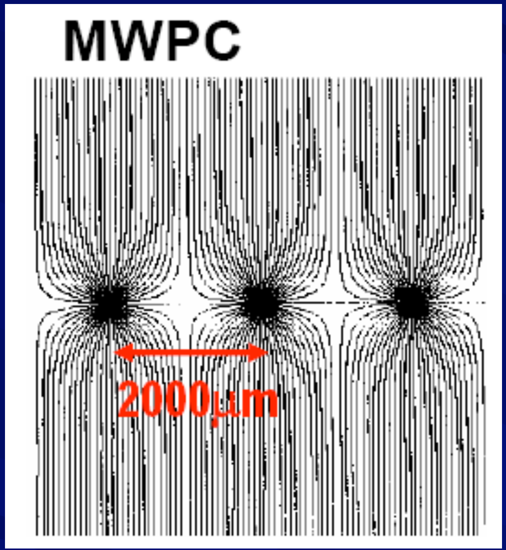
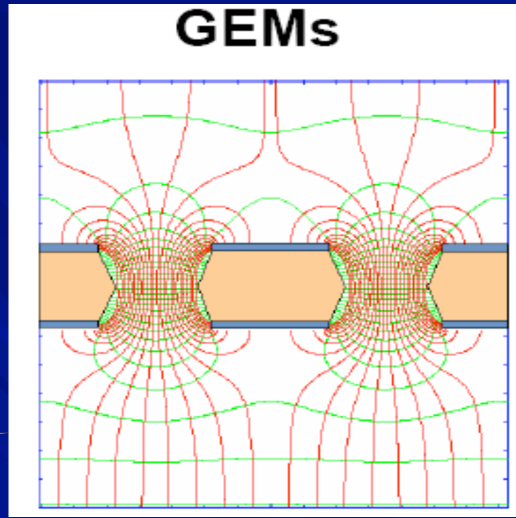


Gaseous detectors

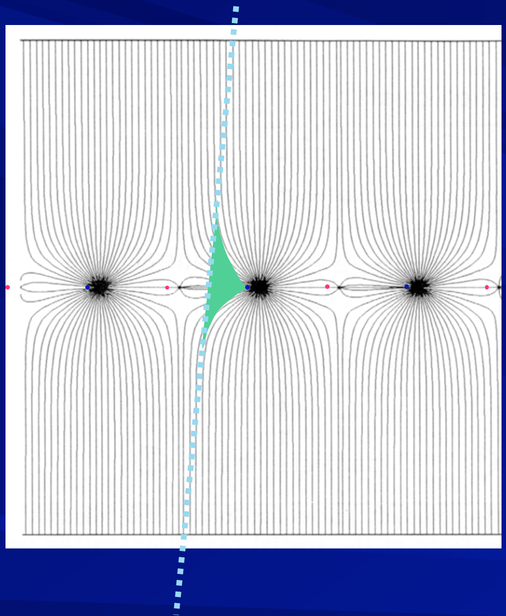
From basics ideas
to
complex systems



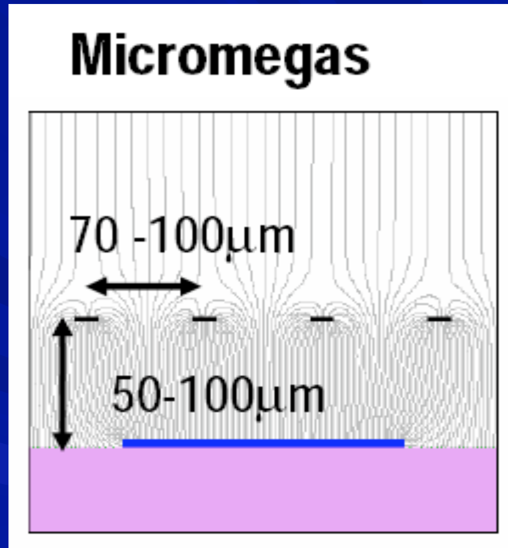
By P. Le Dû

dapnia
cea
saclay

patrick.le-du@cea.fr



Drift Chamber



MPGD
MicroPattern
Gas Detectors

Thanks to Fabio Sauli (CERN)
And to Maxim Titov, SPP/DAPNIA/CEA Saclay

Example: Gaseous Detector in the LHC Experiments

ALICE: TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)

ATLAS: TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)

CMS: Muon detector (drift tubes, CSC), RPC (muon trigger)

LHCb: Tracker (straw tubes), Muon detector (MWPC, GEM)

Present

Relativistic Heavy Ion Collider at Brookhaven

High particle multiplicities
Low beam intensities

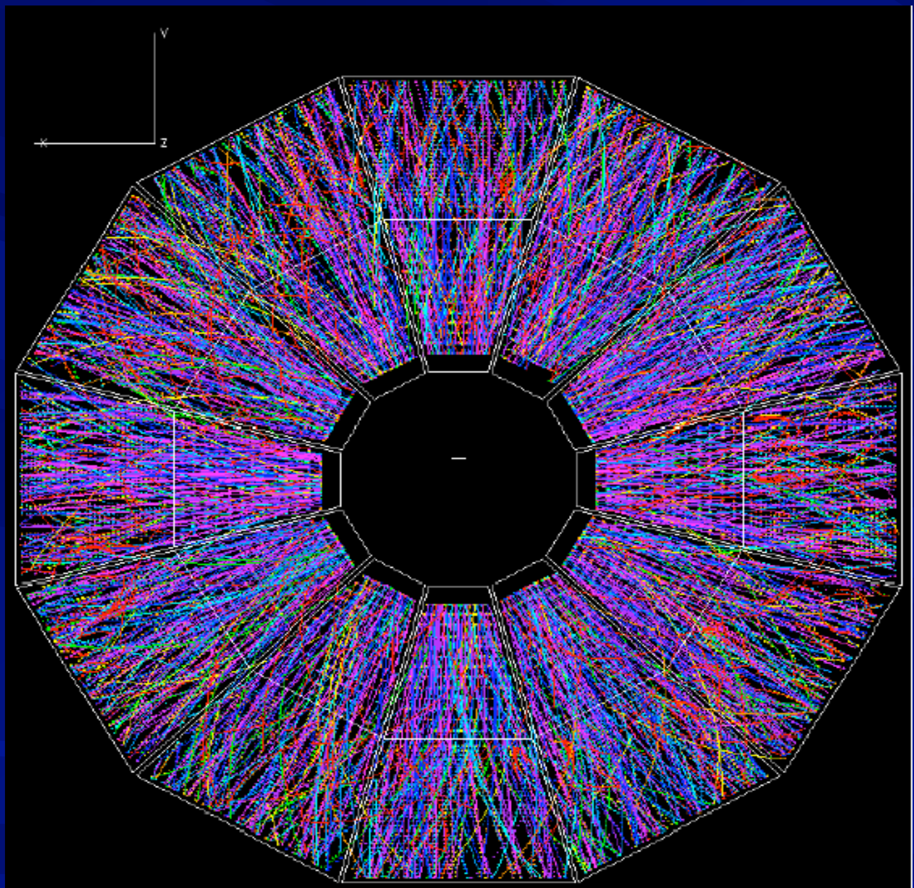


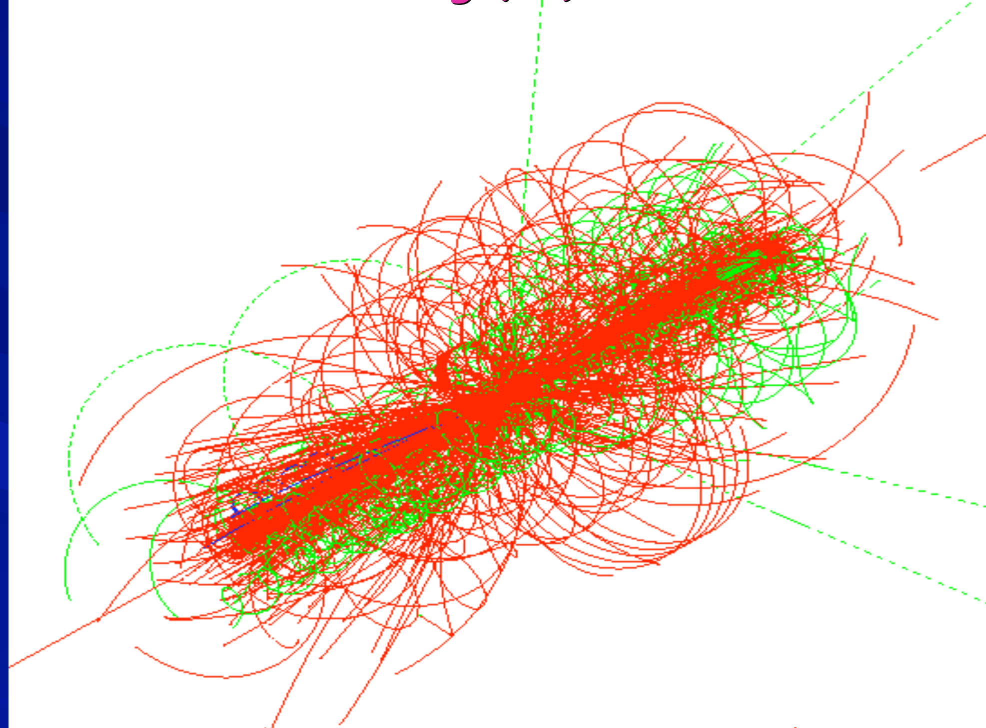
Image of Au-Au collision in STAR Time Projection Chamber (TPC)

Future

ATLAS and CMS Experiments at CERN:

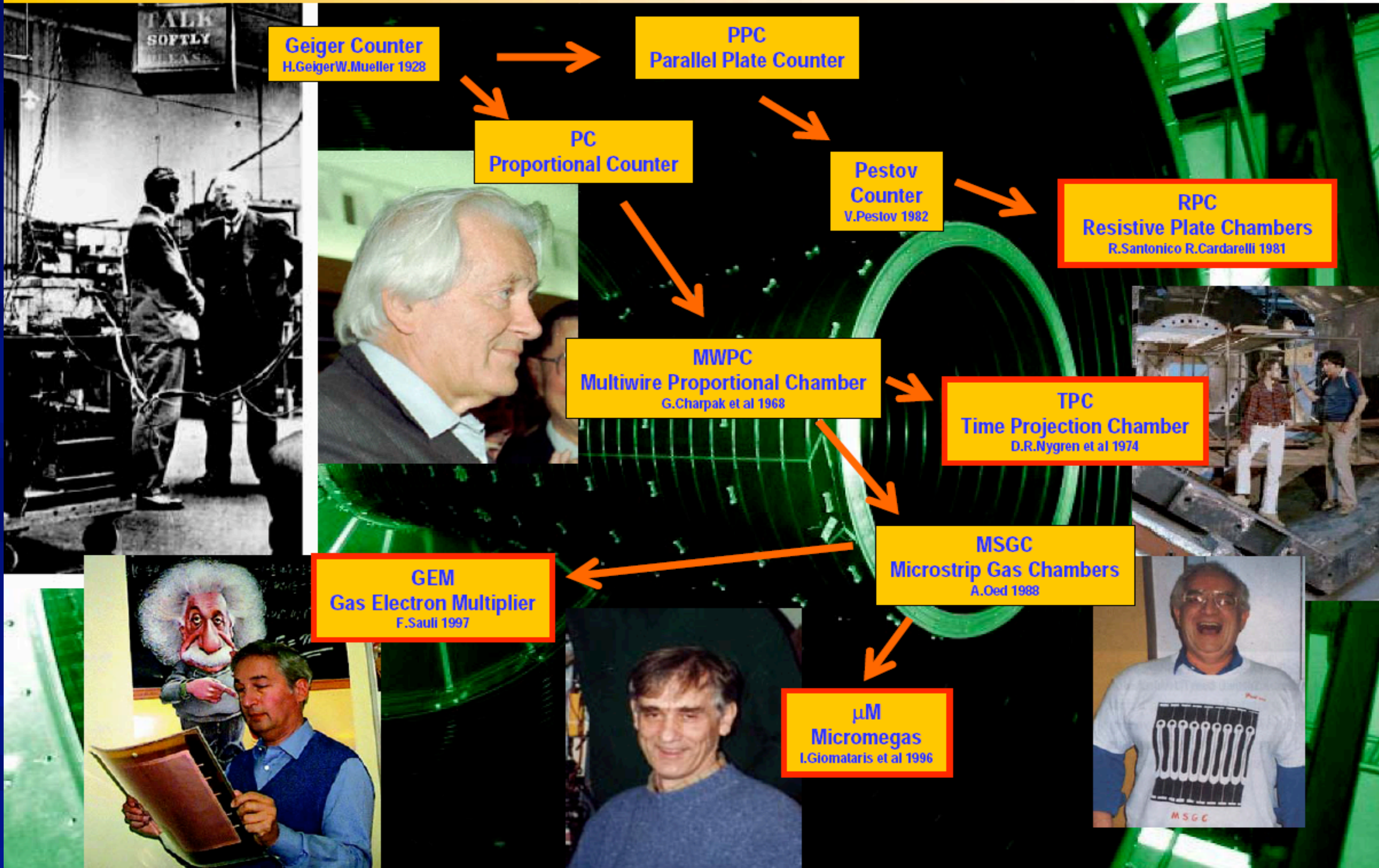
High particle multiplicities
High beam intensities

pp collision at Ös = 14 TeV
Bunch crossing (BC) each ~ 25 ns



- *23 overlapping minimum bias events / BC*
- *1900 charged + 1600 neutral particles / BC*

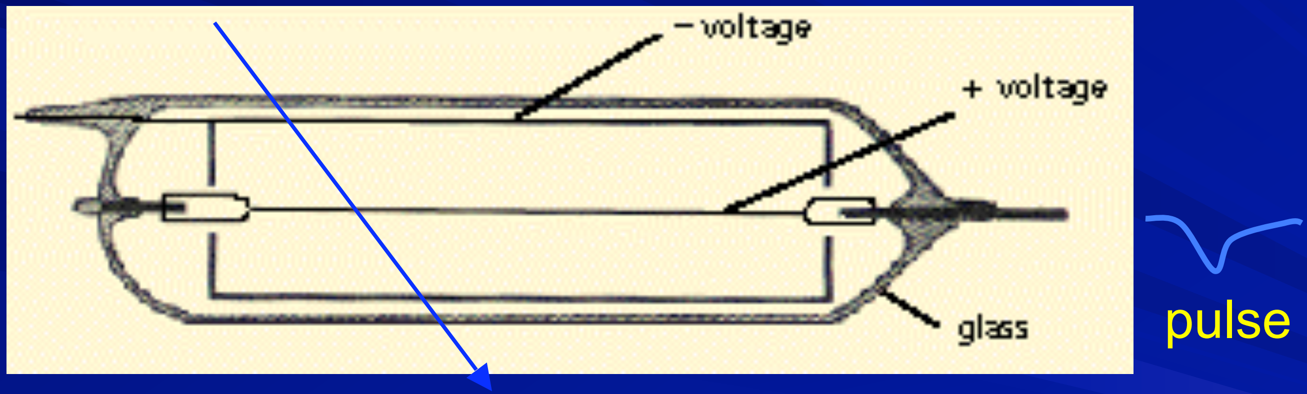
Gas Detector History



Geiger Counter

E. Rutherford 1909

H. Geiger



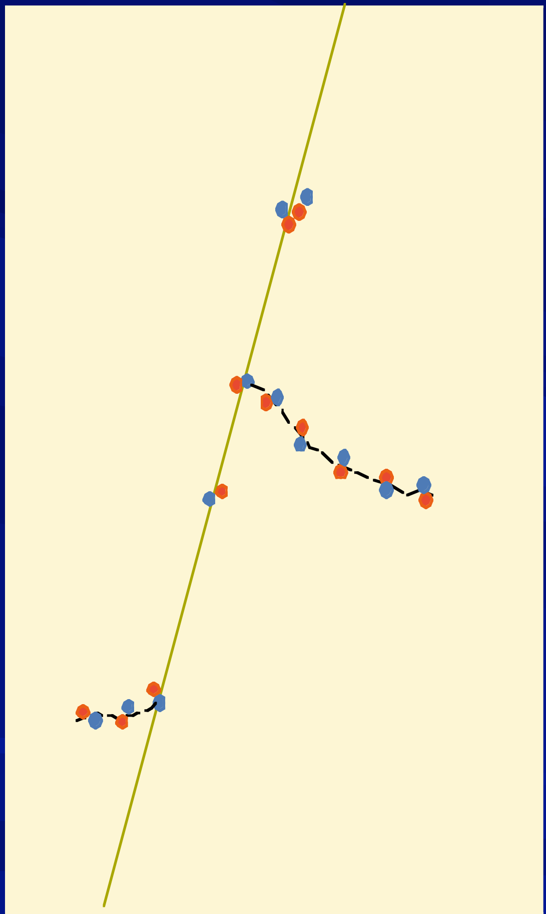
The Geiger counter, later further developed and then called Geiger-Müller counter

First electrical signal from a particle

Energy Loss due to Electromagnetic Interaction (1)

TOTAL IONIZATION:

- **Primary electron-ion pairs**
- **Clusters**
- **Delta-electrons**



Statistics of primary ionization:

Poisson: $P_k^n = \frac{n^k}{k!} e^{-n}$

n: *average*
k: *actual number*

Detection efficiency of a perfect detector is limited to:

$e = 1 - e^{-n}$

GAS (STP)	*thickness*	*e (%)*
Helium	1 mm	45
	2 mm	70
Argon	1 mm	91.8
	2 mm	99.3

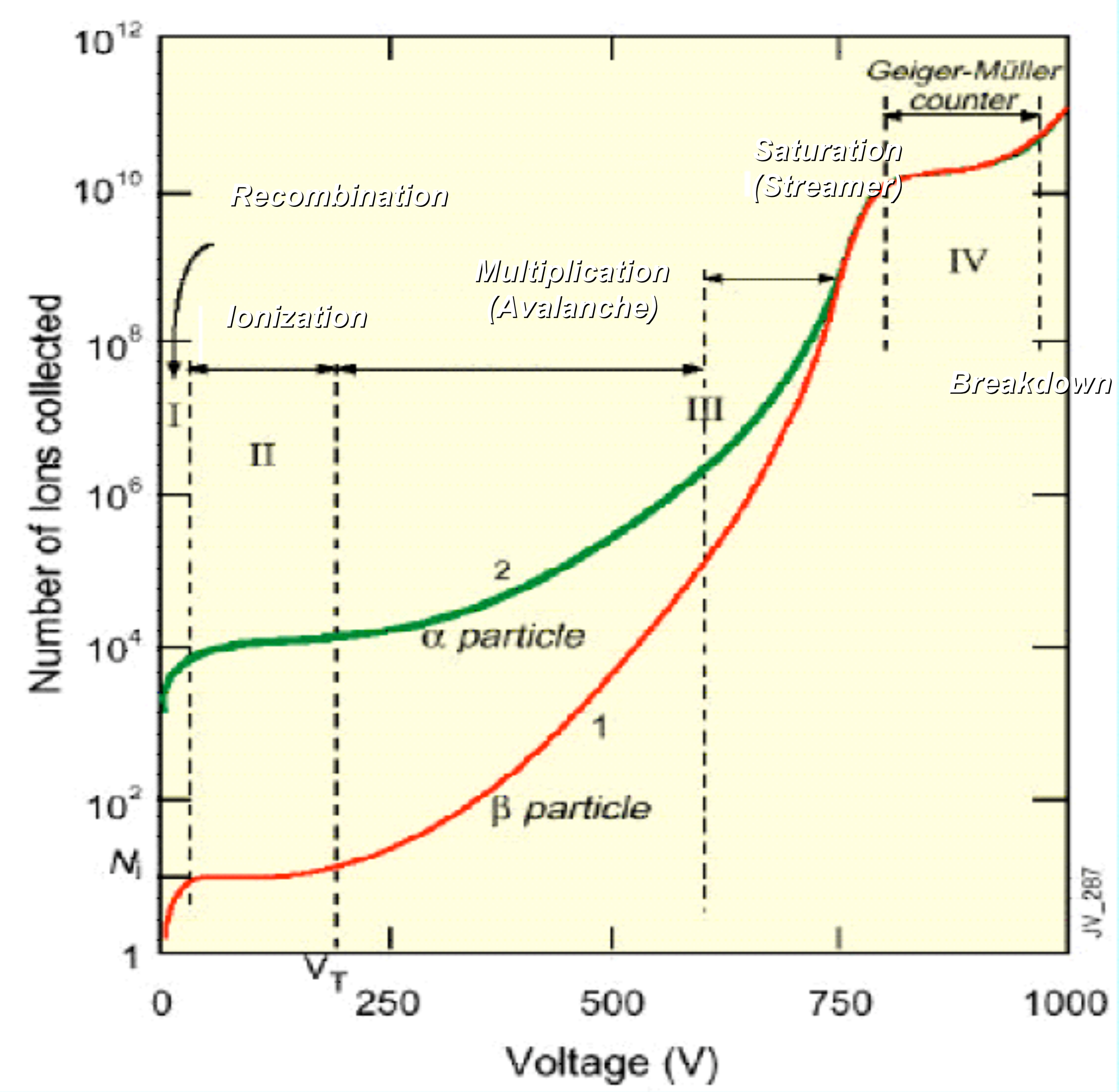
Minimum ionizing particles - total number N of ion-electron pairs subject to non-Poissonian fluctuations (Landau tails):

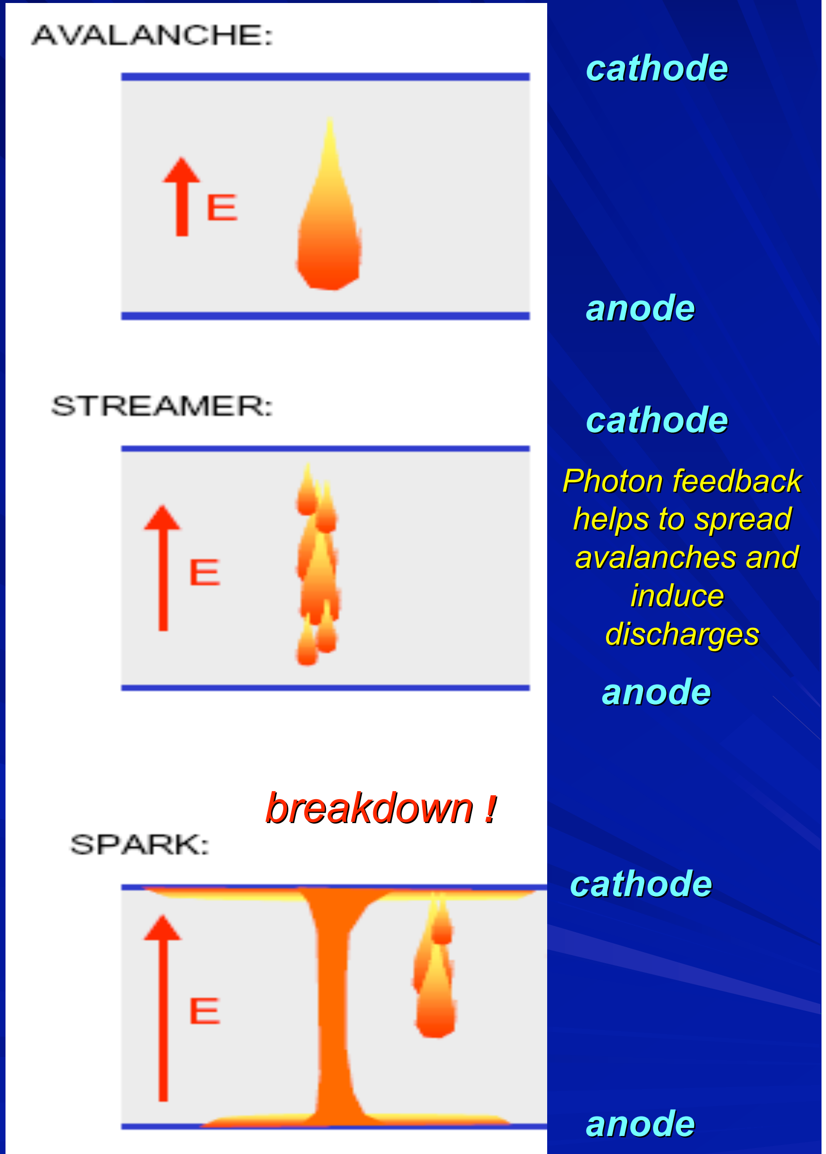
GAS (STP)	Helium	Argon	Xenon	CH_4	DME
n (ion pairs/cm)	6	25	44	16	55
N (ion pairs/cm)	8	90	300	53	160

N: total ion-electron pairs to < N / n > ~ 3

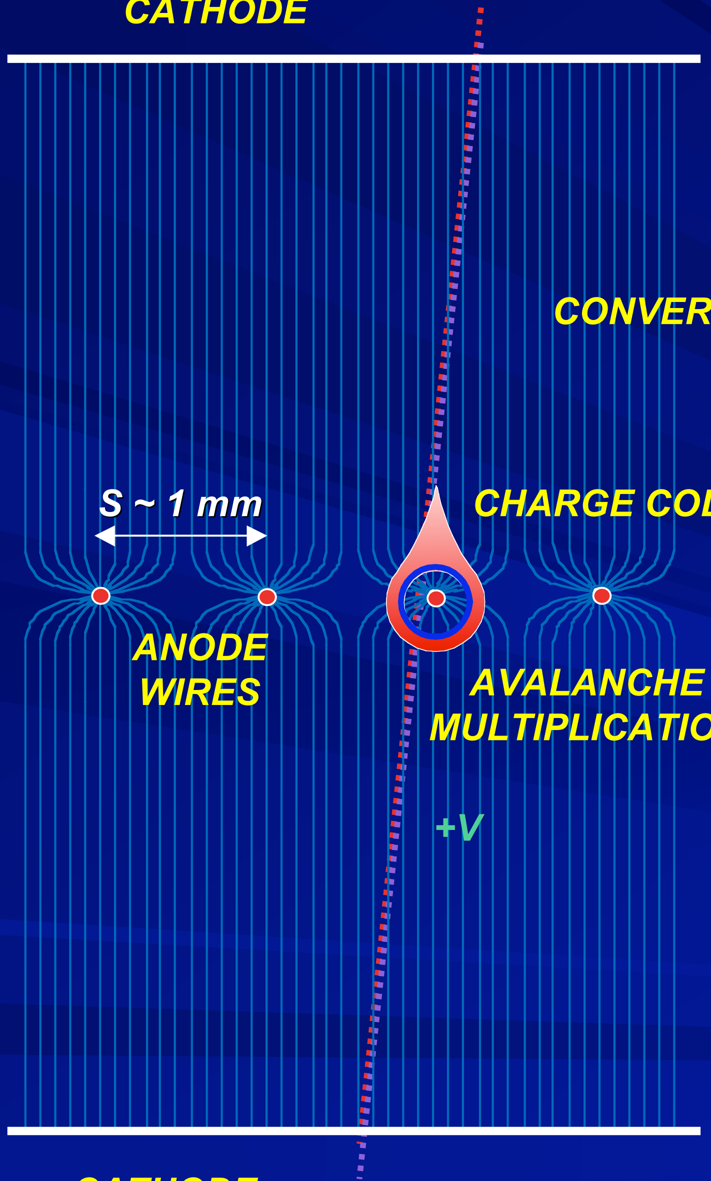
H. Fischle et al, Nucl. Instr. and Meth. A301(1991)202

Wire Proportional Counter : Gain-Voltage Characteristic



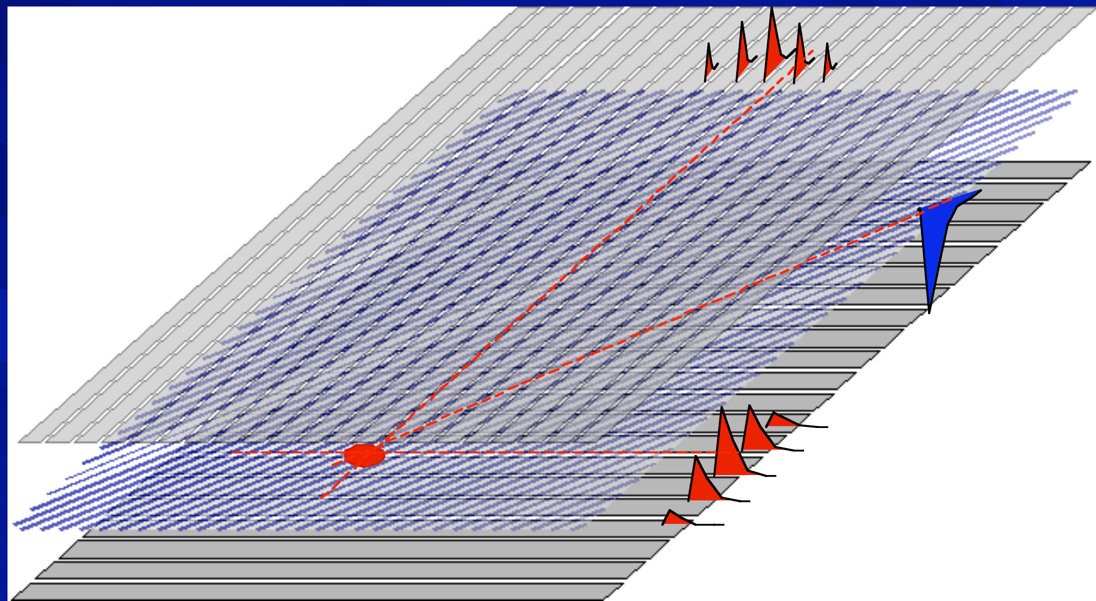


Multi Wires Proportional chambers MWPC



MODERN GASEOUS DETECTORS:
POWERFUL TOOLS FOR RADIATION DETECTION AND LOCALIZATION IN PARTICLE PHYSICS, BASED ON THE MULTIWIRE PROPORTIONAL CHAMBER (Georges Charpak, 1967)

TWO-DIMENSIONAL MWPC READOUT CATHODE INDUCED CHARGE (Charpak and Sauli, 1973)

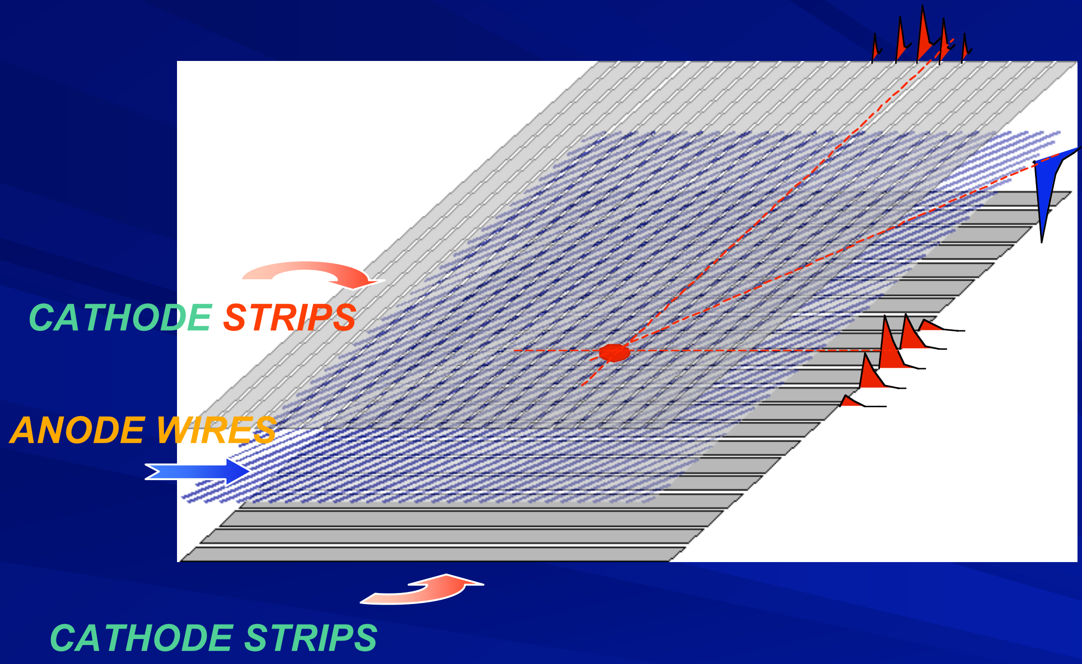


Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

E. Gatti et al, Optimum geometry for strip cathodes … , Nucl. Instr. and Meth. 163(1979)83

TWO-DIMENSIONAL LOCALIZATION

TWO-DIMENSIONAL LOCALIZATION FROM SIGNALS INDUCED ON CATHODE PLANES (Charpak & Fabio Sauli, ~1973)

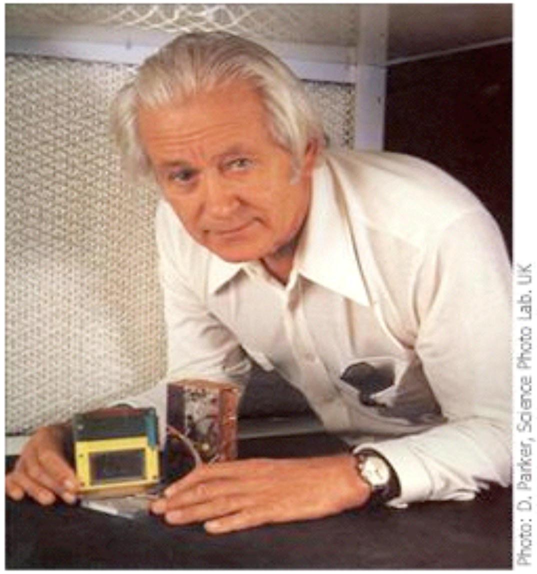


LOW-DOSE DIGITAL RADIOGRAPHY WITH MWPC:
CHARPAK'S HAND (2002):

Large size Multi Wire proportional Chamber (1972)

The Nobel Prize in Physics 1992

The Royal Swedish Academy of Sciences awards the 1992 Nobel Prize in Physics to **Georges Charpak** for his invention and development of particle detectors, in particular the multiwire proportional chamber.



Georges Charpak
CERN, Geneva, Switzerland

Drift Chambers

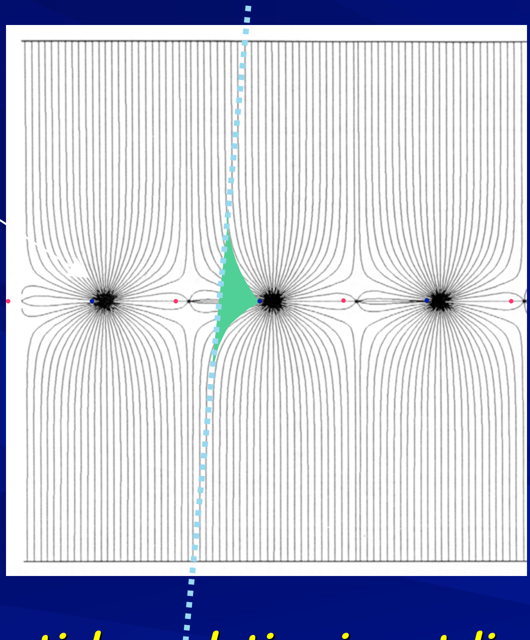
FIRST DRIFT CHAMBER OPERATION (H. WALENTA ~ 1971)

HIGH ACCURACY DRIFT CHAMBERS (Charpak-Breskin-Sauli ~ 1973-75)

THE ELECTRONS DRIFT TIME PROVIDES THE DISTANCE OF THE TRACK FROM THE ANODE:

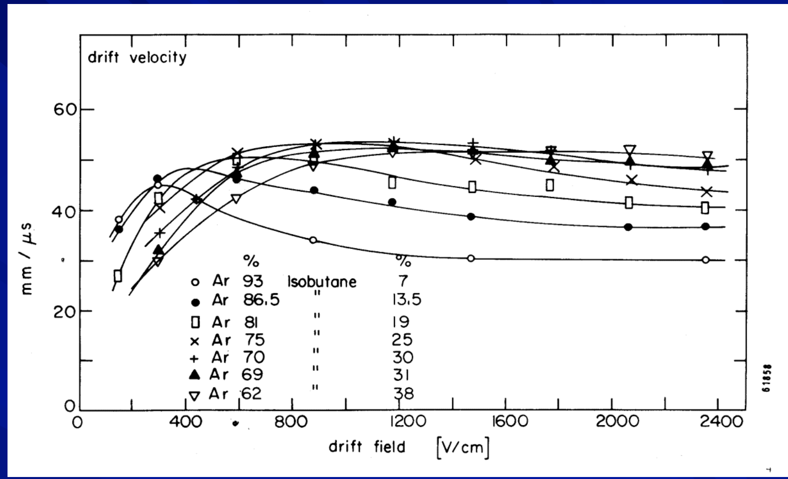
ANODE

FIELD



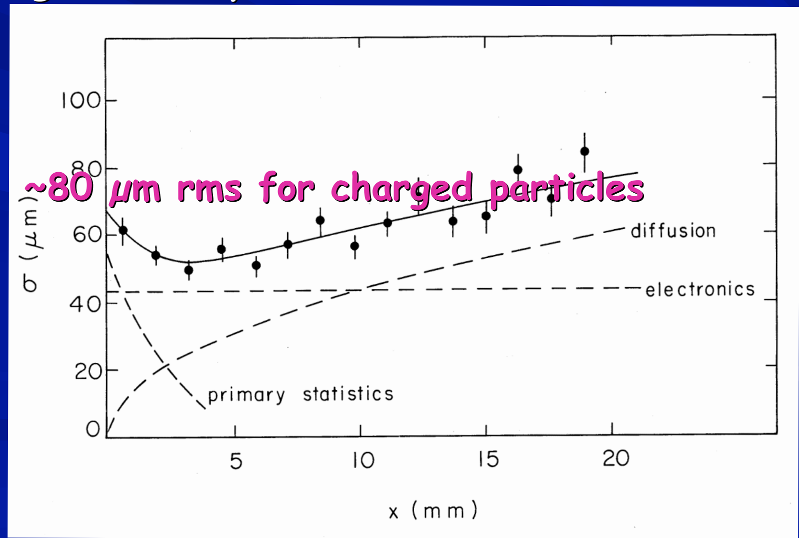
HIGH AND UNIFORM ELECTRIC FIELD IN MOST OF THE VOLUME

Preferetially GAS MIXTURE WITH SATURATED DRIFT VELOCITY (linear space-time relation)



The spatial resolution is not limited to the cell size

High accuracy drift chambers at low rates:



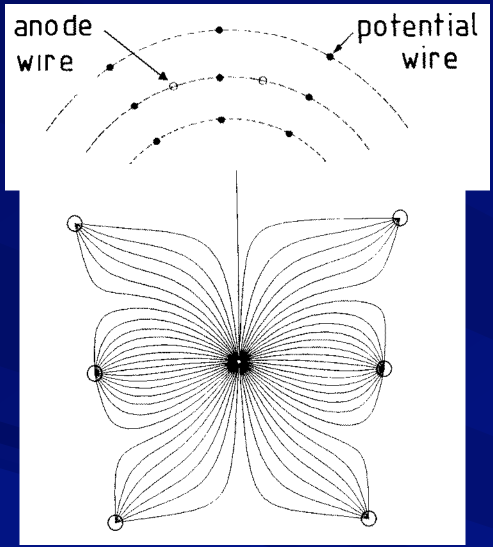
Space resolution determined by:

- *Distribution of primary ionization*
- *Diffusion*
- *Readout electronics*
- *Electric field (gas amplification)*
- *Range of 'delta electrons'*

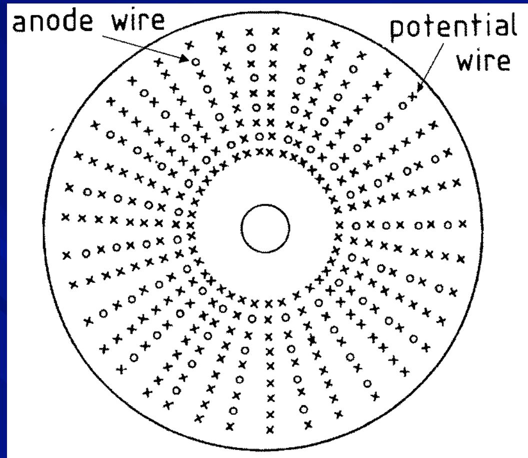
A. Breskin et al, Nucl. Instr. and Meth. 124(1975)189

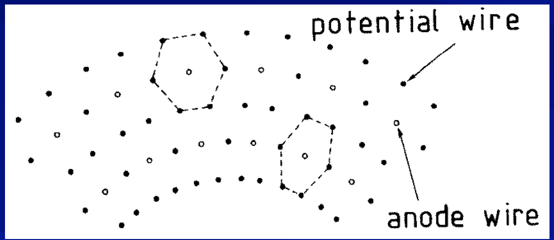
(N. Filatova et al., NIM 143 (1977) 17)

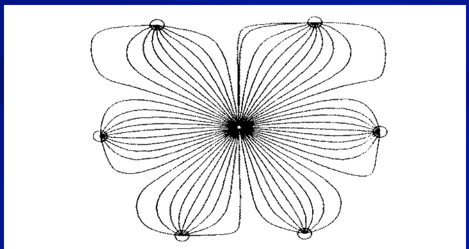
Drift Chambers

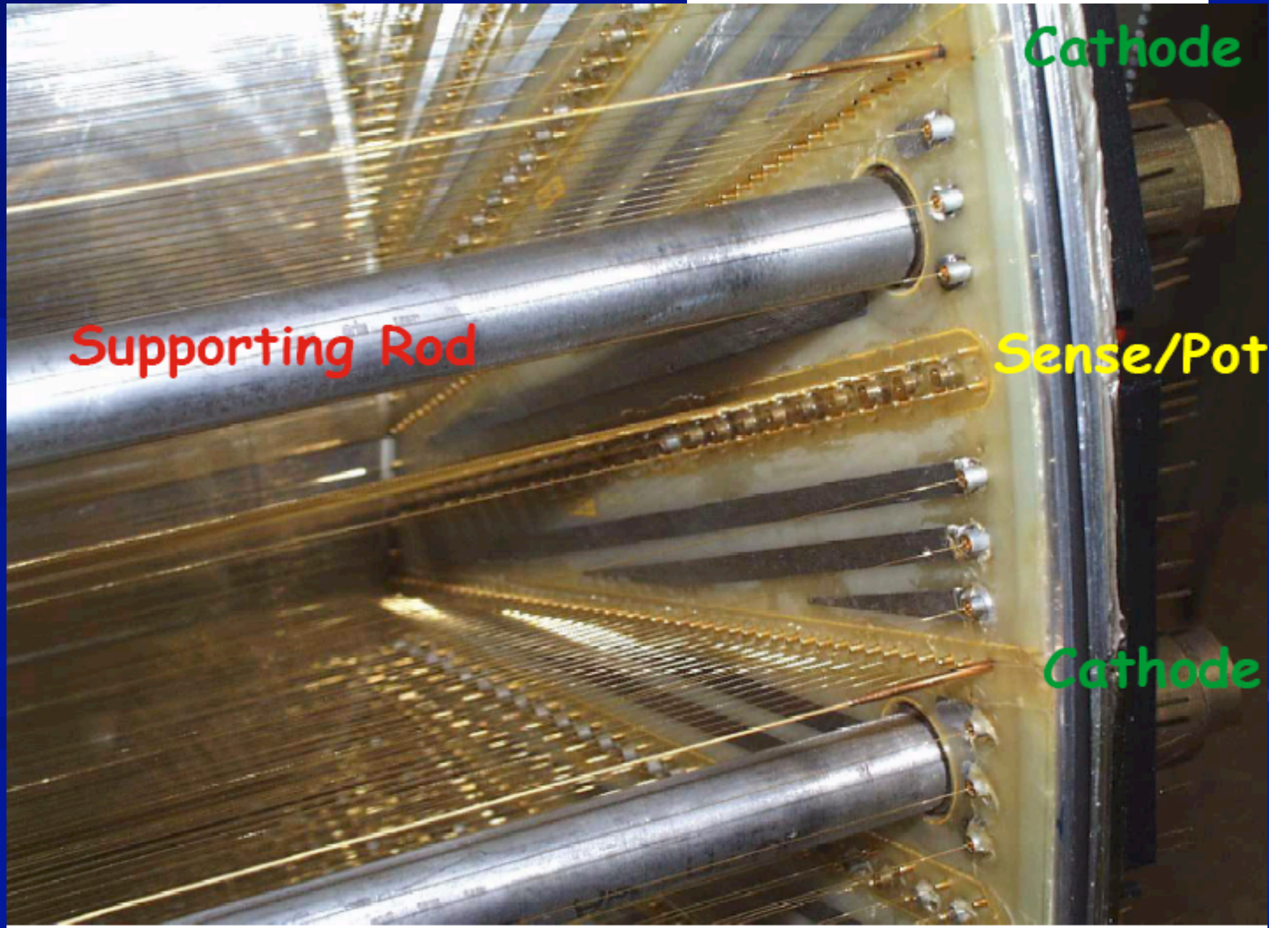


Various geometries of cylindrical drift chambers





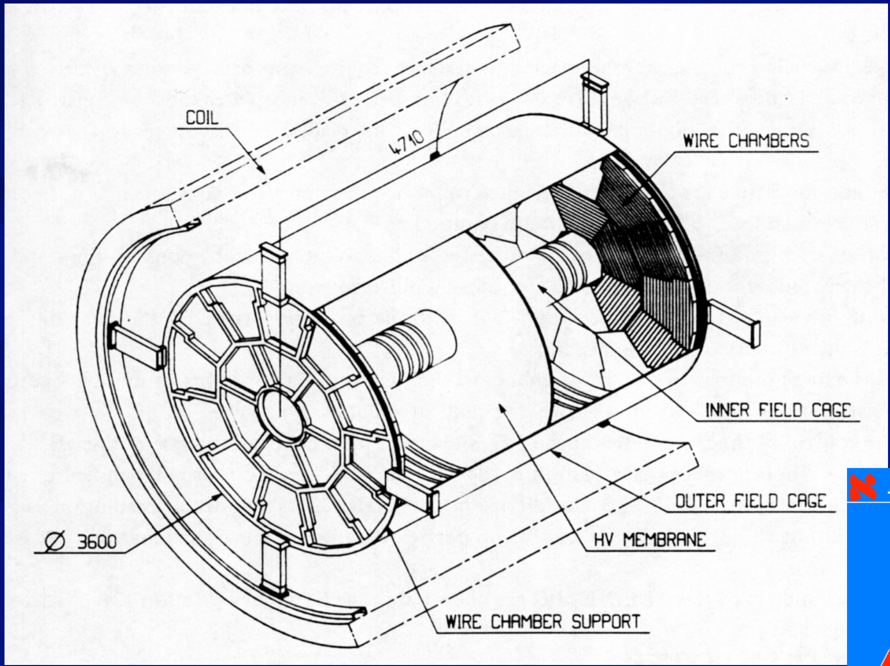


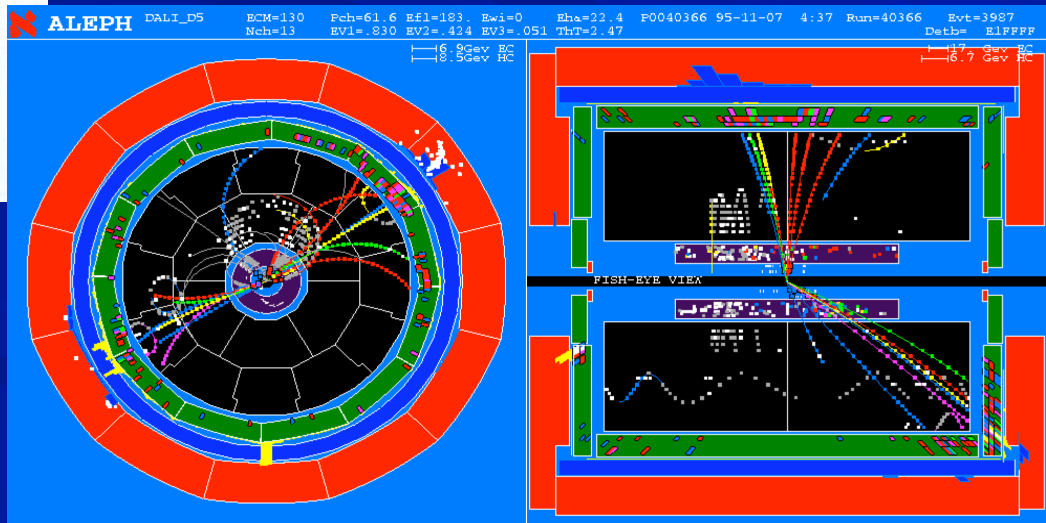


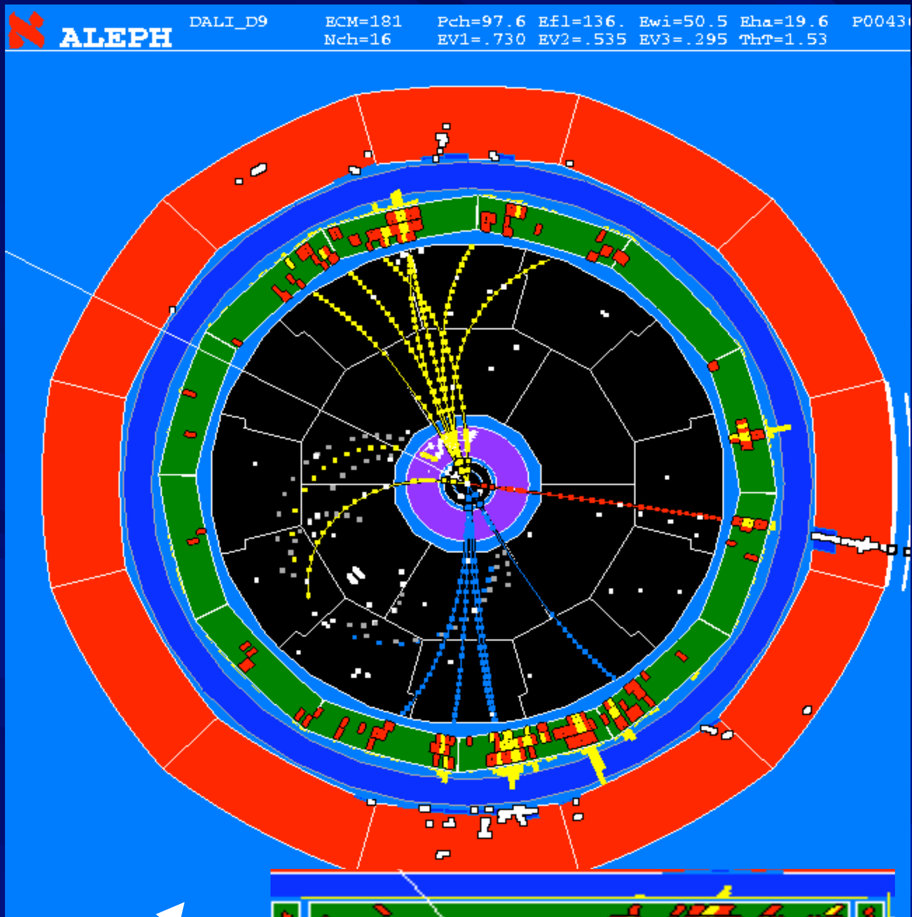
TPC

PATTERN DETECTORS IN PARTICLE PHYSICS: TIME PROJECTION CHAMBER
POWERFUL, THREE-DIMENSIONAL IMAGING OF COMPLEX EVENTS

ALEPH TPC, CERN 1990-2001







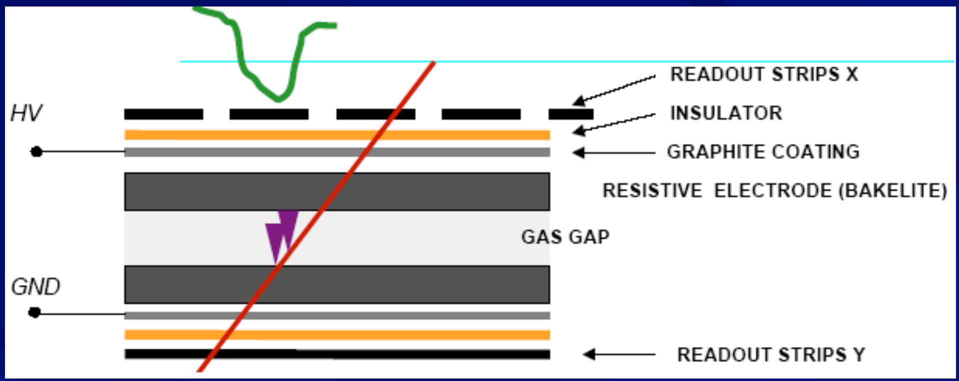
Front View:

Side View:

Image of the W+W- decay from the collision of e^+e^- ($\sqrt{s}$=181 GeV) $\rightarrow W^+W^- \rightarrow qq\mu\nu_\mu$ $\rightarrow$ 2 hadronic jets + μ + missing momentum

Conceptual View of a Resistive Plate Chamber (RPC)

Parallel-Plate capacitor: E> 100kV/cm

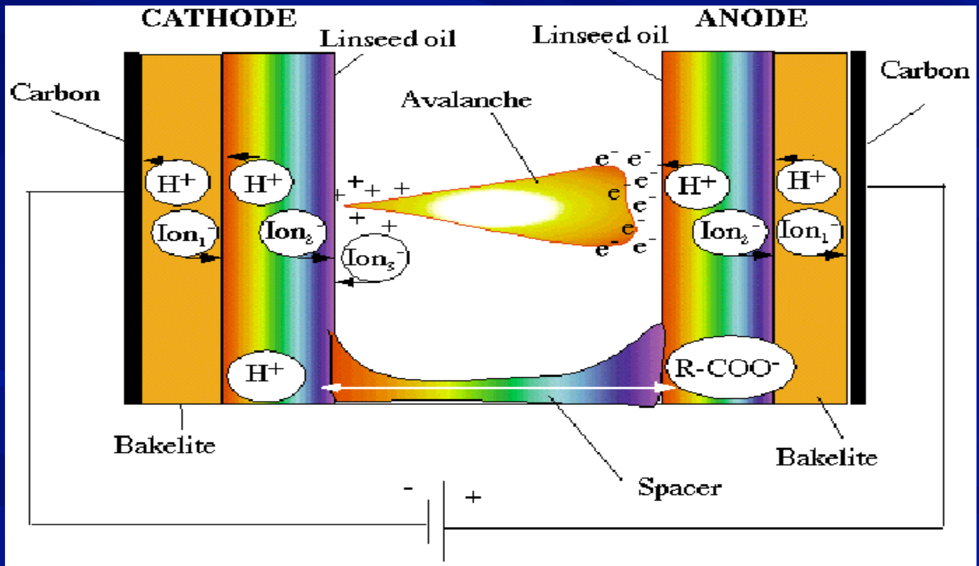


Resistive plate: Oiled bakelite or ionic-conductive glass

High electrode resistivity (10^9-10^{12} W cm) limits energy contained in charge avalanche

Resistivity limits the rate capability

Major applications: good time resolution (~1 ns), large area coverage at affordable cost



R. Santonico, Nucl. Instr. and Meth. A 187(1981)377
R. Santonico, Nucl. Instr. and Meth.A 263(1988)20
J. Va'vra, Nucl. Instrum. Methods A515(2003)1

Ionic conduction model of RPC:

There are several ions involved in the current flow.

The charge exchange has to work well to prevent charging effects at various boundaries: gas, the linseed oil, the Bakelite and the graphite.

If a resistivity buildup occurs at some boundary, there may be a charging effect à subsequent 'RPC death'

RPC Systems in HEP experiments

Experiment	Status	Electrodes material & resistivity	Gas mixture	Operation mode; charge/track	Particle rates ; Accumulated charge
L3	Finished	Oiled bakelite $2{*}10^{11}$ Ωcm	$Ar/iC_4H_{10}/C_2H_2F_4$ (57:37:6)	Streamer	Consistent with cosmic rays
Belle	In progress	Float glass 10^{12} - 10^{13} Ωcm	$Ar/iC_4H_{10}/C_2H_2F_4$ (30:8:62)	Streamer	~10-20 Hz/cm^2;
BaBar	In progress	Oiled bakelite 10^{11} - 10^{12} Ωcm	$Ar/iC_4H_{10}/C_2H_2F_4$ (60.6:4.7:34.7)	Streamer 1000pC/track	~10-20 Hz/cm^2; <10 C/cm^2 (in 2010)
ATLAS	Planned	Oiled bakelite $2{*}10^{10}$ Ωcm	$C_2H_2F_4/iC_4H_{10}/SF_6$ (96.7:3:0.3)	Avalanche 30 pC/track	<0.1 kHz/cm^2; <0.3 C/cm^2
CMS barrel	Planned	Oiled bakelite: 10^{10} Ωcm	$C_2H_2F_4/iC_4H_{10}/SF_6$ (96:3.5:0.5)	Avalanche 30 pC/track	<0.1 kHz/cm^2; <0.3 C/cm^2
ALICE	Planned	Oiled bakelite $3{*}10^9$ Ωcm	$Ar/iC_4H_{10}/C_2H_2F_4/SF_6$ (49:40:7:1)	Streamer	<0.1 kHz/cm^2; <0.2 C/cm^2
LHC-b	Abandon	Oiled bakelite $9{*}10^9$ Ωcm	$C_2H_2F_4/iC_4H_{10}/SF_6$ (95:4:1)	Avalanche 30 pC/track	0.25-0.75 kHz/cm^2; 0.35-1.1 C/cm^2

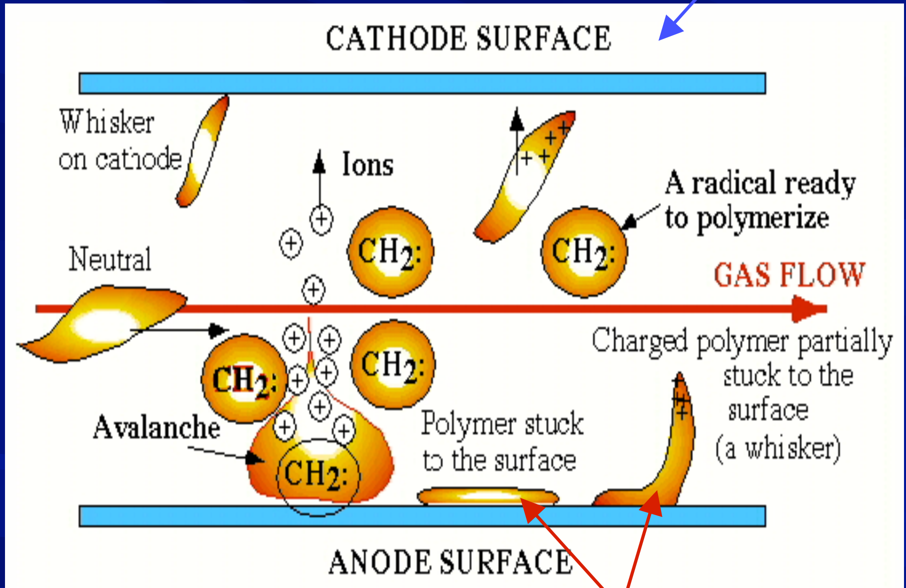
Studies to find 'safe' operational parameters of the large RPC systems in the LHC-like environment are ongoing

Limits for the High Rate Wire Chambers : Aging

During gaseous discharges many molecules break up due to collisions with electrons, de-excitation of atoms, and UV-absoprtion processes

Whereas most ionization processes require electron energies > 10 eV, the breaking of chemical bonds and formation of free radicals requires ~ 3-4 eV

Free-radical polymerization seems to be a dominating mechanism of the wire chamber aging



Modification of electric field

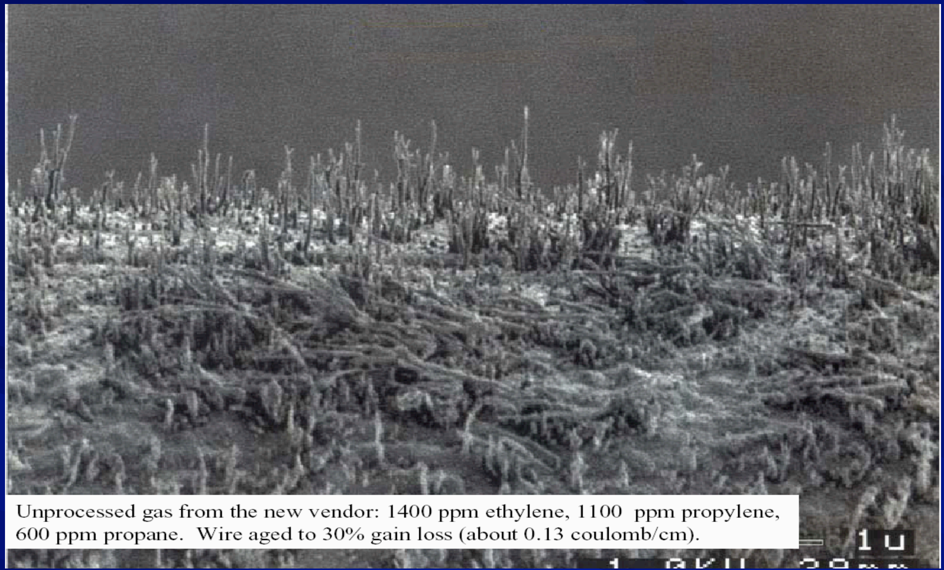
Polymer deposition mechanism (chemistry of gaseous discharges and nearby electrodes)

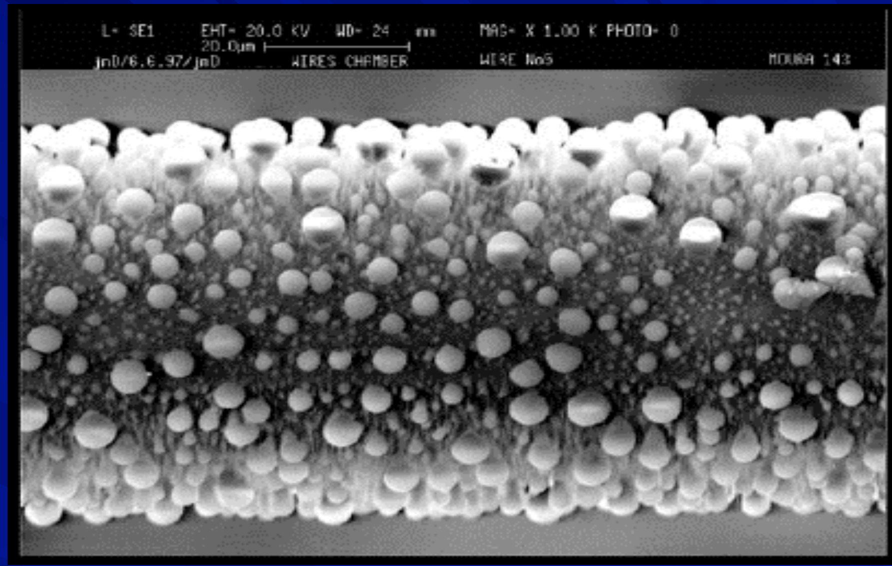
- Chemical reactions between polymer fragments and atoms of the electrode material
- Electrostatic attraction to the electrode (many chemical radicals are expected to have permanent or induced dipole moments)

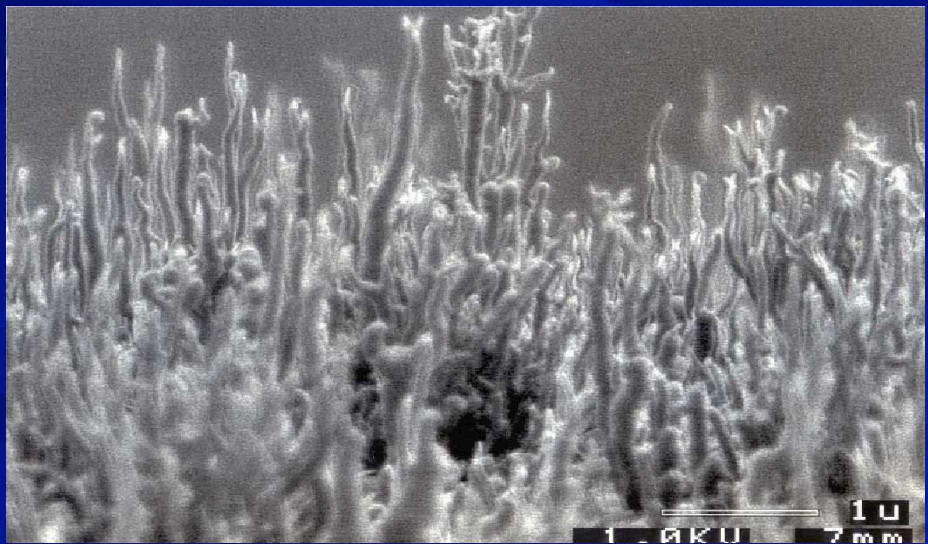
J. Va'vra, Nucl. Instrum. Methods A515(2003)1

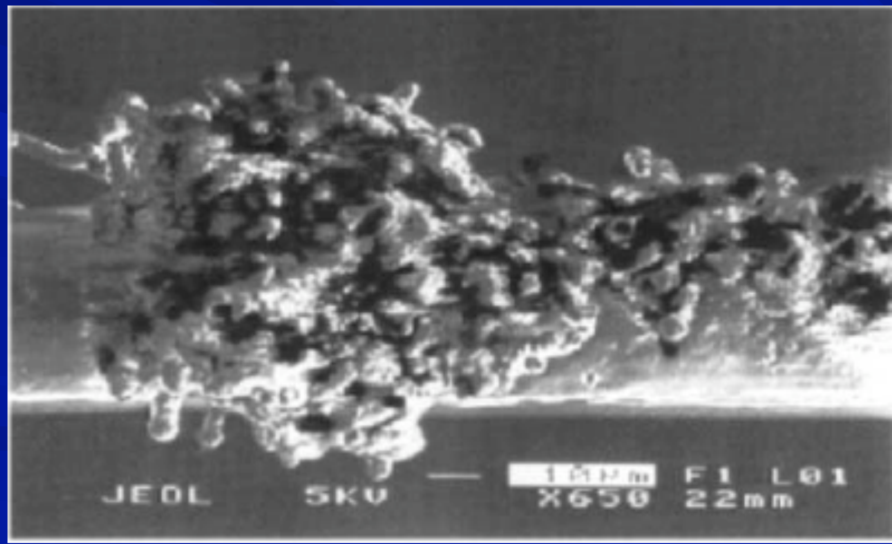
Classical Aging Affect : Anode Wire Deposits

Formation of deposits, conducting or insulating, on the anode/cathode surfaces, following molecular dissociation of polyatomic gases in the avalanche plasmas







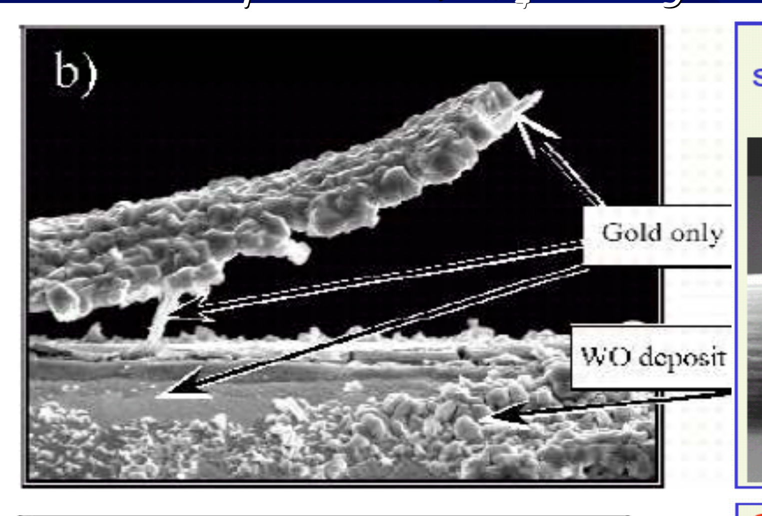


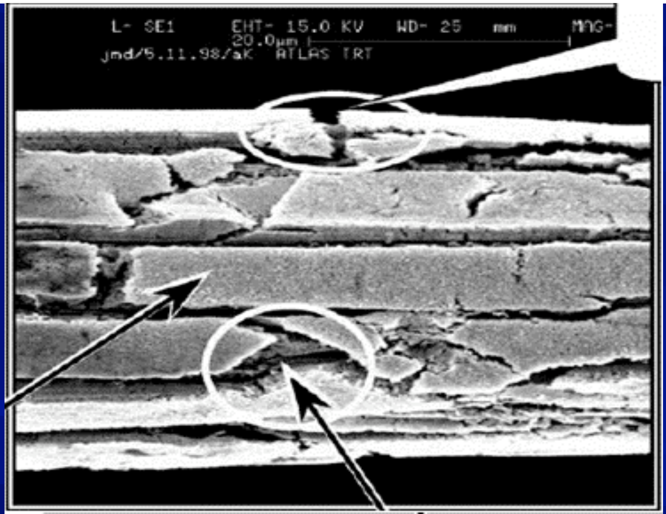
*M. Binkley , **Nucl. Instrum. Methods A515(2003)25***
T. Ferguson et al, Nucl. Instrum. Methods A488(2002)240

M. Titov et al., Nucl. Instrum. Methods A515(2003)202

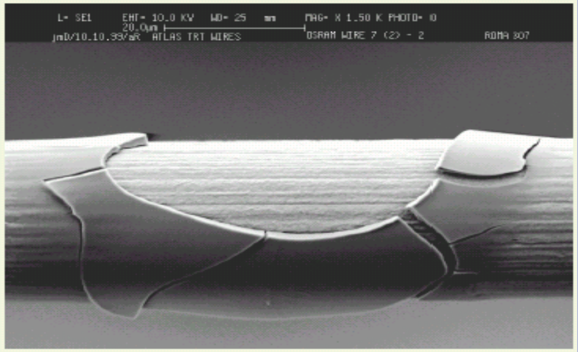
Chemical Etching Procecesses : Dammage of Wire gold-plating

Main components responsible for gold wire damage are harmful radicals à products of CF_4 disintegration in connection with H_2O (effects depend on type of wire)

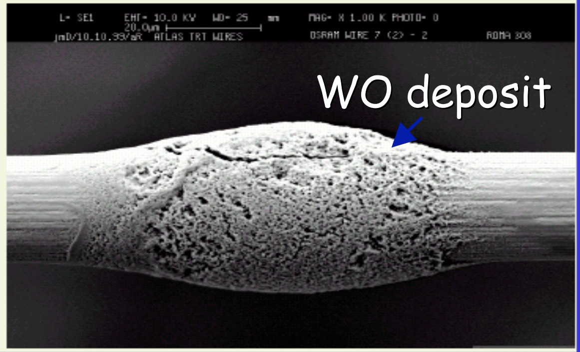




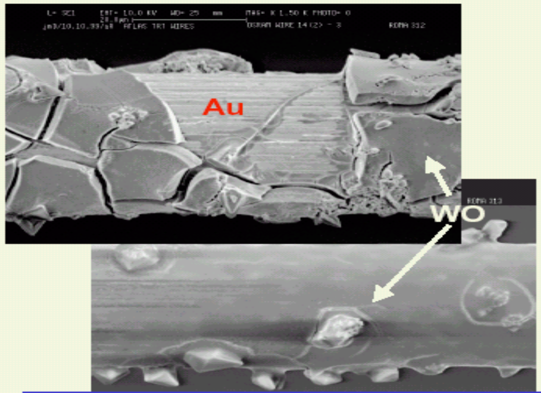
OSRAM wire, 3 % Au
Standard mixture +1.2% H_20 and 1.5%O_2
0.5 C/cm



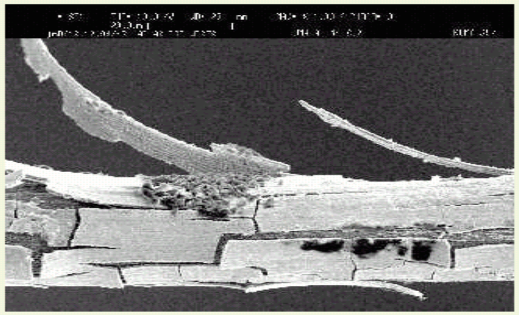
OSRAM wire, 3 % Au
Standard mixture +1.2% H_20 and 1.5%O_2
0.5 C/cm



OSRAM wire, 3 % Au
Standard mixture +1.2% H_20 and 1.5%O_2
Total dose: *0.5 C/cm*



Luma wire, 5 % Au,
Ni-substrate
Standard mixture +1.2% H_20 and 1.5%O_2
Total dose: ~3 C/cm



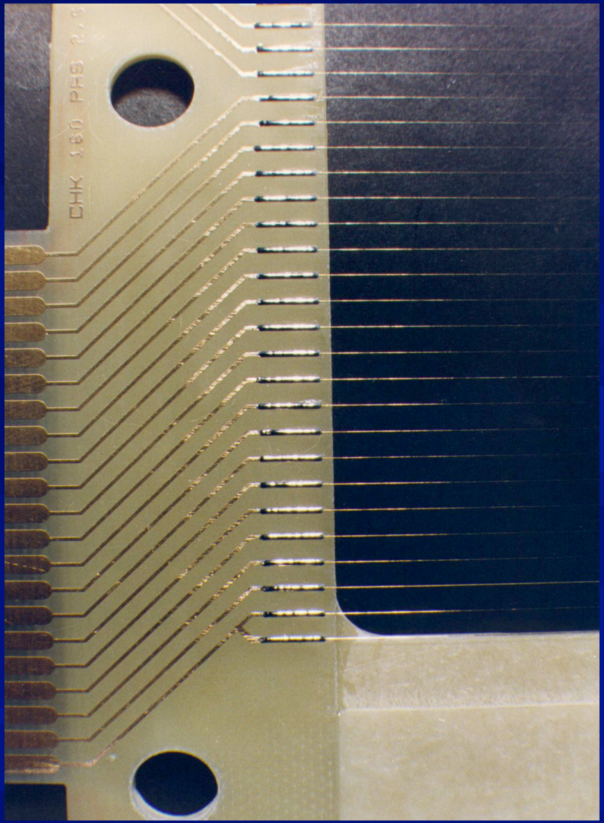
A. Romaniuk et al., Nucl. Instrum. Methods A515(2003)166

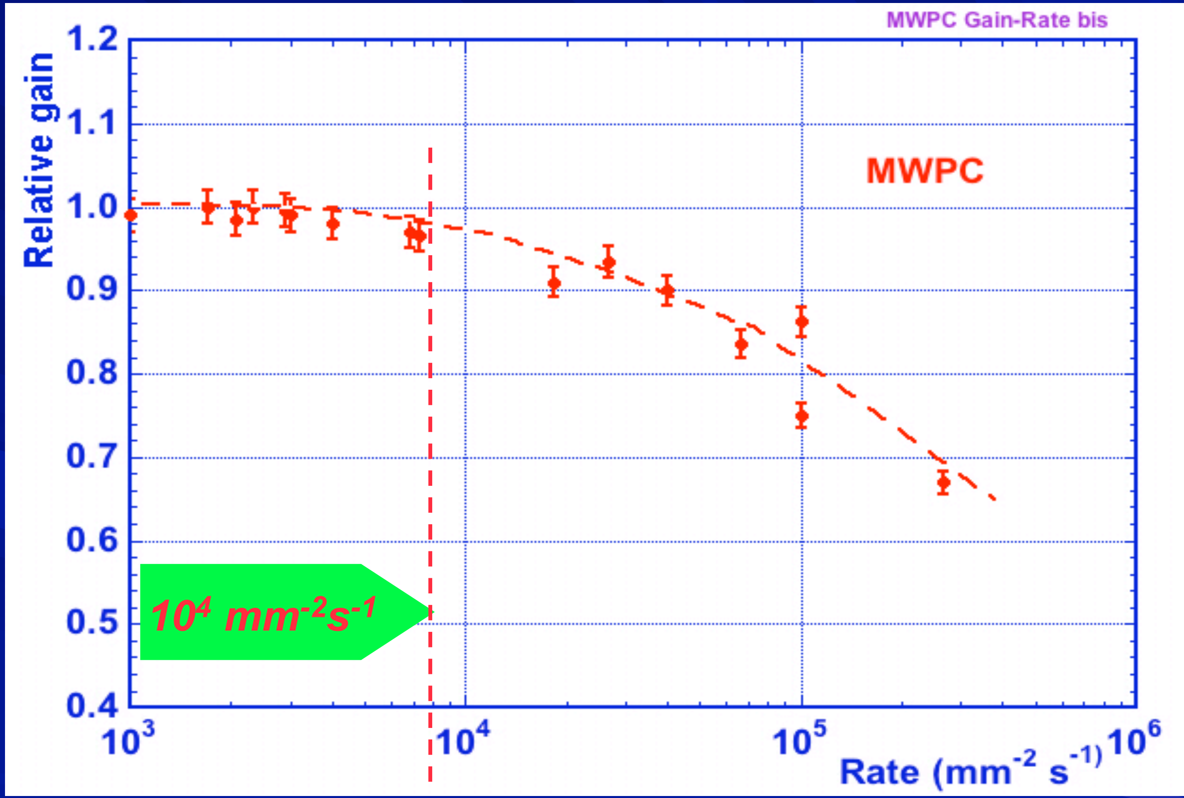
More information on Gas Detector Aging:

J. Va'vra, Nucl. Instr. and Meth. A252(1986) 547
J. Kadyk, Nucl. Instr. and Meth. A300(1991) 436
R. Bouclier et al, Nucl. Instr. and Meth. A381(1996) 289
M. Titov et al, IEEE Trans. Nucl. Sci. , 49(4), (2002) 1609
M. Titov, arXiv: physics/0403055 (2004)

MWPC others LIMITATIONS

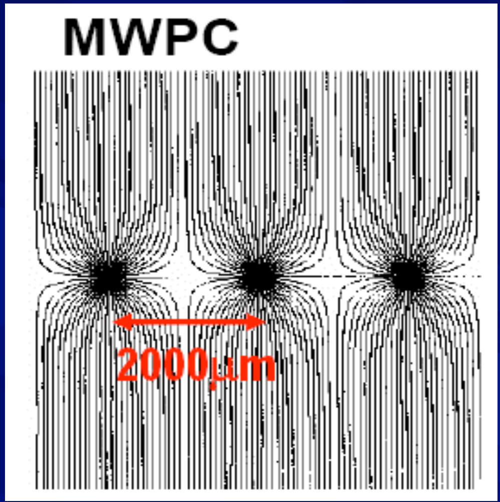
DIFFICULT TO BUILD (THIN WIRES)
POOR TWO-TRACK RESOLUTION (~ 5 mm)



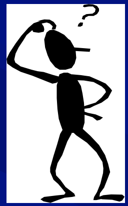


THE GAIN DECREASES WITH DETECTED FLUX (POSITIVE IONS SPACE CHARGE)

Micro-Pattern Gas Detectors
MPGD:
Closing the Gap between Wire Chambers and Silicon detectors

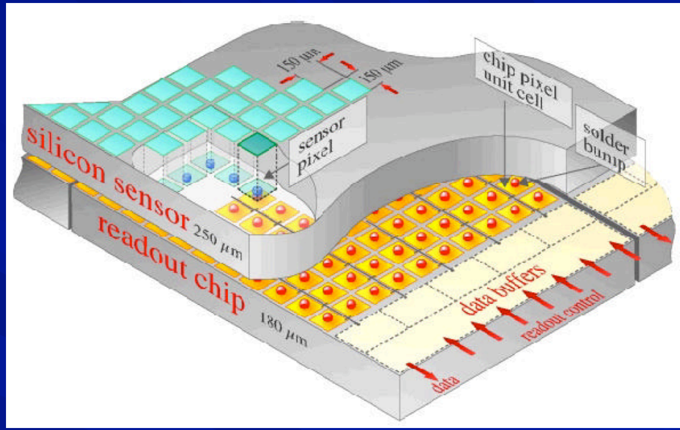


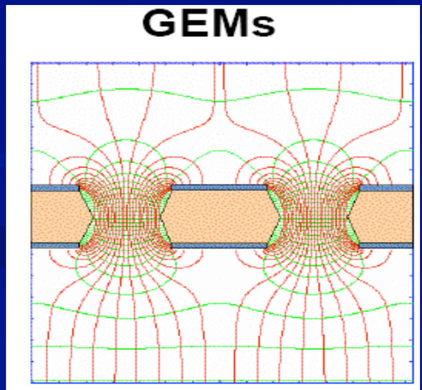
$\sigma \sim 100\ \mu m$

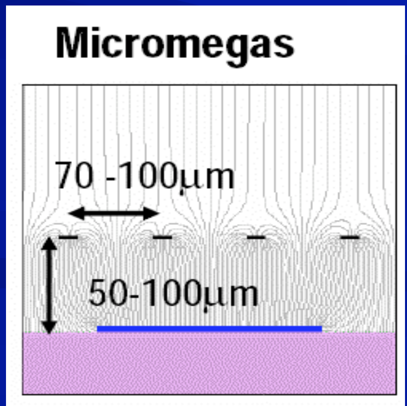


$\sigma < 10\ \mu m$

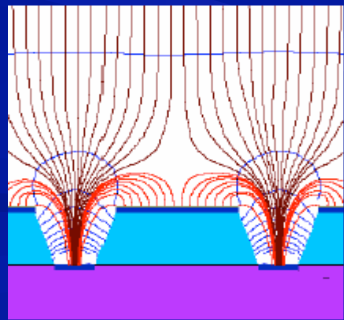
Novel Pixel System:







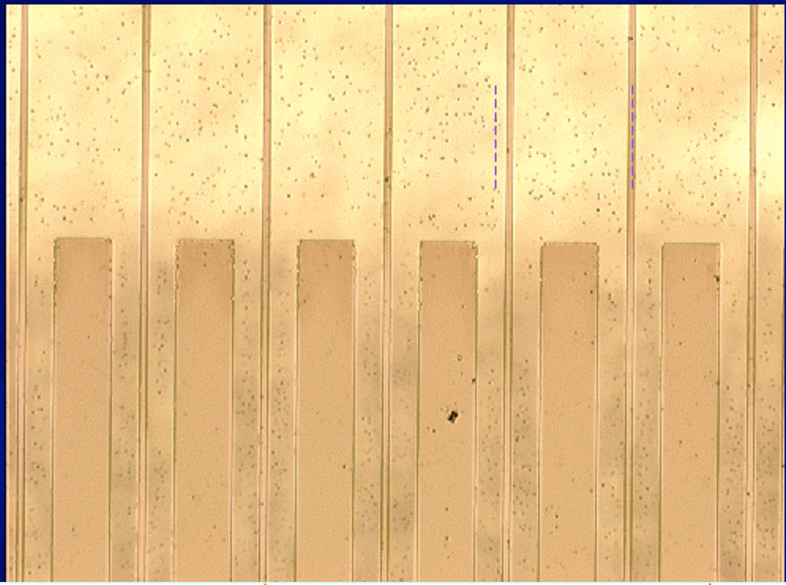
CAT, μCAT, mGROOVE, …

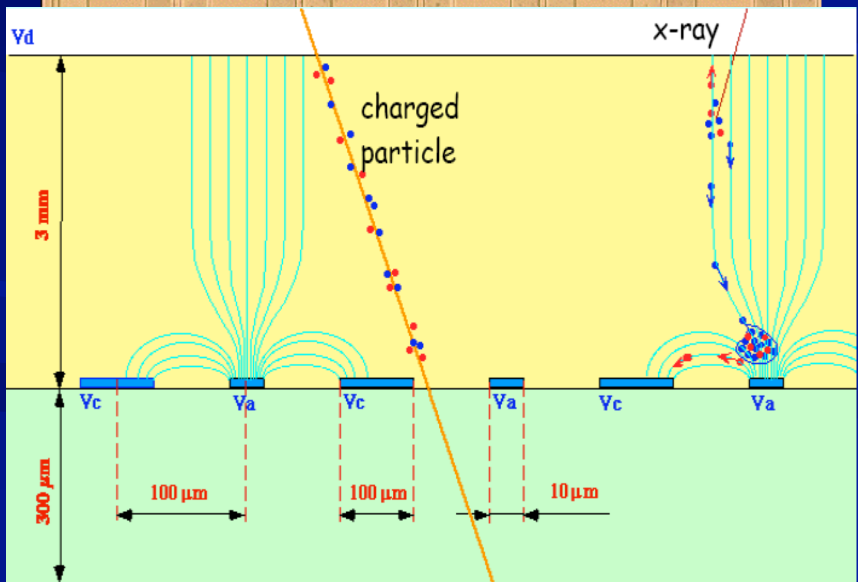


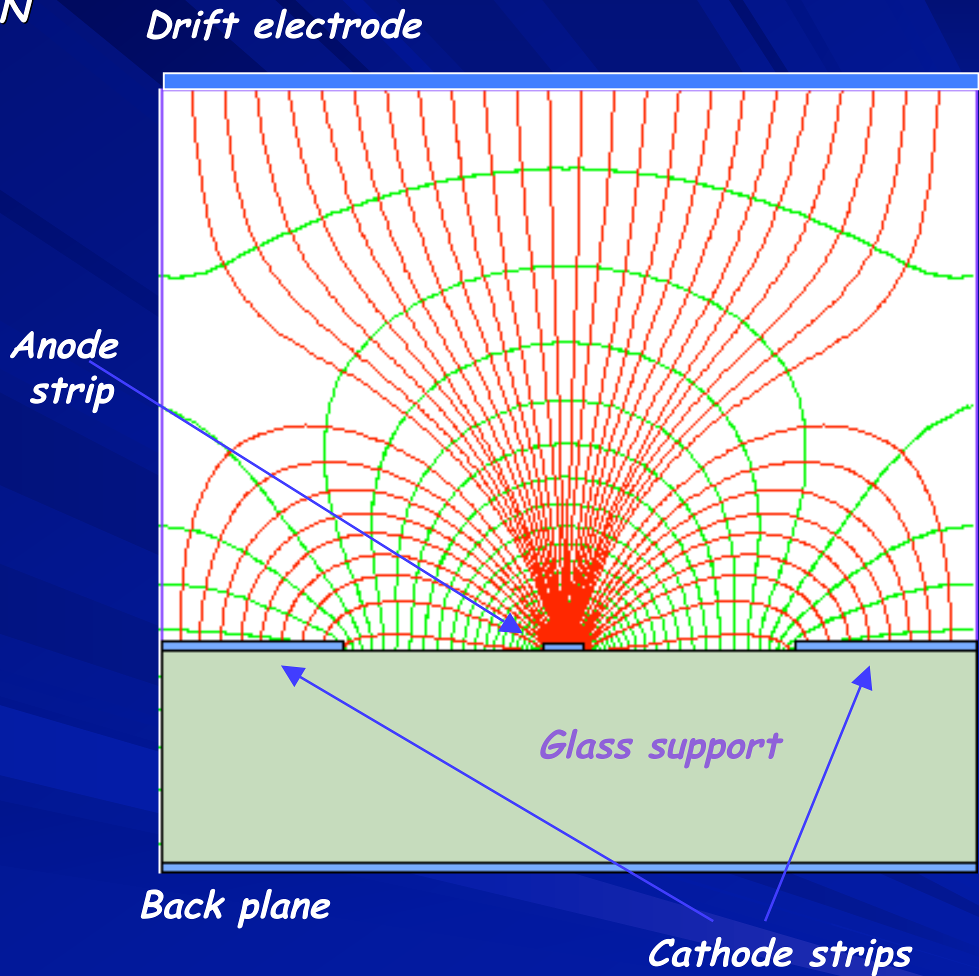
Microstrip Gas Chammber (MSGC)

FIRST MICRO-PATTERN GAS DETECTORS

THIN ANODE AND CATHODE STRIPS ON AN INSULATING SUPPORT



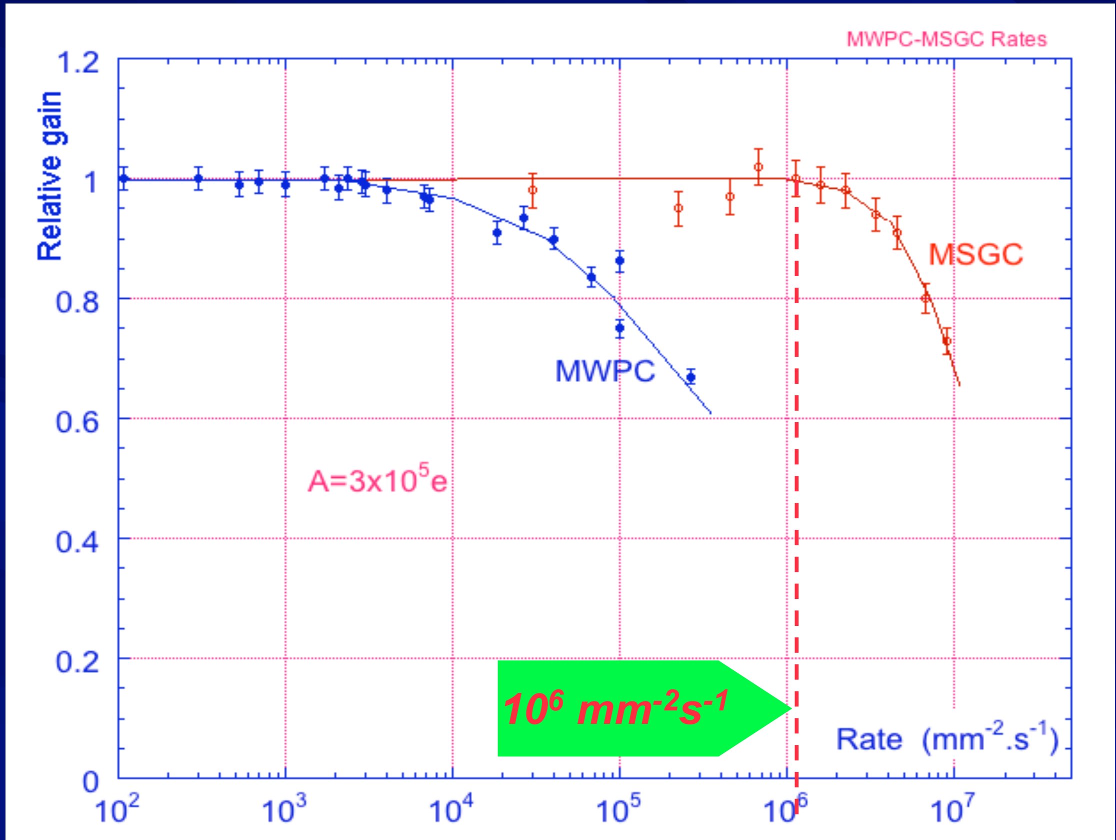


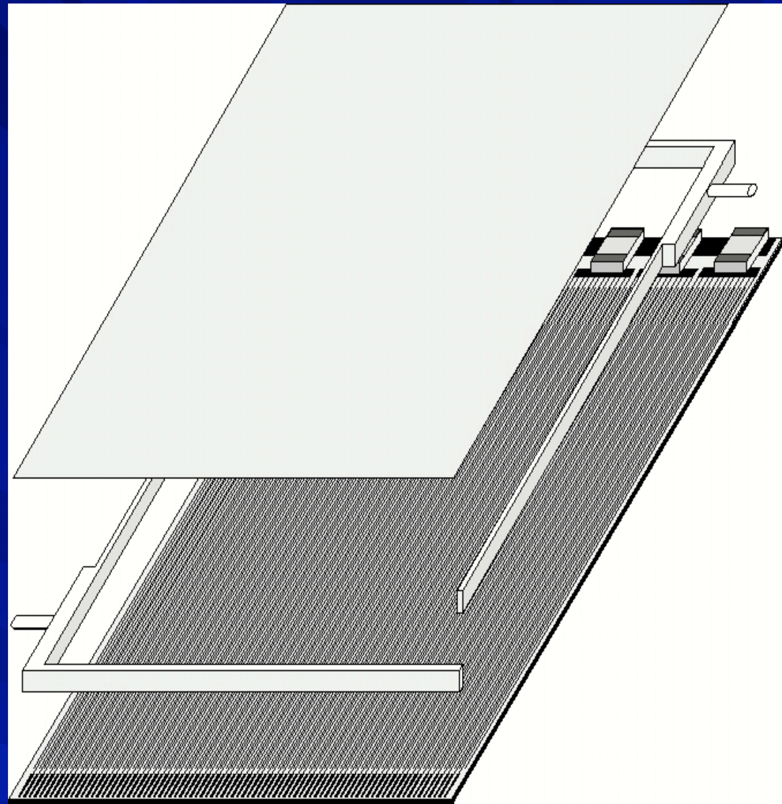


A. Oed, Nucl. Instr. and Meth. A263 (1988) 351.

MSGC PERFORMANCES

VERY HIGH RATE **CAPABILITY:**





COMPACT, LIGHT CONSTRUCTION

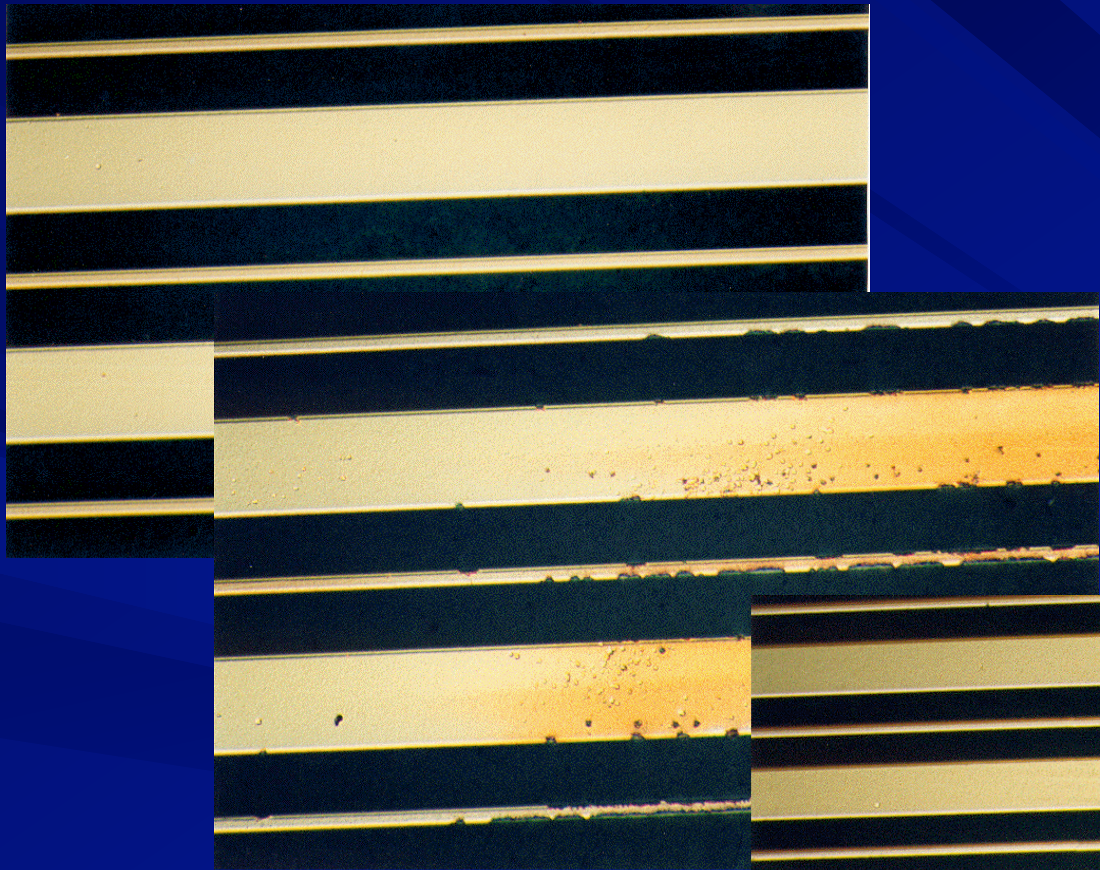
RATE CAPABILITY > $10^6/mm^2$ s

SPACE ACCURACY ~ 40 μm rms

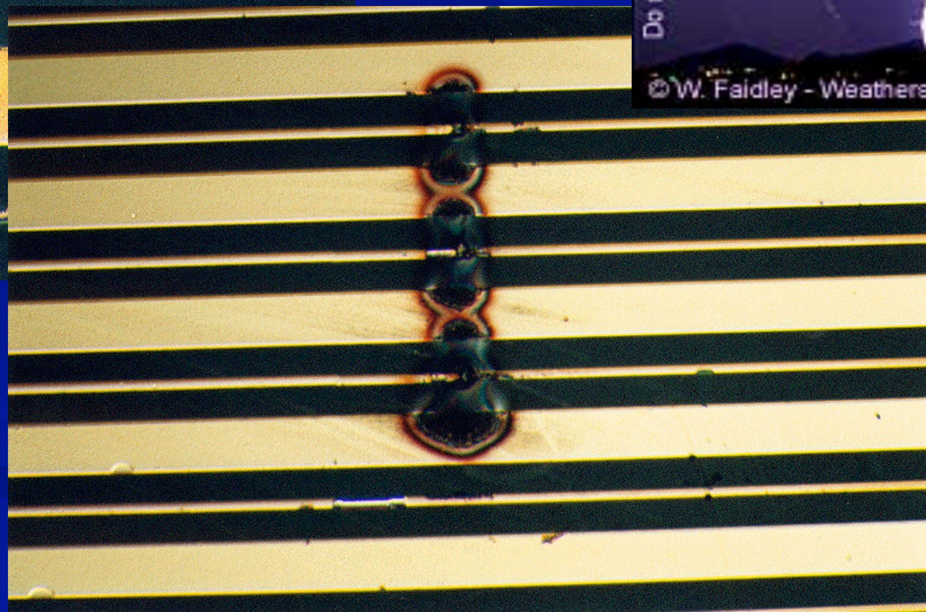
2-TRACK RESOLUTION ~ 400 μm

R. Bouclier et al, Nucl. Instr. And Meth. A367(1995)168

BUT… TOO FRAGILE : EFFECT OF A DISCHARGES



MICRODISCHARGES

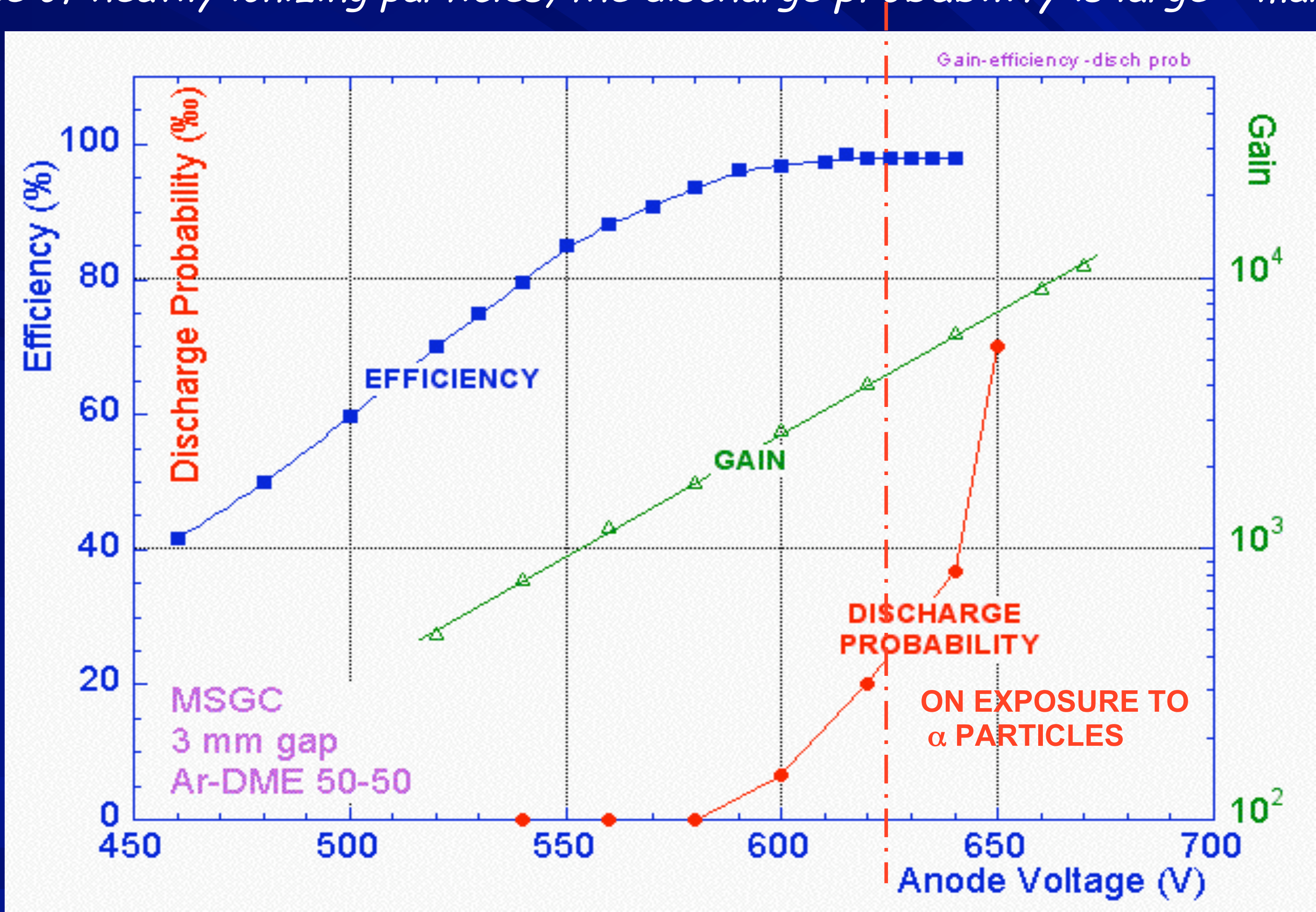


FULL BREAKDOWN

Discharge is very fast (~ns)
***Difficult to predict or** prevent*

MSGC Discharges Problems

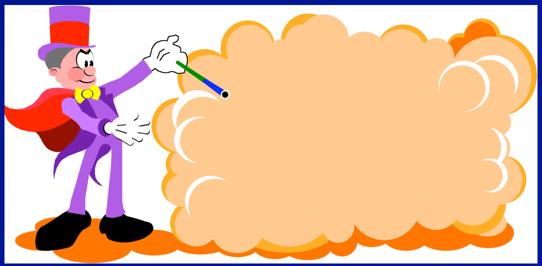
For efficient detection of minimum ionizing tracks a gain ~ 3000 is needed;
No discharges with X-rays and electrons;
In presence of heavily ionizing particles, the discharge probability is large ~ many per min



Induced discharges are intrinsic property of all single stage micropattern detectors in hadronic beams (MSGC** turned **out to be prone to** irreversible **damages)

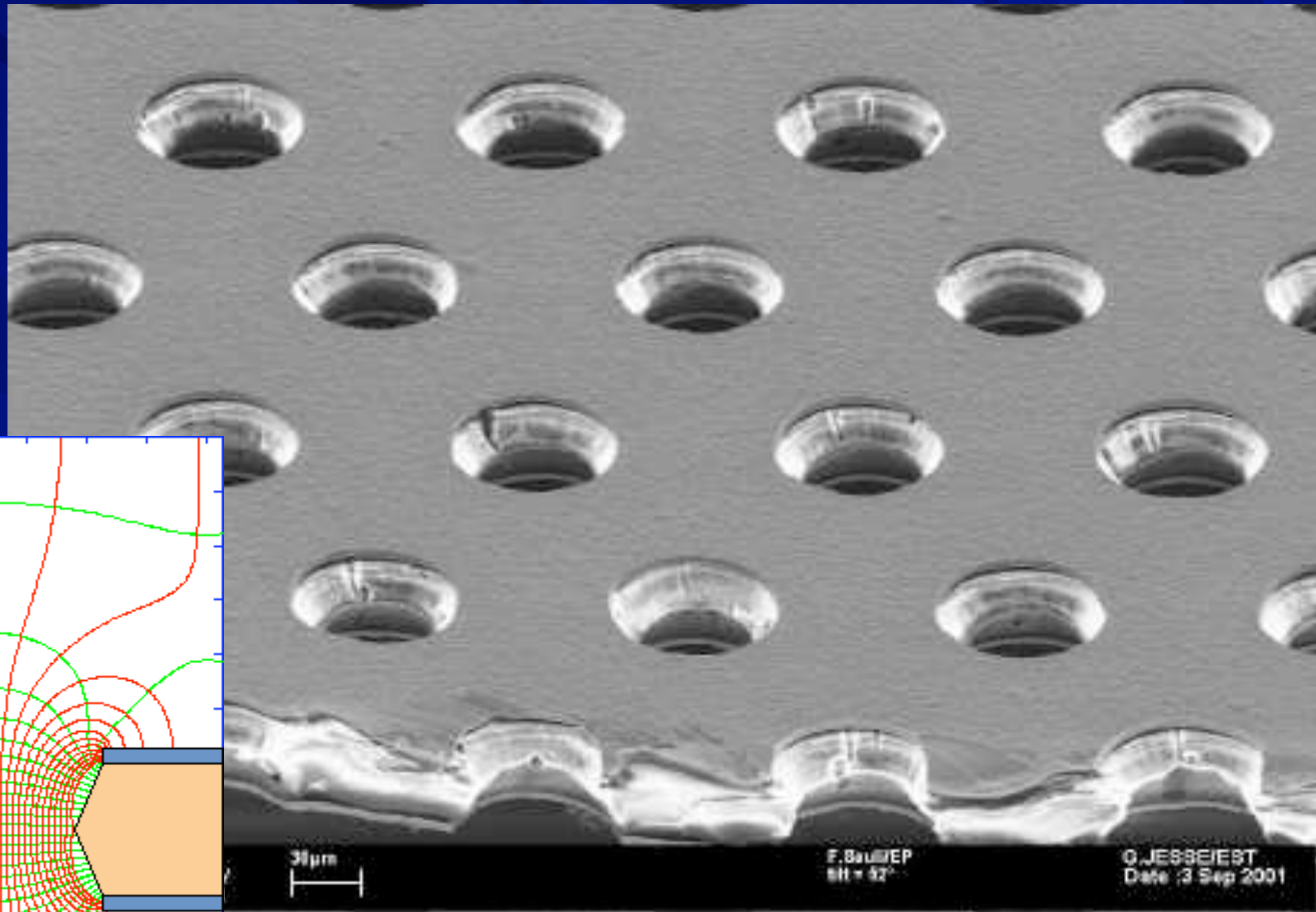
Micro Pattern Gas Detectors (MGPD)

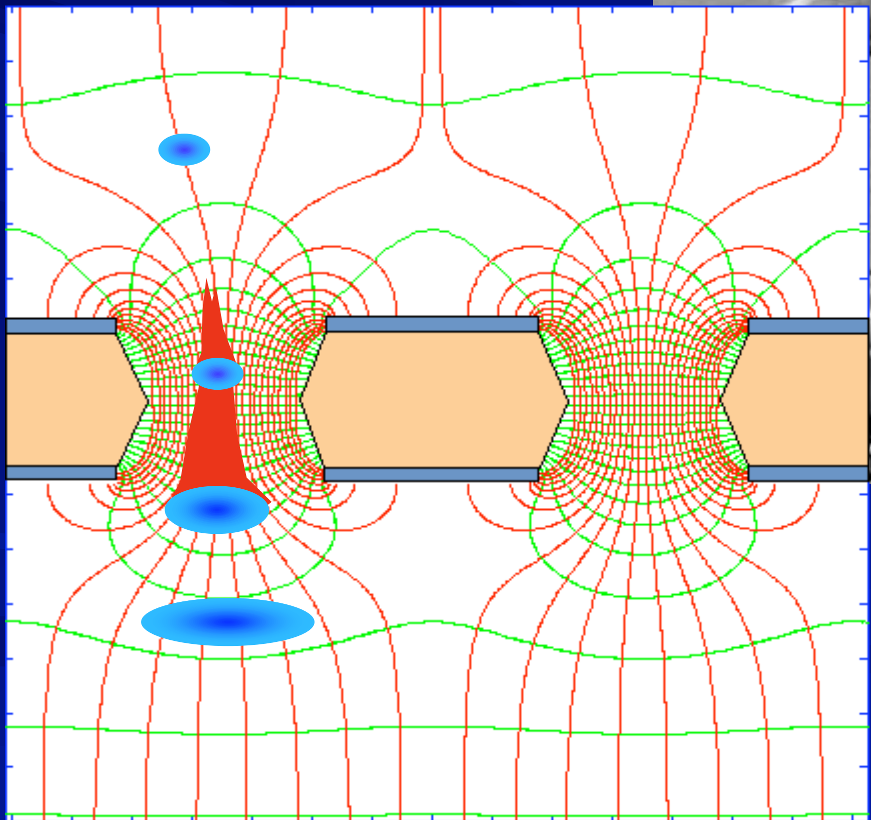
GEM & MICROMEGAS



GEM : Gas Electron Multiplier

Thin metal-coated polymer foil chemically pierced by a high density of holes (technology developed at CERN)





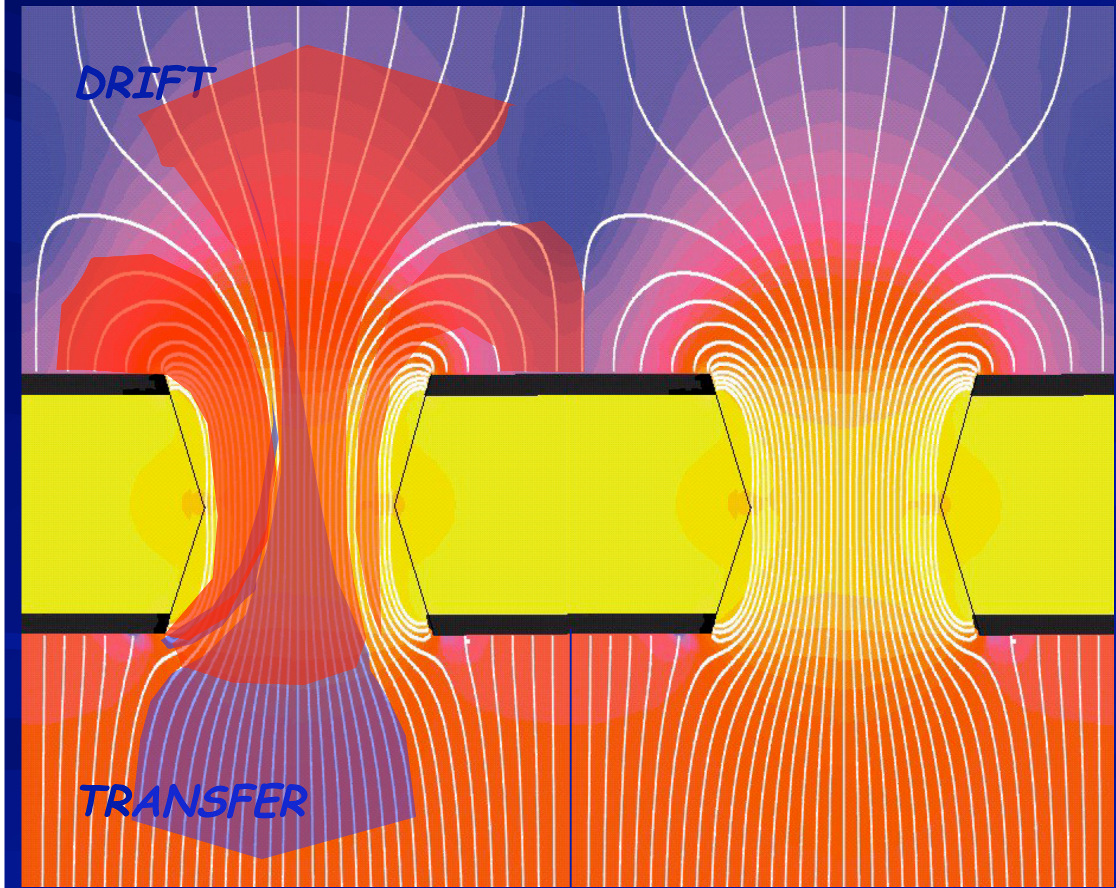
Typical geometry:
5 µm Cu on 50 µm Kapton
70 µm holes at 140 mm pitch

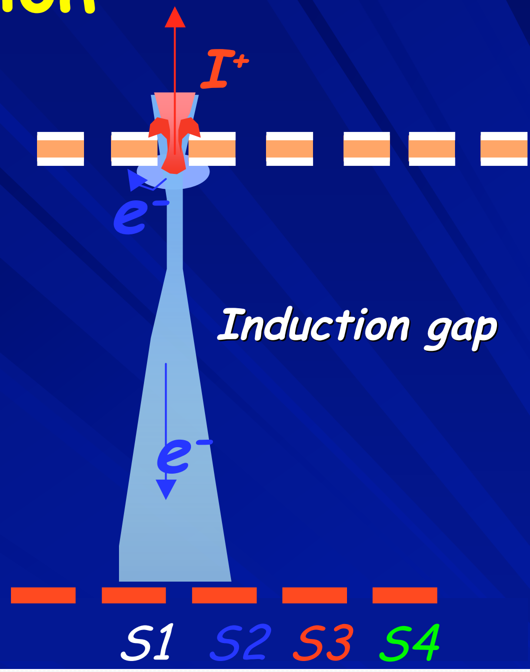
F. Sauli, Nucl. Instrum. Methods A386(1997)531
F. Sauli, http://www.cern.ch/GDD

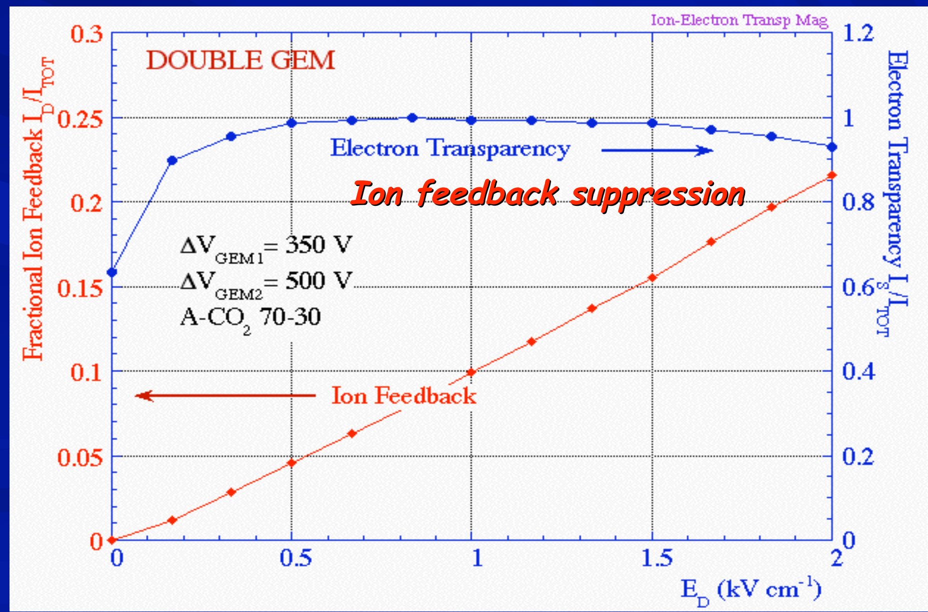
GEM Signal formation

The total length of the detected signal corresponds to the electron drift time in the induction gap:

Fast electron signal only
No positive ion tail in the induction gap à
very good multi-track resolution



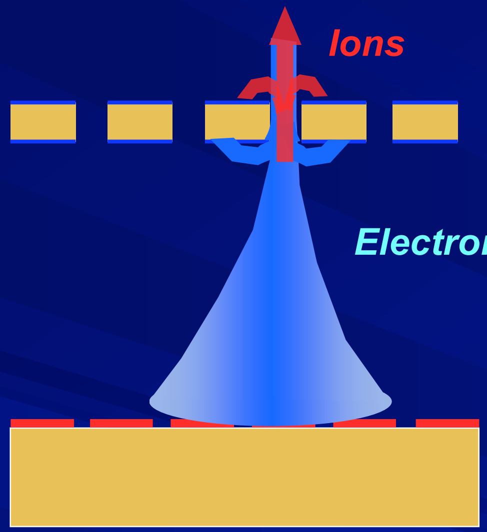




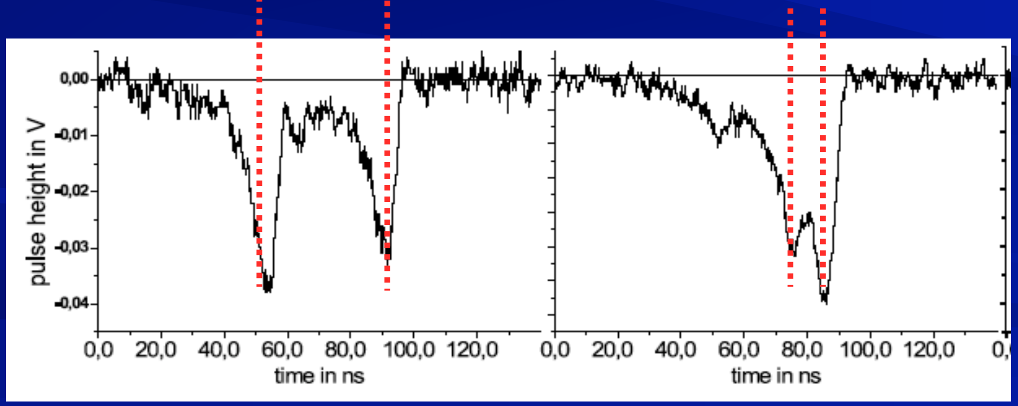
S. Bachmann et al, Nucl. Instr. and Meth. A 438(1999)376, F. Sauli, http://www.cern.ch/GDD

GEM PERFORMANCES

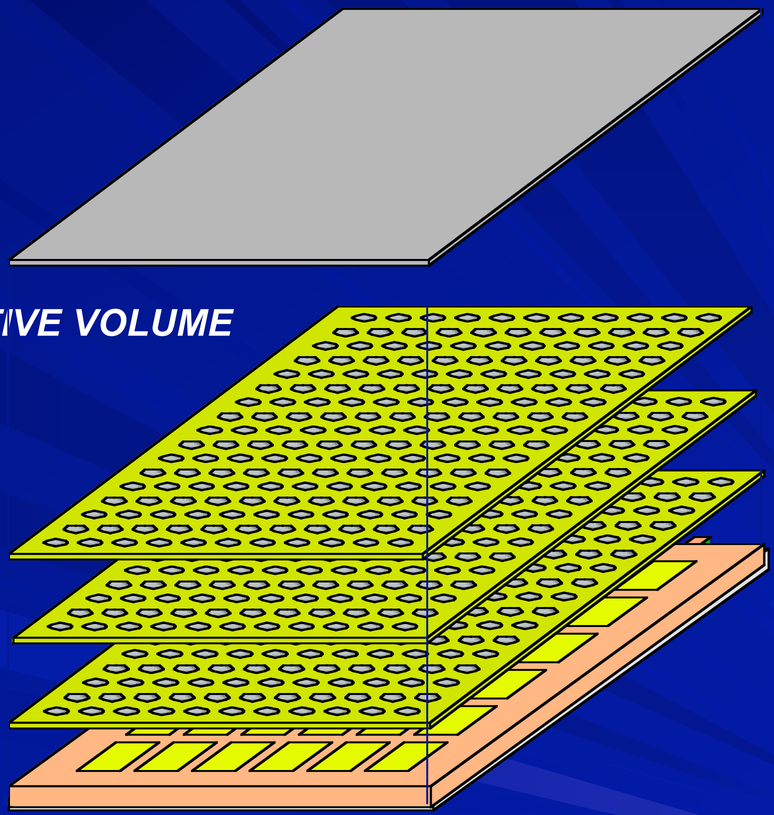
GEM:
WIDER AVALANCHE, FAST ELECTRON SIGNAL ONLY



30 ns *10 ns (~ 1 mm)*



GEMs CAN BE CASCADED:
MULTI-STAGE AMPLIFICATION



HIGHER SAFE GAINS!

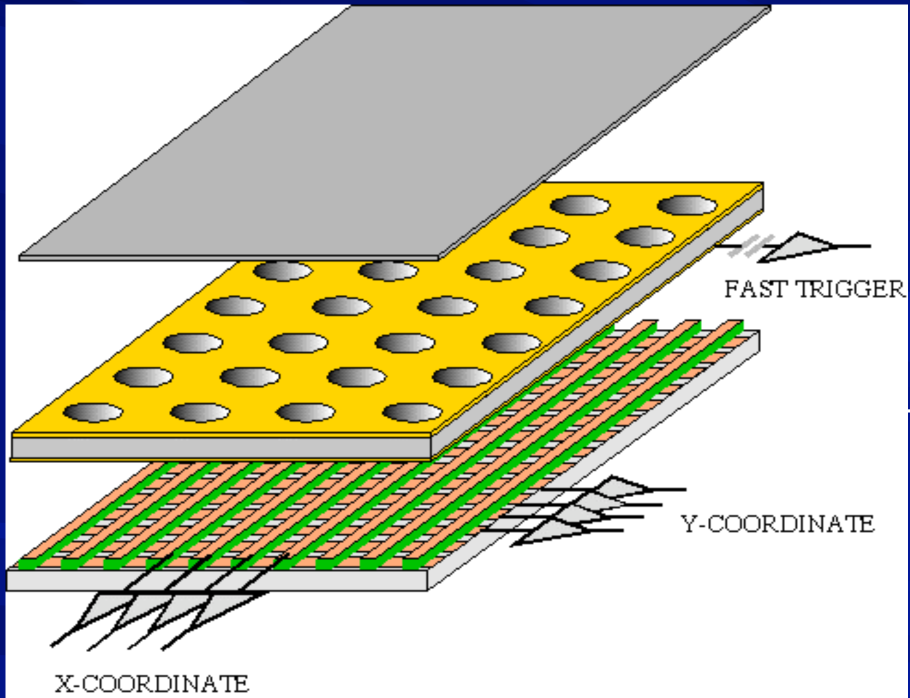
GEM Detector and Read-out (PCB)

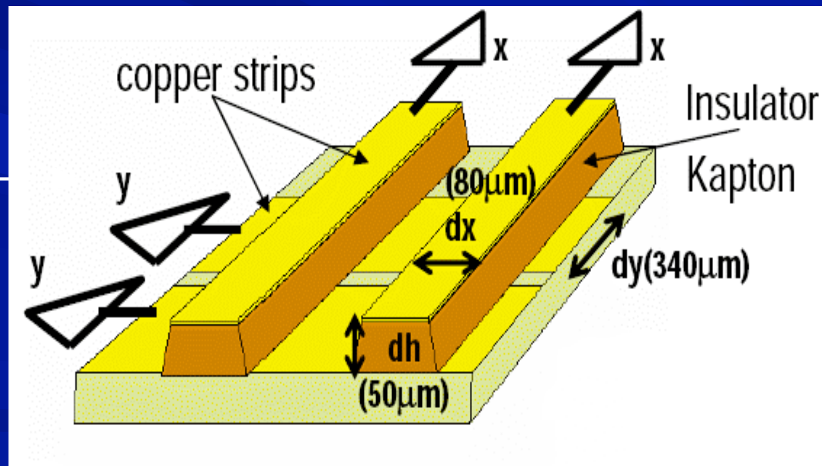
- Separation of gas amplification (GEM) and readout stage – printed circuit board (PCB), which operate at unity gain
- Electron charge collected on strips or pads: 2-D readout
- Fast electron signal (no ion tail)
- Multiple cascaded structures possible
- Small material budget, large acive area
- Cheap and reliable

Readout electrode at 0 V – only serves as a charge collector

COMPASS GEM (2D READOUT):

Two orthogonal sets of parallel strips at 400 µm pitch engraved on 50 µm Kapton 80 µm wide on upper side, 350 µm wide on lower side (for equal charge sharing)





GEM manufacturing

50 μm Kapton
+5 μm Cu both sides

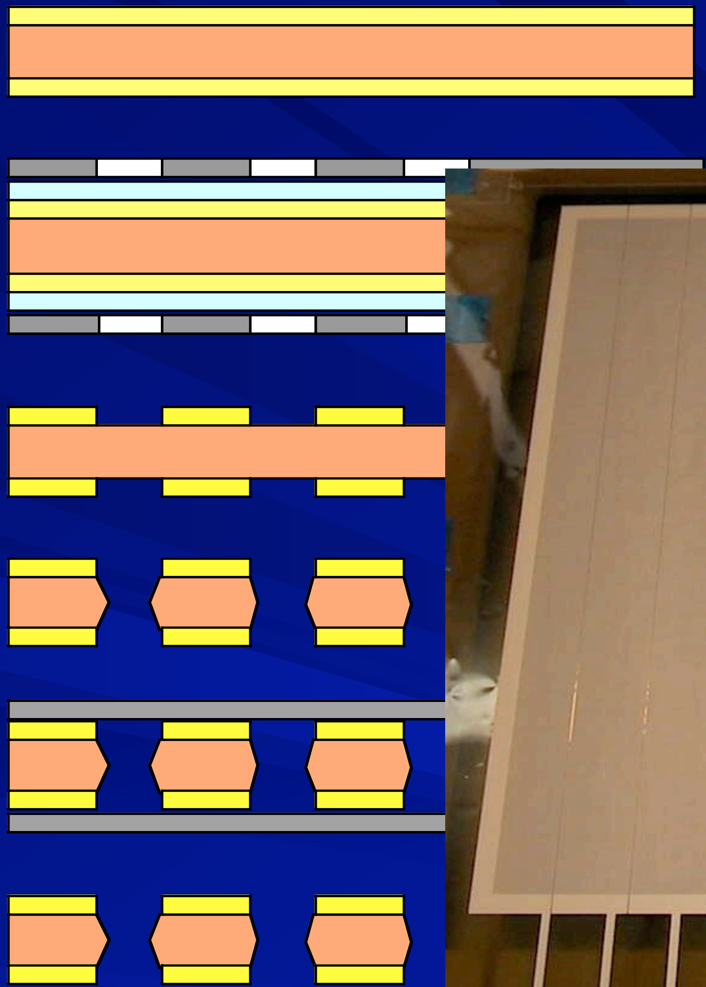
Photoresist coating,
masking and exposure
to UV light

Metal etching

Kapton etching

Second masking

Metal etching
and cleaning

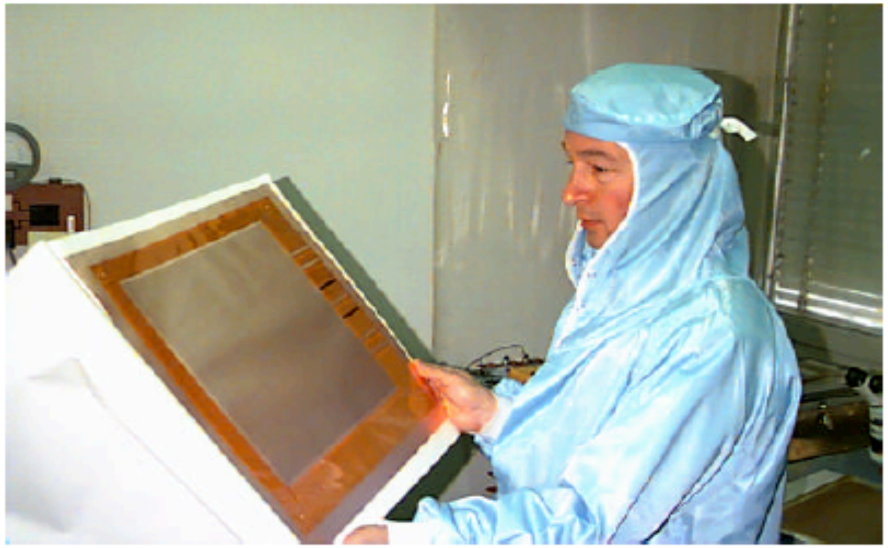


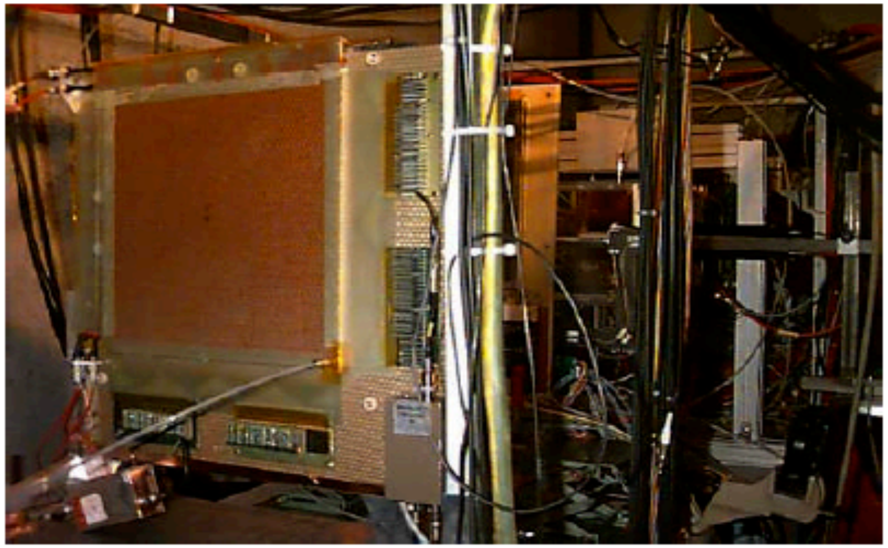
3M GEM Mass *production* ***recently started – thousands of GEMs delived***

F. Sauli, Nucl. Instrum. Methods A386(1997)531
F. Sauli, http://www.cern.ch/GDD

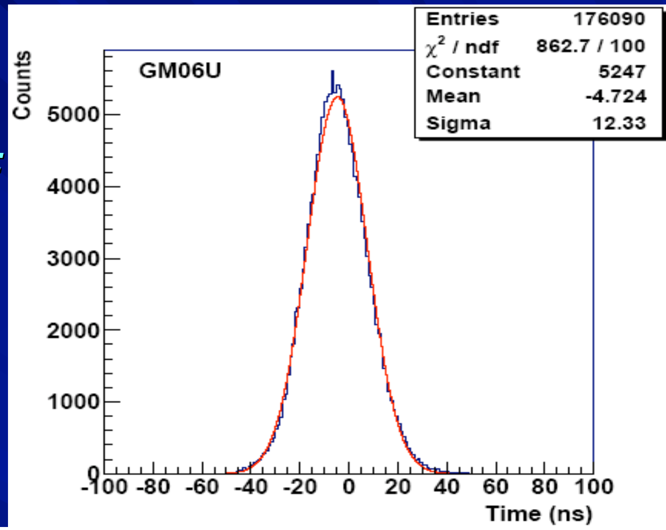
Triple GEM detectors in Compass Experiment

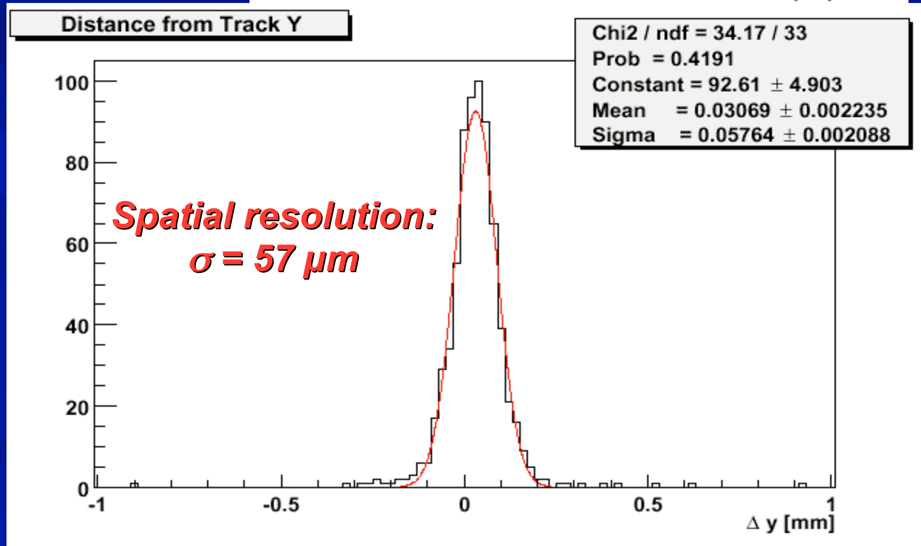
20 LARGE (31*31 cm²) TRIPLE GEM DETECTORS OPERATIONAL SINCE 2001 – 2002;
COMPASS beam: High rate beam ~ 10^7 muons/s with $2*10^4$ hadrons/s





Time resolution:
σ= 12 ns
(Convolution of intrinsic time resolution with 25 ns sampling readout)





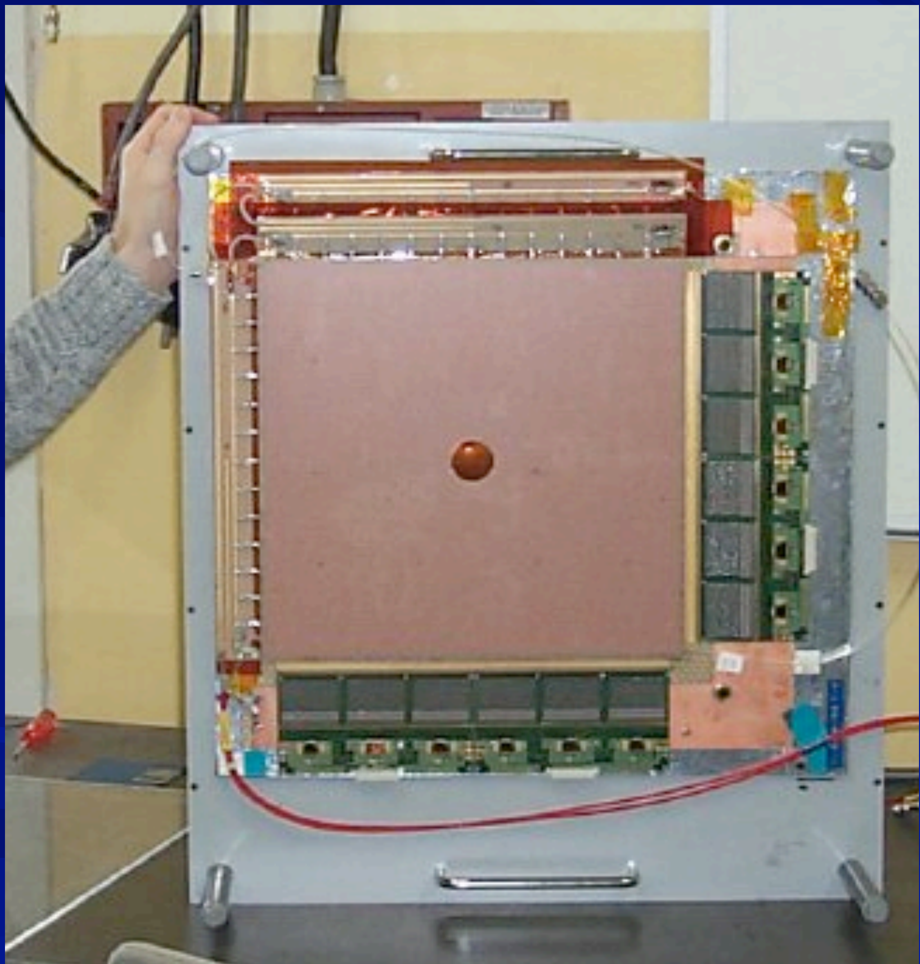
Spatial resolution:
σ = 57 μm

B. Ketzer, Wire Chamber Conference (2004)
F. Sauli, http://www.cern.ch/GDD

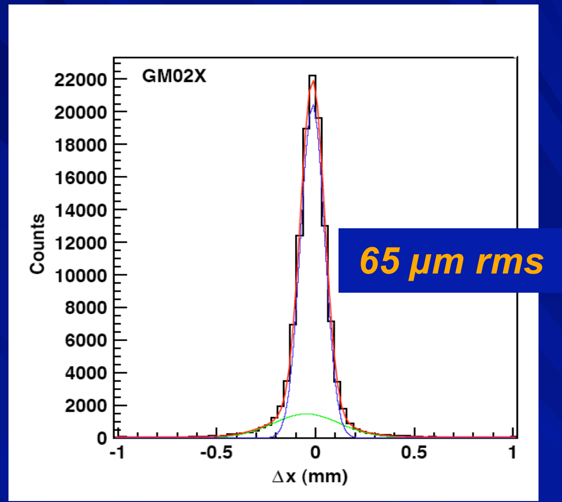
MPGD IN EXPERIMENTS

GEM DETECTORS FOR COMPASS

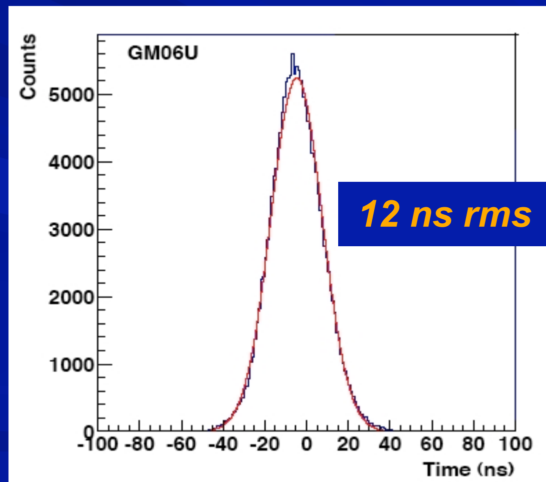
22 TRIPLE-GEM CHAMBERS
31x31 cm^2 ACTIVE
2-D CHARGE READOUT



SPACE RESOLUTION:



TIME RESOLUTION (FROM 3-BIN FIT):

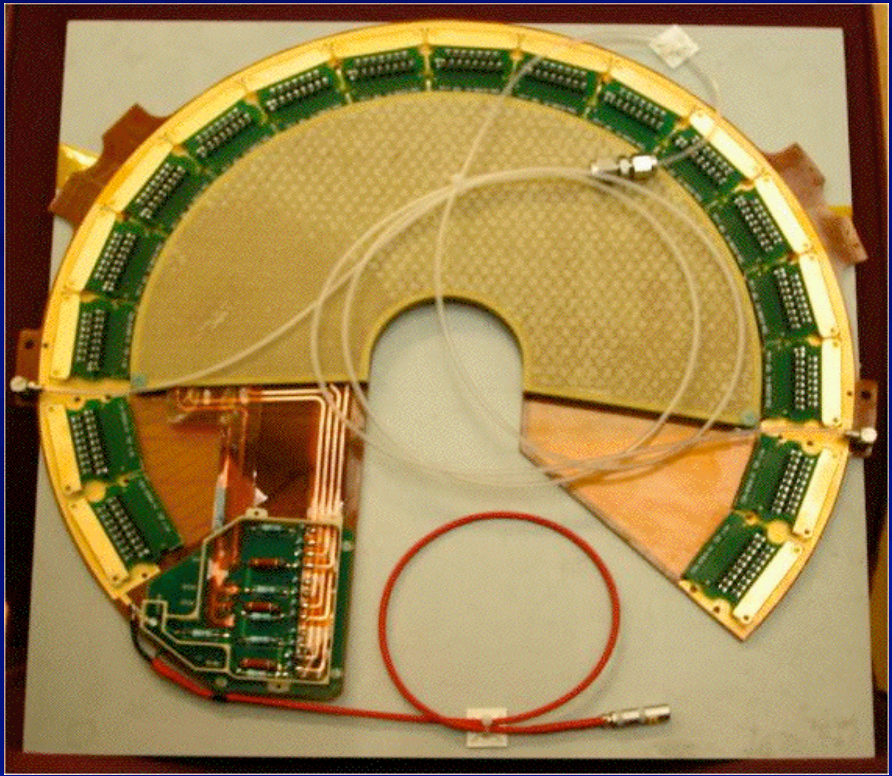


B. Ketzer et al, Nucl. Instr. and Meth. A535(2004)314

GEM DETECTORS

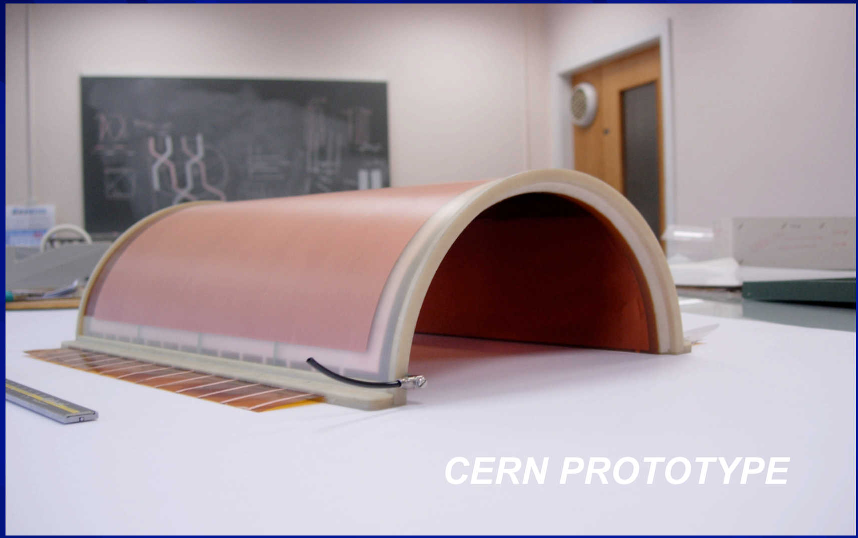
GEM DETECTOR FOR TOTEM
CERN-HELSINKI (IN CONSTRUCTION)

HALF-MOON SHAPED

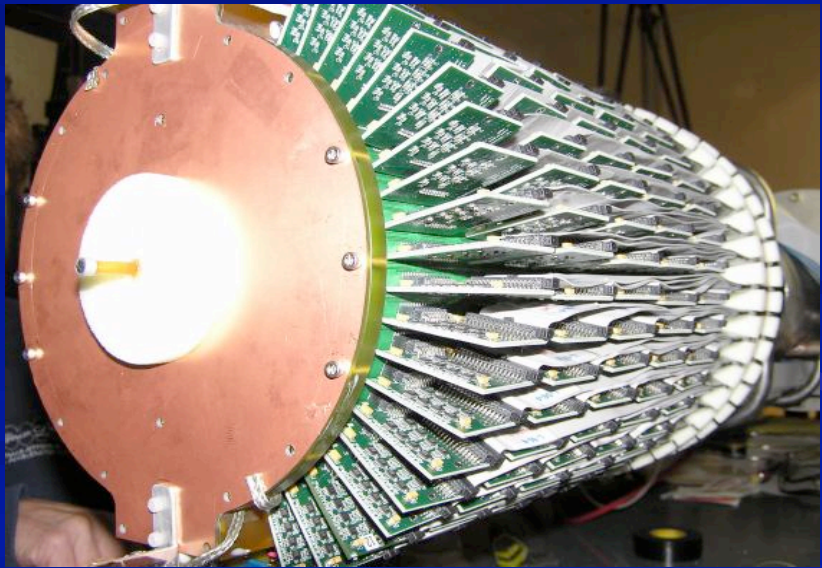


M. Bozzo et al, IEEE NSS 2004 Conf. Records

CYLINDRICAL GEM DETECTORS:



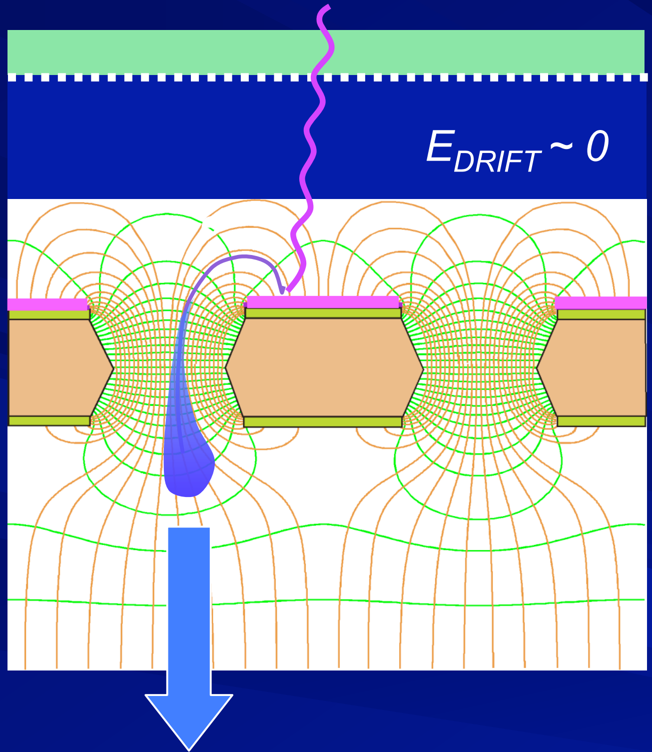
RADIAL DRIFT CHAMBER (BONUS, JLAB):



H. Fenker, JLAB (2006)

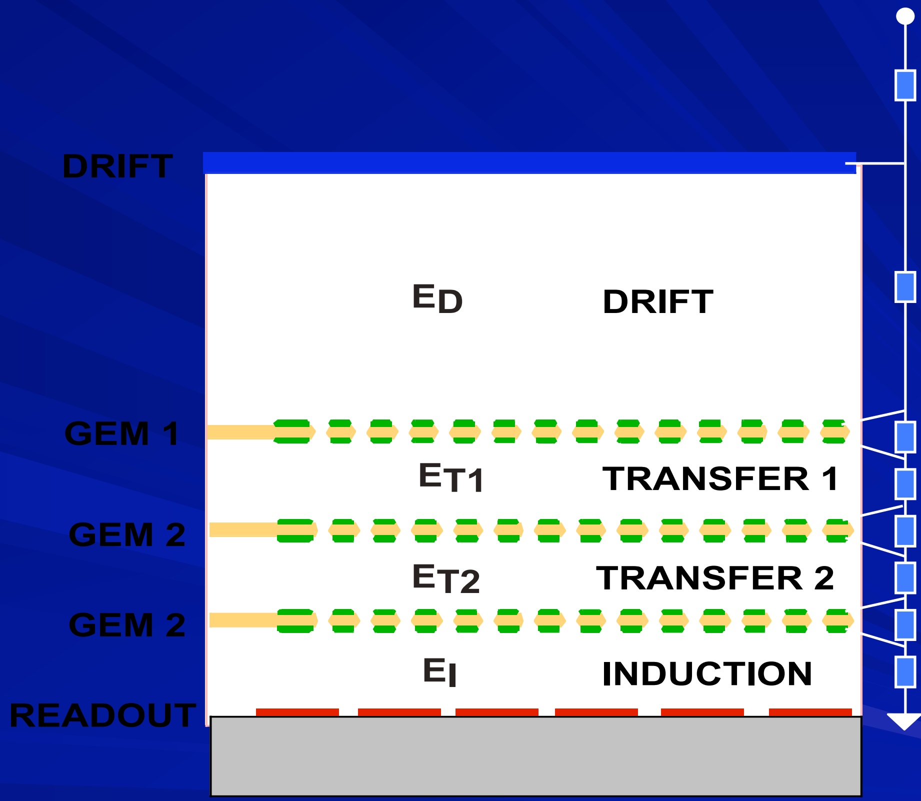
GEM PHOTON DETECTORS

REFLECTIVE CsI PHOTOCAHODE



FURTHER MULTIPLICATION

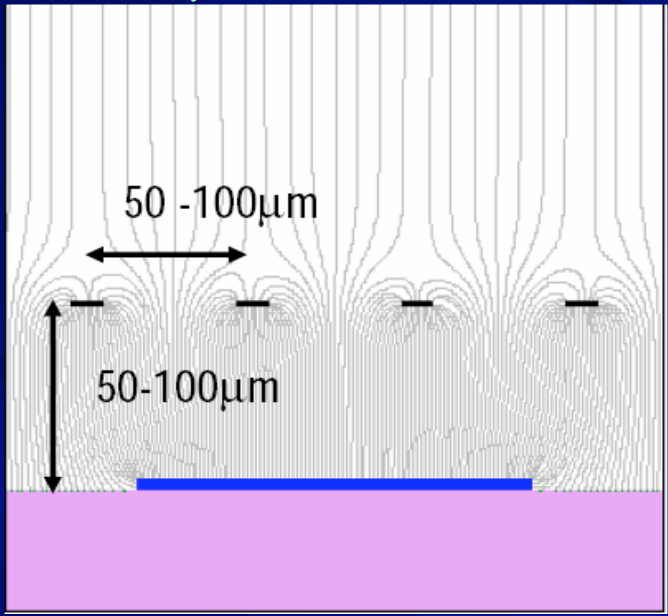
MULTIPLE GEM DETECTORS:
VERY HIGH GAIN (> 10^5) FOR SINGLE PHOTON DETECTION AND LOCALIZATION



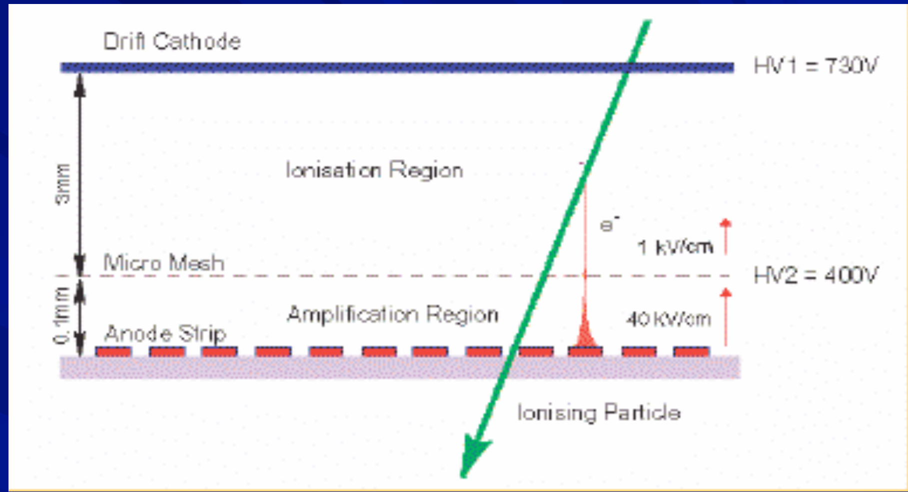
R. Bouclier et al, IEEE Trans. Nucl. Science NS-44(1997)646

Micromegas

Thin-gap (~ 100 parallel plate chamber
(no multiplication in the mesh)



MICROMEGAS resembles one side GEM
(parallel plate multiplication in thin gaps between a fine mesh and anode plate)



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

Spatial resolution: pushing to the limit

MICROMEGAS spatial resolution

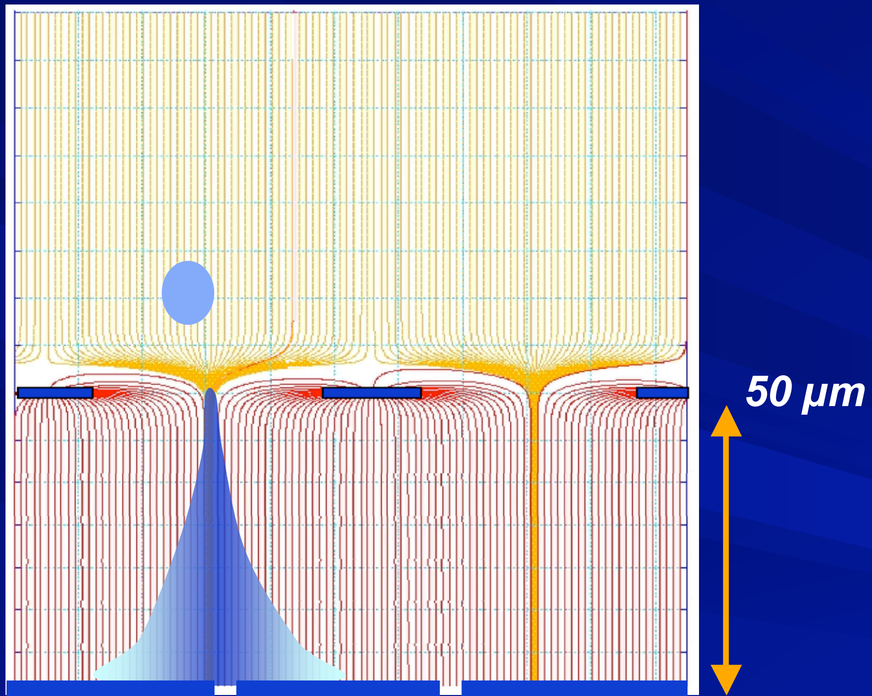
σ (μm)	PITCH (μm)	Gas mixture	Institute
50	317	Ar + 7% iso	Saclay [2]
60	317	Ar + 15% DME	Saclay [3]
45	200	Ar + 25% CO_2	Subatech
50	200	Ne + 10% DME	UNI-Mulhouse
42.5	100	Ar + 10% iso	Saclay
24	50	He + 20% DME	Saclay
14	100	CF_4 + 20% iso	Saclay
35	100	He + 6% iso + 5% CF_4	Saclay
29	100	He + 6% iso + 10% CF_4	Saclay

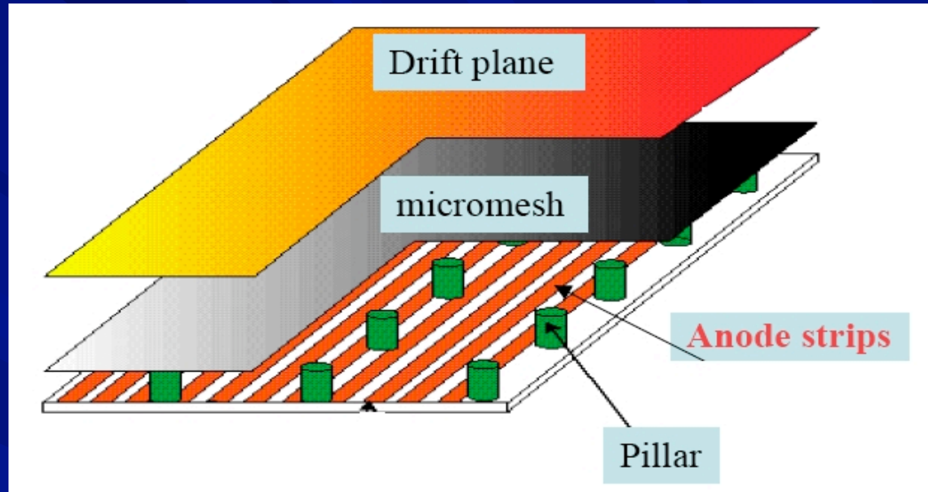
Y. Derre et al, Nucl. Instr. and Meth. A477(2002)23

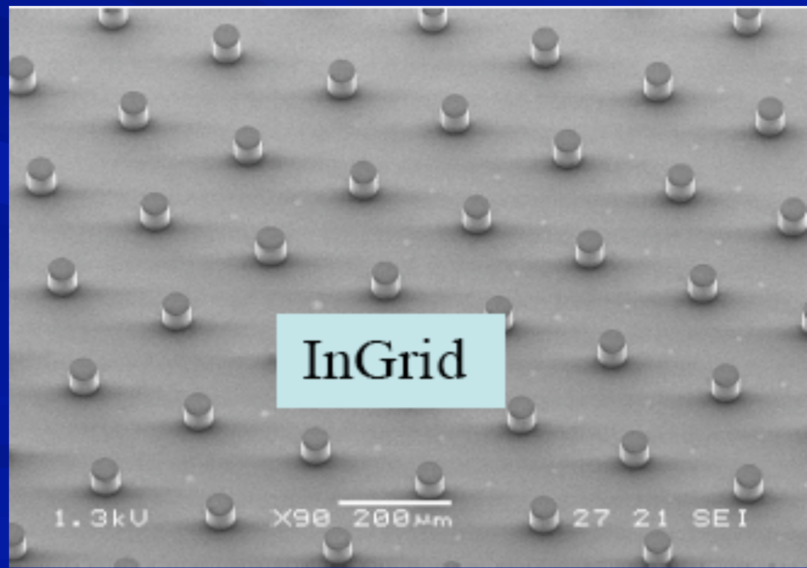
MICROMEGAS

NEW MICROPATTERN GAS DETECTORS

MICROMEGAS: THIN-GAP PARALLEL PLATE COUNTER





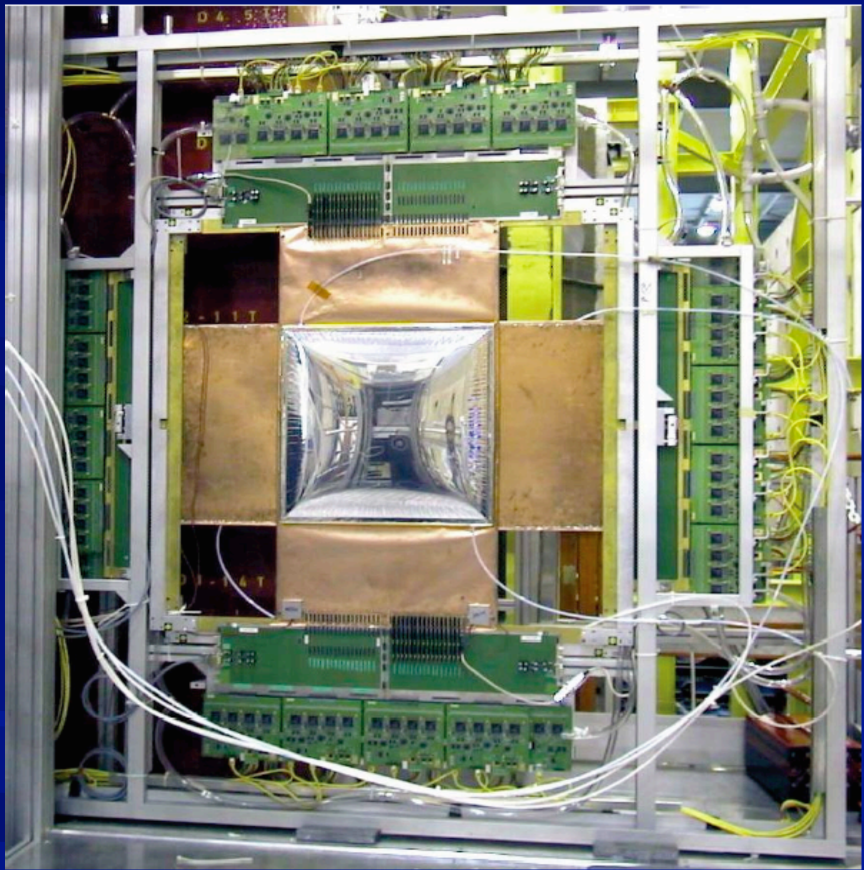


Y. Giomataris et al,
Nucl. Instr. and Meth. A376(1996)29

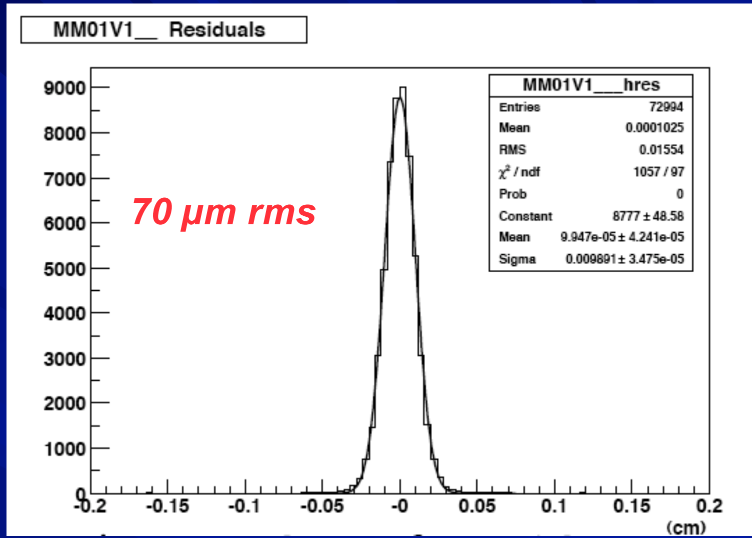
MICROMEGAS in COMPASS SPECTROMETER

12 PLANES IN 3 STATIONS X,Y, U, V

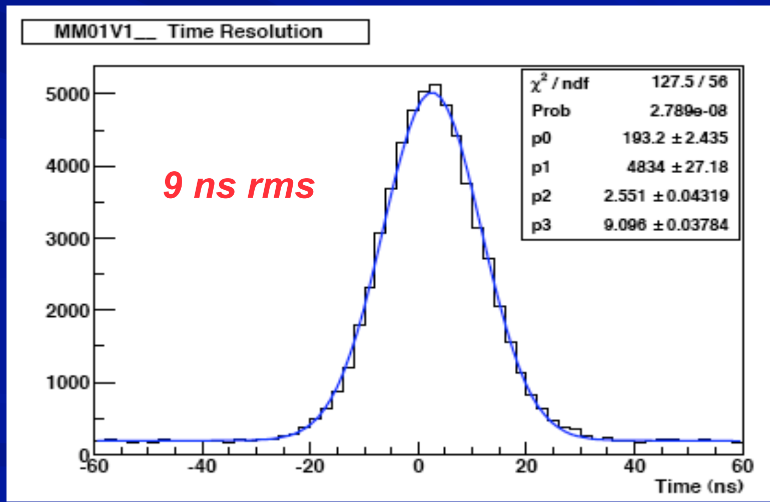
40x40 cm^2 ACTIVE
350 μm STRIPS - DIGITAL READOUT



SPACE RESOLUTION:



TIME RESOLUTION:

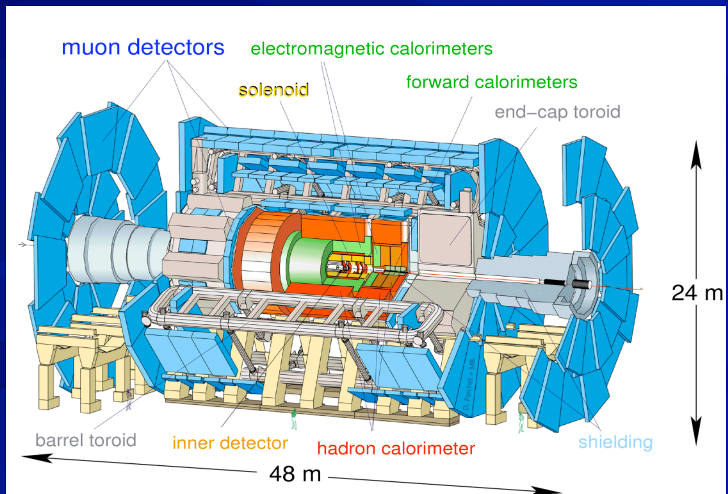


C. Bernet et al, Nucl. Instr. and Meth. A536(2005)61

From Particle Physics to Applications

Progress in micro-pattern detector developments (GEM,MICROMEGAS,…) promises to extent the applicability of gaseous detectors to the precision tracking at high counting rates in a hostile environments an area mostly accessible to silicon detectors at present

Detector	Radiation Hardness	σ_x, µm	σ_t, ns	S/N	X_0, %	Rate capability Hz/mm^2	Size of detector
Straw tubes	**> 10 C/cm (>10^{12} MIPs/mm^2)**	**100**	**50**	**15-20**	**0.2**	**~ 10^4**	**300*0.4 cm^2**
GEM	**> 20 mC/mm^2; (> 6*10^{11} MIPs/mm^2)**	**30(70)**	**5(12)**	**>20**	**0.4**	**~5*10^5**	**30*30 cm^2**
Micromegas	**20 mC/mm^2 (6*10^{11} MIPs/mm^2)**	**15(70)**	**5(10)**	**>20**	**0.4**	**~5*10^5**	**40*40 cm^2**
Si µ-strips (300 µm)	**3*10^{12} (24 GeV protons)/mm^2**	**< 10**	**~20**	**15-20**	**1.2**	**(a)**	**8*8 cm^2**



X Ray imaging

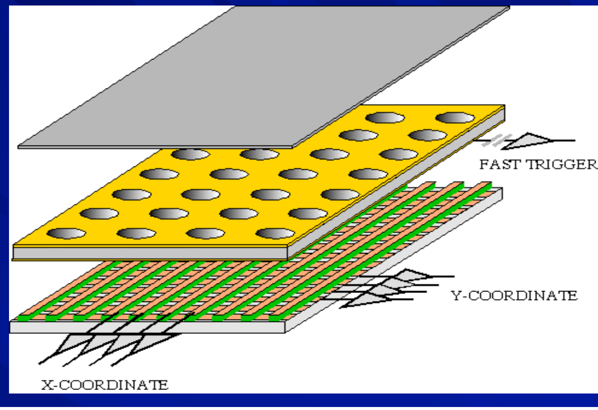
Wire Chamber Radiography:

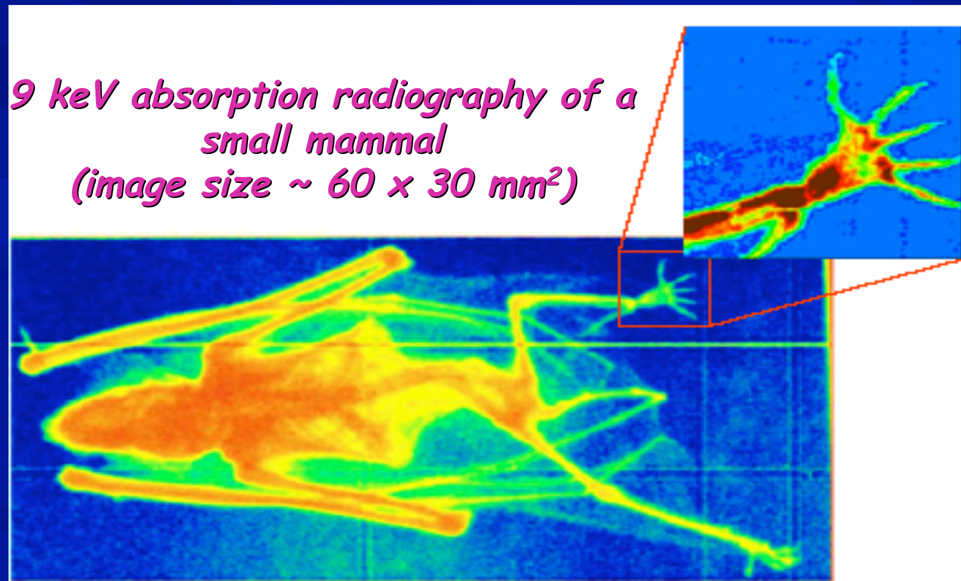
Position resolution ~ 250 μm

A. Bressan et al, Nucl. Instr. and Meth. A 425(1999)254
F. Sauli, Nucl. Instr. and Meth.A 461(2001)47
G. Charpak, Eur. Phys. J. C 34, 77-83 (2004)
F. Sauli, http://www.cern.ch/GDD

GEM for 2D Imaging:

Using the lower GEM signal, the readout can be self-triggered with energy discrimination:





9 keV absorption radiography of a small mammal (image size ~ 60 x 30 mm²)

Position resolution ~ 100 μm
(limited by photoelectron range in the gas)

PORTAL IMAGING

PORTAL IMAGING: VERY HIGH RATE GAMMA RAYS DETECTION

ROYAL INSTITUTE OF TECHNOLOGY AND KAROLINSKA HOAPITAL (STOKHOLM)

IACOBAEUS *et al.*: PORTAL IMAGING DEVICE FOR ADVANCED RADIATION THERAPY 1497

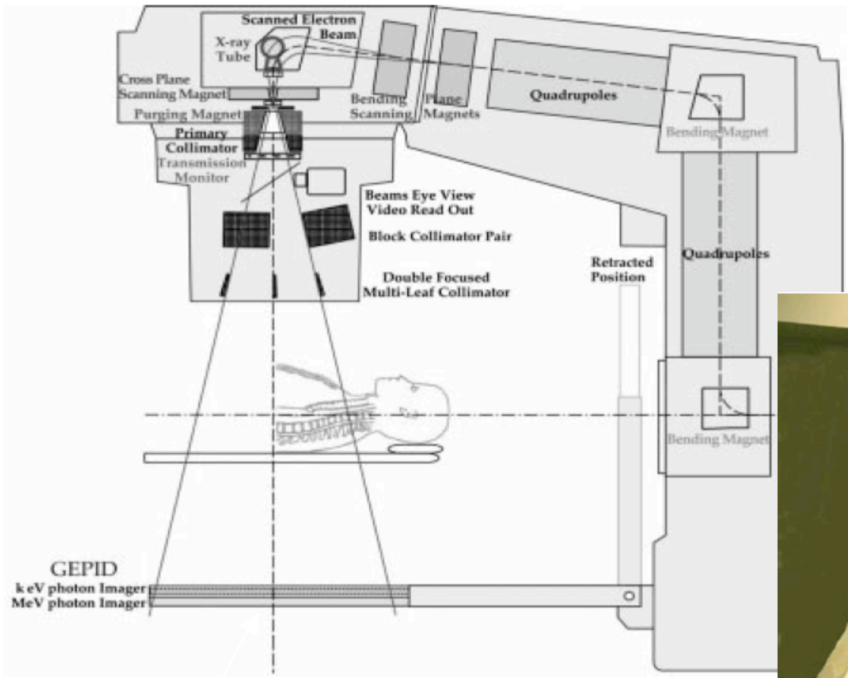


Fig. 1. Radiation treatment setup. A portal imaging device is placed under the patient.

Real Time Imaging and Dosimetry

GEM-BASED PIXEL DETECTOR

C. Iacobaeus et al, IEEE Trans. Nucl. Sci. NS-48 (2001)1496

Outlook Future of Gas Detectors

- *Gaseous detectors are still the first choice whenever the larg particle detection of medium accuracy is required*
- *New micro-pattern detector concepts (MICROMEGAS, GEM) are rather insensitive to radiation damage effects compared to micro-strip structures (separation of multiplication and readout stages, lacking fragile thin anodes, gain beingobtained by avalanche multiplication along an extended high field region)*
- *If properly designed and constructed, these detectors can be robust and stablein presence of high rates and heavily ionizing particles*
- *Gas detectors proven to be robust and reliable devices, adaptable to many applications*
- *Operating gases can be tuned and optimized to fulfill desired requirements*