GASEOUS DETECTORS

LECTURE 4 PART 1

CONTENT

REFERENCES

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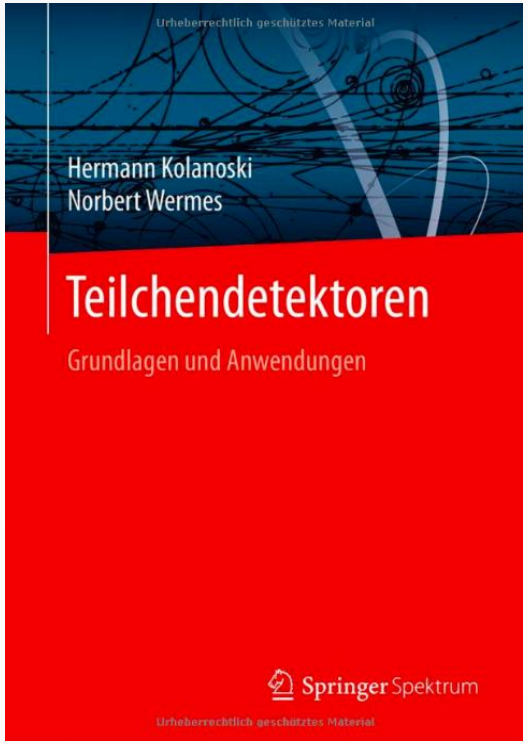
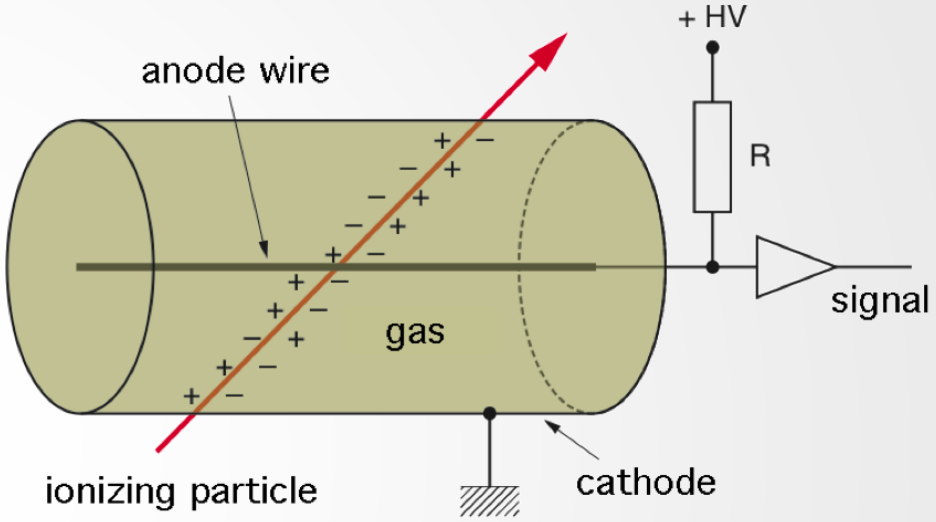
- Erika Garutti, Lecture notes, "The Physics of Particle Detectors", DESY, SS 2012
- Kolanoski, Wermes "Teilchendetektoren", 2015
- K. Kleinknecht, "Detektoren für Teilchenstrahlung"
- C. Grupen, "Teilchendetektoren", 1993



1. OPERATING PRINCIPLES

1.1 OVERVIEW

- Charged particles penetrating a gas volume ionize atoms, and hence produce electron-ion pairs. The average number of primary electron-ion pairs produced is proportional to the dE/dx of the particle.
- Electrons and ions drift in the an applied electric fields
- Due to the high mobility of electrons and ions, gases are ideal detectors to instrument large volumes.
- The drift of the electrons and ions induce the signal (not the collection of charge at the electrodes). True in all other detector types as well!
- A simple wire chamber consists of
  - Gas filled cylinder with an anode wire.
  - The cylinder surface is the cathode.
  - The applied voltage *V* creates an electric field E.



$$E(r) = \frac{1}{r}\frac{V}{\ln(b/a)}$$

r … distance from the wire
a … radius of anode wire
b … radius of cathode cylinder

- The radius of the wire is an important design element.
- If the field close to the anode wire is high enough, secondary ionization multiplies the signal!
  - This way, single particles can be detected.

1.2 DIFFUSION AND DRIFT

- In the absence of an external field the electrons and ions move uniformly away from the point of creation due to disordered thermal movement. Brownian movement ⟶ diffusion.

- The electrons and ions loose energy by multiple scattering until thermal equilibrium is reached.

$$v_{\text{diff}} = \sqrt{\frac{8\,kT}{\pi\, m}}$$

e- $v_{\text{diff}} \approx 10^6$ cm/s = 10 μm/ns
ions $v_{\text{diff}} \approx 10^4$ cm/s

- The diffusion coefficient is determined by the average free path length λ of e- and ions in the gas:

$$D = \tfrac{1}{3} v_{\text{diff}} \lambda \qquad \lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma p}$$

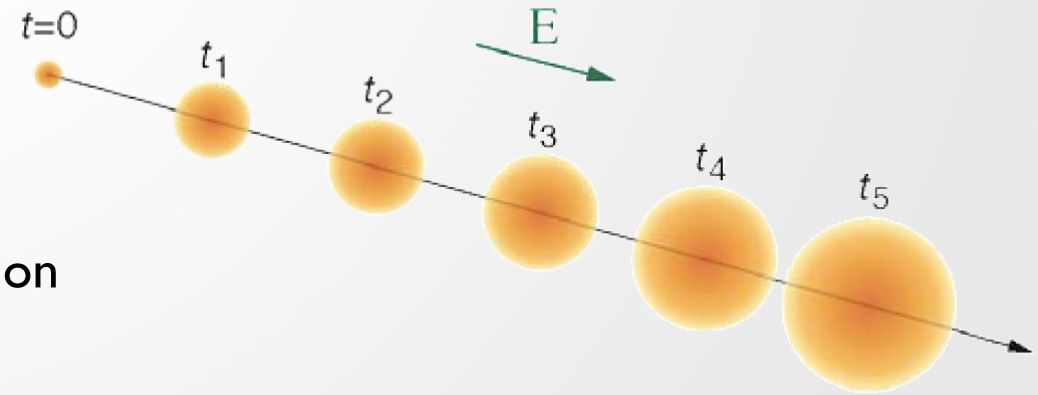
p … gas pressure, T …temperature,
k … Boltzmann constant, $k = 1.3807 \cdot 10^{-23}$ J/K
σ … total cross section for collision with a gas molecule

- Solving the Boltzman equation for a initial point-like ionization deposit, the charge carrier distribution evolves as a time-dependent Gaussian

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

from where we read off the width $\boldsymbol{\sigma}_x$ and the volume diffusion

$$\sigma_x = \sqrt{2Dt} \qquad \sigma_{\text{vol}} = \sqrt{3} \cdot \sigma_x = \sqrt{6Dt}$$



1.2 DIFFUSION AND DRIFT

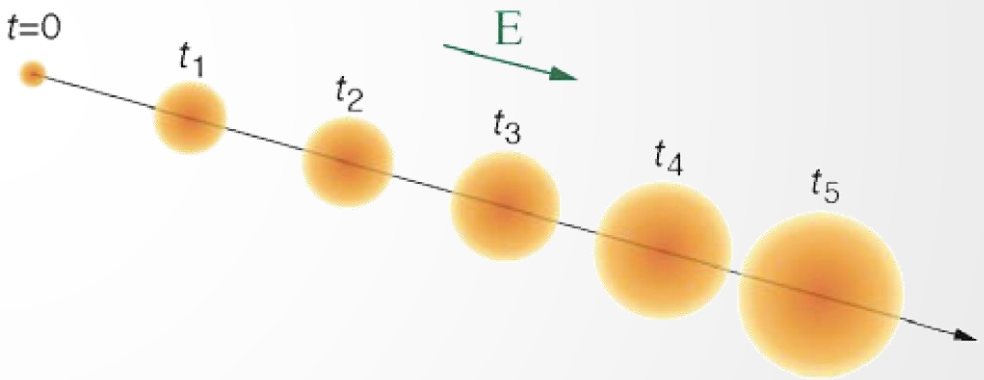
- If an external electric field is applied the electrons and ions are accelerated and move along the field lines ⟶ a drift is induced
  - The drift is superimposed onto the diffusion movement
- Acceleration is interrupted by collision with gas atoms, this limits the drift velocity.
- The mean drift velocity v_D is

$$\vec{v}_D = \frac{q}{m} \cdot \tau(\vec{E}, \sigma) \cdot \vec{E} \cdot \frac{p_0}{p} = \mu \cdot \vec{E} \cdot \frac{p_0}{p}$$

where

q, m … charge and mass
E … electric field
τ … mean time between collisions
p … gas pressure, p_0 … standard pressure
μ … mobility, $\mu = \tau \cdot q/m$,

and typical values 10-100 μm/ns.



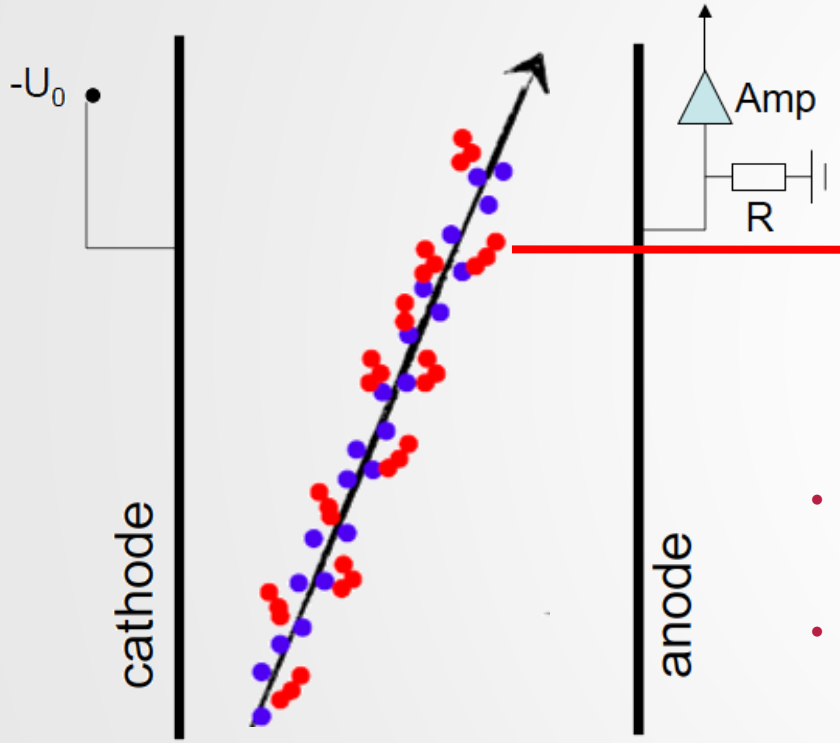
- If a magnetic field parallel to the electric field is present (E.g. cylindrical drift chamber, solenoid magnet)

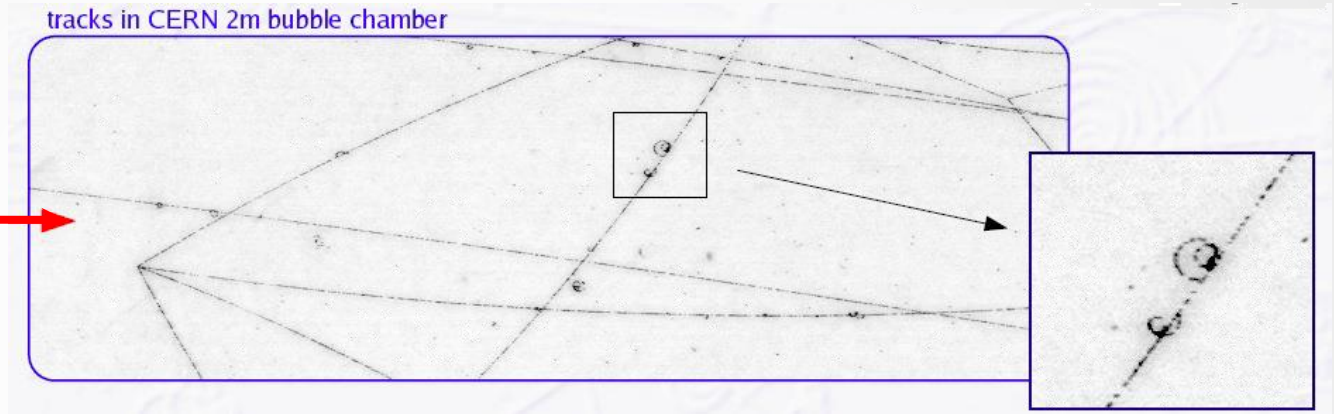
$$v_D = |\vec{v}_D| = \frac{\mu E}{\sqrt{1+\omega^2\tau^2}}$$

where **ω** is the cyclotron frequency.

1.3 PRIMARY AND SECONDARY IONIZATION

- A large fraction of the electron/ion pairs is from δ-electons (secondary ionization)





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

- There is thus a large difference between the number of primary ionizations per length vs. the total number of ionizations per length
- Example: Ar at normal pressure: A energy of 1cm · dE/dx = 2.44 keV creates 29.4 e/ion pairs per cm (83 eV/pair). Secondary ionization accounts for the difference to 94 pairs/cm (x 3!), such that the average energy to create an e/ion pair is w_i = 26 eV (See next slide).
- The optimal gas has a high ionization density ($\propto Z$), but low rate of multiple nuclear scattering ($\propto Z^2$). He has low multiple scattering (and large X_0) and low ionization density. The opposite is true for Xe. A frequent compromise choice is Ar.
- High Z materials (Xe,…) are e.g. used in transition radiation detectors to detect the X-rays.

1.4 GAS PARAMETERS

Gas	Z	A	ρ (g/cm^3)	E_{ex} (eV)	E_{ion} (eV)	I (eV)	w_i (eV)	$dE/(\rho dx)$ (MeV cm^2/g)	dE/dx (keV/cm)	n_p (cm^{-1})	n_{tot} (cm^{-1})	X_0 (m)
H_2	2	2	$8.38 \cdot 10^{-5}$	10.8	15.4	19.2	37	4.03	0.34	5.2	9.2	7522
He	2	4	$1.66 \cdot 10^{-4}$	19.8	24.5	41.8	41	1.94	0.32	5.9	7.8	5682
N_2	7	28	$1.17 \cdot 10^{-3}$	8.1	15.6	82	35	1.68	1.96	(10)	56	325
O_2	8	32	$1.33 \cdot 10^{-3}$	7.9	12.1	95	31	1.69	2.26	22	73	257
Ne	10	20.2	$8.39 \cdot 10^{-4}$	16.6	21.6	137	36	1.68	1.41	12	39	345
Ar	18	39.9	$1.66 \cdot 10^{-3}$	11.5	15.8	188	26	1.47	2.44	29.4	94	118
Kr	36	83.8	$3.49 \cdot 10^{-3}$	10.0	14.0	352	24	1.32	4.60	31.6	192	33
Xe	54	131.3	$5.49 \cdot 10^{-3}$	8.4	12.1	482	22	1.23	6.76	44	307	15
CO_2	6,8	44	$1.86 \cdot 10^{-3}$	5.2	13.8	85	33	1.62	3.01	35.5	91	183
CH_4	6,1	16	$0.71 \cdot 10^{-3}$	9.8	15.2	41.7	28	2.21	1.48	25	53	646
C_2H_6	6,1	30	$1.34 \cdot 10^{-3}$	8.7	11.7	45.4	27	2.30	1.15	41	111	340
i-C_4H_{10}	6,1	58	$2.59 \cdot 10^{-3}$	6.5	10.6	48.3	23	1.86	5.93	84	195	169
CF_4	6,9	88	$3.78 \cdot 10^{-3}$	12.5	15.9	115	34.3	1.69	7	51	100	92
C_2H_6O (DME)	6,1,8	46	$2.2 \cdot 10^{-3}$	6.4	10.0	60	23.9	1.77	3.9	55	160	222

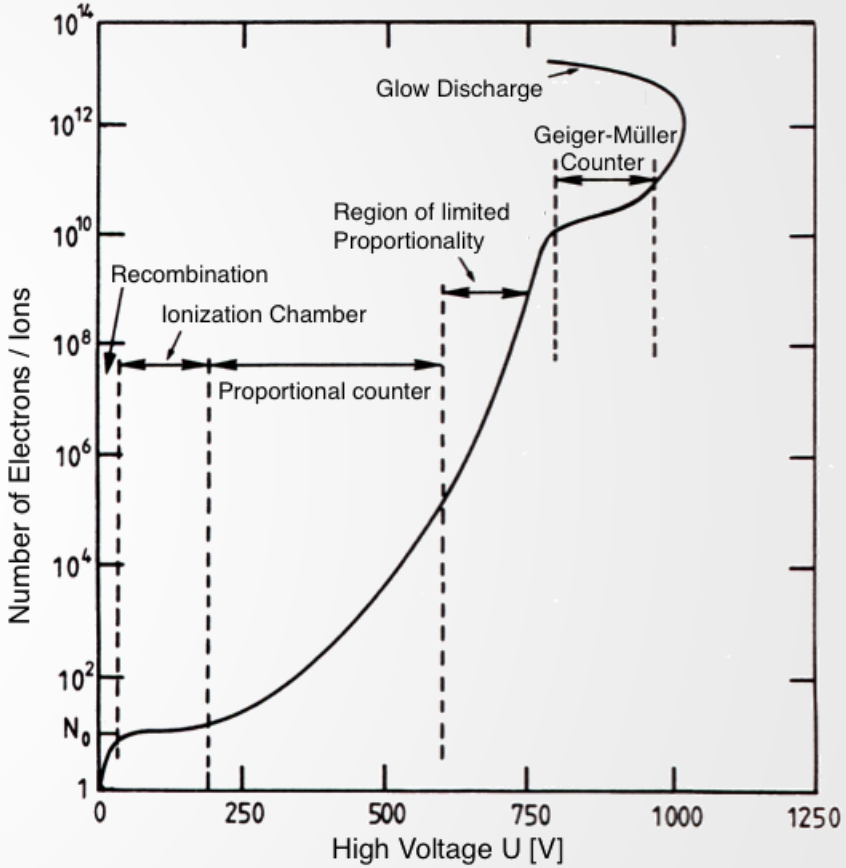
numbers for room temperature, and normal pressure

- E_{ex} … excitation energy threshold
- E_{ion} … ionisation threshold
- w_i … average energy to create an e^-/h^+ pair
- I … average Ionization energy (Bethe Bloch)
- n_p, n_{tot} … primary /total ionisations per cm (difference because of δ-electrons)
- w_i … average energy to create an e/h pair
- X_0 … radiation length
- DME … Dimethylether

2. OPERATION MODES

2.1 OVERVIEW

- The amplification G is defined as the ratio of collected electrons at the anode wire N_A to the number of primary electrons N, $G = N_A/N$.
- G<1: Recombination
  - most of the e/ion pairs recombine because the field is too weak to separate them
- G≈1: Ionisation chamber
  - no amplification, only primary particles collected. Useful for dosimetry/flux meas.
- $G \approx 10^3$-10^5: Proportional counter / proportional mode
  - An avalanche develops and the total number of charge carriers is proportional to the number of primary carriers.
- $G \approx 10^5$-10^8: Region of limited proportionality
  - The slowly moving ions begin to shield the electric field around the anode. This effect increases with the primary ionization (nonlinear E dependence)
- $G \gtrsim 10^8$: Geiger (or saturation) region
  - The signal is independent of the primary ionization. The detector counts.

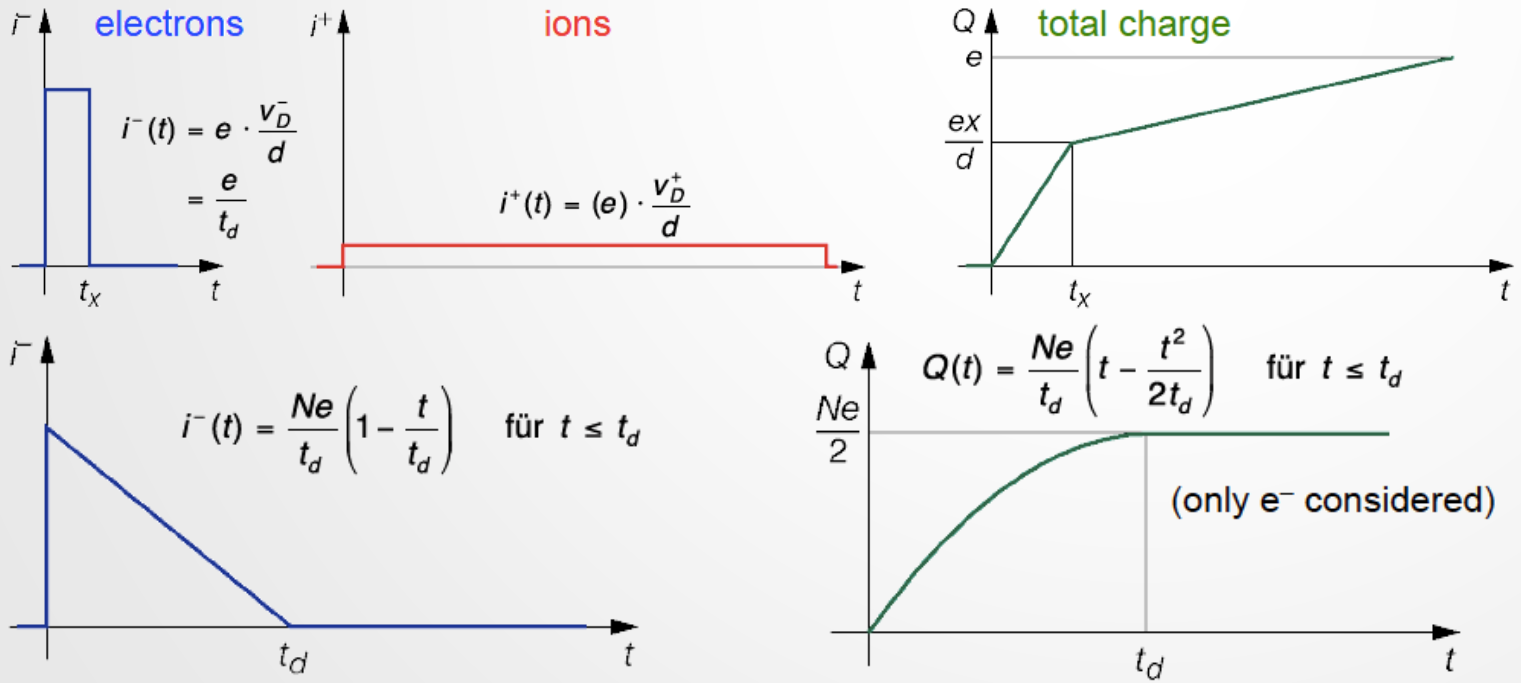


note: numbers only exemplary.
Strong dependence on gas and geometry

- discharge operation: triggered by a single e^-/ion pair, the electrodes connect by a streamer (extended avalanche in the direction of the E field) that develops into an extended plasma flux tube which fully discharges the electrodes.

2.2 IONIZATION CHAMBER AND TIME DEPENDENCE

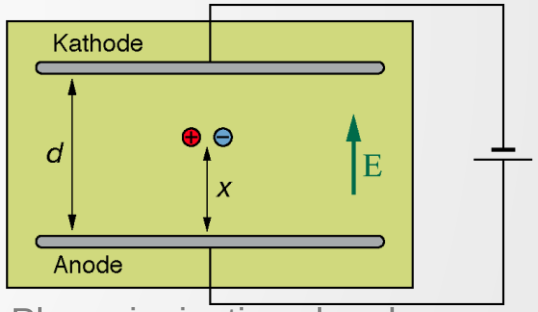
- An ionization chamber is operated at a voltage which allows full collection of charges, but below the threshold of amplification.
  - For a typical field strength 500 V/cm and typical drift velocities the collection time for 10 cm drift is about 2 µs for e^- and 2 ms for the ions.
  - Ionization chambers are used in nuclear industry but rarely in particle physics (too low signal, too slow, not possible to measure single particles: $C_{min} \approx 10^4 e \approx 1$ fC).
- ICs however illustrate that the time dependence of the signal is dominated by the ions



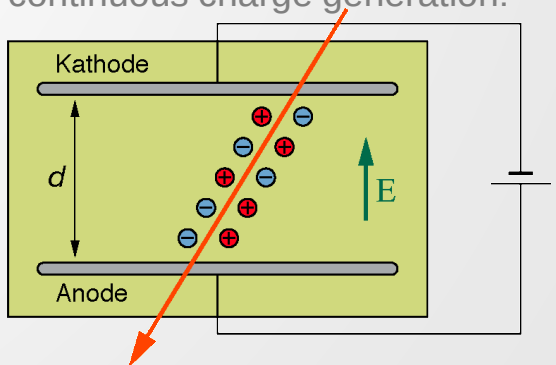
Shockley–Ramo theorem:
The instantaneous current *i* induced on a given electrode due to the motion of a charge is given by $i = E_v q v$.

i is NOT given by the arrival of the electrons!

Planar ionization chambers:



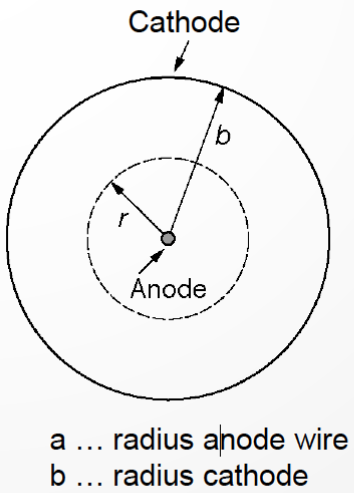
Planar ionization chambers, continuous charge generation:

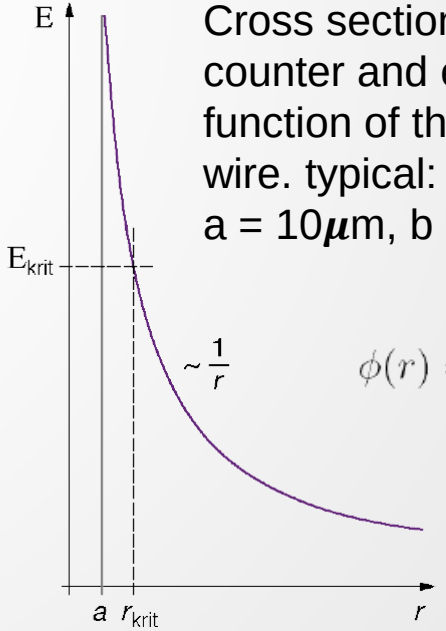


2.3 PROPORTIONAL MODE

- Signal amplification through secondary ionization:
  - electrons in a strong field acquire enough energy to create secondary electron/ion pairs
  - The amplification factor in gas detectors operating in the proportional mode is independent of the primary ionization ⟶ signal is proportional to the primary ionization
  - Amplification factors in proportional mode ≈ 10^3 to $10^{5\text{-}6}$
  - if p is known, can be used for dE/dx and thus particle Id
  - Limit of the proportional mode is reached when the slowly moving ion cloud begins to shield the electric field and reduces the field strength locally.
  - If the field is shielded (high ion densities), recombination can produce photons that needs to be removed with admixtures of a "quenching" gas (e.g. CH_4, CO_2). These gases absorb UV photons and prevent secondary avalanches.

- Typical geometry: cylindrical cathode with thin central anode wire.
  - Electric field in vicinity of the wire ∝1/r, at $r \leq r_{krit}$ field strength high enough to cause secondary ionization.
  - wire diameter 10 - 100 µm.





Cross section of a proportional counter and electric field *E* as function of the distance to the wire. typical:
a = 10μm, b = 10mm, r_{krit} = 1μm

$$\phi(r) = -\frac{CV_0}{2\pi\epsilon_0} \ln \frac{r}{a}$$

2.4 FORMATION OF AND SIGNAL FROM AN AVALANCHE

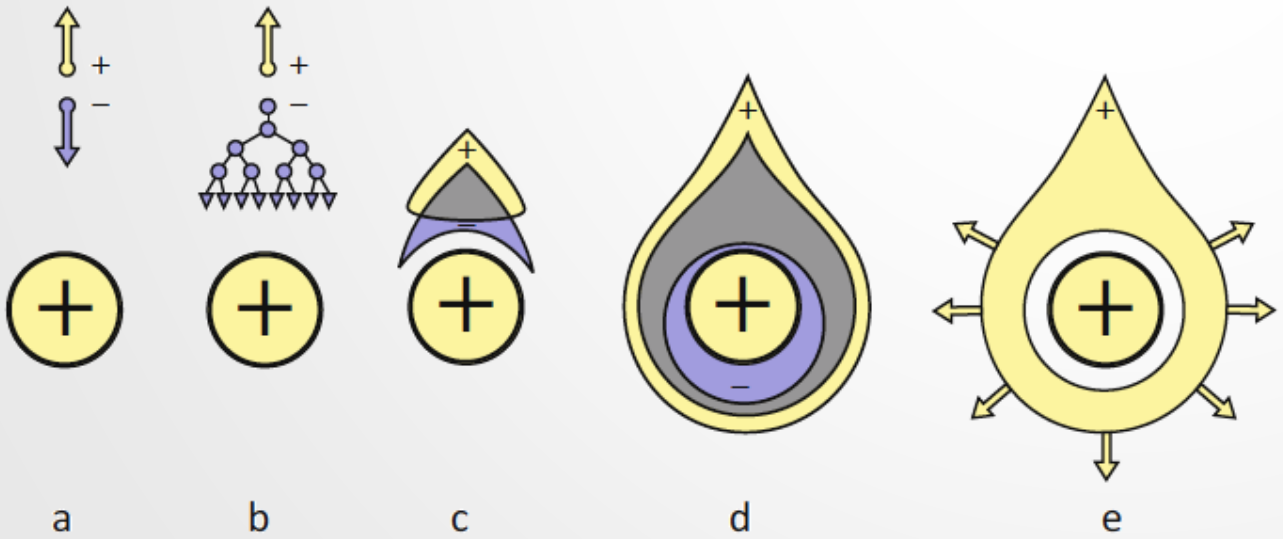
a. Electrons produced by the primary particle drift towards the anode wire.

b. These reach the area of high fields in the vicinity of the anode wire, where secondary ionization occurs

c. The positive ions and negative electrons separate

d. The electrons diffuse around the anode wire, the ion cloud resembles a droplet

e. The electrons reach the anode wire (timescale of ns) and the ions drift slowly to the cathode generating the avalanche signal at the electrodes. Signal almost entirely due to ions!

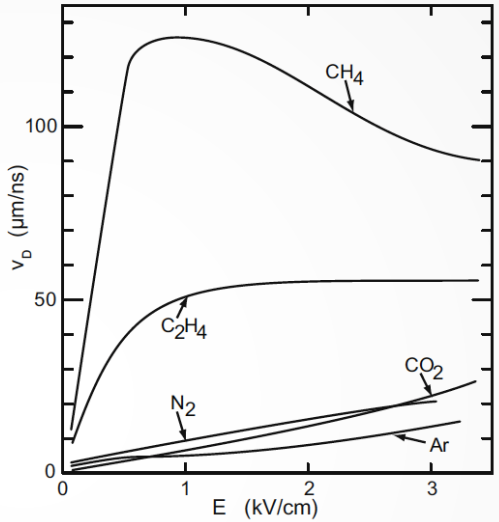


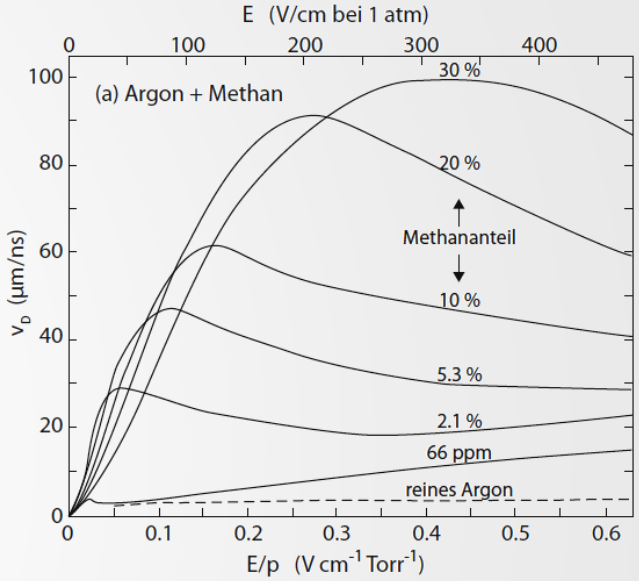
The potential in a cylindrical tube predicts (example on the previous slide):

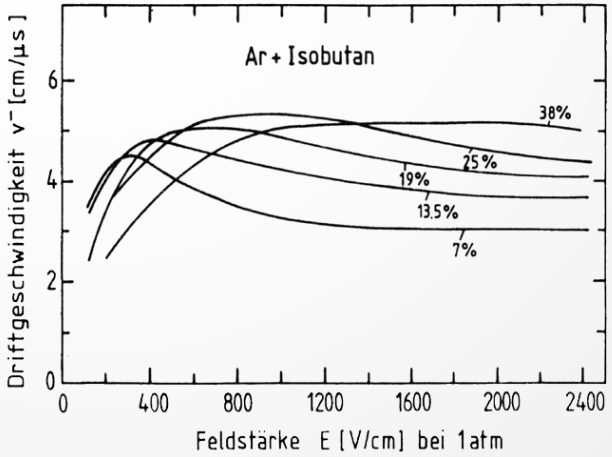
$$\frac{V^-}{V^+} = \frac{\ln\left(\frac{a+r_{\mathrm{krit}}}{a}\right)}{\ln\left(\frac{b}{a+r_{\mathrm{krit}}}\right)} \approx 1.4\,\%$$

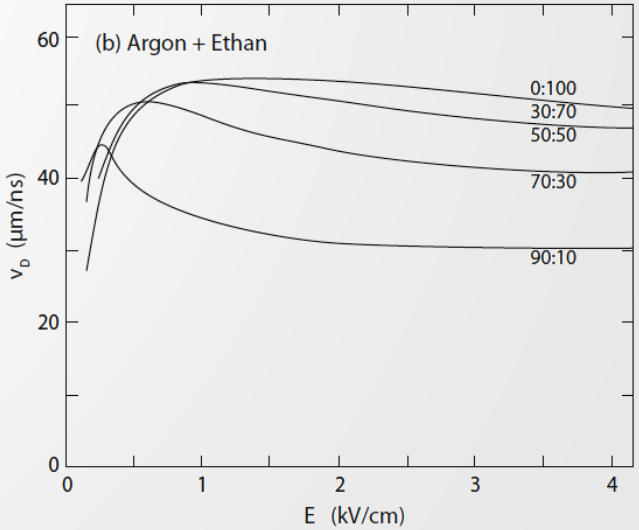
2.5 DRIFT VELOCITIES AND CHOICE OF GAS

- for high signal: need high ionisation density
  - noble gases Ar, Kr, Xe, also CO_2, CF_4, DME.
  - Impurities from electronegative gases (e.g. O_2) are critical, these capture electrons, form slowly moving ions, and attenuate the signal
  - Ar is a good compromise between low multiple scattering (favoring low Z) and high ionization density (favoring high Z, e.g Xe).
- Pure noble gases can not be operated stably because they do not absorb photons created in the amplification process. These can cause further ionization!
  - Ar de-excites by 11.6 eV photon ⟶ ionize copper electrode (7.7 eV) ⟶ new avalanche
- Need to add molecular quencher gas with a broad absorption spectrum to absorb photons



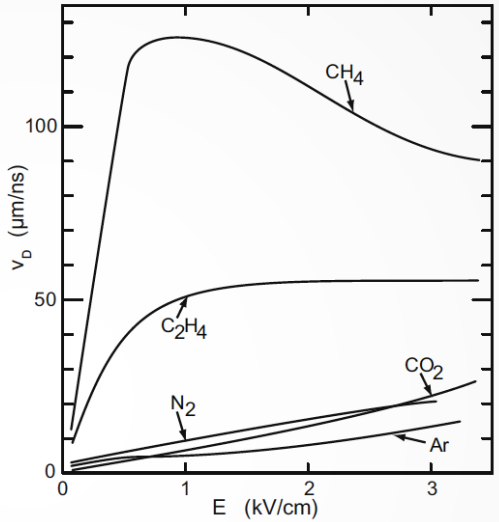


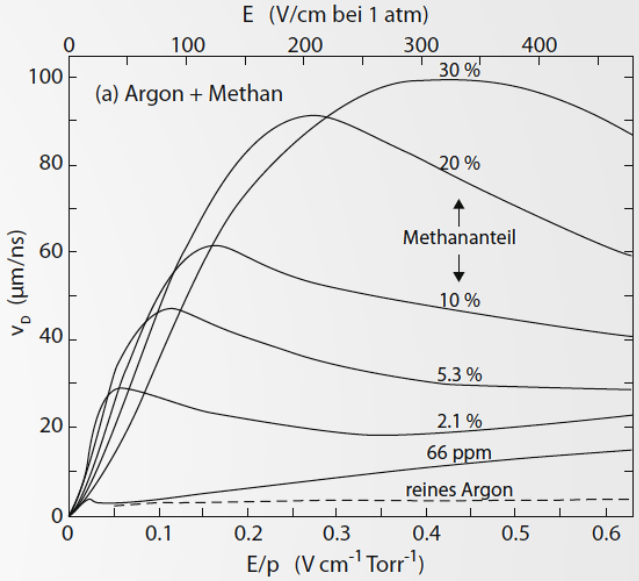


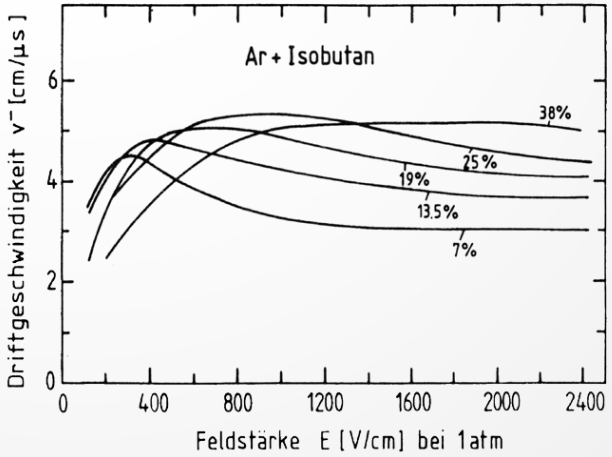


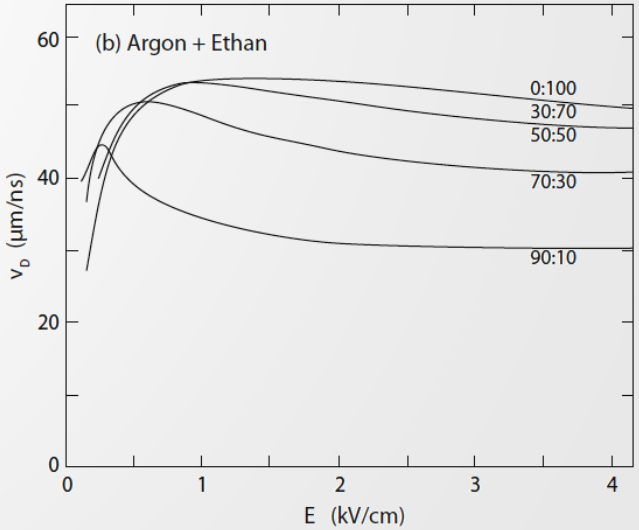
2.5 DRIFT VELOCITIES AND CHOICE OF GAS

- Benefit: limits (=stabilize) drift velocity when the E field varies.
  - High inelastic cross section at higher energies and non-radiatively energy transfer among gas molecules
  - constant drift velocity in inhomogeneous fields
  - very important tuning in drift chambers
  - Plots: v_{drift} in pure gases (top left) and different Ar mixtures (and units…)
- Kr and Xe have short radiation length which
  - disadvantage for tracking detectors
  - advantage for photo detection
- Other design criteria:
  - polymerization (main lifetime limitation) of the gas during operation
  - toxicity, cost, …







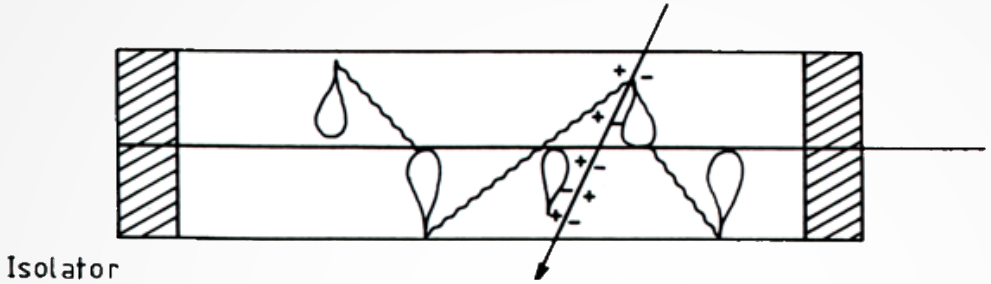


3. DETECTOR APPLICATIONS

3.1 GEIGER MÜLLER COUNTER

C. Grupen, Teilchendetektoren, B.I. Wissenschaftsverlag, 1993

- Is the electric field large enough, the detector is operating in the Geiger-Müller mode.



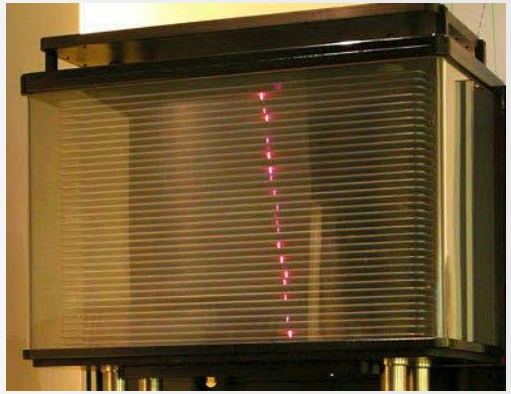
charged particle

- The UV photons are spreading transversal to the field and create photoelectrons in the whole gas volume. The discharge is no longer localized and avalanches are created everywhere.
- The produced total charge is independent from the primary ionization. The charge depends only on the capacitance of the counter and the applied voltage.
- Gas amplification in Geiger-Müller mode is 10^8 to 10^{10}, depending on the gas mixture.
- The e^- are collected quickly, whereas the positive ions create a plasma tubes (space charge) along the anode wire
  - reduce field around the wire and prevent secondary ionization
  - ions drift slowly to the cathode (~ 1 ms), where they may create secondary e^-
  - avalanche production continues.

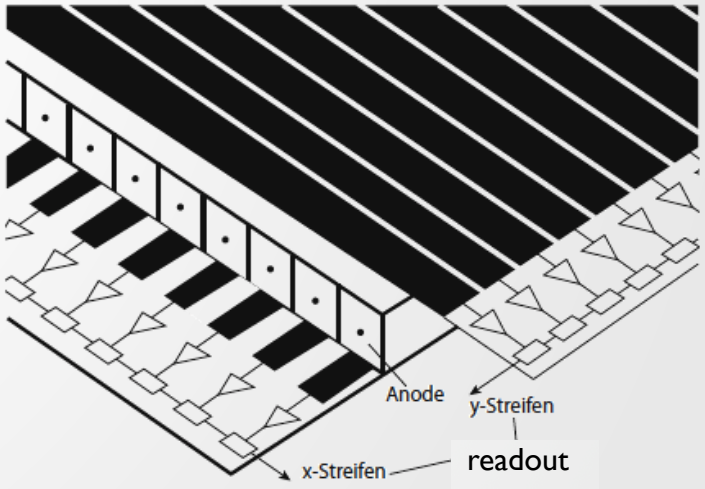
3.2 SPARK CHAMBERS

- A discharge has to be stopped. Various methods are used:
- Charging resistor reducing the high voltage to U_0–IR.
  Time constant RC must be long enough to allow all ions to reach the cathode
  - very long detector dead time of ~10 ms.
- Change of polarity for a short time
  - ions created close to the anode are then absorbed quickly
  - This is the operation mode of many spark chambers, consisting of parallel planes
  - These detectors are mostly used for outreach purposes
- Streamer chambers: pulsed operation allow short dead time and avoid spark
  - shorter dead time ~10 µs, used e.g. in Streamer chambers
    - Cheap detectors for low occupancy and large volumes. Wires run in rectangular plastic pipes. The streamer influences a signal on the x- and y readout strips.
  - methane (CH_4), ethane (C_2H_6), isobutane, ethanol, "quencher" gases mixed in
  - The absorption of UV photons reduces range to O(100µm) within the anode

Spark chamber



Streamer chambers in plastic boxes with readout of influenced signal



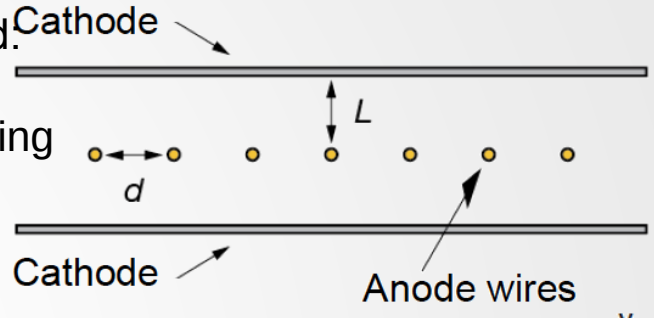
3.3 MULTI WIRE PROPORTIONAL CHAMBER

W.R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer, 1987

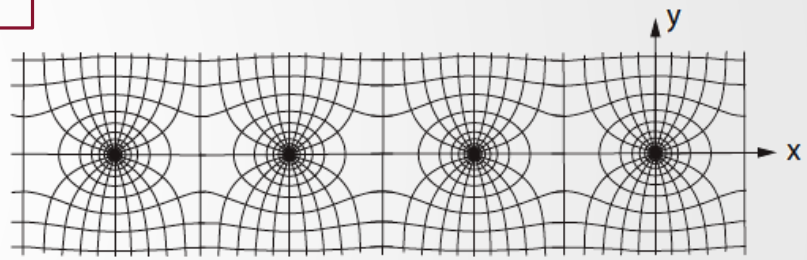
- Geometry of a MWPC:
  row of proportional counters without walls
  - Diameter of anode wires 10 – 50 µm
  - Distances between wires 1 – 5 mm
  - Each wire connected to an amplifier
  - Typical gas amplification in MWPC is 10^5
  - Max. particle rate ~10 kHz/mm^2
  - used consecutively, rotated by 90°: measure full track
  - mostly replaced by drift chambers (higher resolution, fewer channels)

'magic' gas mixture is often used:

75% Ar	large signal
+ 24% Isobutan	fast quenching
+ 0.5% Freon (CCl_2F_2)	(e-negative) fast decay of the signal

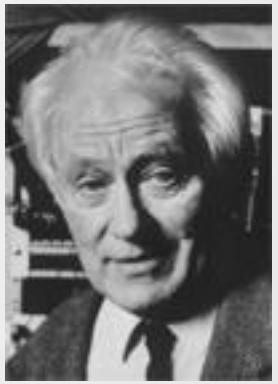


typical electrostatic potential in an MWPC



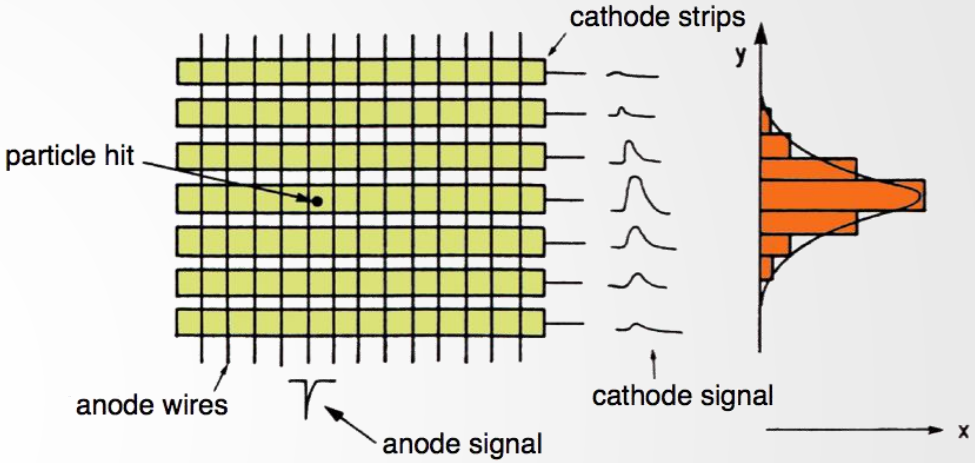
- Operating in proportionality mode improves position resolution
  - The measured position depends on wire distance e.g. for d = 2 mm
  - By simply using the wire position: $\sigma_x \approx d/\sqrt{12} \approx 500\ \mu m$
  - Using also the center of charge calculation: 50 μm achievable.
  - Proportional mode also reduces dead-time (small signal, fast re-charge of electrodes)

MWPC was the first electronic detector (1968)!
Georges Charpak (1924-2010)
Nobel prize 1992

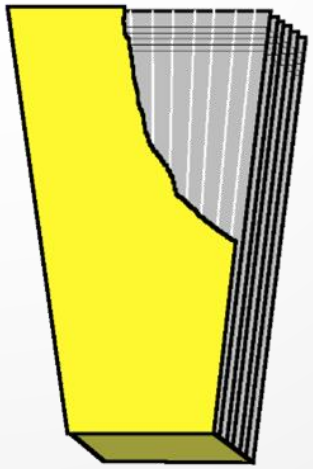


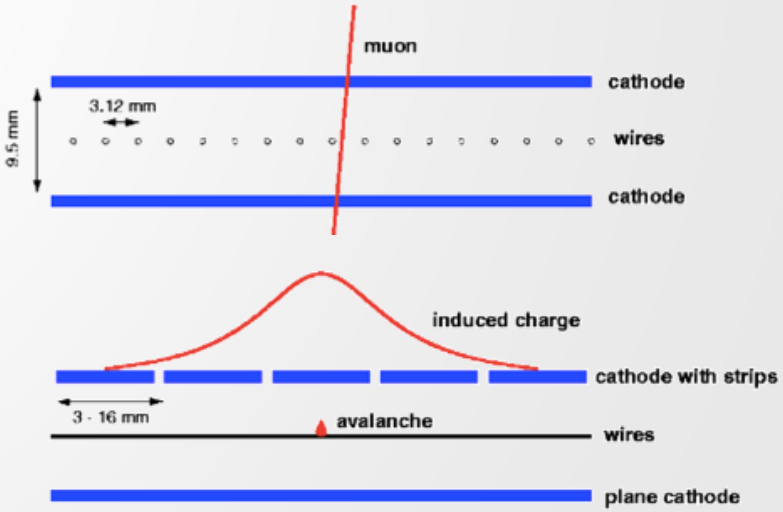
3.4 CATHODE STRIP CHAMBER (CSC)

- A MWPC can only measure the coordinate perpendicular to the wires. No position measurement along the wires.
- If the cathode is segmented perpendicular to the wires, the signal induced can be used to determine the second coordinate.
- Example: CSC system of the CMS detector
  - 7 trapezidoal panels for 6 gas gaps
  - 40% Ar 50% CO_2 10% CF_4
  - main muon detector in the endcap
  - good compromise of spatial-, time and trigger capability
- Application of proportional chambers (CSC, MWPC):
  - Trigger applications (fast, large area)
  - for tracking, drift tubes are often preferred because of their better position resolution
  - with photosensitive addons (gas or coating of electrodes) used as photo-detectors for e.g. Čerenkov or transition radiation



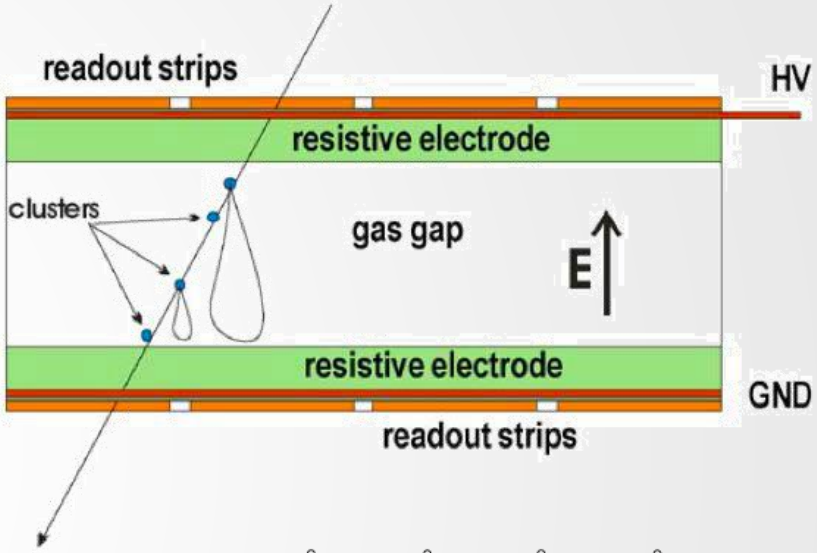
wedge of CSC detectors in CMS endcap

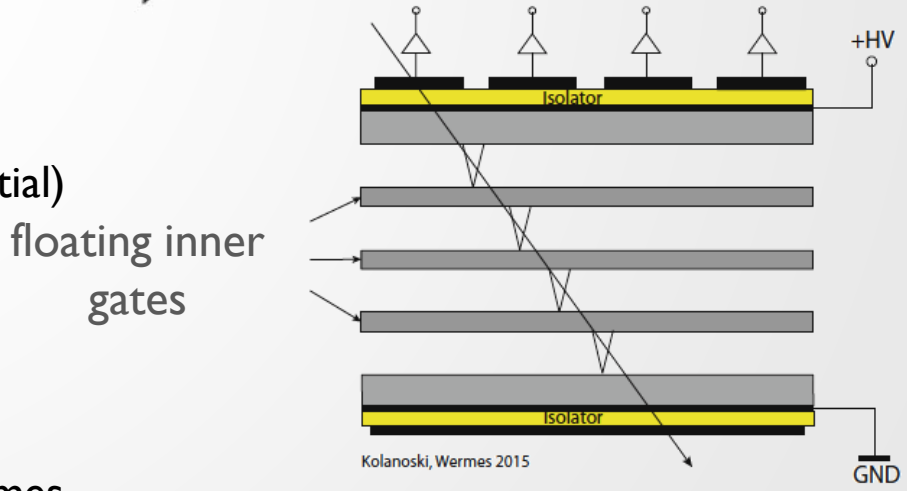




3.5 RESISTIVE PLATE CHAMBERS (RPC)

- Simple construction, usually operated at normal pressure
  - Gas gap typically 0.3 - 2 mm, trade-off between signal strength and timing
  - highly resistive electrodes made of Bakelite plates, covered with a thin layer of Melamine (isolator)
  - electrodes apply high voltage and insulated from the read-out electrodes
- operated in avalanche mode or streamer mode
  - the signal current reduces the gap voltage : $U_{gap} - IR$
  - high gas amplification leads to fast self-quenching, high rate capacity
- large area detectors are possible – 'cheap' detectors
  - Space resolution ~ mm from influenced charge in readout strips
  - Very fast timing (~ 1 ns) (high gas ionization and fast quenching essential)
  - sufficient high rate capability (~ 100 Hz/cm^2)
- ideal devices for trigger detectors (e.g. used in CMS)
- multi-gap RPCs have floating inner gates
  - current conservation stabilizes the discharge in the different gas volumes, improving timing resolution to 20-50 ps. Used e.g. in the Alice TOF.



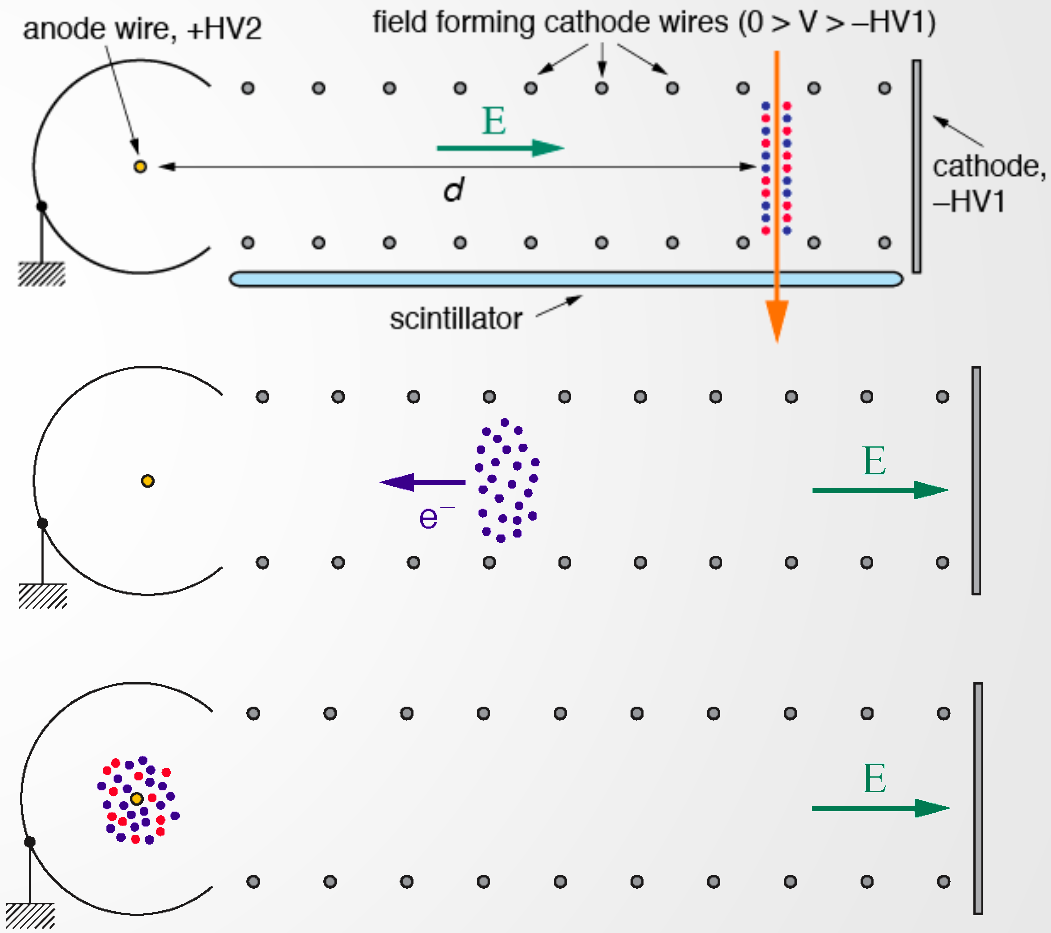


3.6 DRIFT CHAMBERS (DC)

- Operating principle:
  Take into account e^- drift time and separate drift and amplification

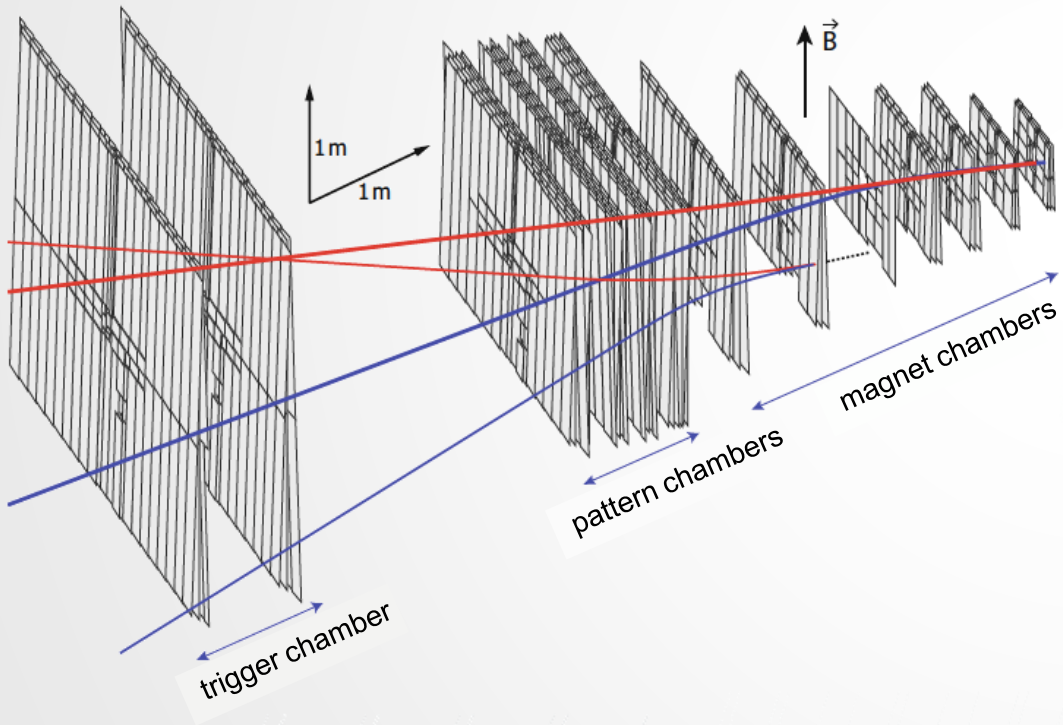
1. Charged particle traversing the chamber produce ionization.
   - Need to be supplemented with e.g. an scintillator signal that starts a timer ($t = t_0$), or
   - other subdetector components provide a trigger.
2. Electrons drift to the anode wire.
3. Electrons reaching the wire create secondary ionization (avalanche) and trigger a signal ($t = t_1$).

- From the time difference the distance of the traversing particle to the wire is deduced:
  - $\Delta t = t_1 - t_0$, $x = v \cdot \Delta t$

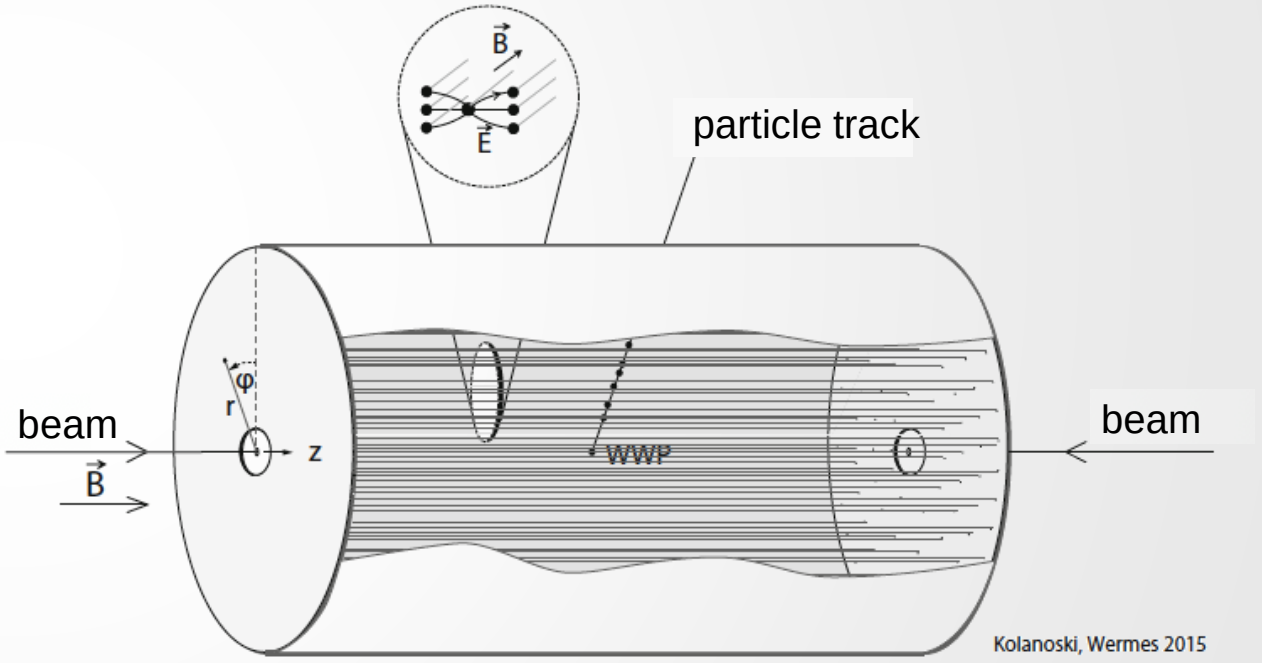


3.6 DRIFT CHAMBERS (DC) - GEOMETRIES

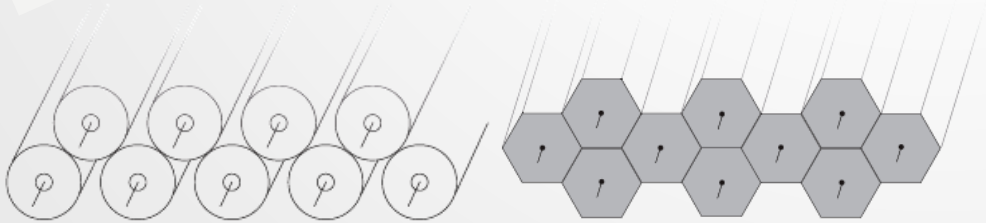
Fixed target (Hera-B outer tracker): planar drift chambers, partially tilted, wires orthogonal to the beam



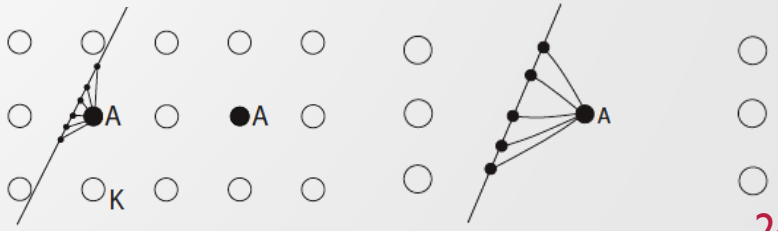
Cylindrical drift chamber with cathode and anode wires parallel to the beam.



different pipes: round and hexagonal

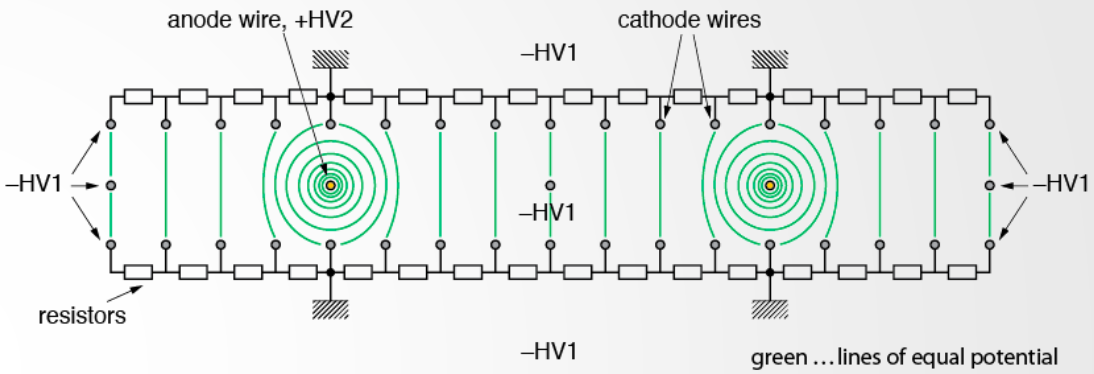


different cathode (K) and anode (A) wire assemblies:

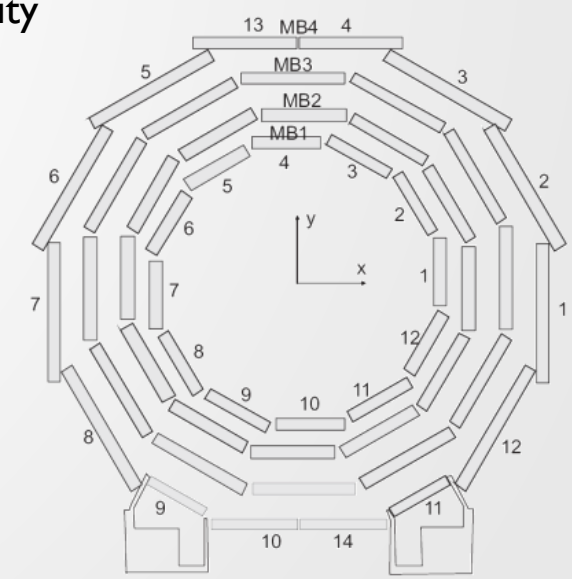


3.6 DRIFT CHAMBERS (DC)

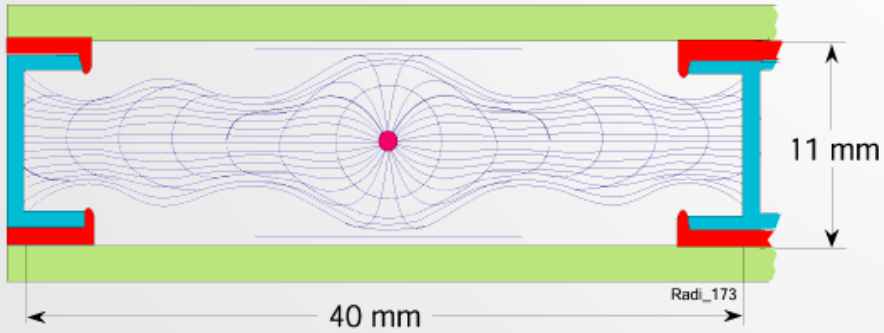
- The electric field has to be homogeneous and the drift velocity constant and known.
- Additional field wires can improve the homogeneity.
- Position resolution for large area chambers ca. 200 µm,
  small chambers as good as 20 µm with O(cm) anode wire distances
- Various gases are used. distinguish between
  - fast gases (high v_D for high particle rates) and
  - slow gases (low v_D for high spatial precision)
- Compared to MWPC: fewer wires and electronic channels, higher precision, but lower rate capability
- Electronegative gas impurities are dangerous and attenuate the signal



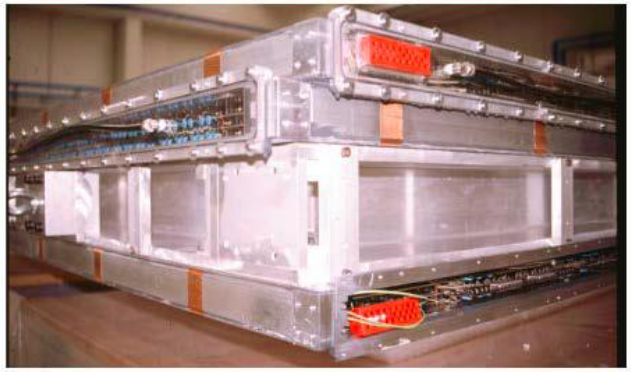
CMS DT system layout



single CMS Muon drift chamber

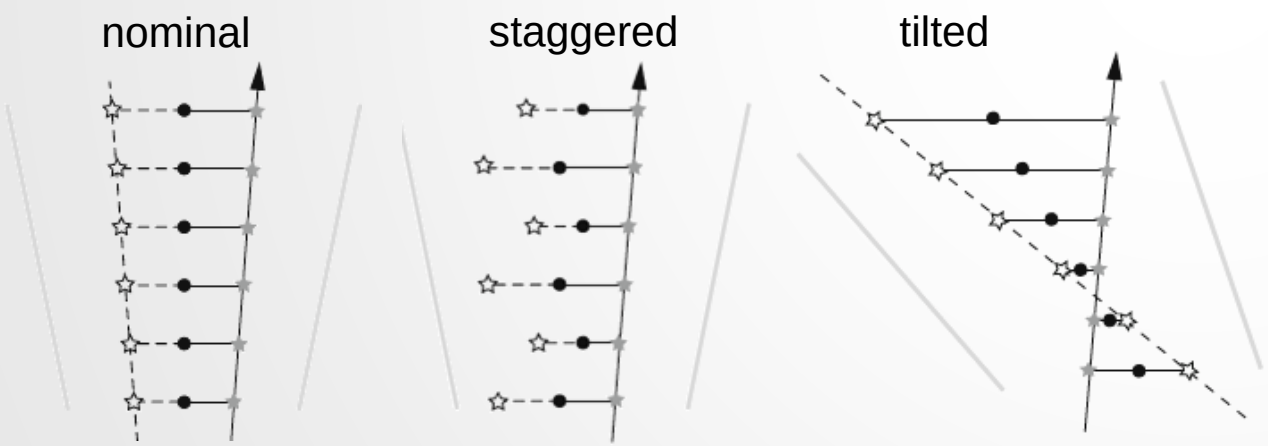


CMS DT holding several chambers:

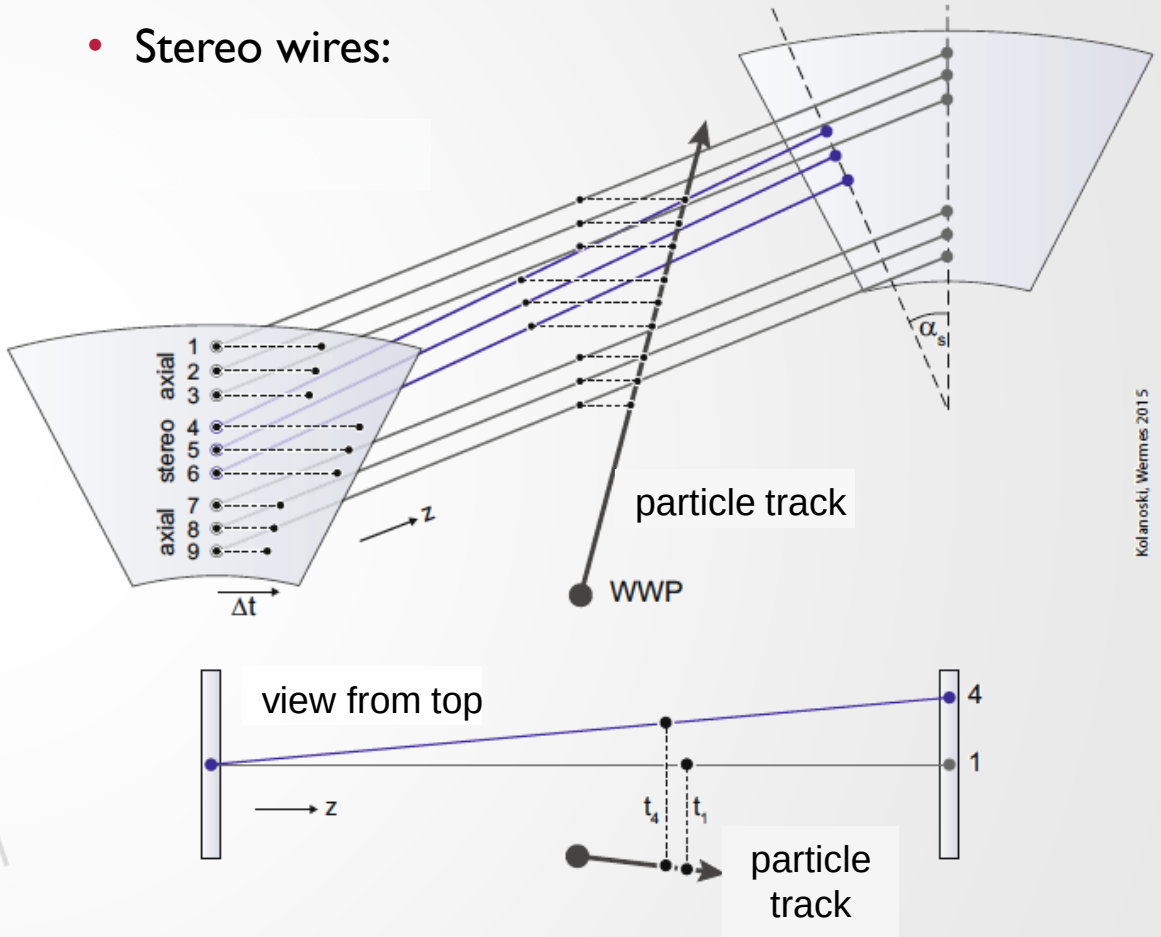


3.6 DRIFT CHAMBERS (DC)

- Track reconstruction in (here: cylindrical) drift chambers can resolve in ambiguities (left)
- Staggering helps resolve the left/right ambiguity (middle)
- Tilting in the radial direction causes the mirror track to point away from the interaction vertex (right)



- Stereo wires:

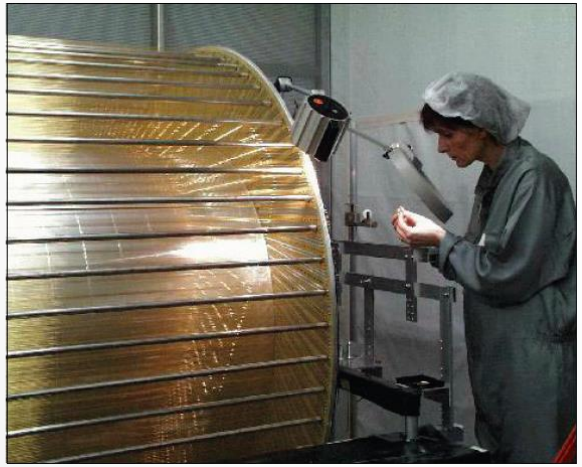


- If some of the wires are placed under a 'stereo angle', the resulting drift time differences can be used to measure the z coordinate.

3.7 EXAMPLES OF CYLINDRICAL DRIFT CHAMBERS

Cylindrical drift chamber
of the H1 experiment
at HERA/DESY

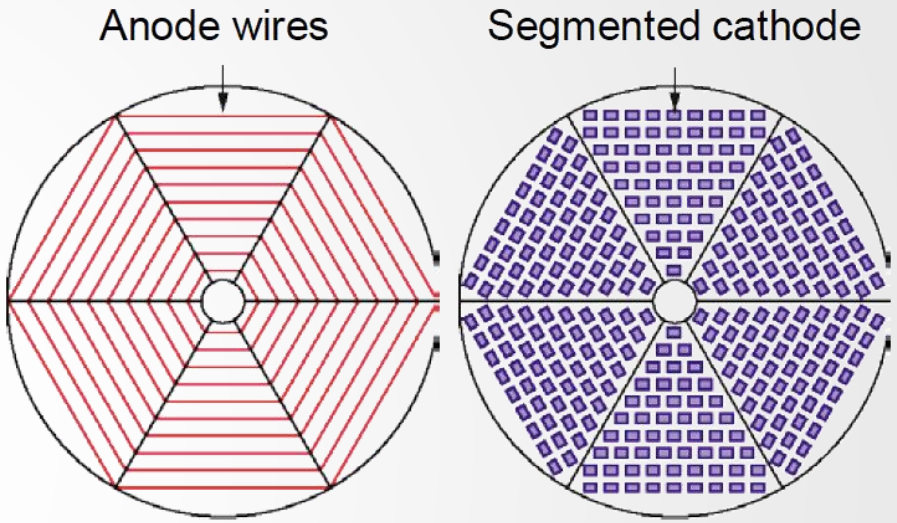
Number of wires: ~ 15000
Total force from wire tension: ~ 6 t

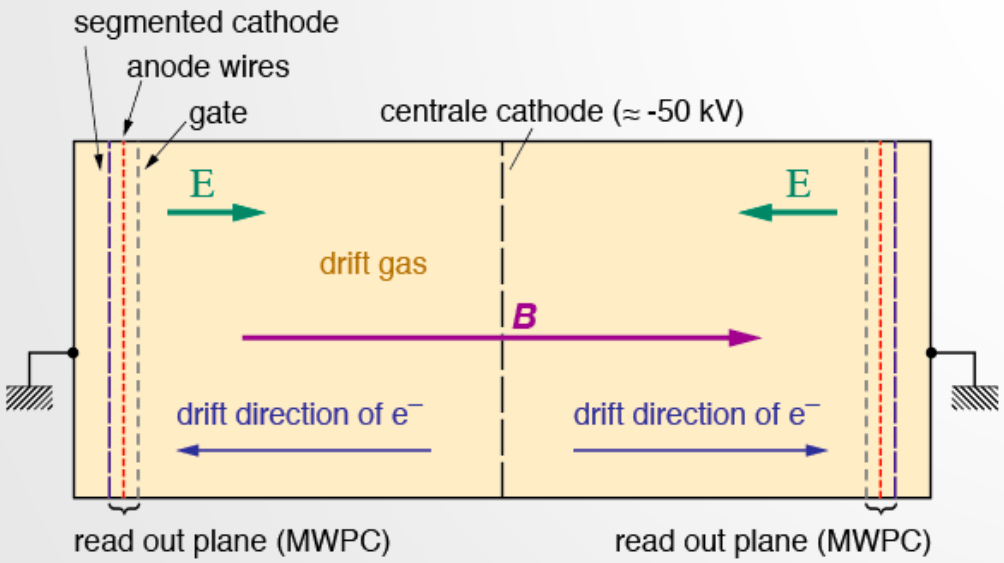


Belle Central drift chamber
50 cylindrical wire layers, 8400 drift cells

3.8 TIME PROJECTION CHAMBER (TPC)

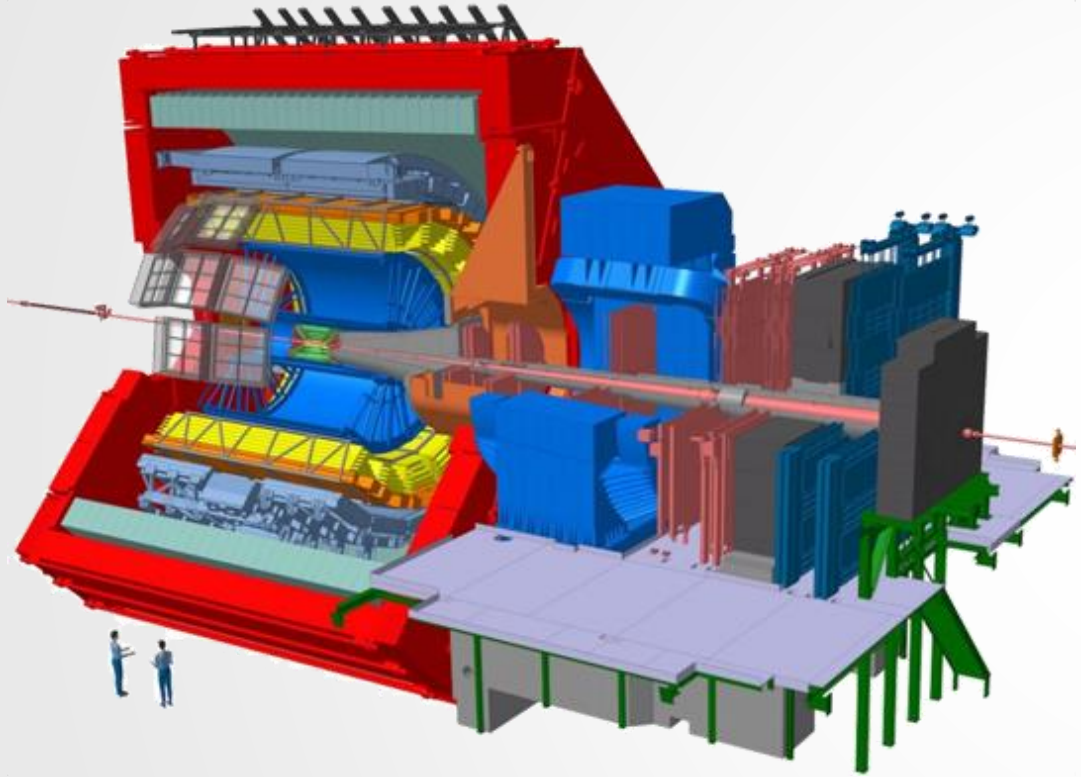
- Principle: (Very) big gas filled volume
  - Usually a central cathode at very high negative voltage
  - On both sides: detectors for 2 dimensions (end plates)
  - Geometry: Electric field created by anode plane and central cathode plane parallel to the magnetic field of the experiment.
  - Charged particles create ionization along the path.

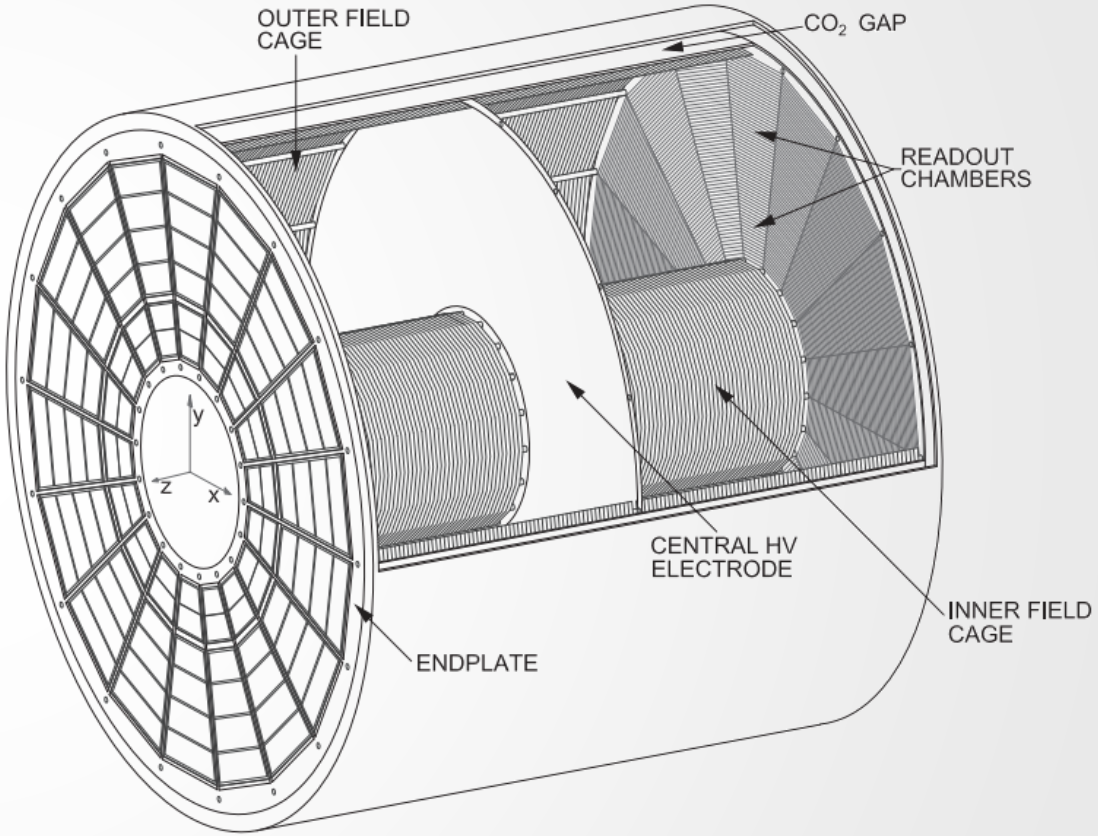




- Electrons drift to the end plates and ions to the central cathode.
- A two dimensional projection of the particles path is measured by the position detectors at the end plates.
- The third coordinate is deduced from the time of arrival of the electrons at the anode wires.
- The gate electrodes are used to absorb ions drifting back (most ions come from the amplification region near the anode wires)

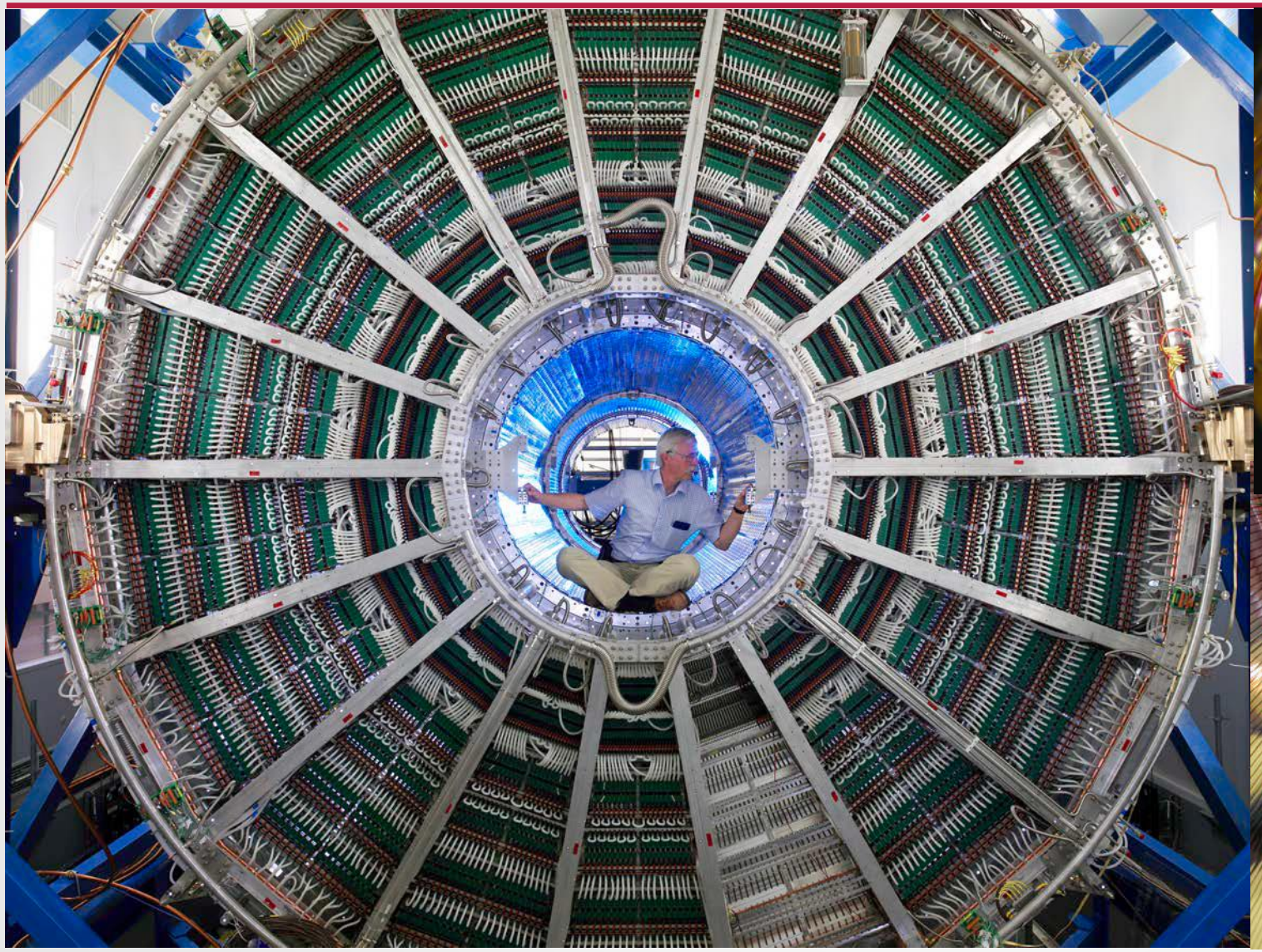
3.9 THE ALICE TPC

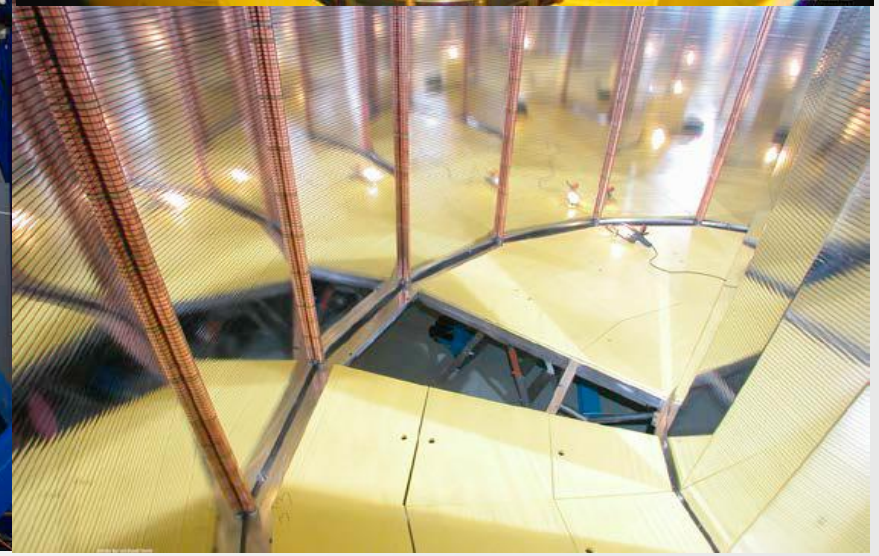




- A TPC can tolerate extreme occupancies – ideal for heavy ion collisions
- Long dead-time of 280 μs implying a principal rate limitation of 3.5 kHz (bandwith is limiting to 300 Hz)
- Gas in the Alice TPC: Ne-CO_2-N_2 to reduce multiple scattering, accept ~40% of the ionization density of Ar.

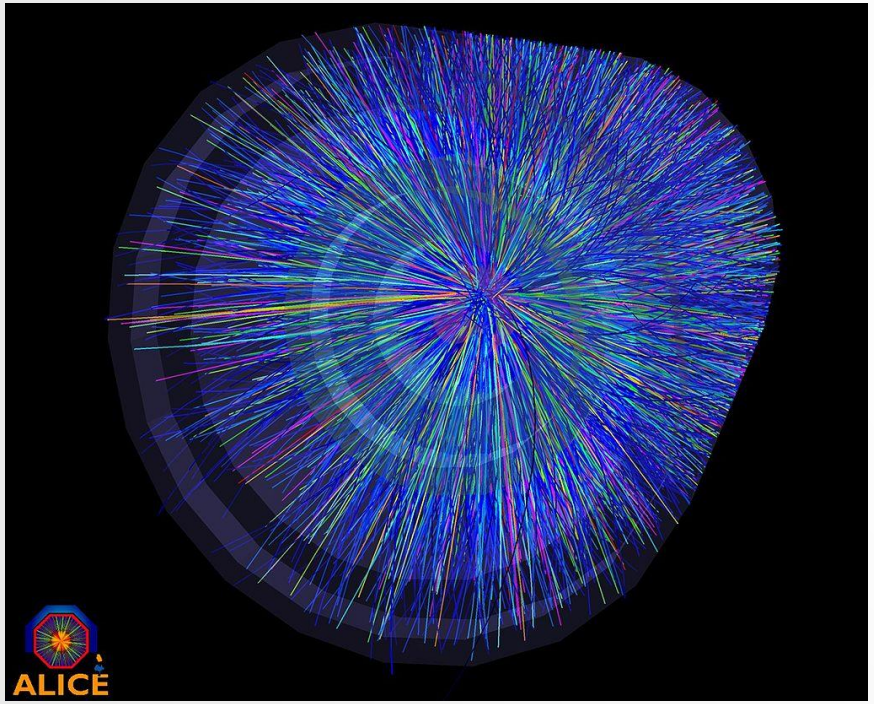
3.9 THE ALICE TPC

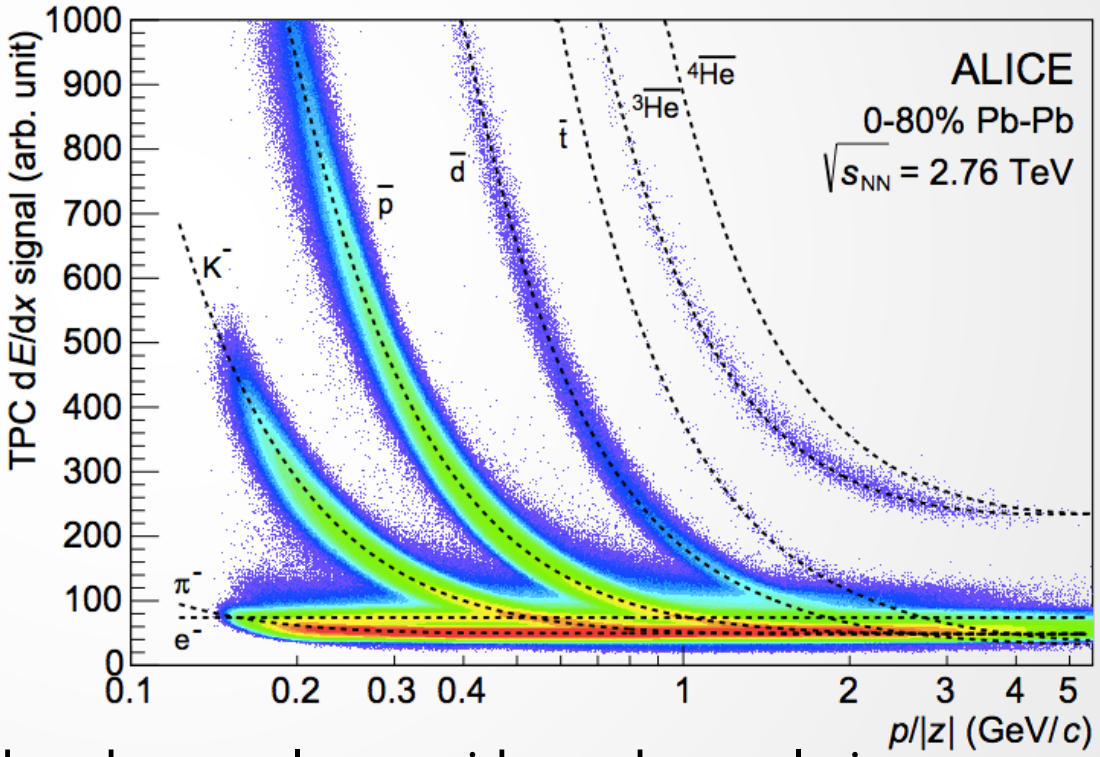




3.9 THE ALICE TPC

- Left: Event display from the first PbPb collisions at 2.36 TeV
- Right: Particle Id with the dE/dx measurement from the TPC in the same data taking period





- cylindrical TPCs often supplemented with other detector layers with good z resolution
- true 3D reconstruction of an event is possible

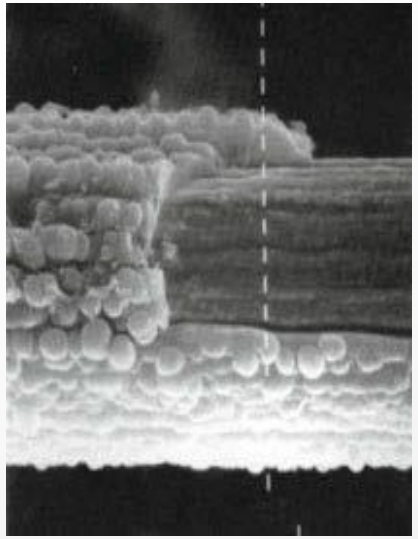
3.10 HISTORY OF DRIFT DETECTORS

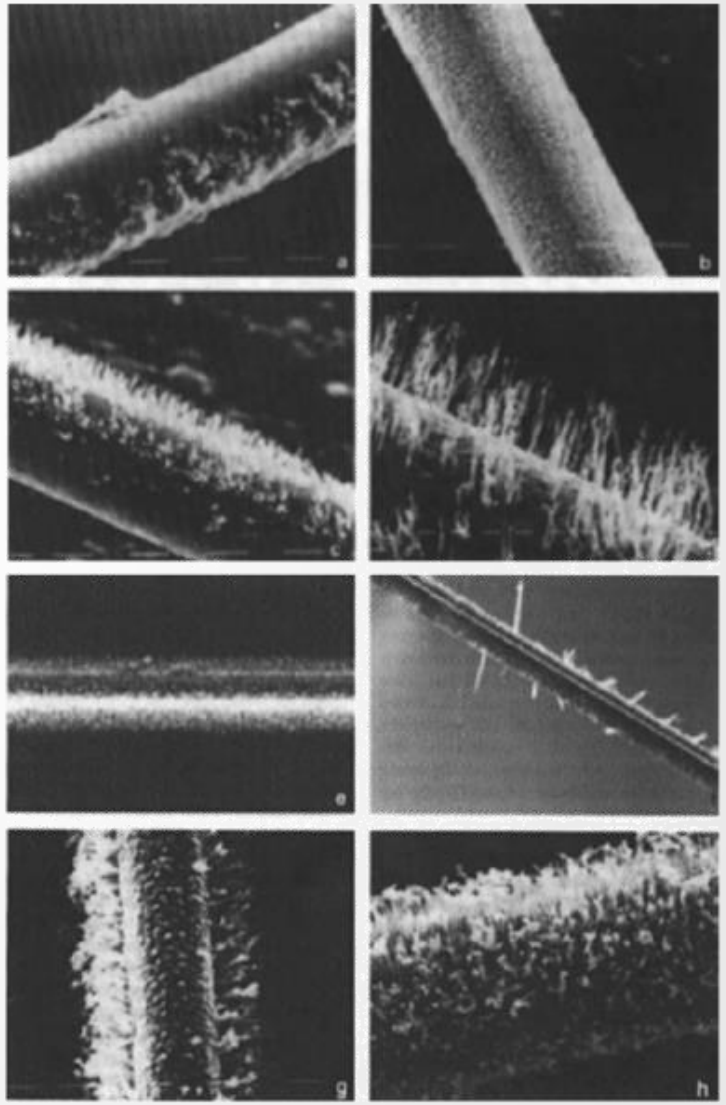
Chamber type	Drift volume	Invented	Inventors
Multi-wire proportional chamber	$\sim$ mm	1968	Georges Charpak then at CERN was awarded the 1992 Nobel Prize in Physics "for his invention and development of particle detectors, in particular the multi-wire proportional chamber".
Drift chamber	$\sim$ cm	1969	Bressani, Charpak, Rahm and Zupancic added a 3cm long drift space to a conventional 12 $\times$ 12 cm multi-wire proportional chamber at CERN.
Time projection chamber	$\sim$ m	1979	The time projection chamber was invented by David Nygren at the Lawrence Berkeley Laboratory. Its first major application was in the PEP-4 detector, which studied 29 GeV e^+e^- collisions at SLAC.

(1984)

3.11 AGING OF WIRES

- Avalanche formation can be considered a micro plasma discharge.
- Consequences:
  - Formation of radicals (molecular fragments)
  - Polymerisation yields long chains of molecules
  - Polymers attach to electrodes
  - Reduction of gas amplification
- Contamination must be avoided!
  - Halogens (electronegative)
  - polymers, silicon, …
  - oil, fat,…
- It's advantageous to avoid wires alltogether…



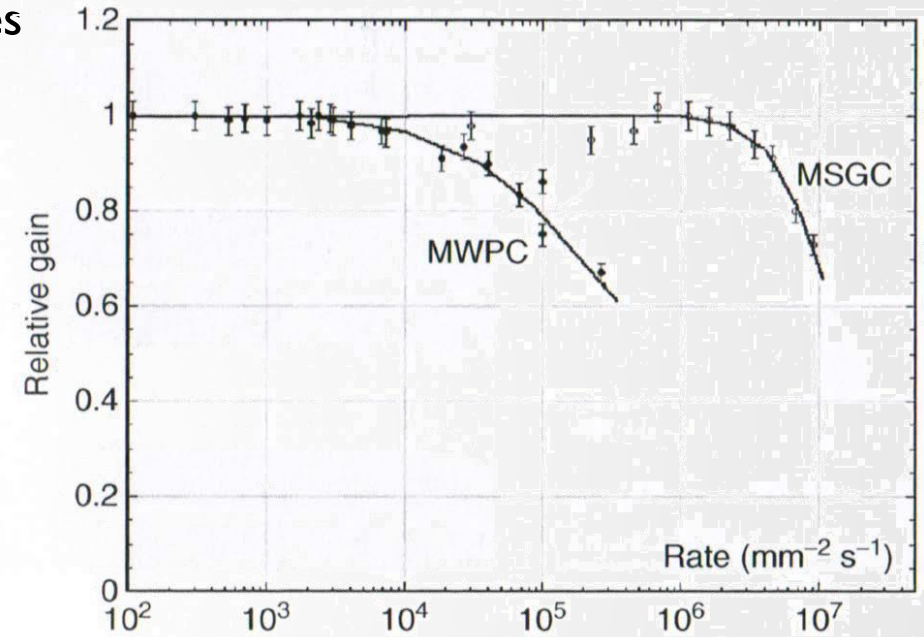


3.12 MICRO PATTERN GAS DETECTORS

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

(MSGC) A. Barr et al., Nucl. Phys. B 61B (1998)

- The separation of hits of particles at high rate experiments requires high granularity of subdetectors. However, gaseous detectors with wires can not be made arbitrary small.
- micropattern gas detectors (MPGD) have
  - No wires – electrodes are deposited materials or printed structures.
    - no risk from catastrophic damage from broken wires
  - Photolithography of these processes allow for very fine structures.
  - Many different detector geometries
  - Smaller cell sizes → improved position resolution ~ 30 µm
  - high rate capability ~ MHz / mm^2
  - small volumina: gas should have high primary ionisation (e.g. DME)
- We'll look at
  - Micro strip gas chambers (MSGC)
  - Gas electron multipliers (GEM)
  - Micromegas

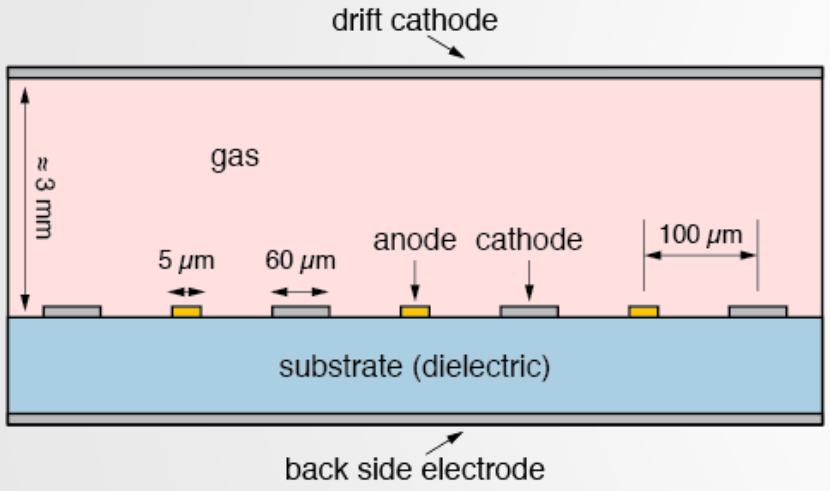


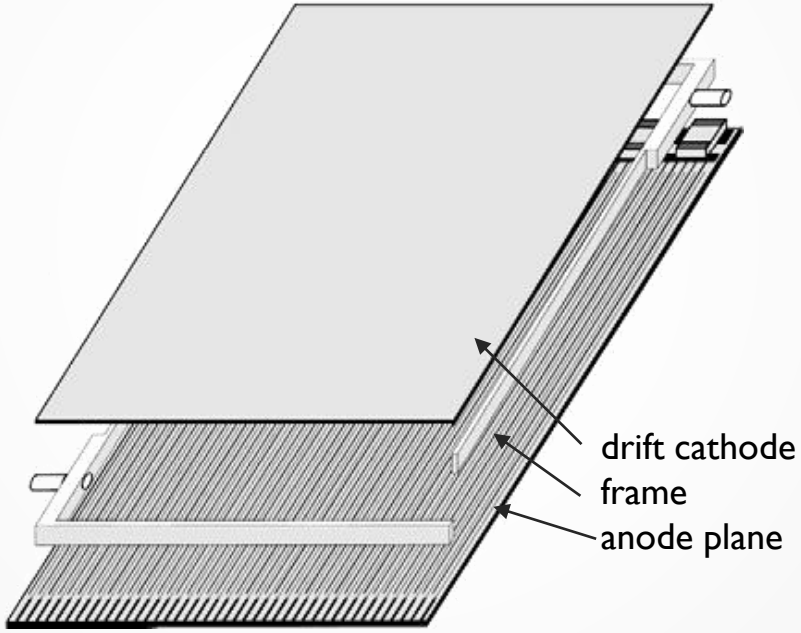
comparison of rate capacity of an MWPC and a MSGC: relative gain vs. rate

- If hits accumulate, spatial charges from ion clouds attenuate the signal. These are greatly reduced by e.g. cathode strips (next slide) that collect the avalanche ions and thus allow much higher rates

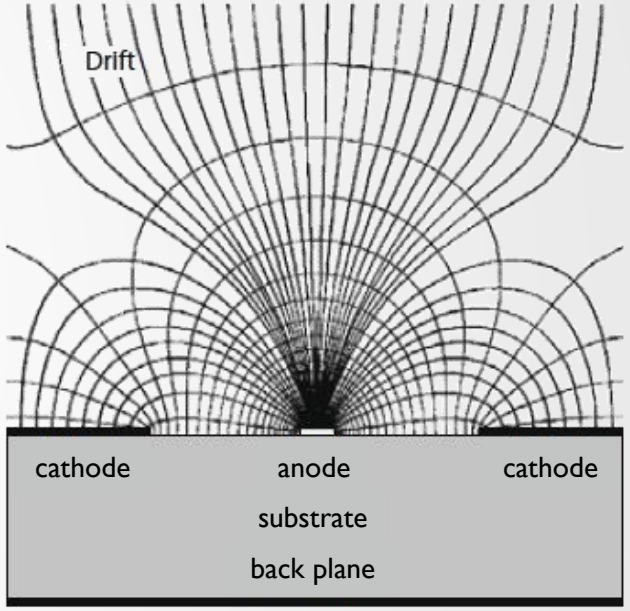
3.13 MICRO STRIP GAS CHAMBER

- Thin amplifying anodes and cathode strips on a substrate (glas, ceramic, plastic)
  - Gas volume above the detector plane, few mm wide
  - Cathode strips improve the field geometry, and collect the ions from the amplification



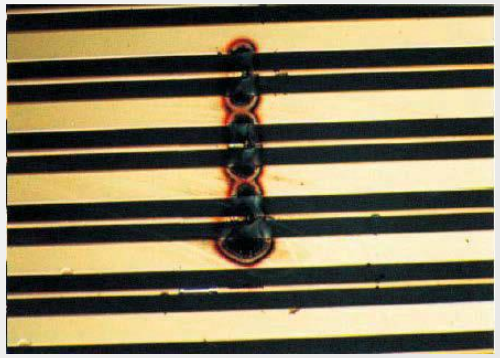


Field lines in a MSGC cell (anode strip in the middle):



- Resolution: 30μm
  - 10x better than MWPC

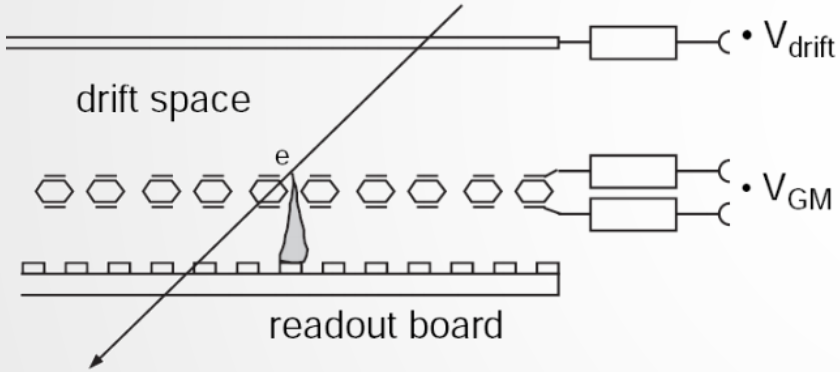
damage from discharge in a MSGC

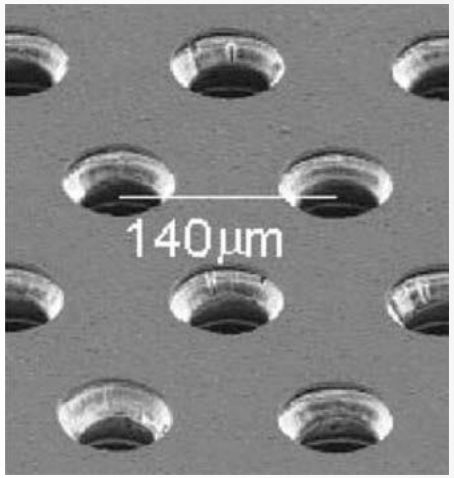


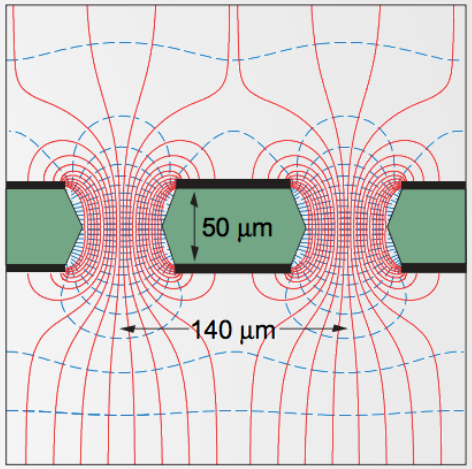
- Problems:
  - Ions accumulate in the isolating substrate leading to inhomogenous gas amplification
  - a rare, highly ionizing (heavy, slow) nucleus creating a damaging discharge. Bethe-Bloch $\propto z^2$!

3.14 GAS ELECTRON MULTIPLIER (GEM)

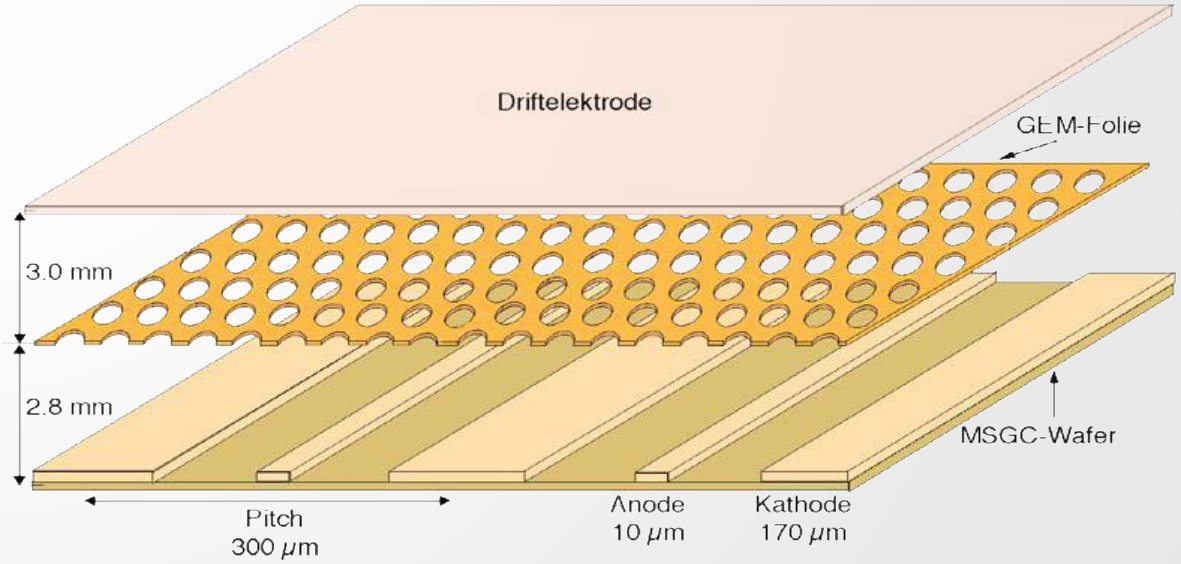
- Improve radiation resistance by separating ionization and amplification structures.
- The gas volume is separated into a drift gap and an induction gap by a GEM foil. No readout of GEM foil, only amplification.
- A MSGC plane (readout board) is underneath.





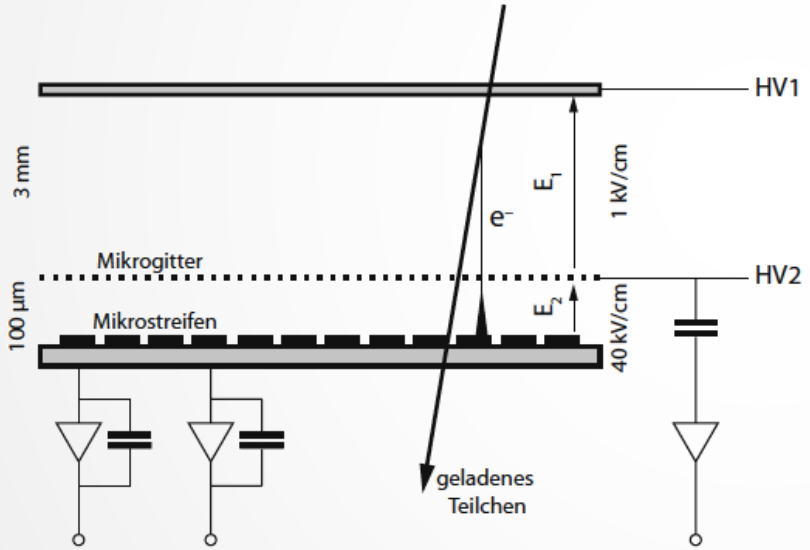


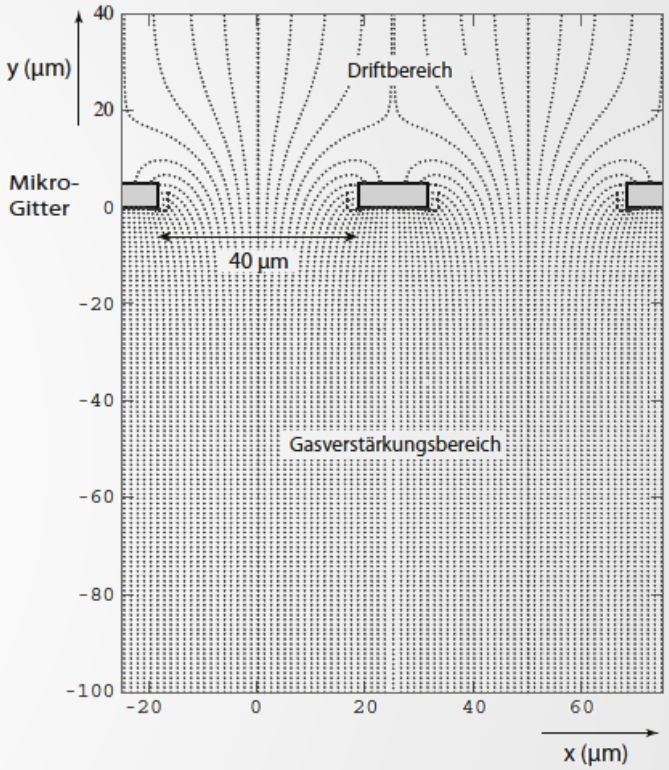
- The foil (e.g. 50 µm thickness) is metalized on both sides and has a pattern of holes (e.g. 70 µm with a 140 µm pitch).
- A high voltage (≈ 400 V) applied on the two faces of the foil creates a high field. Triple foils are common with $G=10^4$ - 10^5
- electron multiplication takes place in the holes

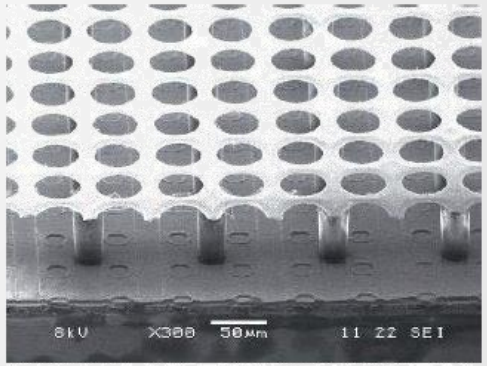


3.15 MICROMEGAS

- Micro Mesh Gaseous structure (Micromegas)
- Separate ionization region (3mm) from amplification region (100 μm)
- Fast signal: Collect electrons within 1ns and ions on the mesh within 100ns







- allows homogenous readout and integration with CMOS pixel readout chips
- 100μm spatial resolution achievable
- used e.g. for tracking in the COMPASS experiment

3.16 SUMMARY- TIME AND SPATIAL RESOLUTION

Pdg Review 2017

Detector Type	Intrinsinc Spatial Resolution (rms)	Time Resolution	Dead Time
Resistive plate chamber	$\lesssim 10$ mm	1 ns (50 ps[a])	—
Streamer chamber	300 μm[b]	2 μs	100 ms
Liquid argon drift [7]	$\sim$175–450 μm	$\sim$ 200 ns	$\sim$ 2 μs
Scintillation tracker	$\sim$100 μm	100 ps/n[c]	10 ns
Bubble chamber	10–150 μm	1 ms	50 ms[d]
Proportional chamber	50–100 μm[e]	2 ns	20-200 ns
Drift chamber	50–100 μm	2 ns[f]	20-100 ns
Micro-pattern gas detectors	30–40 μm	$<$ 10 ns	10-100 ns
Silicon strip	pitch/(3 to 7)[g]	few ns[h]	$\lesssim$50 ns[h]
Silicon pixel	$\lesssim 10$ μm	few ns[h]	$\lesssim$50 ns[h]
Emulsion	1 μm	—	—

[a] For multiple-gap RPCs.
[b] 300 μm is for 1 mm pitch (wirespacing/$\sqrt{12}$).
[c] n = index of refraction.
[d] Multiple pulsing time.
[e] Delay line cathode readout can give $\pm$150 μm parallel to anode wire.
[f] For two chambers.
[g] The highest resolution ("7") is obtained for small-pitch detectors ($\lesssim$25 μm) with pulse-height-weighted center finding.
[h] Limited by the readout electronics [8].

And here is what we've not discussed:

- Liquid argon drift chambers (e.g. MiniBoone)
- Bubble Chambers
- Nuclear emulsion: Discovery of nuclear spallation (Mariette Blau, Herta Wambacher)

THE END!