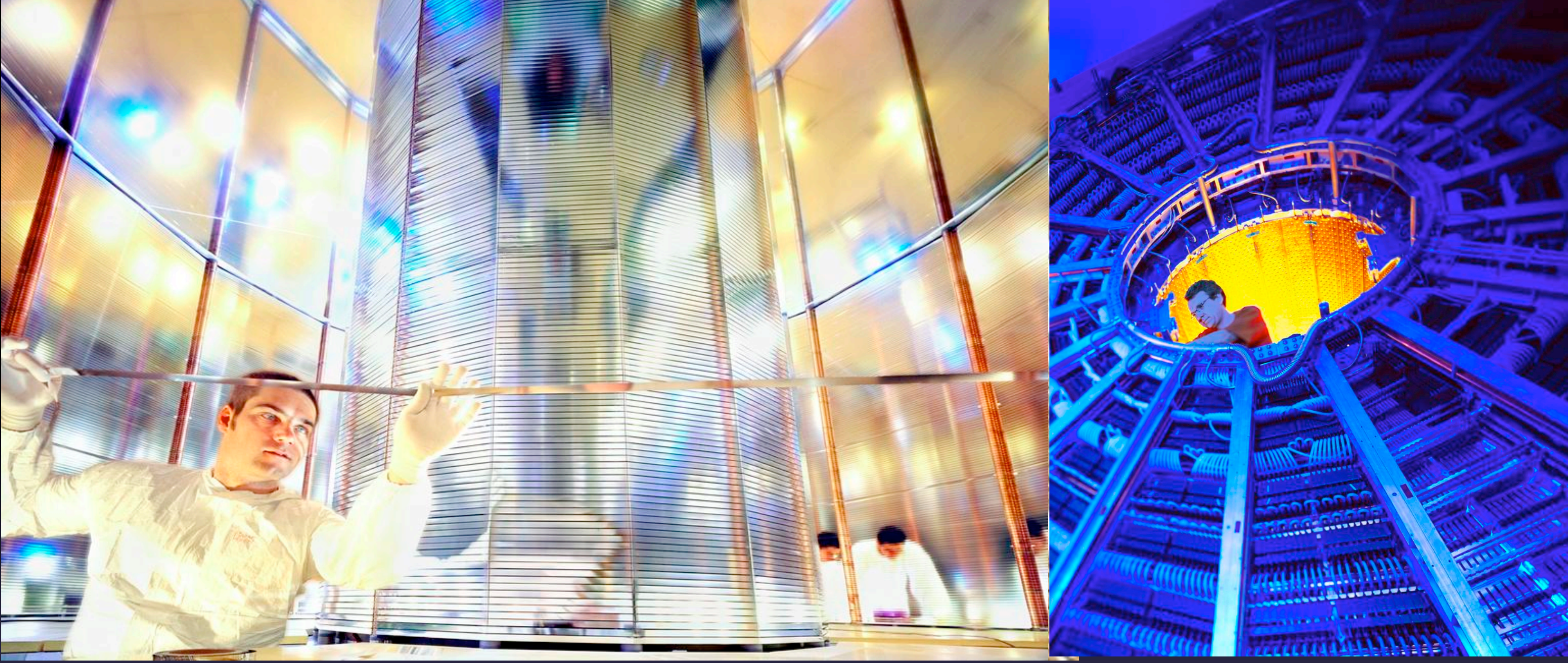


Detectors for Particle Physics

Scintillators and Gaseous detector

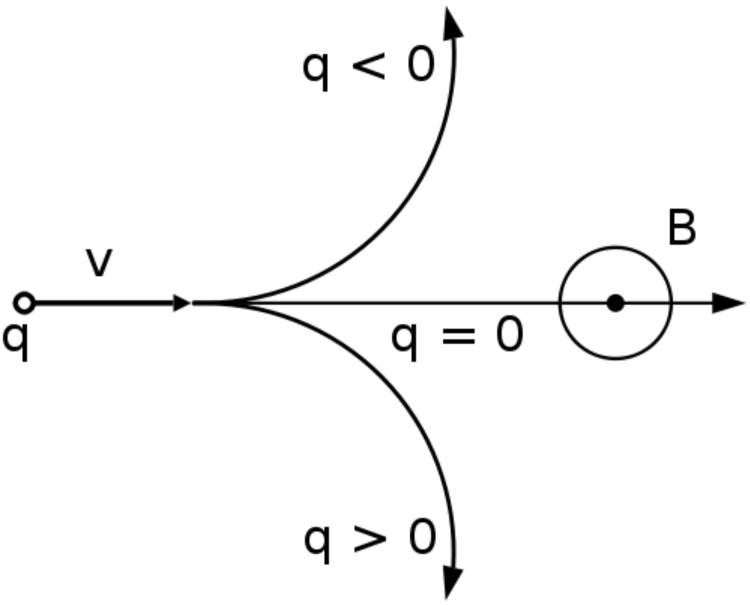
D. Bortoletto
University of Oxford & Purdue University

Tracking


© Rolf Hicker

- 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:

$$\vec{F} = q\vec{v} \times \vec{B}$$

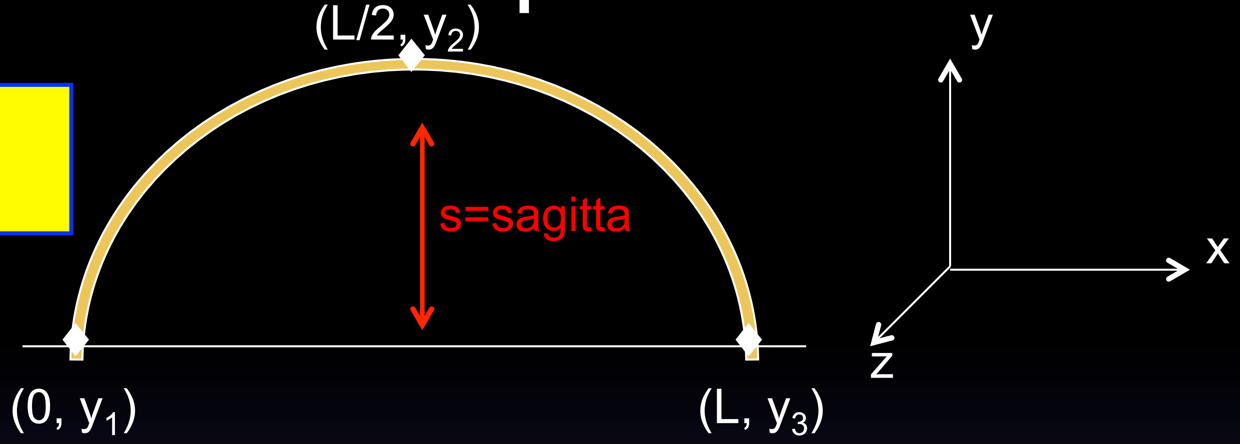


$$\rho = \frac{p_T}{q|B|} = \frac{\gamma m_0 \beta c}{q|B|}$$

- 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.

Momentum and position resolution

Trajectory of charged particle



Assume: we measure y at 3 points in (x, y) plane (z=0) with precision σ_y and a constant B field in z direction so $p_\perp = 0.3Br$.

$$s = y_2 - \frac{y_1 + y_3}{2} \approx \frac{L^2}{8r} = \frac{L^2}{8p_\perp/(0.3B)} = \frac{0.3BL^2}{8p_\perp}$$

The exact expression is

$$s = r - \sqrt{r^2 - \frac{L^2}{4}}$$

The error on the sagitta, σ_s, due to measurement error is (using propagation of errors):

$$\sigma_s = \sqrt{3/2}\,\sigma_y$$

Thus the momentum (⊥ to B) resolution due to position measurement error is:

$$\frac{\sigma_{p_\perp}}{p_\perp} = \frac{\sigma_s}{s} = \frac{\sqrt{3/2}\,\sigma_y}{(0.3L^2B)/(8p_\perp)} = \frac{8p_\perp\sqrt{3/2}\,\sigma_y}{0.3L^2B} = 32.6\frac{p_\perp\sigma_y}{L^2B} \ \textbf{(m, GeV/c, T)}$$

Momentum and Position Measurement

- The momentum resolution expression can be generalized for the case of n measurements, each with a different σ_y (Gluckstern's classic article, NIM, 24, P381, 1963).

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\frac{720}{n+4}}\,\frac{\sigma_y p_\perp}{(0.3BL^2)} \quad \textbf{(m, GeV/c, T)}$$

You can improve this component of momentum resolution by:

- Increasing B
- Increasing L
- Increasing n
- Decreasing σ_y

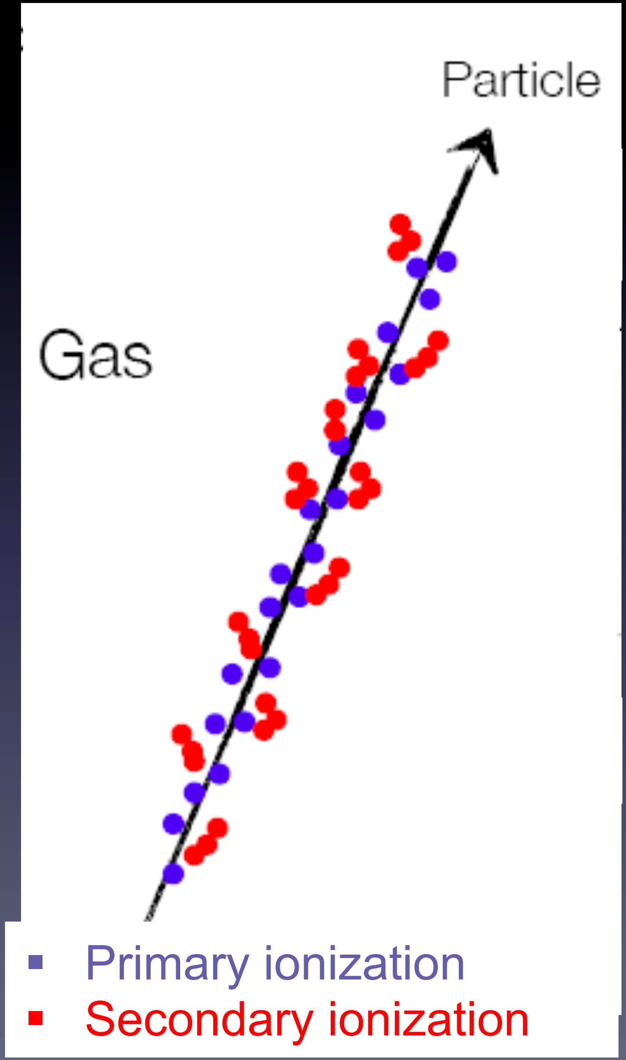
If we assume L=4m, B=1T and p=1TeV then:

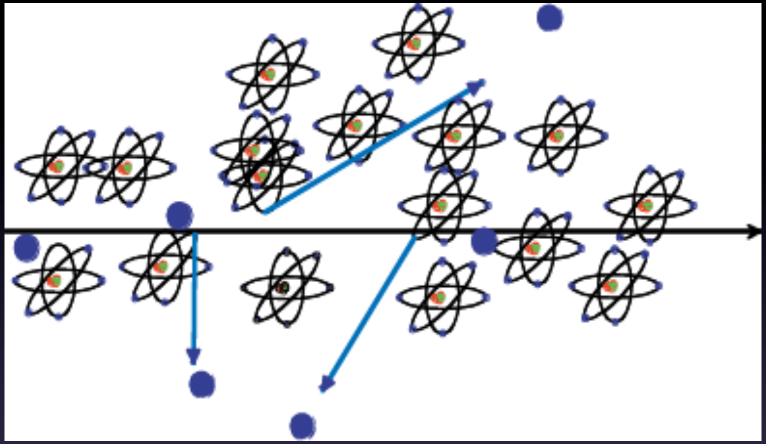
- R = p/(0.3 B) = 1000 / 0.3 = 3300 m
- s ≈ 16/(8*3300) ≈ 0.6 mm

If we want to measure the momentum With $\sigma_p/p \approx \Delta s/s \approx 10\%$ (at p = 1 TeV) we need: $(\sigma_s/s) \approx 60$ μm

Signal creation

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





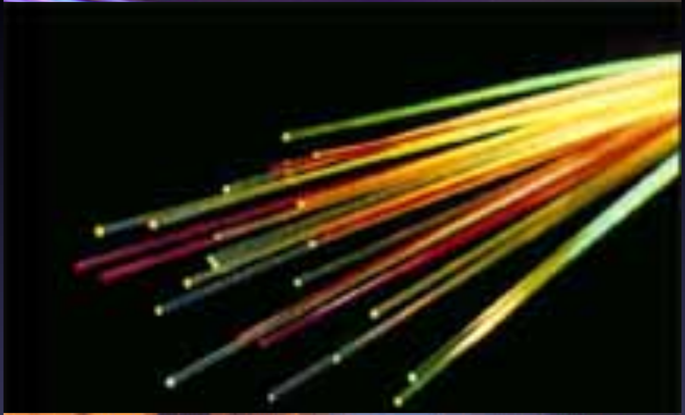
- Excitation: Photons emitted by the excited atoms in transparent materials can be detected with photon detectors

- Ionization: By applying an electric field in the detector volume, the ionization electrons and ions can be collected on electrodes and readout

Scintillators

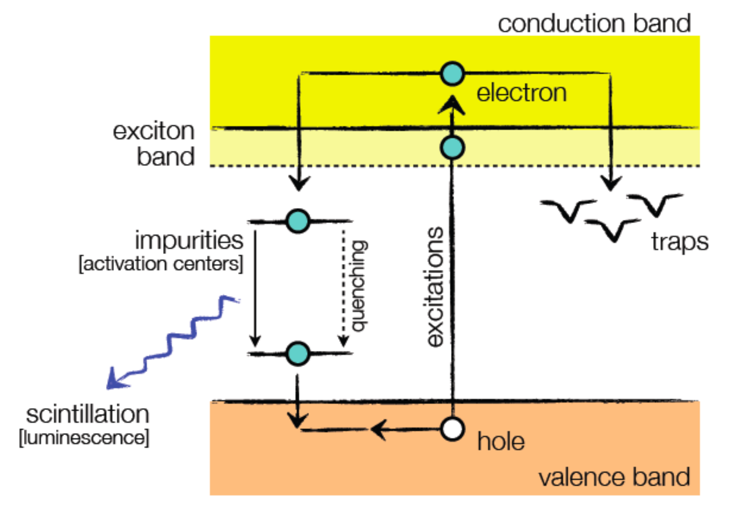
- dE/dx converted into light and then it is detected via photo-sensor (photomultipliers, SiPM,….)
- Main features
  - Sensitivity to energy
  - Fast time response
  - Pulse shape discrimination
- Requirements:
  - High efficiency for conversion of exciting energy to fluorescent radiation
  - Transparency to its fluorescent radiation to allow transmission of light
  - Emission of light in a spectral range detectable for photo-sensors
  - Short decay time to allow fast response

Plastic Scintillator BC412

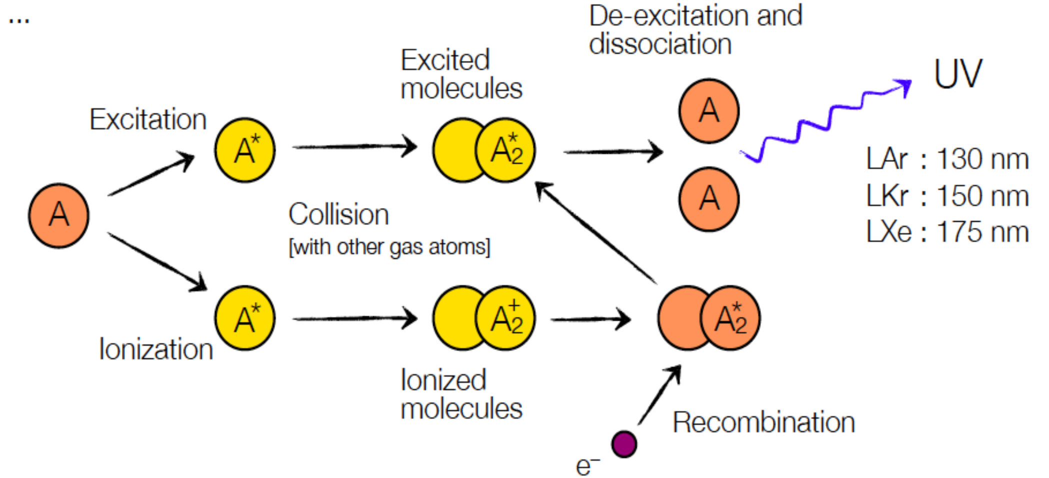


Scintillators

- Inorganic (Sodium iodide (NaI), Cesium iodide (CsI),…)

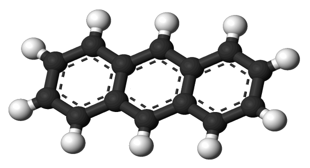


…



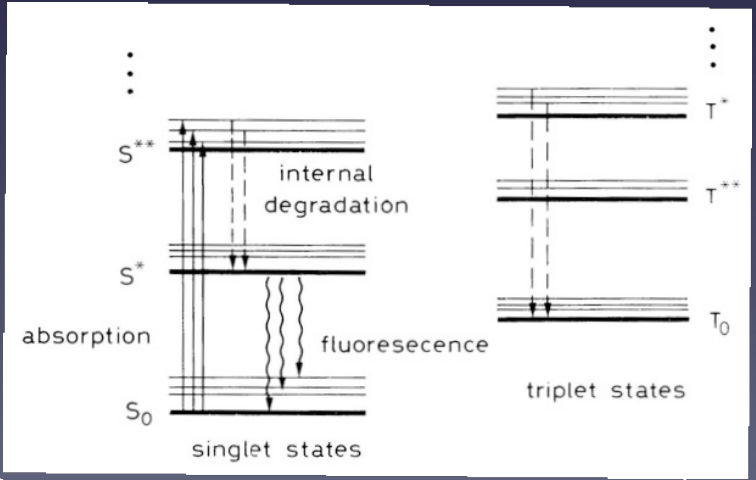
- Noble gasses (Liquid Argon, Liquid Xenon…)

- Organic crystals
  - Aromatic hydrocarbon compounds with benzene rings such as Anthracene (C14H10), etc



- Plastic scintillators
  - Organic scintillators suspended in the aromatic polymer (easy to mold and machine)
- Liquid scintillators

- Molecule structure generates energy levels with transition λ=360-500 nm



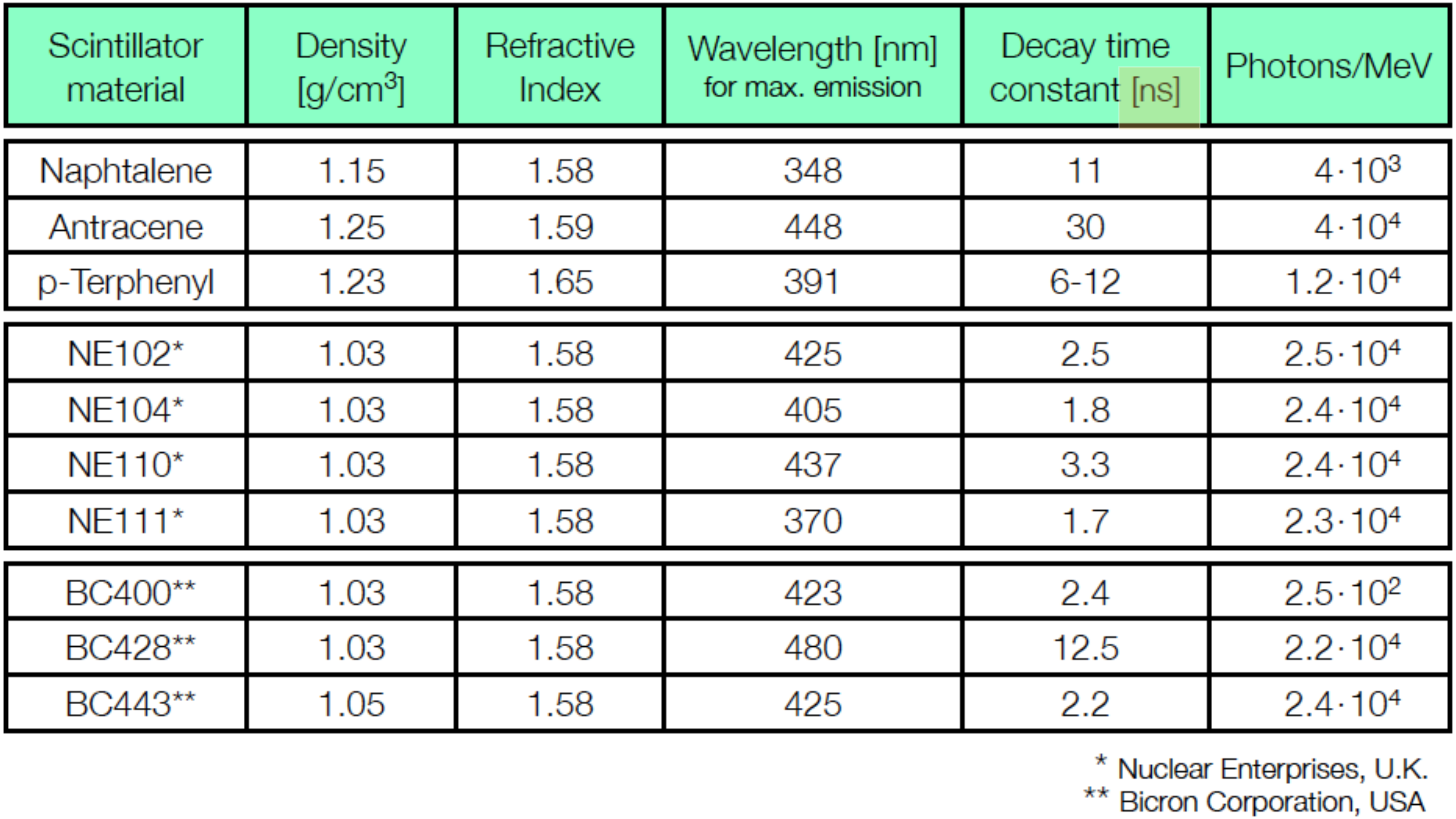
Inorganic scintillators

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)				.25	$4 \cdot 10^4$
CsI(Tl)				1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$				.30	$2.8 \cdot 10^3$
CsF				003	$2 \cdot 10^3$
LSO				.04	$1.4 \cdot 10^4$
$PbWO_4$				006	$2 \cdot 10^2$
LHe				1/1.6	$2 \cdot 10^2$
LAr				5/0.86	$4 \cdot 10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4 \cdot 10^4$

* at 170 nm

CMS: PbWO4 75,848 crystals

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; $\boldsymbol{\varepsilon}_{sc} \approx 0.13$]
    - high density [e.g. $PBWO_4$: 8.3 g/cm^3]
    - good energy resolution (→Calorimeters)
  - Disadvantages complicated crystal growth
  - large temperature dependence

Light yield $\boldsymbol{\varepsilon}_{sc} \equiv$ fraction of energy loss going into photons

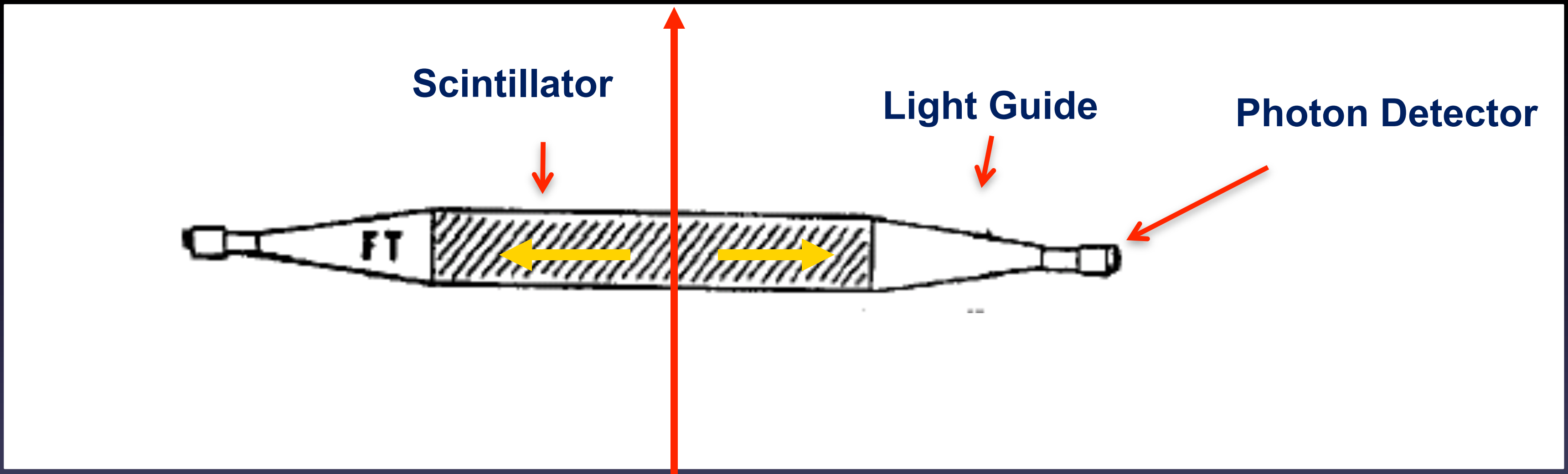
EXPENSIVE

- Organic Scintillators
  - Advantages
    - very fast ➔pulse shape discrimination possible
    - easily shaped
    - small temperature dependence
  - Disadvantages
    - lower light yield [typical; $\boldsymbol{\varepsilon}_{sc} \approx 0.03$]
    - low density [e.g. 1 g/cm^3]
    - radiation damage

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 obtain 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

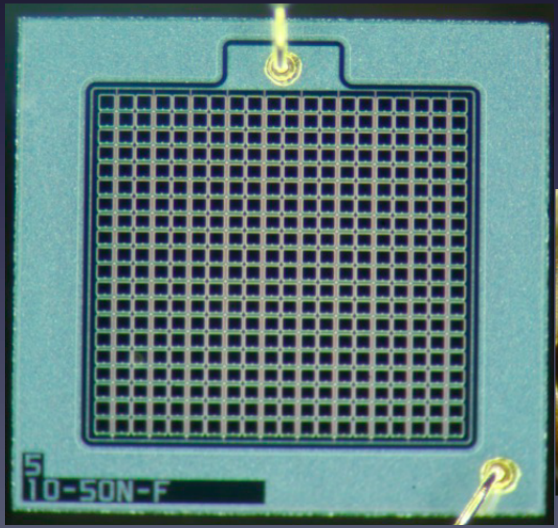
Photo-detectors

- 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. = $N_{p.e.}/N_{photons}$

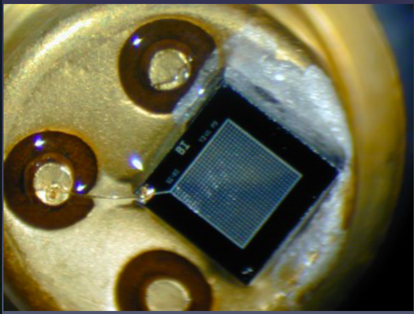
- Photomultipliers

- SiPM

Hamamatsu MPPC

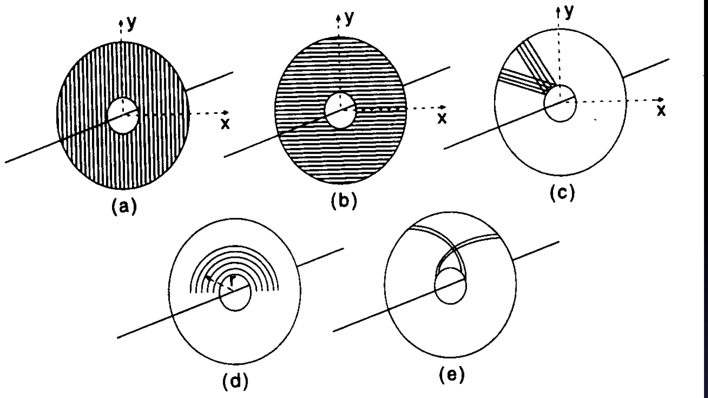


One of the first SiPM
Pulsar, Moscow

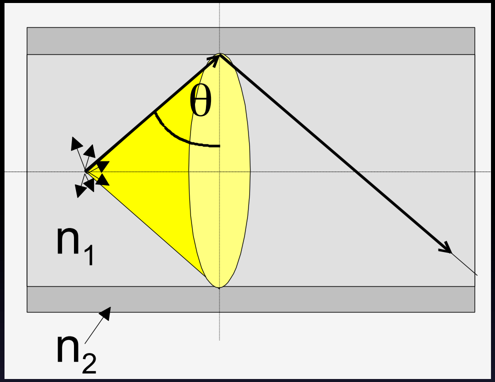


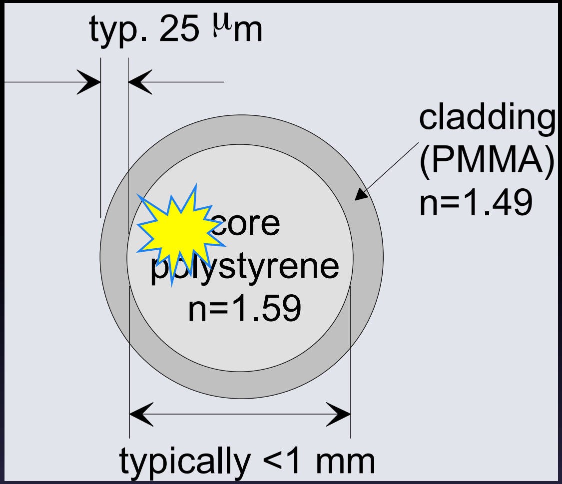
Fiber Tracking

Planar geometries (end cap)

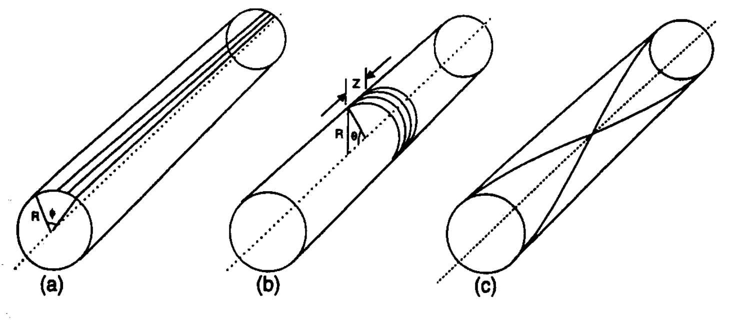


Light transport by total internal reflection





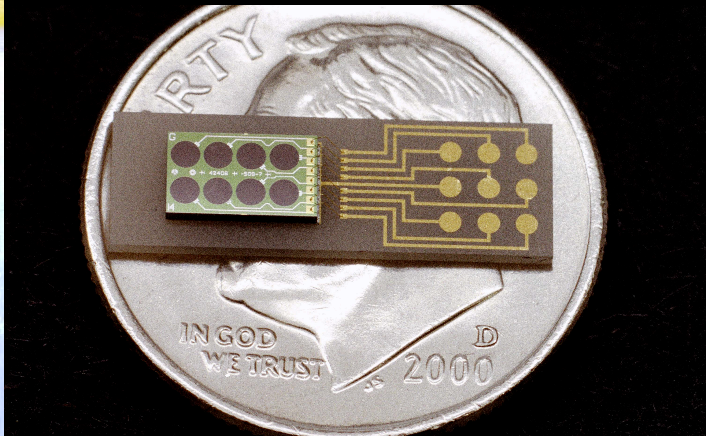
Circular geometries (barrel)



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

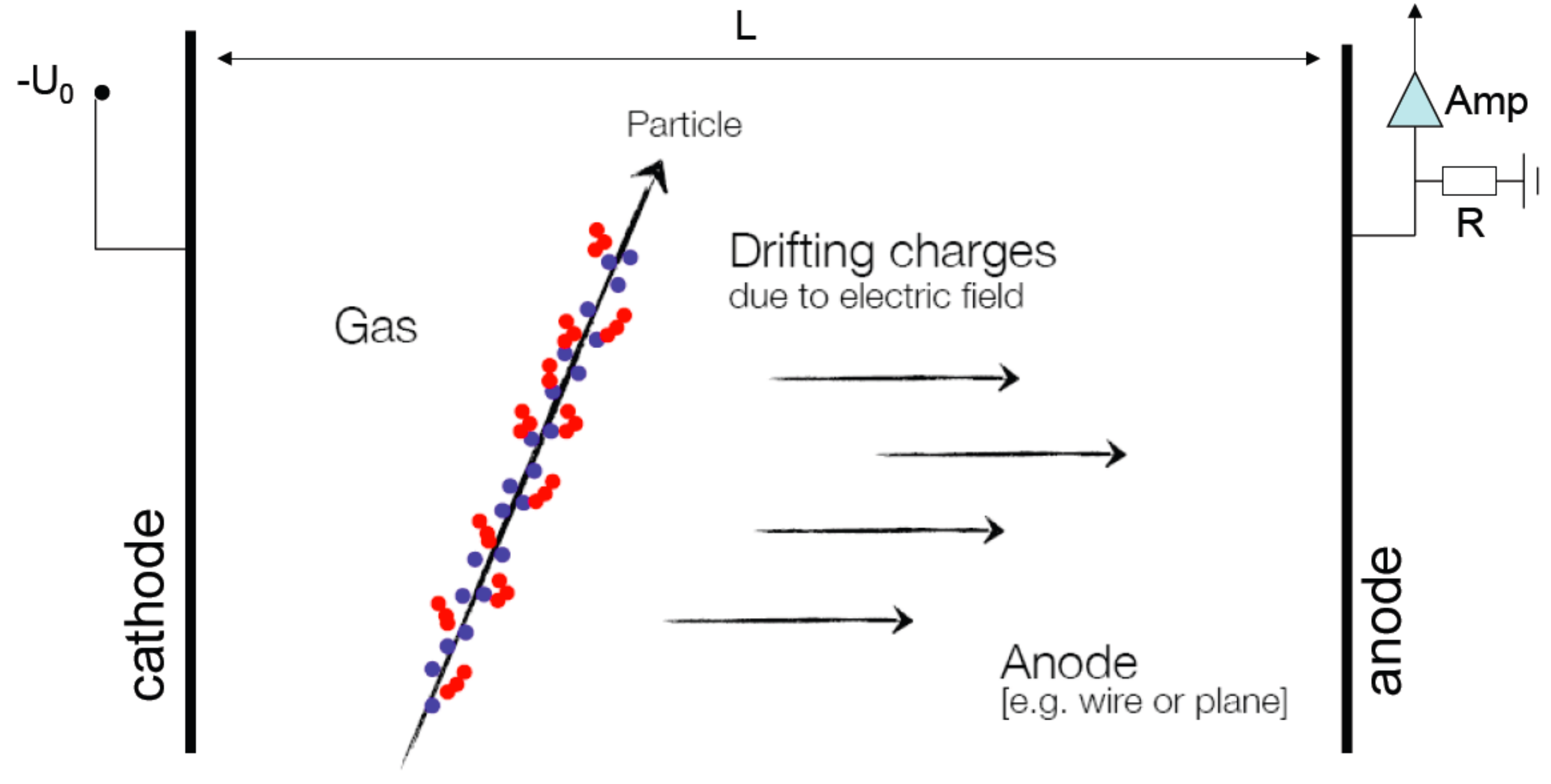
- High geometrical flexibility
- Fine granularity
- Low mass
- Fast response (ns)

Visible Light Photon Counters (VLPC)



D0 fiber tracker

Gas Detectors: primary

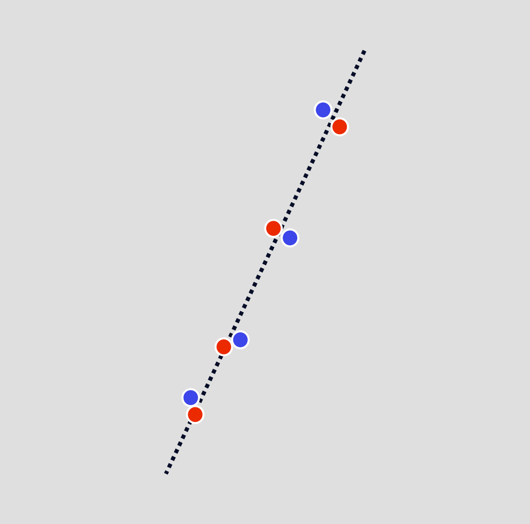


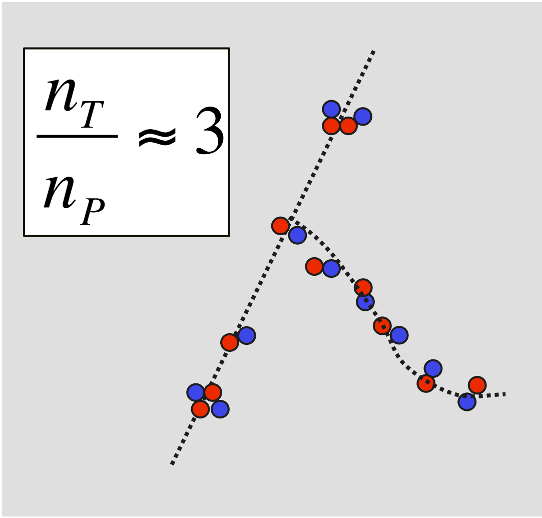
- ● Primary Ionization
- ● Secondary Ionization (due to δ-electrons)

Primary and secondary ionization

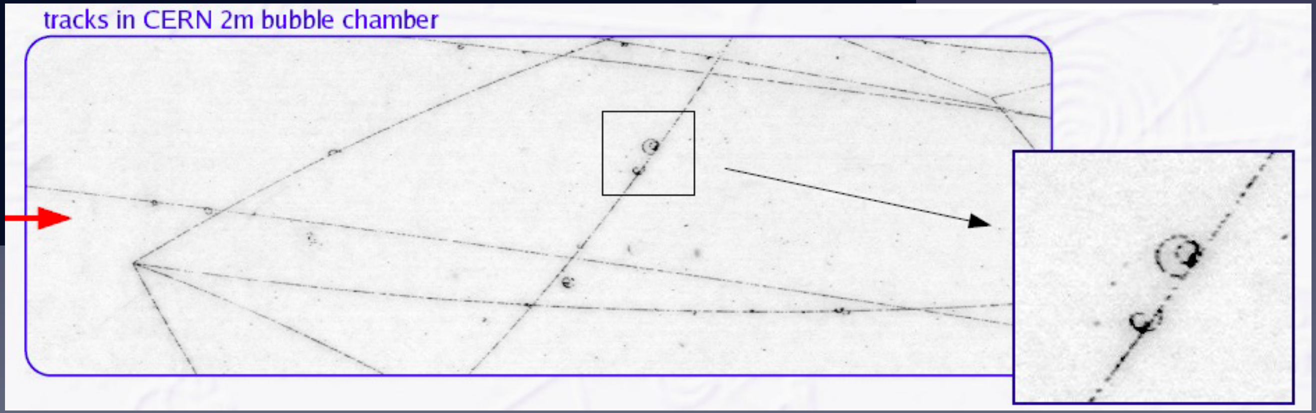
- Coulomb interactions between E field of the particle and of the molecules of the medium produce electron-ion pairs.
- Minimum ionizing particles in argon NTP
  - $\langle n_P \rangle$: 25 cm^{-1}
- Primary electrons can ionize the medium producing local e-ion clusters. Electron can have energy to produce a long trail (delta electron).
- Total number of ion pairs n_T:
  - *E:* energy loss
  - w_i : average energy per ion pair

$$n_T = \frac{\Delta E}{w_i}$$

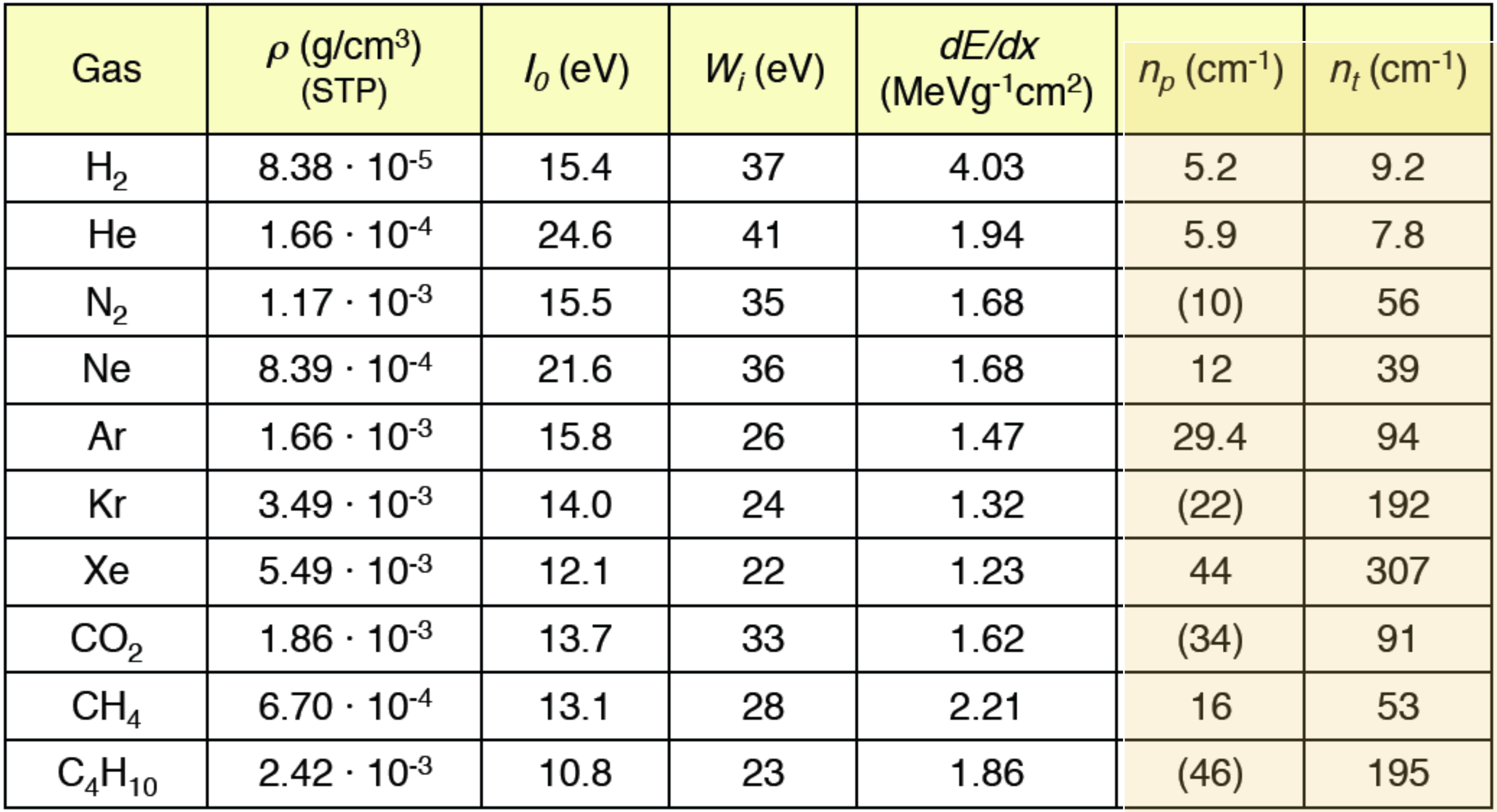




$$\frac{n_T}{n_P} \approx 3$$



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

- Multiple ionizing collisions follow Poisson's statistics:

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

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

$$P_{n_P}^{\langle n_P \rangle} = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

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

- Efficiency:

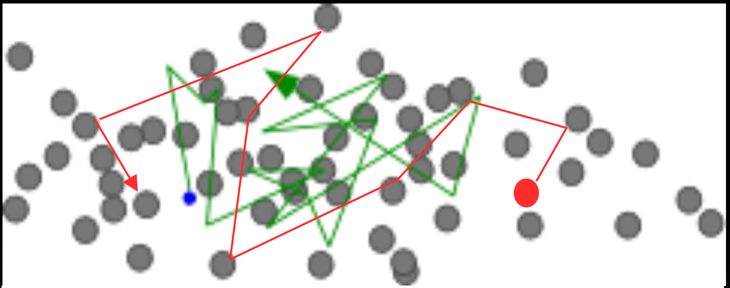
$$\varepsilon = 1 - P_0^{\langle n_p \rangle} = 1 - e^{-\langle n_p \rangle}$$

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

- Other important parameters are:
  - Recombination and electron attachment due to 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
  - Electronic noise in amplifier is typically 1000 e- (ENC)→Amplification is needed → Important for the gain factor of the gas detector ...

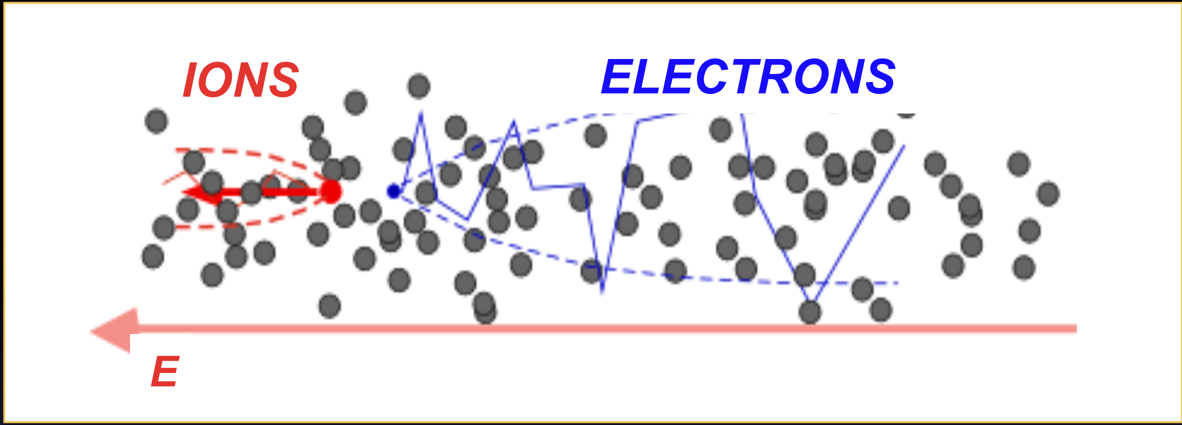
Diffusion & Drift

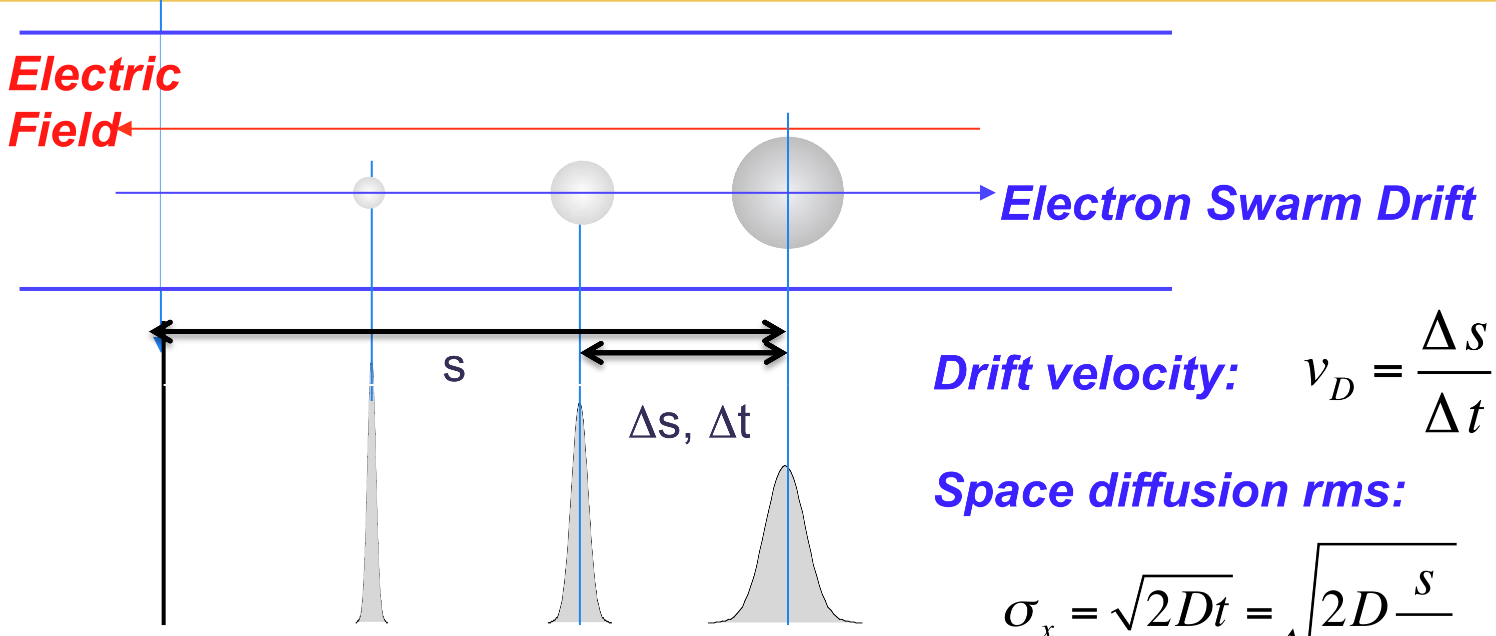
E = 0: Thermal diffusion



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

E >0: Charge Transport and Thermal diffusion





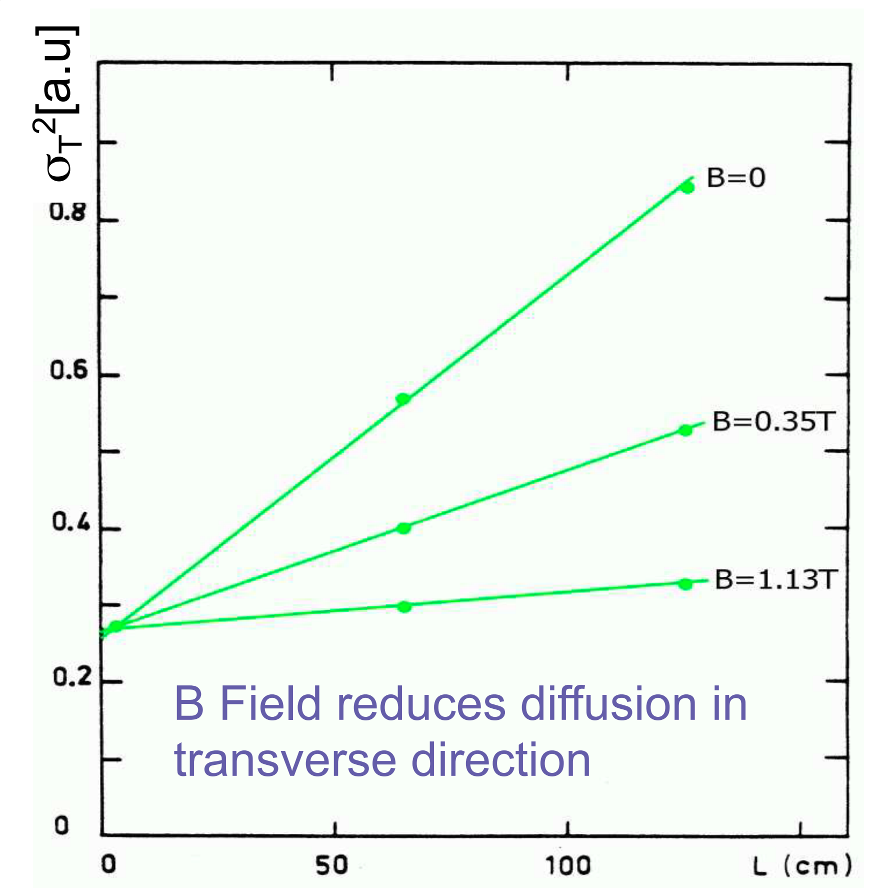
Drift velocity: $v_D = \frac{\Delta s}{\Delta t}$

Space diffusion rms:

$$\sigma_x = \sqrt{2Dt} = \sqrt{2D\frac{s}{v_D}}$$

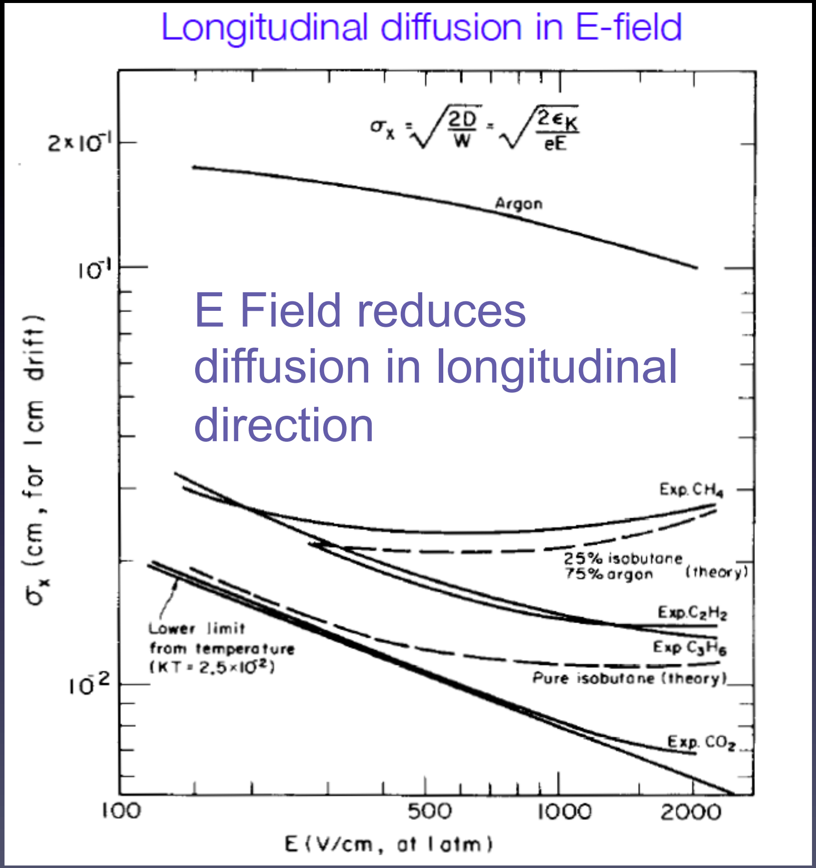
Drift and diffusion in E and B fields

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



B Field reduces diffusion in transverse direction

- Longitudinal diffusion as function of E field

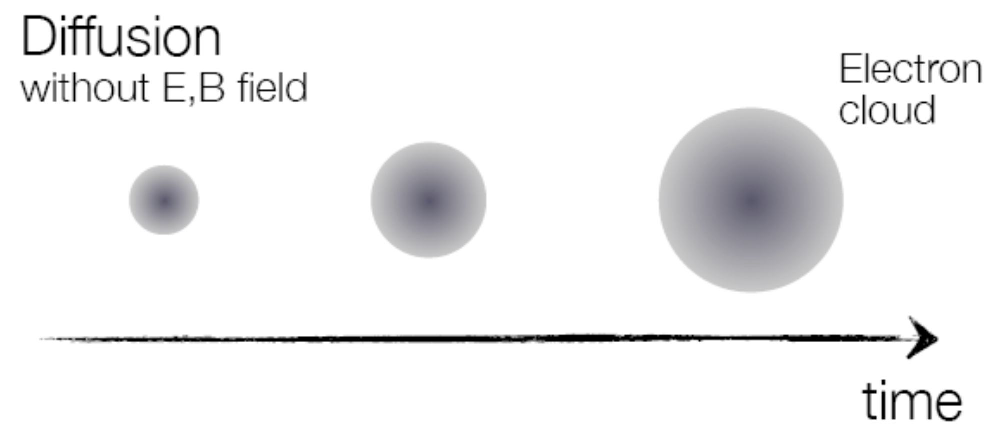

Longitudinal diffusion in E-field

E Field reduces diffusion in longitudinal direction

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

Diffusion in a gas

- Diffusion is evaluated using the classical theory of gases.
- Due to multiple collisions the distribution of charge at time t in a length dx after a distance x is given by a Gaussian



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

- Linear diffusion

$$\sigma_x = \sqrt{2Dt}$$

D=diffusion coefficient 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 is given by the Maxwell distribution where m is the mass of the particle

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

Drift and mobility

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

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

Typical values of v_D

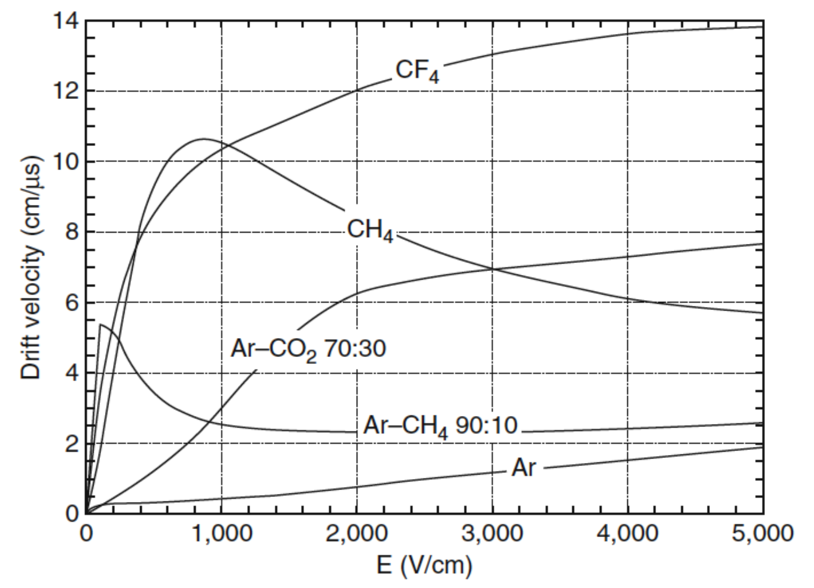
- E ~ 1 kV / cm
- v_D ≈cm/ms for ions
- v_D≈cm/µs for e-

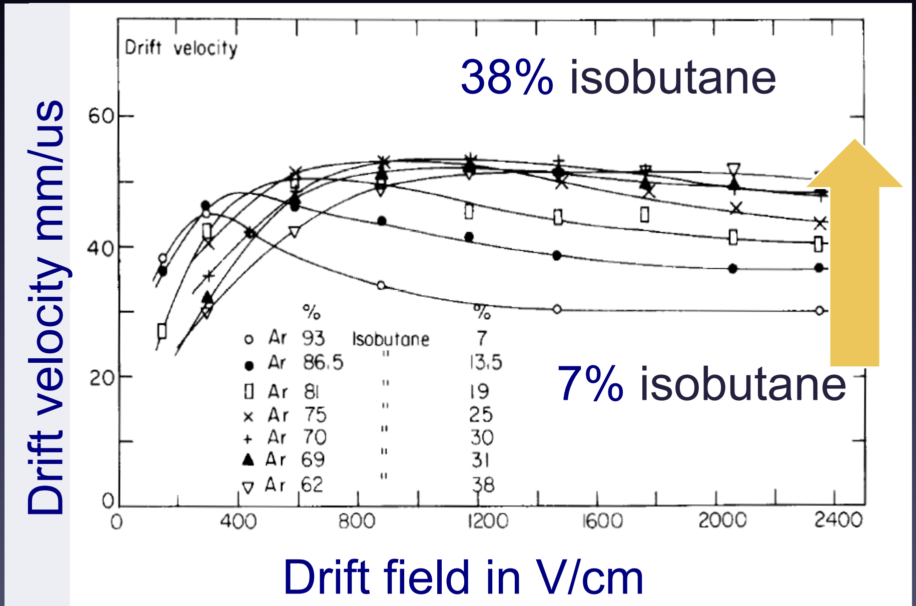
MWPC: 1 cm gap, Ar-CH_4, 5 kV/cm

Total ions drift time τ^+ ~ 120 µs

TPC: 1 m drift, Ar-CH4, 200 V/cm

Total ions drift time τ^+ ~ 300 ms





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

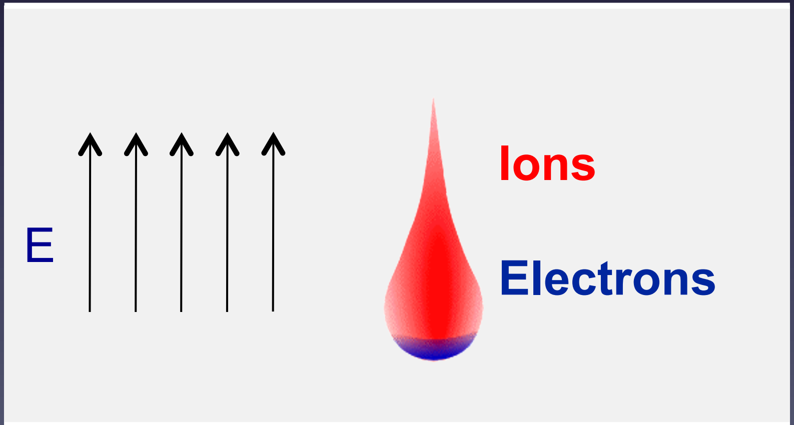
- τ(collection) ≈1/v_d → diffusion effects are reduced in gases such as CF_4 that have high drift

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 increase 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:

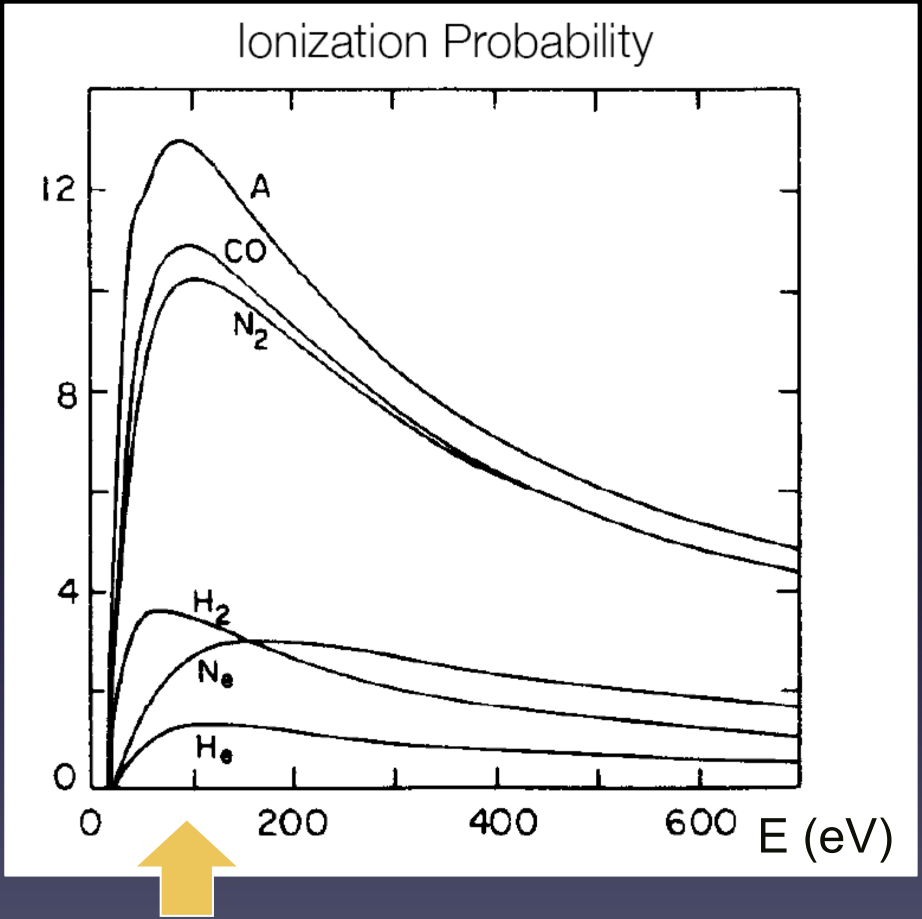
$$G = \frac{n}{n_0} = e^{\alpha x}$$

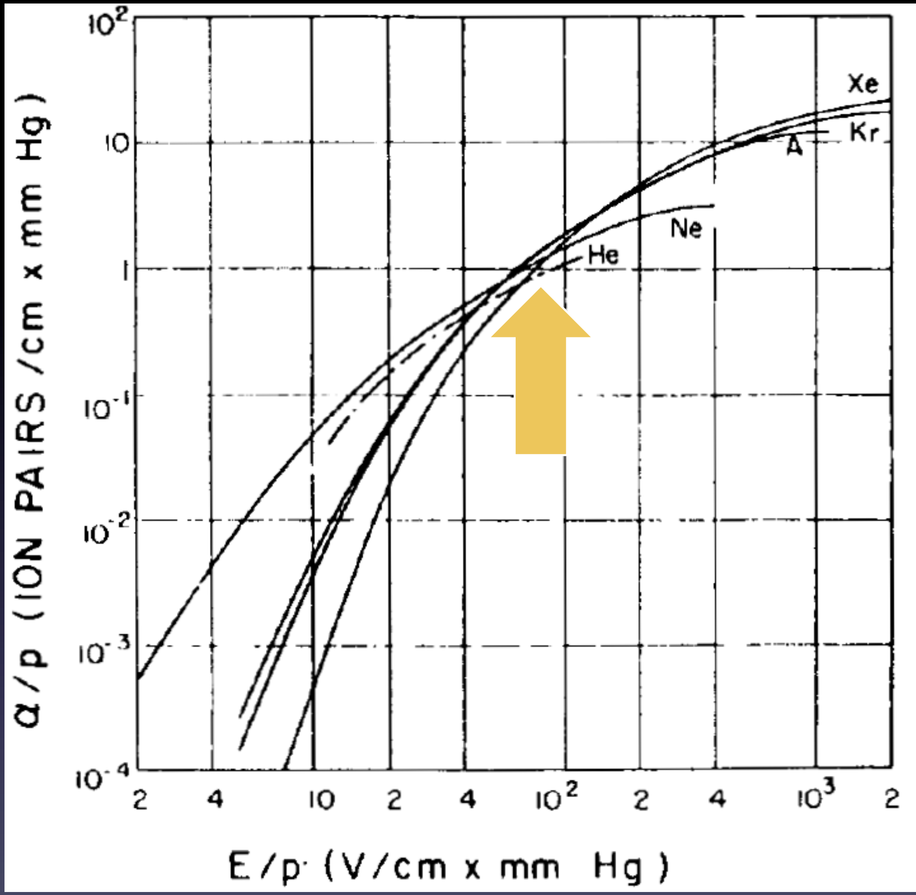
- Raether's limit G≈10^8, since after that sparking can occur



Drop-like shape of an avalanche

Avalanche multiplication

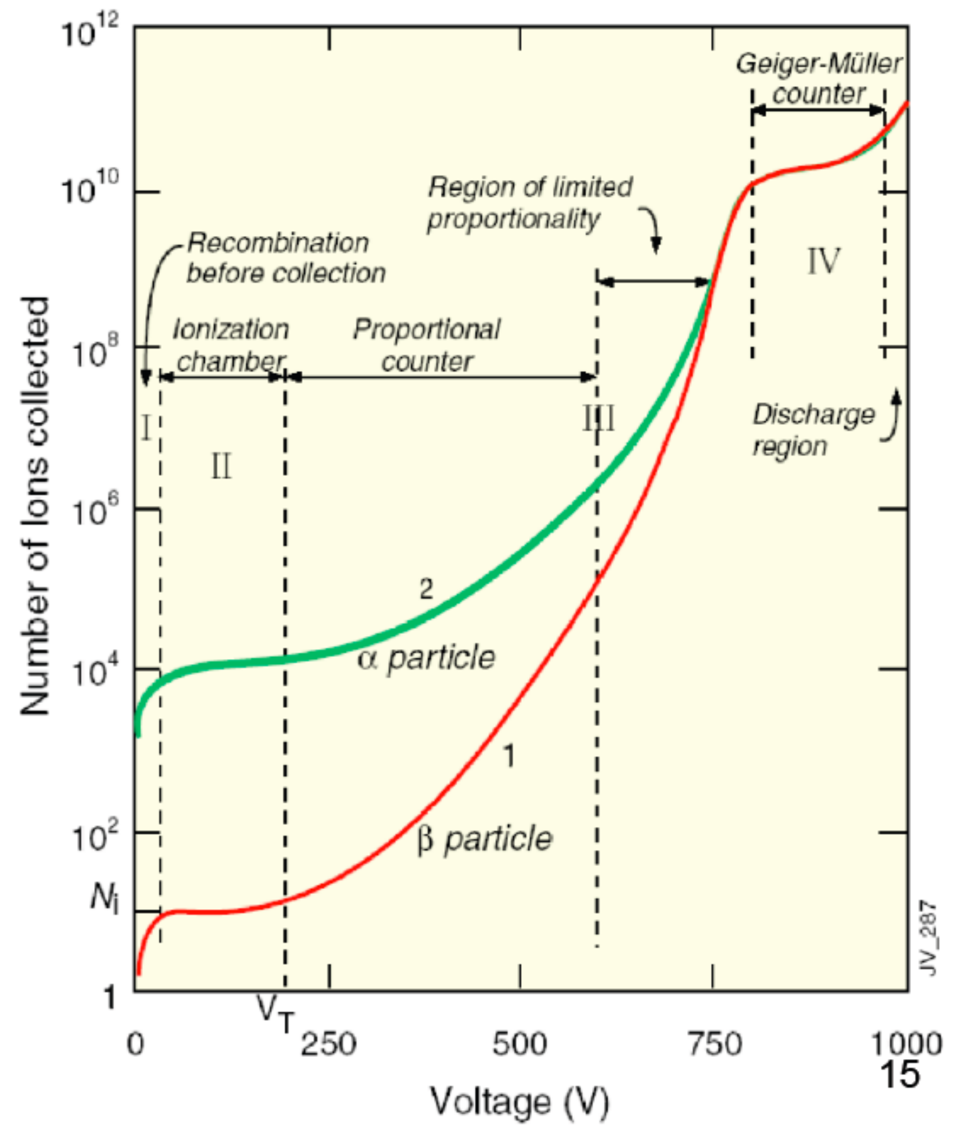




- Need an energy of 75-100 eV for High ionization probability (and need to gain it in a few μm)
- E=75 kV/cm to reach α=1

Gas amplification factor

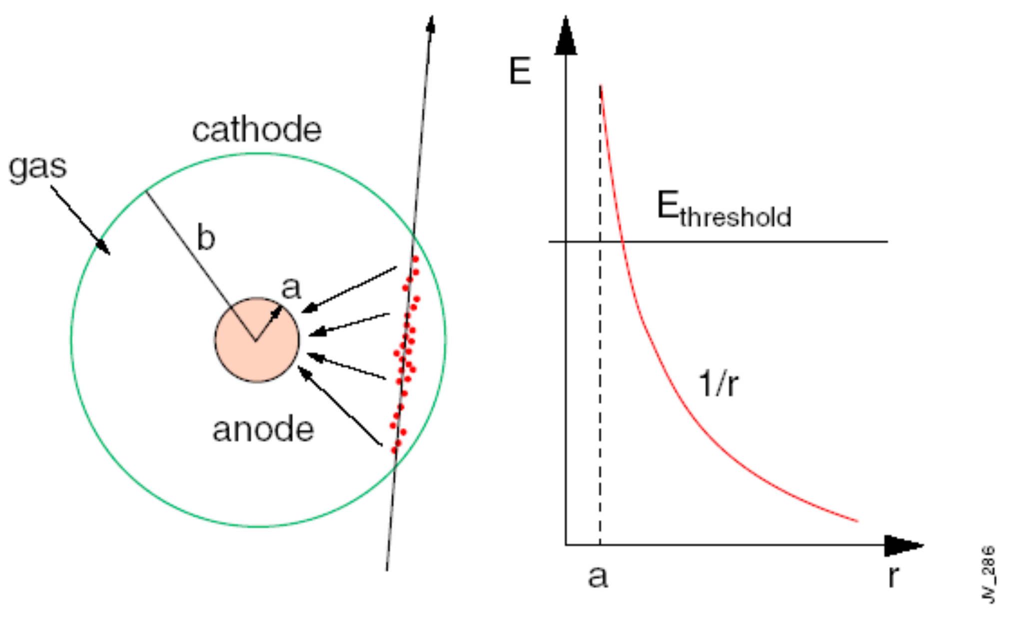
- Ionization mode: full charge collection; no amplification; G=1
- Proportional mode: multiplication; signal proportional to original ionization ⇒ measurement of dE/dx. Secondary avalanches needs quenching; G ≈10^4-10^5
- Limited Proportional (Saturated, Streamer mode): strong photo-emission; Require 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

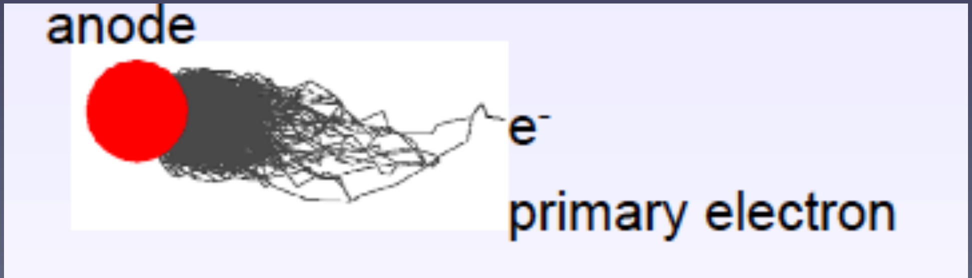
- Cylindrical proportional counter:
  - Single anode wire in a cylindrical cathode
  - e^-/ions drift in the volume

$$E = \frac{V_0}{r \ln(a/b)}$$



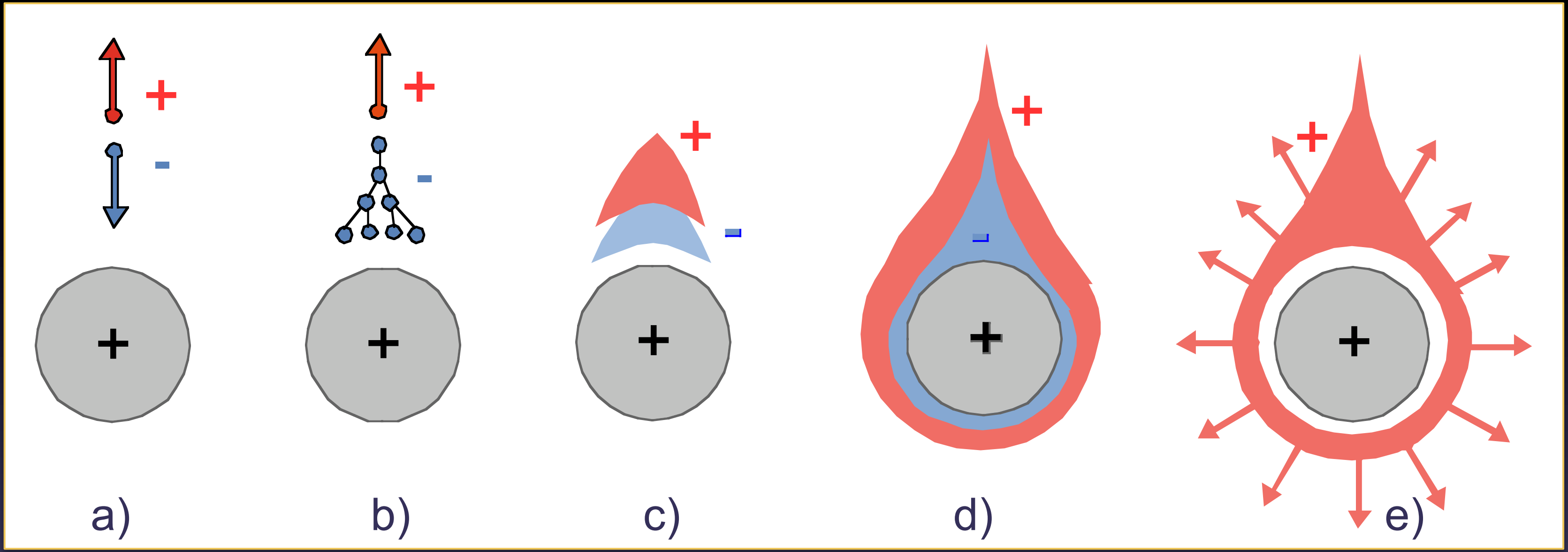
- V_0= potential between anode and cathode
- Close to wire (diameter 10 μm) E-field very large (> 10 kV/cm) kinetic energy of the electrons becomes very large → can produce secondary ionization

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



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,

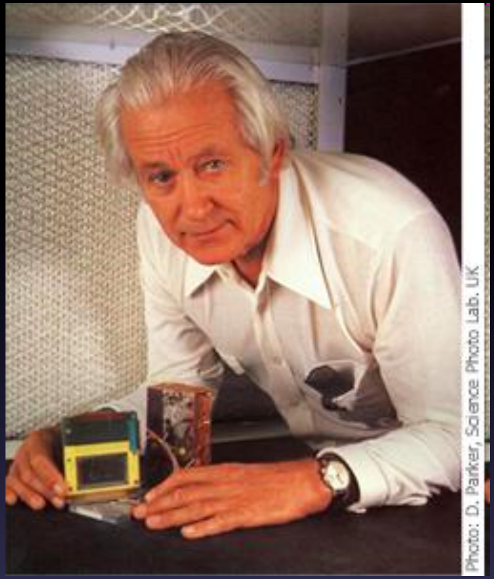
d) a drop-like avalanche develops which surrounds the anode wire,

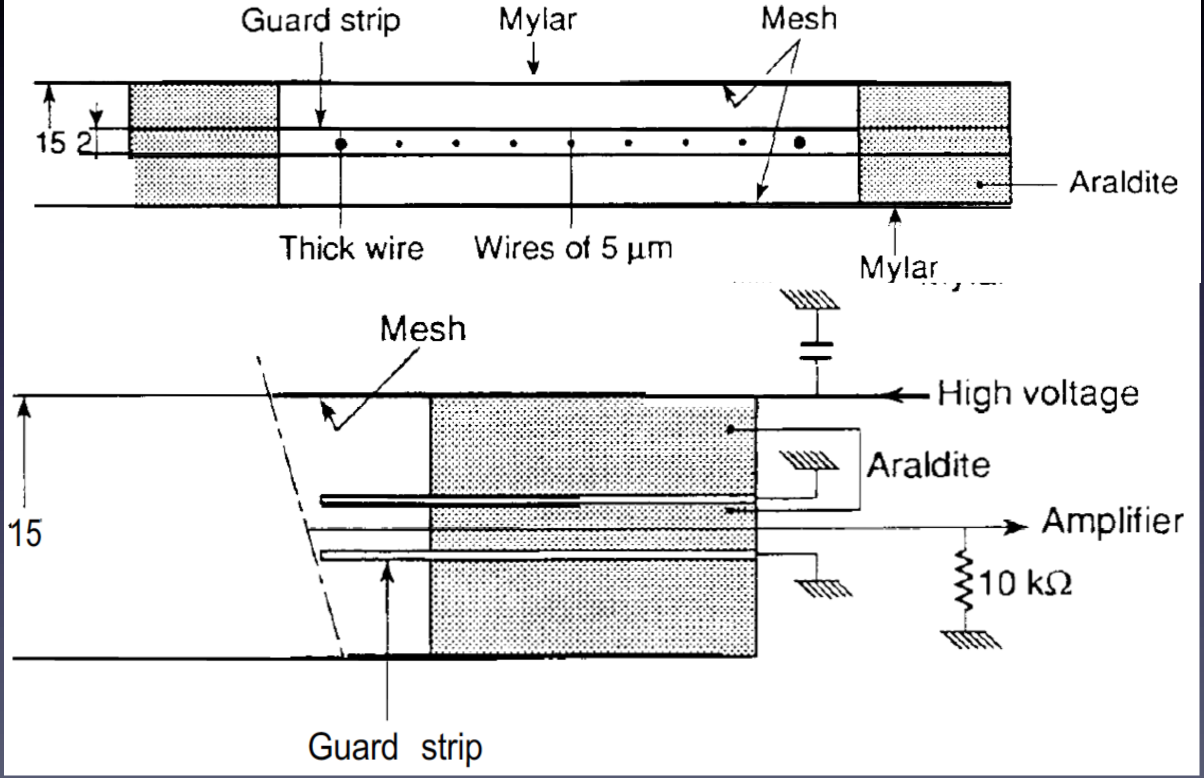
e) the electrons are quickly collected (~1ns) while the ions begin drifting towards the cathode generating the signal at the electrodes

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)

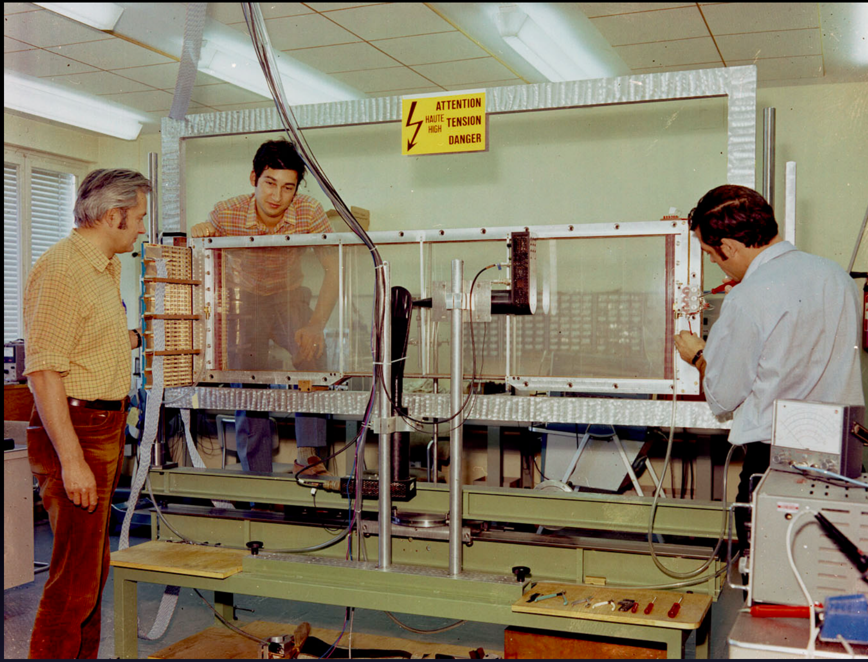
Anode wire =20µ diameter
d=2 mm

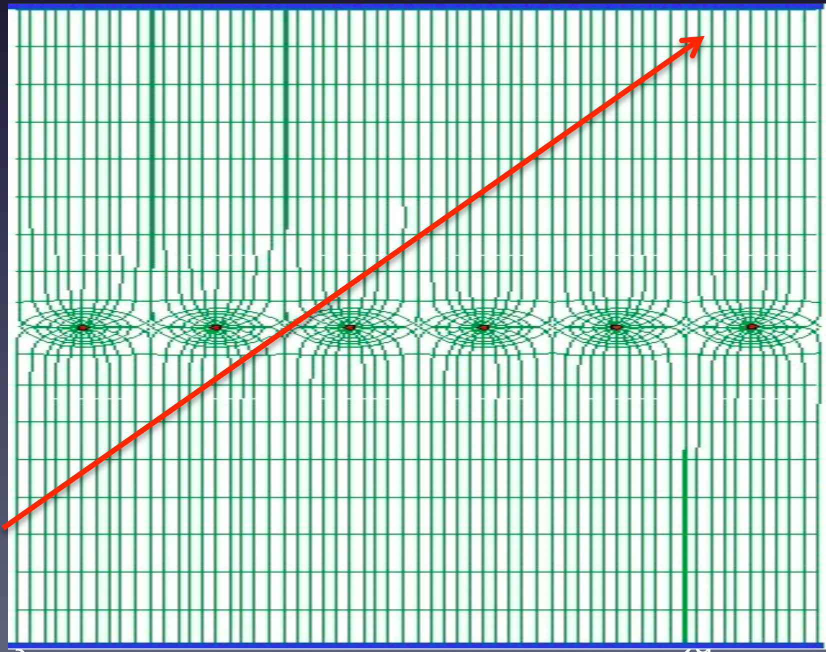
MWPC

- First large area MWPC
- First electronic device allowing high rate experiments
- PID capabilities through dE/dx

- Resolution
  - Wire spacing 1 mm
  - Wire diameter 20μm
  - Digital readout
  - $\sigma_x \approx 300\ \mu m$

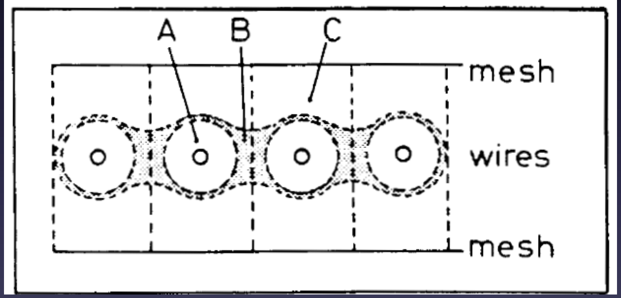
$$\langle x^2 \rangle = \frac{\int_0^{d/2} x^2 dx}{\int_0^{d/2} dx} = \frac{2}{d}\frac{x^3}{3}\Big|_0^{d/2} = \frac{d^2}{12}$$

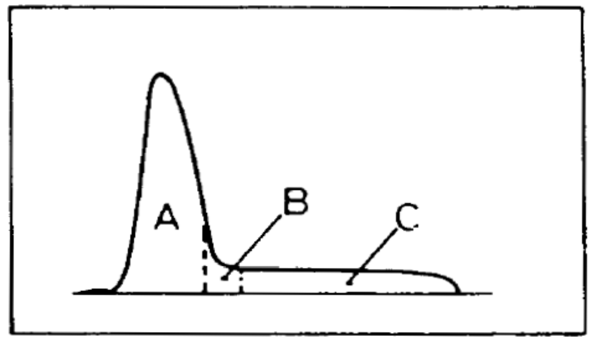


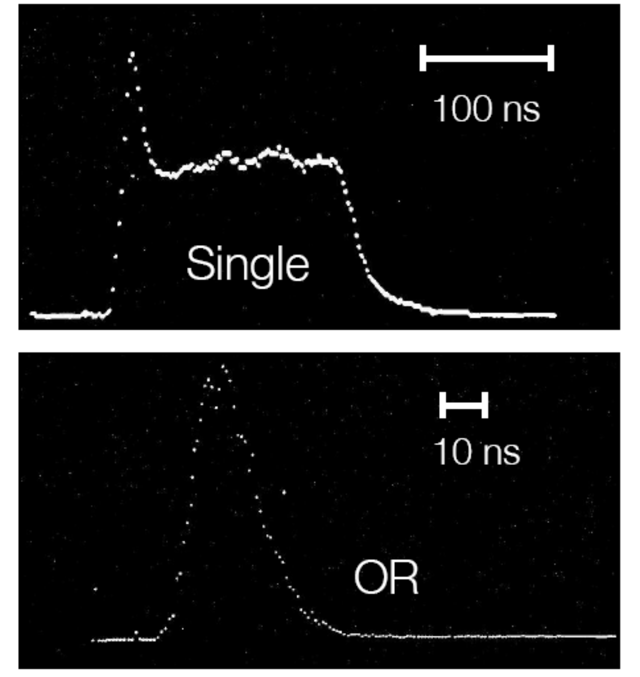


MWPC performance

- 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]

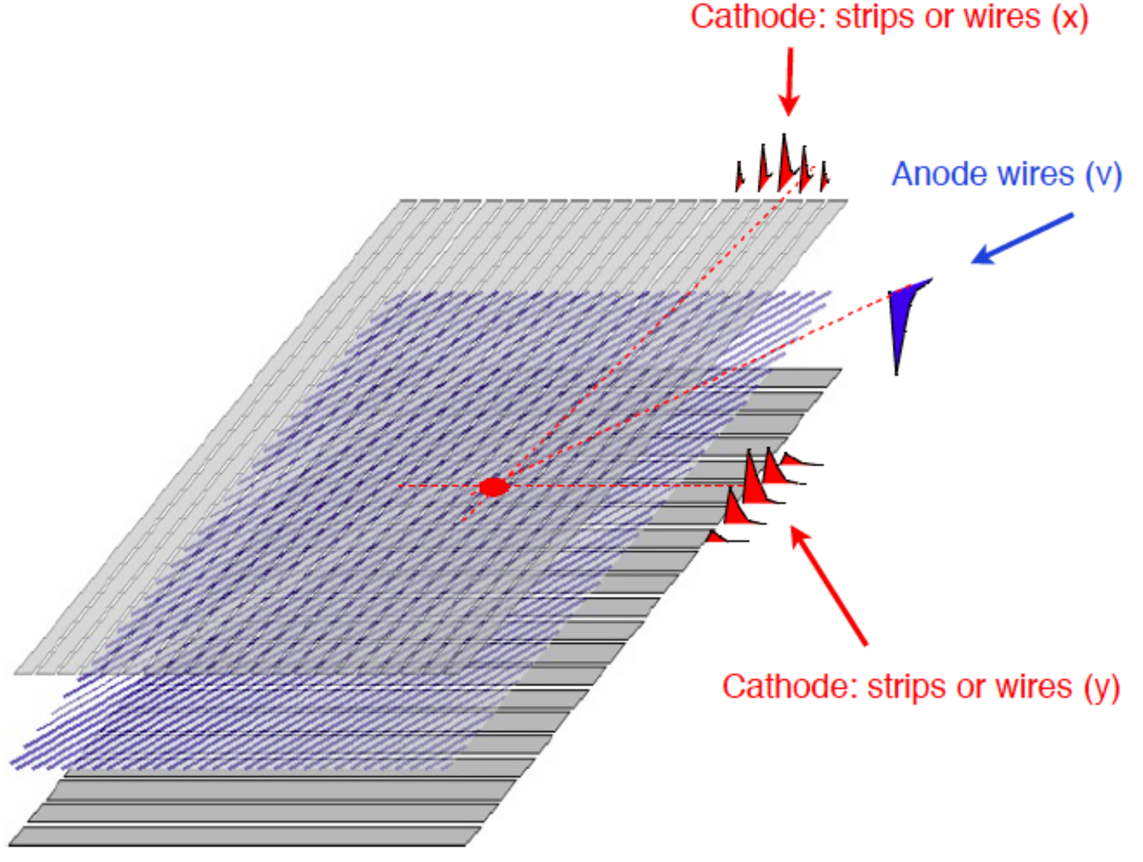






2D MWPC

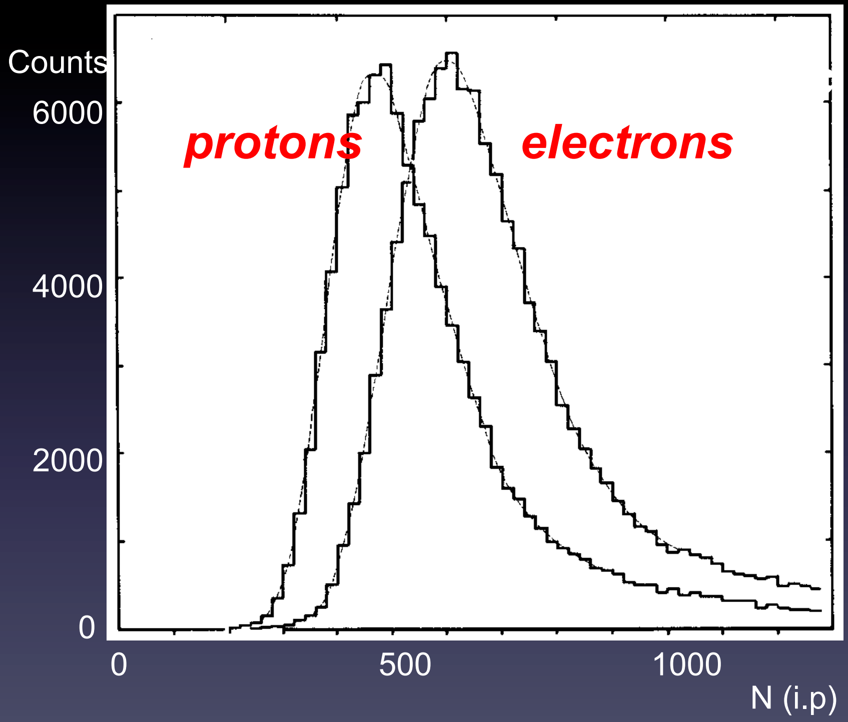
- Two coordinates (x,y) of the track hit can be determined from the position of the anode wire and the signal induced on the cathode strips (or wires)
  - High spatial resolutions due to center of gravity
  - Resolve ambiguities using strip pattern



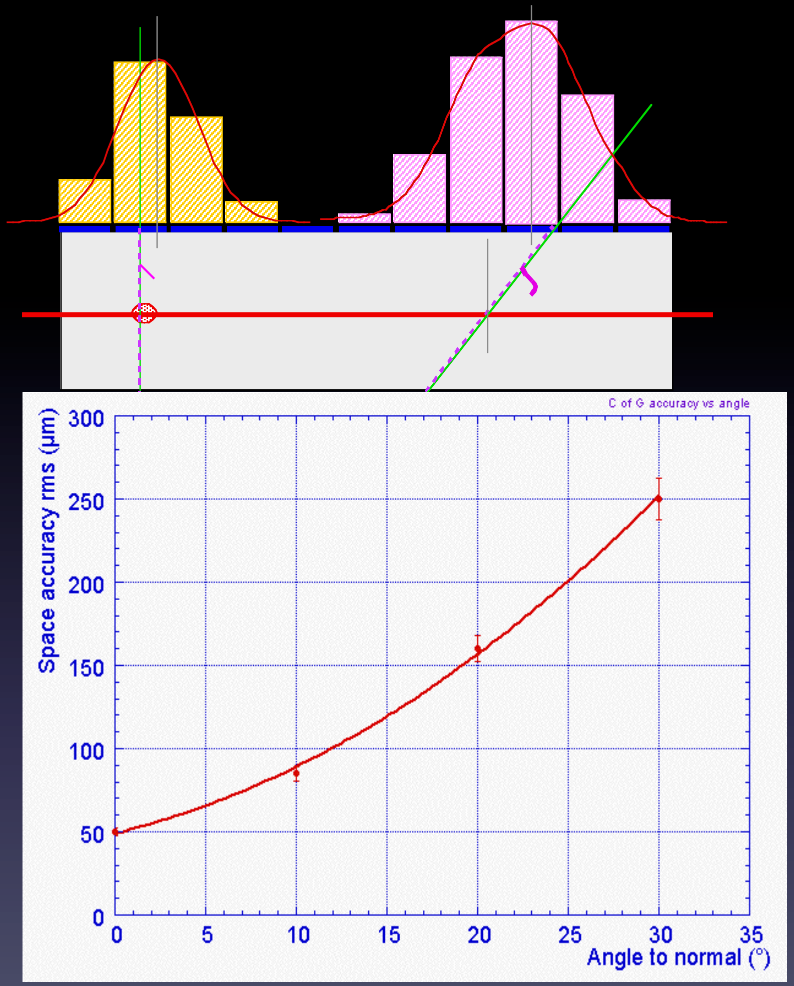
Particle ID & space accuracy

Particle identification

- **Requires statistical analysis of hundreds of samples**



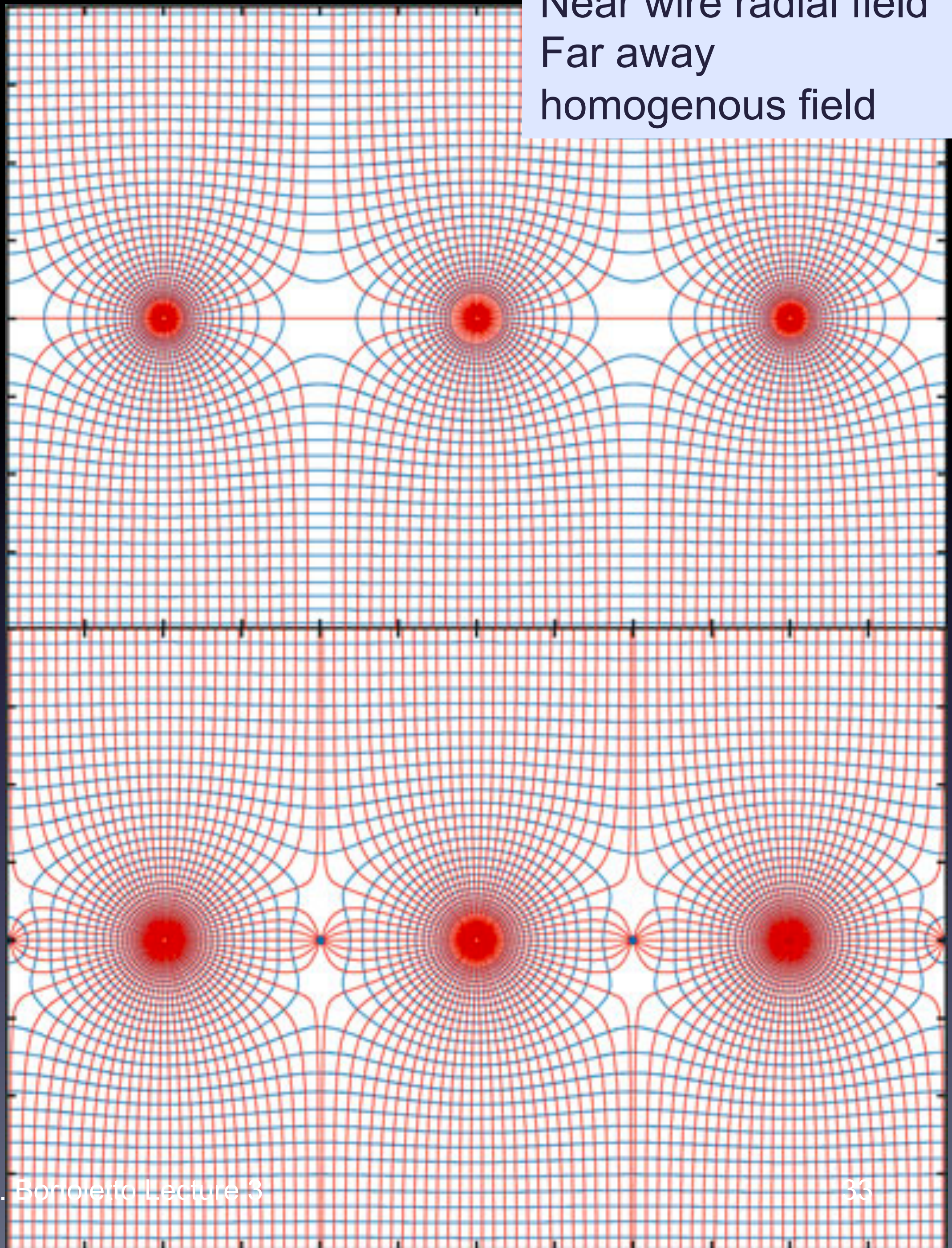
I. Lehraus et al, Phys. Scripta 23(1981)727



Position accuracy as a function of the track angle to the normal to the chamber

Field distribution

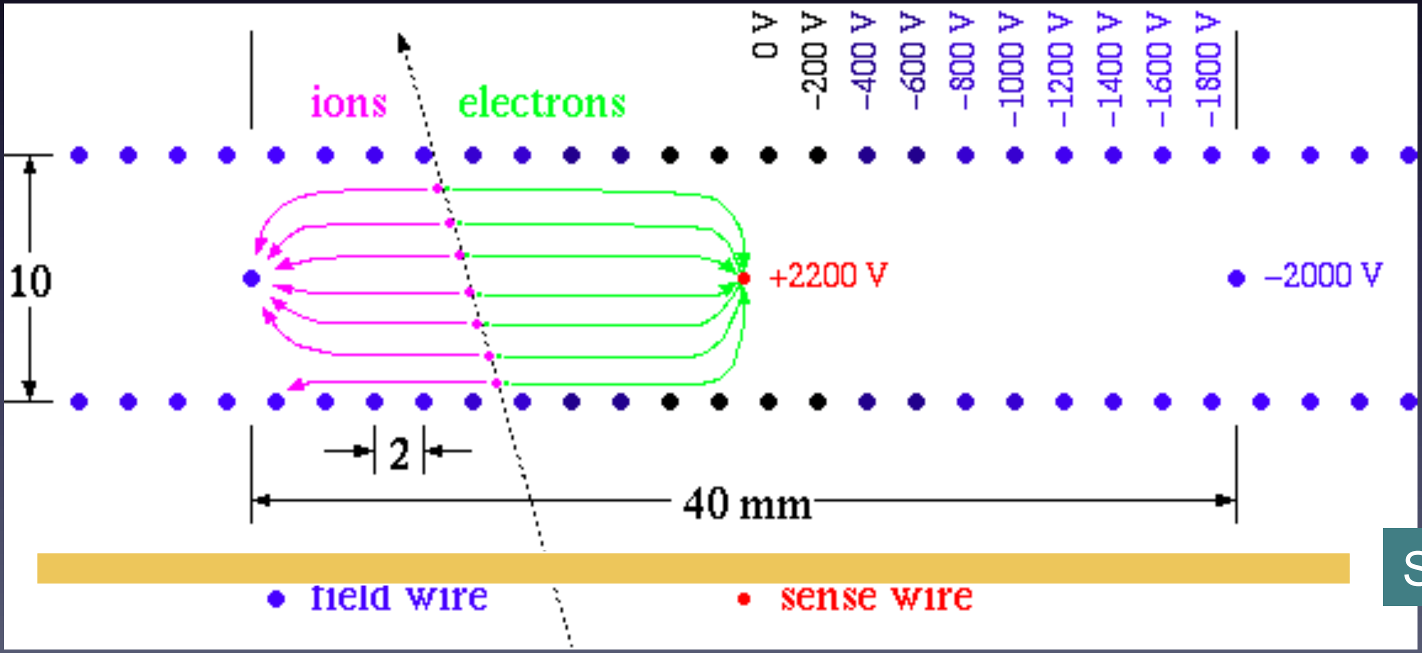
- MWPC: Operation is difficult at smaller wire spacings.
  - The electrostatic repulsion for thin (10 µm) anode wires causes mechanical instability above a critical wire length of less than 25 cm for 1-mm
- Drift chambers
  - a thicker wire at proper voltage between anodes (field wire) reduces the field inhomogeneity 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

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



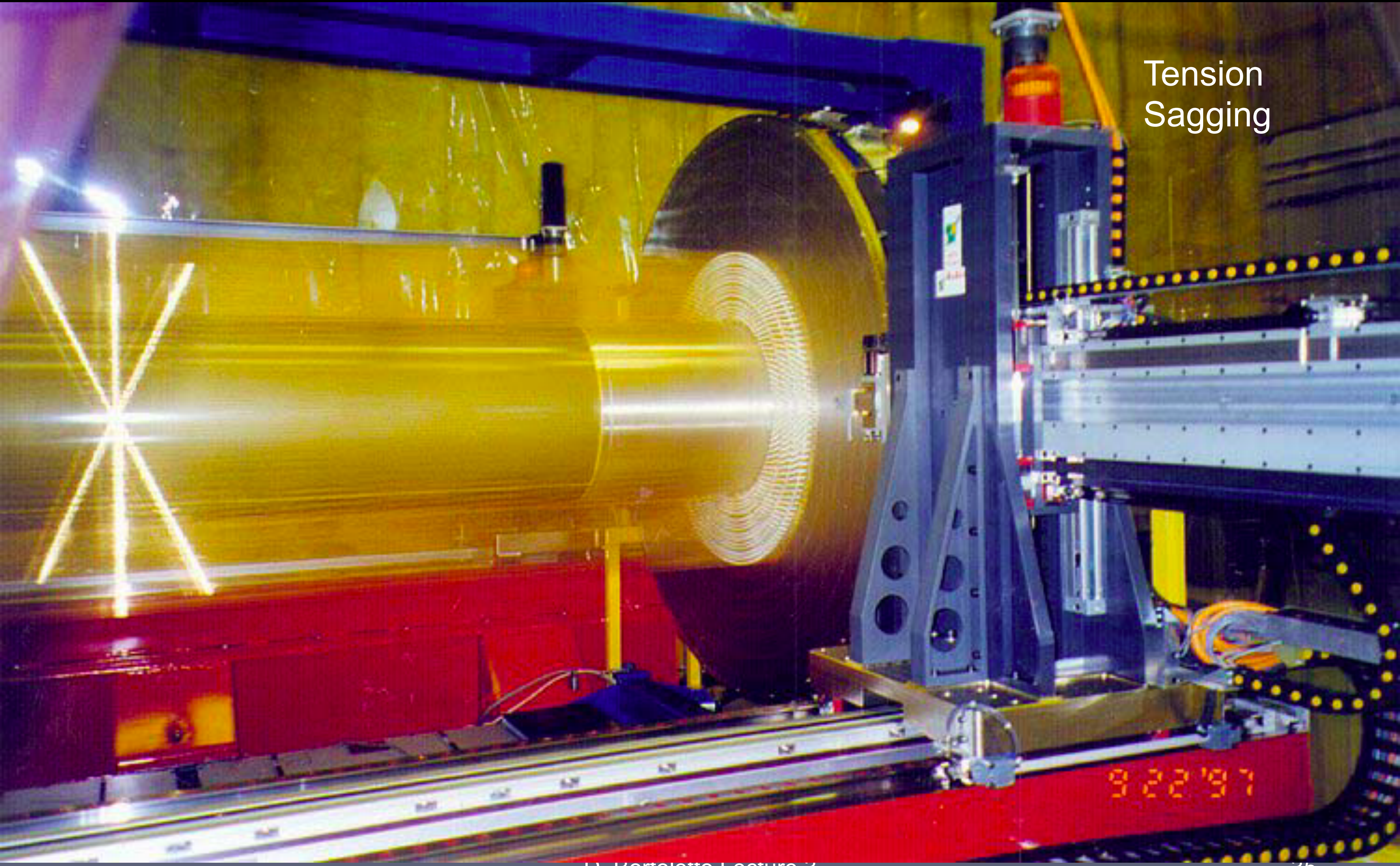
$$x = \int_{0}^{t_D} v_D\,dt$$

Need well-defined drift field

Scintillator counter

J. Heintze, 1971

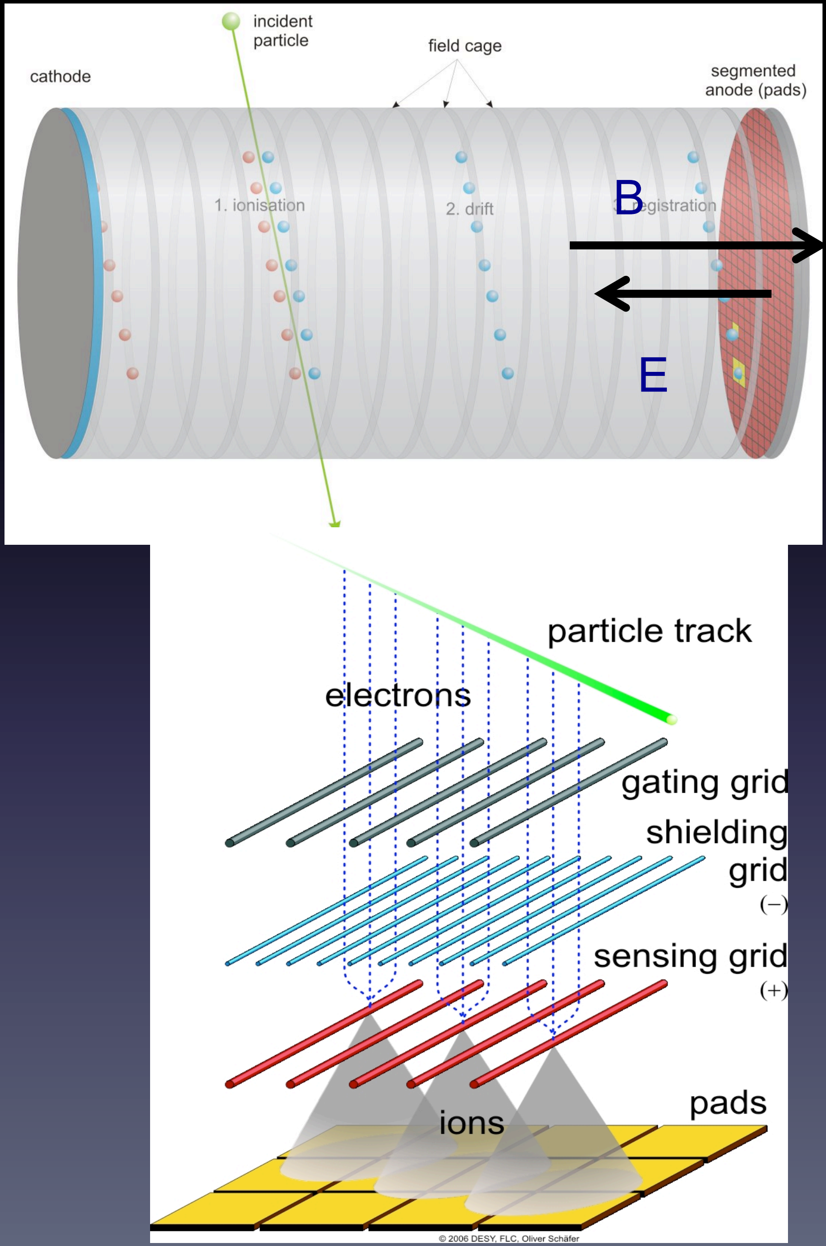
Wire stringing



Tension
Sagging

Time Projection chamber (TPC)

- D.R. Nygren in 1976
- Full 3-D reconstruction
  - XY: MWPC and pads of MWPC at the endcap
  - Z: from drift time measurement (several meters)
    - Field cage for very homogenous electric field
- Typical resolution
  - z and y ≈mm, x=150-300 μm
  - dE/dx ≈5-10%
- Advantages:
  - Complete track information → good momentum resolution
  - Good particle ID by dE/dx
- Challenges
  - Long drift time limited rate
  - Large volume (precision)
  - Large voltages (discharges)
  - Large data volume
  - Difficult operation at high rate



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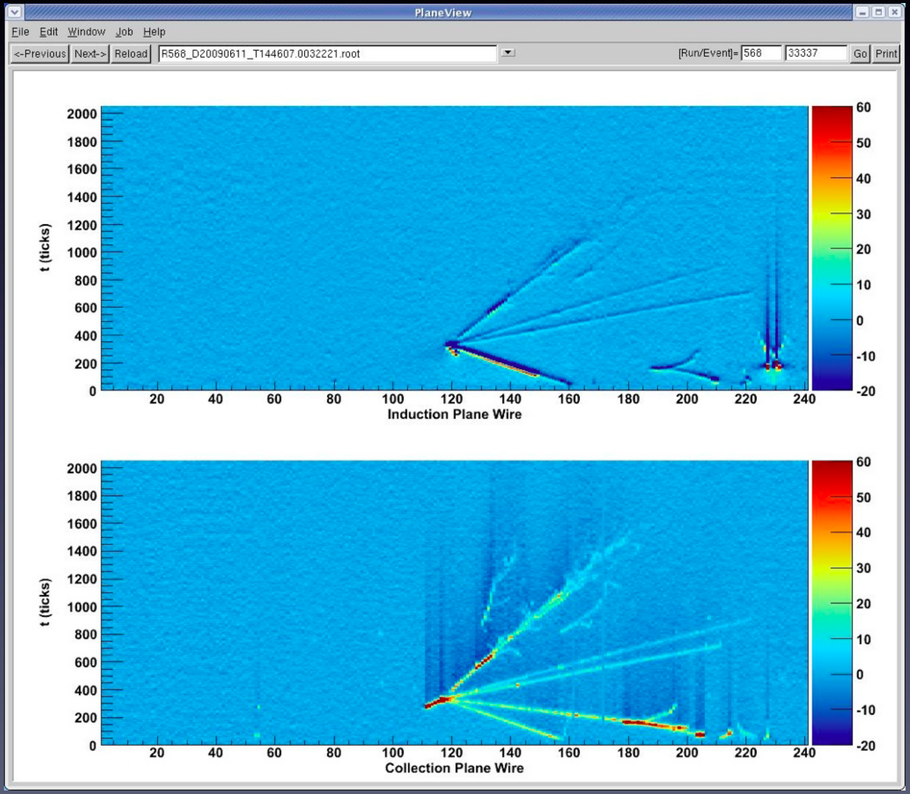
Liquid Argon TPC as a bubble Chamber

- LAr provides a dense target for neutrinos and for ionization/ Scintillation detection.
- Particle identification comes primarily from dE/dx (energy deposited) along track.
  - Wire spacing ≈ mm and digital sampling provides fine-grained resolution
  - Photons and Electrons can be cleanly separated
- Ideal for neutrino experiments

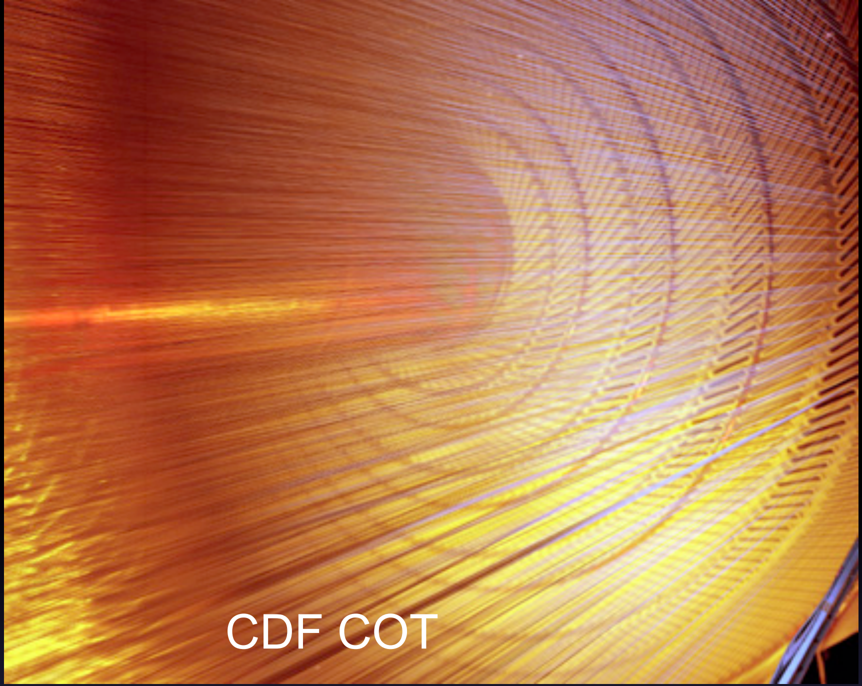


R568_D20090611_T144607.0032221.root

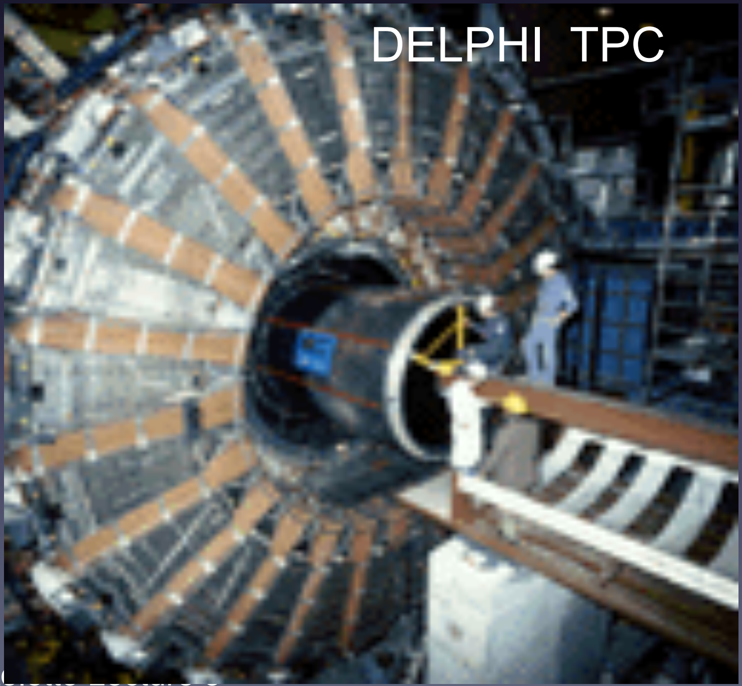
[Run/Event]= 568 33337

- Microboone and LBNF neutrino experiments


ALEPH TPC

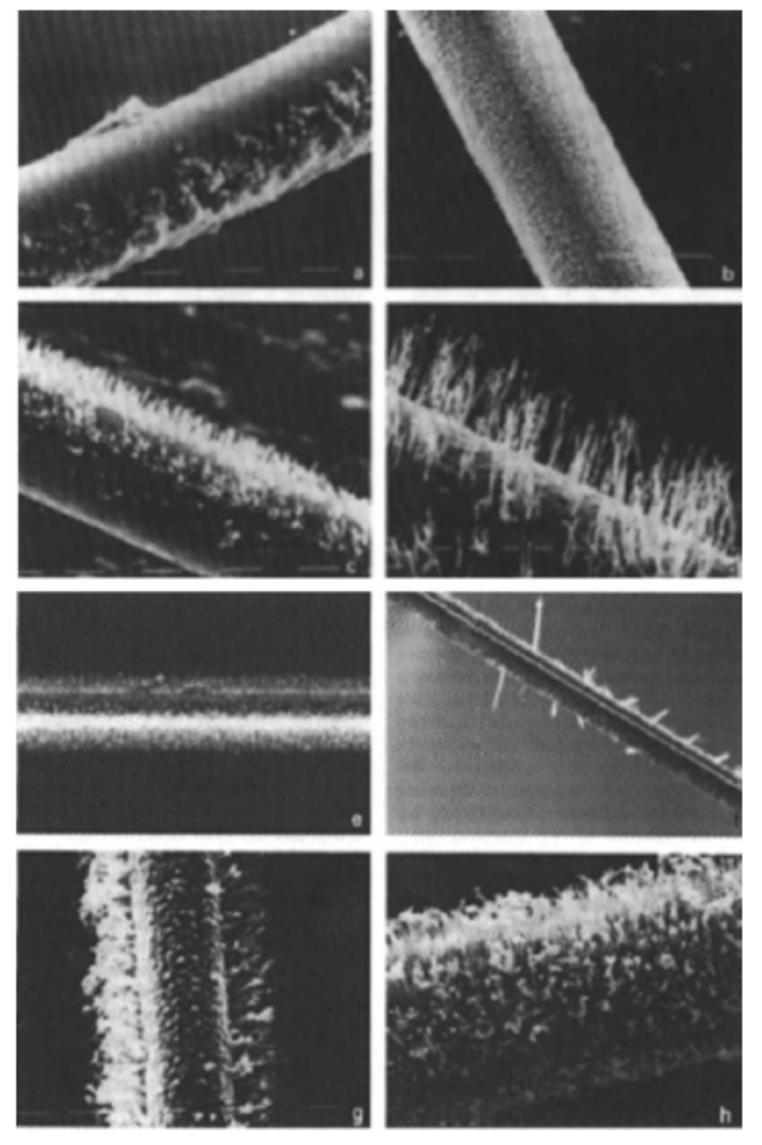

CDF COT


OPAL JET
CHAMBER


DELPHI TPC

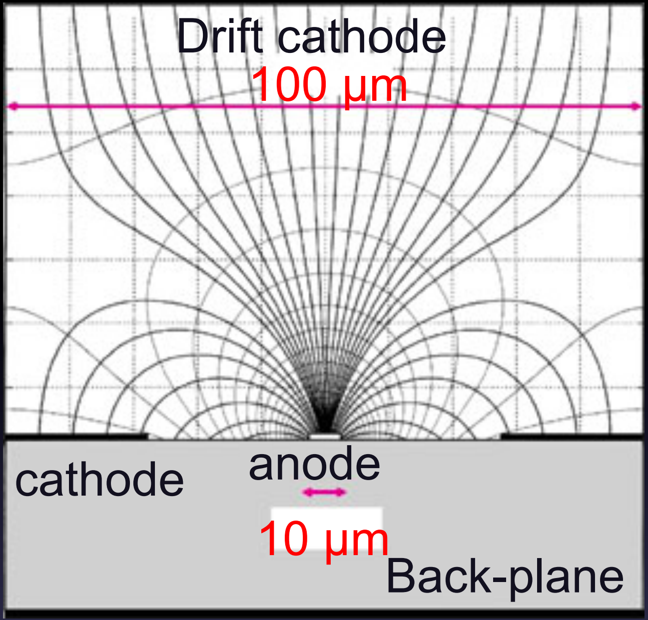
Aging in wire chambers

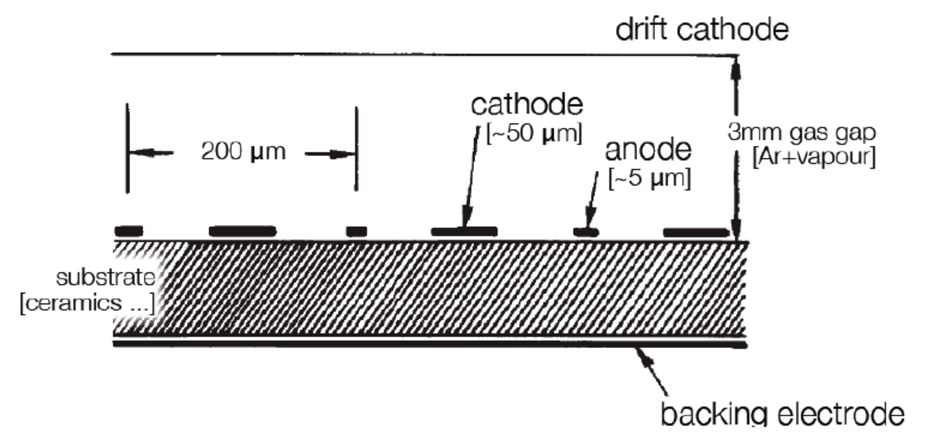
- Consequences of avalanche
  - Formation of radicals i.e. molecule fragments
  - Polymerization yield long chains of molecules
  - Polymers may be attached to the electrodes
  - Reduction of gas amplification
- Important to avoid contamination

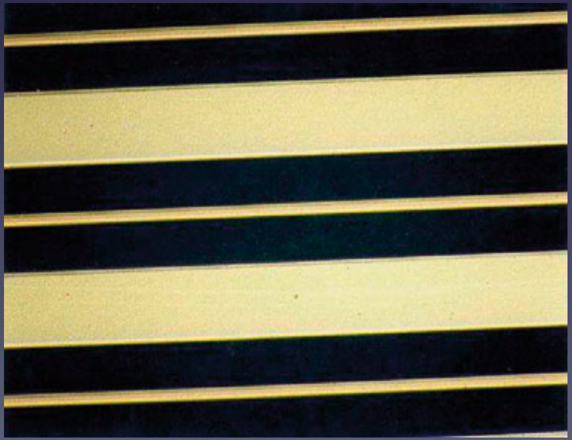


Micro-strip gas chambers (MSGC)

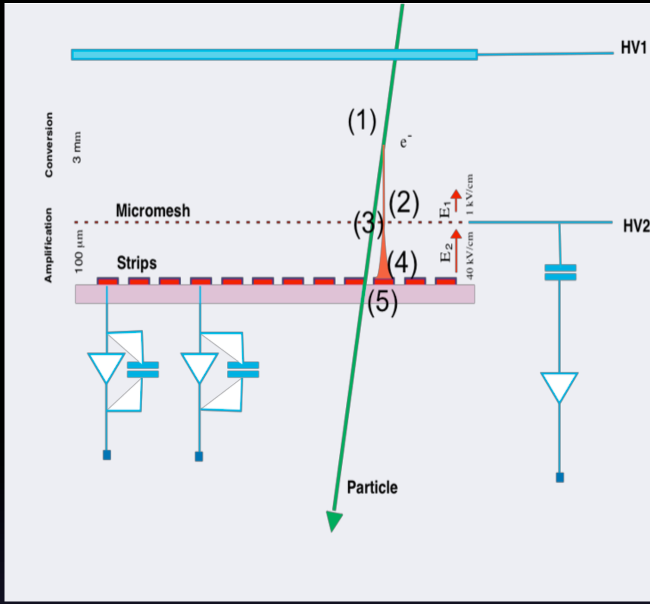
- Replace wires with electrodes on printed circuit board
- Photolithography techniques allow 100 **µ**m pitch
  - Higher granularity over wire chambers
  - High-rate capability **>10⁶** Hz/mm²
  - Excellent spatial resolution (~30**µ**m)
  - Time resolution in the ns range.
- MSGC were first developed in 1990s
  - Initial problems sparks and anode destruction



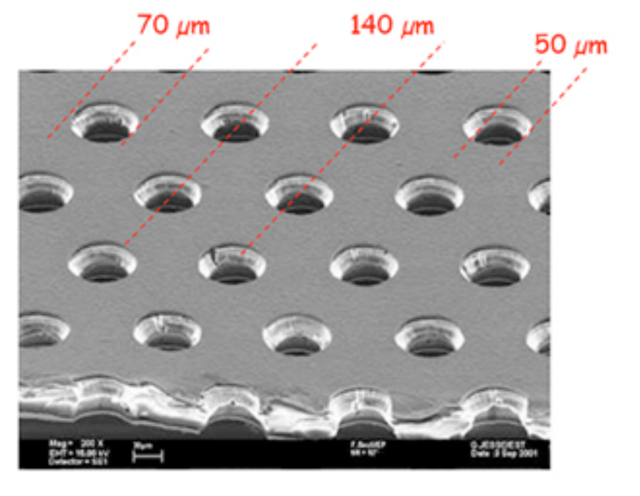


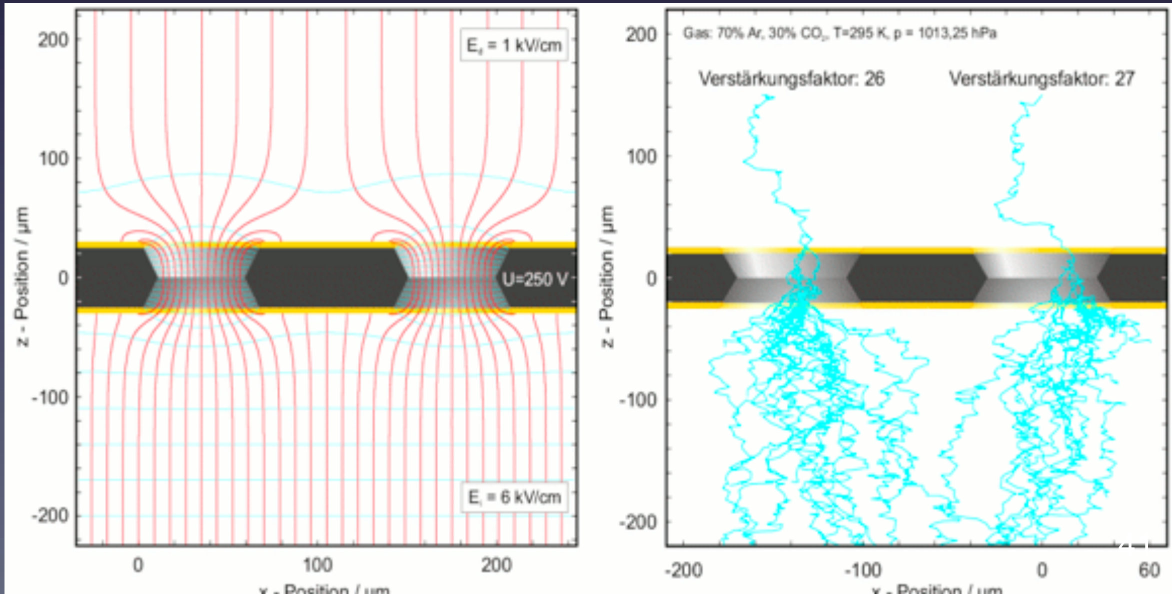


Micromegas and GEM



- Micromegas
  - Gas volume divided in two by metallic micro-mesh
  - Gain = 10^4 and a fast signal of 100ns.
- GEM (Gas Electron Multipliers, Sauli 1996)
  - Thin insulating Kapton foil coated with metal film
  - Chemically produced holes pitch ≈100 **µ**m
  - Electrons are guided by high drift field of GEM which generates avalanche
    - Electric field strength is in the order of some 10 kV/cm
    - Avalanche gain of 100 – 1000



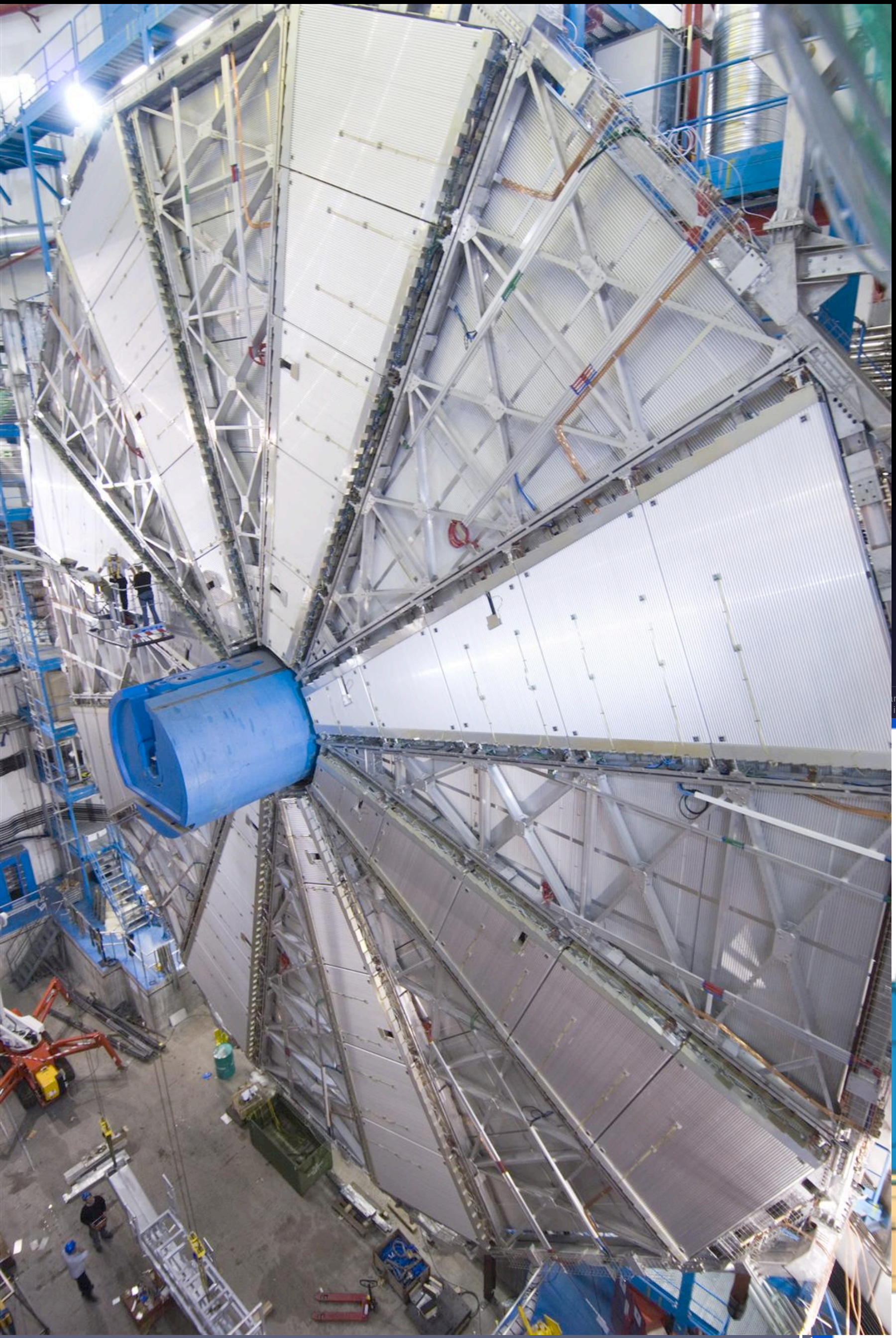


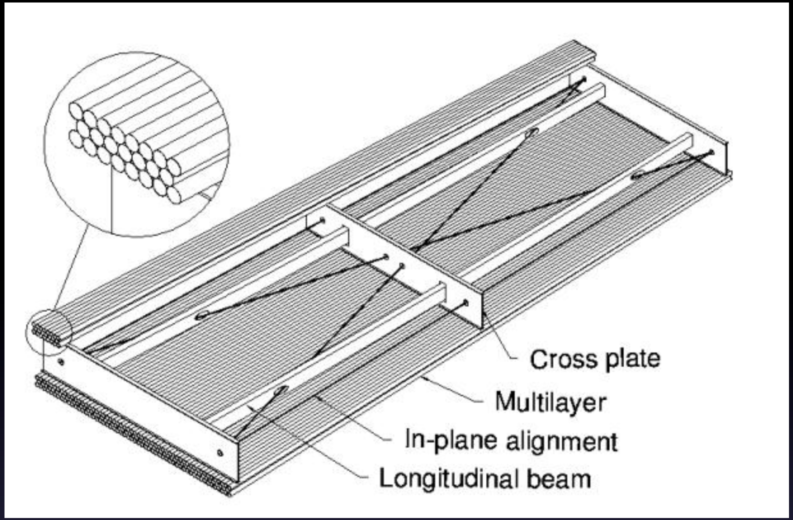
GAS detectors at the LHC

- 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)
- TOTEM: Tracker & trigger (CSC , GEM)

- The LHC experiments use gas detectors mainly for large scale muons detectors
- While the principle detecting elements are quit traditional many 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.

ATLAS drift tubes





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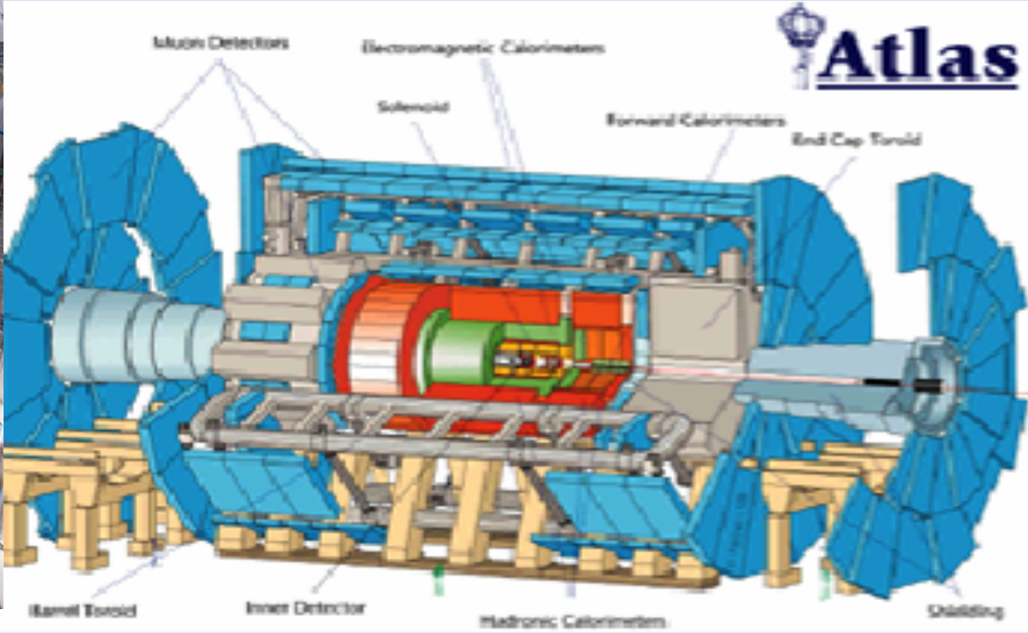
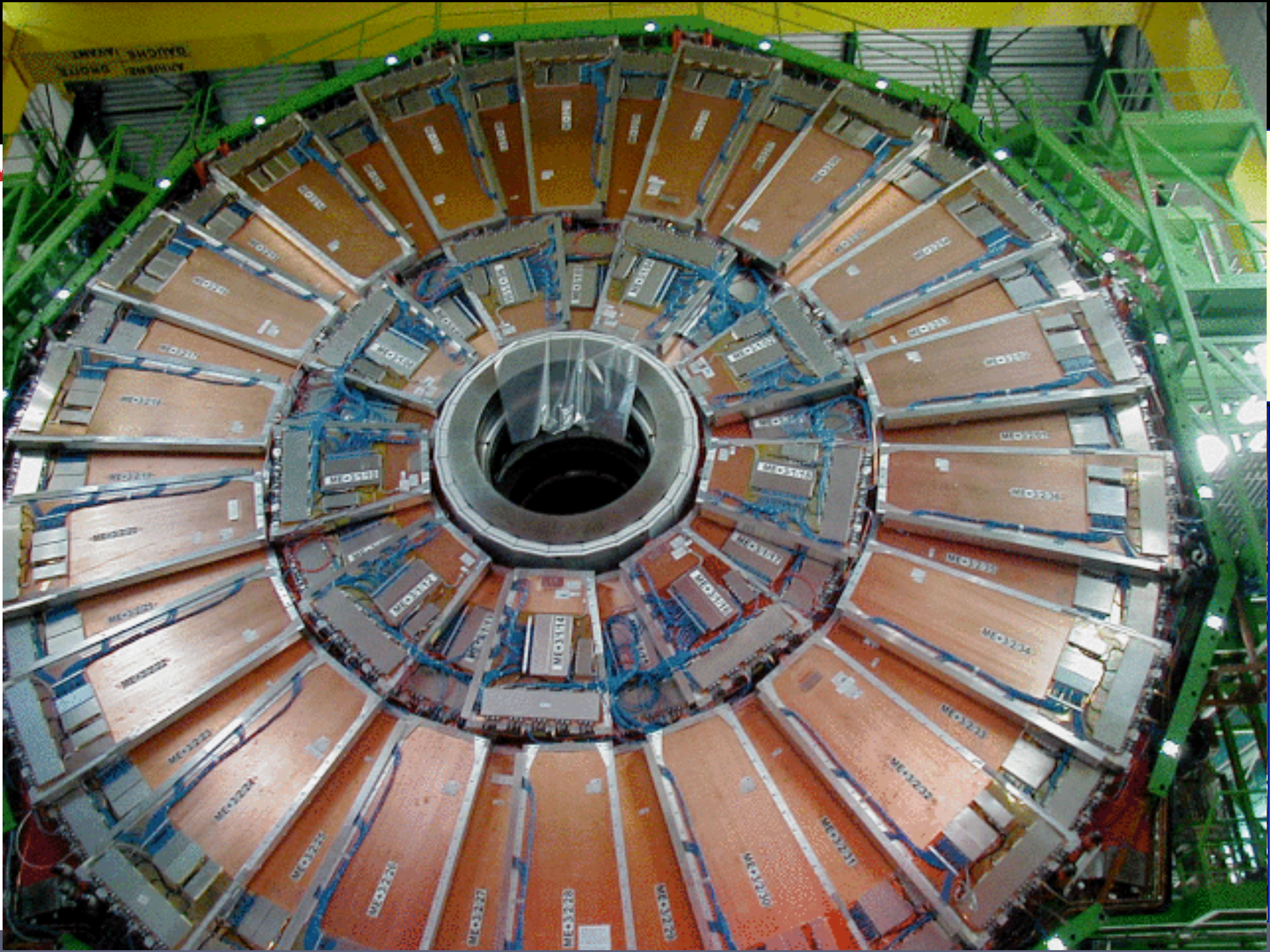
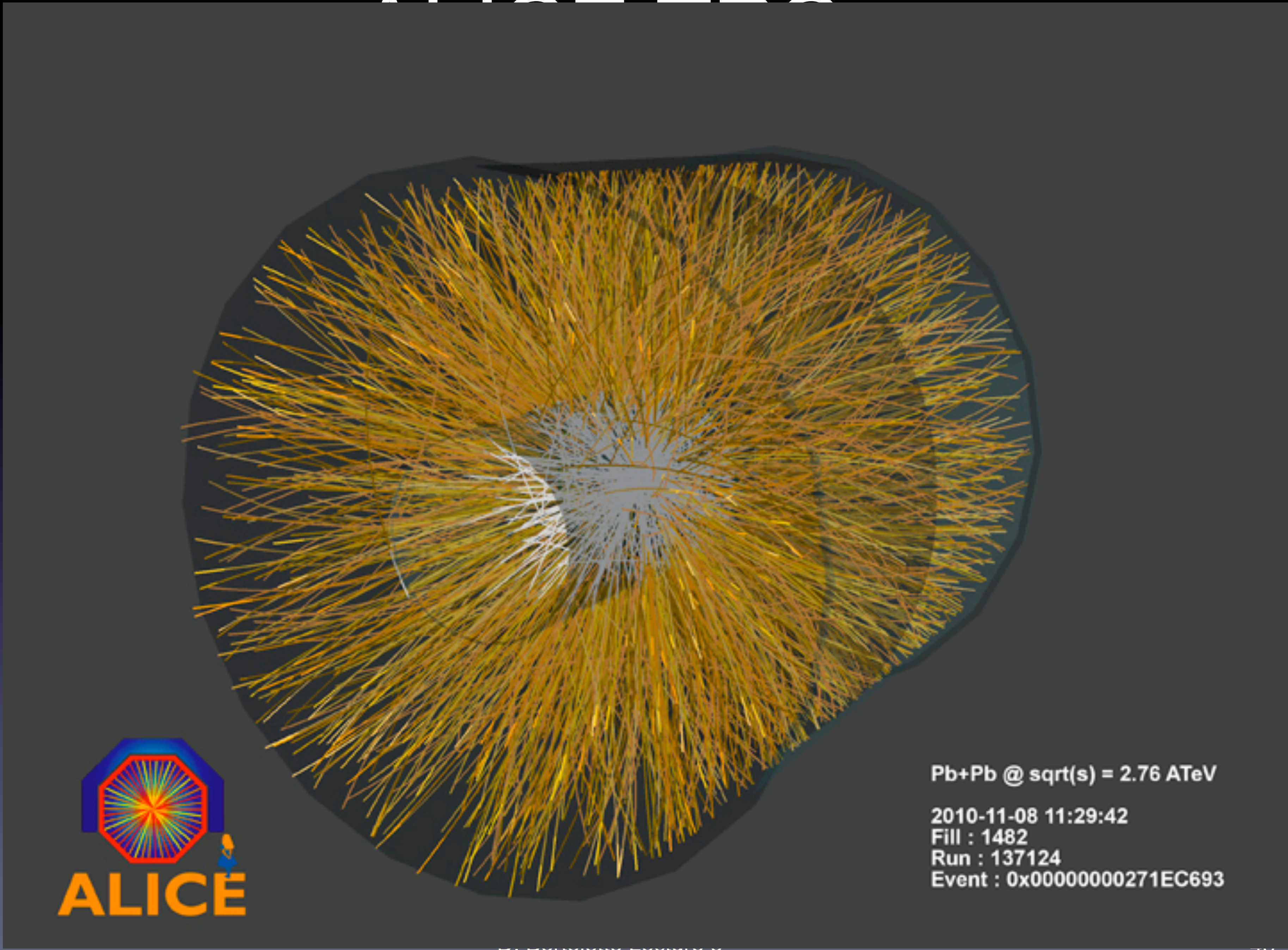


EM



ALICE TPC


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:29:42
Fill : 1482
Run : 137124
Event : 0x00000000271EC693

The upgrades

- **ATLAS:**
  - **TRT (Transition Radiation Tracker) 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

Literature

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- Th. Ferbel, Editor: *Techniques and Concepts of High-energy Physics* (Plenum, 1983)
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- W.R. Leo: *Techniques for Nuclear and Particle Physics Experiments* (Springer, 1987)
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- F. Sauli, ed.: *Instrumentation in High Energy Physics* (World Scientific, 1992)
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- K. Kleinknecht: *Detectors for Particle Radiation* (Cambridge Univ. Press 1998)
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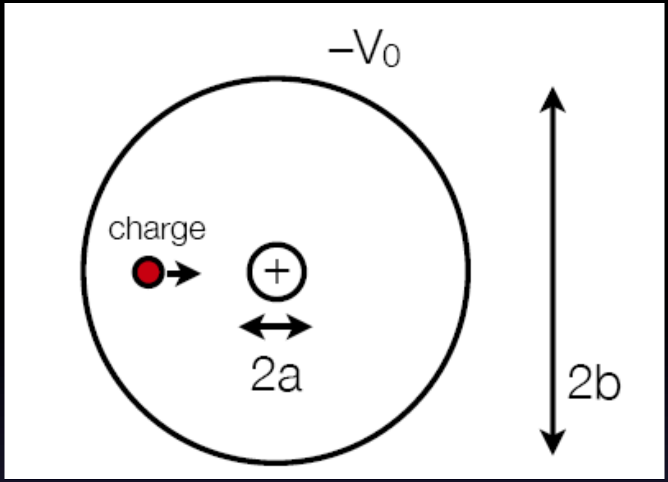
- W. Blum, W. Riegler and L. Rolandi: *Particle Detection with Drift Chambers, 2d Ed.* (Springer 2008)

- BACKUP

Signal pulse formation and

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



- 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

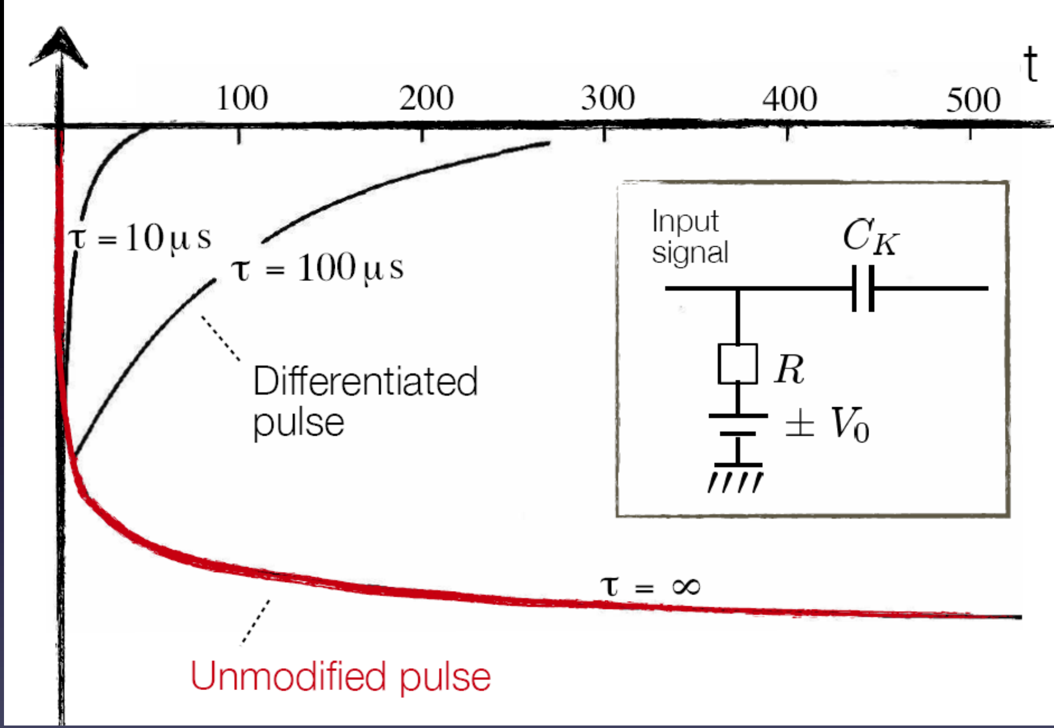
- Ignoring electron signal and setting r(0)=a

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

$$v_D=\frac{dr}{dt}=\mu E(r)=\frac{\mu CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

$$rdr=\frac{\mu CV_0}{2\pi\varepsilon_0}dr$$

$$r(t)=\left(a^2+\frac{\mu CV_0}{\pi\varepsilon_0}t\right)^{1/2}$$



$$V(t)=-\frac{q}{4\pi\varepsilon_0 l}\ln\left(1+\frac{\mu CV_0}{\pi\varepsilon_0 a^2}t\right)=-\frac{q}{4\pi\varepsilon_0 l}\ln\left(1+\frac{t}{t_0}\right)$$

$$t_0=\pi\varepsilon_0 a^2\big/\mu CV_0$$

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)

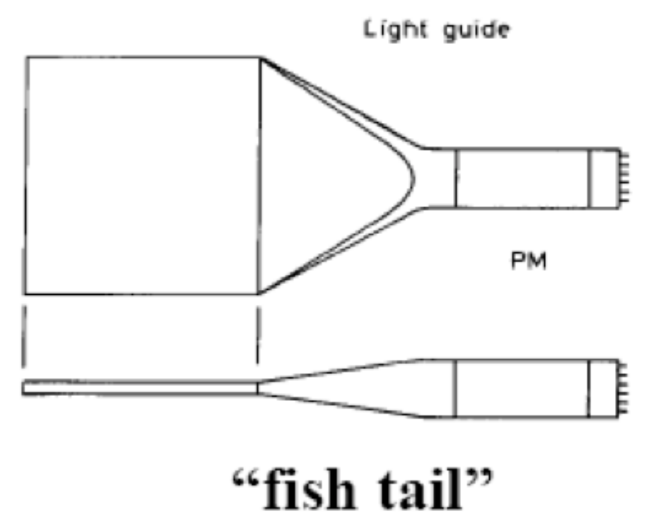
$$V\left(\frac{a}{b} \cdot T \right) = -\frac{q}{4\pi\varepsilon_0} \ln \left(1 + \frac{\frac{a}{b} \cdot T}{t_0} \right) = -\frac{q}{4\pi\varepsilon_0} \ln \left(1 + \frac{a}{b} \left(\frac{b^2}{a^2} - 1 \right) \right)$$

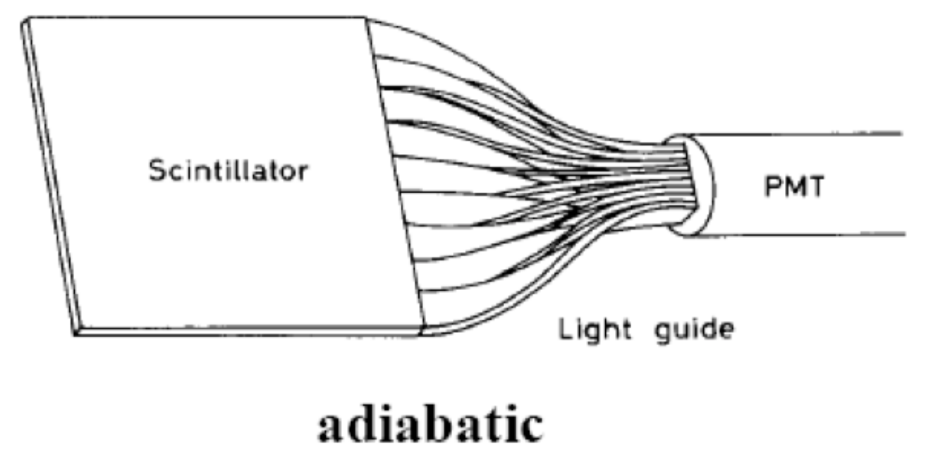
$$= -\frac{q}{4\pi\varepsilon_0} \ln \left(\frac{b}{a} \right) = -\frac{1}{2} \frac{q}{lC} \qquad with \;\; C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$

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

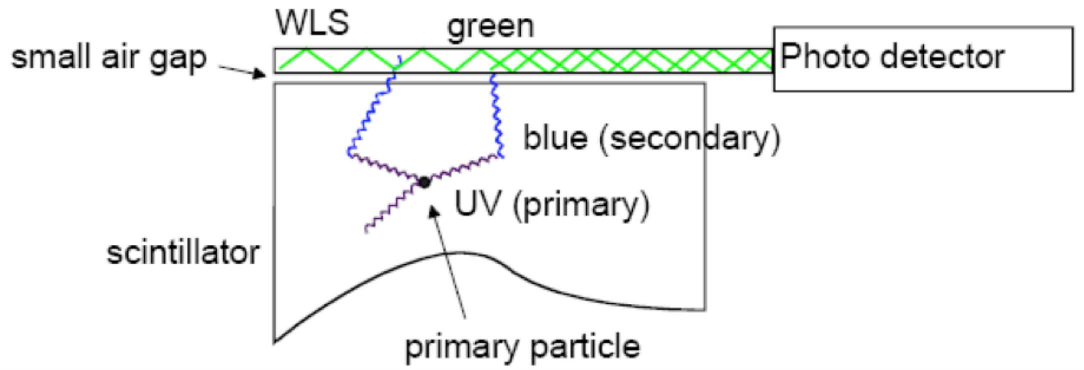




- UV light enters the WLS material
- Light is transformed into longer wavelength

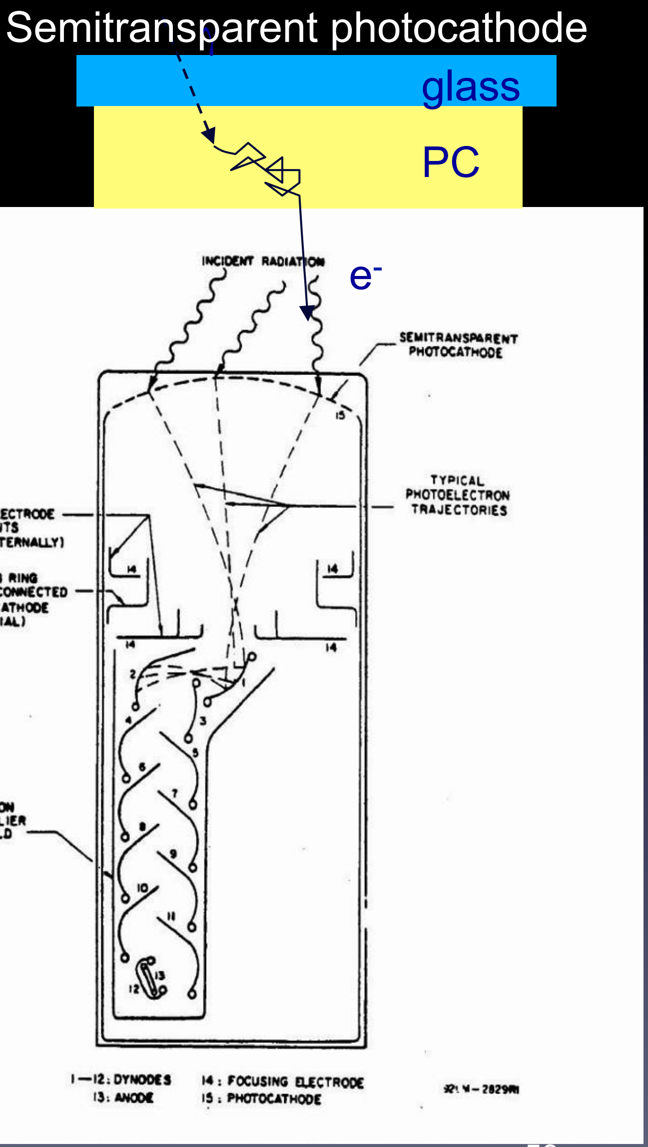
→ Total internal reflection inside the WLS material

→ 'Transport' of the light to the photo detector

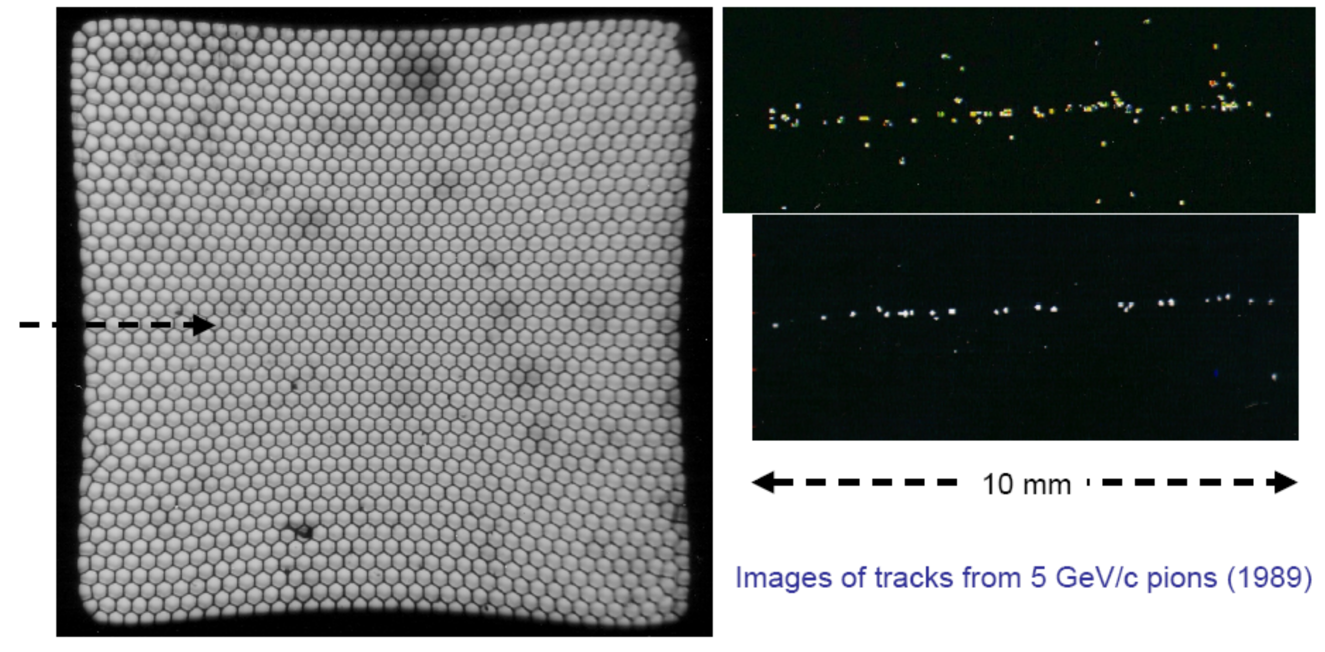


Photomultipliers

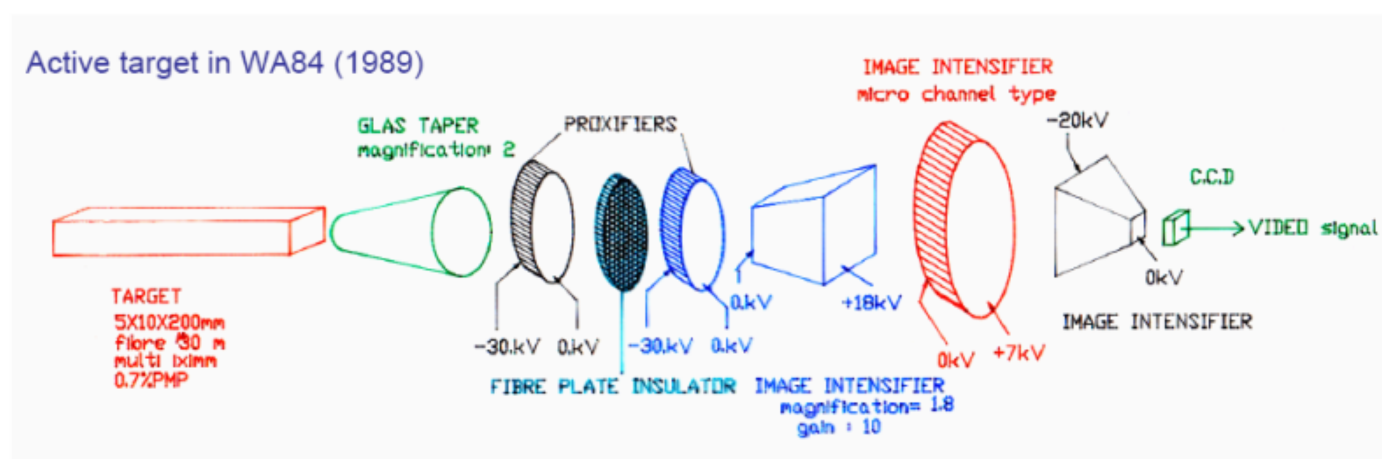
- Scintillators are well established and cheap techniques to detect photons → Photomultipliers and the fast response time → 1 to 100ns
- Schematic of a Photomultiplier:
  - Typical Gains (as a function of the applied voltage): 10^8 to 10^{10}
  - Typical efficiency for photon detection: < 20%
  - For 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.

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

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

μ_+ : ion mobility
for ions $\mathbf{v}_D$ ~ E/P, i.e. for constant pressure constant mobility

μ_- : electron mobility in cold gas approximation (T_{kin}~ kT)
➔$\mathbf{v}_D$ ~ E, $\boldsymbol{\mu}$ = const.
in a hot gas (T_{kin}>> kT) ➔$\mathbf{v}_D$ = const., $\boldsymbol{\mu}$ = not const.

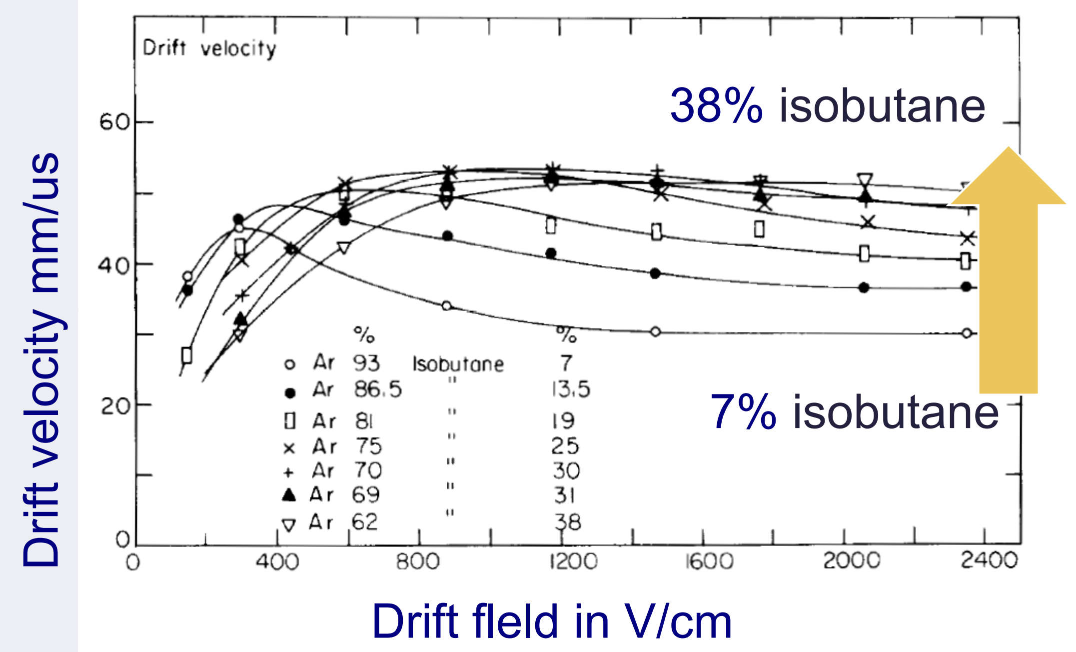
typical:
E ~ 1 kV / cm-atm
v_d ≈cm/ms for ions
v_d ≈cm/μs for e-

$$\frac{D}{\mu} = \frac{kT}{e}$$

Einstein relation for ideal gases in thermal equilibrium
The gain in velocity may affect the diffusion rate and thereby the time behavior of the detector (e.g. drift chamber)

Drift Velocity

- v_d and D of e^- depend the inelastic cross section involving the rotational and vibrational levels of molecules.
- The inelastic cross section in noble gasses =0 below excitation and ionization thresholds.

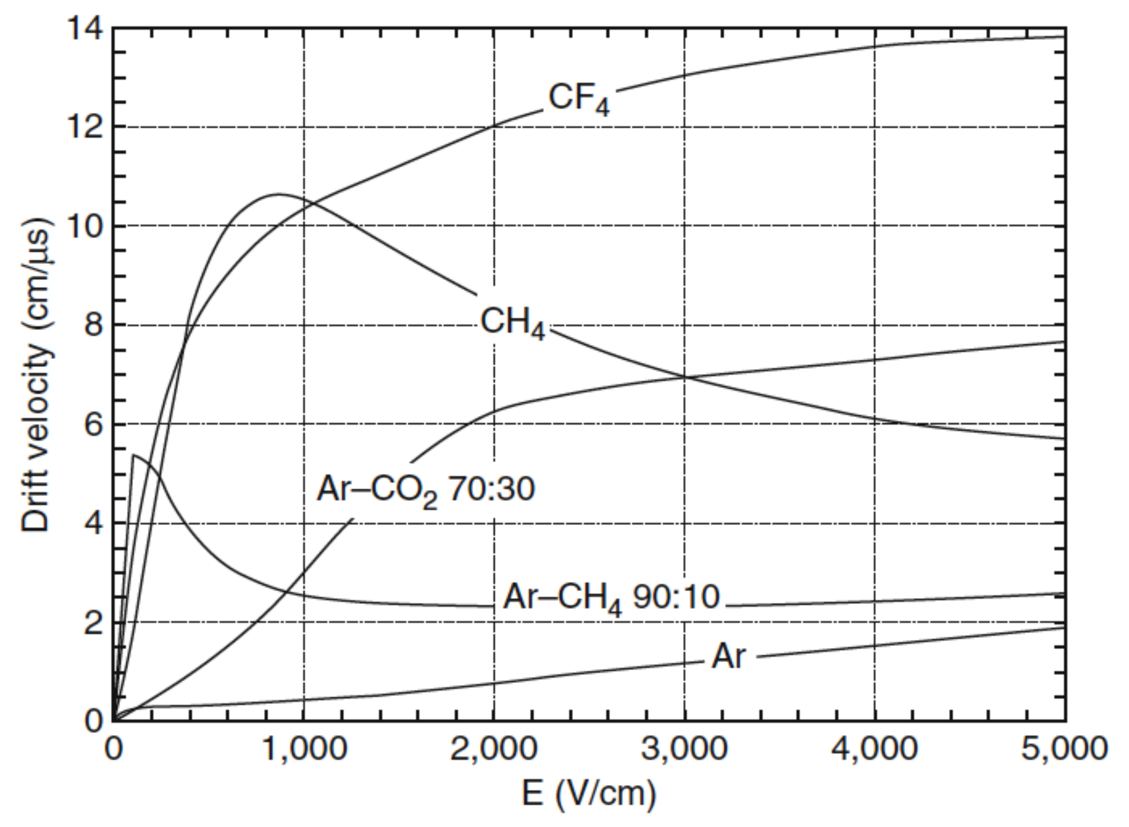


Drift velocity in several argon-isobutane (C_4H_{10}) mixtures

- Large v_d are achieved by adding polyatomic gases (usually CH_4, CO_2, or CF_4), which "cool" the electrons (because of their large inelastic cross section at moderate energies) and absorb the ultraviolet (UV) photons emitted by the excited inert gas atoms

Drift velocity

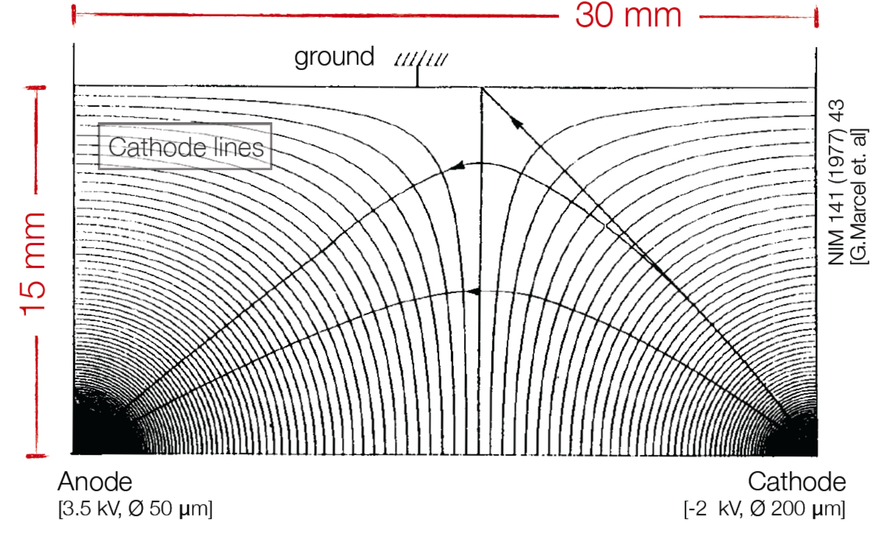
- Values of drift velocity for some commonly used gases at NTP, computed with the MAGBOLTZ program (see http://consult.cern.ch/writeup/magboltz)



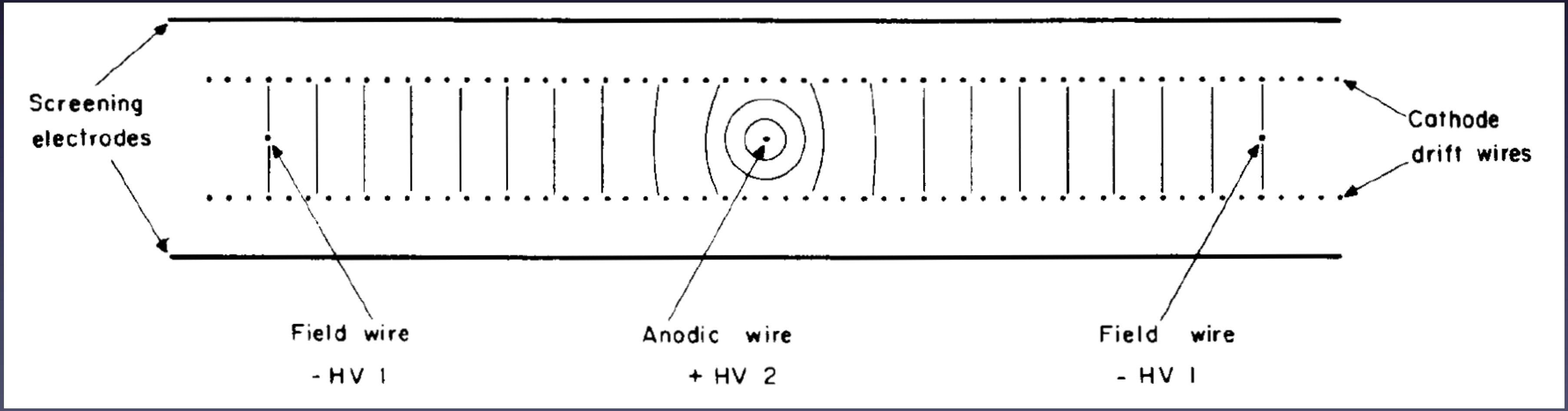
- Using fast CF_4-based mixtures at fields around kV/cm^{-1}, the electron drift velocity is around 10cm · μs^{-1} .
- Since the collection time is inversely proportional to the drift velocity, diffusion effects are reduced in gases such as CF_4 that have high drift

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)



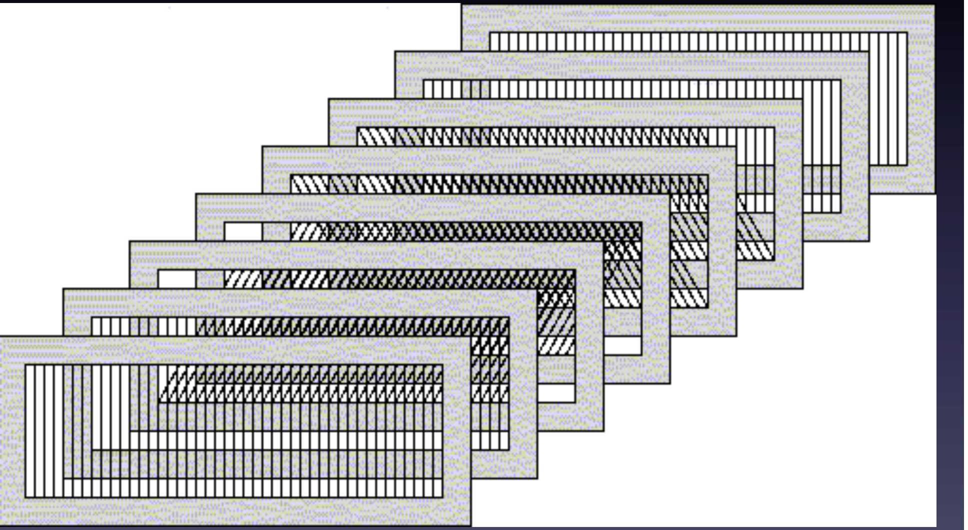
NIM 141 (1977) 43 [G.Marcel et. al]



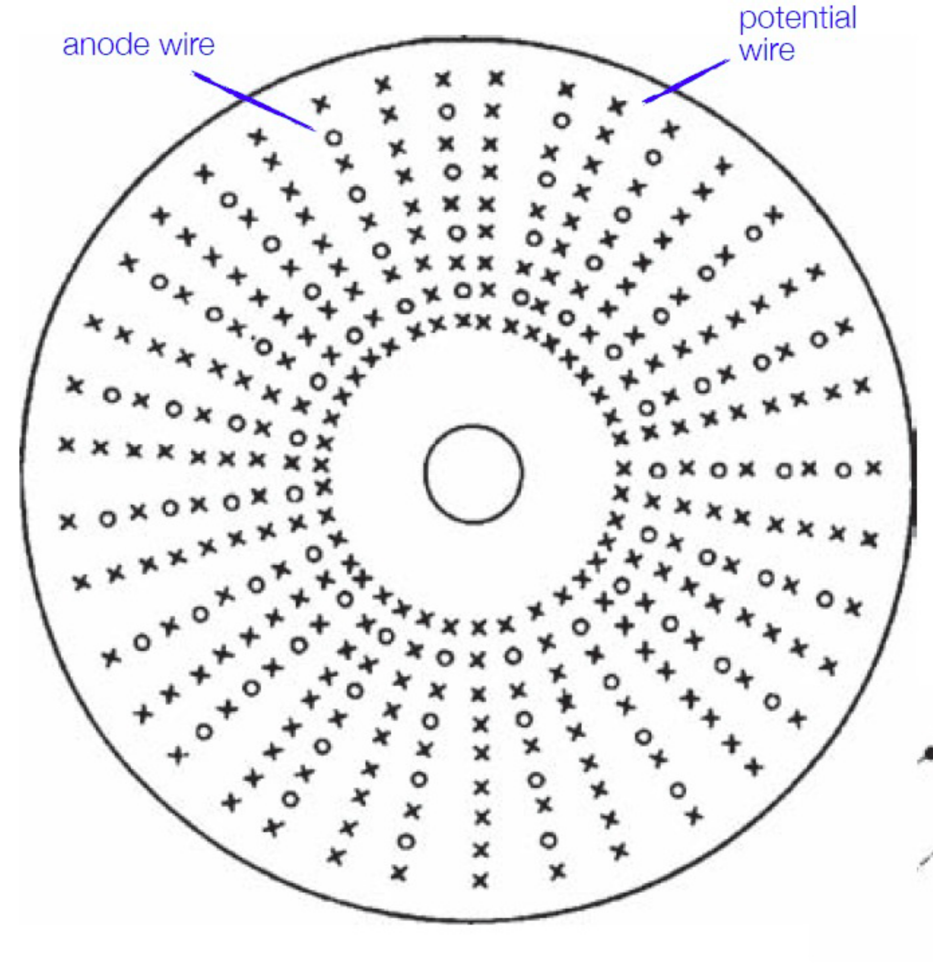
- Adjustable field multi-wire drift chamber with voltage divider via cathode wire planes
- Space point resolution limited by mechanical accuracy ≈200 μm
- Hit density needs to be low.

Tracking detectors

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



- Tracking at collider experiments:
  - cylindrical drift chamber



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