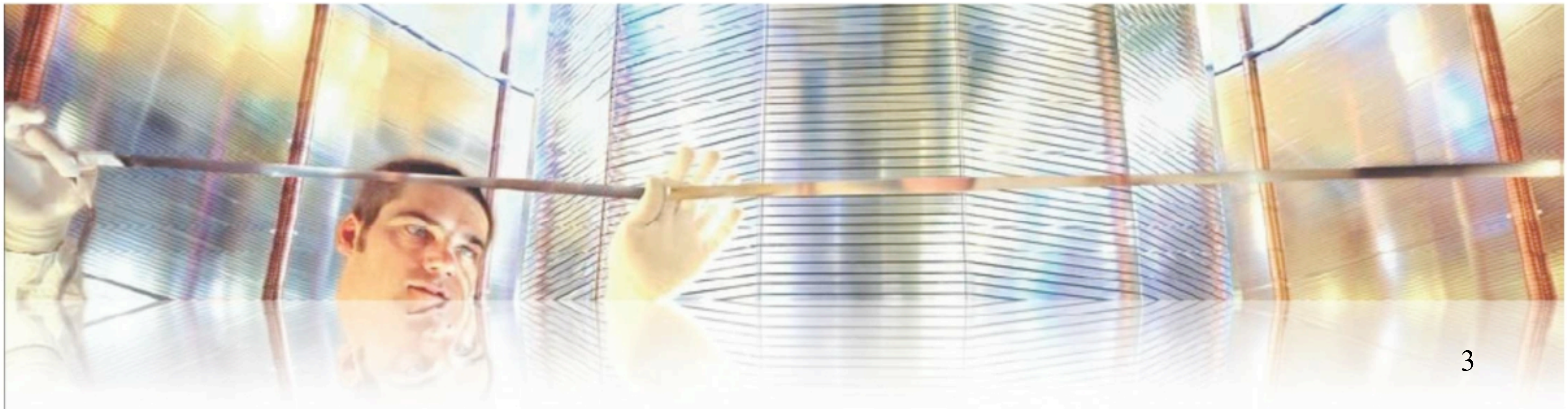
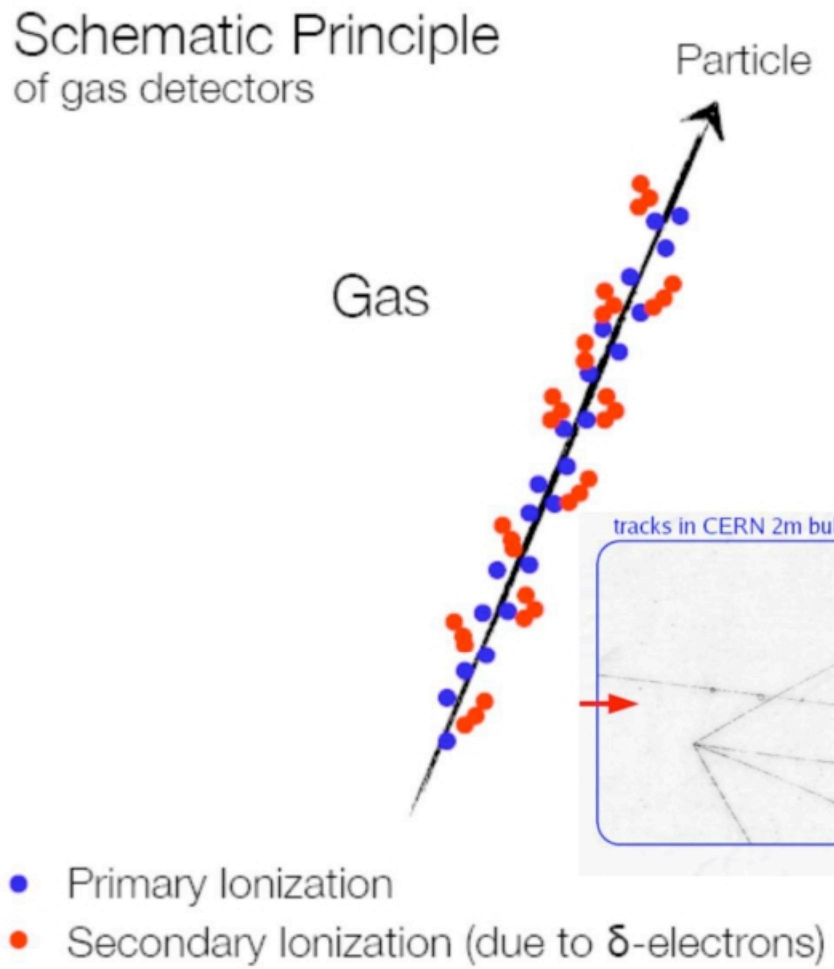
Gaseous detectors

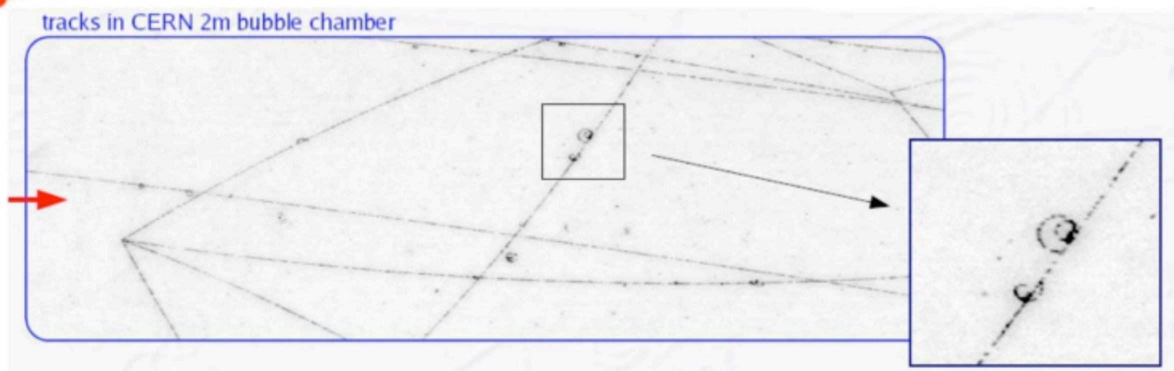
measurement of ionization
position determination



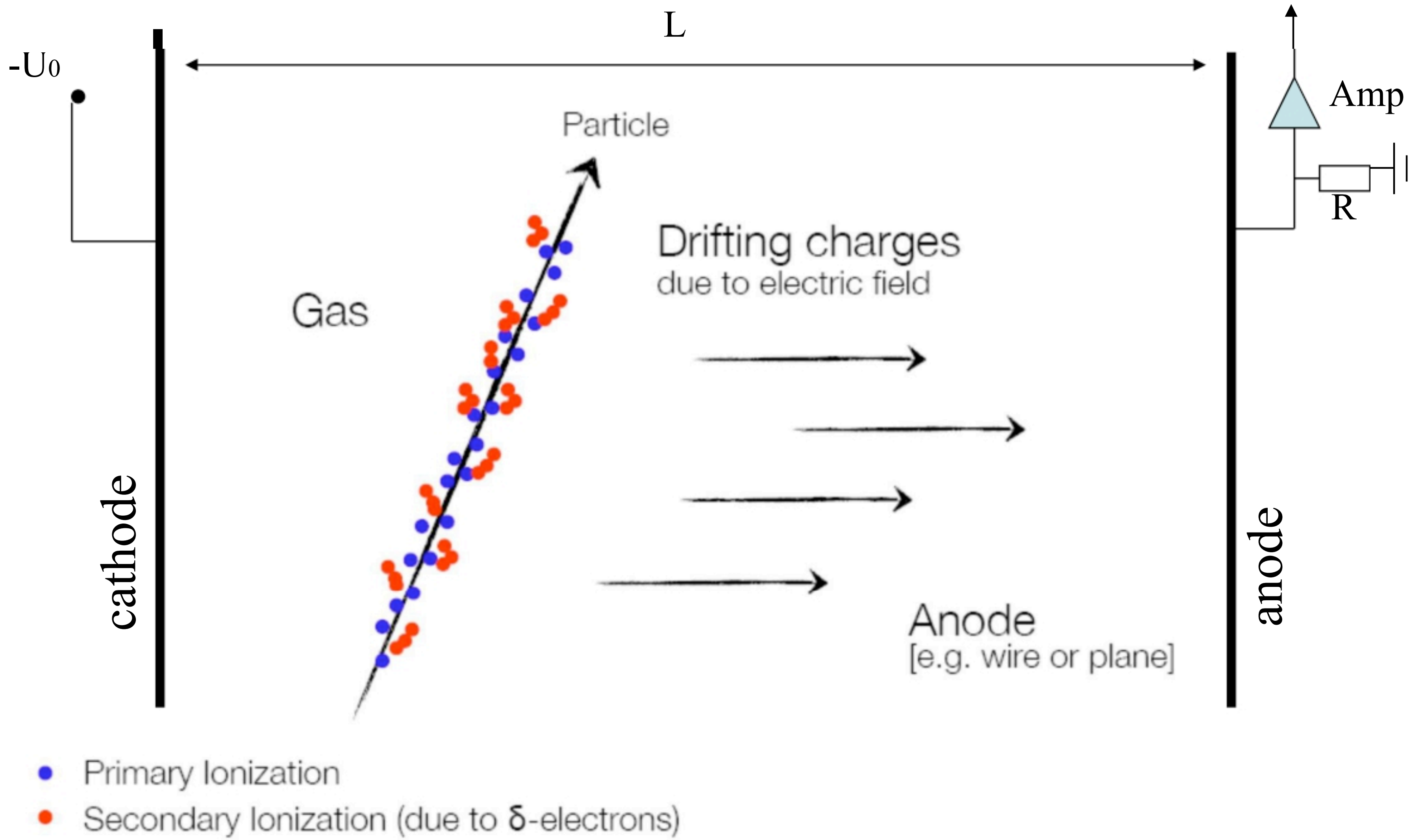
Introduction



δ-electron



Introduction



Ionization

Primary ionization

$$p + X \rightarrow p + X^{+} + e^{-}$$

p = charged particle traversing the gas
X = gas atom
e^{-} = delta-electron (δ)

Secondary ionization

if E_δ is high enough ($E_\delta > E_i$)

$$X + e^{-} \rightarrow X^{+} + e^{-} + e^{-}$$

Relevant Parameters

for gas detectors

Ionization energy	:	E_i
Average energy/ion pair	:	W_i
Average number of primary ion pairs [per cm]	:	n_p
Average number of ion pairs [per cm]	:	n_T

Differences due to δ-electrons

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

[about 2-6 times n_p]
[L: layer thickness]

Typical values:

$E_i \sim 30$ eV
$n_T \sim 100$ pairs / 3 keV incident particle

Table for most common gases

($E_i = I_o$)

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

Production of ion/electron pairs follows a Poisson distribution

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

with $\langle n_p \rangle = L/\lambda$ and $\lambda = 1/(n_e \sigma_I)$

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

Recombination and electron attachment:
Admixture of electronegative gases (O_2 , F, Cl) influences detection efficiency

Diffusion:

Influences the spatial resolution ...

Mobility of charges:

Influences the timing behavior of gas detectors ...

Avalanche process via impact ionization:

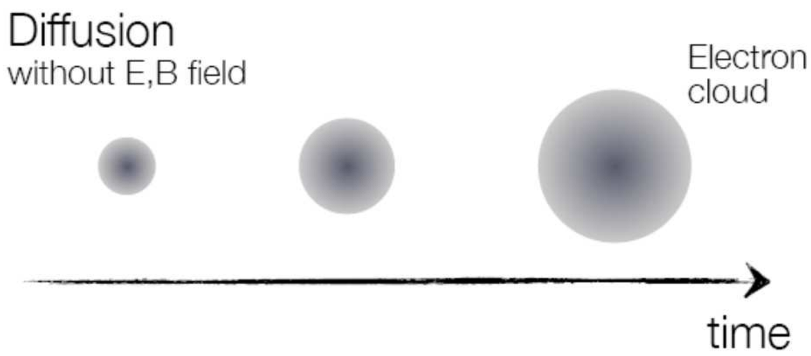
Important for the gain factor of the gas detector ...

Transport of electrons/ions in gas

Diffusion:

classical kinetic theory of gases

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



after a diffusion time t the electrons/ions are Gaussian distributed with a spread

$$\sigma(x) = \sqrt{2Dt}$$

where D is the diffusion coefficient

$$\boxed{D = \frac{1}{3} v \lambda}$$

the mean free path of electrons/ions in the gas:

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

the mean velocity according to Maxwell distribution:

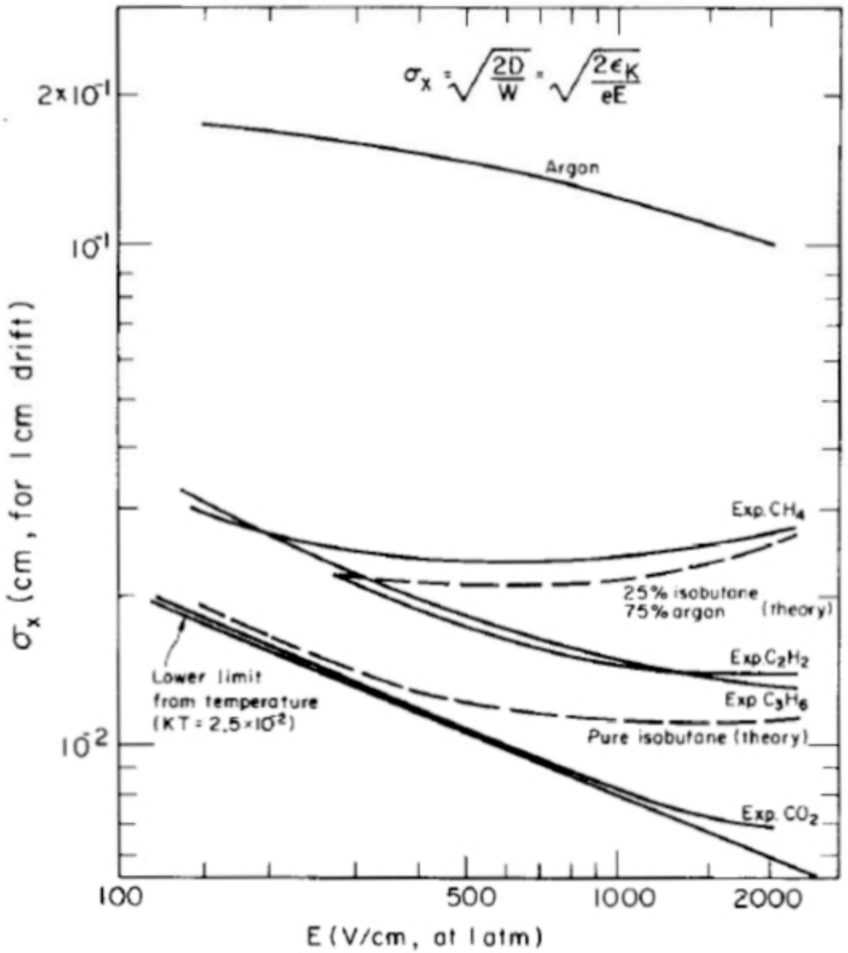
$$v = \sqrt{\frac{8kT}{\pi m}}$$

m=mass of particle

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

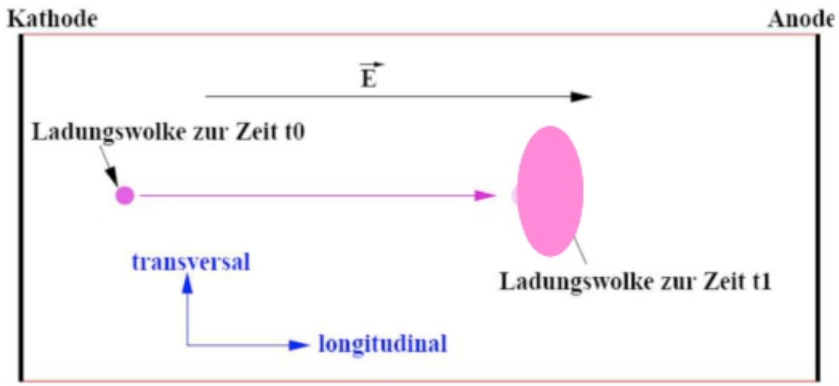
D depends on gas pressure P and temperature T

Diffusion in electric field



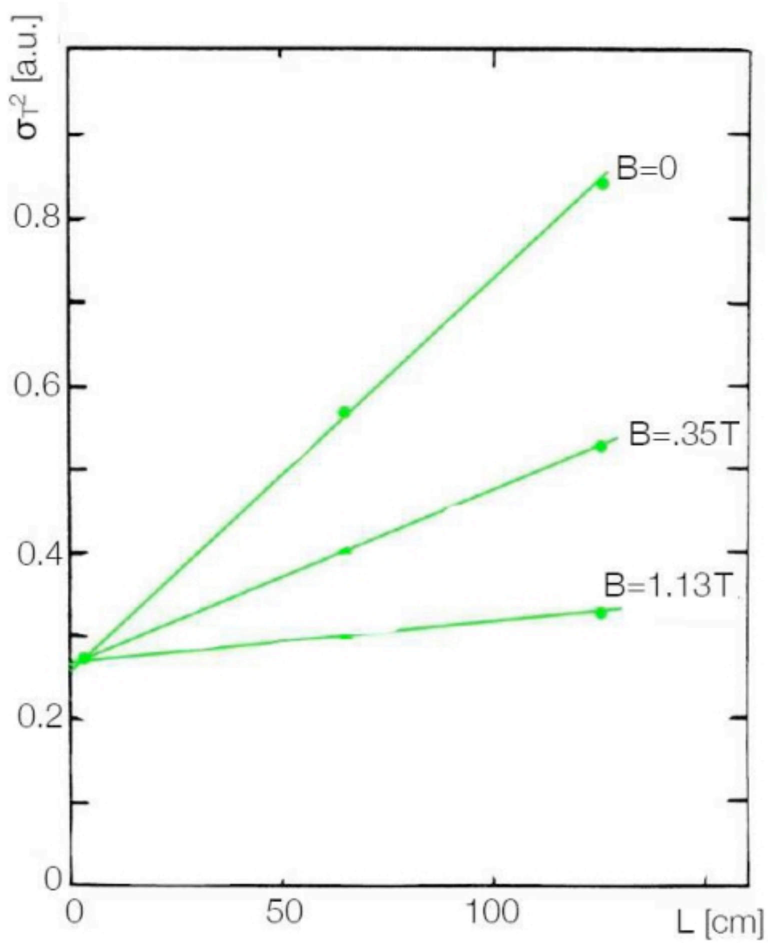
Drift in direction of E-field superimposed to statistical diffusion

Extra velocity influences longitudinal diffusion
Transverse diffusion not affected



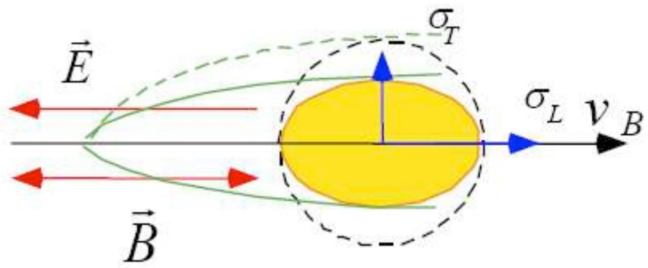
E-field reduced diffusion in longitudinal direction

Diffusion in magnetic field



In the presence of a B-field different effects on longitudinal and transverse diffusion

No Lorentz force along B-field direction



Transverse diffusion as function of drift length for different B fields

B-Field can substantially reduce diffusion in transverse direction

Transport of electrons/ions in gas

Drift and Mobility:

with external E-field: electrons/ions obtain velocity v_D in addition to thermal motion; on average electrons/ions move along field lines of electric field E

$\vec{v}_D = \mu_\pm \mid \vec{E} \mid$

typical:
E ~ 1 kV / cm-atm`

μ_+ : ion mobility
for ions v_D ~ E/P, i.e. for constant pressure constant mobility

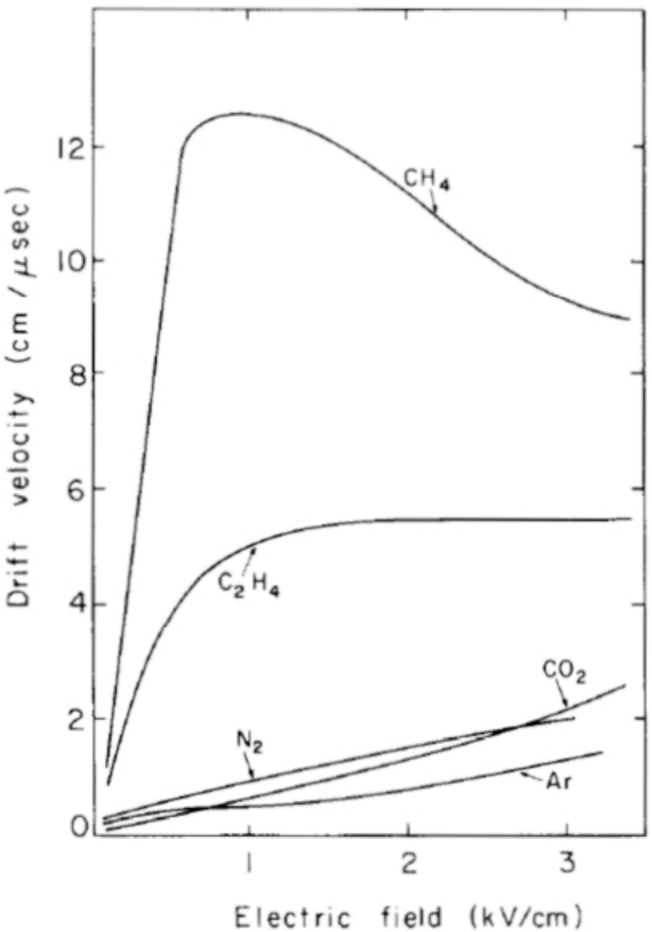
μ_- : electron mobility
in cold gas approximation (T_{kin}~ kT) ➔ v_D ~ E, μ = const.
in hot gas (T_{kin}>> kT) ➔ v_D = const., μ = not const.

Compare:
Electrons: v_D of order cm/µs
Ions: v_D of order cm/ms

$\boxed{D/\mu = kT/e}$

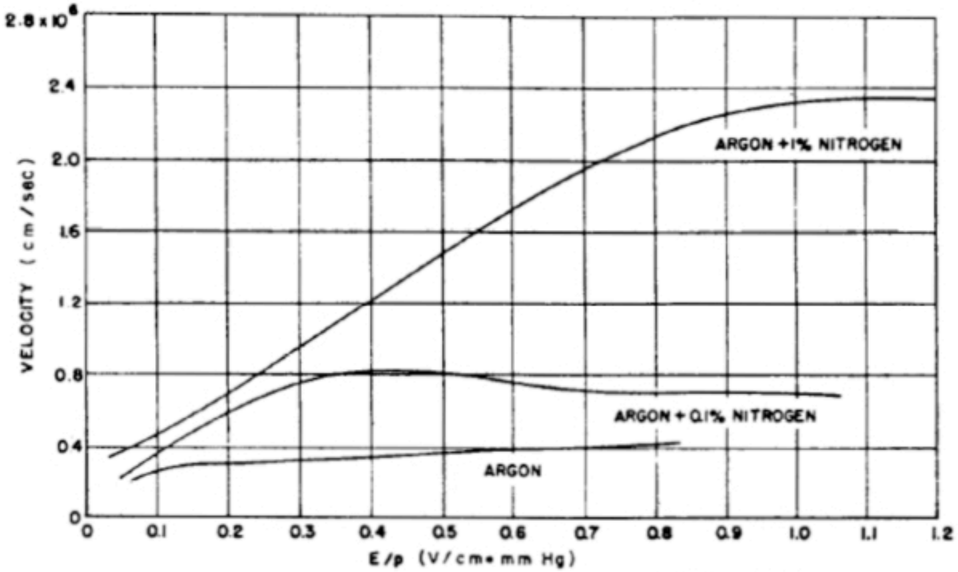
Einstein relation for ideal gases in thermal equilibrium
the gain in velocity may affect the diffusion rate and thereby the time behavior of the detector (e.g. drift chamber)

Drift velocity



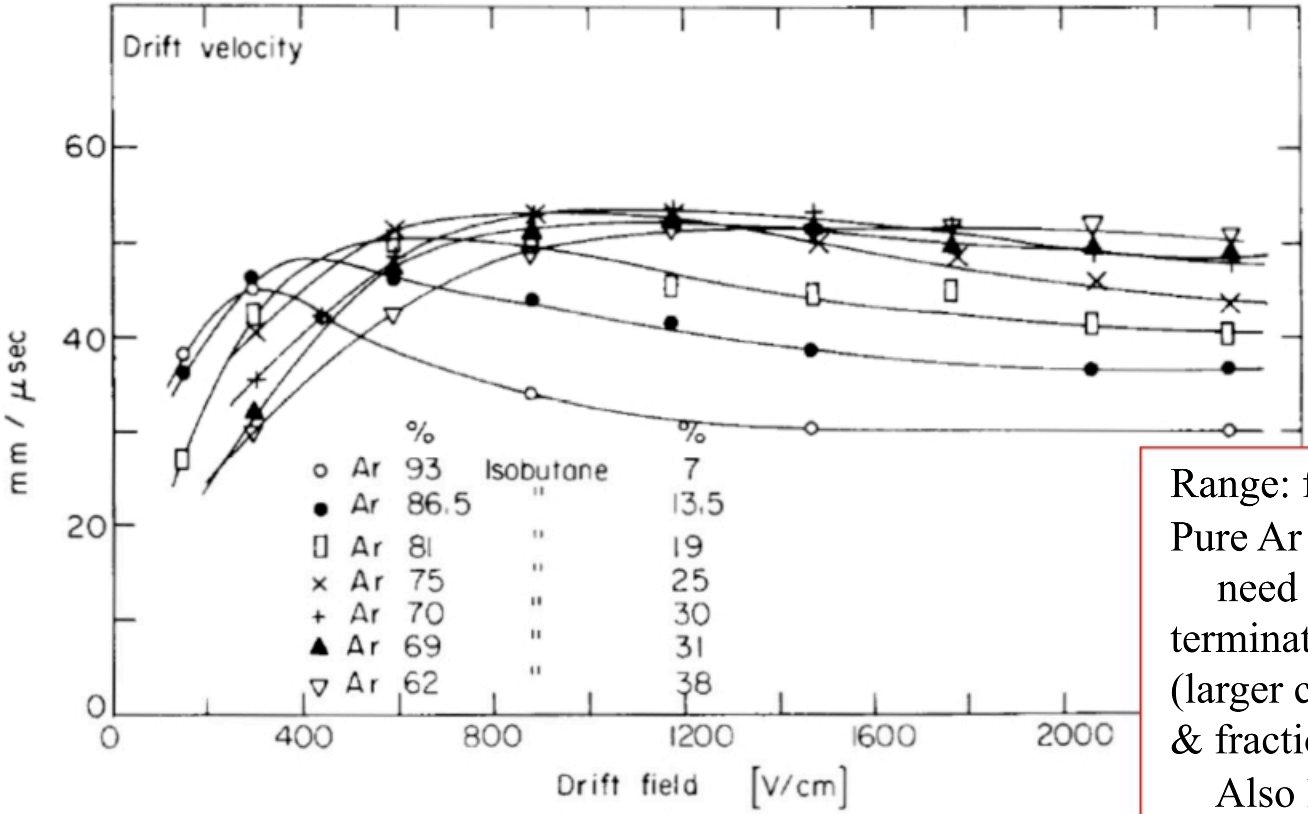
Drift velocity of electrons
in several gases at normal conditions

Use gas mixture to obtain constant v_D
Important for applications using drift time to get spatial information



E-Field/pressure

Drift velocity



Range: few 10 mm/ μs
Pure Ar : ~10 mm/ μs
need quenching gas to terminate a pulse discharge
(larger cross-sections & fractional energy loss)
Also less diffusion

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

Avalanche multiplication

Large electric field yields
large kinetic energy of electrons ...

➛ Avalanche formation

Larger mobility of electrons results in liquid
drop like avalanche with electrons near head ...

Mean free path: λ_{ion}
[for a secondary ionization]

Probability of an ionization per
unit path length: $\alpha = 1/\lambda_{ion}$ [1st Townsend coefficient]

$$dn = n \cdot \alpha\, dx$$

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

n(x) = electrons
at location x

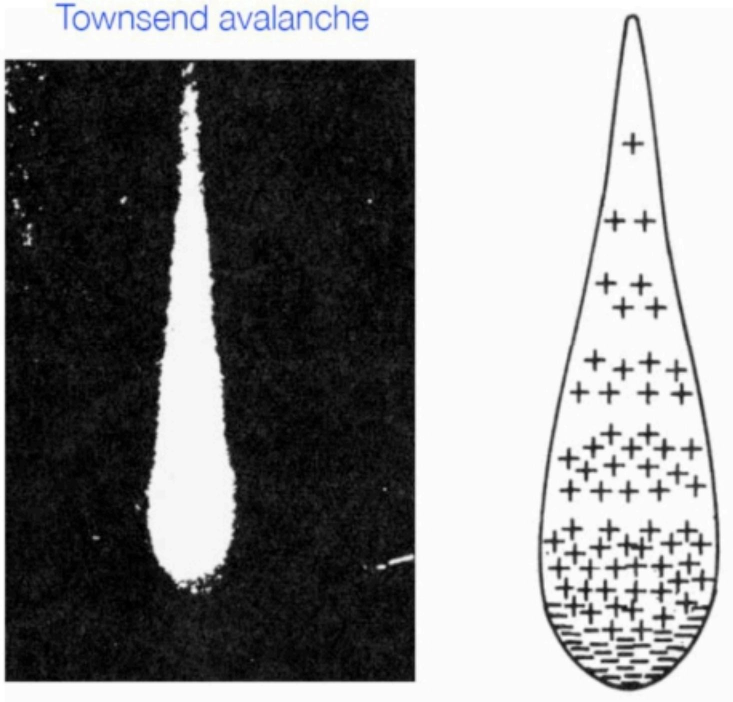
Gain:

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

and more general for $\alpha = \alpha(x)$: $G = \frac{n}{n_0} = \exp\left[\int_{x_1}^{x_2} \alpha(x)dx\right]$

[Raether limit: $G \approx 10^8$; $\alpha x = 20$; then sparking sets in ...]

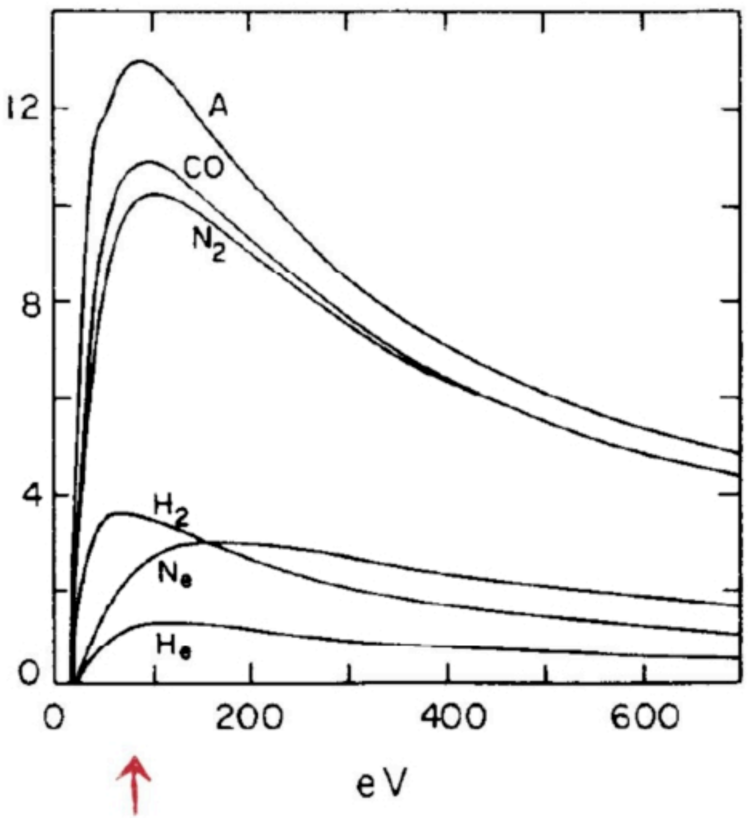
Townsend avalanche



Drop-like shape of an avalanche
Left: cloud champer picture
Right: schematic view

Avalanche multiplication

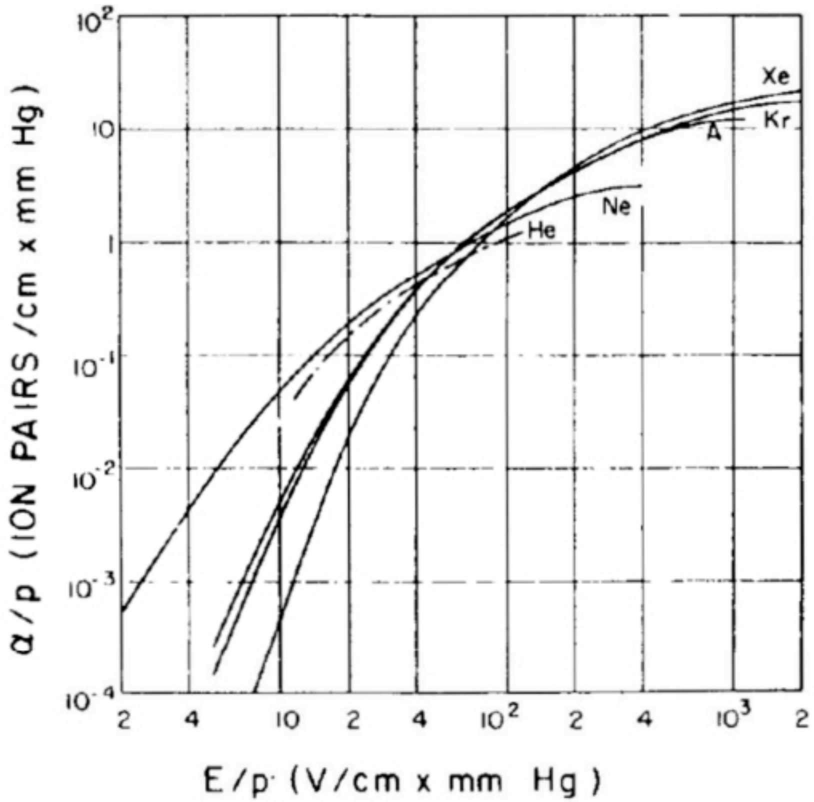
Ionization Probability



Need about 75-100 eV
for high ionization probability

[need to gain this energy within few microns]

Townsend Coefficient



E ≈ 75 V/cm
needed to reach $\alpha = 1$

Gas amplification factor

Ionization mode:

full charge collection
no multiplication; gain ≈ 1

Proportional mode:

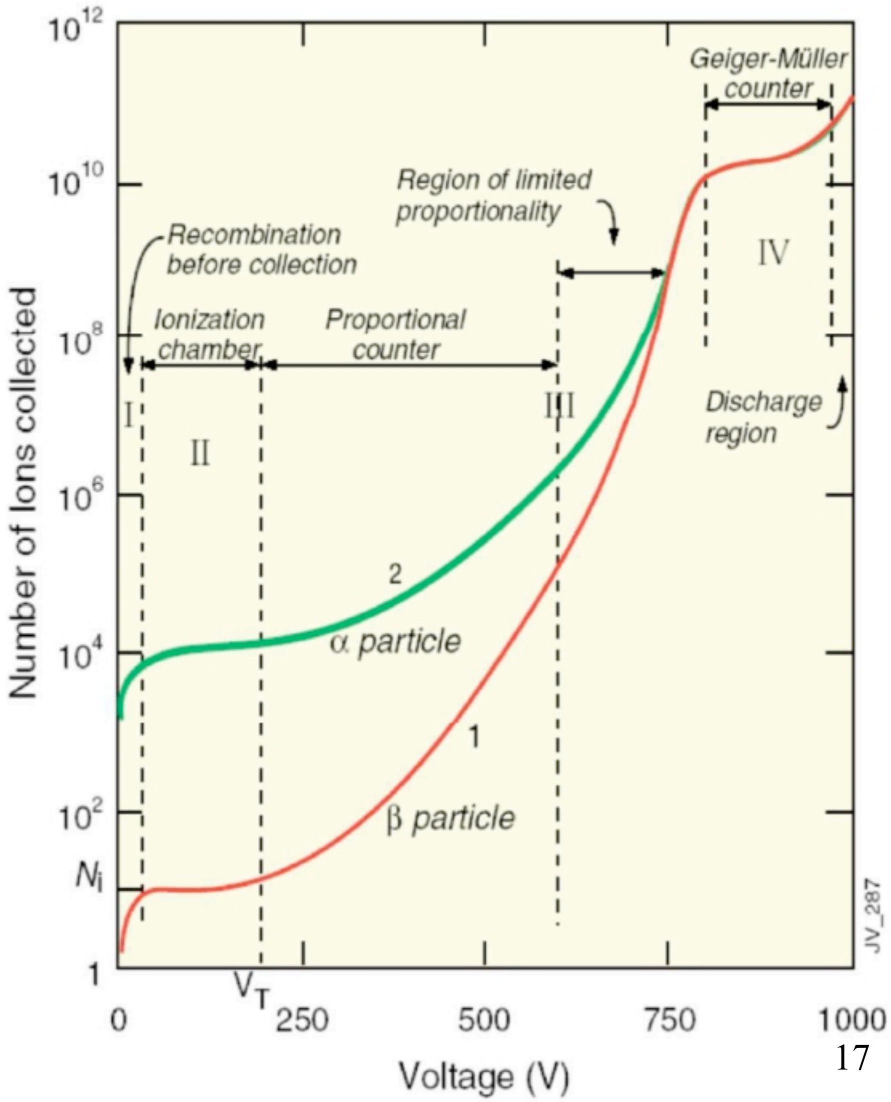
multiplication of ionization
signal proportional to ionization
measurement of dE/dx
secondary avalanches need quenching;
gain ≈ $10^4 – 10^5$

Limited proportional mode:
[saturated, streamer]

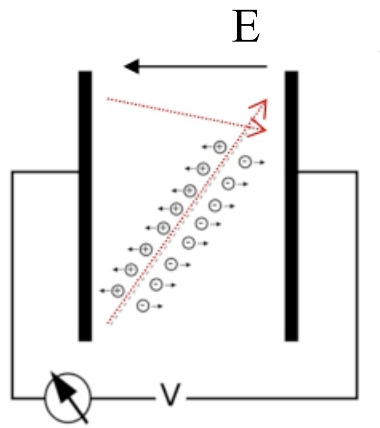
strong photoemission
requires strong quenchers or pulsed HV;
gain ≈ 10^{10}

Geiger mode:

massive photoemission;
full length of the anode wire affected;
discharge stopped by HV cut



Proportional counter



Planar design disadvantage:

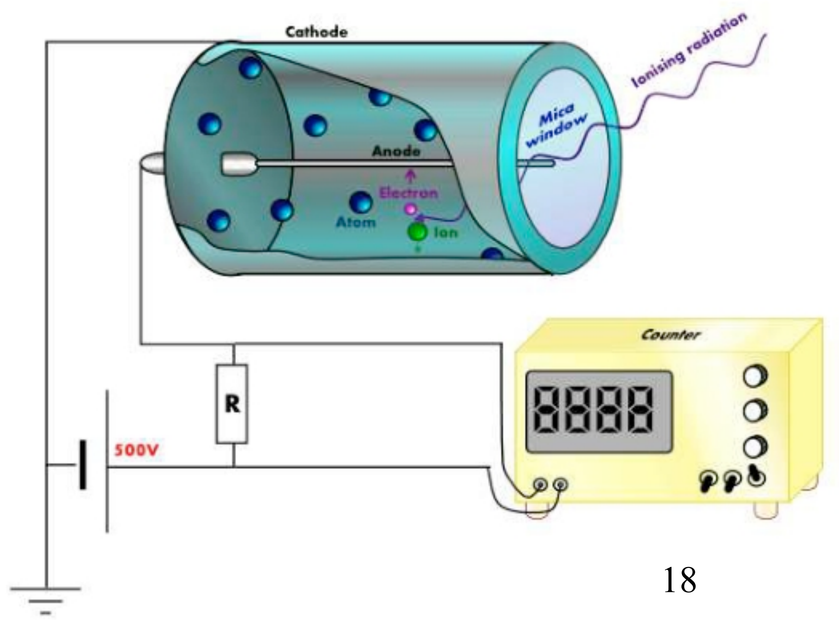
E uniform and $\perp$ to the electrodes

amount of ionization produced proportional to path length and to position where the ionization occurs

not proportional to energy

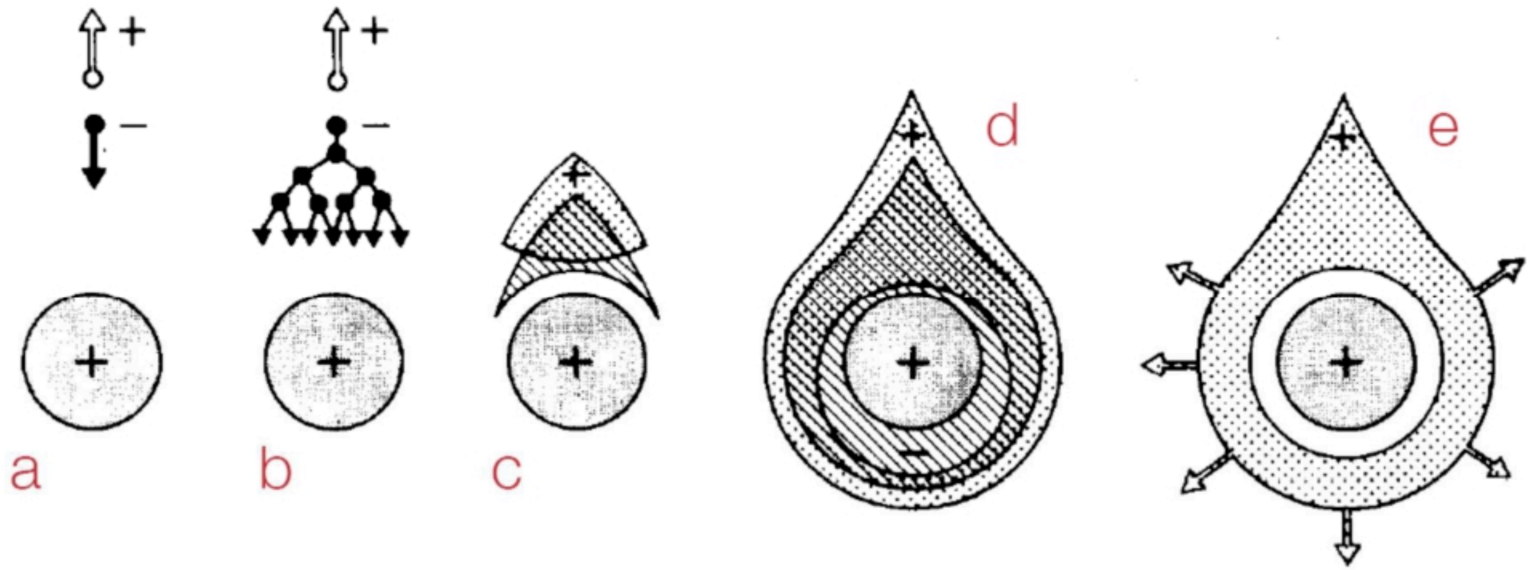
Problem solved using Cylindrical proportional counter:

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



Avalanche development

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



a) a single primary electron proceeds towards the wire anode,
b) in the region of increasingly high field the electron experiences ionizing collisions (avalanche multiplication),
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 .

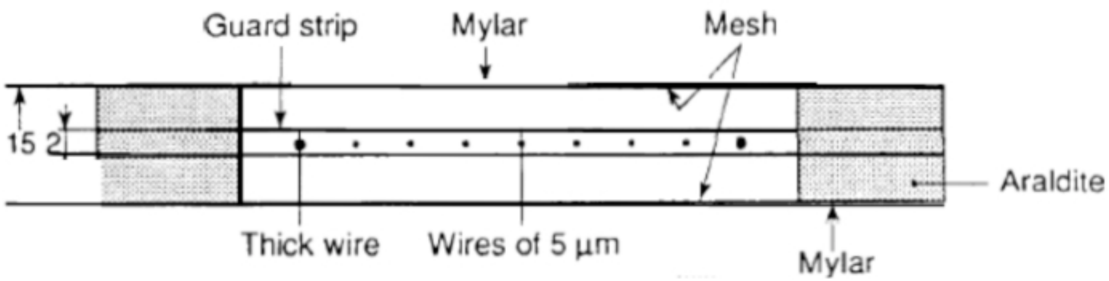
Brief recap

So far:

- we have defined the ionization and avalanche multiplication process
- we have the design of a single wire proportional counter
- with it we can measure the pulse signal from ionization

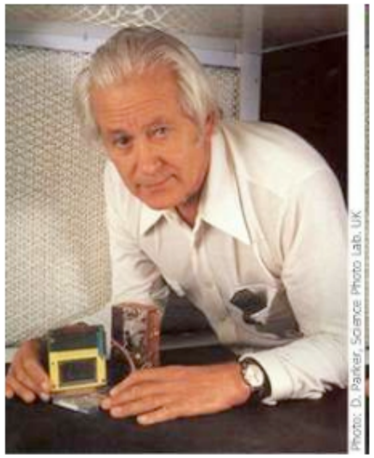
A proportional counter does not yet give a position measurement of the incident particle …

multi-wire proportional chamber



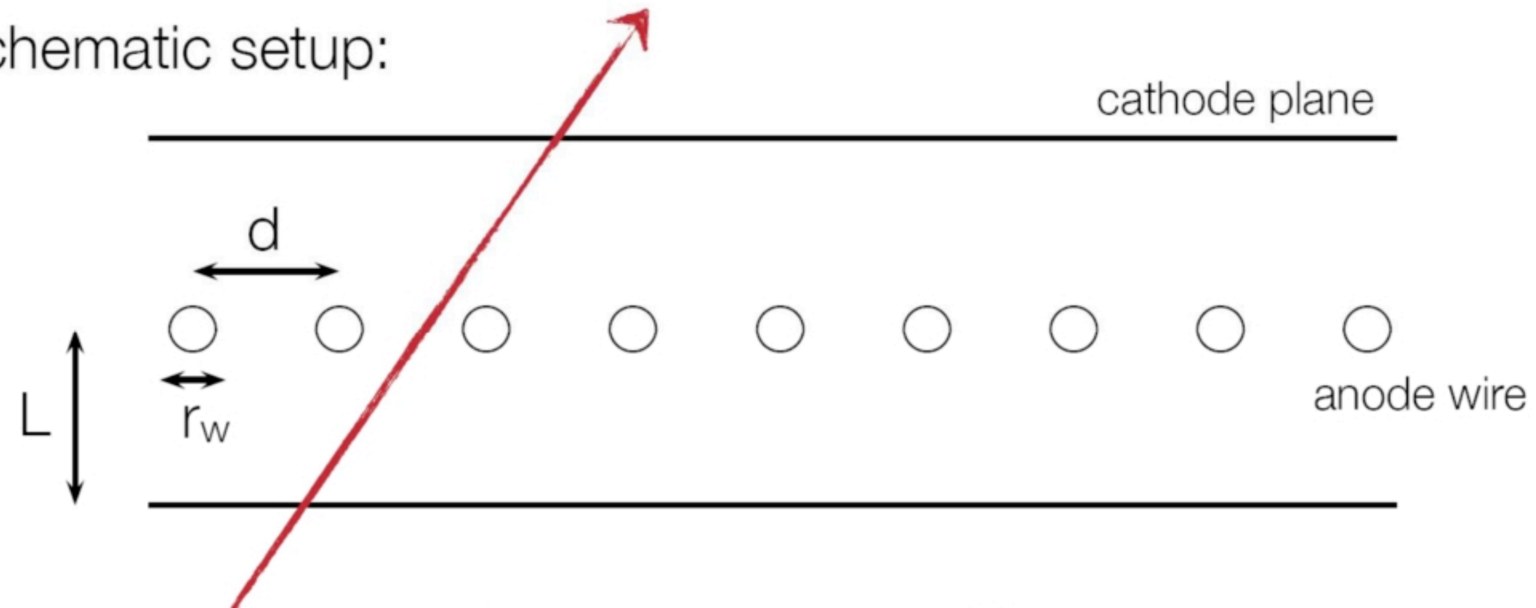
construction details of the original design of Charpak's multi-wire chambers

G. Charpak
Nobel price (1992)



Multi-wire proportional chamber (MWPC)

Schematic setup:



Parameters:

d	=	2 - 4 mm
r_w	=	20 - 25 µm
L	=	3 - 6 mm
U_0	=	several kV

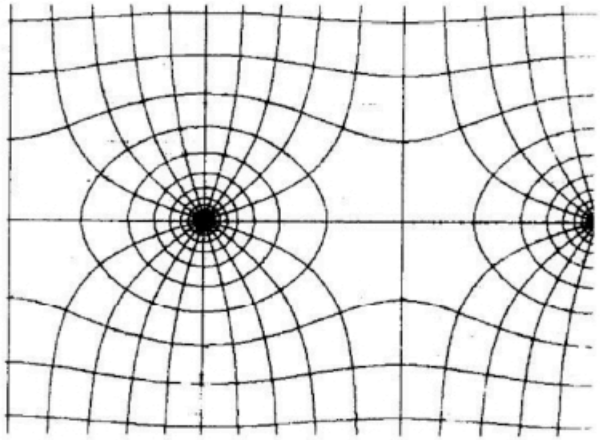
Total area: $O(m^2)$

Features:

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

MWPC – field distribution

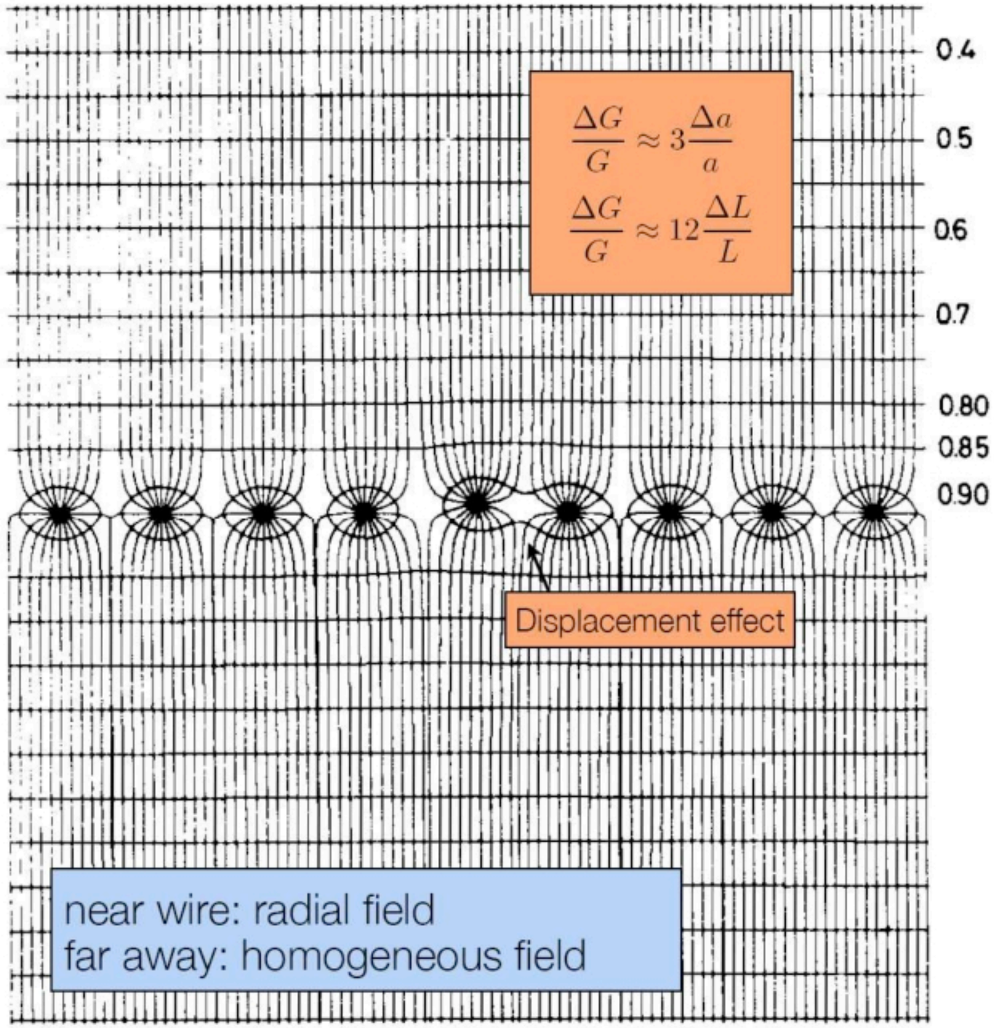
Electric field lines
and equipotentials



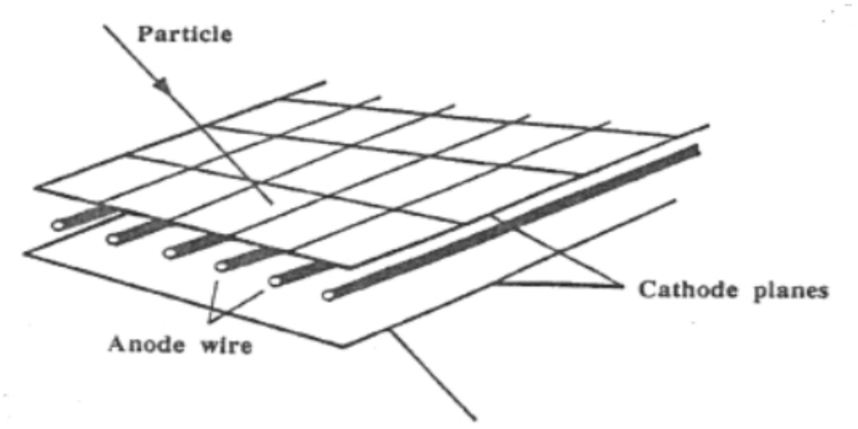
Small wire displacements
reduce field quality ...

Need high mechanical precision
both for geometry and wire tension ...

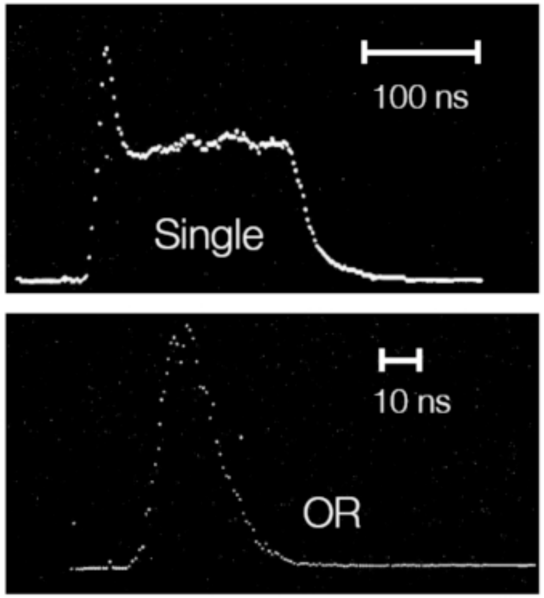
[electrostatics and gravitation; wire sag]



MWPC – signal



Signal generation:
Electrons drift to closest wire
Gas amplification near wire ➛ avalanche
Signal generation due to electrons and
mainly slow ions



Timing resolution:
Depends on location of penetration
for fast response: OR of all channels ...
[typical: $\sigma_t = 10$ ns]

Multi-wire proportional chamber

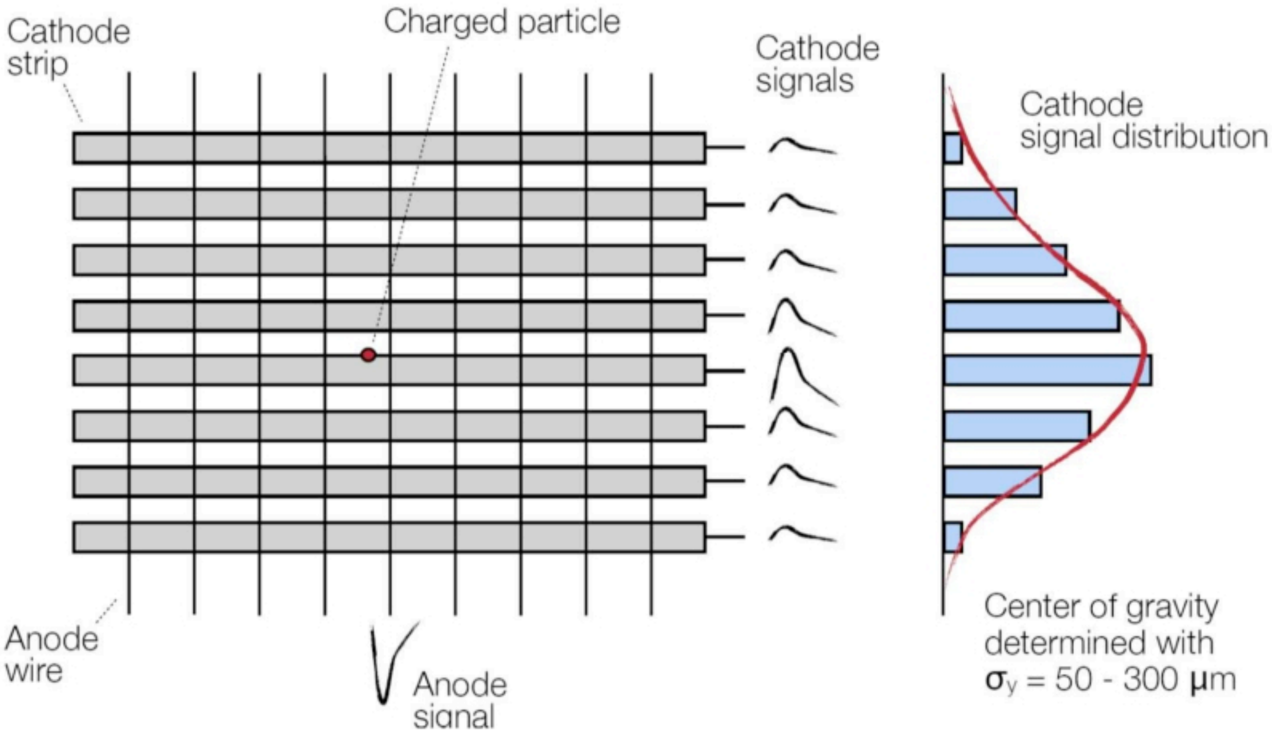
Space point resolution:

Only information about closest wire ➛ $\sigma_x = d/\sqrt{12}$ [d=2-4 mm, σ_x ~0.6-1mm]

[Only one dimensional information]

Possible improvements:

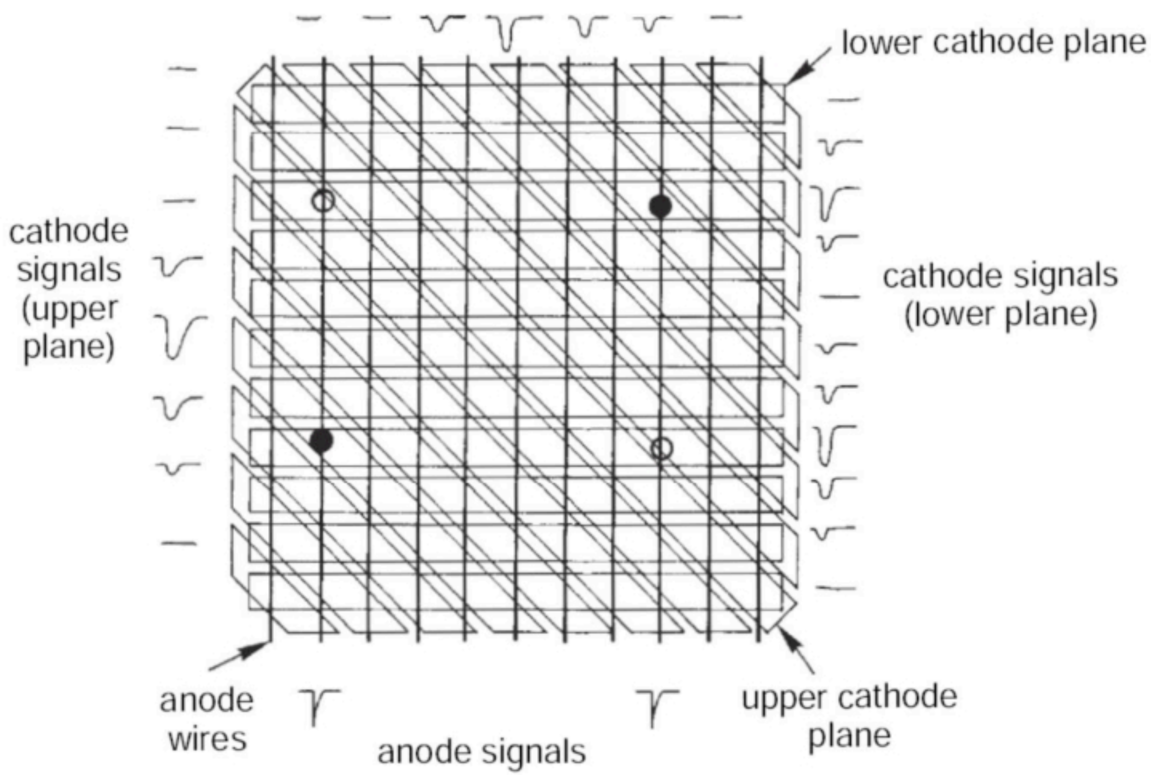
- segmented cathode



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

2D - MWPC

substantial functionality improvement
due to cathode strips/pads ...



- ● true hit
- ○ ghost hit

Cathode readout yields:

2-dim. information
true 2d: use pads ...

high spatial resolution
due to center of gravity reconstruction

resolving ambiguities
using second strip pattern or pads

Can wires be avoided?

Aging in wire chambers

Avalanche formation can be considered as micro plasma discharge.

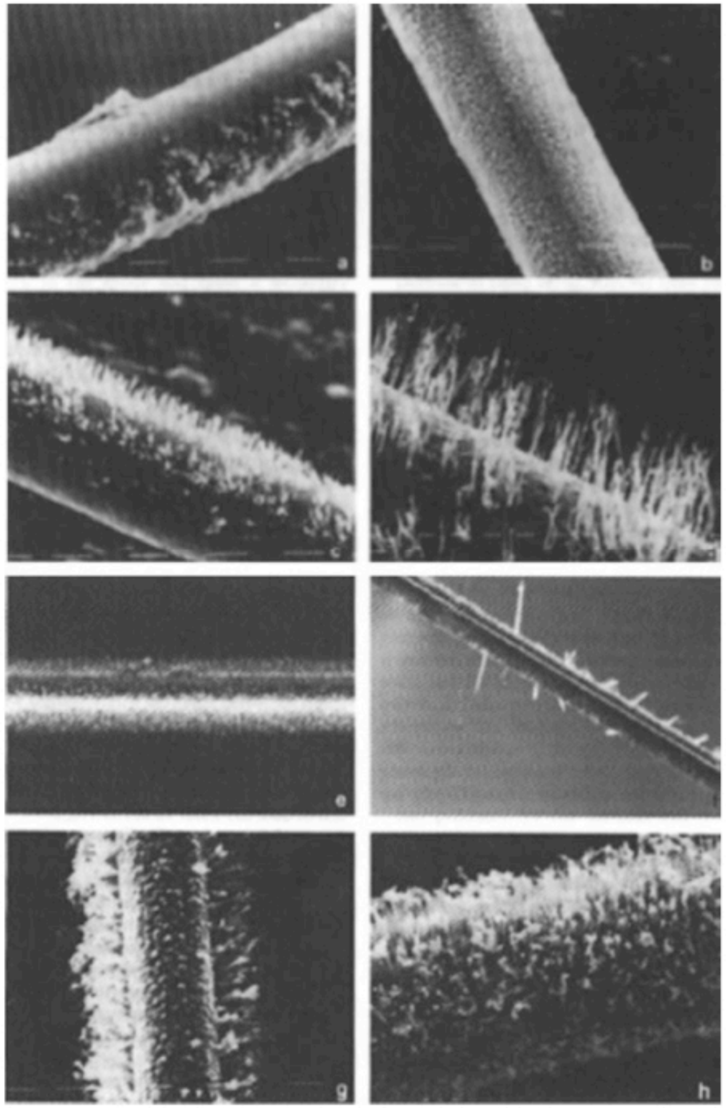
Consequences:

Formation of radicals i.e. molecule fragments
Polymerisation yields long chains of molecules
Polymers may be attached to the electrodes
Reduction of gas amplification

Important:
Avoid unnecessary contamination ...

Harmful are ...

Halogens or halogen compounds
Silicon compounds
Carbonates, halocarbons
Polymers
Oil, fat ...
....



Can wires be avoided?

Micro-strip gas chambers (MSGC)

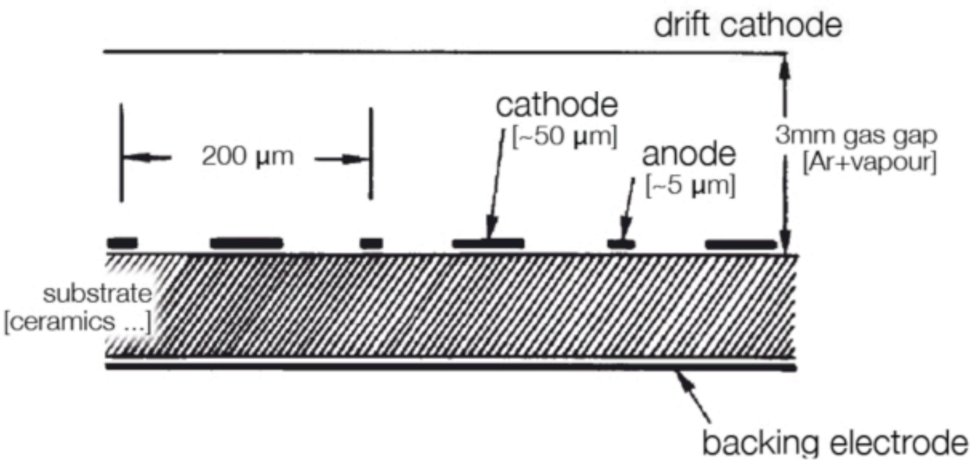
Can one avoid wires?

Anode realized via microstructures on dielectrics ...

Simple construction (today)
Enhanced stability & flexibility
Improved rate capabilities

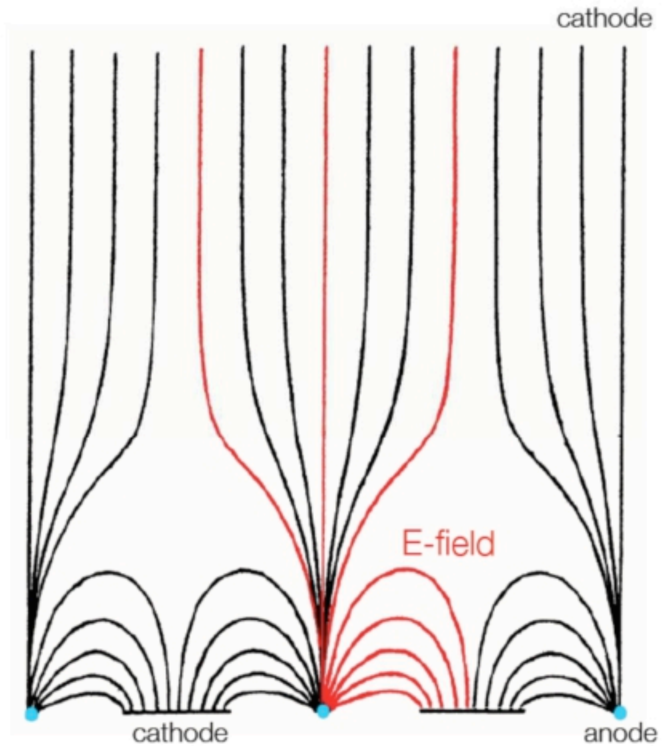
First MSGCs developed in 1990ies ...

Problems: charging of isolation structure
[➛ time-dependent gain; sparks, anode destruction]



Schematics of MSGC field lines

high field directly above anode
ions drift only 100 μm; yields low dead time ...



MSGC – technical solutions

MGSCs prone to aging problems ...
Solution: intermediate grid ...

e.g.: Micromegas
GEM detectors [Sauli, 1997]

Micromegas:

Fine cathode mesh collects ions
still fast; no wires ...

GEM (Gas Electron Multiplier):

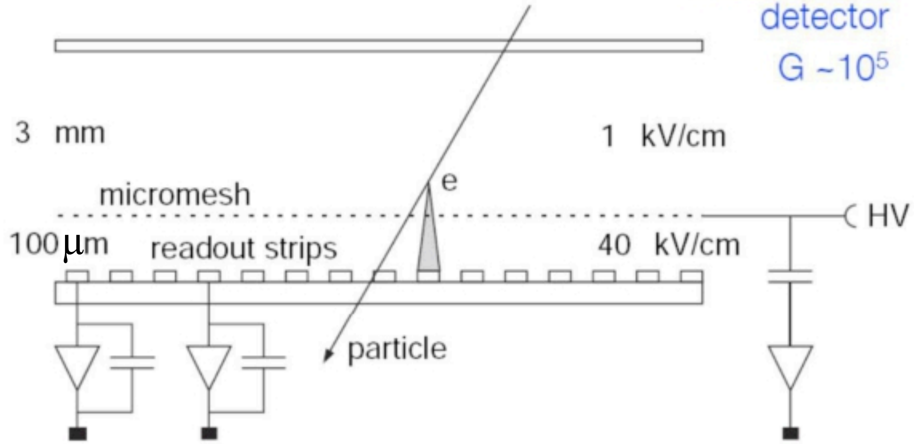
Thin insulating kapton foil
coated with metal film ...

Contains chemically produced
holes [100-200 μm]

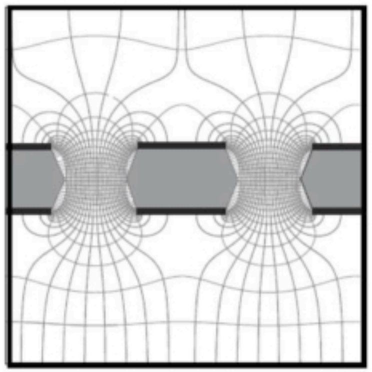
Electrons are guided by high
electric drift field of GEMs ...

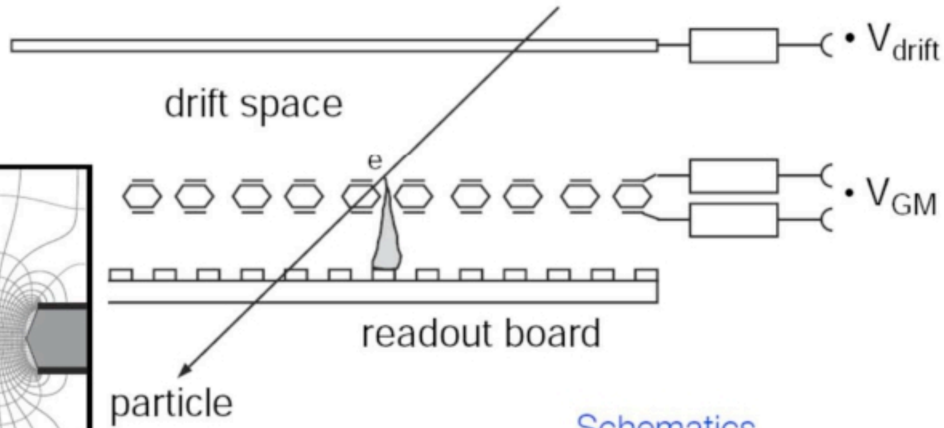
Avalanche production ...

Electrons drift to anode
GEM collects ions



Micromegas detector
$G \sim 10^5$



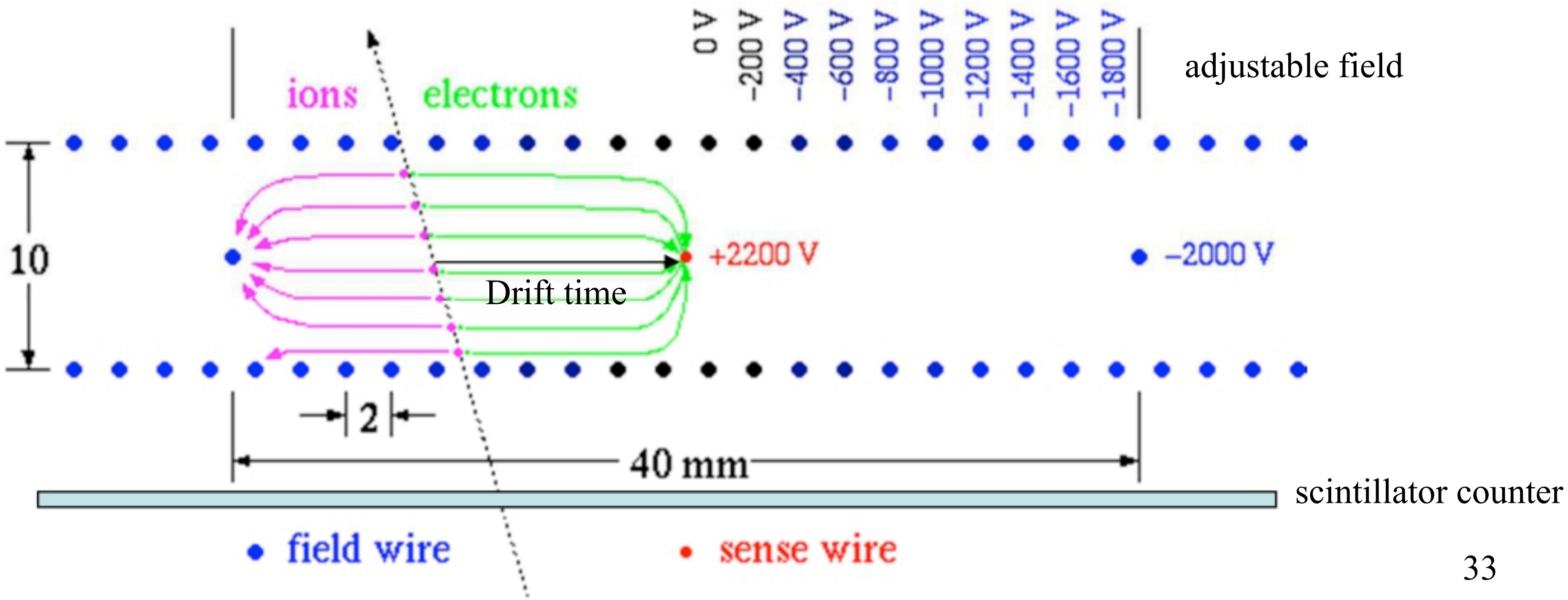


Schematics of GEM detector

Drift chamber

Alternative way to obtain spatial information: measure the electrons drift time

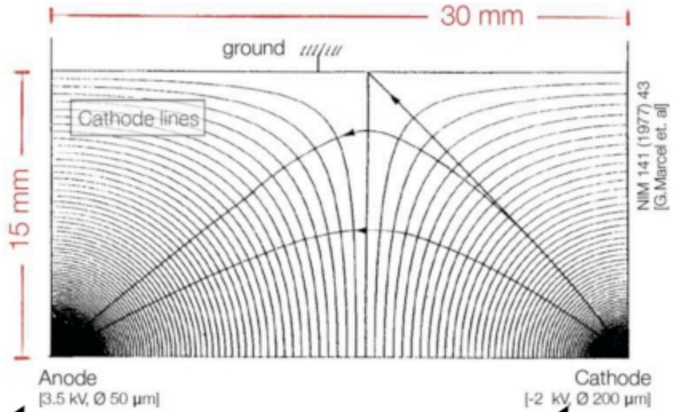
- time measurement started by an external (fast) detector, i.e. scintillator counter
- electrons drift to the anode (sense wire), in the field created by the cathodes
- the electron arrival at the anode stops the time measurement
- one-coordinate measurement: $$x = \int_0^{t_D} v_D \, dt$$

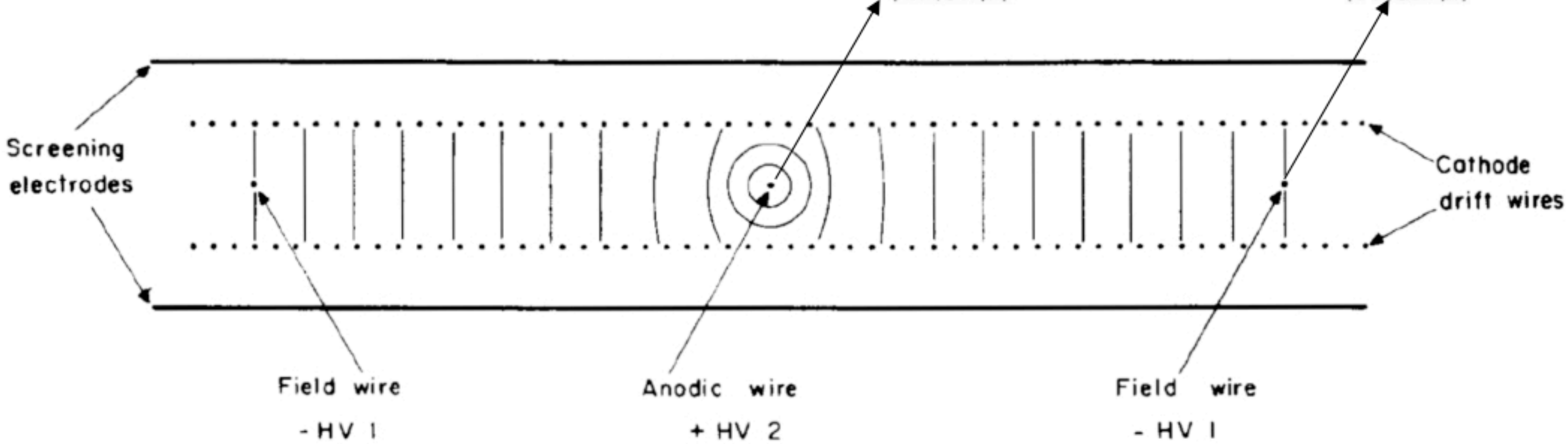


Drift chamber – field formation

Introduce field wires to avoid
low field regions, i.e. long drift-times

Uniform drift field requires:
Gap length/wire spacing ≈ 1
i.e. for typical convenient wire spacing
one needs thick chambers O(cm)



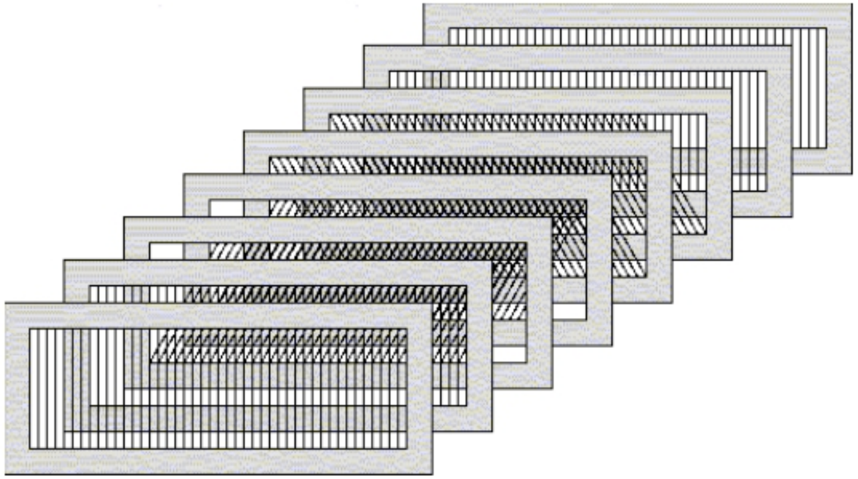


Adjustable field multi-wire drift chamber:
introduction of voltage divider
via cathode wire planes

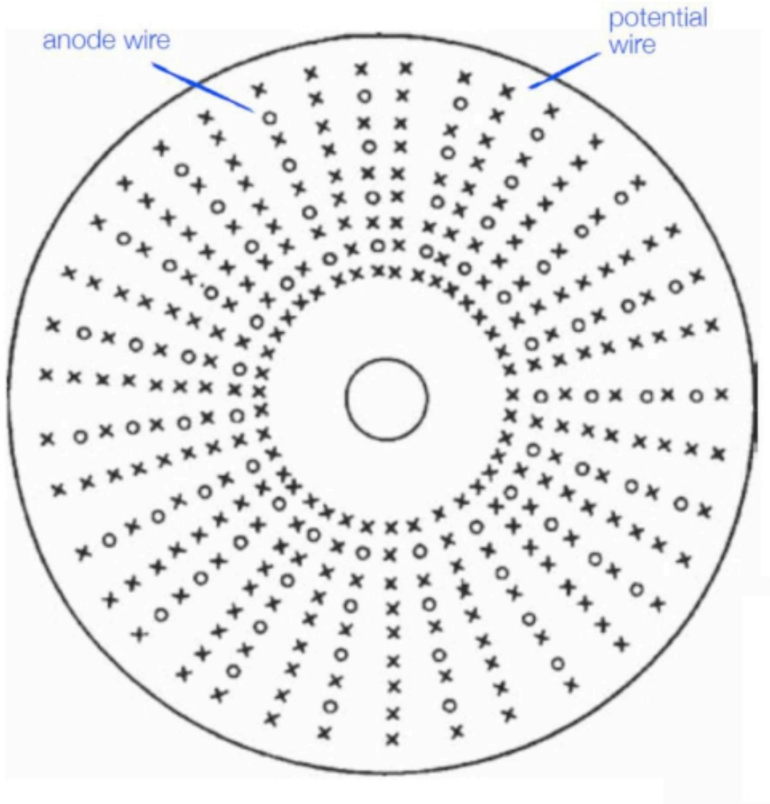
very few (or only one) anode wires
space point resolution limited by mechanical accuracy
[for large chambers: σ ≈ 200 µm]
But: hit density needs to be low.

Tracking detector

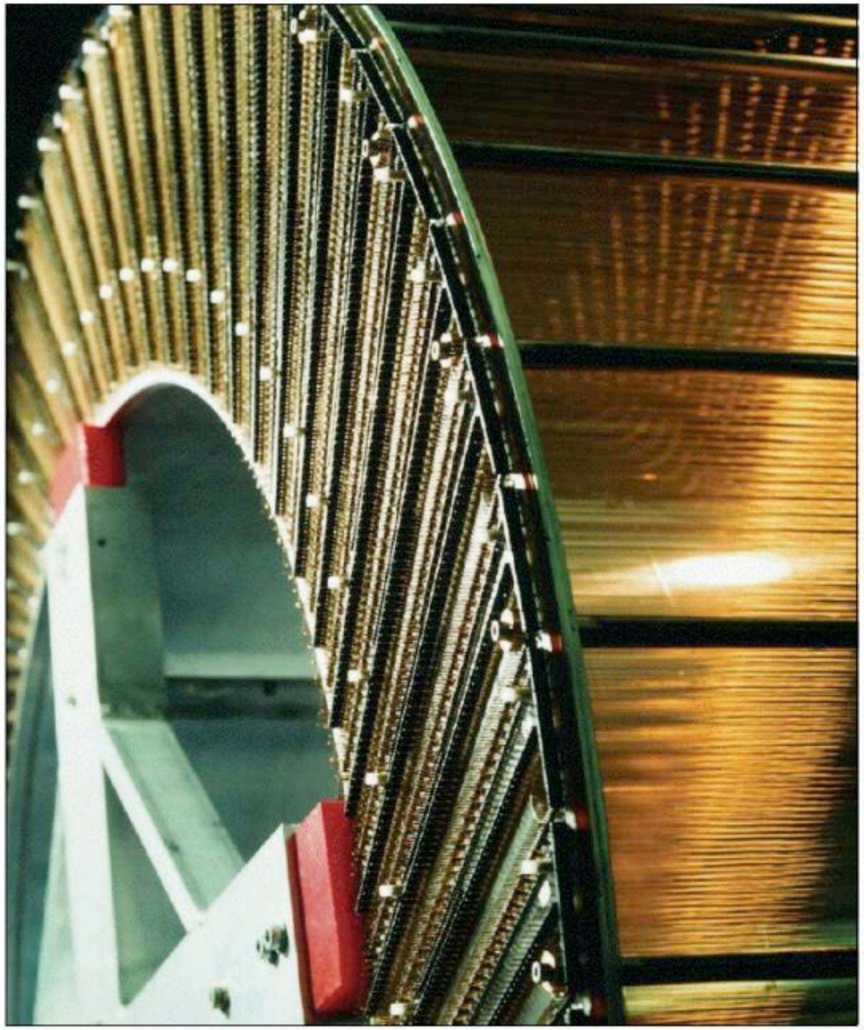
Tracking at fixed target experiments:
Multi-layer MWPC or drift chamber



Tracking at collider experiments:
cylindrical drift chamber



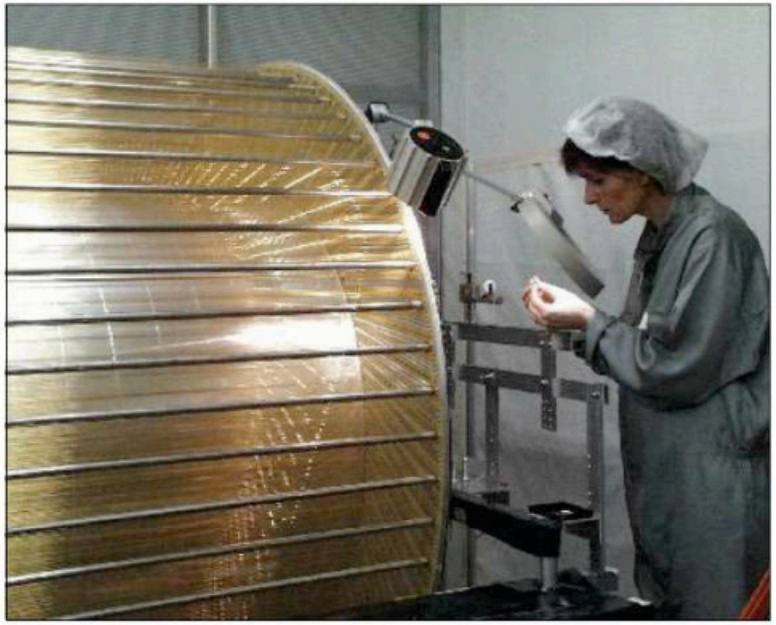
H1 - Cylindrical drift chamber



Cylindrical
Drift Chamber

[H1 Experiment]

Number of wires: ~ 15000
Total force from wire tension: ~ 6 t



Time projection chamber

Electronic 'bubble chamber'
Full 3D reconstruction ...

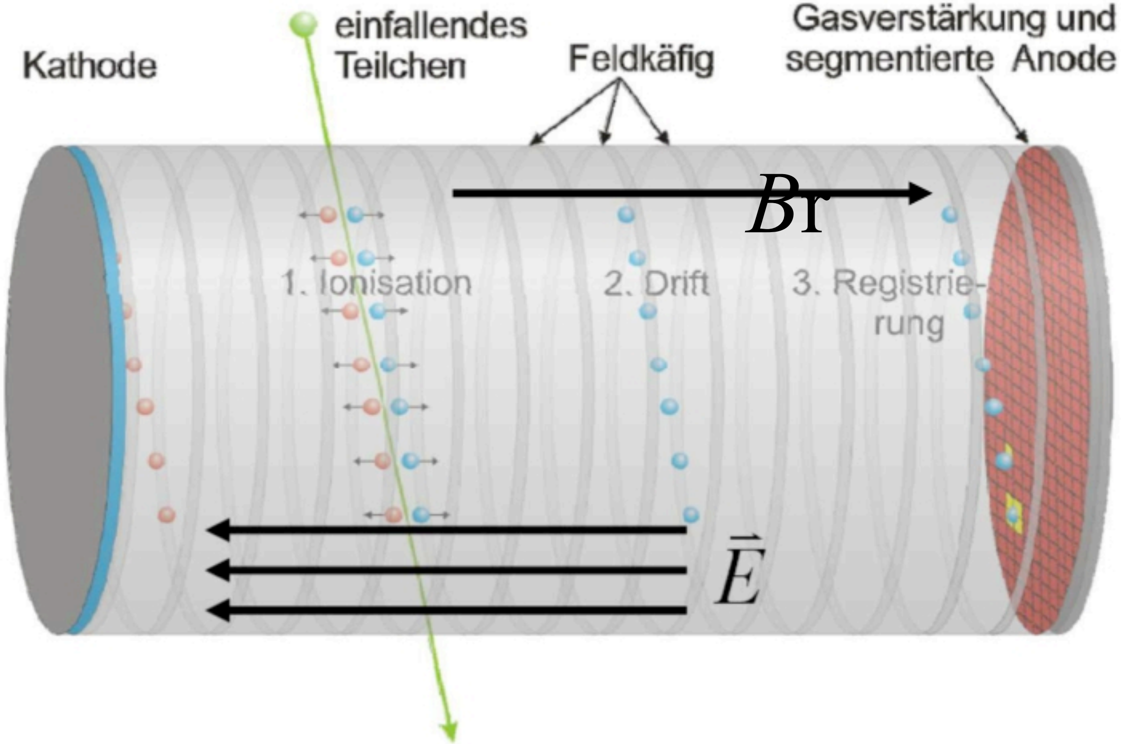
- xy : from wires and pads of MWPC
- z : from drift time measurement

Momentum measurement ...

- space point measurement plus B field ...

Energy measurement ...

- via dE/dx ...



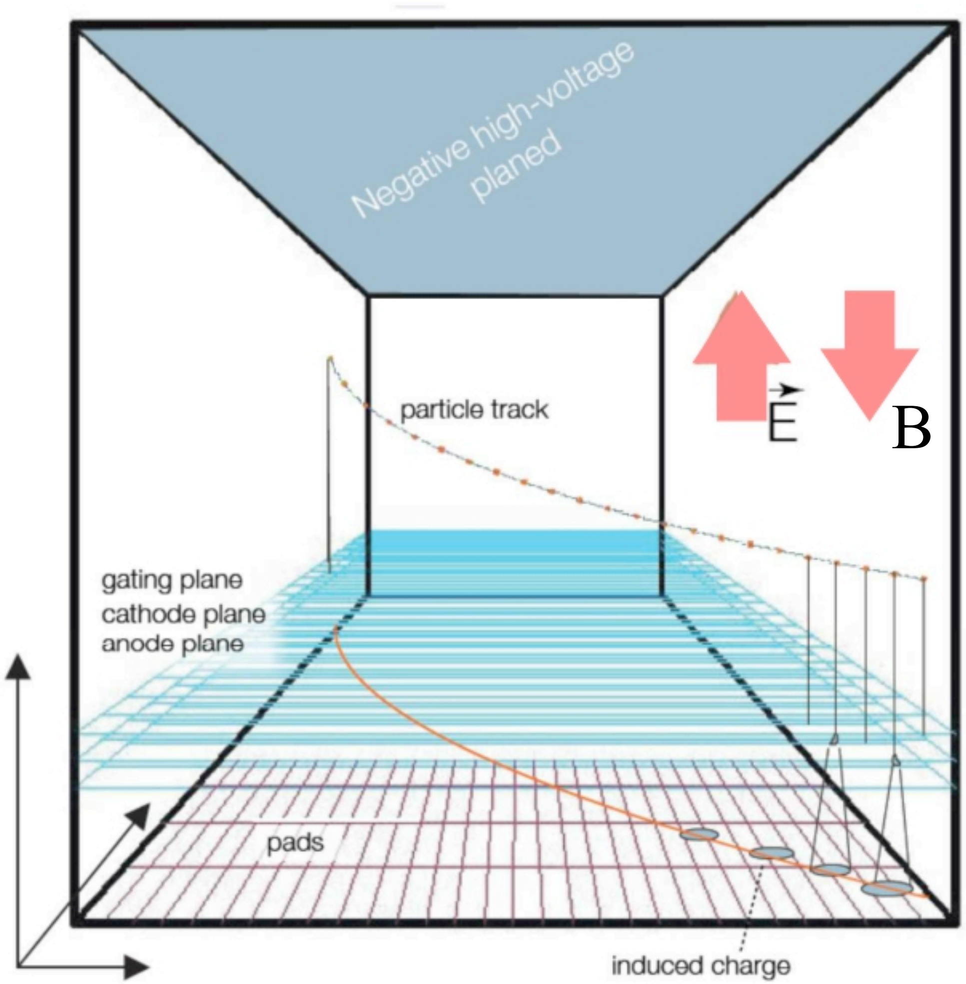
TPC setup:

- (mostly) cylindrical detector
- central HV cathode
- MWPCs at end-caps of cylinder
- B || to E ➛ Lorentz angle = 0

Charge transport :

- Electrons drift to end-caps
- Drift distance several meters
- Continuous sampling of induced charges in MWPC

Time projection chamber



Advantages:

Complete track within one detector yields good momentum resolution

Relative few, short wires (MWPC only)

Good particle ID via dE/dx

Drift parallel to B suppresses transverse diffusion by factors 10 to 100

Challenges:

Long drift time; limited rate capability [attachment, diffusion ...]

Large volume [precision]

Large voltages [discharges]

Large data volume ...

Extreme load at high luminosity; gating grid opened for triggered events only ...

Typical resolution:

z: mm; x: 150 - 300 μm; y: mm
dE/dx: 5 - 10%

TPC – technical solution

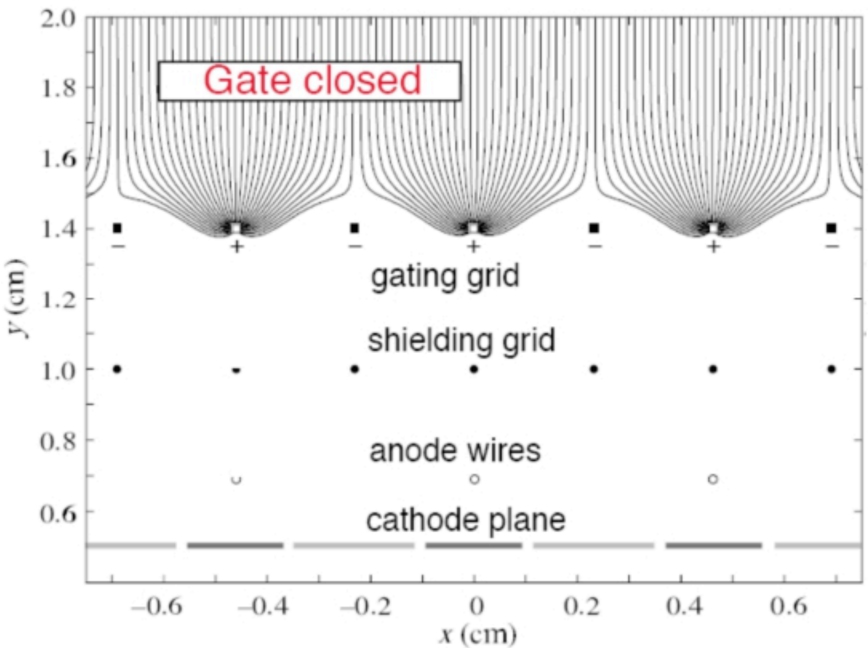
Difficulty: space charge effects due to slow moving ions change effective E-field in drift region ....

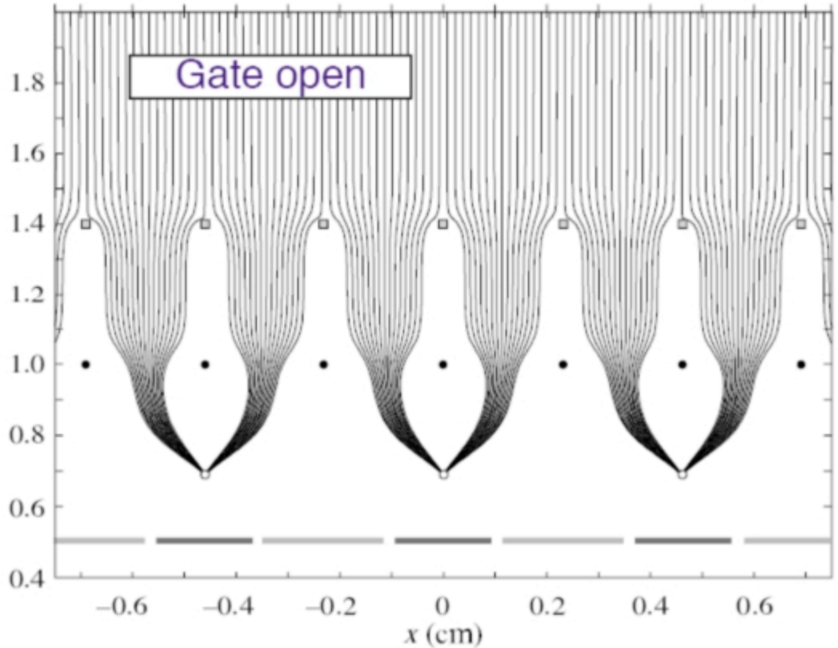
Important: most ions come from amplification region

Solution: Invention of gating grid; ions drift towards grid ...

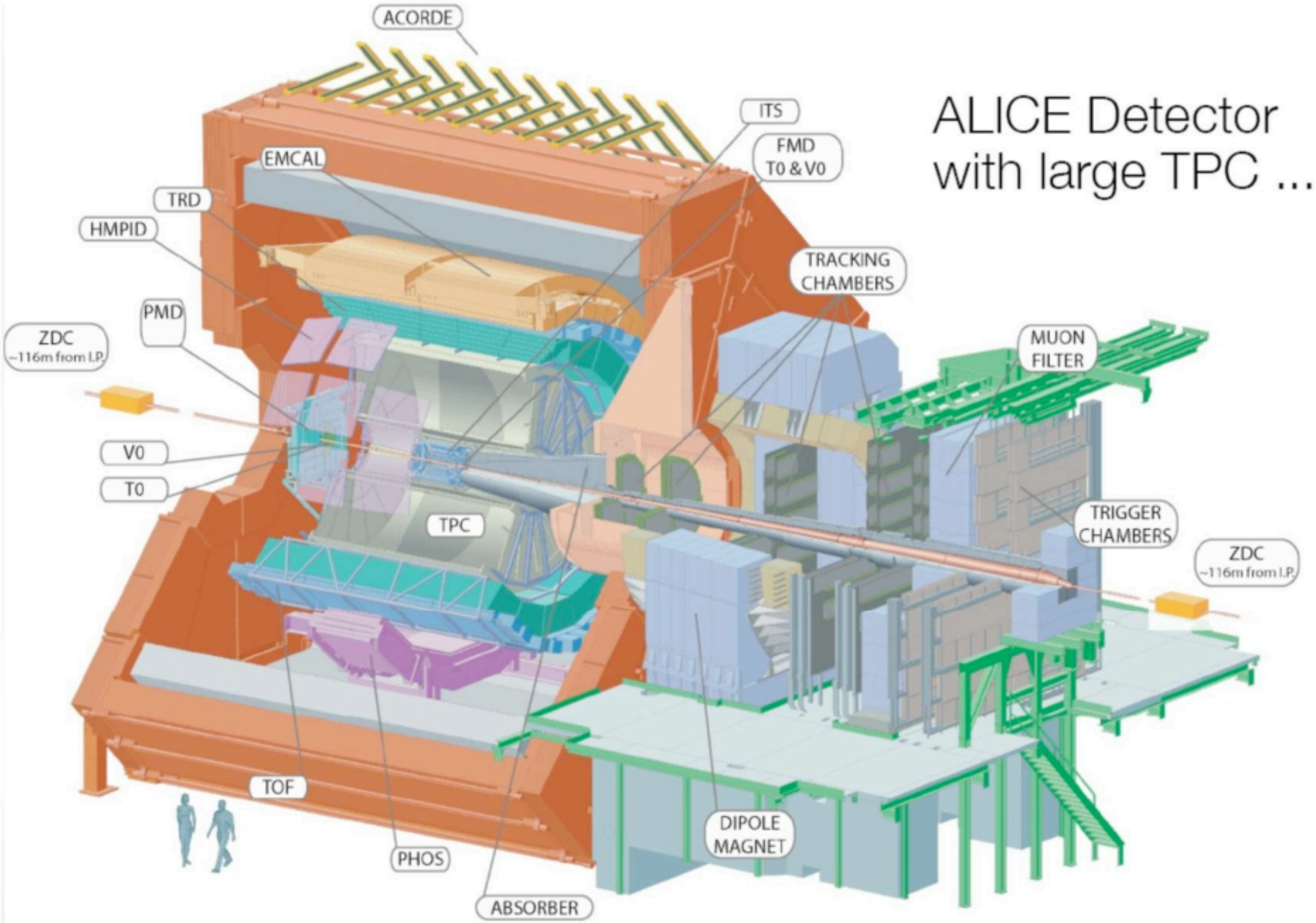
[Also: shielding grid to avoid sense wire disturbance when switching]

Requires external trigger to switch gating grid ...





ALICE - TPC


ACORDE
ITS
FMD
T0 & V0
ALICE Detector
with large TPC ...
EMCAL
TRD
HMPID
PMD
ZDC
~116m from I.P.
TRACKING
CHAMBERS
MUON
FILTER
V0
T0
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
TOF
DIPOLE
MAGNET
PHOS
ABSORBER

ALICE - TPC

Length: 5 meter
Radius: 2.5 meter
Gas volume: 88 m^3

Total drift time: 92 μs
High voltage: 100 kV

End-caps detectors: 32 m^2
Readout pads: 557568

159 samples radially
1000 samples in time

Gas: $Ne/CO_2/N_2$ (90-10-5)
Low diffusion (cold gas)

Gain: $> 10^4$

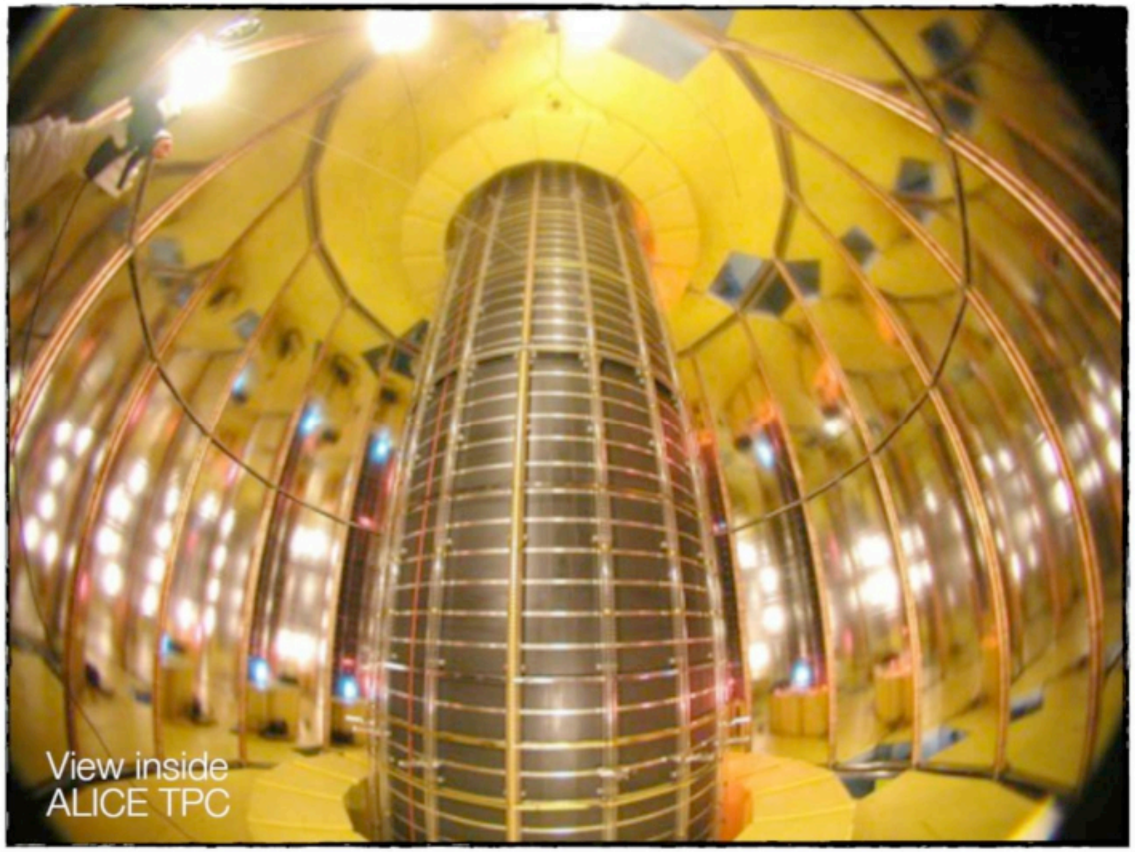
Diffusion: $\sigma_t = 250\ \mu m$
Resolution: $\sigma \approx 0.2$ mm

$\sigma_p/p \sim 1\%$ p; $\varepsilon \sim 97\%$
$\sigma_{dE/dx}/(dE/dx) \sim 6\%$

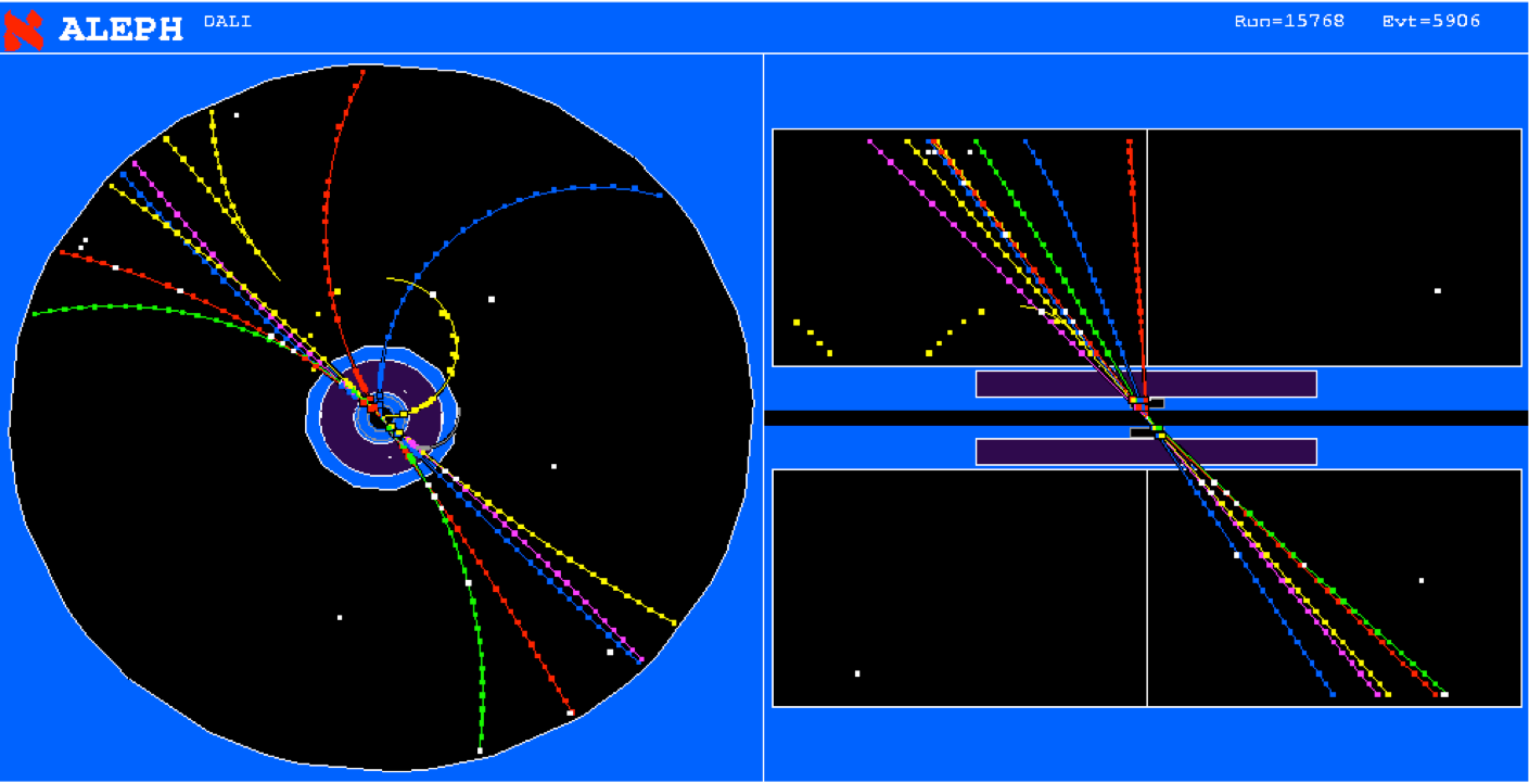
Magnetic field: 0.5 T

Pad size: 5x7.5 mm^2 (inner)
6x15 mm^2 (outer)

Temperature control: 0.1 K
[also resistors ...]



ALEPH event: $e^+e^- \to q\bar{q}$, $E_{CMS} = 91$ GeV



Alice TPC event: Pb-Pb interaction, E_{CMS} = 2.57 GeV