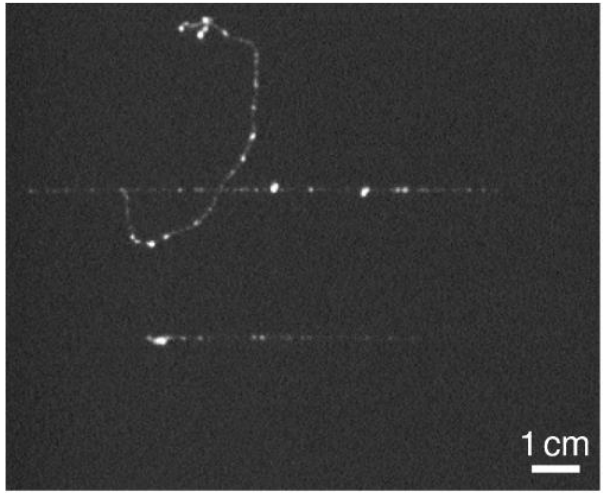
In the readout part we do have in fact several – technology driven - new options/strategies that can be explored to push performances to the limit …

Primary charge

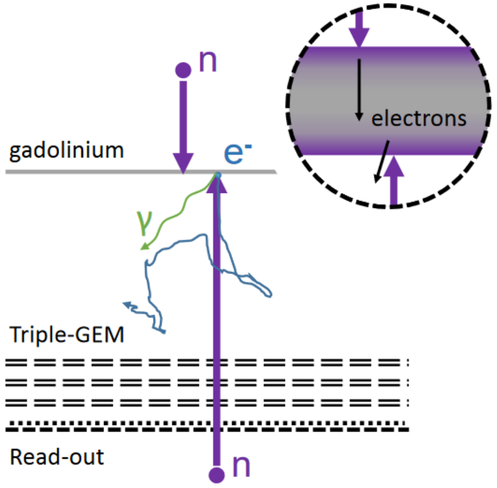


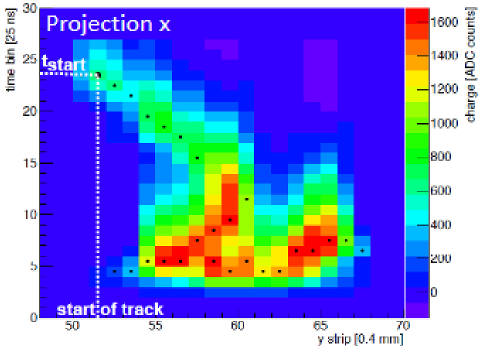
X-ray polarimetry: a new window in the high energy sky

Ronaldo Bellazzini
INFN - Pisa



F.M. Brunbauer *et al* 2018 *JINST* **13** T02006





Detectors and electronics for neutron detection in the NMX instrument of European Spallation Source, M. Lupberger

! *@PSD12 Detectors for Neutron Facilities , Richard Hall-Wilton*

“Guessing the future” from F.Sauli @ PSD5

Primary charge (primary ionization in gas or via converters)

EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN-EP/99-147
11 October 1999

MICRO-PATTERN GAS DETECTORS

Fabio Sauli
CERN, CH-1211 Geneva, Switzerland

ABSTRACT

Micro-strip gas chambers, with their excellent localization properties, high rate capability and good granularity, have been adopted by many experiments in particle physics. Two recurrent problems however have been reported: a slow degradation under sustained irradiation (or aging), and the rare but devastating occurrence of discharges. New breeds of detectors aim at improving on these crucial points; the micro-dot, CAT, micromegas, the gas electron multiplier are examples. Very performing, they are moreover robust and reliable. Two-stage devices, making use of a gas electron multiplier as first element, permit larger gains in presence of high rates and heavily ionizing tracks. Possible promising future developments in the field are outlined.

Invited review talk at the
5th Conference on Position Sensitive Detectors
University College London, September 13-17, 1999

Corresponding author: fabio.sauli@cern.ch

6. GUESSING THE FUTURE

The low density of gaseous media sets basic limitations to the performances of detectors. Statistical fluctuations in the energy loss result in a wide, asymmetric spectra, and, in the thin layers required for fast response, in poor efficiency and position accuracy, quickly degrading with the incidence angle. Operation at pressures higher than atmospheric is possible, but implies the use of containment vessels adding unacceptable amount of material to the experiment. A very interesting possibility is to exploit secondary electron emission from cathodes, a process well known in vacuum, hindered however by back-scattering in presence of gas molecules. Good secondary emitters are low density layers of KCl, KBr, LiF, CsI [38]; for a review of secondary emission in gaseous detectors see for example Ref. [39].

In a gas counter having the cathode coated with a columnar CsI layer, around 200 µm thick , the authors of ref. [40] have demonstrated a substantial enhancement of the detected charge signal. In a more tantalizing device, realized with wires embedded in a thick low-density emitter and operating in vacuum, large secondary emission followed by multiplication has been observed [38]. Despite the marginal efficiency obtained so far, exploiting the secondary emission process with its intrinsic independence on the incidence angle and sub-nanosecond timing remains a very challenging possibility for future detection systems.

observed [38]. Despite the marginal efficiency obtained so far, exploiting the secondary emission process with its intrinsic independence on the incidence angle and sub-nanosecond timing remains a very challenging possibility for future detection systems.

20years later.. @PSD …
Photocathodes & Timing.. & Position…

Primary charge (primary ionization in gas or via converters)


Nuclear Inst. and Methods in Physics Research, A 993 (2021) 165076

Contents lists available at ScienceDirect

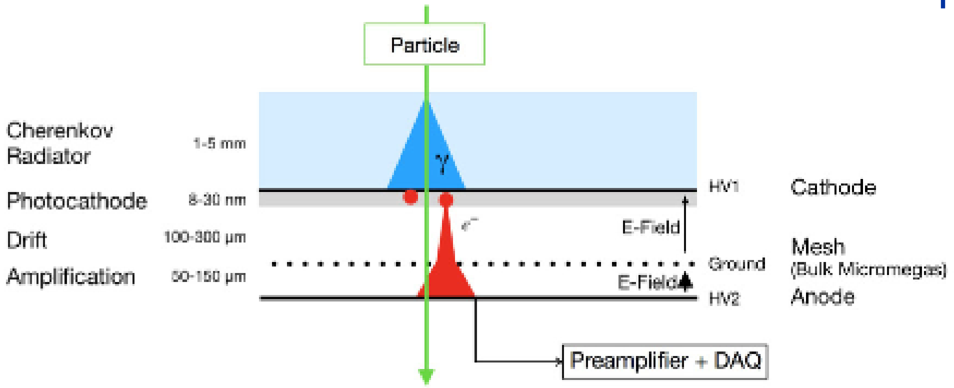
Nuclear Inst. and Methods in Physics Research, A

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

ELSEVIER

Timing performance of a multi-pad PICOSEC-Micromegas detector prototype

From ns to tens of ps



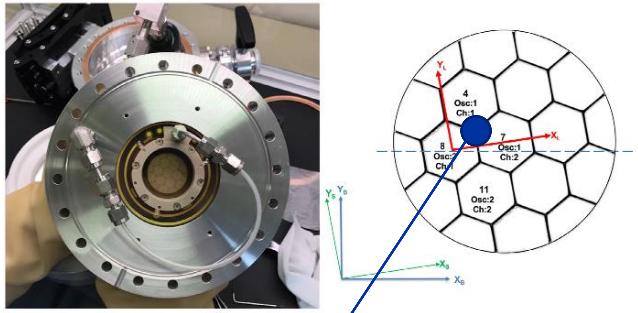


Fig. 3. (left) Photograph of the multi-pad chamber during assembly in the clean room. The hexagonal pad structure of the readout is visible in the centre. (right) A schematic diagram of the anode segmentation. Notice that there is a gap between adjacent pad edges represented by the thick black lines. The pads No. 4, 7, 8 and 11 are fully instrumented and their signals are digitized by the oscilloscope channels as indicated. The red axes, labelled as X_L and Y_L, represent the local coordinate frame, while the blue axes, labelled as X_B and Y_B, represent the global tracking coordinate frame (or else beam-frame). The green axes, labelled as X_S and Y_S, represent the symmetry frame, which is used in the alignment procedure as described in the text.

<35ps for signal shared between 3 pads from first prototype

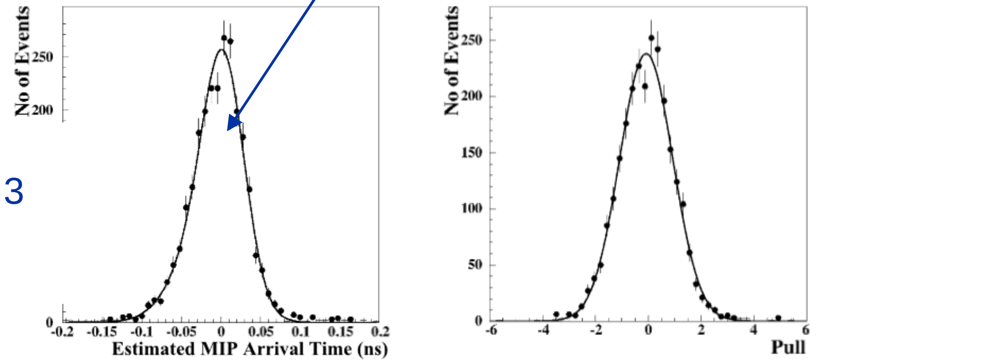


Fig. 19. (left) Distribution of the arrival time of MIPs, passing within 2 mm of a common pad corner (pads No. 4, 7 and 8), estimated by Eq. (9) combining the individual single-pad measurements and their expected errors. The solid line represents a fit to the data points by a sum of two Gaussian functions corresponding to an RMS of 32.2 ± 0.5 ps. (right) Pull distribution of estimated arrival times by Eq. (9). The solid line represents a Gaussian fit to the data points, consistent with mean and σ values equal to 0 and 1 respectively.

! @PSD12:

Precise timing and recent advancements with segmented anode PICOSEC Micromegas prototypes, Ioannis Manthos

Timing techniques with picosecond-order accuracy for novel gaseous detectors, Aggelos Tsiamis

Recovering time resolution when signal is shared between several electrodes open the door to optimization studies focused on position resolution.

Diffusion and distortions

Diffusion

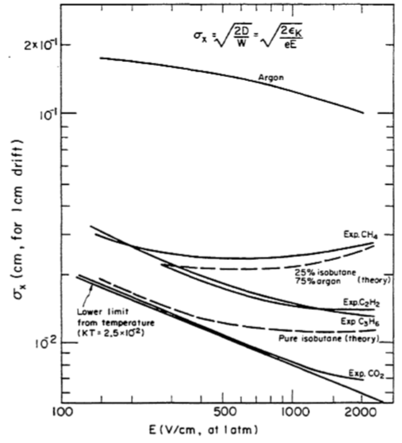


Fig. 35 Computed and experimental dependence of the standard deviation of electron diffusion from the electric field for 1 cm drift, in several gases at normal conditions[25])

F.Sauli, Principles of operation of multiwire proportional and drift chambers, CERN, 1977 (https://cds.cern.ch/record/117989)

Magnetic Field and TPC

The Time-Projection Chamber
- A new 4π detector for charged particles

David R. Nygren

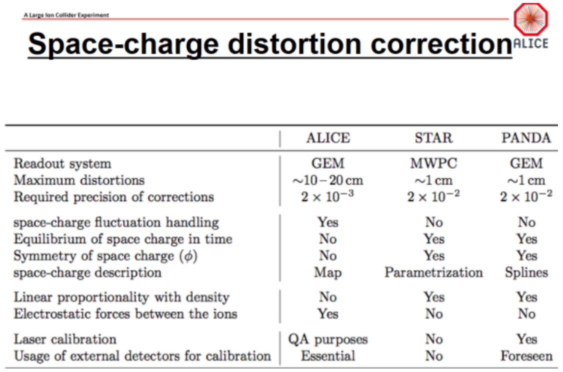
Lawrence Berkeley Laboratory
Berkeley, California 97420

Abstract

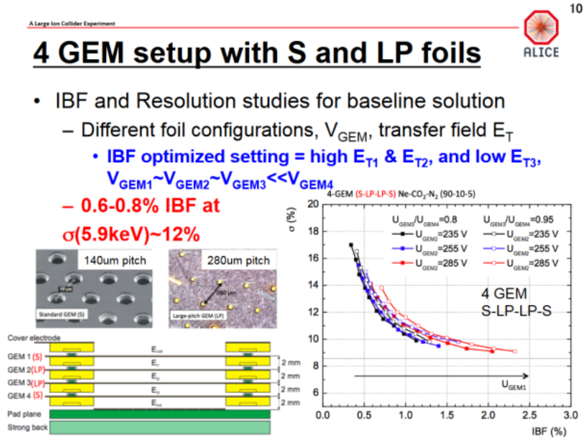
A new approach to the problems of track recognition and momentum measurement of high energy charged particles is described, and a detector particularly suitable for PEP energies is discussed.

The central idea is the utilization of a large methane-filled drift chamber placed in a strong magnetic field, with the drift field oriented parallel to the magnetic field. In this configuration transverse diffusion of the ionization electrons can be very substantially suppressed by the magnetic field. This in turn leads to the possibility of measurement accuracies on the order of 100 microns after one meter of drift.

Distortion / Space Charge (IBF)



	ALICE	STAR	PANDA
Readout system	GEM	MWPC	GEM
Maximum distortions	~10 − 20 cm	~1 cm	~1 cm
Required precision of corrections	2×10^{-3}	2×10^{-2}	2×10^{-2}
space-charge fluctuation handling	Yes	No	No
Equilibrium of space charge in time	No	Yes	Yes
Symmetry of space charge (ϕ)	No	Yes	Yes
space-charge description	Map	Parametrization	Splines
Linear proportionality with density	No	Yes	Yes
Electrostatic forces between the ions	Yes	No	No
Laser calibration	QA purposes	No	Yes
Usage of external detectors for calibration	Essential	No	Foreseen



https://indico.cern.ch/event/219436/contributions/1523143/attachments/355808/495528/gunji_alice_upgrade_v2_3.pdf

Distortion / Field lines

A Rubin *et al* 2013 *JINST* **8** P08001

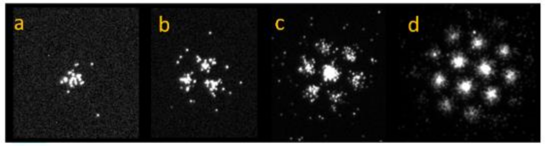


Figure 2. Examples of non-collimated 5.9 keV x-ray induced single-event avalanches recorded in different detector configurations of the setup shown in figure 1. a) Single-THGEM with a reversed drift field of 0.3 kV/cm and gain ~ 10^4; b) Single-THGEM (E_{drift} 0.5 kV/cm, gain ~ 10^4); c) Double-THGEM with 8 mm transfer gap (E_{drift} 0.5 kV/cm, E_{trans} 0.5 kV/cm, gain ~ 5×10^5); d) Triple-THGEM with 8 mm and 10 mm transfer gaps (E_{drift} 0.5 kV/cm, E_{trans} 0.5 kV/cm, gain ~ 10^7). The images are unprocessed, but the contrast has been adjusted to improve visibility. THGEM type 1 (table 1); gas: Ne/CF_4 (95/5).

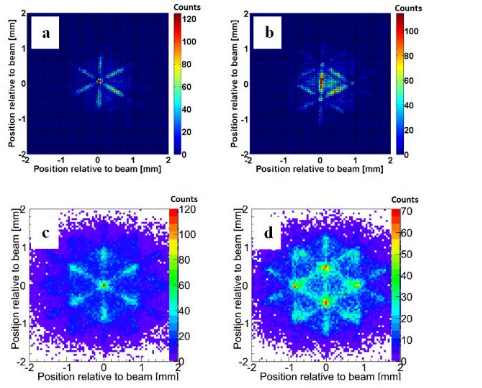


Figure 10. Reconstruction of the points of interaction, from the center-of-gravity of the light emitted from several holes, when irradiating a THGEM type 1, configuration g (table 3) at the center of a hole and in-between holes. a) and b) are experimental results (with 8 keV x-rays) at gain 10^4; c) and d) are simulation results (with 8 keV electrons). See text for explanations of the figures, and section 2.3.3 for explanations of the experiment and simulation.

Amplification and Transfer stages (gas and micro pattern structures)

Diffusion… Negative Ions TPC

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 555, Issues 1–2, 15 December 2005, Pages 55-58

Negative ion drift and diffusion in a TPC near 1 bar

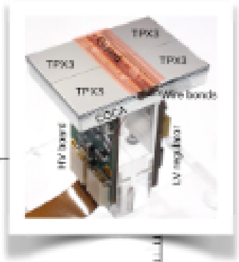
C.J. Martoff, R. Ayad, M. Katz-Hyman, G. Bonvicini, A. Schreiner

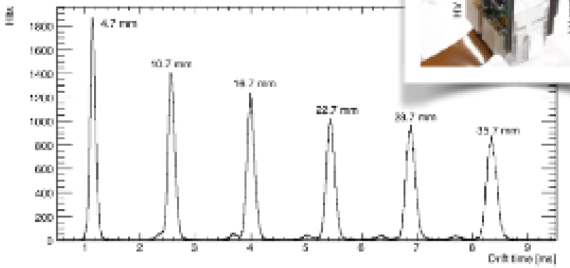
A TPC which drifts negative ions (in this paper, CS_2^-) rather than electrons, was invented to reduce diffusion in three dimensions to its thermal (lower) limit without applying a magnetic field [1], [2], [3]. This provides the highest 3D space-point resolution attainable for long drifts, without the power requirements and expense of a magnet.

https://doi.org/10.1016/j.nima.2005.08.103

GridPix NI TPC readout

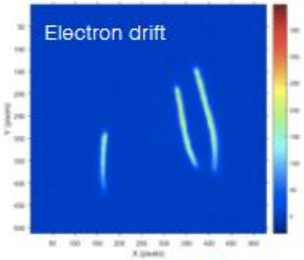
1.6ns time resolution of Timepix3 for precise drift time measurements



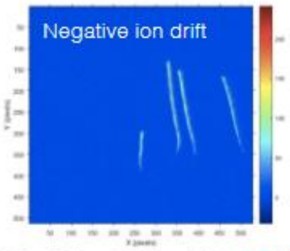


C. Ligtenberg et al., https://indico.nikhef.nl/event/2372/contributions/5576/subcontributions/225/attachments/2601/3036/NITPC_paper_v0612.pdf

NI Optical TPC



150 Torr CF_4, σ ~ 450 um



150 Torr CF_4 + 5.9 Torr CS_2, σ ~ 150 um

D. Loomba, UNM

Ultra-fast imaging sensors

High-speed CMOS sensors can deliver up to **1 million frames per second** at limited resolution. Can be used for rapid imaging (integrated imaging limited by incident radiation flux) and beam monitoring with active feedback.

Rapid radiation imaging or **beam monitoring** already feasible (kHz at megapixel resolution).

3D track reconstruction (NI?) requires lower read noise sensors and increased resolution at maximum frame rates.

Phantom v2512

- 1 megapixel **CMOS** sensor
- **25 kfps** at 1280 x 800
- **1 Mfps** at 128x32
- Higher read noise

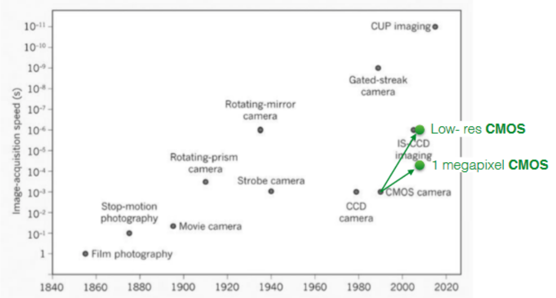
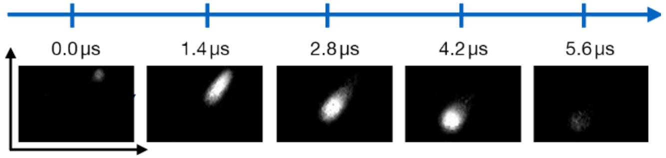


Image adapted from: B. Pogue, Nature 516 (2014) 46–47

Sequence of images displaying alpha track segments in gaseous TPC recorded at 700 kHz.



Optical readout, novel readout electrodes, hybrids with ASICs, F.M.Brunbauer (CERN GDD), April 29, 2021 - ECFA Detector R&D Roadmap Symposium - TF1 Gaseous Detectors

Readout stage

Focusing on current trends with potentially strong impact (personal comment) on position sensors (and resolution)

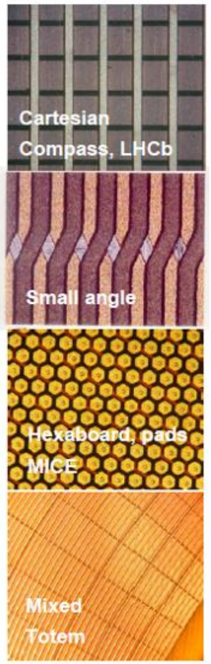
- Readout layouts and resistive elements (charge induced signals)
- Modelling & Simulation and new FE electronics
- High granularity Pixel readout (charge and photon)

Readout stage (I) / Layout

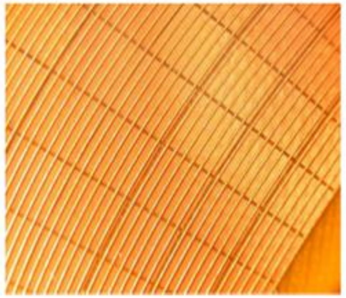
Focusing on current trends with potentially strong impact (personal comment) on position sensors (and resolution)

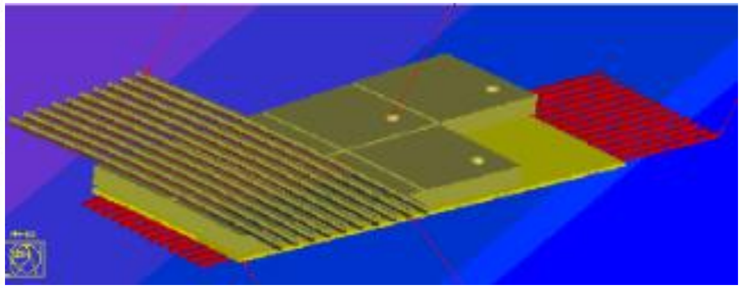
- **Readout layouts and resistive elements (charge induced signals)**
- Modelling & Simulation and new FE electronics
- High granularity Pixel readout (charge and photon)

Readout Layout / Manufacturing capabilities



TOTEM T2 forwards tracking and triggering telescope: tracking with high eta (radial) coarse phi resolution and triggering rods for trigger





M. Berretti, http://indico.cern.ch/event/252473/session/0/contribution/5/material/slides/0.pdf

Several coordinates (ambiguities)

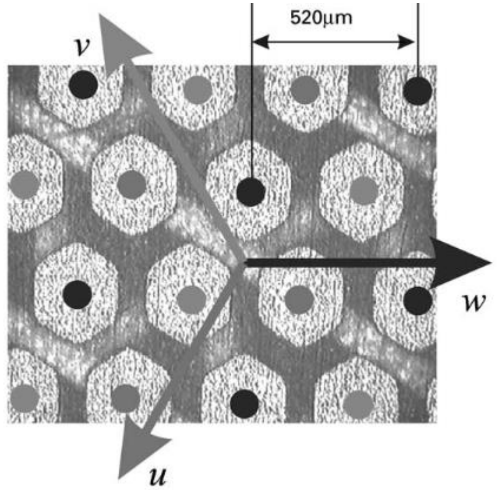


Fig. 4. Microscope photograph of the novel micropad readout. The micropads are alternately connected to three different layers of strips.

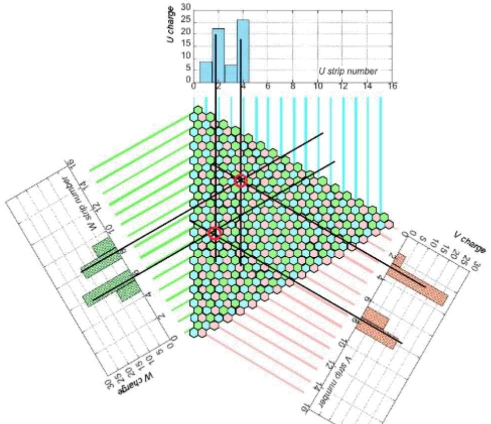
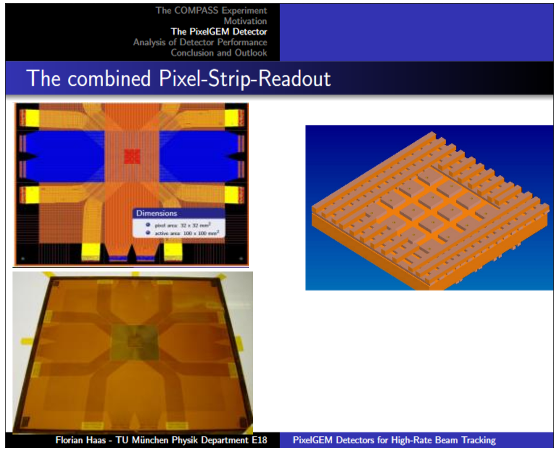


Fig. 4. Double photon event recorded with the hexaboard

Bachmannet al. High rate X-ray imaging using multi-GEM detectors with a novel readout design,,NIMA 478, 2002, https://doi.org/10.1016/S0168-9002(01)01719-3.

COMPASS GEM & MM (strips & pads)



https://wwwcompass.cern.ch/compass/publications/talks/t2007/haas_vienna07.pdf

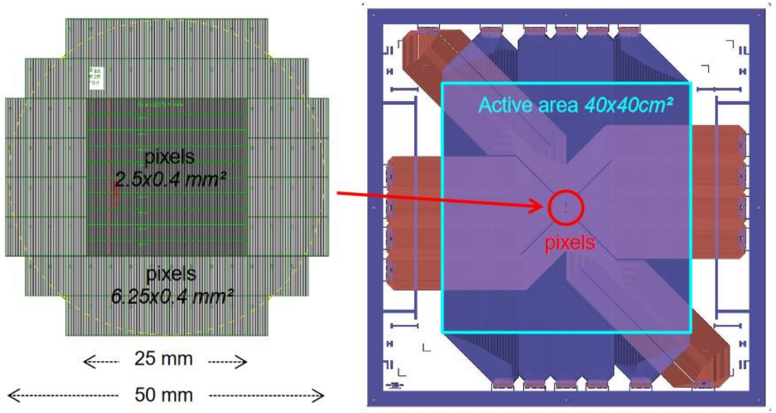


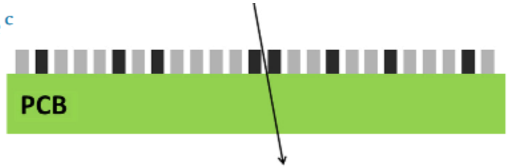
Figure 2: Sketch of large pixelized Micromegas detector (right). Zoom of the pixel area (left)

https://cds.cern.ch/record/1399058/files/arXiv:1111.3337.pdf

Encoding

Genetic multiplexing and first results with a 50×50 cm^2 Micromegas

S. Procureur [a,*], R. Dupré [a,b], S. Aune [c]

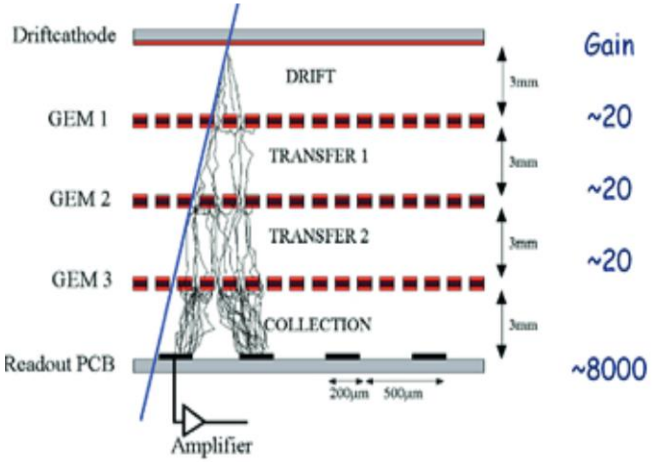


https://doi.org/10.1016/j.nima.2013.08.071

Fig. 4. Principle of the genetic multiplexing. A particle (array) leaves a signal on two neighbouring strips which are connected to two given channels. These channels are connected to other, non-neighbouring strips in the detector. The recorded signals on these two channels therefore localize without ambiguities the particle in the only place where strips are consecutive.

Charge sharing (geometrical)

Geometrical sharing



Profiting from diffusion

Design Studies for a TPC Readout Plane Using Zigzag Patterns with Multistage GEM Detectors

B. Azmoun, P. Garg, T.K. Hemmick, M. Hohlmann, A. Kiselev, M.L. Purschke, C. Woody, A. Zhang

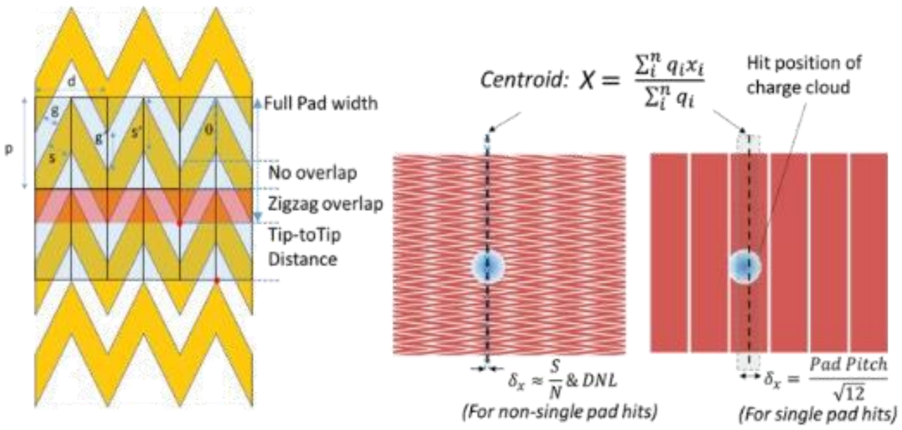


Fig. 1 The sketch on the left shows the 4 basic parameters of the zigzag pattern, including the pitch, zigzag period, gap width, and trace width, denoted by *p*, *d*, *g*, and *s* respectively. (*θ*, *s'*, and *g'* are resultant parameters representing the characteristic angle, the trace width, and gap width at the zigzag apex.) The sketches on the right demonstrate charge sharing and centroid calculations for a zigzag and rectangular pad readout. 6 channels are shown for each pattern with a pitch of 2mm. (The drawings on the right are to scale.)

B. Azmoun et al., "Design Studies for a TPC Readout Plane Using Zigzag Patterns With Multistage GEM Detectors," in IEEE Transactions on Nuclear Science, vol. 65, no. 7, pp. 1416-1423, July 2018, doi: 10.1109/TNS.2018.2846403.

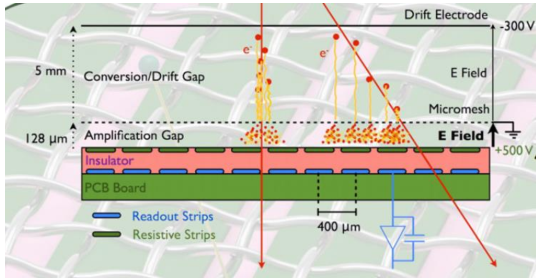
! *@**PSD12** Novel zigzag and diamond pattern for Micromegas and Gas-based detector, Maxence Revolle*

Readout Layout / Resistive elements (I)

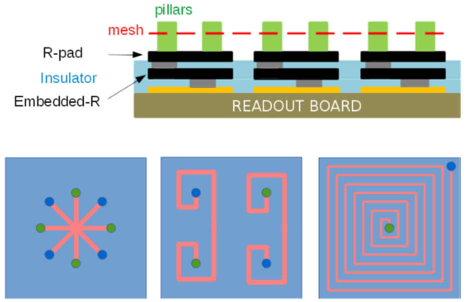
Re-introduced by ATLAS NSW micromegas for stability…

It is playing a key role in the field of MPGD and position sensitive detectors…

ATLAS NSW
Resistive strips

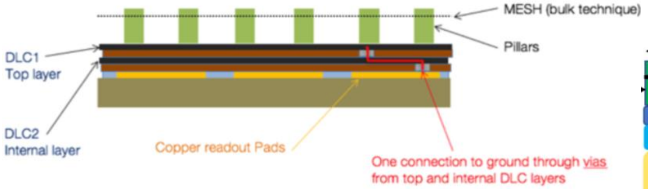


SCREAM (embedded resistors – introducing vertical evacuation)



https://lappweb.in2p3.fr/~chefdevi/Work_LAPP/Scream/Scream_paper.pdf

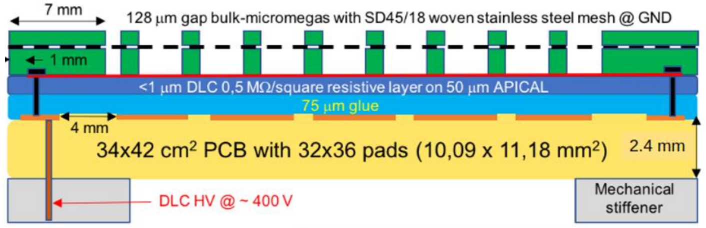
Small-Pad Resistive Micromegas



M. Iodice *et al* 2020 *JINST* **15** C09043

! *@PSD12 High Granularity Resistive Micromegas for high particle rates environment, Massimo Della Pietra*

T2K pad micromegas (resistive spreading)



Signal spread

Vertical charge evacuation = high rate/high multiplicities

Readout Layout / Resistive elements (II)

Re-introduced by ATLAS NSW micromegas for stability…

It offers the possibility of recover and develop new structures …

uRWELL detectors

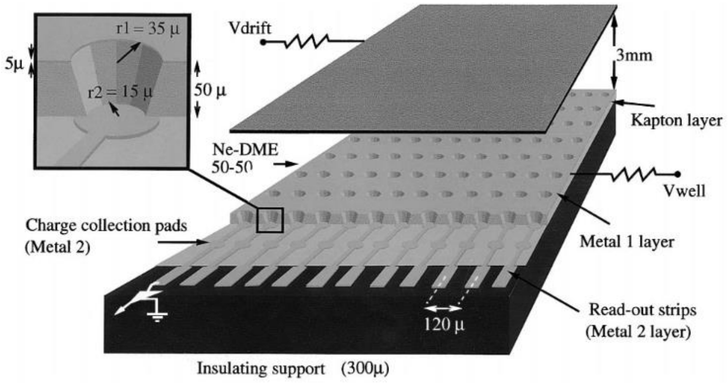
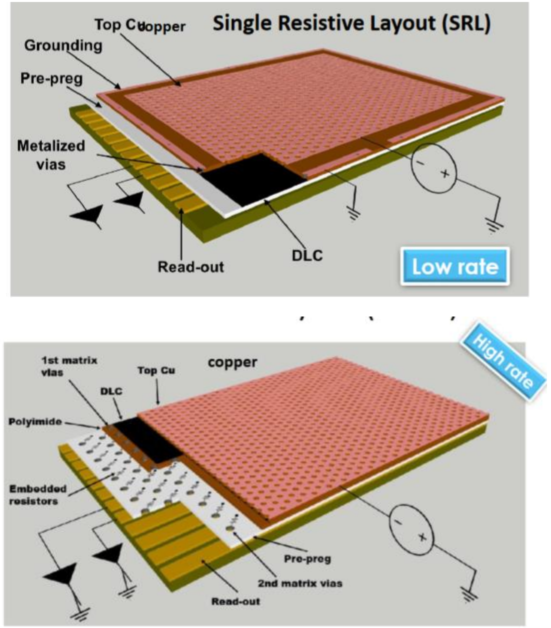
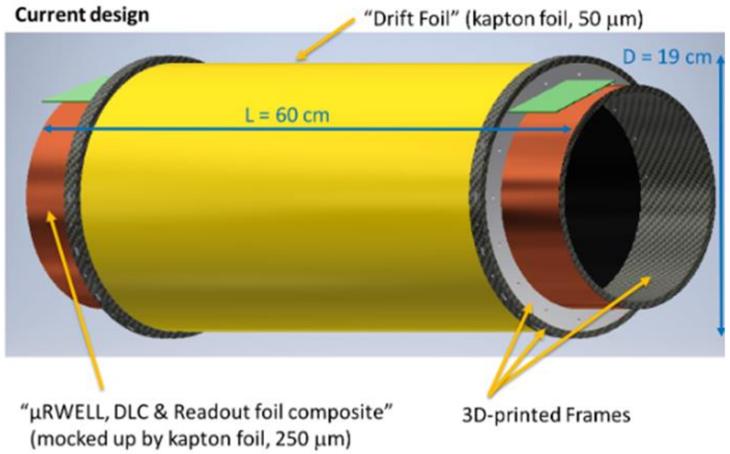


Fig. 1. Schematic diagram of a WELL detector.

R. Bellazzini et al.,The WELL detector,Nucl. Instrum. Meth.A 423(1999) 125.



G. Bencivenni et al., The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD, 2015 JINST 10 P02008



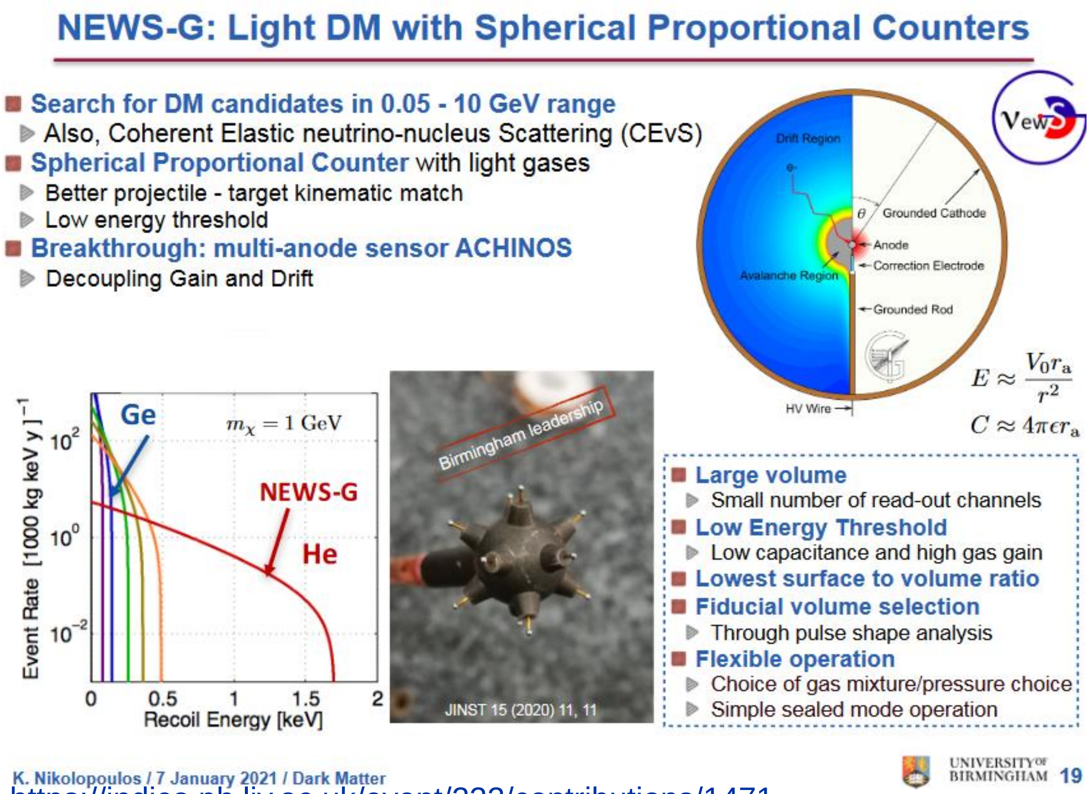
EIC Yellow Report Meeting March 19-21, 2020

! ***@PSD12** Precision tracking micro-pattern gaseous detectors at Budker INP, Timofei Maltsev*

Readout stage (coupled to charge/photons sensitive electronics)

Resistive elements (III) @ Birmingham…

Spherical Proportional Counter



https://indico.ph.liv.ac.uk/event/222/contributions/1471/attachments/710/912/20210107_kn_DarkMatter.pdf

! ***@PSD12:*** *ACHINOS: A multi-anode read-out for position reconstruction and tracking with spherical proportional counters, Dr Patrick Ryan Knights*

A resistive ACHINOS multi-anode structure with DLC coating for spherical proportional counters

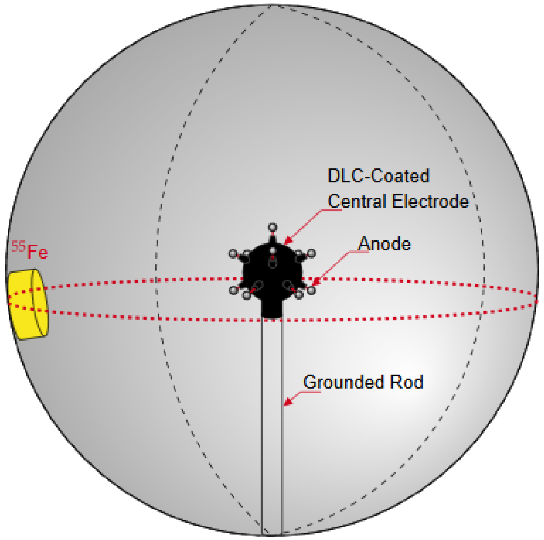
I. Giomataris[1], M. Gros[1], I. Katsioulas[2], P. Knights[1,2], J.-P. Mols[1], T. Neep[2], K. Nikolopoulos[2], G. Savvidis[3], I. Savvidis[4], L. Shang[5] + Show full author list

Published 12 November 2020 • © 2020 The Author(s)

Journal of Instrumentation, Volume 15, November 2020

Citation I. Giomataris *et al* 2020 *JINST* **15** P11023

Field uniformity & spark quenching



Additionally, it is possible to read out each anode individually, allowing the three-dimensional reconstruction of the ionisation tracks.

Charge sharing (resistive division)

Readout stage (coupled to charge/photons sensitive electronics)

Nuclear Instruments and Methods in Physics Research A 392 (1997) 244–248

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

An interpolating 2D pixel readout structure for synchrotron X-ray diffraction in protein crystallography

H.J. Besch, M. Junk*, W. Meißner, A. Sarvestani, R. Stiehler, A.H. Walenta

ZESS, Center for Sensor Systems, University of Siegen, Adolf-Reichwein-Strasse 2, 57068 Siegen, Germany

Abstract

The high rates available now at synchrotron beam lines ask for detectors allowing online measurements with good spatial resolution and a precise intensity measurement. For this purpose gaseous detectors operating in the single photon counting mode are well suited. An interpolating 2D pixel readout structure will be presented. It has been tested as backplane of a MSGC or a CAT-detector (recently developed by the group of M. Lemonnier at LURE), and it operates on the principle of resistive charge partition, allowing asynchronous readout. A resolution of 200 μm is reached. Under similar conditions the energy resolution from the signals of the readout structure presented is nearly the same as that of standard readout. In combination with a CAT an energy resolution of 20% is reached. A prototype of 64 channels with a sensitive area of 14 mm × 14 mm was tested at the synchrotron at LURE (Orsay). Diffraction patterns from a collagenase protein crystal were measured and rocking curves were obtained with an angular resolution of 1.5×10^{-5}.

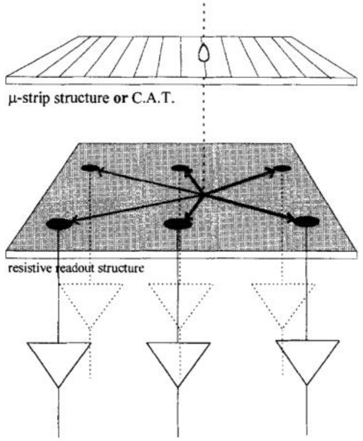


Fig. 1. 2D resistive charge division – schematic.

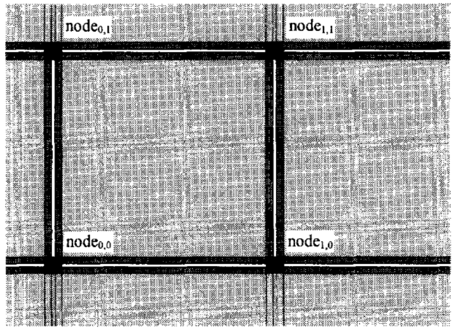


Fig. 2. Improved resistive cell, readout nodes for currents I_μ. Eq. (1): y is calculated analog.

https://www-sciencedirect-com.ezproxy.cern.ch/science/article/pii/S0168900297002799/pdfft?md5=9a977f8961fbe6a613a4d424c24358ab&pid=1-s2.0-S0168900297002799-main.pdf

On image reconstruction with the two-dimensional interpolating resistive readout structure of the Virtual-Pixel detector ⋆

H. Wagner [a,*], A. Orthen [a], H.J. Besch [a], S. Martoiu [a], R.H. Menk [b], A.H. Walenta [a], U. Werthenbach [a]

[a] Universität Siegen, Fachbereich Physik, Emmy-Noether-Campus, Walter-Flex-Str. 3, 57068 Siegen, Germany

[b] Sincrotrone Trieste, S.S. 14, km 163.5, Basovizza, 34012 Trieste, Italy

https://arxiv.org/pdf/physics/0310137.pdf

1.75mm cell, 200um resolution

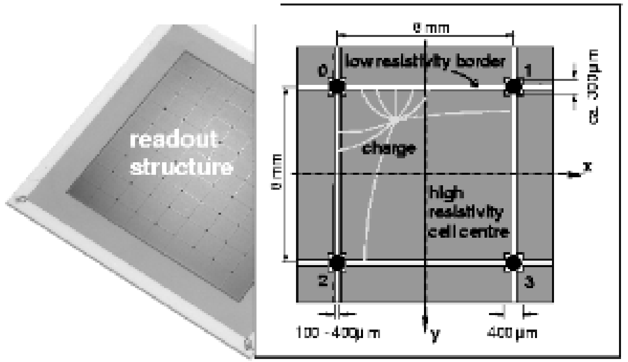


Fig. 1. Schematic of the two-dimensional interpolating resistive readout anode printed on a ceramic substrate. The gas gain structure (e.g. GEM or MicroCAT) is mounted above the anode. The structure is subdivided into 9 × 9 cells, whereby the inner 7 × 7 cells, corresponding to a sensitive area of 56 × 56 mm^2, can be read out. A detailed magnification of one single cell of the interpolating readout structure on a ceramic substrate is illustrated on the right hand side. The charge, generated by a photon, is collected by readout nodes situated at the cell corners (represented by the black circles). The robust readout structure itself is absolutely insensitive against sparking or uncontrolled discharges.

Charge sharing (resistive spread)

arXiv:physics/0307152v2 [physics.ins-det] 31 Oct 2003

Position Sensing from Charge Dispersion in Micro-Pattern Gas Detectors with a Resistive Anode

M. S. Dixit [a,d,*], J. Dubeau [b], J.-P. Martin [c] and K. Sachs [a]

[a] Department of Physics, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6 Canada
[b] DETEC, Aylmer, QC, Canada
[c] University of Montreal, Montreal, QC, Canada
[d] TRIUMF, Vancouver, BC Canada

Abstract

Micro-pattern gas detectors, such as the Gas Electron Multiplier (GEM) and the Micromegas need narrow high density anode readout elements to achieve good spatial resolution. A high-density anode readout would require an unmanageable number of electronics channels for certain potential micro-detector applications such as the Time Projection Chamber. We describe below a new technique to achieve good spatial resolution without increasing the electronics channel count in a modified micro-detector outfitted with a high surface resistivity anode readout structure. The concept and preliminary measurements of spatial resolution from charge dispersion in a modified GEM detector with a resistive anode are described below.

Key words: Gaseous Detectors, Position-Sensitive Detectors, Micro-Pattern Gas Detectors, Gas Electron Multiplier, Micromegas
PACS: 29.40.Cs, 29.40.Gx

1 Introduction

A new class of high-resolution multi-channel gas avalanche micro-detectors has been developed during the past decade for charged particle tracking. The Gas Electron Multiplier (GEM) [1] and the Micromegas [2] are examples of some of

* Corresponding author. Tel.: +1-613-520-2600, ext. 7535; fax: +1-613-520-7546. Email address: msd@physics.carleton.ca (M. S. Dixit).

Preprint submitted to Elsevier Science 31 October 2018

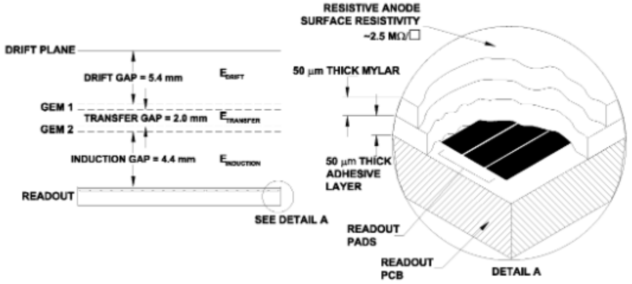


Fig. 1. Schematics of the resistive anode double-GEM detector used for charge dispersion studies.

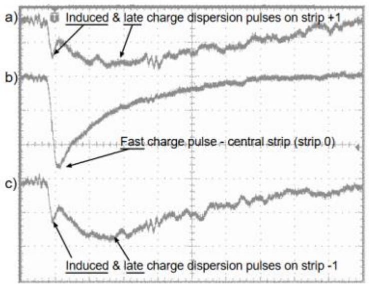
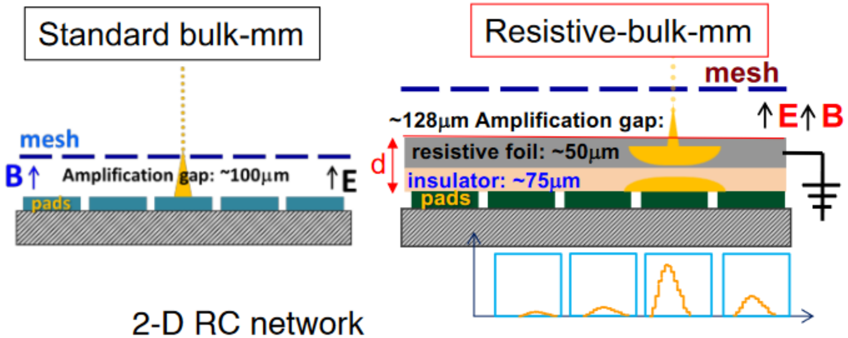
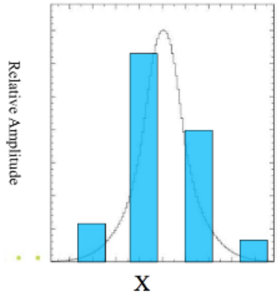


Fig. 4. Observed charge dispersion signals on three adjacent strips for a single x-ray photon conversion in the double-GEM detector. Tektronix scope pulses with 400 ns/div on the a) right strip (20 mV/div), b) central strip (50 mV/div) and c) left strip (20 mV/div).

https://arxiv.org/pdf/physics/0307152.pdf

T2K/ND280





2-D RC network

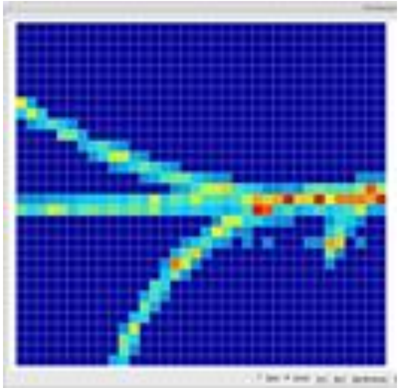
Gaussian spreading as a function of time with :

$$\rho(r,t) = \frac{RC}{2t}\exp\left[-\frac{r^2 RC}{4t}\right]$$

R- surface resistivity
C- capacitance/unit area

$$\sigma_r = \sqrt{\frac{2t}{RC}} \qquad \begin{cases} t \approx \text{shaping time (few 100 ns)} \\ RC_{[ns/mm^2]} = \dfrac{180\, R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}/175} \end{cases}$$

Pads 1cmx1cm



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https://indico.cern.ch/event/872501/contributions/3734984/attachments/1985334/3307899/MiniweekRD51_Lehuraux.pptx

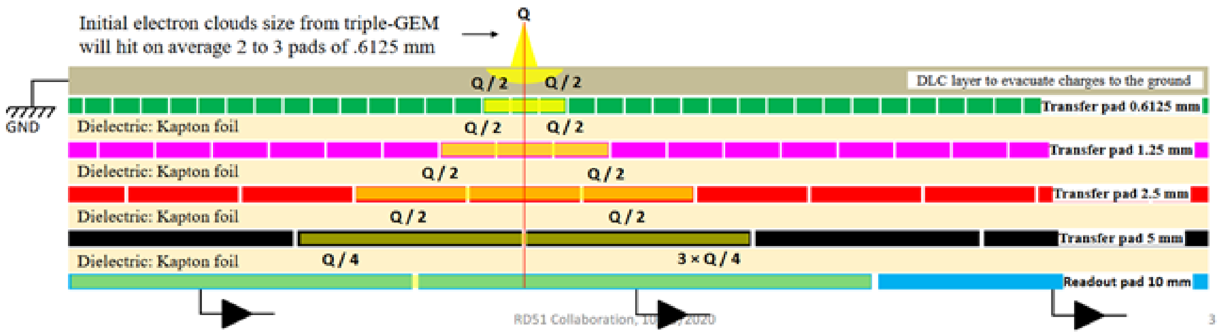
Charge sharing (Capacitive)

Readout: Space resolution / readout channels

CAPACITIVE SHARING

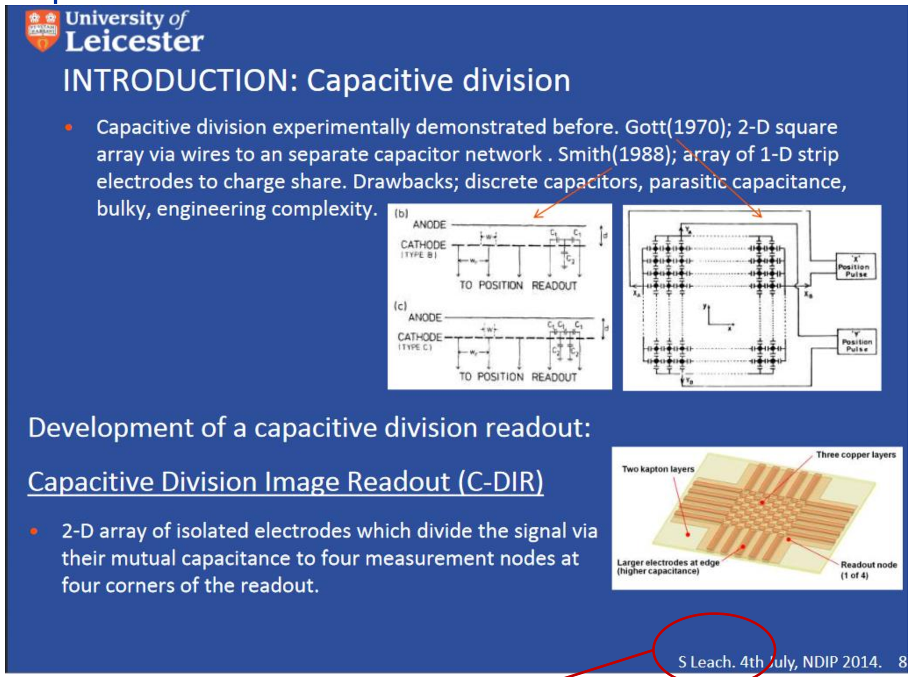
Preliminary Results of Spatial Resolution Performances of Capacitive Sharing Large Pad Readout in Test Beam

Kondo Gnanvo, University of Virginia, Charlottesville, US



https://indico.cern.ch/event/889369/contributions/4042739/attachments/2119963/3567713/20201009_KG_RD51_Coll_Meeting.pdf

Similar concept (capacitive network in the pcb) in capacitive division for MCP



http://ndip.in2p3.fr/tours14/AGENDA/AGENDA-by-DAY/Presentations/5Friday/AM/ID34315_Leach.pdf

S. Leach @PSD12 with "Extensive Air Shower Tracker using Cherenkov Detection"

Noise and cross talk under investigation for EIC.. encouraging preliminary results reported
Pro: easy to realize the coupling that you need (easier than with resistive layers), fast signals…

Readout stage (II) / M&S-FE

Focusing on current trends with potentially strong impact (personal comment) on position sensors (and resolution)

- Readout layouts and resistive elements (charge induced signals)
- **Modelling & Simulation and new FE electronics**
- High granularity Pixel readout (charge and photon)

Modelling & Simulation

Readout stage (coupled to charge/photons sensitive electronics)

D. Janssens, ***An update on the modelling of signal formation in detectors with resistive elements,*** June 17th, 2021, RD51 Collaboration Meeting

Electric fields, weighting fields, signals and charge diffusion in detectors including resistive materials

W. Riegler[1]

Published 7 November 2016 • © CERN 2016

Journal of Instrumentation, Volume 11, November 2016

Citation W. Riegler 2016 *JINST* **11** P11002

Abstract: In this report we discuss static and time dependent electric fields in detector geometries with an arbitrary number of parallel layers of a given permittivity and weak conductivity. We derive the Green's functions i.e. the field of a point charge, as well as the weighting fields for readout pads and readout strips in these geometries. The effect of 'bulk' resistivity on electric fields and signals is investigated. The spreading of charge on thin resistive layers is also discussed in detail, and the conditions for allowing the effect to be described by the diffusion equation is discussed. We apply the results to derive fields and induced signals in Resistive Plate Chambers, MICROMEGAS detectors including resistive layers for charge spreading and discharge protection as well as detectors using resistive charge division readout like the MicroCAT detector. We also discuss in detail how resistive layers affect signal shapes and increase crosstalk between readout electrodes.

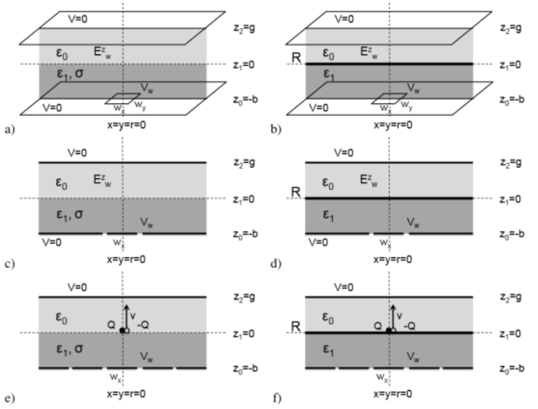
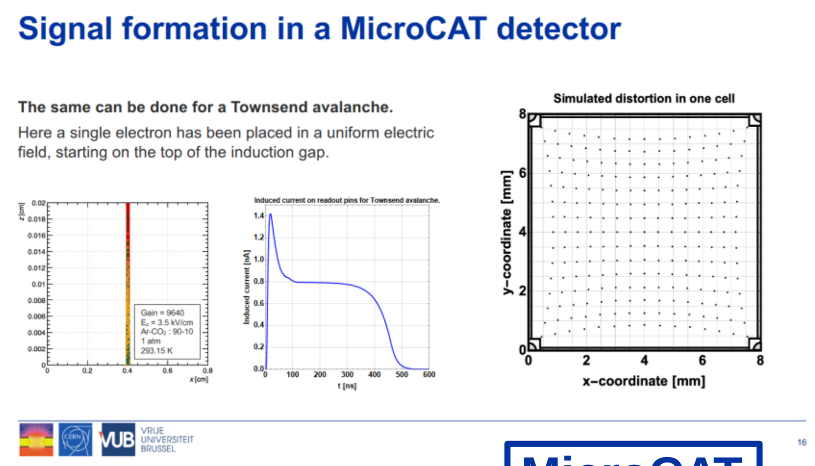
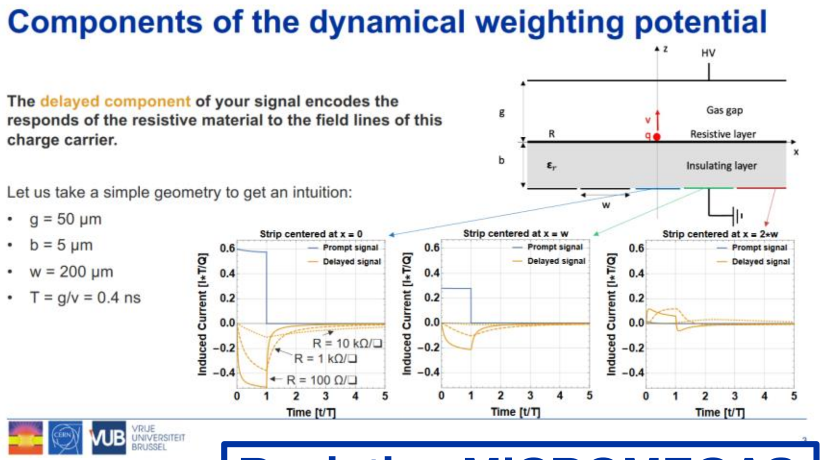


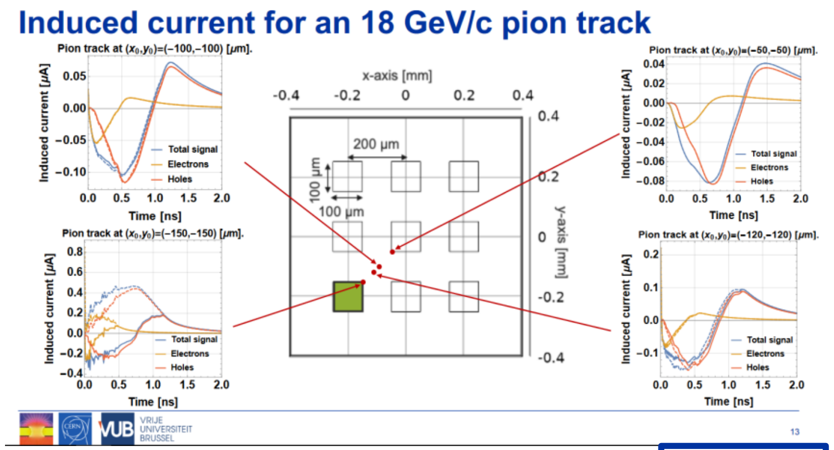
Figure 30. Weighting field for a geometry with a resistive layer having a bulk resistivity of $\rho = 1/\sigma[\Omega\text{cm}]$ (left) and a geometry with a thin resistive layer of value R [Ω/square] (right).



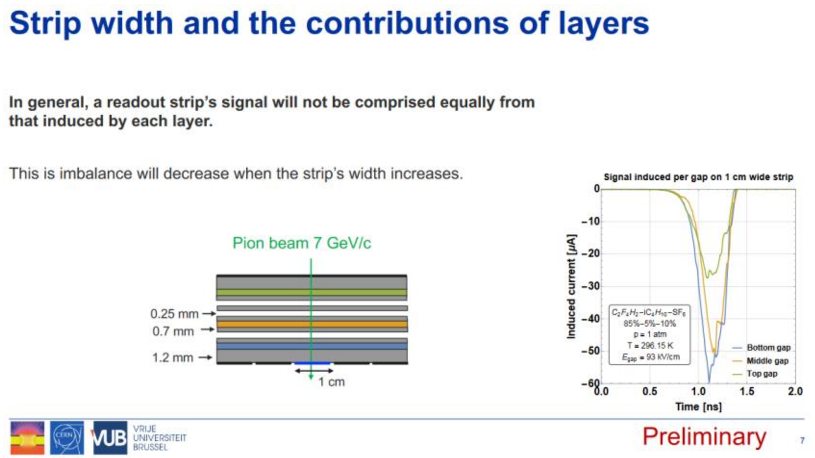
MicroCAT



Resistive MICROMEGAS



LGAD



mRPC

https://indico.cern.ch/event/1040996/contributions/4396429/attachments/2265907/3847202/RD51_DjunesJanssens_June2021.pdf

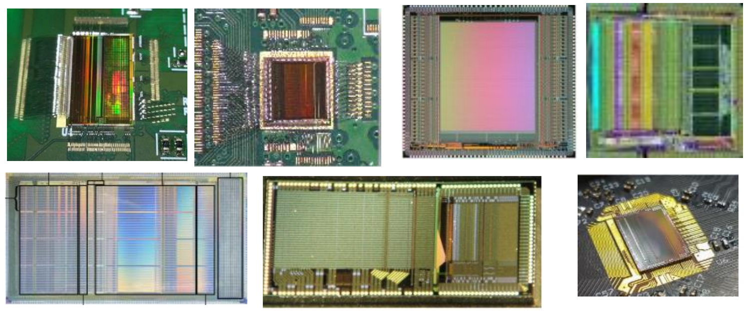
Multichannel Front End electronics

New developments in FE electronics, digitizers, TDC,.. can open to or drive new detection concept…

RD51 Topical Workshop on FE electronics for gas detectors

BIS78 RPC RO	Luca Pizzimento et al.	remote-only by Zoom	14:55 - 15:15
APIC, a study case for discrete detector electronics	Hans Muller	remote-only by Zoom	15:15 - 15:35
Discussion		remote-only by Zoom	15:35 - 15:55
Coffee Break		remote-only by Zoom	15:55 - 16:10
Fast Digitizer for Particle Physics	Nicola Minafra	remote-only by Zoom	16:10 - 16:25
Architecture of the SAMPIC digitizer	Dominique Robert Breton	remote-only by Zoom	16:25 - 16:40
Fast timing electronics R&D based on waveform digitization	Jiajun Qin et al.	remote-only by Zoom	16:40 - 16:55
TimePix and MediPix	Michael Campbell	remote-only by Zoom	17:00 - 17:20
Pixel Integration - GridPix	Jochen Kaminski	remote-only by Zoom	17:20 - 17:40
Pixel Integration - GEMPix	Fabrizio Murtas	remote-only by Zoom	17:40 - 18:00
Pixel chip development for tracking type gaseous detectors	Anatoli Romaniouk	remote-only by Zoom	18:00 - 18:15

https://indico.cern.ch/event/1051087/timetable/#all.detailed



ROC (OMEGA) Family	Stephane CALLIER et al.	remote-only by Zoom	14:30 - 14:40
nXYTER	Krzysztof Kasiński et al.	remote-only by Zoom	14:40 - 14:50
GEMROC (AGH)	Tomasz Andrzej Fiutowski	remote-only by Zoom	14:50 - 15:00
TIGER	Manuel Dionisio DA ROCHA ROLO et al.	remote-only by Zoom	15:00 - 15:10
New ASIC (INFN TO)	Manuel Dionisio DA ROCHA ROLO et al.	remote-only by Zoom	15:10 - 15:20
VFAT	Francesco Licciulli	remote-only by Zoom	15:20 - 15:30
New ASIC (INFN Ba)	Francesco Licciulli	remote-only by Zoom	15:30 - 15:40
VMM	George Iakovidis	remote-only by Zoom	15:40 - 15:50

AFTER/AGET	Pascal Baron	remote-only by Zoom	16:10 - 16:20
SAMPA	Marco Bregant	remote-only by Zoom	16:20 - 16:30
New ASIC (TPC)	Damien Neyret et al.	remote-only by Zoom	16:30 - 16:40
WASA	Zhi Deng et al.	remote-only by Zoom	16:40 - 16:50
PADI	Mircea Iuliu Ciobanu	remote-only by Zoom	16:50 - 17:00
GEMINI	abba andrea	remote-only by Zoom	17:00 - 17:10
PicoTDC	Jorgen Christiansen	remote-only by Zoom	17:10 - 17:40

new structures/M&S/ new FE electronics + old strategies…

GAS PROPORTIONAL DETECTORS
WITH INTERPOLATING CATHODE PAD READOUT
FOR HIGH TRACK MULTIPLICITIES

Bo Yu

December 1991

Instrumentation Division
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, New York 11973

https://inis.iaea.org/collection/NCLCollectionStore/_Public/23/040/23040284.pdf

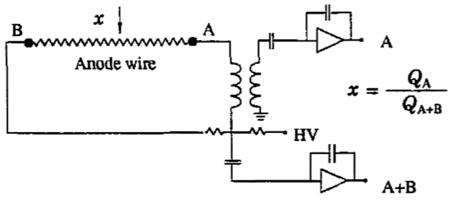


Figure 3.1.1: Schematics of a large scale MWPC with resistive charge division

Resistive Charge Division

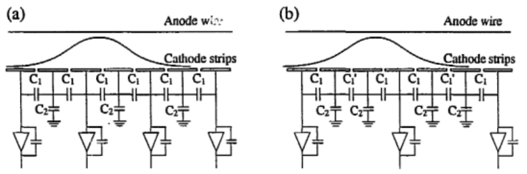


Figure 3.3.1: Examples of the capacitive charge division method. (a) Single Intermediate Strip method; (b) Two Intermediate Strip method.

Capacitive Charge Division

Encoding

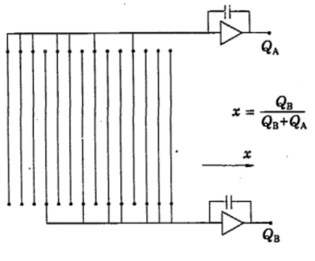


Figure 3.2.3: Graded Density Cathode

Delay lines

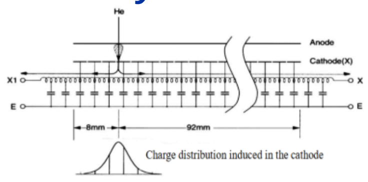


Fig. 8. Equivalent circuit of the delay-line PPAC detector.

https://arxiv.org/ftp/arxiv/papers/1311/1311.0215.pdf

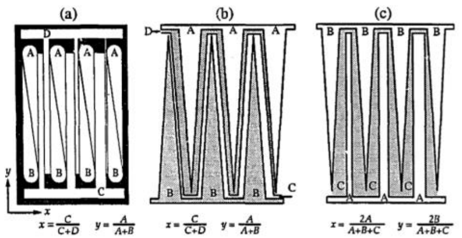
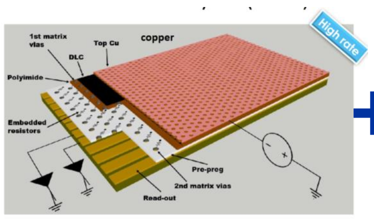


Figure 3.2.1: (a) The original wedge and strip electrode developed by Anger. (b, c) Variations of the wedge and strip pattern.

Geometrical Charge Division



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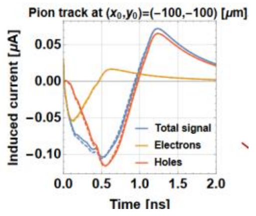

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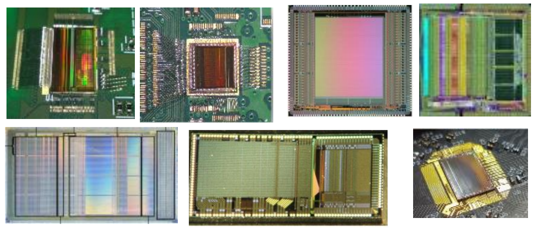


“Old” readout concepts can be reviewed/revisited by the existing and future FE electronics

Resistive Strips Micromegas & APV25 (MAMMA/ATLAS NSW)

Readout stage (coupled to charge/photons sensitive electronics)

https://iopscience.iop.org/article/10.1088/1748-0221/7/02/C02060/pdf

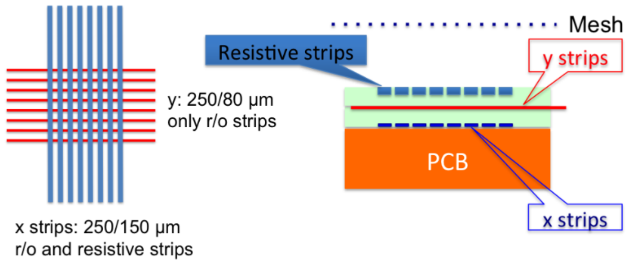
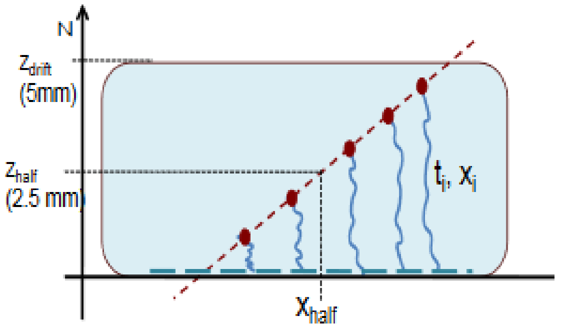
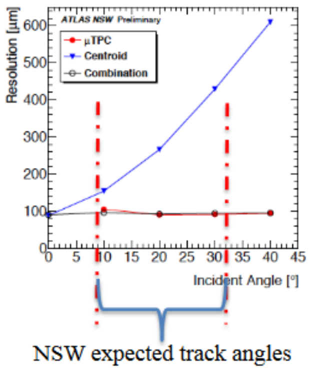


Figure 2. X-Y chamber schematics. Left. Strip layout. The bottom X readout strips are parallel to the resistive strips. The Y strips are at 90°. Right. Vertical cross-section. The X readout strips and the resistive strips are going into the figure.

- X strips (parallel to resistive strips): Main signal component induced by e-/ions moving in the gas (prompt).
- Y strips (perpendicular to resistive strips): Sensitive to the Signal induced by e-/ions moving in the amp. Gap and by charge movement in the resistive strips





µTPC introduced by MAMMA (ATLAS NSW mm) collaboration (*)

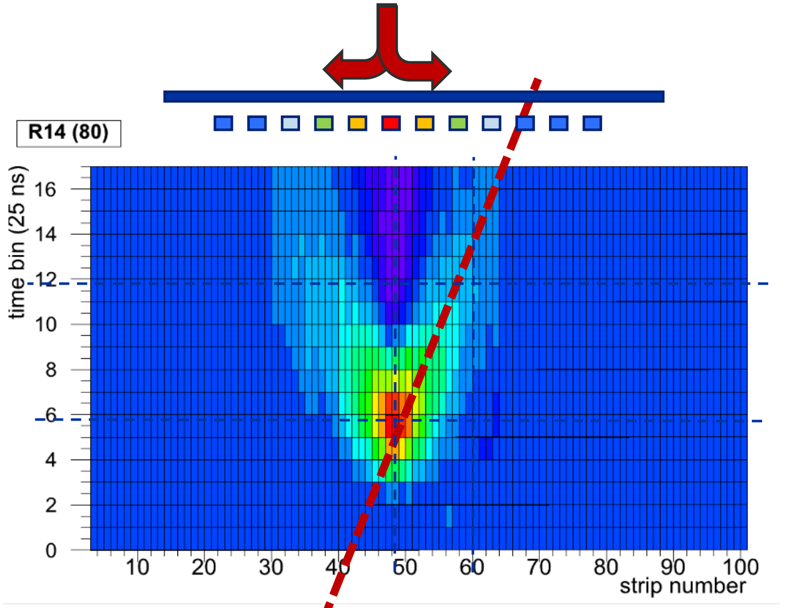


Figure 4. Intensity plot of ADC counts in the R14 chamber plotted against strip number on the horizontal axis and the time bin number (25 ns) on the vertical axis.

ΔT=6*25ns=150ns
ΔY=12*250um
Speed=2cm/µsec

@PSD12

! *Position reconstruction studies with GEM detectors and the charge-sensitive VMM3a ASIC, Lucian Scharenberg*

The Topmetal-CEE Prototype, a Direct Charge Sensor for the Beam Monitor of the CSR External-target Experiment, Dr Chaosong Gao

A Novel Front-End Amplifier for Gain-less Charge Readout in High-Pressure Gas TPC, Dr Chaosong Gao

A congestion awareness and Fault-tolerance Readout Network ASIC for High-Density Electrode Array Targeting Neutrinoless Double-Beta Decay Search in TPC, bihui you

(*) APV25 readout in R&D phase, now performed with BNL/ATLAS VMM3a ASIC

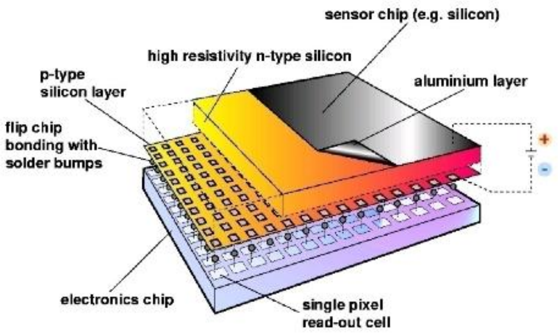
Readout stage (III) / Pixel

Focusing on current trends with potentially strong impact (personal comment) on position sensors (and resolution)

- Readout layouts and resistive elements (charge induced signals)
- Modelling & Simulation and new FE electronics
- **High granularity Pixel readout (charge and photon)**

Pixel / Charge Readout

MPGD on pixel ASICs (here Timepix)



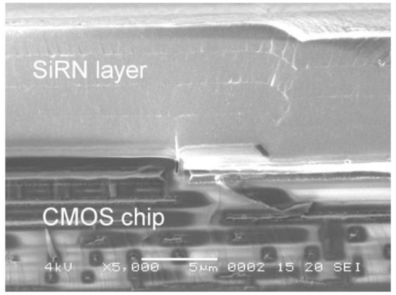


Fig. 3. Cross section SEM picture of a Timepix chip covered with 9 µm SiRN.

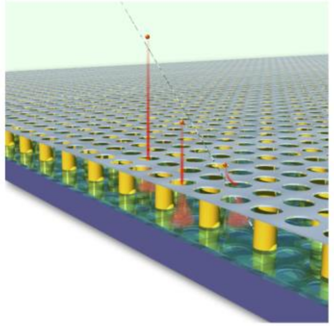
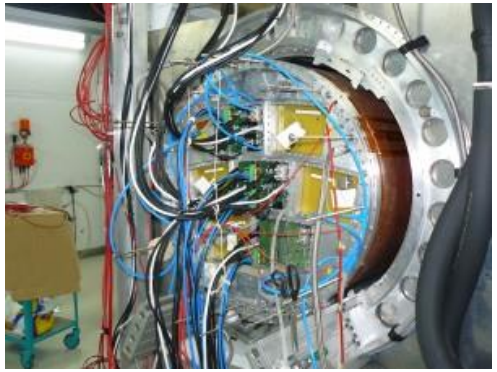
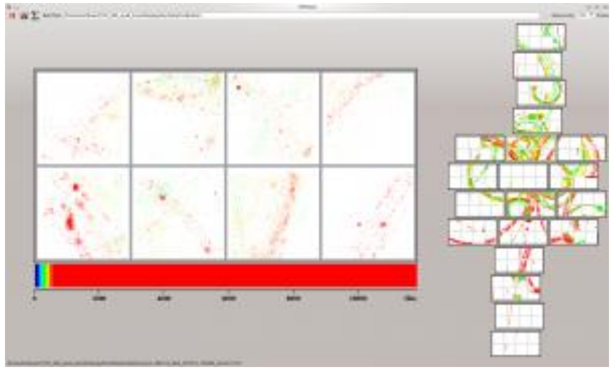


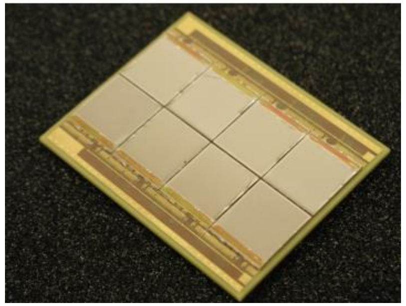
Fig. 1. The InGrid detector. Electrons from the drift volume cause an avalanche in the gap between the pixel chip and the grid.

! *@**PSD12** GridPix: the ultimate electron detector for TPCs, Harry Van Der Graaf*

3D reconstruction (amplitude, position and time)
Implemented on both mm or GEM structures
Proven to be able to cover reasonably large surfaces by tiling the ASICs

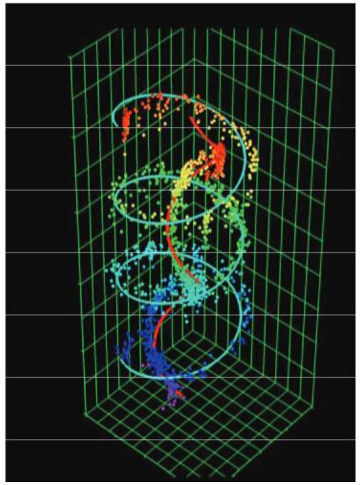






https://newsline.linearcollider.org/2015/04/16/ingrids-on-the-rise/

Pixel / Charge Readout



Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 17 (2011) 224–231
Physics Procedia

Physics of Fundamental Symmetries and Interactions – PSI2010

Gaseous and gasless pixel detectors

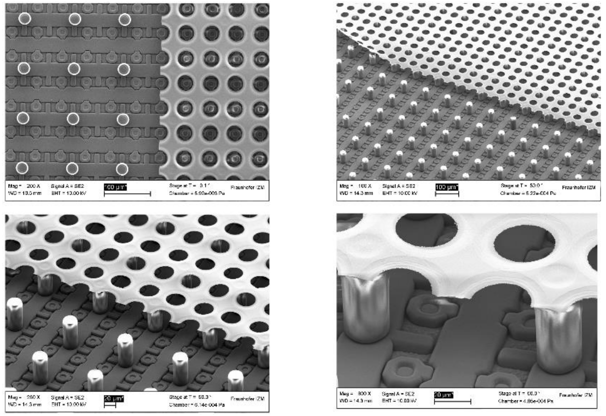
Harry van der Graaf

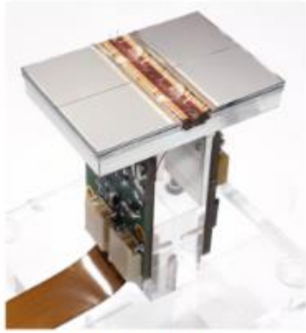
Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands

Fig. 2. Two ß's from a ^{90}Sr source, recorded with a Timepix based GridPix detector. Drift length: 30 mm. Gas: He/i-butane 80/20, with a magnetic field of 0.2 T oriented parallel to the (vertical) drift field. The bottom plane represents the Timepix chip (256 x 256 pixels; square pixel pitch 55 µm).

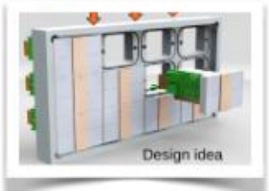
Direct coupling with pixel chips (charge readout/sensor removed – just readout)

Micromegas





QUAD module with fill factor of 68.9%



https://indico.cern.ch/event/581417/contributions/2522462/attachments/1465797/2265982/GridPix_TP3.pdf

GEM

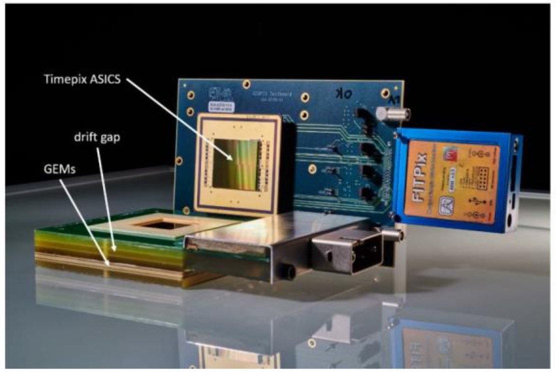


Figure 1. The open GEMPix, showing the four Timepix ASICs and the FITPix readout module. The position of the drift gap and the GEMs is labelled (source: CERN).

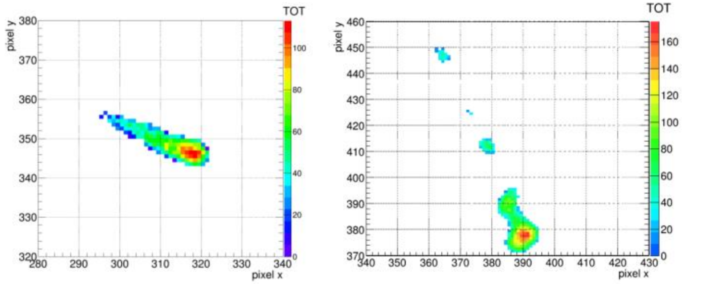


Figure 15. Examples of particle tracks measured with the GEMPix: a proton track (from neutron irradiation) with a visible increase in the energy deposition towards the end of the track (**left**) and an electron track (from ^{137}Cs irradiation, **right**).

Appl. Sci. **2021**, *11*(1), 440; https://doi.org/10.3390/app11010440

using what has been learned to extend to other "appealing" pixel chips

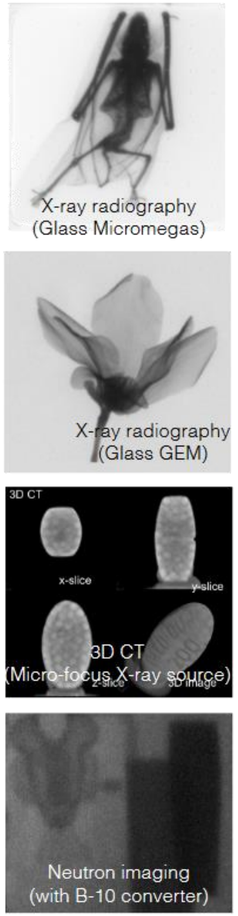
Pixel / Photon Readout

Optical readout

Linked to technological developments and costs..
Versatile readout (lenses, image intensifier,..)..
Hybrids solution can recover third coordinate
Becoming more and more fast..

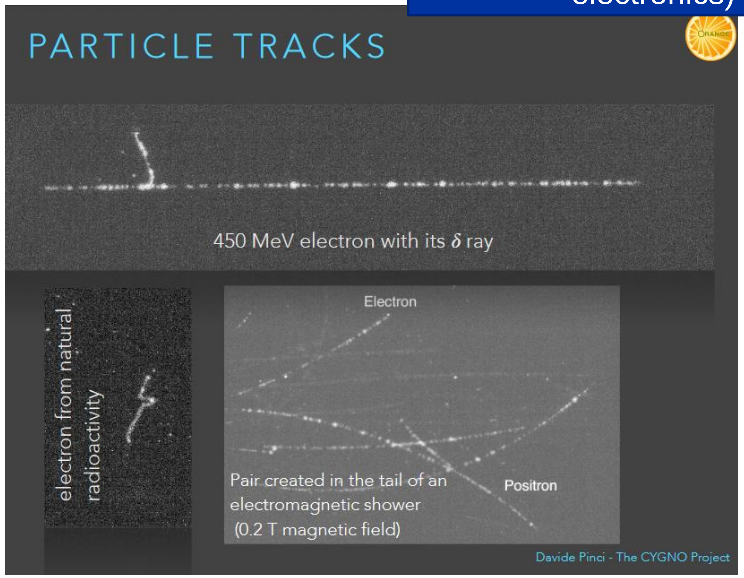
Optical readout, novel readout electrodes, hybrids with ASICs, F.M.Brunbauer (CERN GDD), April 29, 2021 - ECFA Detector R&D Roadmap Symposium - TF1 Gaseous Detectors

! ***@PSD12:*** *F. Brunbauer, High-granularity optical and hybrid readout of gaseous detectors: developments and perspectives*



F. Brunbauer et al., Radiation imaging with glass Micromegas, https://doi.org/10.1016/j.nima.2019.163320

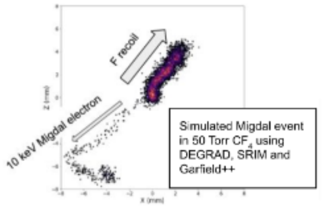
T. Fujiwara, MPGD 2017, https://indico.cern.ch/event/581417/contributions/2556685/attachments/1464089/2262562/MPGD2017_fujiwara.pdf



https://indico.cern.ch/event/757322/contributions/3396494/attachments/1841021/3018431/Cygno_MPGD19.pdf

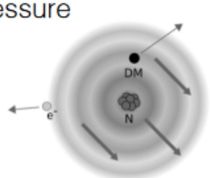
MIGDAL
Migdal In Galactic Dark mAtter expLoration

Low-pressure TPC with optical+electronic readout



Migdal effect search in low-pressure CF_4 for DM searches in

CMOS + electronic readout of **transparent strip anode**

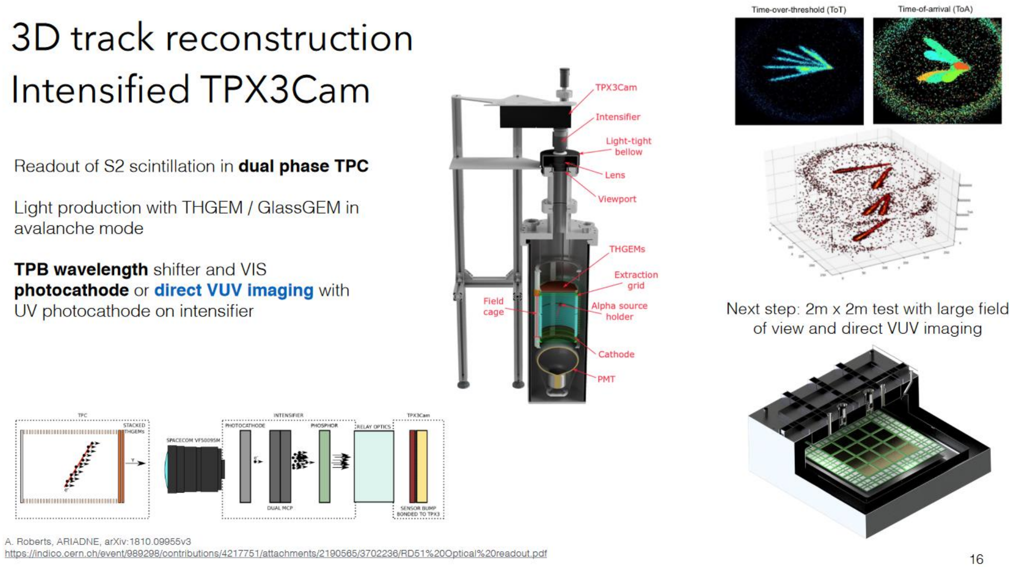


P. Majewski, RD51 Mini-Week 2020, https://indico.cern.ch/event/872501/contributions/3730586/attachments/1985262/3307758/RD51_mini_week_Pawel_Majewski_ver2.pdf

! ***@PSD12:*** *M. Nakhostin & T. Neep, Towards the first observation of the Migdal effect in nuclear scattering I. Design and construction of the MIGDAL experiment*

Pixel / Photon Readout / Position & Timing

Photon & Time & Timepix (ARIADNE)



https://indico.cern.ch/event/999799/contributions/4204161/attachments/2235612/3789884/OpticalHybridReadout.pdf

Photon & Time & SiPM

2.3 The LG-SiPM

The Linearly Graded Silicon Photomultiplier (LG-SiPM) has been designed as a new type of position-sensitive SiPM [19]. When a photon hits the sensor's active area, the current generated by the SiPM microcells is split into four outputs, from which it is possible to calculate the photon's x and y coordinates, down to a theoretical spatial resolution equal to the size of the microcells - on the order of 30 μm. The LG-SiPM has a fast time response - typically on the order of a few tens of ns, and more recent SiPM designs show the possibility of reducing this response time down to less than 5 ns [20].

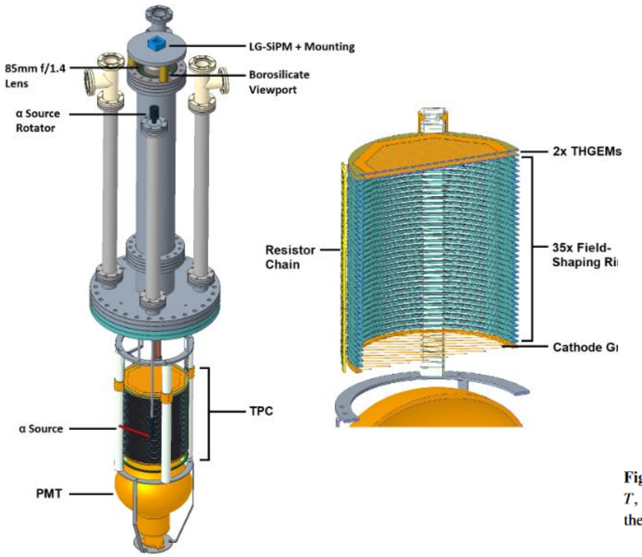
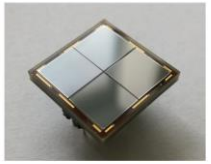


Figure 1. (Left) A 3D model of the Liverpool 40l TPC, with key components labelled. For clarity, the outer wall of the vacuum chamber has been omitted. (Right) A closeup view of the TPC, with key components labelled. The THGEMs are separated by 4 mm, as are the bottom THGEM and the top-most field-shaping ring.



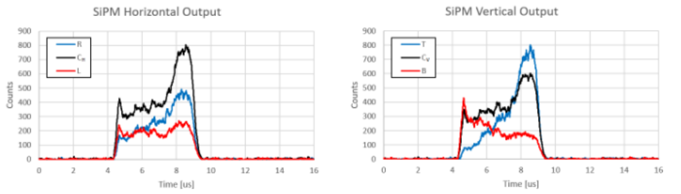


Figure 8. The α-induced LG-SiPM signals from the x axis channels L, C_H and R (left) and y axis channels T, C_V and B (right). This event was recorded at a V_{bias} of -34 V. The origin of the time axis corresponds to the global event trigger as discussed in Section 2.6.

! *@**PSD12** New developments on FBK position sensitive silicon photomultipliers, Stefano Merzi*

Conclusions

Micro Pattern Gas Detectors are **a versatile solution** to develop position sensors for a wide spectrum of applications Technology is able to adapt to a wide range of requirements thanks to the **variety** of micro patterns solutions available, their reciprocal **compatibility**, the achieved **skills in manufacturing techniques** and the available **readout options (charge/photons)**.

In the **charge readout domain** a **rich set of readout solutions/layouts are available** to be used to optimize the detector response to the specific needs of the experiment/application (preserving **good performances in large system** with reasonable **number of channels**). **Resistive elements** are playing today a key role in most of the new developments.

Accurate detector modelling and simulation plus **new FE electronics with unprecedented characteristics** will surely open to new ideas/concept/designs and will further improve current performances.

Pixel readout very attractive and well progressing

- in the **charge domain** … using what learned with Timepix to **extend** to other appealing pixel chips
- in the **photon domain**… … very fertile fields.. new sensors, coupling devices, hybrids solution, SiPM, wavelength shifters.. A lot of fields/technologies to **explore**…