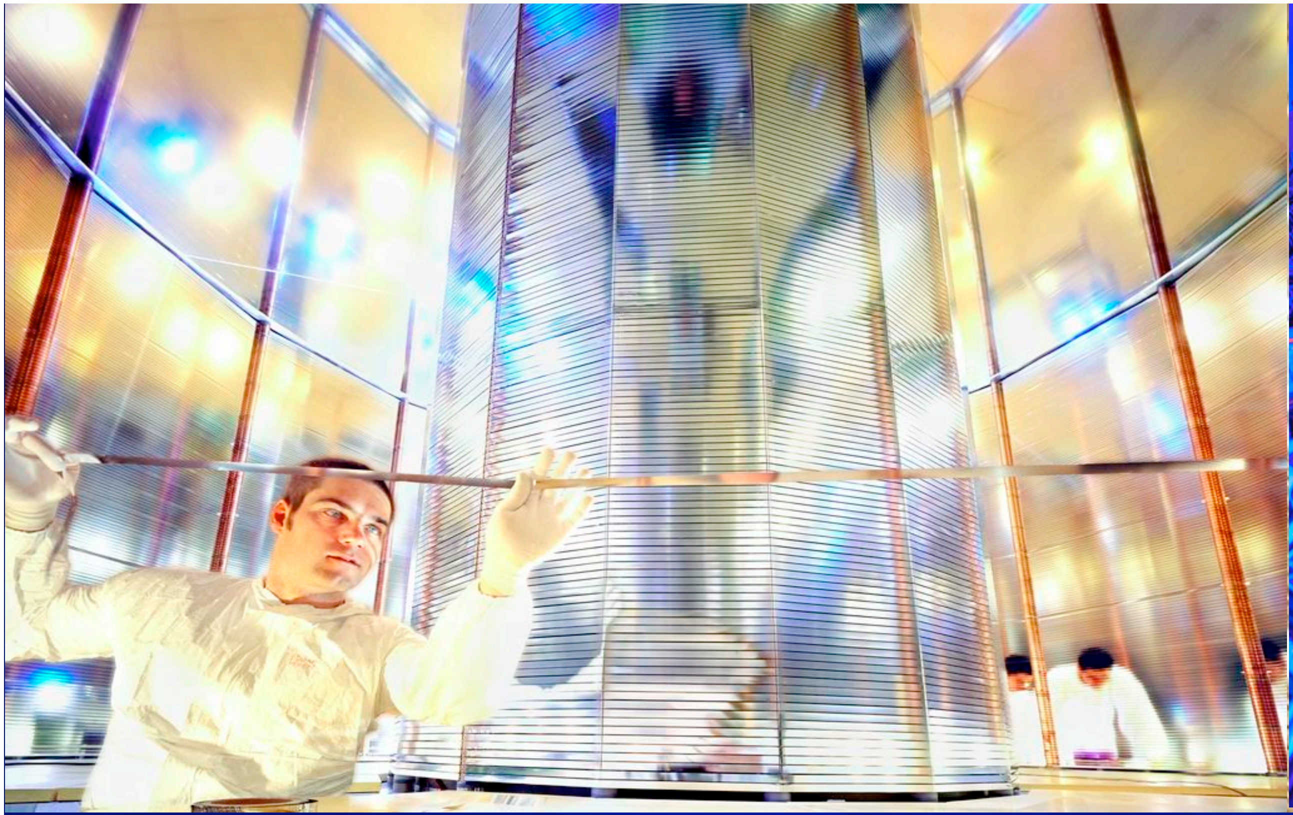
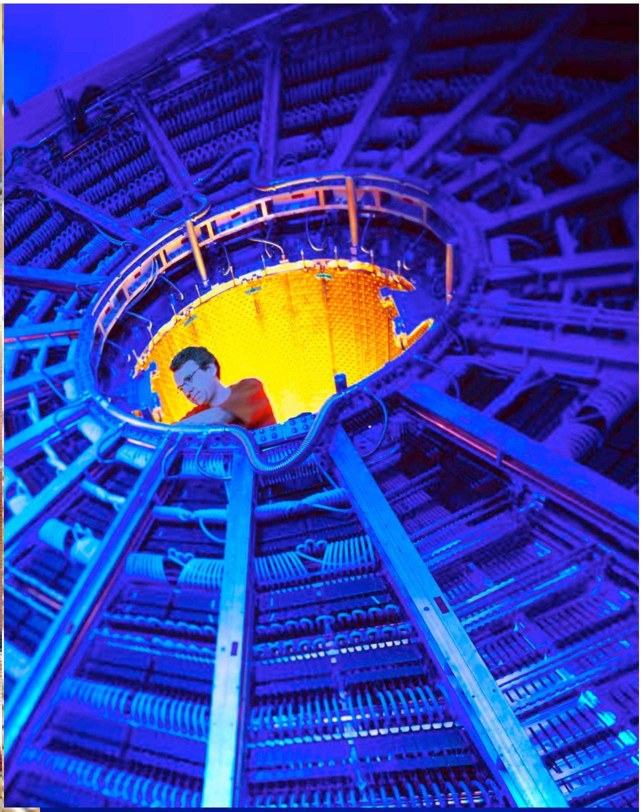



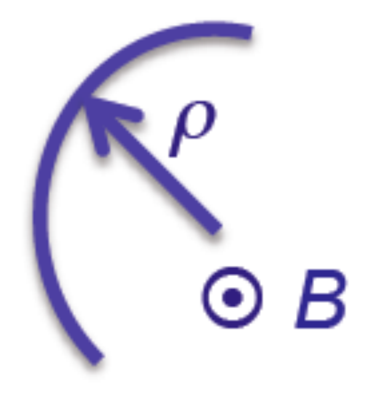
Detectors for Particle Physics

Scintillators and Gaseous detector

D. Bortoletto
Purdue University

Tracking

- Particle detection has many aspects:
  - Particle counting
  - Particle Identification = measurement of mass and charge of the particle
  - Tracking
- Charged particles are deflected by B fields such that:

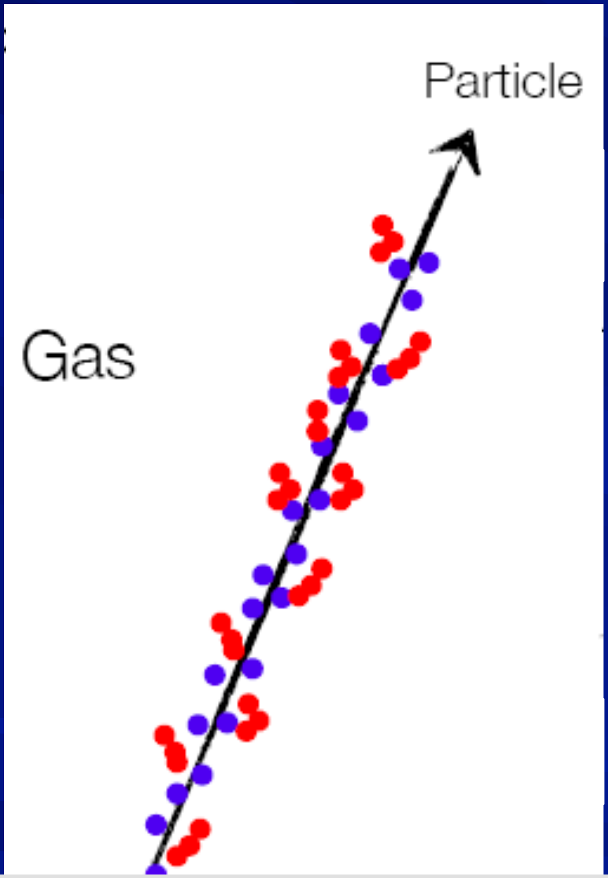


$$\rho = \frac{p_T}{q|B|} = \frac{\gamma m_0 \beta c}{q|B|}$$

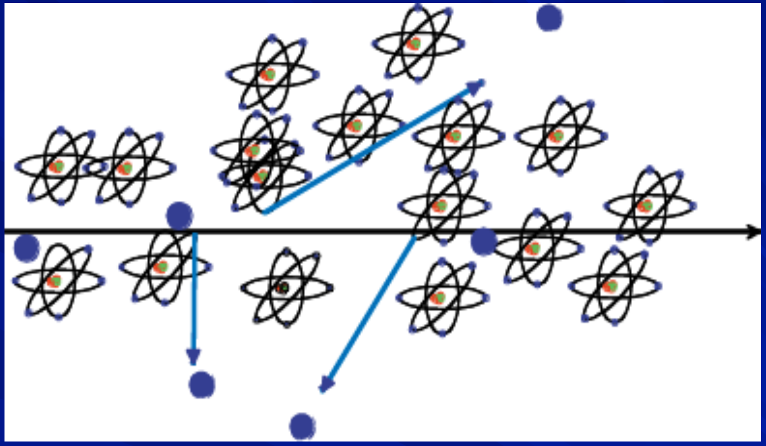
- By measuring the radius of curvature we can determine the momentum of a particle
- If we can measure also β independently we can determine the particle mass.

Signal creation

- Charged particle traversing matter leave excited atoms, electron-ion pairs (gases) electrons-hole pairs (solids)

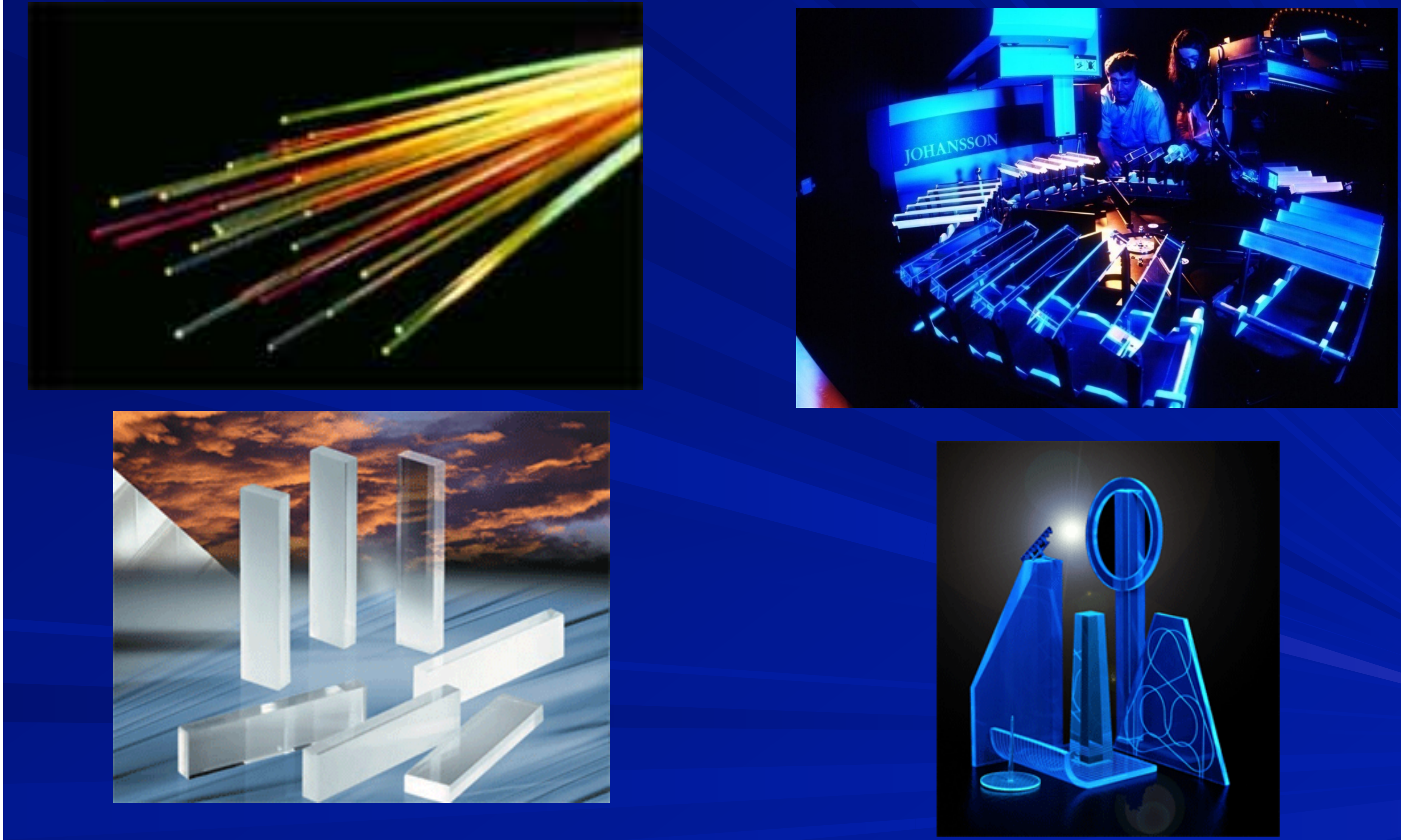


- Primary ionization
- Secondary ionization due to delta electron



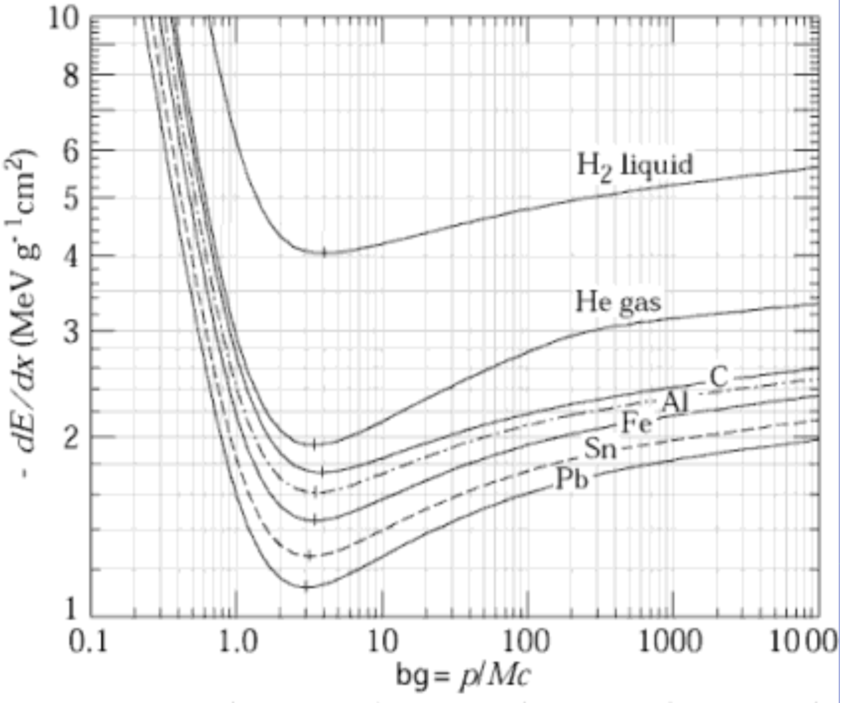
- Excitation: The photons emitted by the excited atoms in transparent materials can be detected with photon detectors
- Ionization: By applying an electric field in the detector volume, the ionization electrons and ions can be collected on electrodes and readout

Scintillator detectors



Scintillators

- dE/dx converted into visible light and then it is detected via photo-sensor (photomultipliers, SiPM,….)
- Emission of photons of by excited Atoms, typically UV- visible light.
  - Noble Gases and liquids (LAr, LXe…)
  - Inorganic Crystal (NaI, CsI…)
    - Largest light yield. Used for precision measurement of energetic Photons and in Nuclear Medicine.
  - Organic scintillatos
    - Polyzyclic Hydrocarbons (Naphtalen, Anthrazen,)
    - Large scale industrial production, mechanically and chemically robust.
- Typical light yield of scintillators
  - Energy in visible photons ≈ few % of the total energy Loss.
  - 1cm plastic scintillator, $\rho \approx 1$, dE/dx=1.5 MeV, ~15 keV in photons; i.e. ~ 15 000 photons produced.

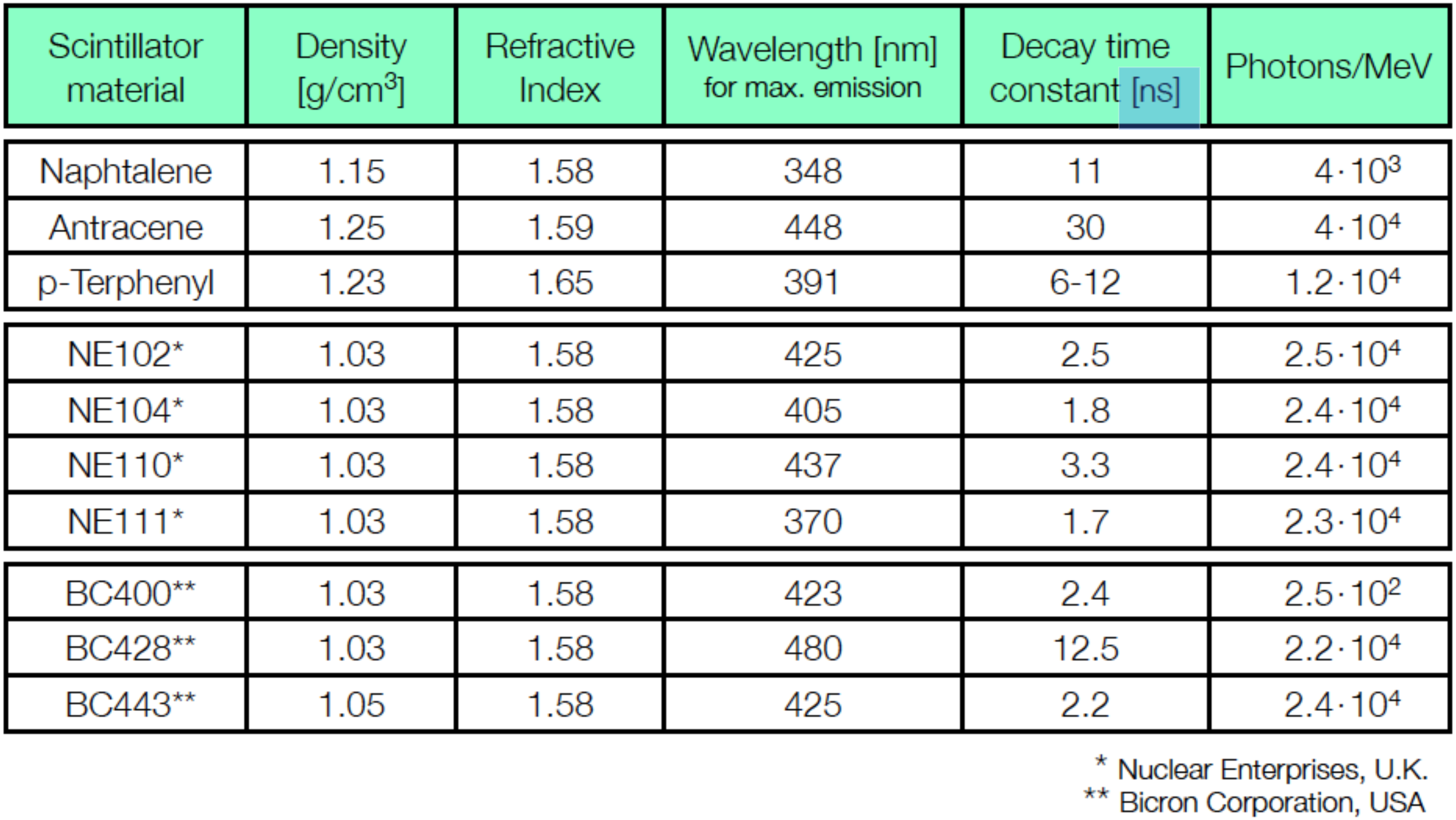


Inorganic scintillators

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29*	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4 \cdot 10^4$

* at 170 nm

Organic Scintillators



Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4\cdot10^3$
Antracene	1.25	1.59	448	30	$4\cdot10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2\cdot10^4$
NE102*	1.03	1.58	425	2.5	$2.5\cdot10^4$
NE104*	1.03	1.58	405	1.8	$2.4\cdot10^4$
NE110*	1.03	1.58	437	3.3	$2.4\cdot10^4$
NE111*	1.03	1.58	370	1.7	$2.3\cdot10^4$
BC400**	1.03	1.58	423	2.4	$2.5\cdot10^2$
BC428**	1.03	1.58	480	12.5	$2.2\cdot10^4$
BC443**	1.05	1.58	425	2.2	$2.4\cdot10^4$

* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Scintillator comparison

- Inorganic Scintillators
  - Advantages
    - high light yield [typical; $\varepsilon_{sc} \approx 0.13$]
    - high density [e.g. $PBWO_4$: 8.3 g/cm^3]
    - good energy resolution
  - Disadvantages complicated crystal growth
  - large temperature dependence
- Organic Scintillators
  - Advantages
    - very fast
    - easily shaped
    - small temperature dependence
    - pulse shape discrimination possible
  - Disadvantages
    - lower light yield [typical; $\varepsilon_{sc} \approx 0.03$]
    - radiation damage

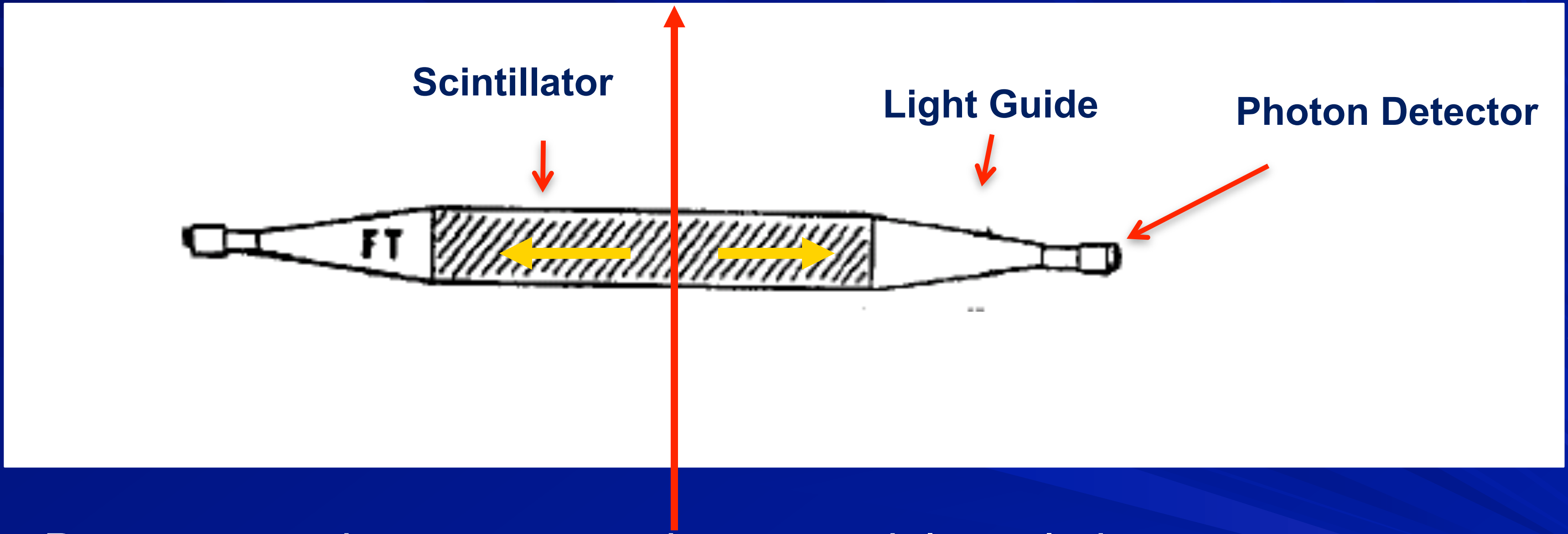
Light yield – $\varepsilon_{sc} \equiv$ fraction of energy loss going into photons

EXPENSIVE

CHEAP

Scintillators

- Photons are being reflected towards the ends of the scintillator.
- A light guide brings the photons to the Photomultipliers where the photons are converted to an electrical signal.



- By segmentation one can arrive at spatial resolution.
- Because of the excellent timing properties (<1ns) the arrival time, or time of flight, can be measured very accurately → Trigger, Time of Flight.

Scintillator

ATLAS Tile Calorimeter

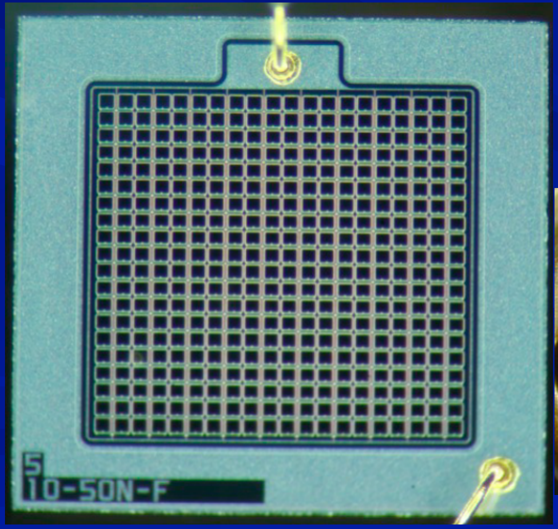
Photo-detectors

- Convert light into an electronic signal by using the photo-electric effect to convert photons into photo-electrons (p.e.)
- Requirement :
  - High Photon Detection Efficiency (PDE) or
  - Quantum Efficiency; Q.E. = $N_{p.e}/N_{photons}$

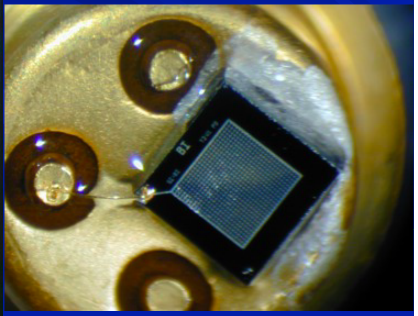
- Photomultipliers

- SiPM

Hammatsu MPPC

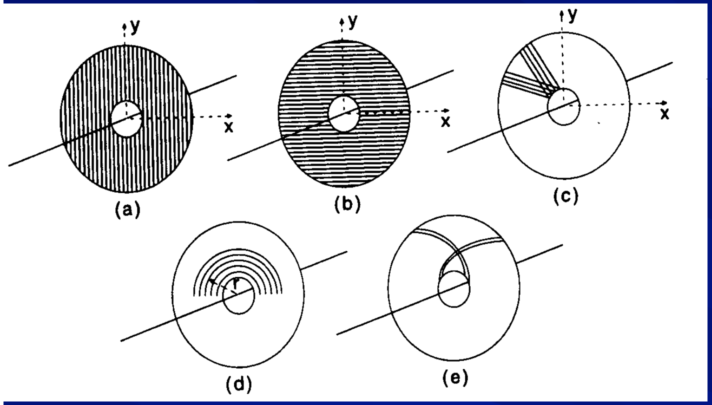


One of the first
SiPM
Pulsar, Moscow

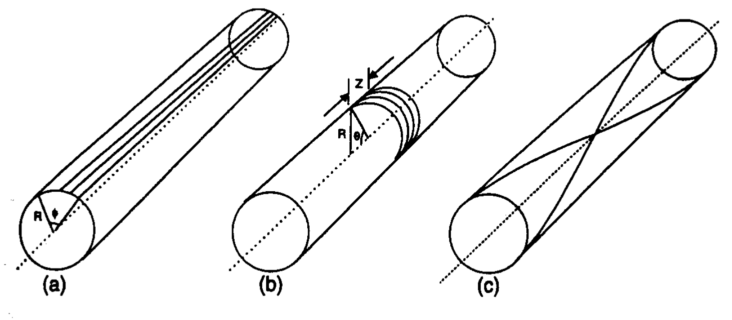


Fiber Tracking

Planar geometries (end cap)

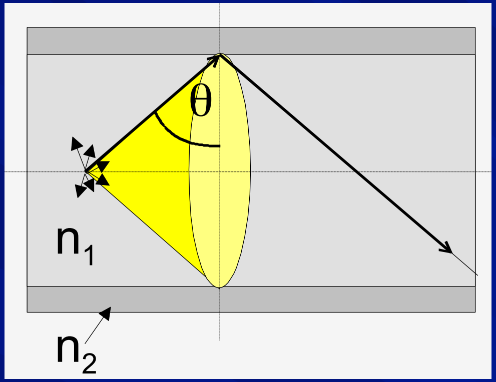


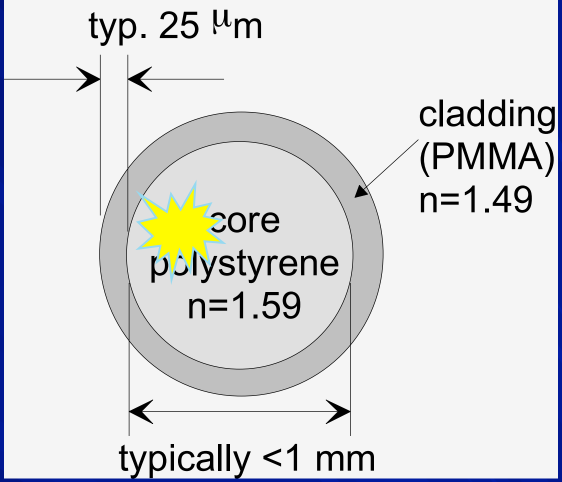
Circular geometries (barrel)



(R.C. Ruchti, Annu. Rev. Nucl. Sci. 1996, 46,281)

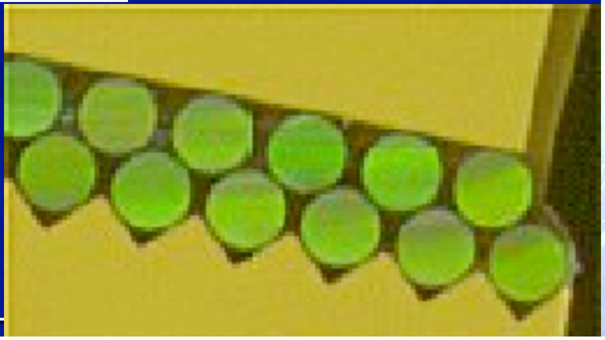
Light transport by total internal reflection

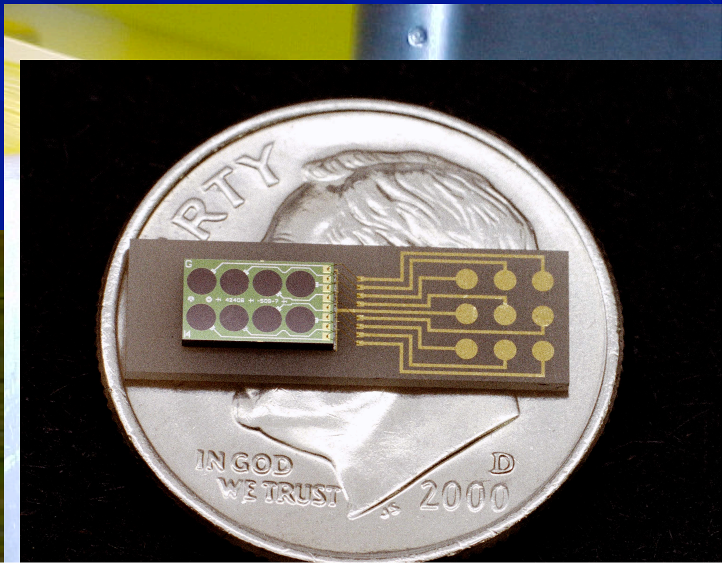




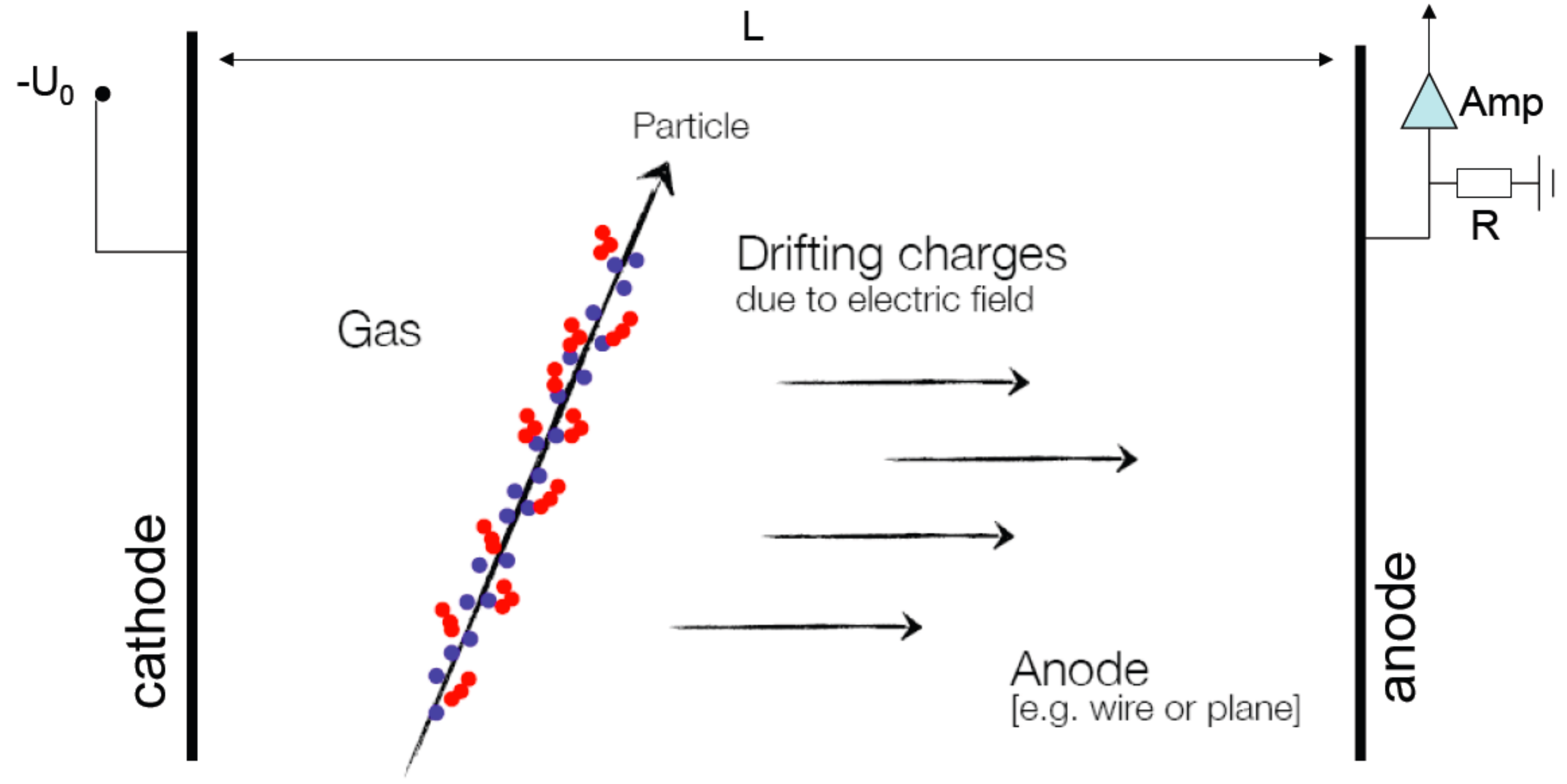
- High geometrical flexibility
- Fine granularity
- Low mass
- Fast response (ns)

D0 fiber tracker





Gas Detectors: primary



- ● Primary Ionization
- ● Secondary Ionization (due to δ-electrons)

Primary and secondary Ionization

- Primary Ionization
  - $X + p \rightarrow X^{+} + p + e^{-}$
- Secondary ionization if $E(\delta) > E_i$
  - $\mathbf{X + e^{-} \rightarrow X + e^{-} + e-}$

Where:
p = charge particle traversing the gas
X = gas atom
e^{-} = delta-electron (**δ**)

Critical parameters for Gas detectors:

- Ionization energy: E_i
- Average energy/ion pair: W_i
- Average number of primary ion pairs/cm^{2} : n_p
- Average number of ion pairs/cm: n_T

$$\langle n_T \rangle = \frac{L \cdot \left\langle \frac{dE}{dx} \right\rangle_i}{W_i}$$

n_T is ≈2-6 x n_p

L= layer thickness

- Typical values:
  - **E_i ~ 30 eV**
  - **n_T ~ 100 pairs / 3 keV incident particle**

Most common gases

Gas	ρ (g/cm^3) (STP)	I_0 (eV)	W_i (eV)	dE/dx (MeVg^{-1}cm^2)	n_p (cm^{-1})	n_t (cm^{-1})
H_2	$8.38 \cdot 10^{-5}$	15.4	37	4.03	5.2	9.2
He	$1.66 \cdot 10^{-4}$	24.6	41	1.94	5.9	7.8
N_2	$1.17 \cdot 10^{-3}$	15.5	35	1.68	(10)	56
Ne	$8.39 \cdot 10^{-4}$	21.6	36	1.68	12	39
Ar	$1.66 \cdot 10^{-3}$	15.8	26	1.47	29.4	94
Kr	$3.49 \cdot 10^{-3}$	14.0	24	1.32	(22)	192
Xe	$5.49 \cdot 10^{-3}$	12.1	22	1.23	44	307
CO_2	$1.86 \cdot 10^{-3}$	13.7	33	1.62	(34)	91
CH_4	$6.70 \cdot 10^{-4}$	13.1	28	2.21	16	53
C_4H_{10}	$2.42 \cdot 10^{-3}$	10.8	23	1.86	(46)	195

Quelle: K. Kleinknecht, *Detektoren für Teilchenstrahlung*, B.G. Teubner, 1992

Ionization statistics

- The ionization statistic has a critical impact on gas detector performance
  - Production of primary ion/electron pairs is a Poissonian distributed

$$\langle n_p \rangle = \frac{L}{\lambda}$$

$$\lambda = \frac{1}{n_e \sigma_I}$$

$$P(n_p, \langle n_p \rangle) = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

σ_I : Ionization x-Section
n_e : Electron density
L : Thickness

Typical values of the mean free path **λ**

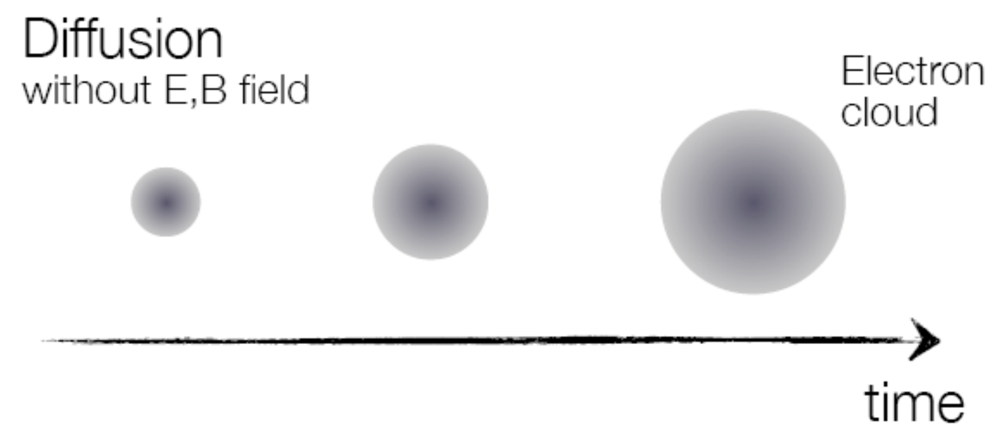
- He 0.25 cm
- Air 0.052 cm
- Xe 0.023 cm

- Other important parameters are:
  - Recombination and electron attachment due eo Electro-negative gases which bind electrons; e.g.: O_2, Freon, Cl_2, SF_6 ... ➔influences detection efficiency
  - Diffusion➔ Influences the spatial resolution
  - Mobility of charges ➔ Influences the timing behavior of gas detectors
  - Avalanche process via impact ionization:➔Important for the gain factor of the gas detector ...

Transport of electrons/ions in a gas

- Diffusion is evaluated using the classical kinetic theory of gases

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$



- e$^-$/ions are distributed with a Gaussian spread σ(r) after a diffusion time t

$$\sigma(r) = \sqrt{6Dt}$$

The diffusion coefficient D, depends on the pressure P and the temperature T

$$D = \frac{1}{3} v\lambda = \frac{2}{3\sqrt{\pi}} \frac{1}{P\sigma_0} \sqrt{\frac{(kT)^3}{m}}$$

- The Mean-free path of electrons/ions in the path

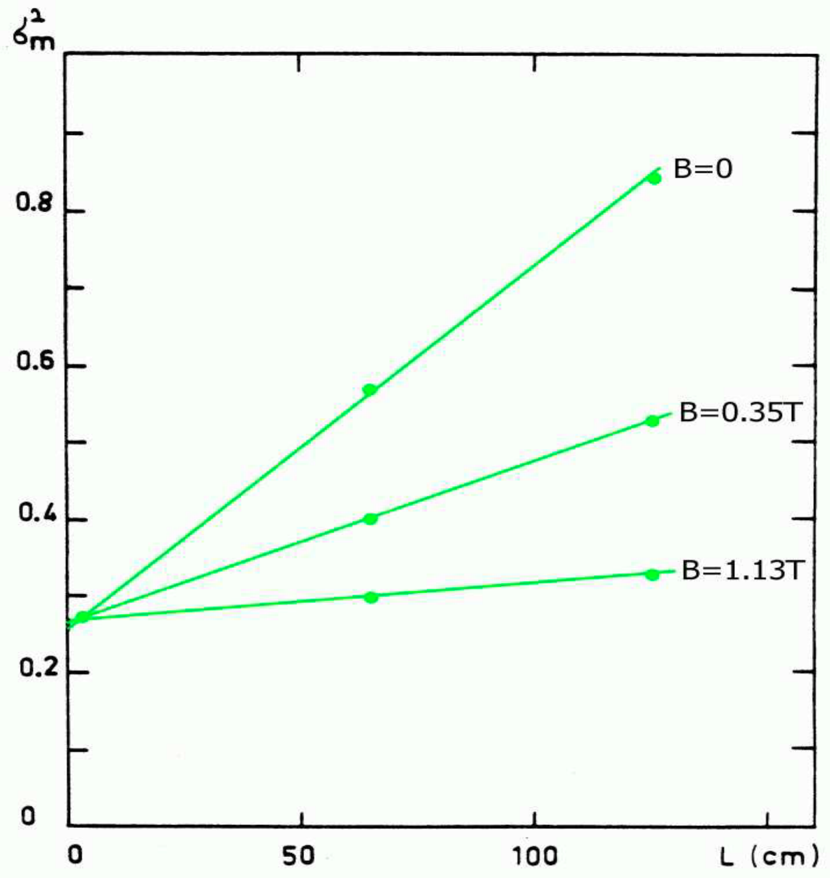
$$\lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 P}$$

- The mean velocity according to Maxwell distribution
- m is the mass of the particle

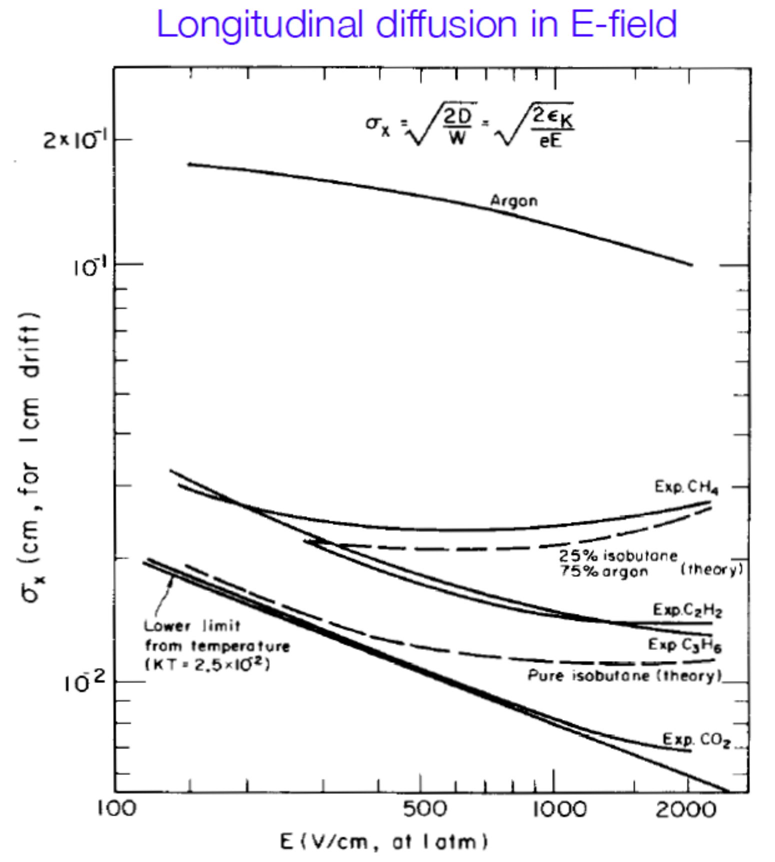
$$v = \sqrt{\frac{8kT}{\pi m}}$$

Drift and diffusion in E and B fields

- Transverse diffusion as function of drift length for different B fields



- Longitudinal diffusion as function of E field


Longitudinal diffusion in E-field

Transport equation is usually solved numerically using programs like Magboltz and Garfield

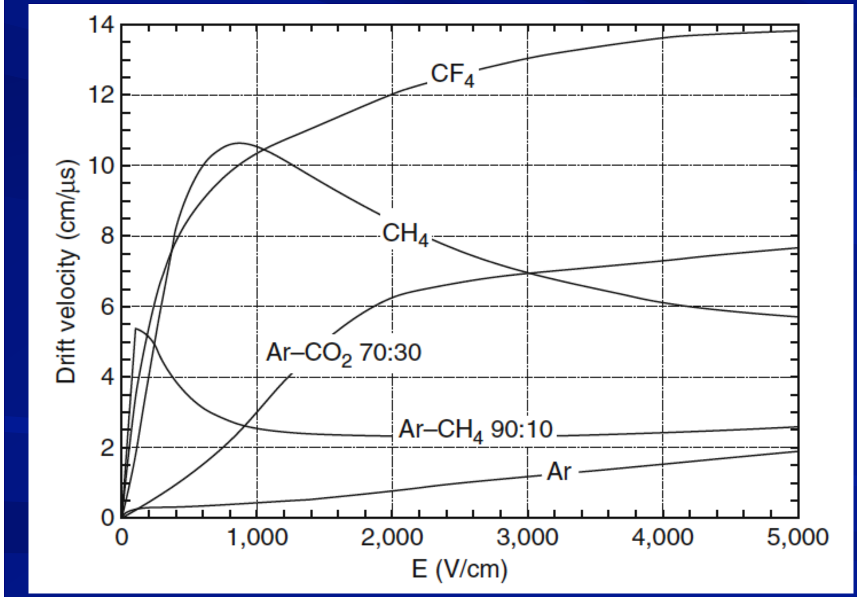
Drift and mobility

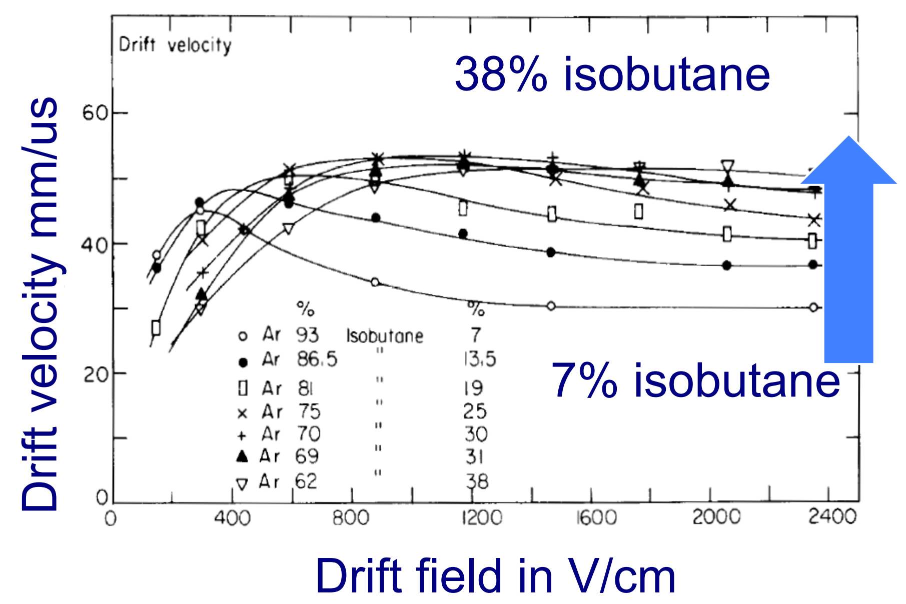
- In an external E-field electrons/ions obtain velocity $\mathbf{v}_D$ in addition to thermal motion; on average electrons/ions move along field lines of electric field E

$$\vec{v}_D = \mu_{\pm} \left| \vec{E} \right|$$

Typical values of v_D

- E ~ 1 kV / cm
- v_d ≈cm/ms for ions
- v_d ≈cm/μs for e-





Drift velocity in several argon-isobutane (C_4H_{10}) mixtures

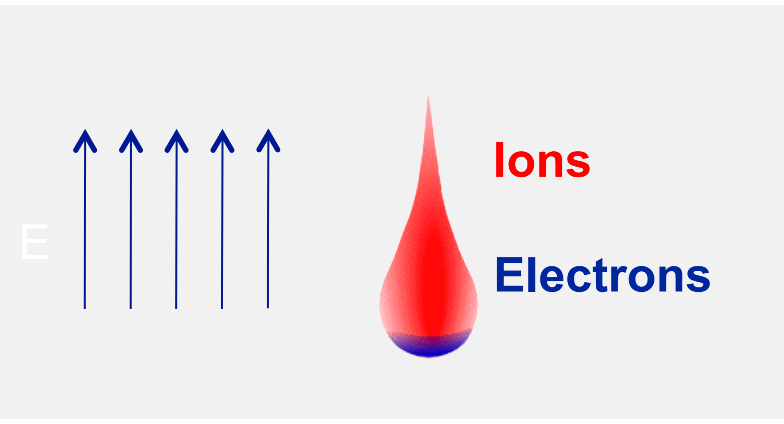
- Fast CF_4-based mixtures reach v_D ≈10 cm · μs^{-1} ➔reduced diffusion

Avalanche Multiplication

- The primary ionization signal is very small in a gas layer: in 1 cm of Ar/CO_2 (70:30) at NTP only ~**100** electron–ion pairs are created ➔use an "internal gas amplification" mechanism to generate a detectable signal
- Large E fields ➔large electron kinetic energy ➔avalanche formation
  - **$dn = n \alpha dx$** **α=Townsend Coefficient**
  - **$n(x) = n_0 e^{\alpha x}$** n(x)=electrons at location x
- Gain or Amplification is:

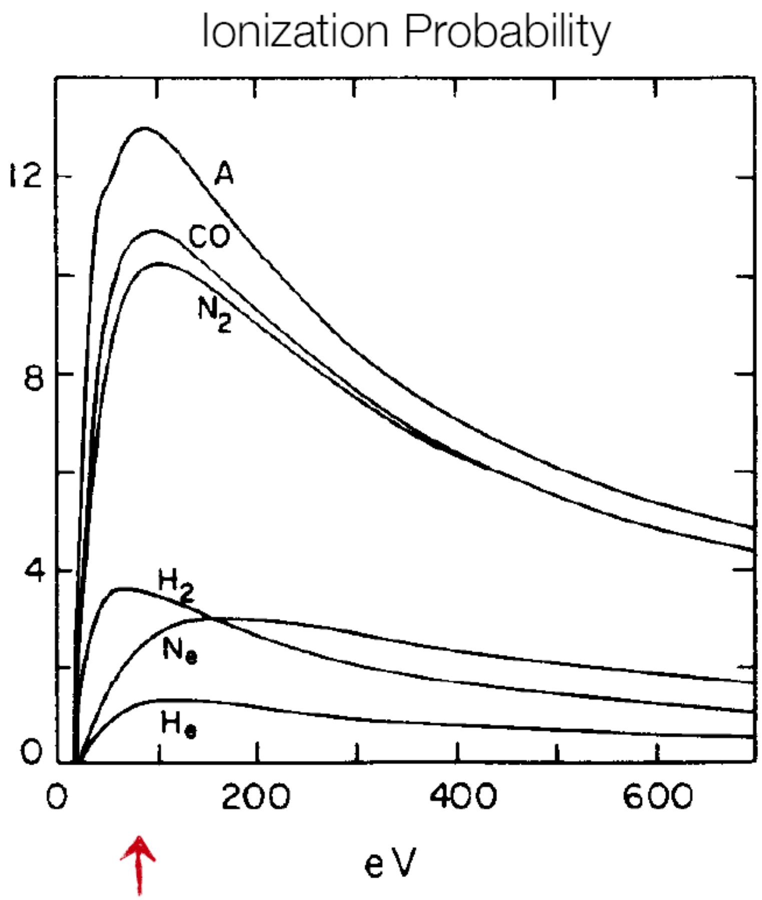
$$G = \frac{n}{n_0} = e^{\alpha x}$$

- Raether's limit $G \approx 10^8$, since after that sparking can occur



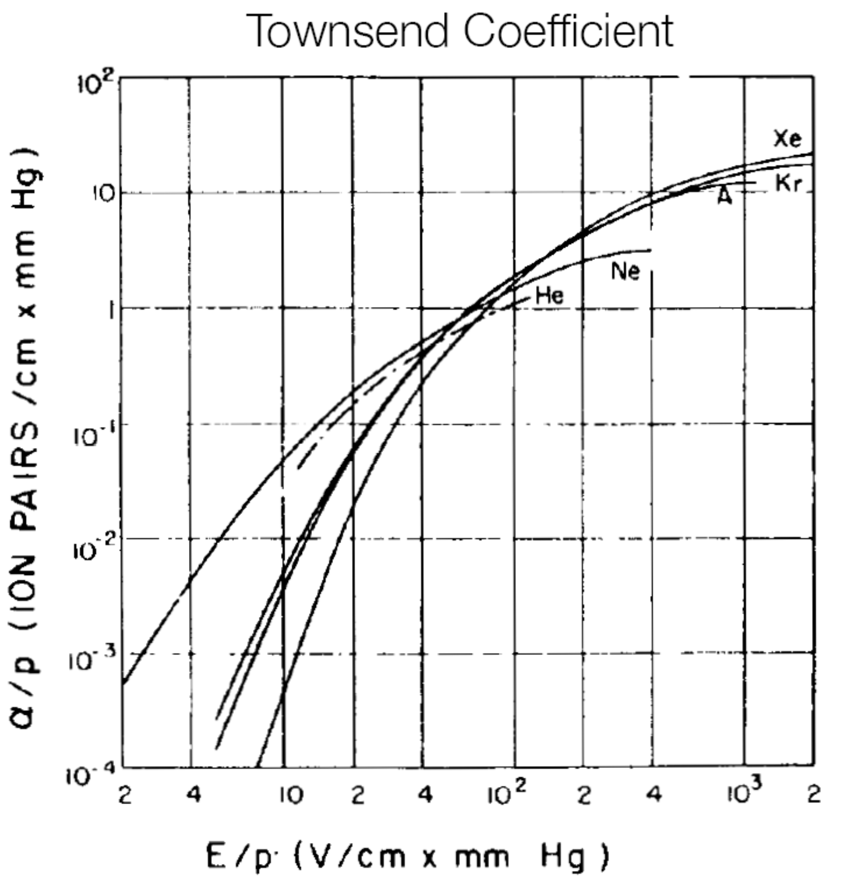
Drop-like shape of an avalanche

Avalanche multiplication



Need about 75-100 eV
for high ionization probability

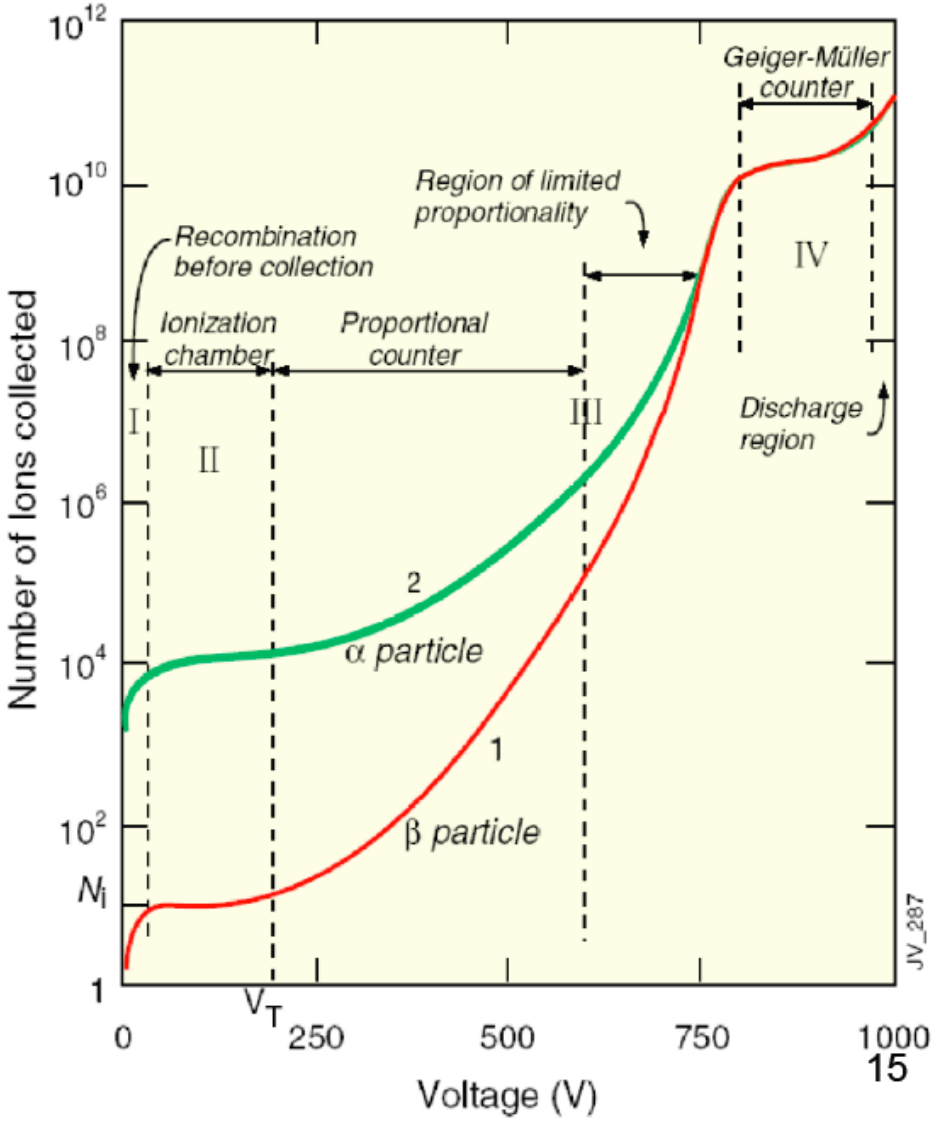
[need to gain this energy within few microns]



E ≈ 75 kV/cm
needed to reach α = 1

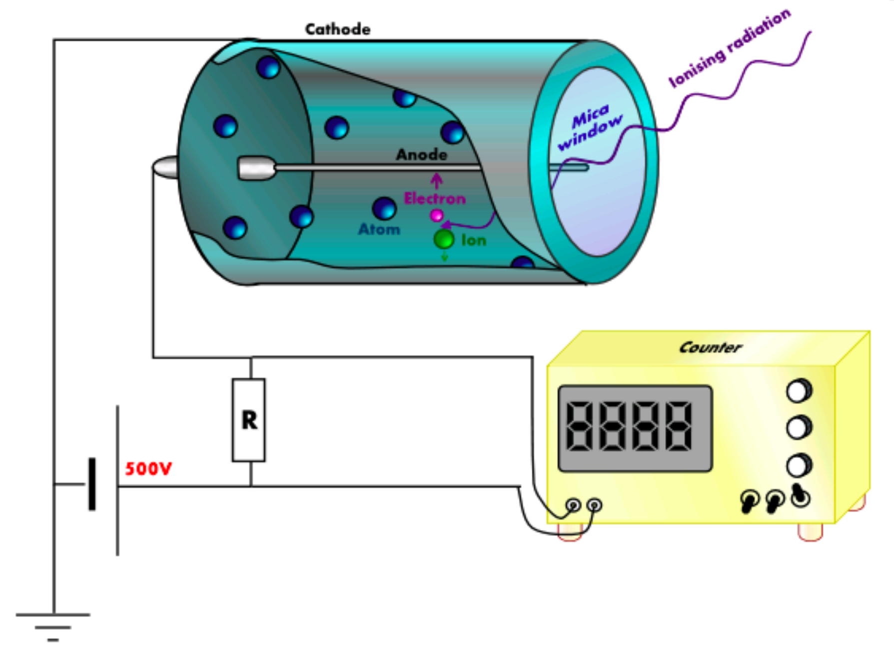
Gas amplification factor

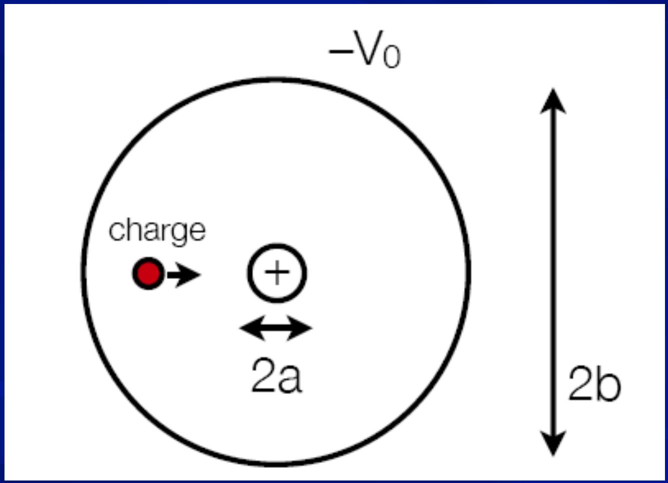
- Ionization mode: full charge collection; no amplification; G=1
- Proportional mode: multiplication; signal proportional to original ionization ⇒ measurement of dE/dx. Secondary avalanches needs quenching; G ≈10^4-10^5
- Limited Proportional (Saturated, Streamer mode): strong photo-emission; Require strong quenchers. High gain 10^{10}⇒ large signal, simple electronics
- Geiger mode: Massive photo emission. Full length of anode affected. Discharge stopped by HV cut



Proportional counter

- Cylindrical proportional counter:
  - Single anode wire in a cylindrical cathode
  - E~1/r: weak field far from the wire
  - electrons/ions drift in the volume
  - multiplication occurs only near the anode





$$E = \frac{V}{r\ln(a/b)}$$

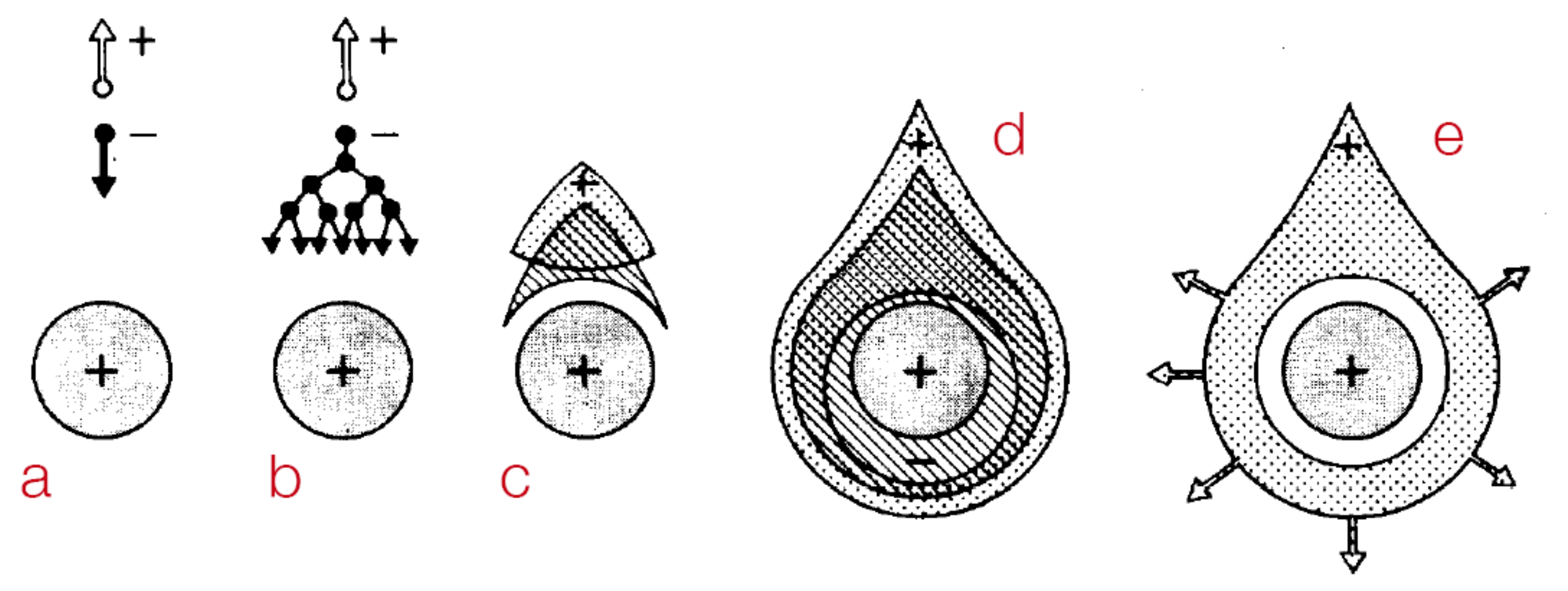
- Close to wire E-field very large
- Use thin wire

- The kinetic energy of the electrons becomes very large near the wire and can produce secondary ionization

$$\Delta T_{kin} = e\Delta U$$

Avalanche development

- Time development of avalanche near the wire of a proportional counter

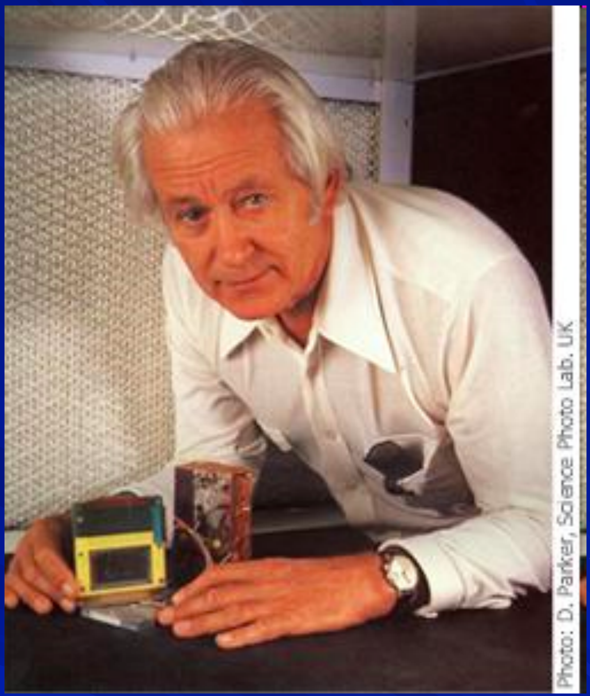


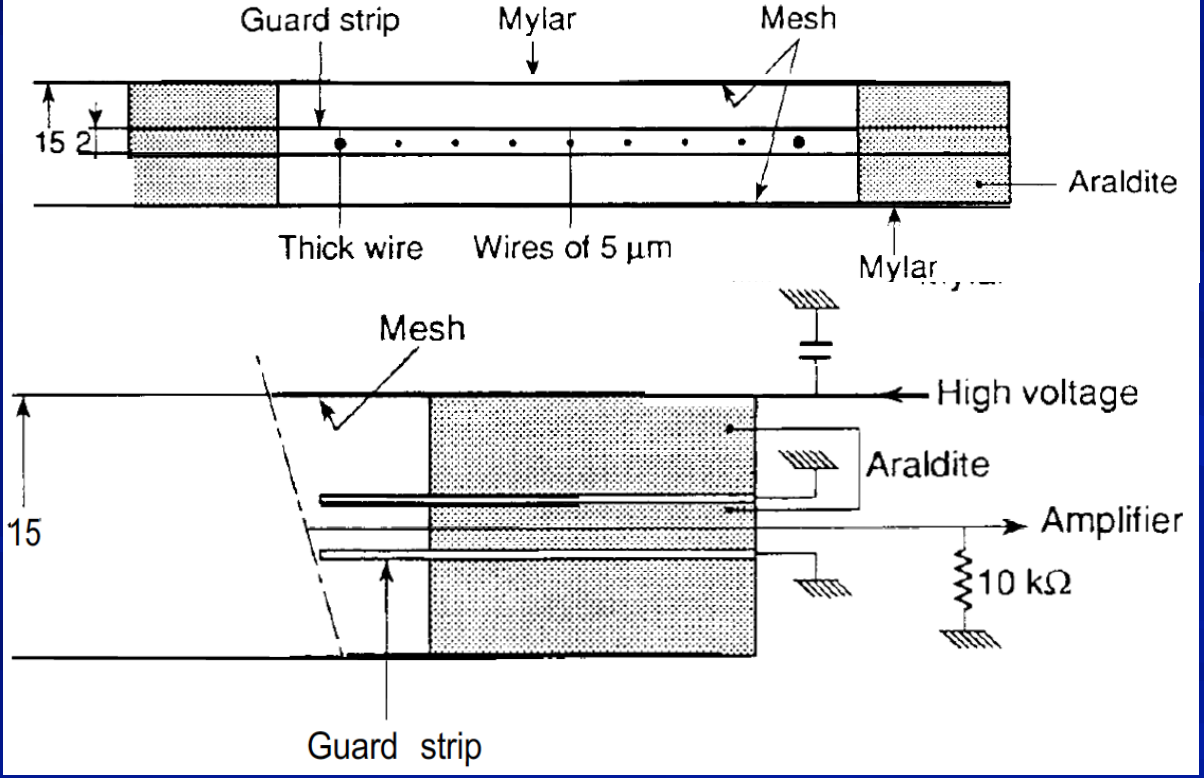
a) single primary electron proceeds towards the wire anode,
b) In the region of increasingly high field avalanche multiplication starts
c) electrons and ions are subject to lateral diffusion,
d) a drop-like avalanche develops which surrounds the anode wire,
e) the electrons are quickly collected (~1ns) while the ions begin drifting
f) towards the cathode generating the signal at the electrodes

Multiwire proportional chambers

- A proportional counter does not provide the position of the incident particle
- Charpak developed of multi-wire proportional chamber

G. Charpak Nobel price ('92)



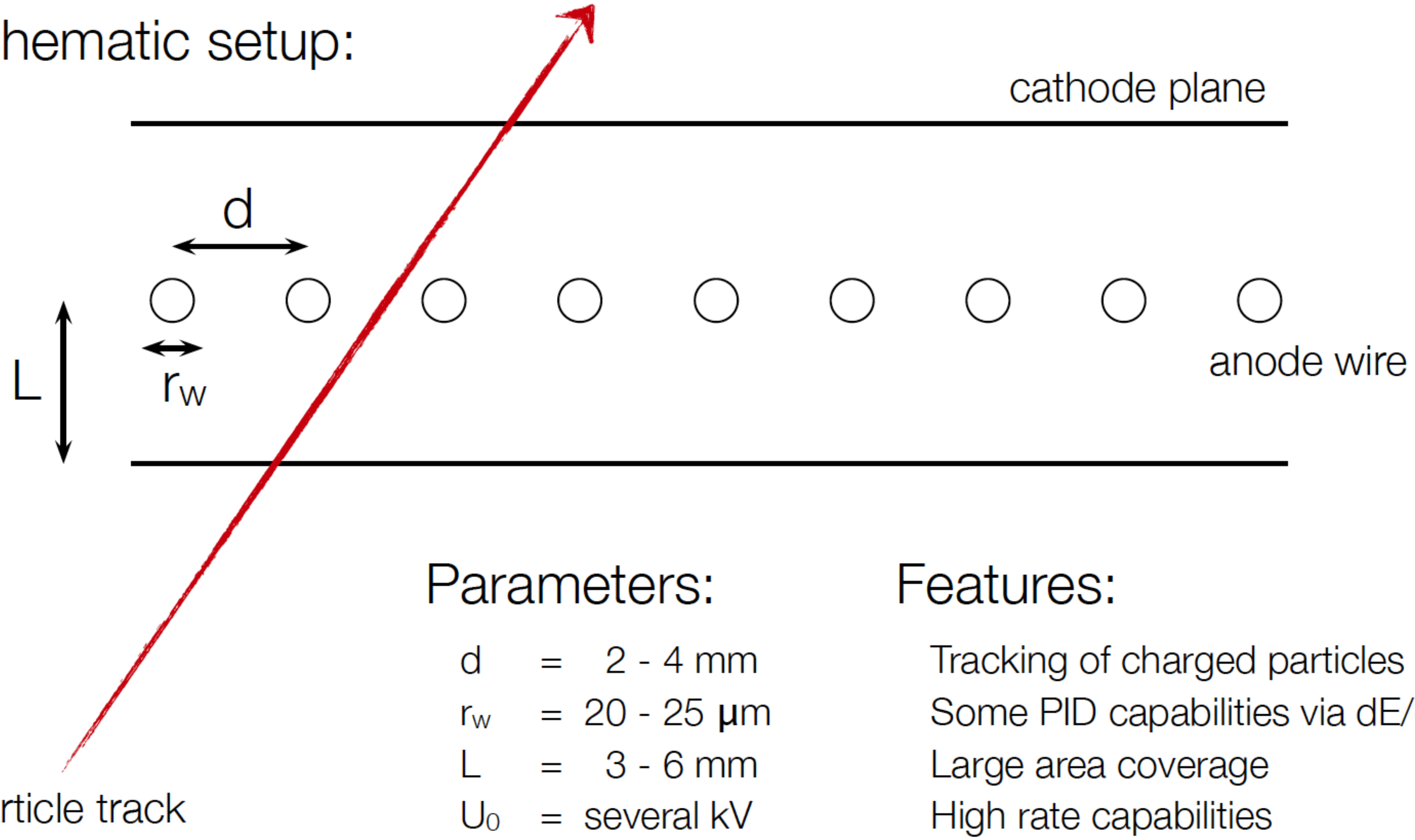


Construction details of the original design
of Charpak's multi-wire chambers (from Nobel lecture)

Sense wire =2μ diameter
d=2 mm

Multi-Wire Proportional Chamber

Schematic setup:



Parameters:

d = 2 - 4 mm

r_W = 20 - 25 µm

L = 3 - 6 mm

U_0 = several kV

Total area: $O(m^2)$

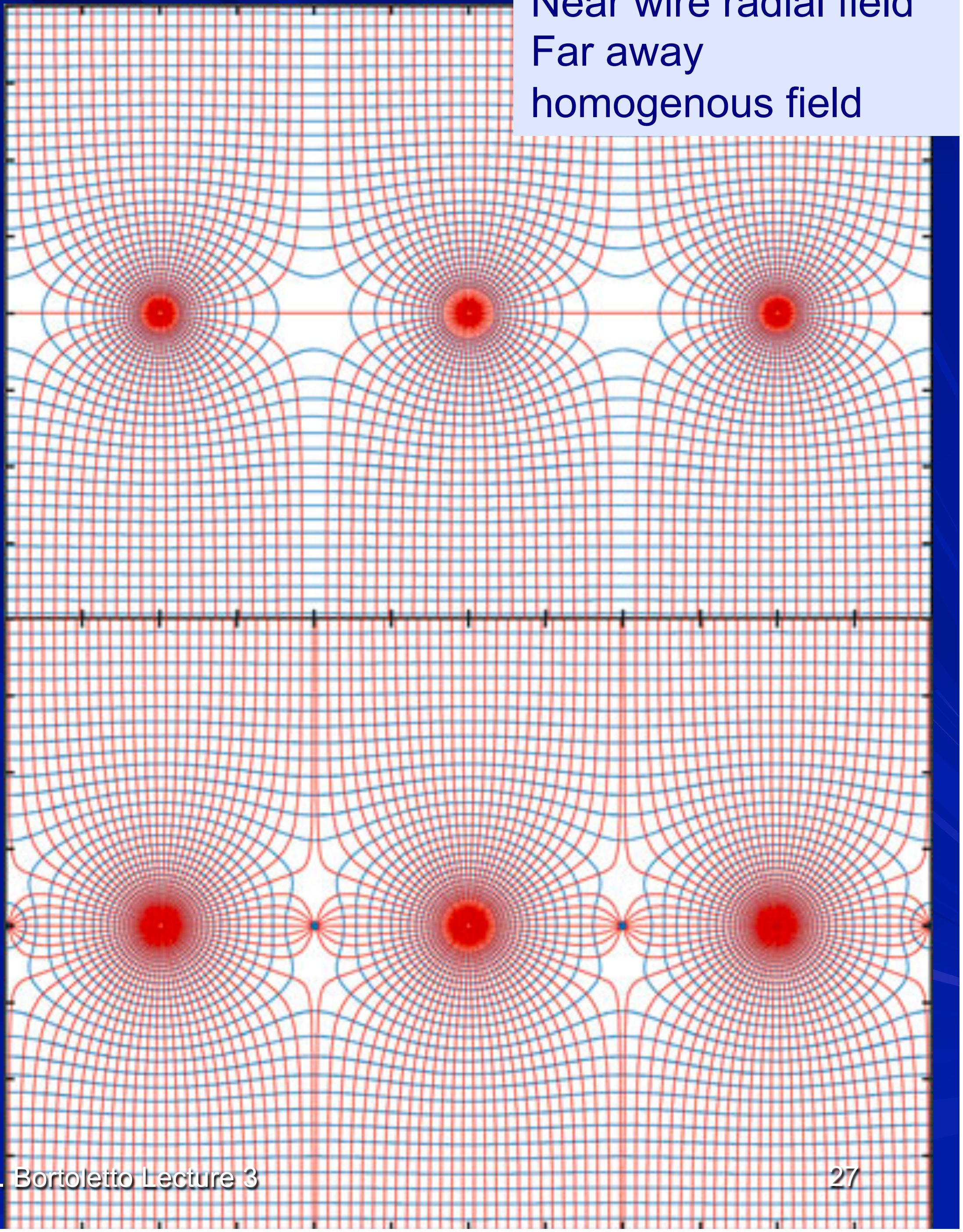
Features:

- Tracking of charged particles
- Some PID capabilities via dE/dx
- Large area coverage
- High rate capabilities

Field distribution

- MWPC: Operation is difficult at smaller wire spacings. For example: the electrostatic repulsion for thin (10 µm) anode wires causes mechanical instability above a critical wire length of less than 25 cm for 1-mm

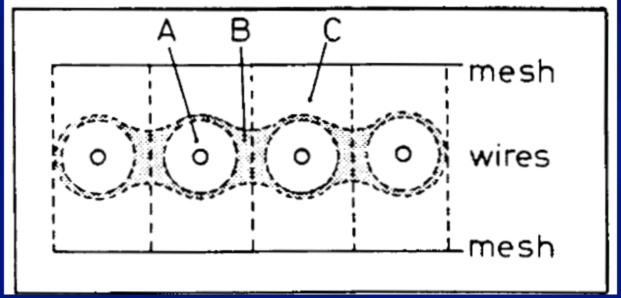
- Drift chambers: a thicker wire at proper voltage between anodes (field wire) reduces the field at the middle point between anodes and improves charge collection
- Linearity of the space-to-drift-time relation→ resulting in better spatial resolution

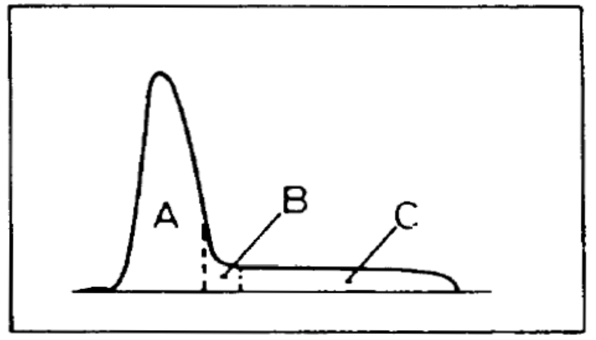


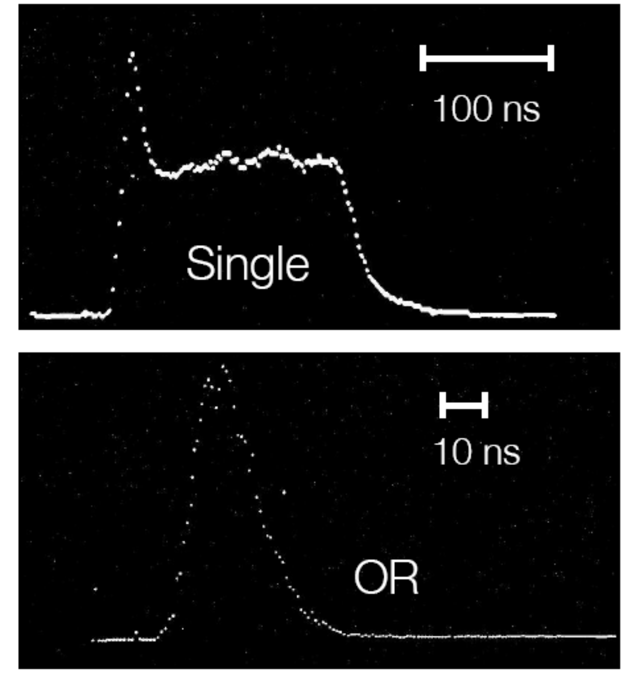
Near wire radial field
Far away homogenous field

MWPC performance

- Signal generation:
  - Electrons drift to closest wire. Gas amplification near wire ➛ avalanche Signal generation due to electrons and slow ions (mainly slow ions, see backup)
- Timing resolution:
  - Depends on location of particle
  - For fast response: OR of all channels …[Typical: $\boldsymbol{\sigma}_t$ = 10 ns]

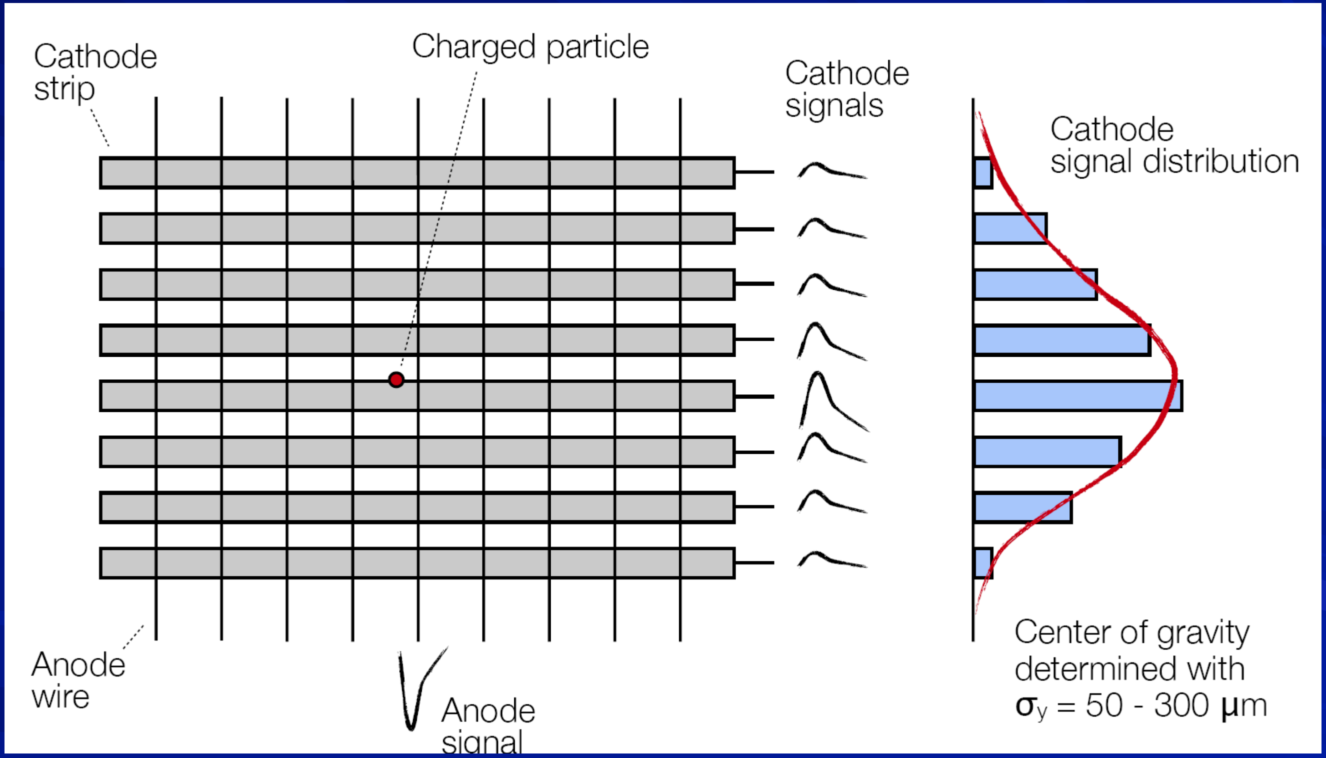






MWPC: space point resolution

- Space point resolution: Only information about closest wire ➛ $\boldsymbol{\sigma}_x$ = d/√12 [d=2-4 mm, $\boldsymbol{\sigma}_x$ ~0.6-1mm]
- Possible improvements: segmented cathode

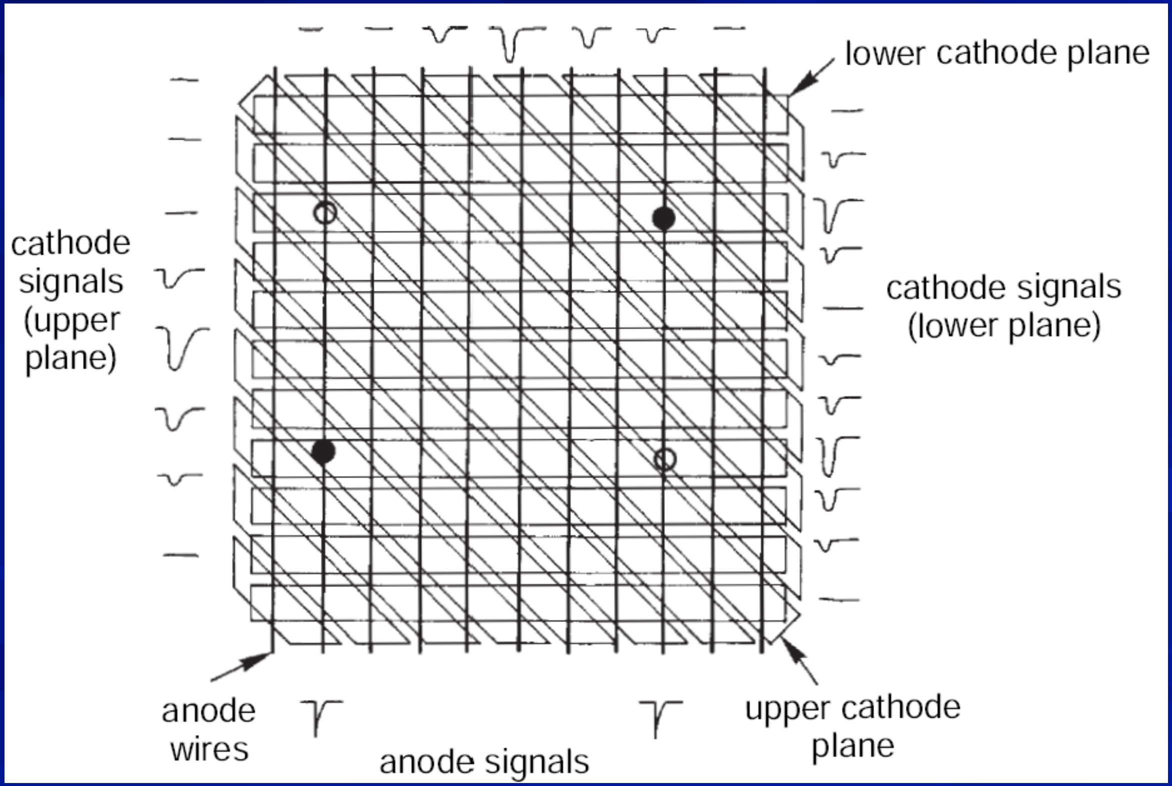


Center of gravity determined with σ_y = 50 - 300 µm

- 2-dim.: use 2 MWPCs with different orientation
- -3-dim.: several layers of such X-Y-MWPC combinations

2D MWPC

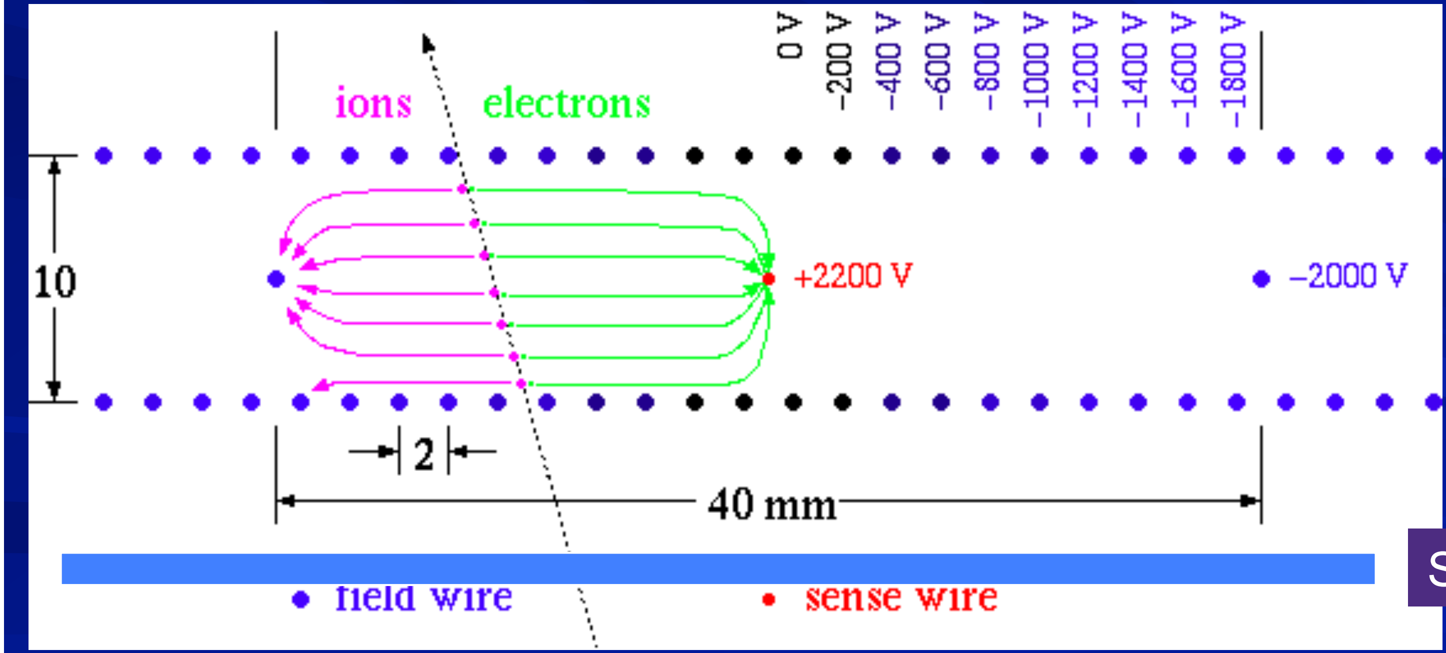
- Substantial improvement can be obtained using cathode strip/pads:
  - 2D information
  - High spatial resolutions due to center of gravity
  - Resolve ambiguities using strip pattern



• true hit
○ ghost hit

Drift chambers

- Obtain spatial information by measuring the electrons drift time
  - time measurement started by an external (fast) detector, i.e. scintillator counter
  - electrons drift to the anode (sense wire), in the field created by the cathodes
  - the electron arrival at the anode stops the time measurement



$$x = \int_0^{t_D} v_D \, dt$$

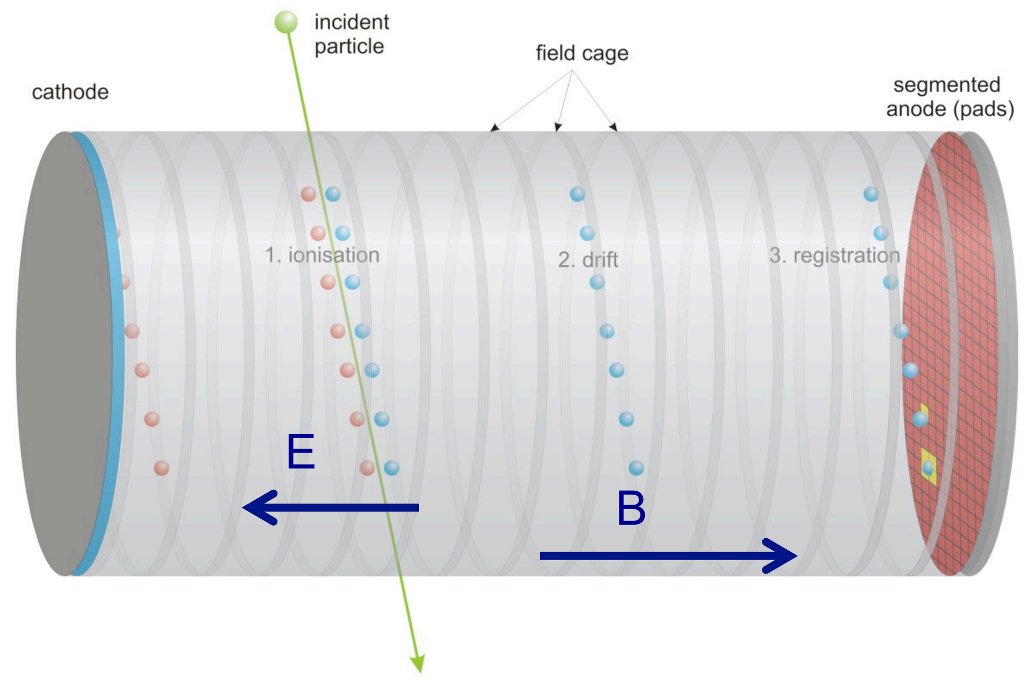
Need well-defined drift field

Scintillator counter

J. Heintze, 1971

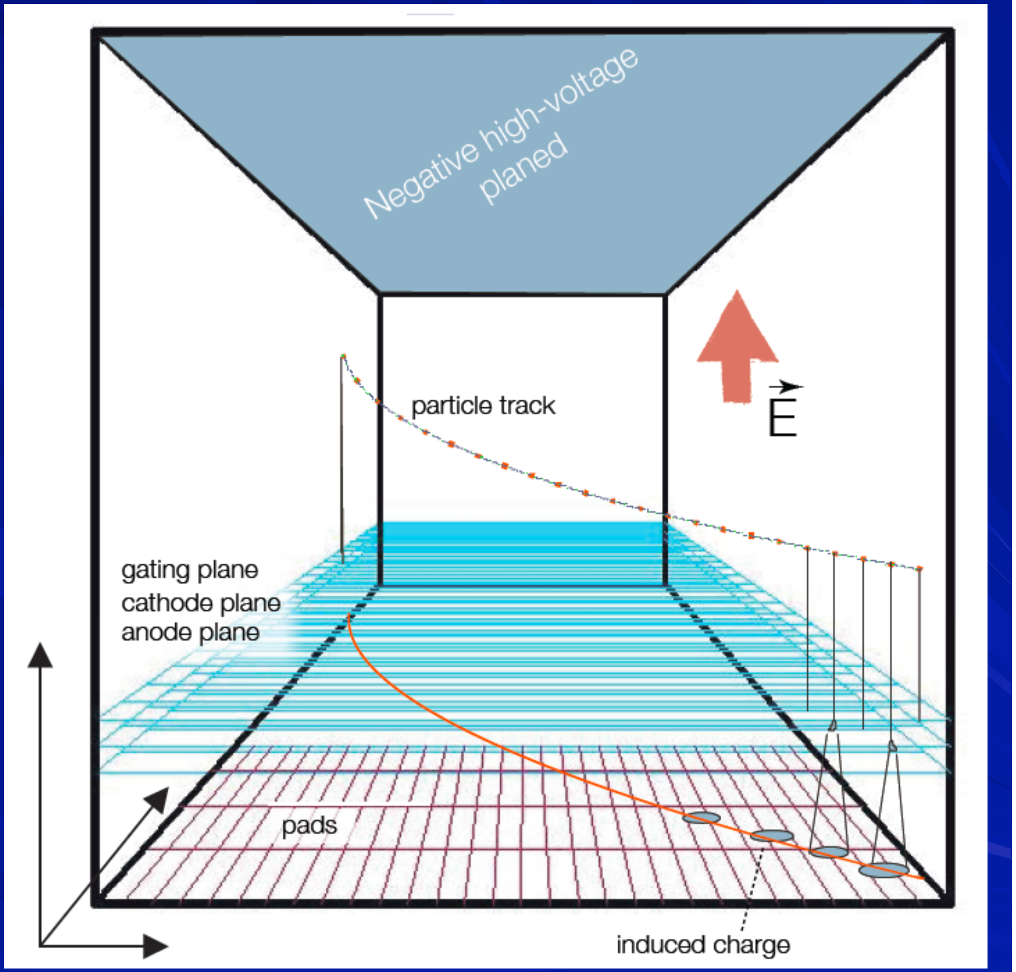
Time Projection chamber (TPC)

- Electronic bubble chamber
- Allow full 3-D reconstruction
  - XY: from wires and pads of MWPC
  - Z: from drift time measurement
- TPC setup:
  - Central HC cathode
  - MWPC at the end-cap of cylinder
  - B parallel to E field
- Charge transport
  - Electrons drift to end-caps
  - Drift distance several meter

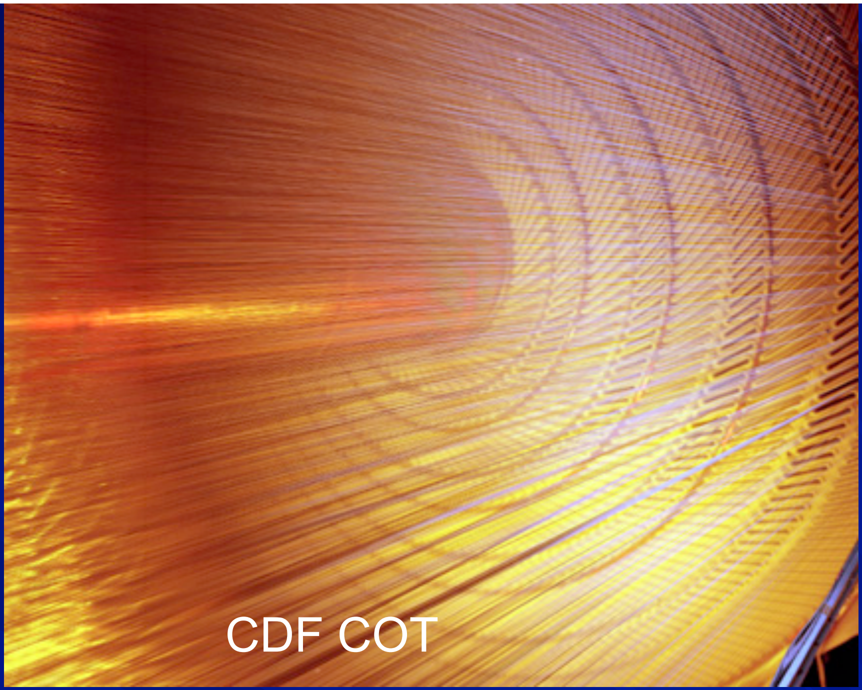


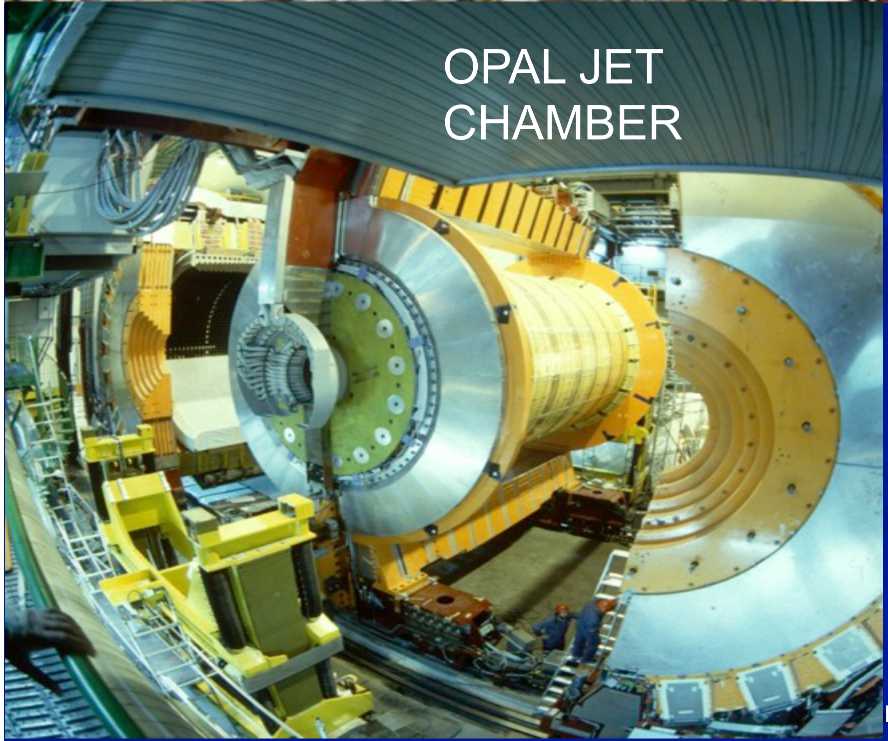
Time projection chamber

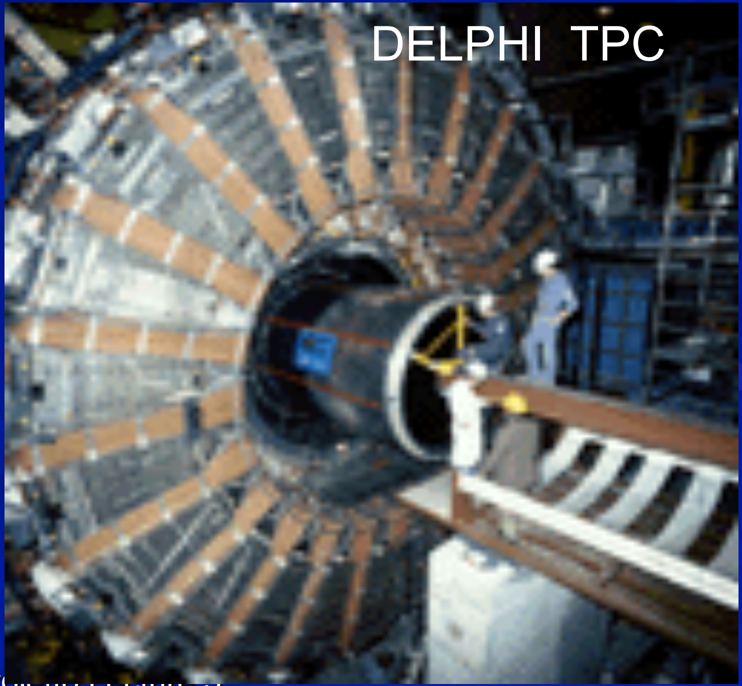
- Advantages:
  - Complete track information ➔ good momentum resolution
  - Good particle ID by dE/dx
  - Drift parallel to B fields suppress transverse diffusion by factors between 10 to 100
- Challenges
  - Long drift time limited rate
  - Large volume (precision)
  - Large voltages (discharges)
  - Large data volume
  - Difficult operation at high rate; gate open only for trigger events
- Typical resolution
  - z and y ≈mm, x=150-300 μm
  - dE/dx ≈5-10%




ALEPH TPC

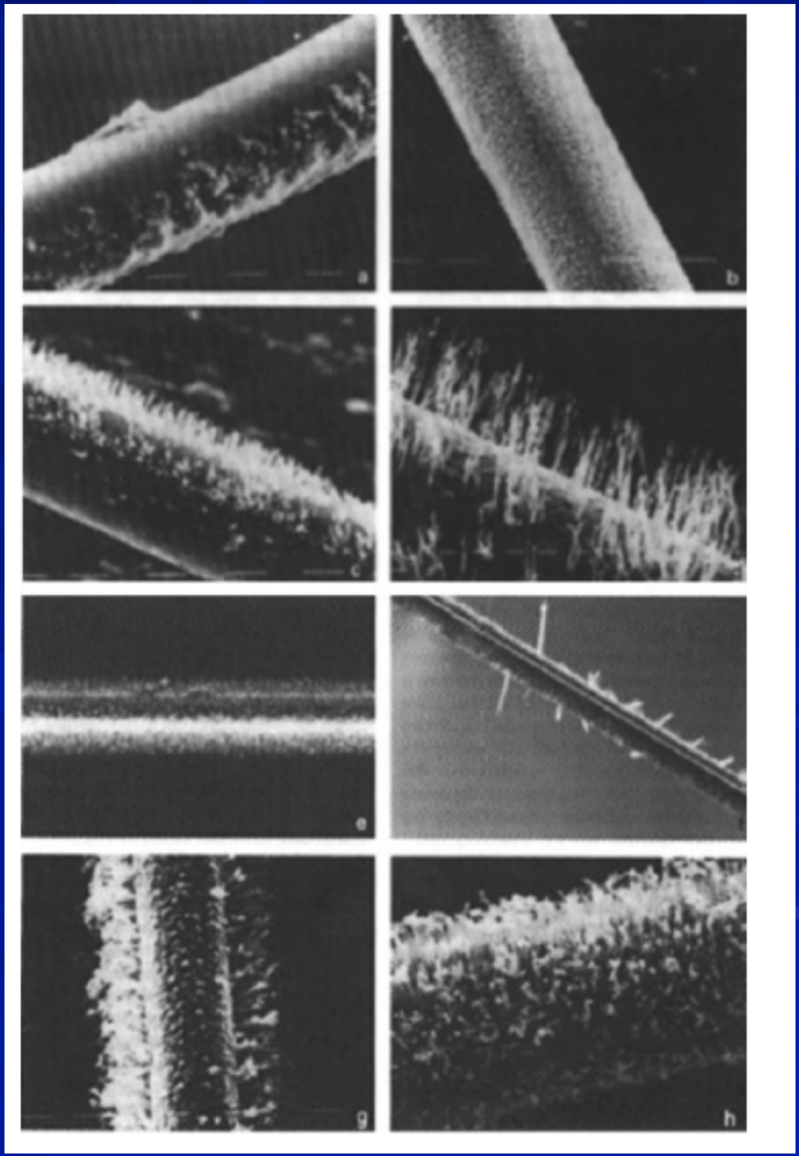

CDF COT


OPAL JET CHAMBER


DELPHI TPC

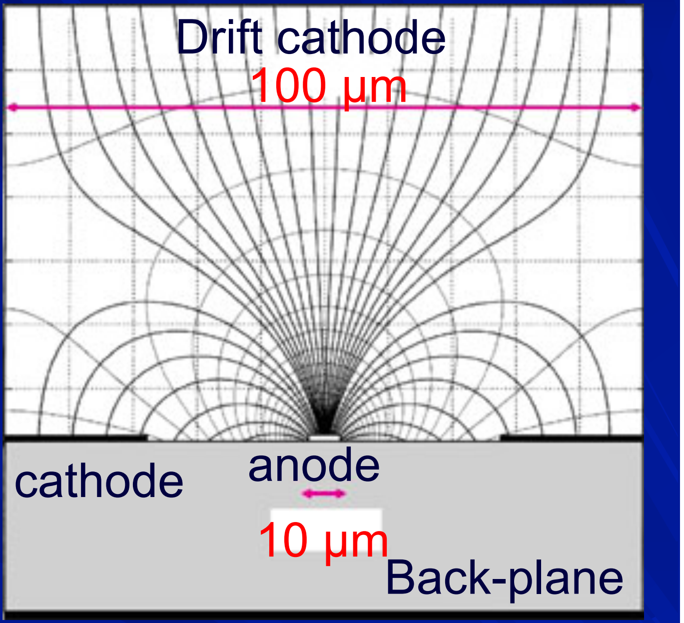
Aging in wire chambers

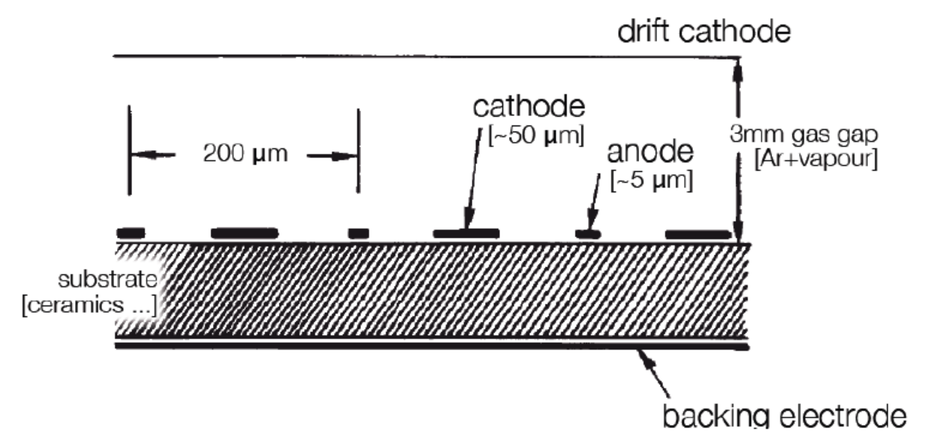
- Consequences of avalanche
  - Formation of radicals i.e. molecule fragments
  - Polymerization yield long chains of molecules
  - Polymers may be attached to the electrodes
  - Reduction of gas amplification
- Important to avoid contamination

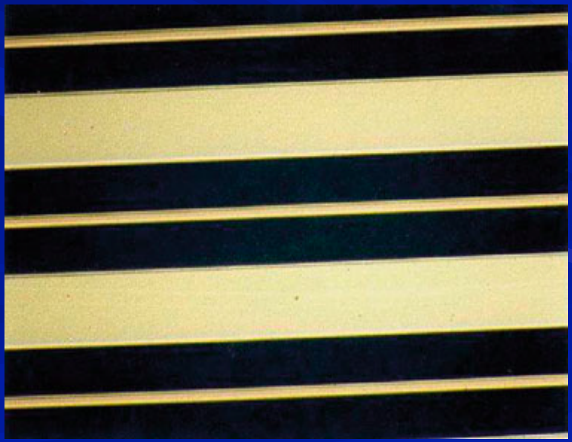


Micro-strip gas chambers (MSGC)

- Avoid wires by realizing anode via microstructures on dielectrics
- Photolithography techniques allow 100 μm pitch
  - Higher granularity over wire chambers
  - High-rate capability >10^6 Hz/mm^2
  - Excellent spatial resolution (~30μm)
  - Time resolution in the ns range.
- MSGC were first developed in 1990s
  - Initial problems sparks and anode destruction

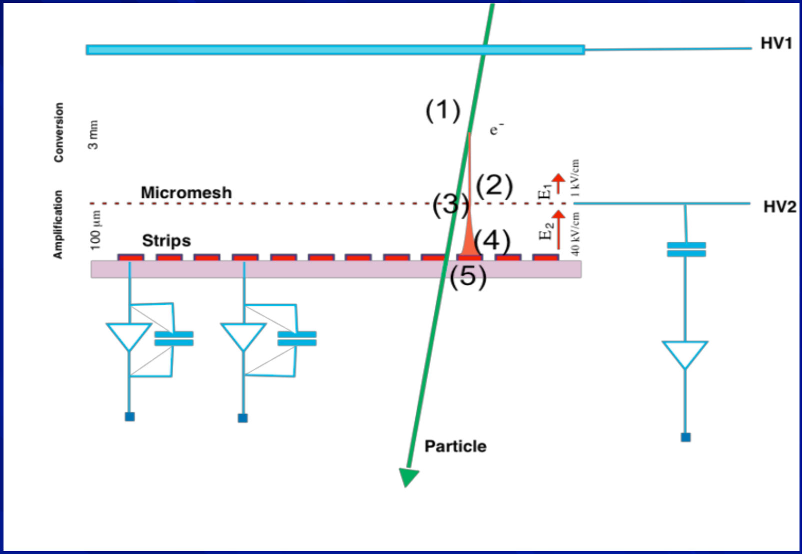


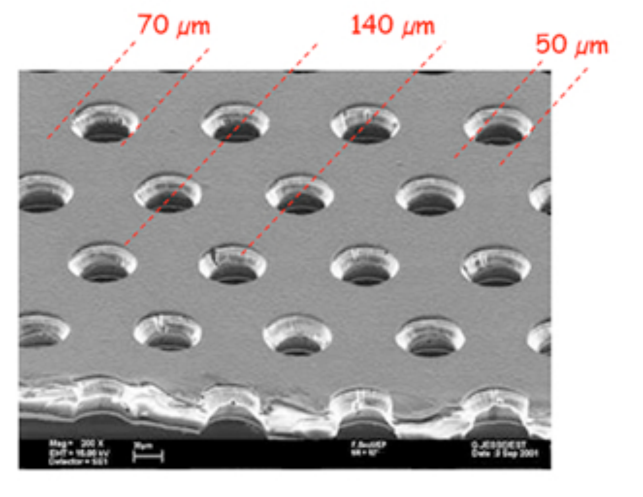


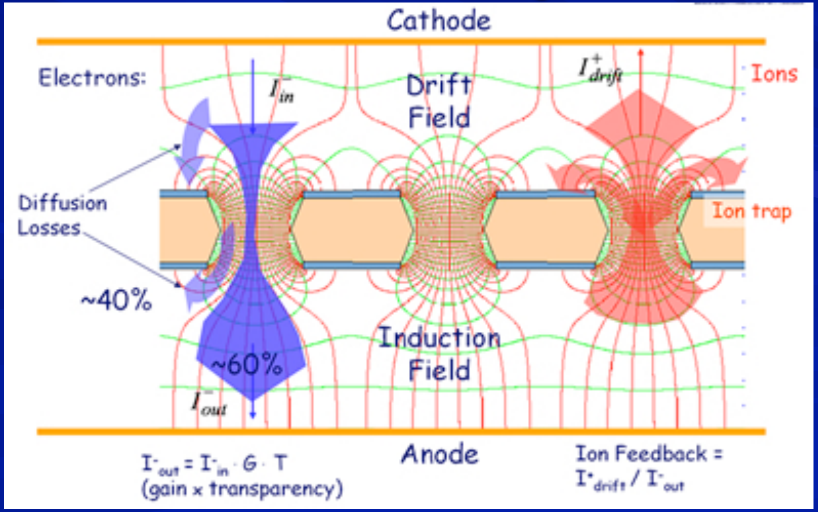


MGSC – technical solutions

- MSGC prone to aging. Solutions:
  - Micromegas
    - Gas volume divided in two by metallic micro-mesh
    - Gain = 10^4 and a fast signal of 100ns.
  - GEM (Gas Electron Multipliers)
    - Thin insulating Kapton foil coated with metal film
    - Chemically produced holes pitch ≈100 µm
    - Electrons are guided by high drift field of GEM which generates avalanche







Sauli, 1997

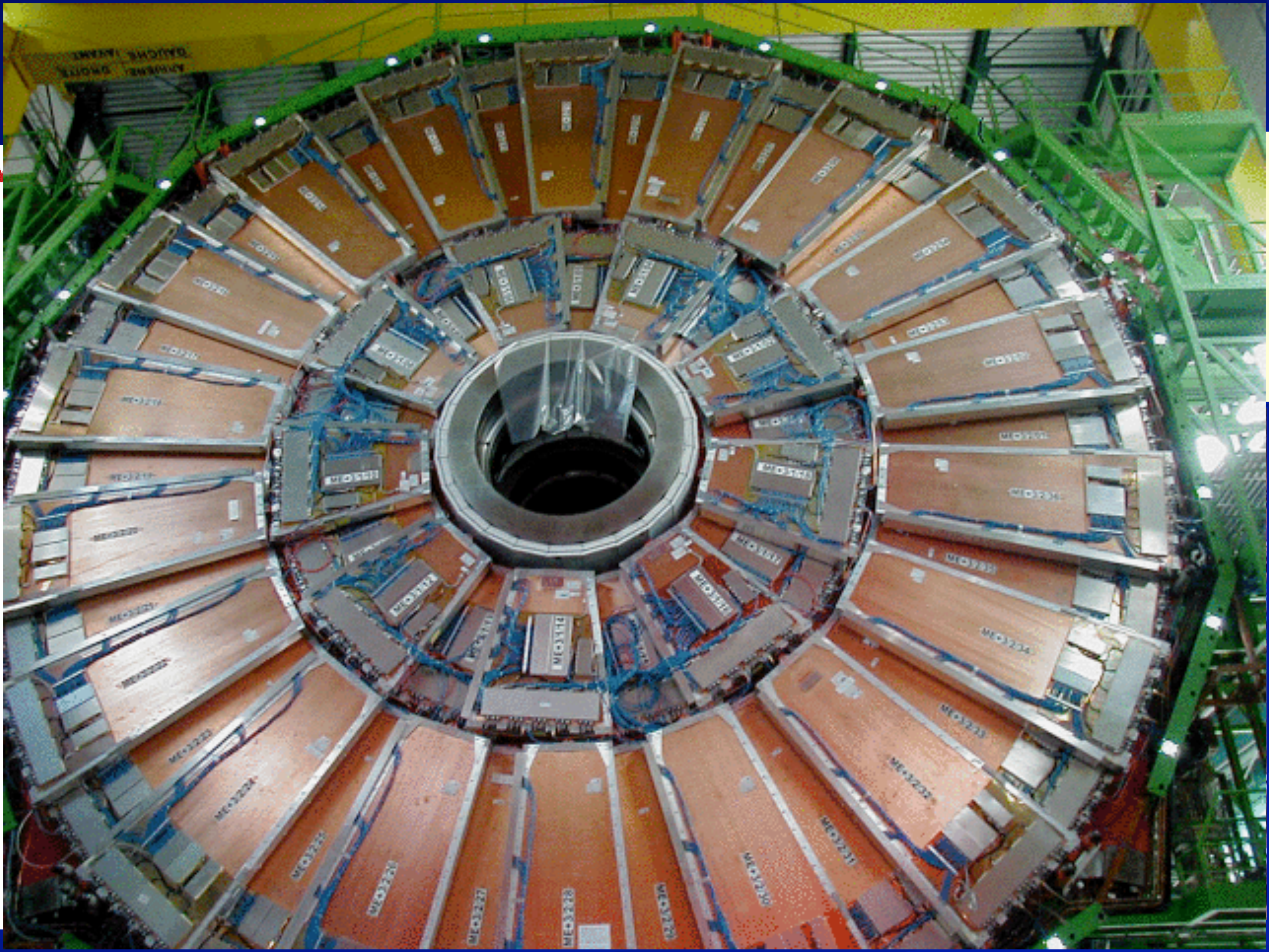
GAS detectors at the LHC

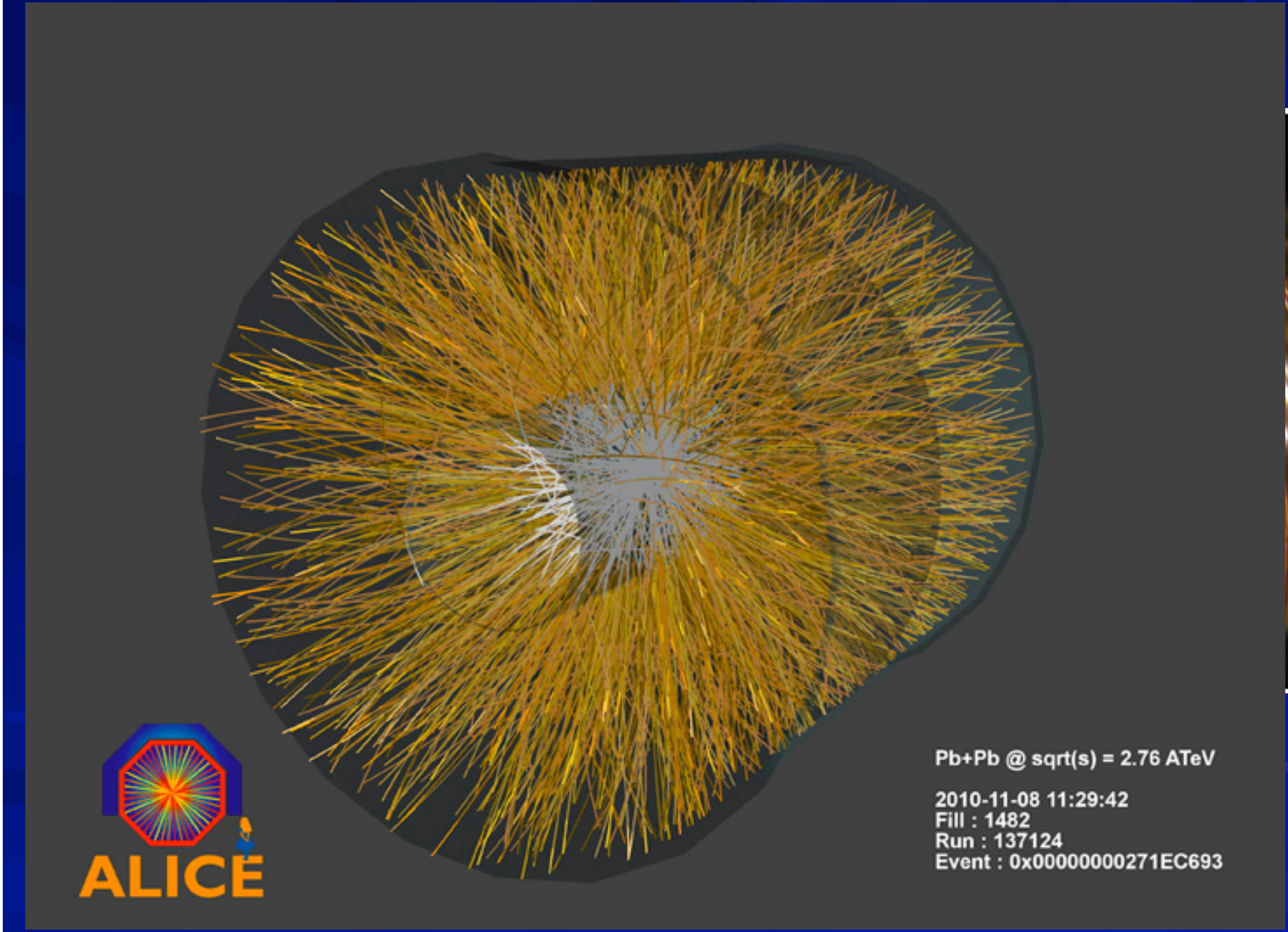
- **The LHC experiments use very ‘conservative’ gas detectors**
- **Mainly for large scale muons detectors**
- **While the principle detecting elements are unchanged since many years, several aspects have improved dramatically:**
- **Readout electronics (integration, radiation resistance)**
- **Excellent understanding and optimization of detector physics effects (HEED, MAGBOLTZ, GARFIELD)**
- **Improvement in ageing characteristics due to special gases**
- **The principles are traditional but all other aspects are 100% state of the art. The ATLAS MDTsare NOT Geiger counters.**

ATLAS drift tubes

- Atlas Muon Spectrometer, 44 m long, from r=5 to11m.
- 1200 Chambers
- 6
- Le
- Po <5
- M
- G

E





Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:29:42
Fill : 1482
Run : 137124
Event : 0x00000000271EC693

The upgrades

- **ATLAS:**
  - **TRT replaced by Silicon Tracker**
- **CMS & ATLAS**
  - **Muons System detectors will mainly remain unchanged**
    - Addition of chambers to add redundancy
    - Possible addition of GEM at low eta where the rates are higher

- BACKUP

Signal pulse formation and shape

$$dV = \frac{q}{lCV_0}\frac{d\phi(r)}{dr}dr \qquad \text{with } \phi(r) = -\frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$$

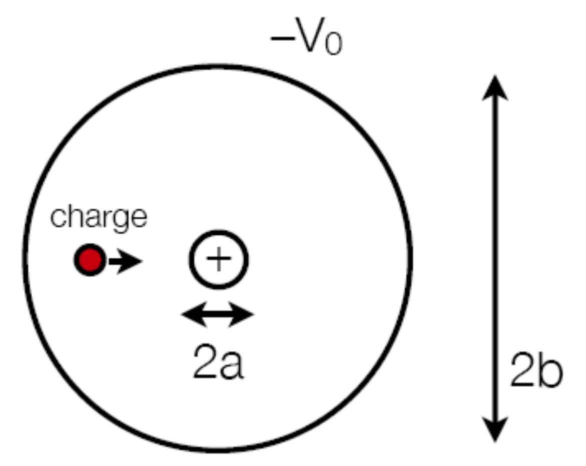
- Integrate from r’ : point where the multiplication starts
- The induced voltage from electrons is:

$$V^- = -\frac{q}{lCV_0}\int_{a+r'}^{a}\frac{d\phi(r)}{dr}dr = -\frac{q}{lCV_0}\left[\frac{CV_0}{2\pi\varepsilon_0}\ln\left(\frac{a+r'}{a}\right)\right]$$

$$= -\frac{q}{2\pi\varepsilon_0 l}\left[\ln\left(\frac{a+r'}{a}\right)\right]$$

- The total induced voltage for ions is

$$V^+ = \frac{q}{lCV_0}\int_{a+r'}^{b}\frac{d\phi(r)}{dr}dr = -\frac{q}{2\pi\varepsilon_0 l}\left[\ln\left(\frac{b}{a+r'}\right)\right]$$



Cross check:
$V=V^++V^-=-q/lC$
$C=2\pi\varepsilon_0/\ln(b/a)$

- The ratio V^-/V^+ is:

$$\frac{V^-}{V^+} = \frac{\ln\left({}^{a+r'}\!/_{a}\right)}{\ln\left({}^{b}\!/_{a+r'}\right)}$$

For a=10 μm, b=10 mm, r’=1 μm ➔$V^-/V^+=0.013$ ➔ Signal is mainly due to ions

Signal pulse formation and shape

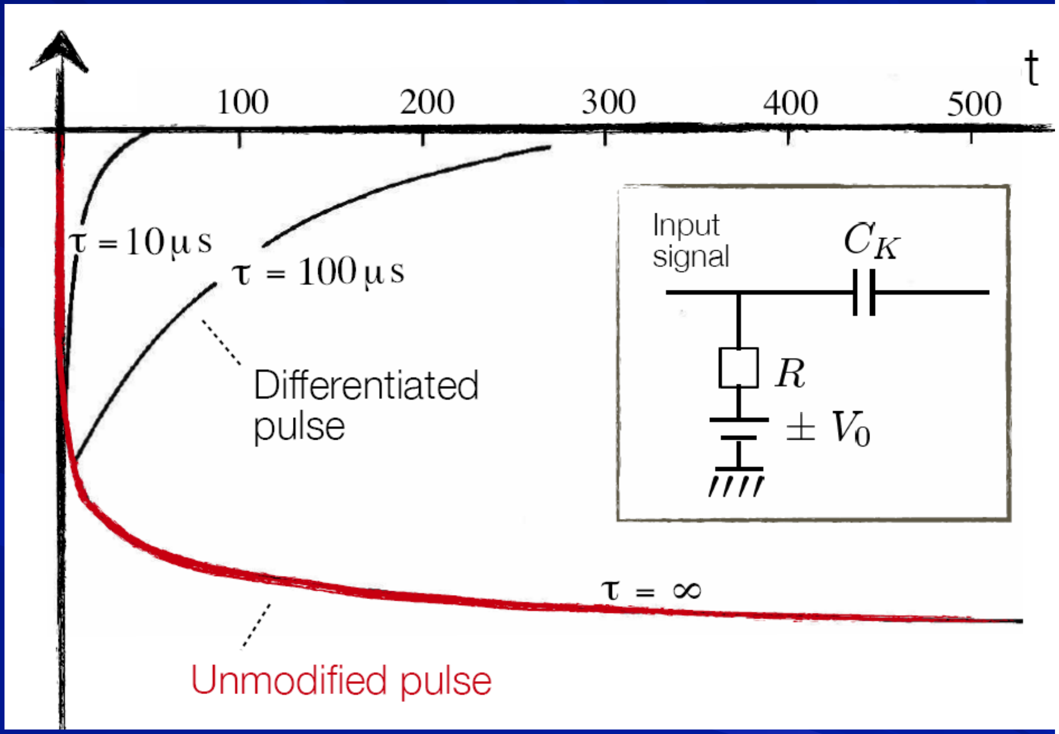
- Ignoring electron signal and setting r(0)=a

$$V(t)=\int_{r(0)}^{r(t)}\frac{dV}{dr}dr=-\frac{q}{2\pi\varepsilon_0 l}\ln\frac{r(t)}{a}$$

$$v_D=\frac{dr}{dt}=\mu E(r)=\frac{\mu C V_0}{2\pi\varepsilon_0}\frac{1}{r}$$

$$rdr=\frac{\mu C V_0}{2\pi\varepsilon_0}dr$$

$$r(t)=\left(a^2+\frac{\mu C V_0}{\pi\varepsilon_0}t\right)^{1/2}$$



$$V(t)=-\frac{q}{4\pi\varepsilon_0 l}\ln\left(1+\frac{\mu C V_0}{\pi\varepsilon_0 a^2}t\right)=-\frac{q}{4\pi\varepsilon_0 l}\ln\left(1+\frac{t}{t_0}\right)$$

$$t_0=\pi\varepsilon_0 a^2\Big/\mu C V_0$$

Leo: techniques for nuclear and particle physisc experiment

Signal shape

- Total drift time T

$$r(T) = b$$

$$b = \left(a^2 + \frac{\mu C V_0}{\pi\varepsilon_0}\right)^{1/2}$$

$$T = \frac{\pi\varepsilon_0}{\mu C V_0}\left(b^2 - a^2\right) = t_0\left(\frac{b^2}{a^2} - 1\right)$$

$$t_0 = \frac{\pi\varepsilon_0}{\mu C V_0}$$

- We can determine V(a/b T)

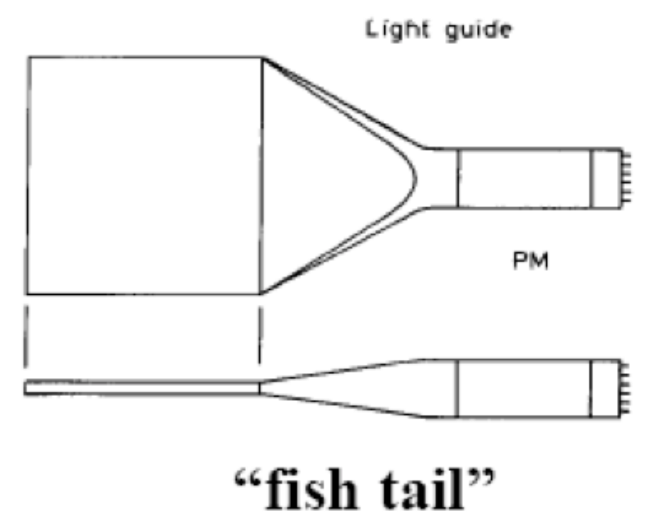
$$V\left(\frac{a}{b}\cdot T\right) = -\frac{q}{4\pi\varepsilon_0}\ln\left(1 + \frac{\frac{a}{b}\cdot T}{t_0}\right) = -\frac{q}{4\pi\varepsilon_0}\ln\left(1 + \frac{a}{b}\left(\frac{b^2}{a^2} - 1\right)\right)$$

$$= -\frac{q}{4\pi\varepsilon_0}\ln\left(\frac{b}{a}\right) = -\frac{1}{2}\frac{q}{lC} \qquad with\ \ C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$

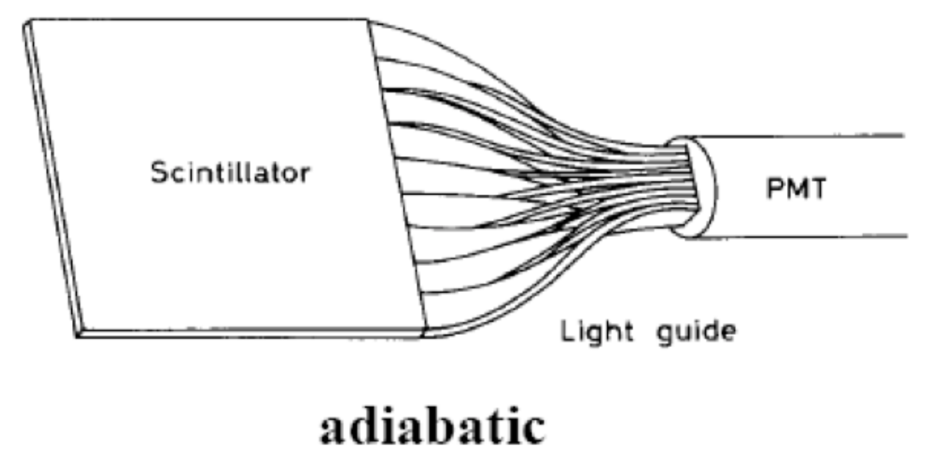
Typically a/b ≈ 10^{-3}, i.e. after 10^{-3} T already half of the signal voltage is reached ... Choice of suitable RC-circuit allows short (differentiated) signals ...

Geometries

- Light guides: transfer by total internal reflection + outer reflector



“fish tail”

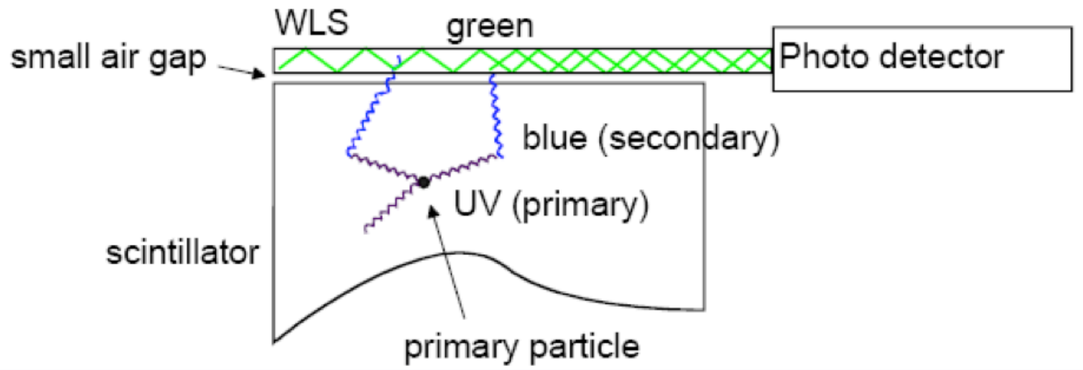


adiabatic

- UV light enters the WLS material
- Light is transformed into longer wavelength

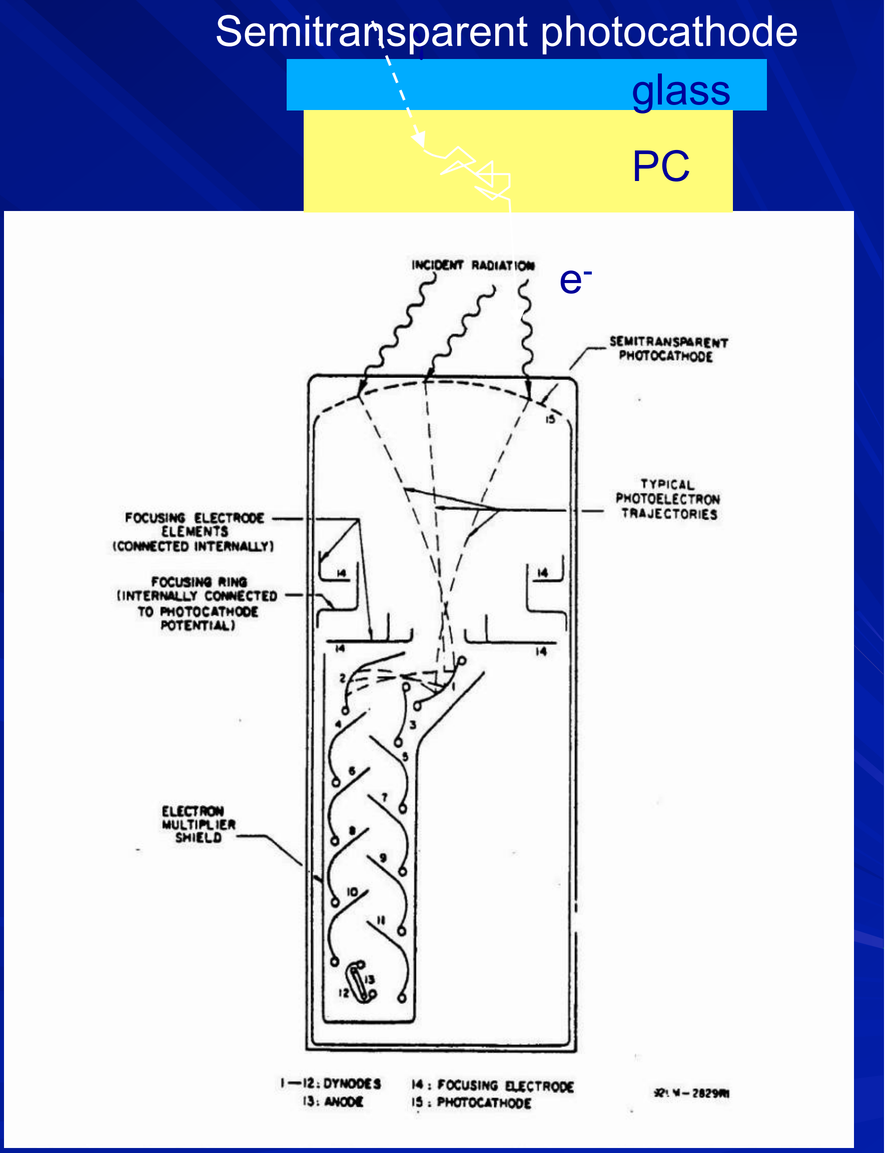
→ Total internal reflection inside the WLS material

→ ‘Transport’ of the light to the photo detector

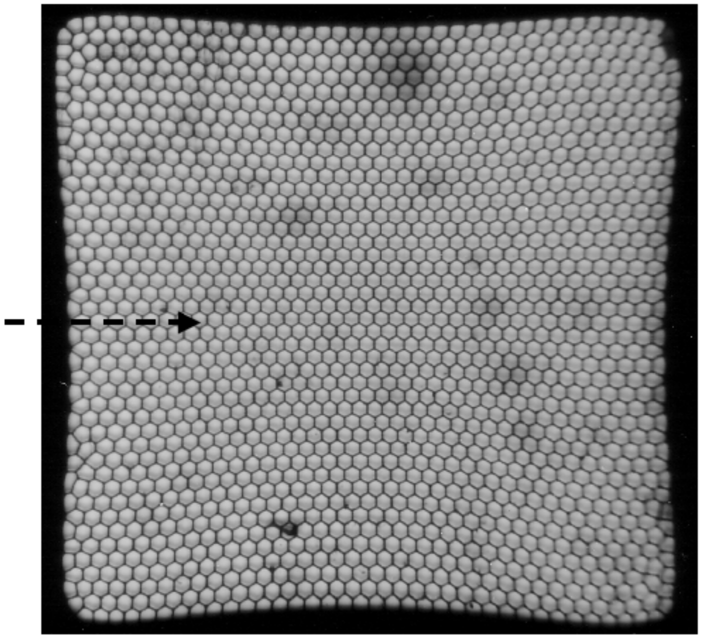


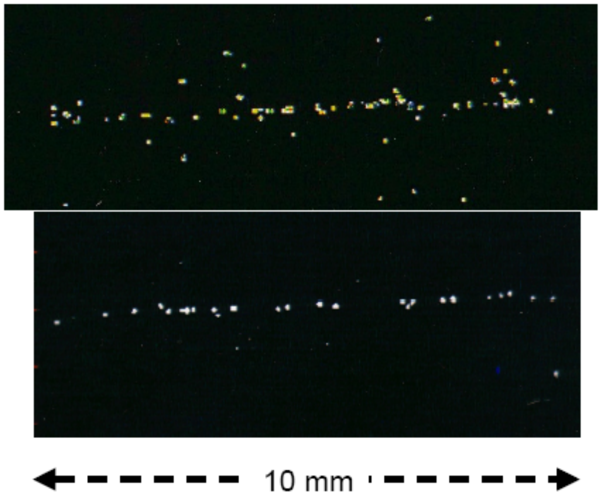
Photomultipliers

- Scintillators are well established and cheap techniques to detect photons → Photomultipliers and the fast response time → 1 to 100ns
- Schematic of a Photomultiplier:
  - Typical Gains (as a function of the applied voltage): 10^8 to 10^{10}
  - Typical efficiency for photon detection: < 20%
  - For very good PMs: registration of single photons possible.
  - Example: 10 primary Electrons, Gain $10^7 \rightarrow 10^8$ electrons in $T \approx 10$ns. $I=Q/T = 10^8 * 1.603 * 10^{-19} / 10 * 10^{-9} =$ 1.6mA.
  - Across a 50 Ω Resistor → $U=R*I=$ 80mV.



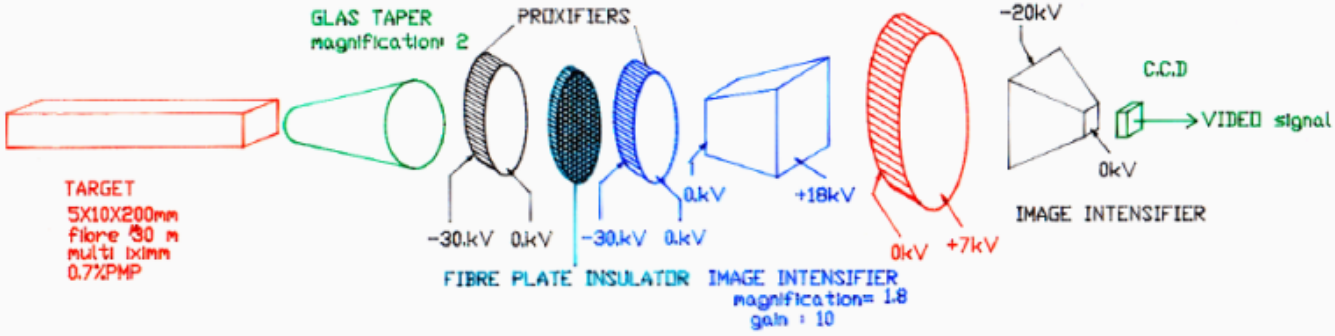
Fiber Tracking





Images of tracks from 5 GeV/c pions (1989)

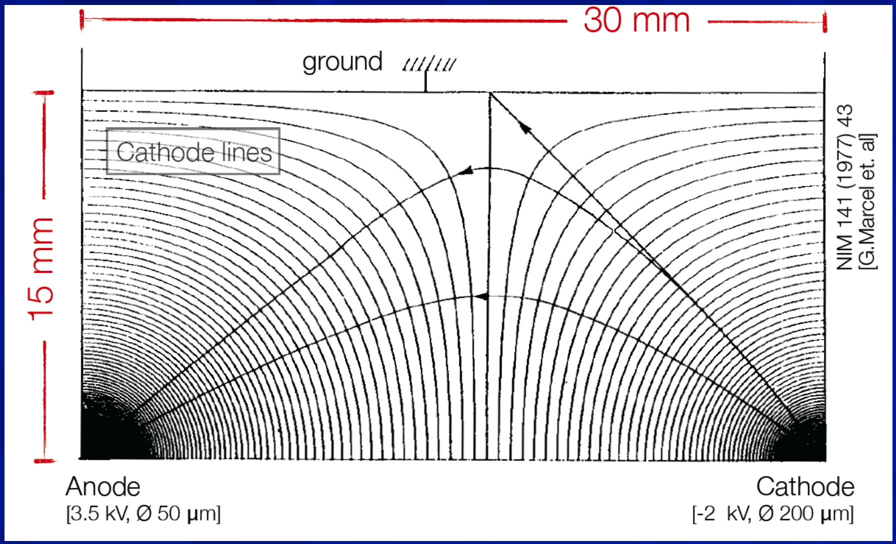
Active target in WA84 (1989)



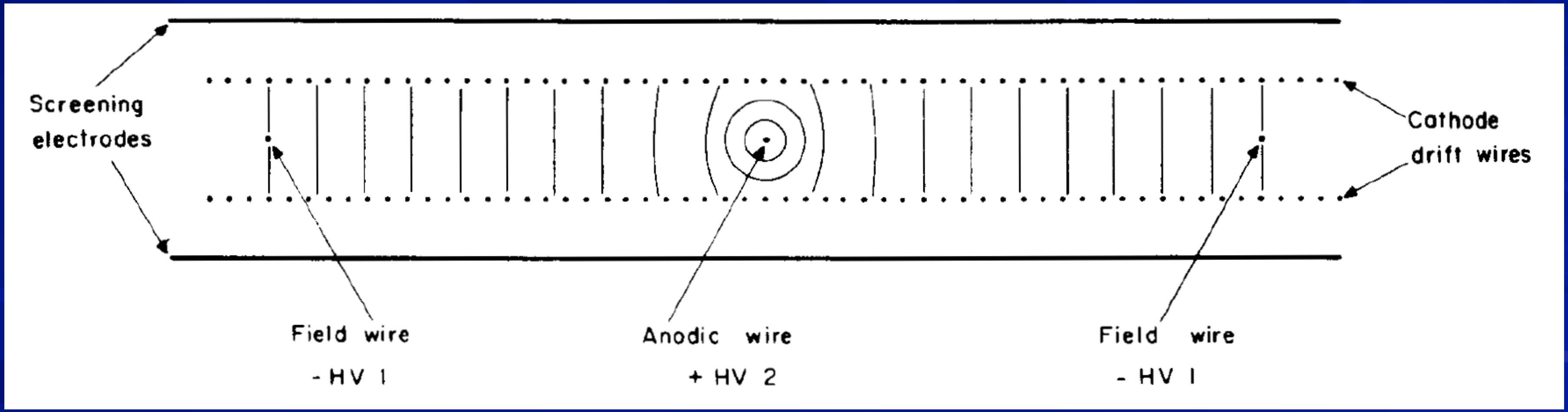
Readout of photons in a cost effective way is rather challenging.

Field in drift chamber

- Field wires avoid low field regions➔ long drift-times
- Uniform drift field requires:
  - Gap length/wire spacing ≈ 1
    - i.e. for typical wire spacing ➔thick chambers O(cm)



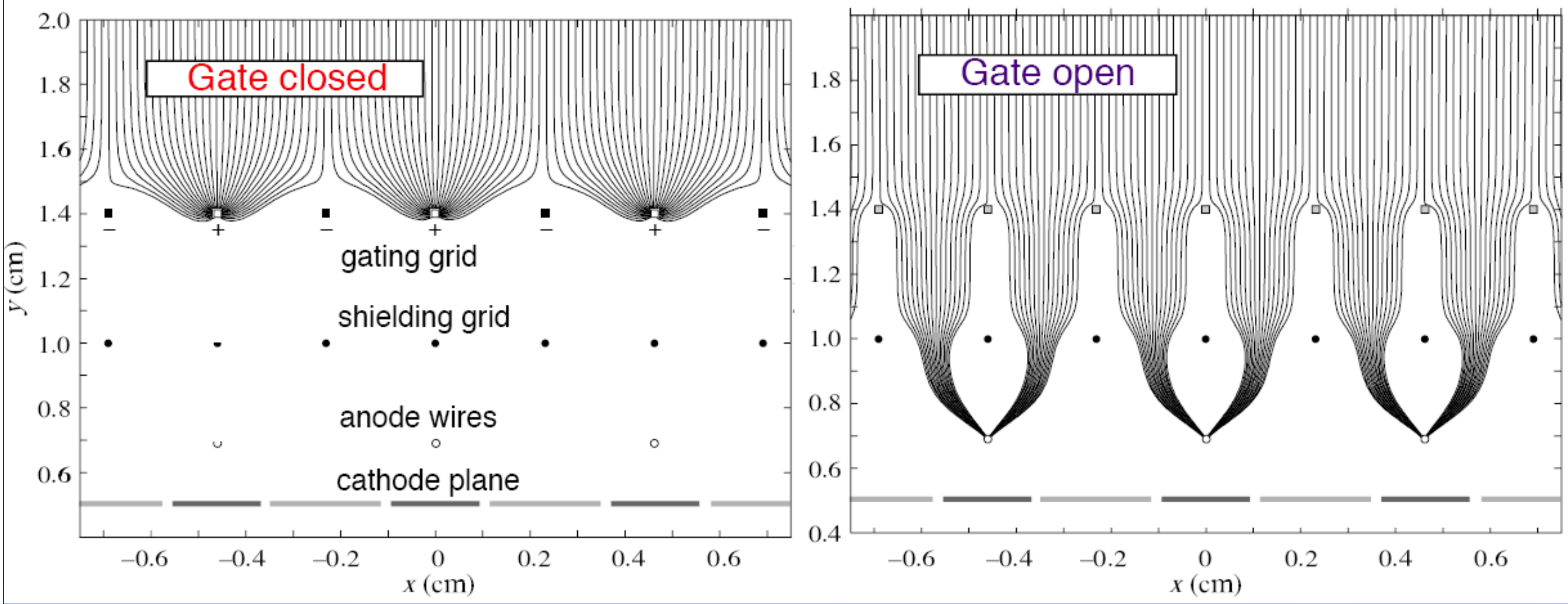
NIM 141 (1977) 43 [G.Marcel et. al]



- Adjustable field multi-wire drift chamber with voltage divider via cathode wire planes
- Space point resolution limited by mechanical accuracy ≈200 µm
- Hit density needs to be low.

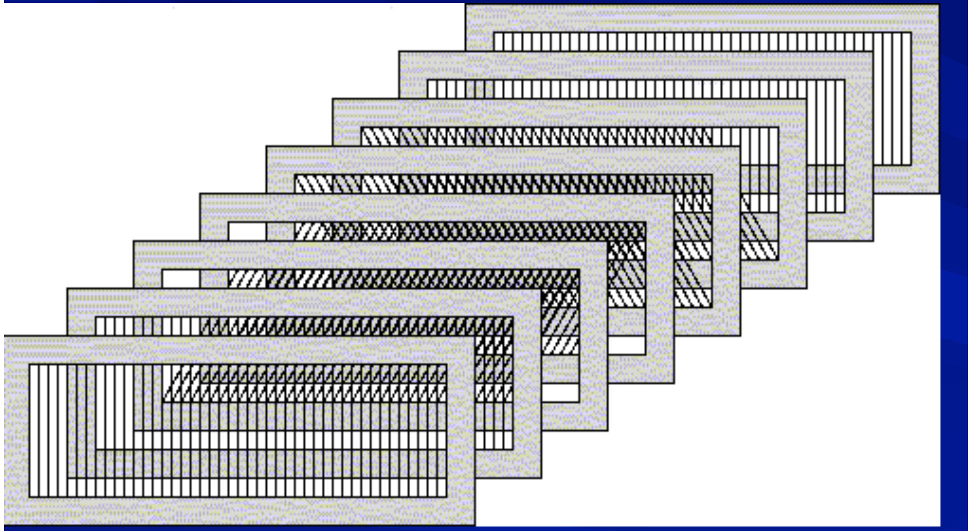
TPC Technical solutions

- Problem with space charge effects due to slow moving ions lead to changes in the drift region E- field
- Solved by gating grid which must be triggered



Tracking detectors

- Tracking at fixed target experiments:
  - Multi-layer MWPC or drift chamber



- Tracking at collider experiments:
  - cylindrical drift chamber