5. Tracking Detectors

5.1 Momentum reconstruction in a magnetic field

5.2 Magnetic spectrometers

5.3 Multi-wire proportional chambers

5.4 Drift chambers

5.5 Time projection chambers

5.6 Microstrip gas chambers

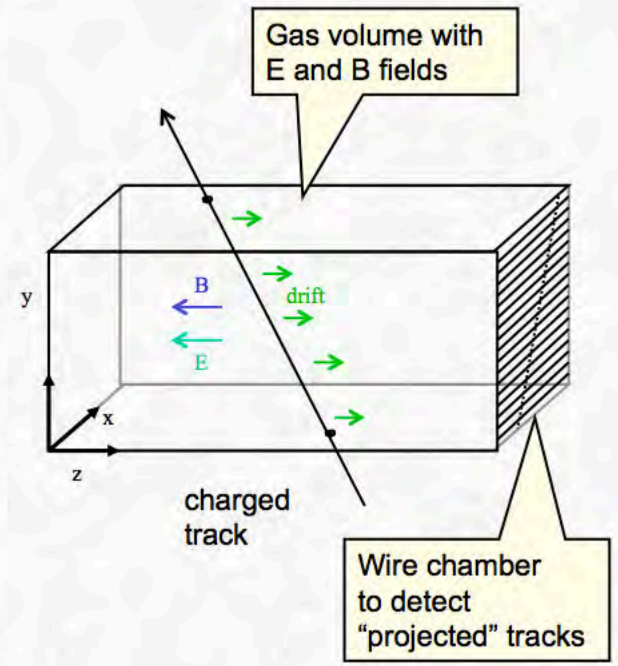
5.7 Ageing of gas detectors

Silicon-based tracking detectors are discussed in Chapter 6
(together with impact parameter resolutions)

5.5 Time Projection Chambers (TPC)

- Basic idea: measure the drift time over large distances in a large gas-filled detector volume

  → no wires, readout at the endplate of the chamber



Time Projection Chamber

Ingredients:

– Gas

E.g.: Ar + (10 - 20 %) CH_4

– E-field

E ~ 100 to 200 V/cm

– B-field

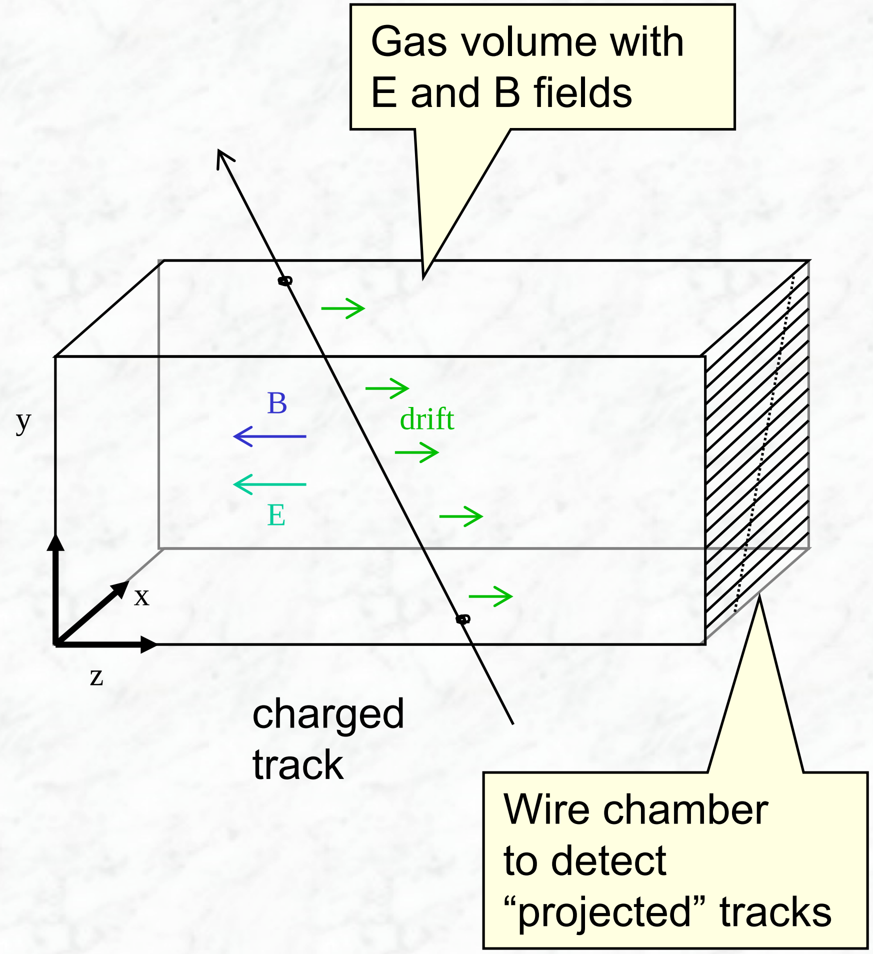
as large as possible to measure momentum and to limit the transverse electron diffusion

$$D_T(B) = \frac{D_T(0)}{1+\omega^2\tau^2}$$

– Wire chamber

(MWPC or MSGC/GEM (→ later))

to detect projected tracks



Principle of Time Projection Chambers (TPC)

- Full 3D track reconstruction
  (x-y)-coordinates from readout on the two endplates

  z-coordinate from drift time

- TPC setup:
  (Mostly) cylindrical detector
  typical dimensions: L = 2 – 4 m
  R = 1 – 2 m

  Central HV cathode (-50 – 100 kV)

- No active detector elements in the large drift volume, except gas (for ionization)

  → largely reduced material (multiple scattering)

central electrode (~50 kV)

dout plane

s

- E-Field parallel to B-field
  (for solenoid magnets)

  → no (E x B) effect

  Drift of electrons is parallel to E-field
  (see Chapter 4.3) since (E || B)

central electrode (~50 kV)

dout plane

Reminder:

$$\vec{v}_D = \frac{\mu|\vec{E}|}{1+\omega^2\tau^2}\left[\hat{\vec{E}} + \overbrace{\omega\tau\hat{\vec{E}}\times\hat{\vec{B}}}^{\text{Component } \perp \text{ to E,B}} + \overbrace{\omega^2\tau^2(\hat{\vec{E}}\cdot\hat{\vec{B}})\hat{\vec{B}}}^{\text{Component in direction of B}}\right]$$

Drift parallel to B suppresses the transverse diffusion

→ drift over long distances possible, without large diffusion and thereby reduced spatial resolution

- drift distances can be several meters, long drift times O(μs)

→ continuous sampling of induced charge in endplate detectors necessary

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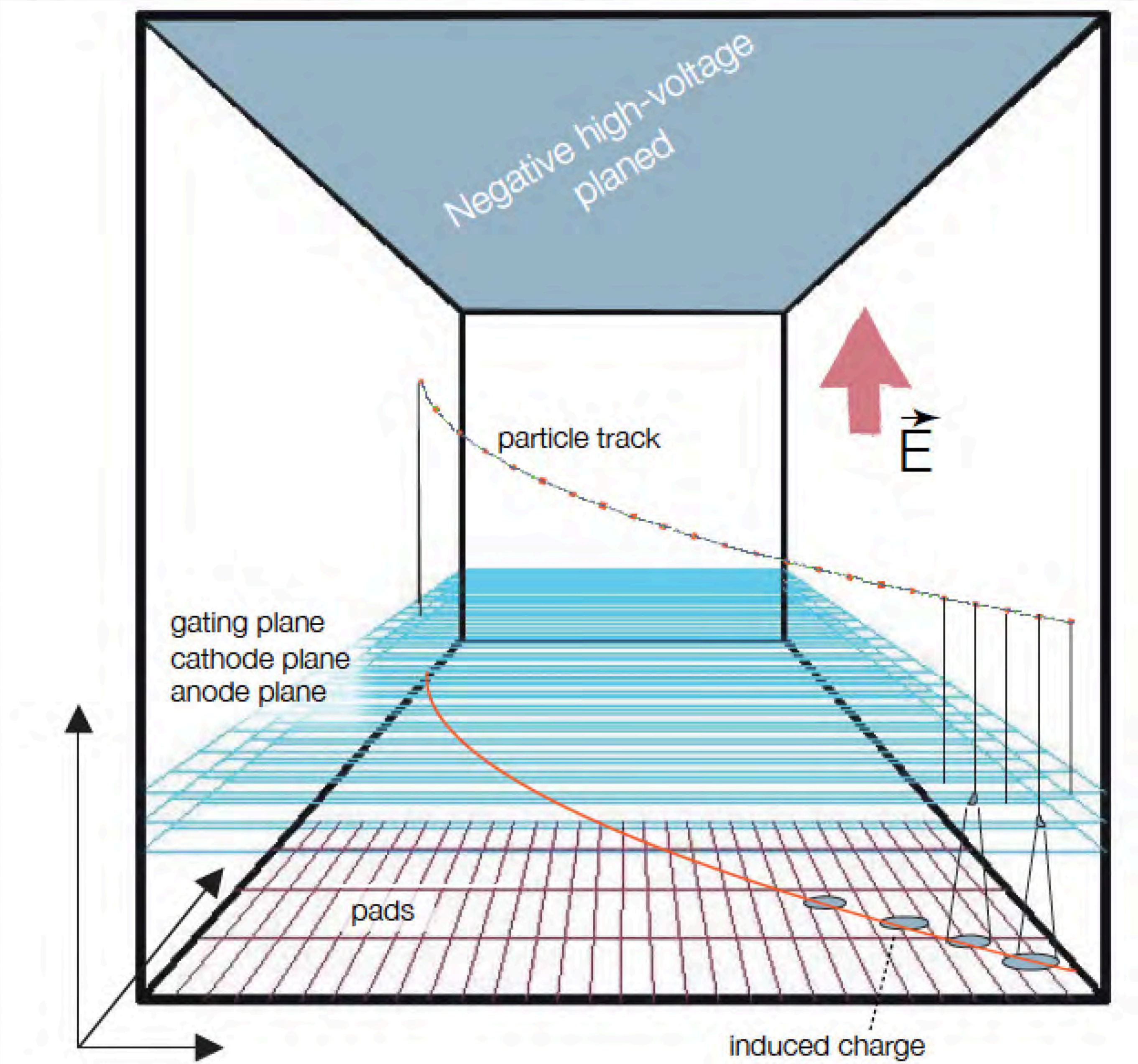
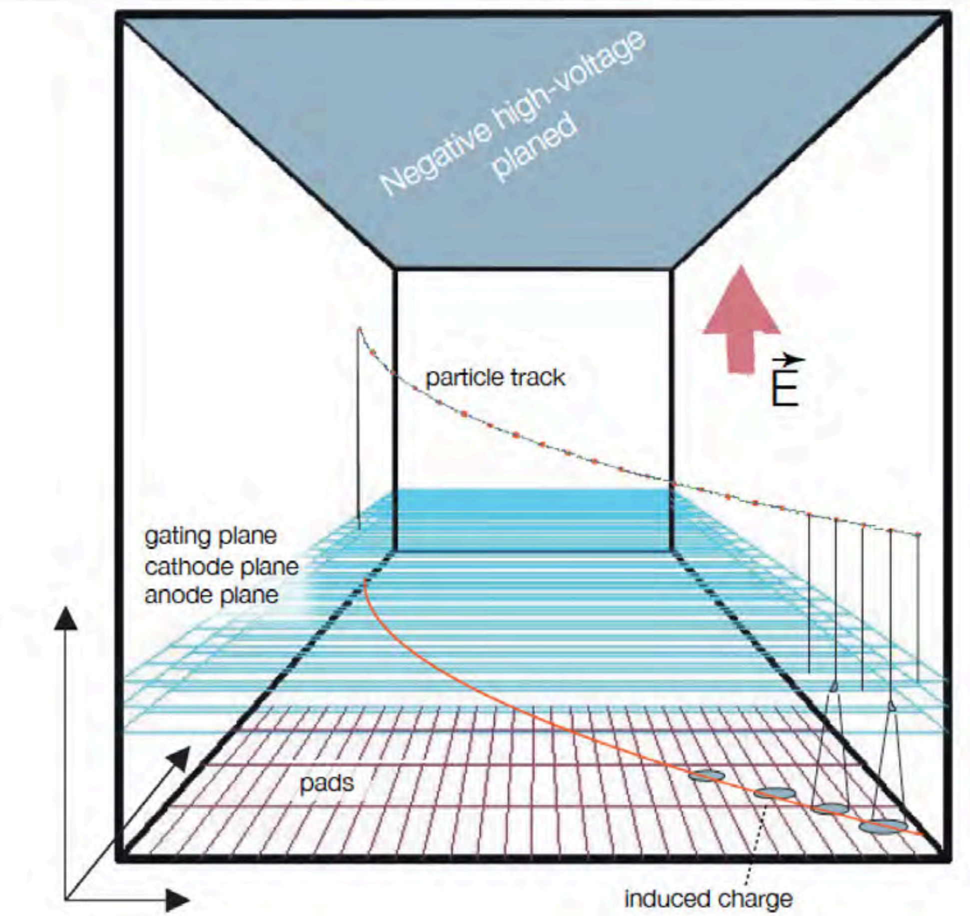

Negative high-voltage
planed
particle track
E
gating plane
cathode plane
anode plane
pads
induced charge



Advantages:

- Complete track reconstructed ("3D picture") with relatively good resolution on all coordinates and a large number of measurements

typical values (endplate with MWPC):
(r-ϕ): 150 – 200 μm (anode wire + pads)
z: 500 - 1000 μm (drift time)

→ good momentum resolution

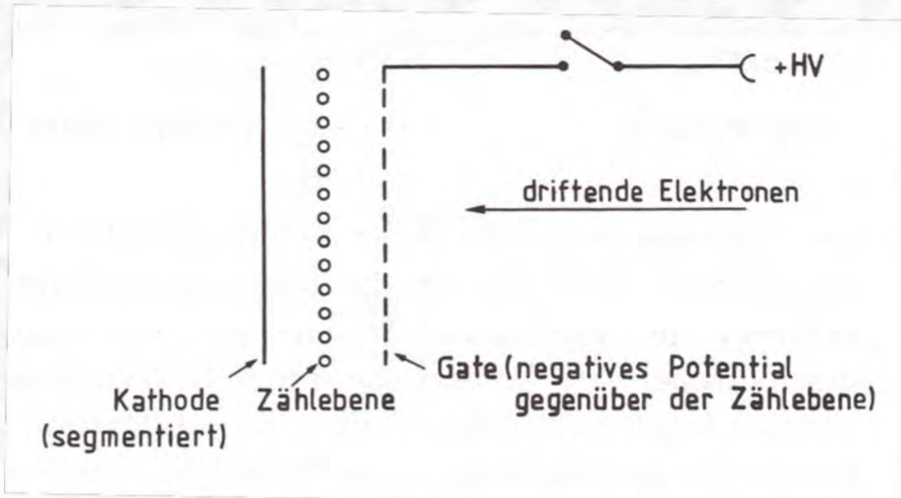
In addition, many (O (100)) dE/dx measurements → particle ID
typical uncertainties on <dE/dx> ~5-10%

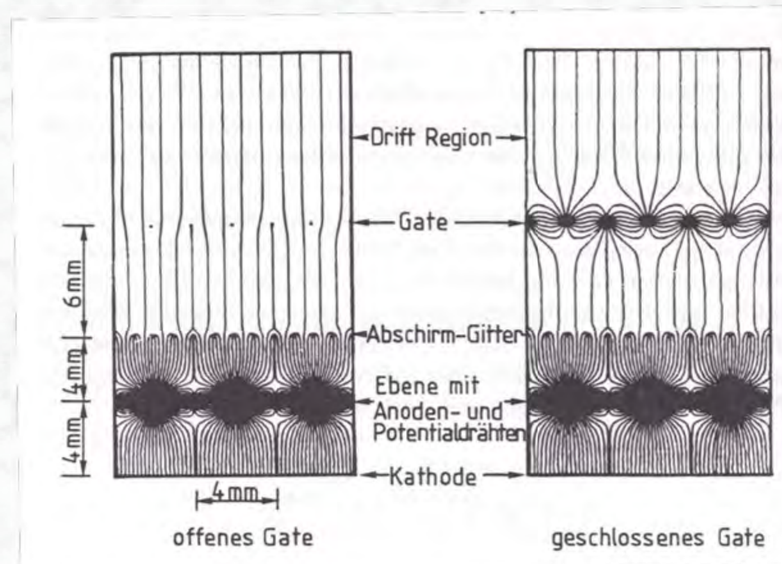
Challenges:

- Long drift times (attachment, diffusion)
- Precise knowledge of drift velocity
  → Laser calibration system
- Large number of positive ions
  (due to gas amplification in endplate region)
  slow drift would lead to distortions of the electric field
  → Gating grid is necessary
  → Rate limitation (triggered events only)

Difficulty: space charge effects due to slowly moving ions;
many positive ions, long drift path (in principle towards the central cathode plane)
→ change of effective E-field in the drift region

Solution: Gating grid
If grid is "closed", i.e. on negative potential w.r.t. anode wires,
the positive ions drift towards this grid;
→ positive ions do not enter the large drift volume → no field distortions, short drift



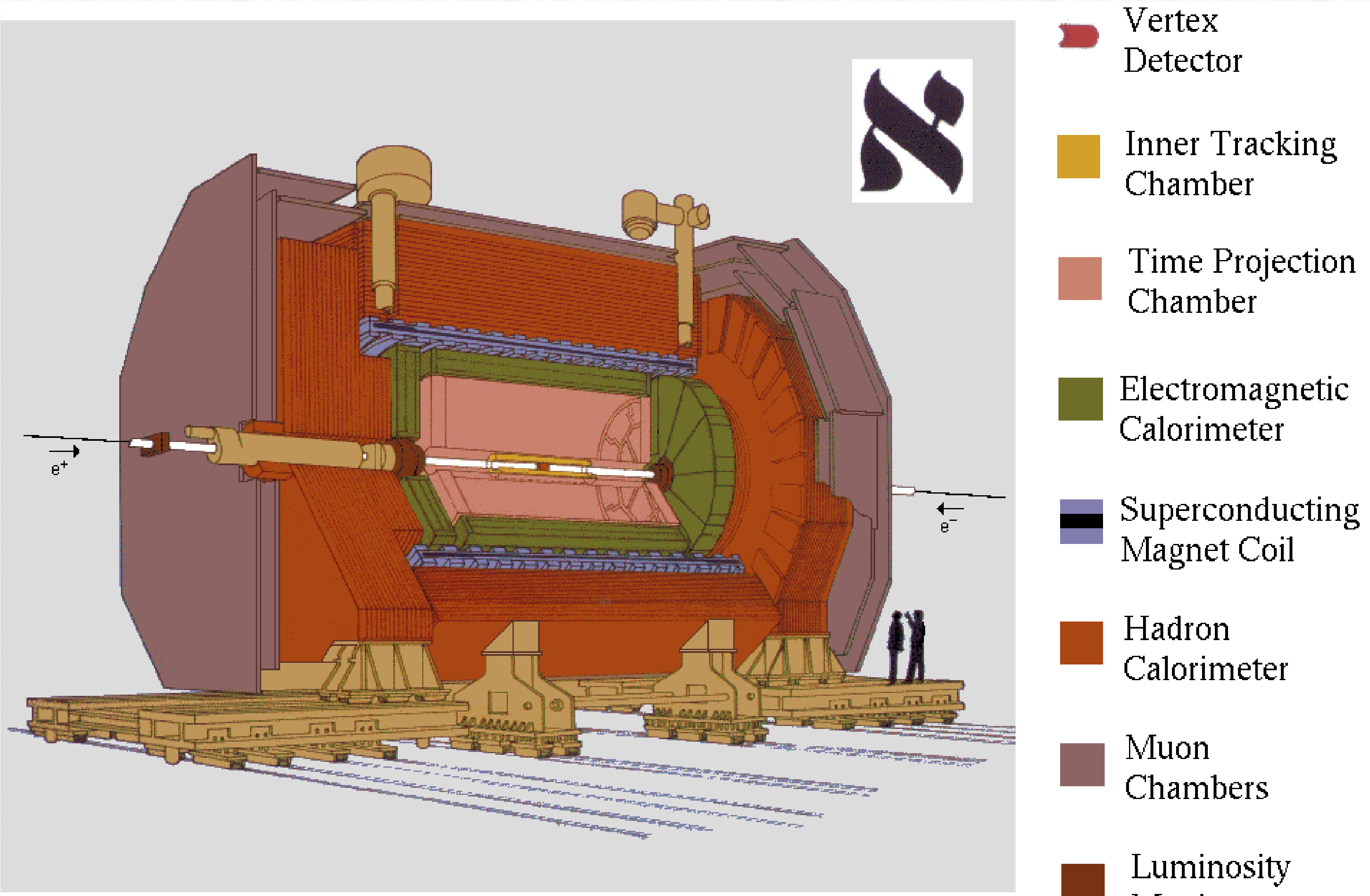


Normal mode of operation: Gate is closed
It is opened for interesting / triggered events !
→ requires external trigger

→ for non-selected events, electrons do not enter the amplification region
(second important function of the gating grid)

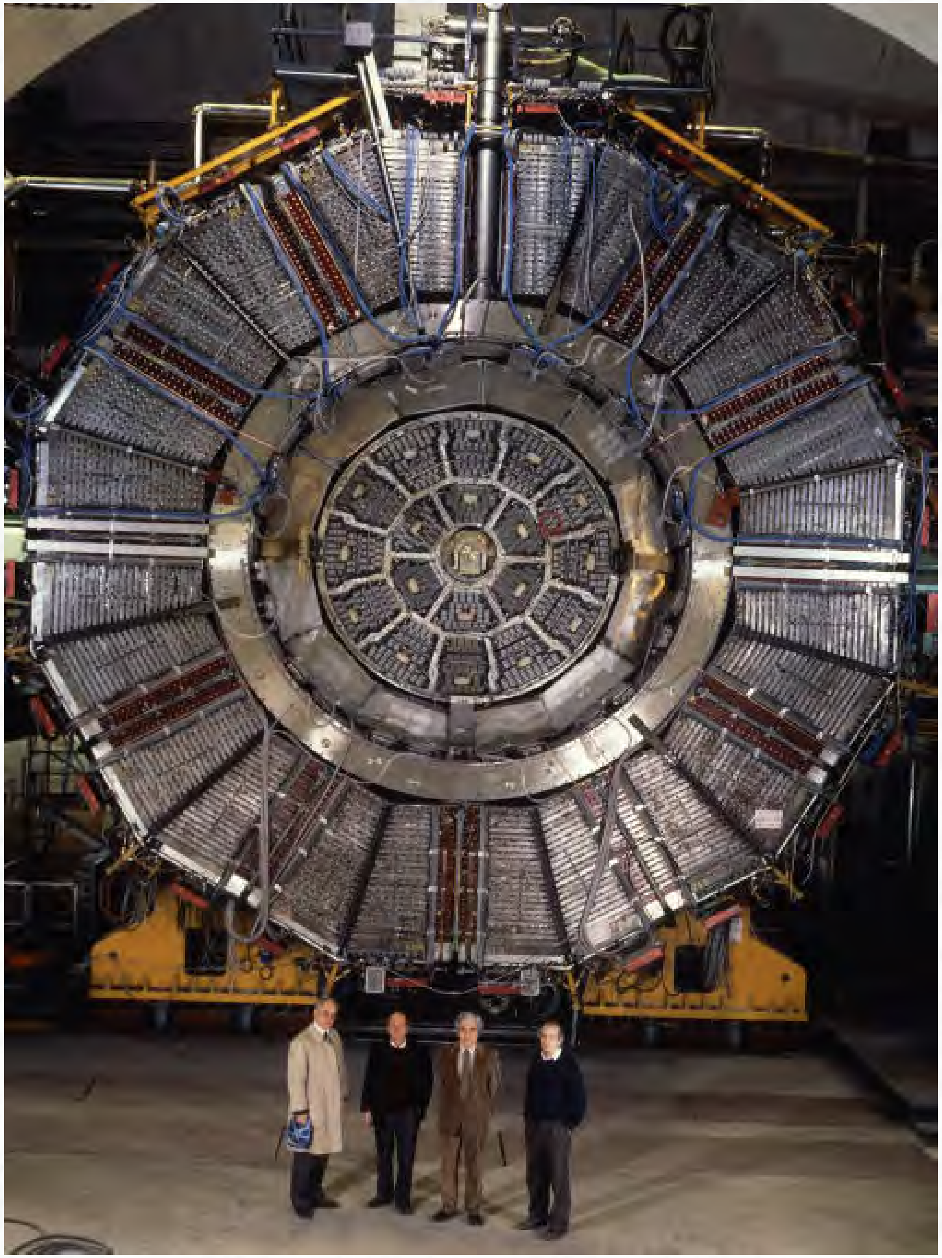
Further illustration of the gating principle;
Field lines seen for electrons

The ALEPH Experiment at LEP

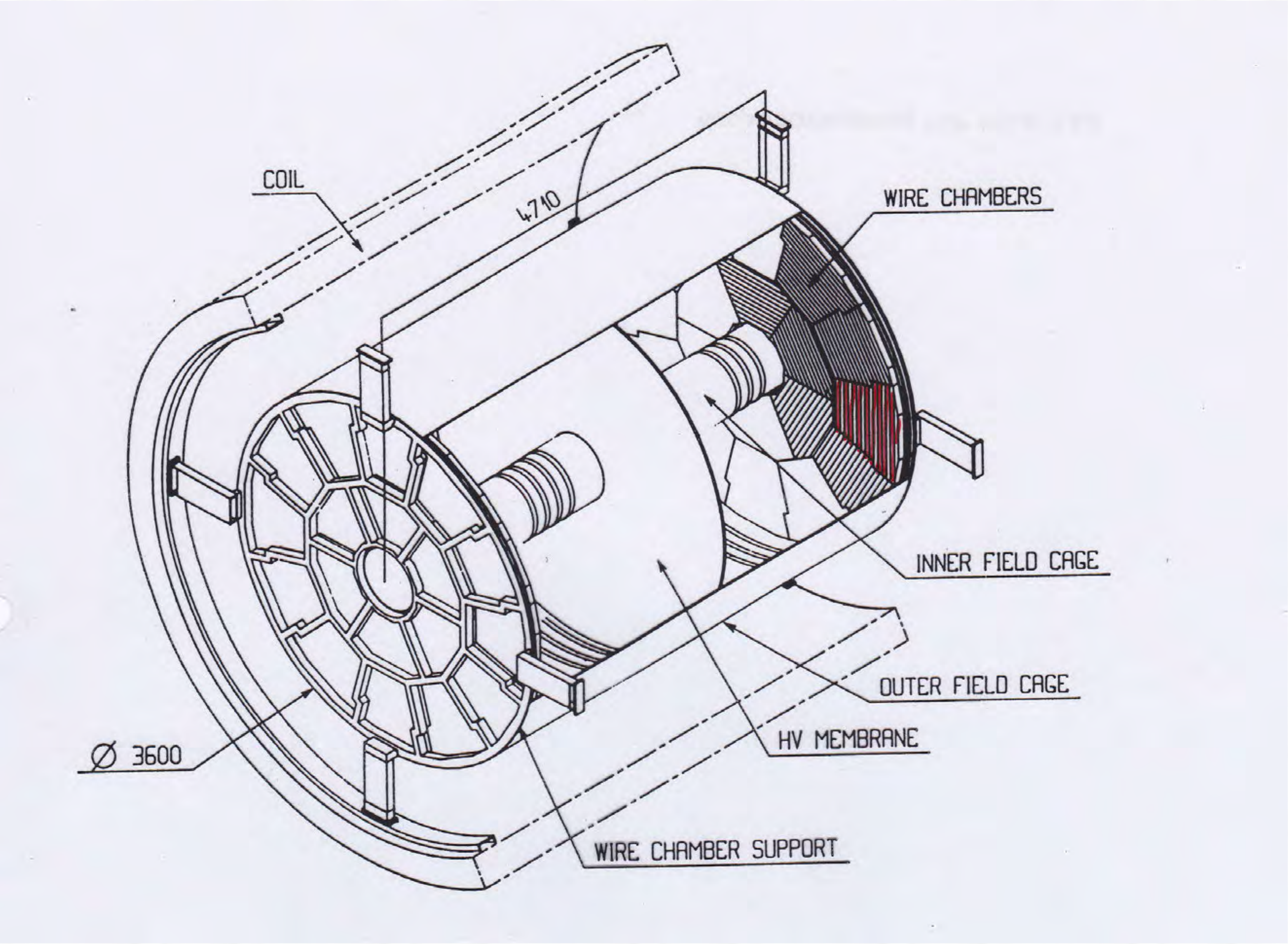


The ALEPH Detector

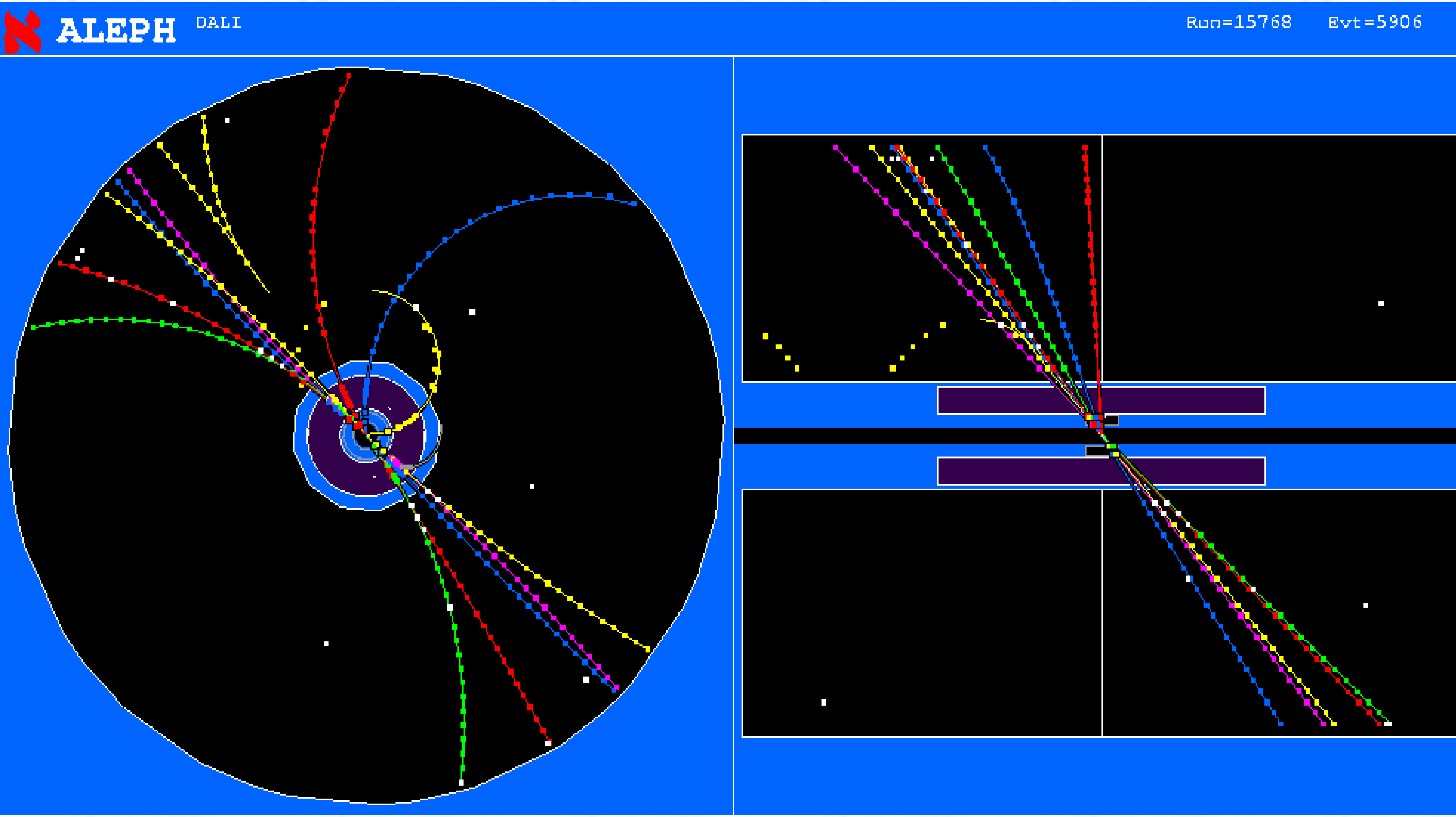
The ALEPH Detector



The ALEPH TPC



An event recorded in the ALEPH TPC



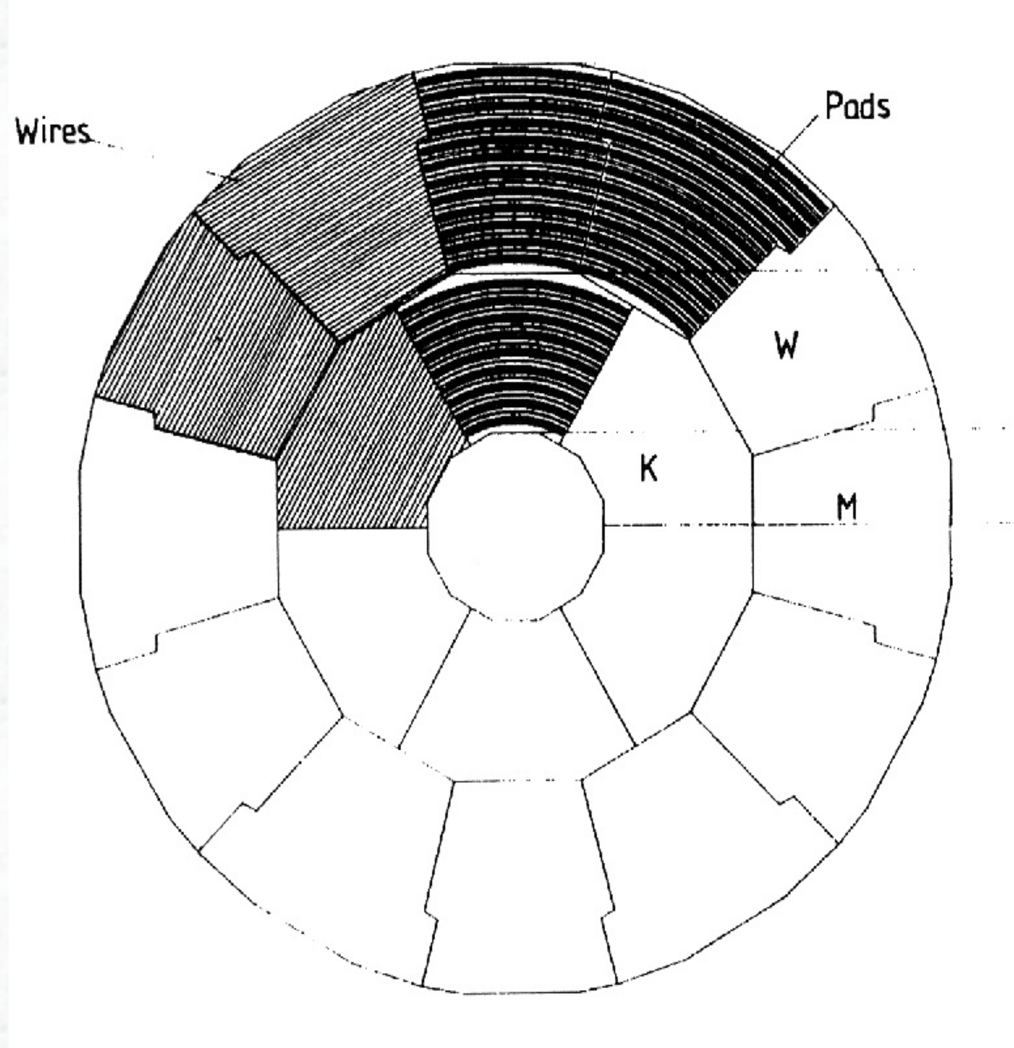
Wire Chambers: ALEPH

36 sectors, 3 types
- no gaps extend full radius

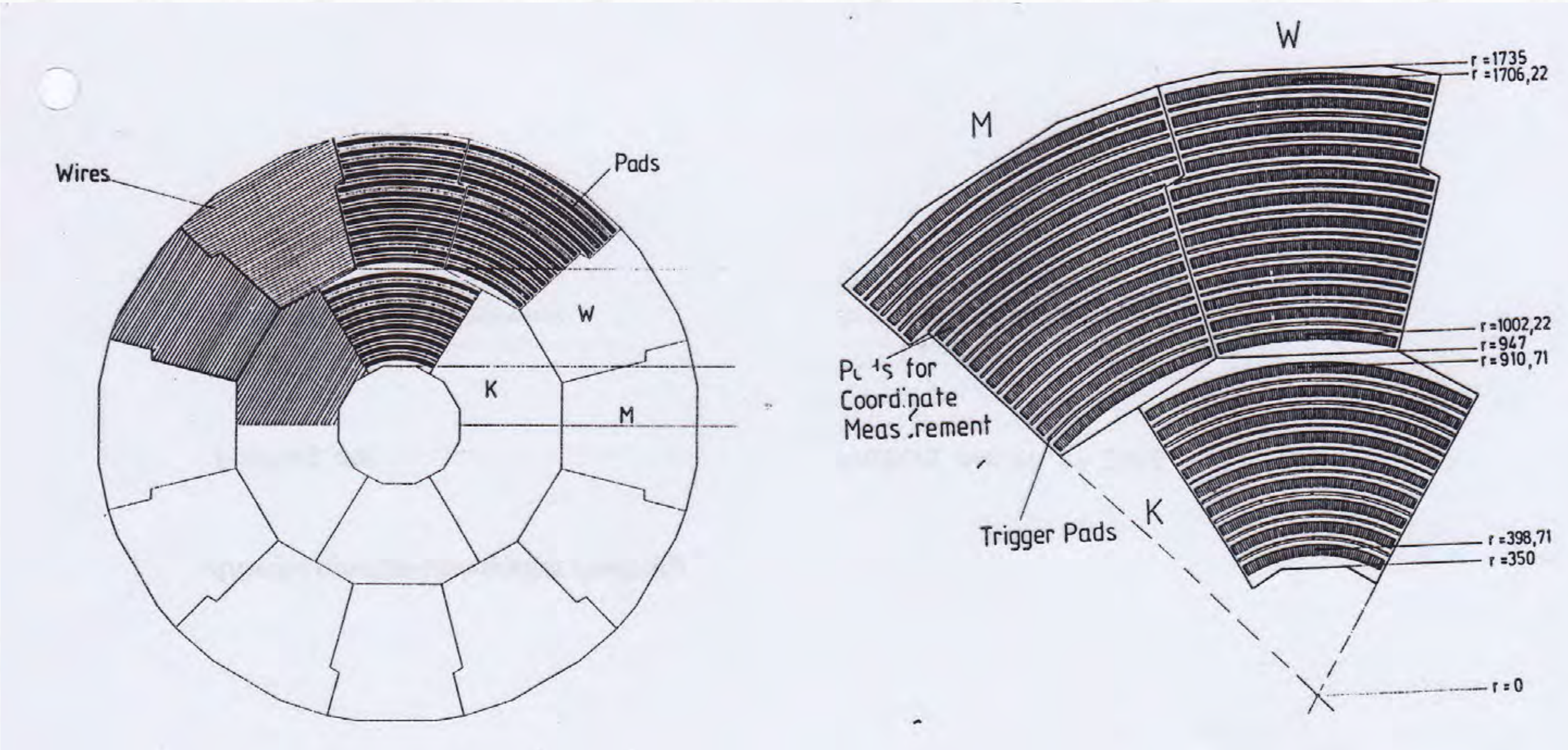
wires
- gating spaced 2 mm
- cathode spaced 1 mm
- sense & field spaced 4 mm

pads
- 6.2 mm x 30 mm
- ~1200 per sector
- total 41004 pads

readout
pads and wires



The ALEPH TPC (endplate)



Wire Chambers

3 planes of wires

- gating grid
- cathode plane (Frisch grid)
- sense and field wire plane

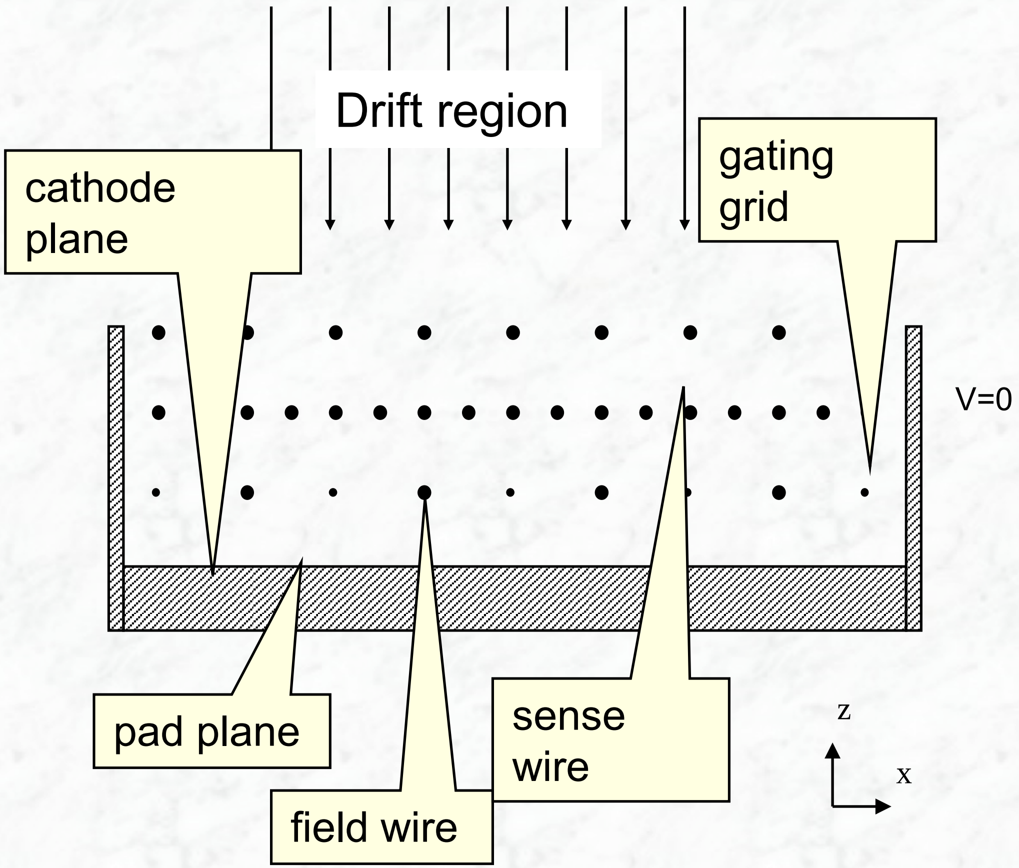
- cathode and field wires at zero potential

pad size

- various sizes & densities
- typically few cm^2

gas gain

- typically $3\text{-}5 \times 10^3$



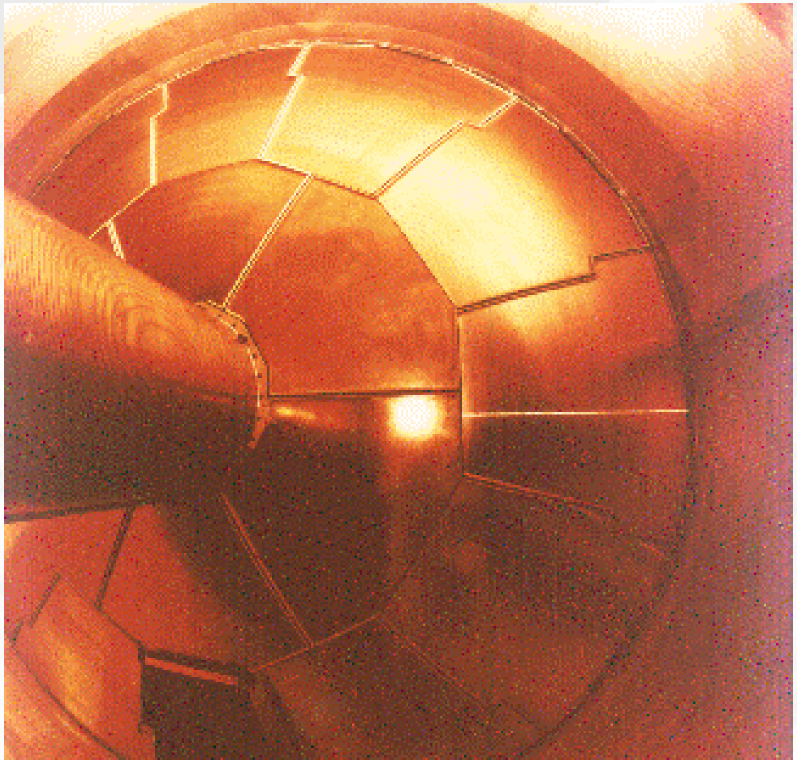
A look inside: ALEPH TPC

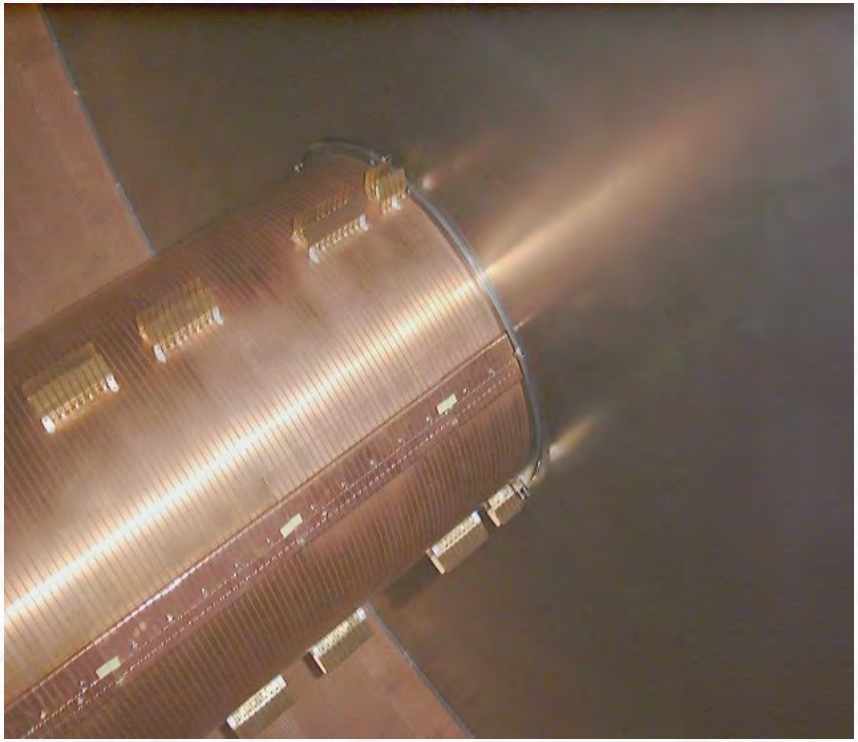
Cylinder Dimensions: 4.7 x 1.8 m

Drift length: 2 x 2.2 m

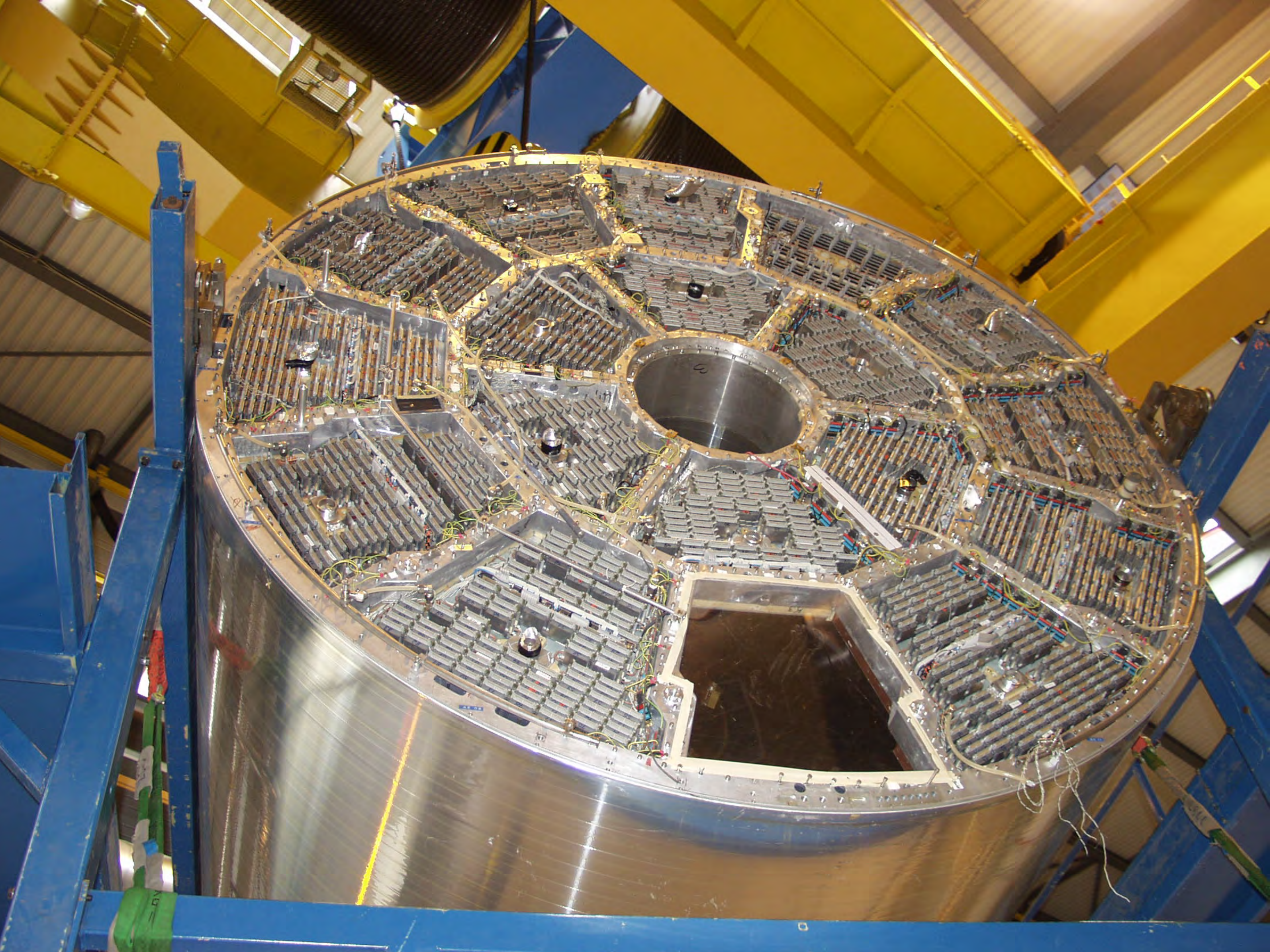
Electric field: 110 V/cm

E-field tolerance: $\Delta V < 6V$

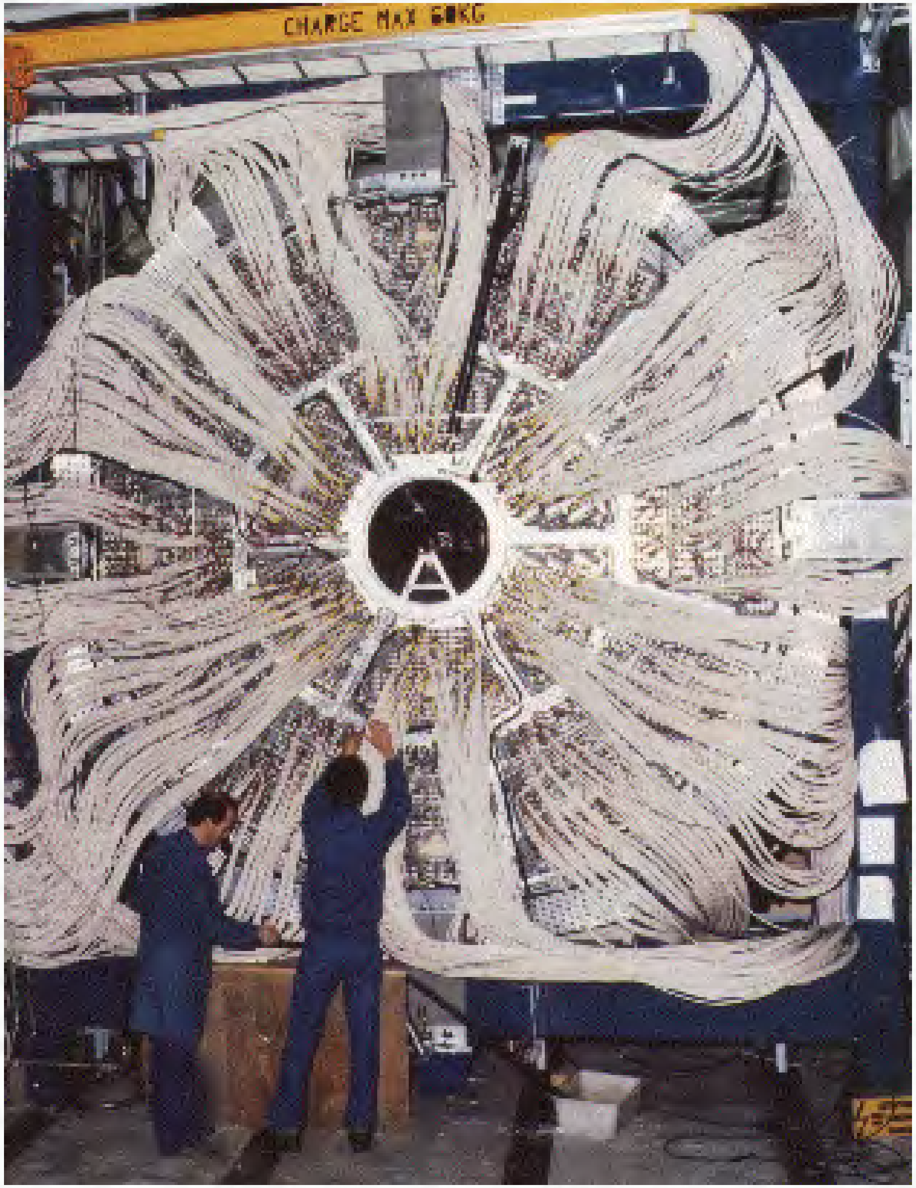




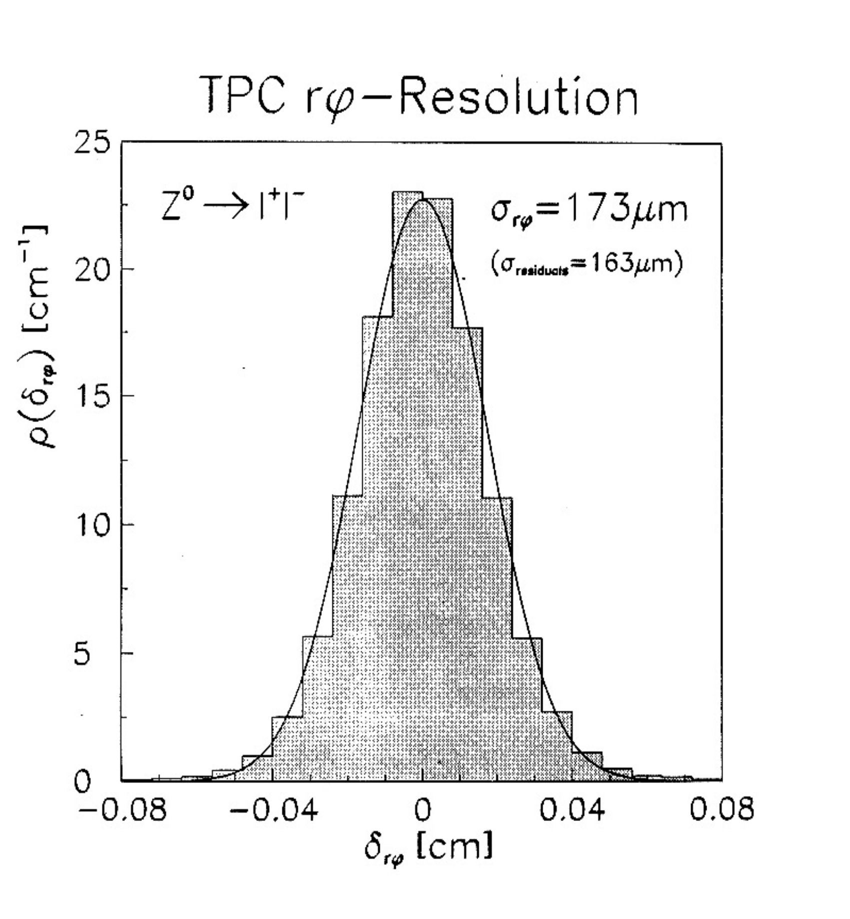
Nucl. Instr. and Meth. A294 (1990) 121

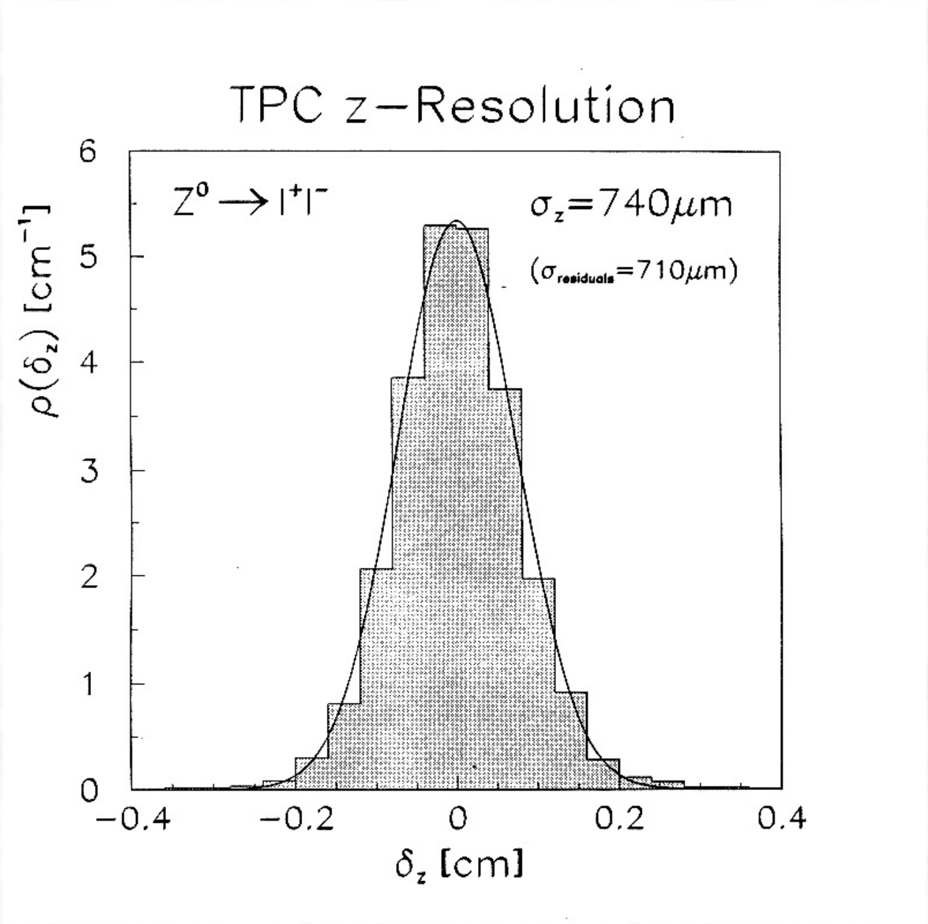


ALEPH TPC endplate after cabeling

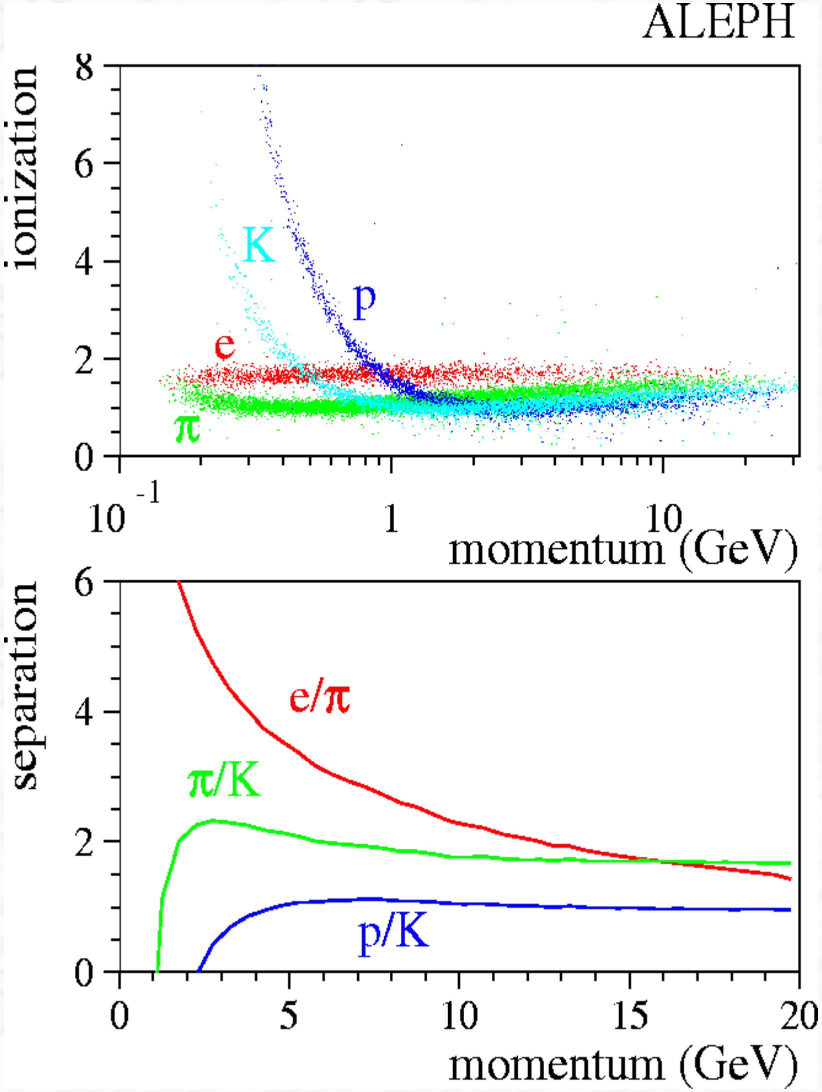


Coordinate Resolutions: ALEPH TPC





ALEPH TPC: dE/dx Results



Good dE/dx resolution requires

long track length

large number of samples/track

good calibration, no noise, ...

ALEPH resolution

up to 330 wire samples / track

truncated (60%)

accuracy on mean: ±5%

ALEPH TPC: Gas system

- Typical gas mixtures:

  Ar (91%) + CH_4 (9%),

  Ar (90%) + CH_4 (5%) + CO_2 (5%)

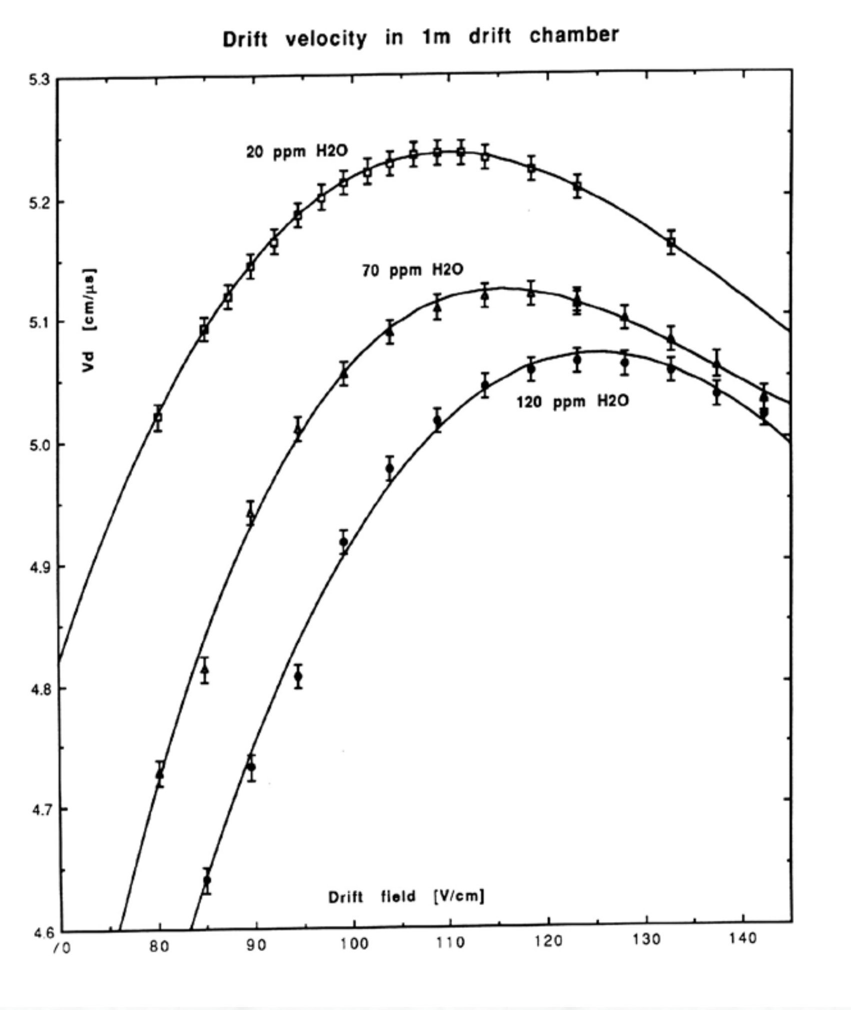
Operation at atmospheric pressure

- Parameters:

- Drift velocity: ~5 cm / μs
- Gas amplification ~5000
- Signal attenuation by electron attachment: <1% / m

- Parameters to control and monitor:

- Gas mixture (change in amplification)
- O_2 content (electron attachment, attenuation)
- H_2O (change in drift velocity, attenuation)
- Other contaminants (attenuation)



Influence of Gas Parameters (*)

Parameter change	Drift velocity, v_d	Effect on gas amplification, A	Signal ettenuation by electron attachment
0.1% ΔCH_4	0.4 %	-2.5% for A = $1x10^4$	
10 ppm O_2	Negligible up to 100 ppm	Negligible up to 100 ppm	0.15%/m of drift
10 ppm H_2O	0.5 %	Negligible at 100 ppm	< 0.03% /m of drift
1 mbar	Negligible if at max.	-(0.5%-0.7%)	

(*) from ALEPH handbook (1995)

ALEPH TPC: Laser Calibration System

Purpose

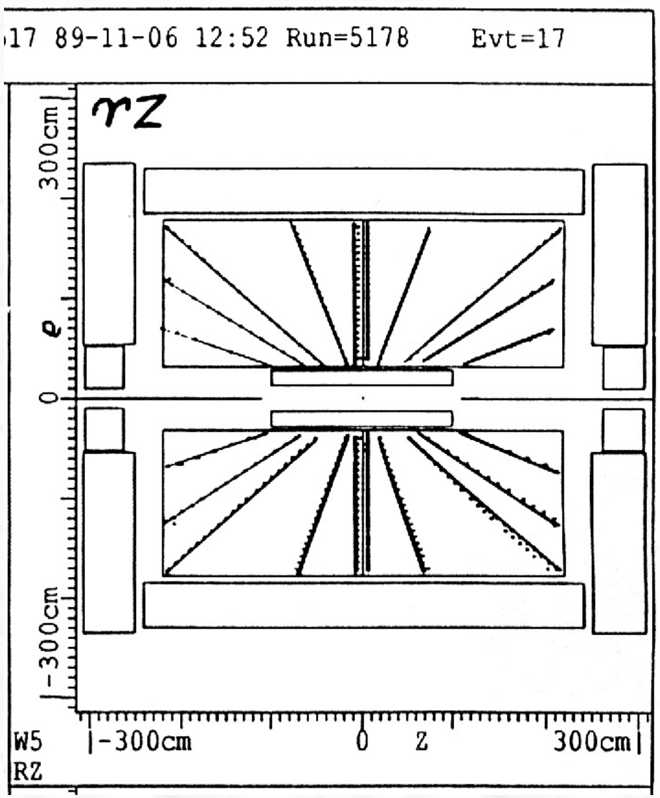
- Measurement of drift velocity
- Determination of E- and B-field distortions

Drift velocity

- Measurement of time arrival difference of ionization from laser tracks with known position

ExB Distortions

- Compensate residuals of straight line
- Compare laser tracks with and without B-field



Laser tracks in the ALEPH TPC

ALEPH TPC: Laser Calibration System

Purpose

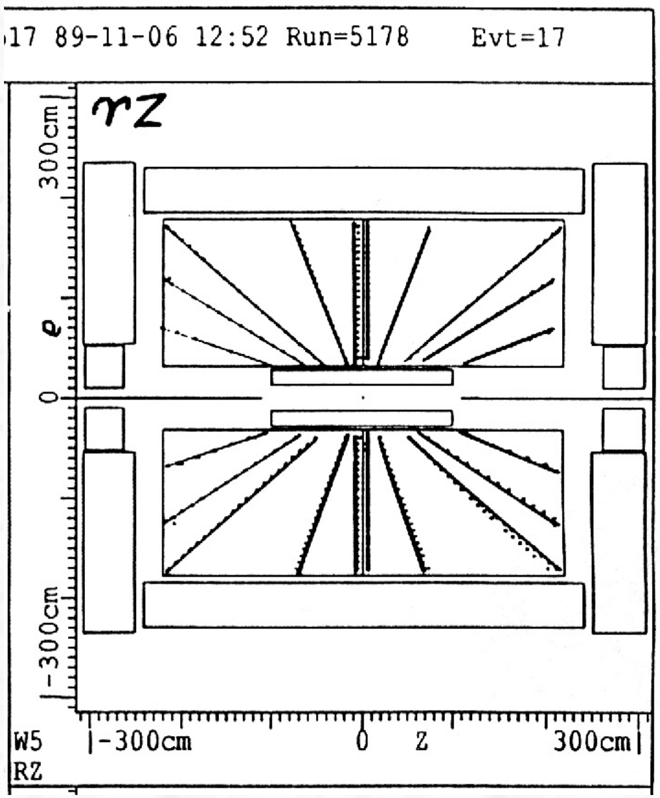
- Measurement of drift velocity
- Determination of E- and B-field distortions

Drift velocity

- Measurement of time arrival difference of ionization from laser tracks with known position

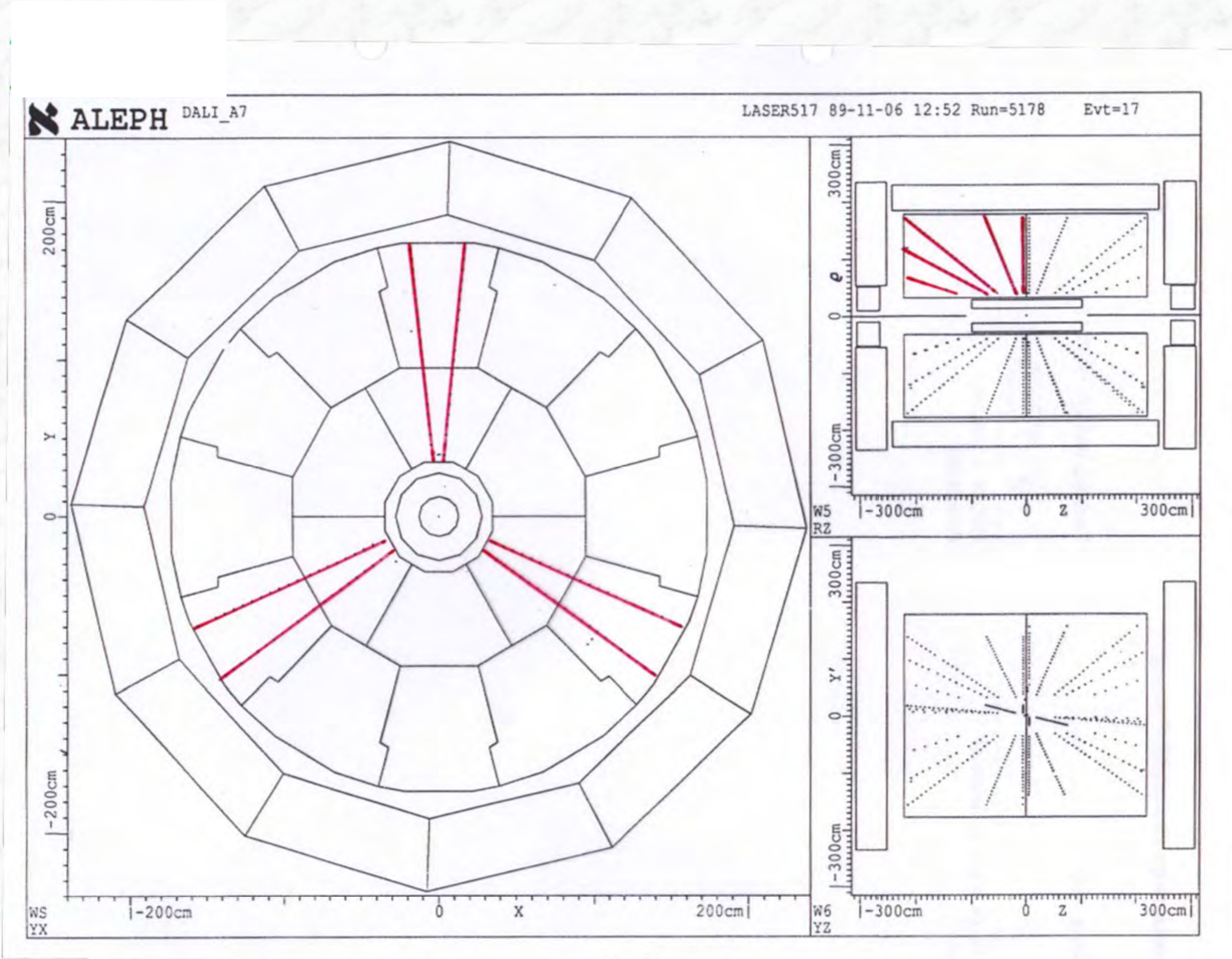
ExB Distortions

- Compensate residuals of straight line
- Compare laser tracks with and without B-field

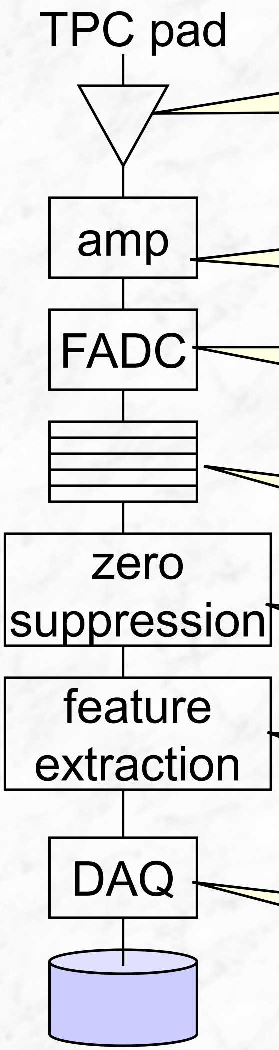


Laser tracks in the ALEPH TPC

Tracks from Laser Ionization in the ALEPH TPC



ALEPH TPC electronics: from pad to storage



- **Pre-amplifier**
  charge sensitive, mounted on wire chamber
- **Shaping amplifier:**
  pole/zero compensation. Typical FWHM ~200ns
- **Flash ADC:**
  8-9 bit resolution. 10 MHz. 512 time buckets
- Multi-event buffer
- Digital data processing: zero-suppression
- Pulse charge and time estimates
- Data acquisition and recording system

TPC in the ALICE experiment

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

Total drift time: 92 μs
High voltage: 100 kV

End-cap 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

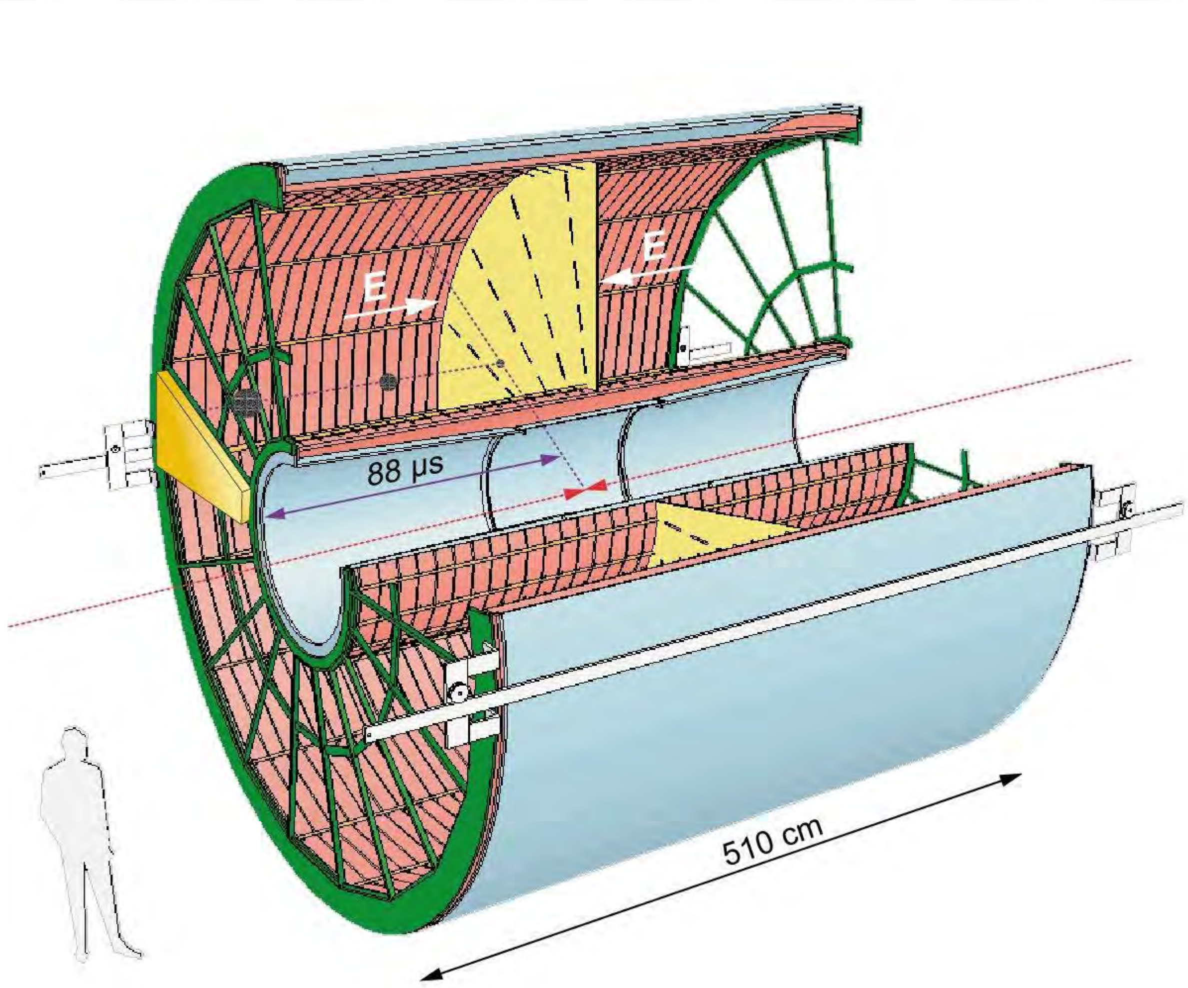
Diffusion: σ_t = 250 μm
Resolution: σ ≈ 0.2 mm

$\sigma_p/p \sim 1\%$ p; ε ~ 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

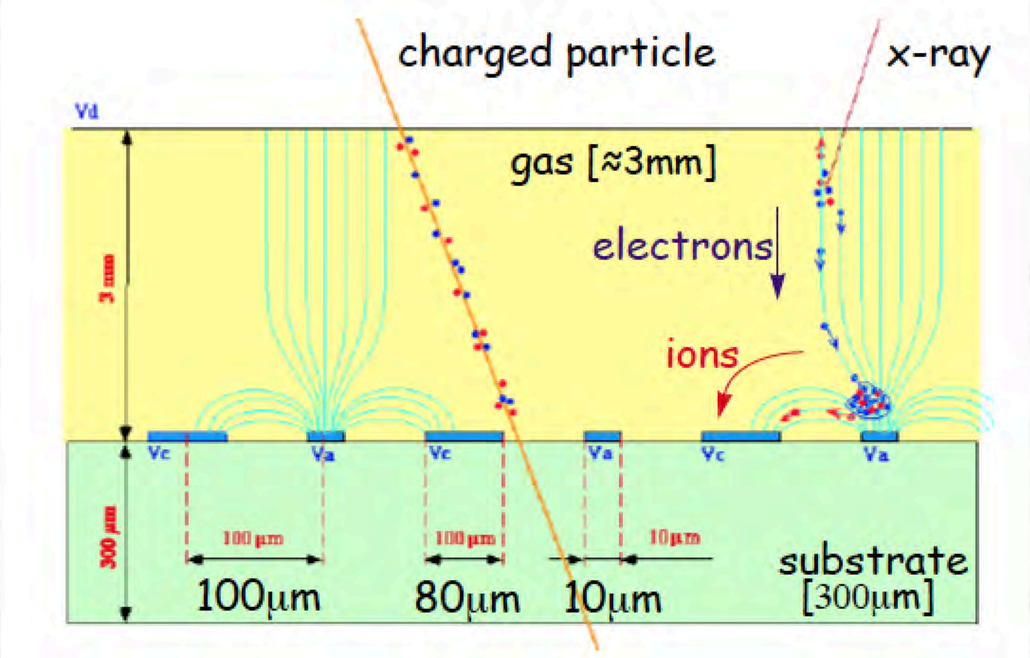


The ALICE TPC

Largest TPC world-wide

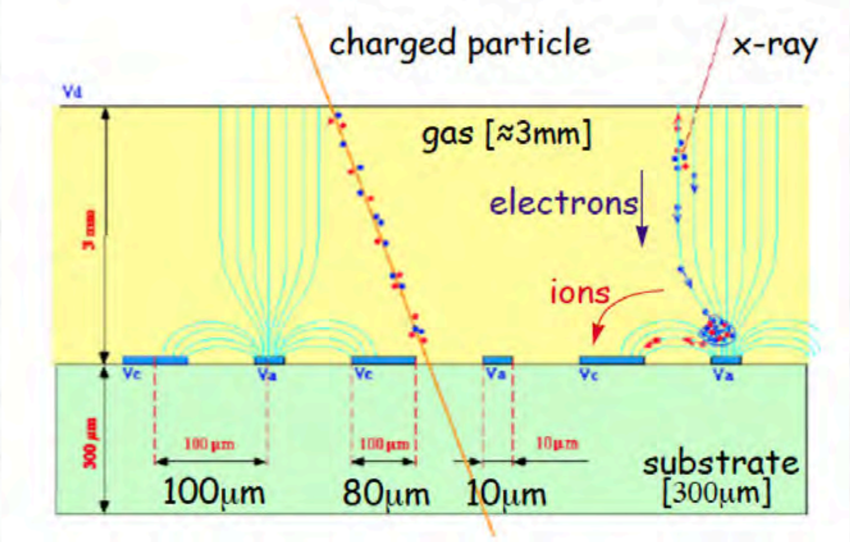
5.6 m diameter, 5 m length
88 m^3 gas volume
560 000 readout channels

5.6 Micro-Strip Gas Chambers (MSGC)



Basic idea: Improve the space resolution of gas-based detectors using micro-structures on dielectrics (e.g. glass or ceramics)

→ reduce the size of the detecting cell using chemical etching techniques developed for microelectronics
+ allow for short ion drift



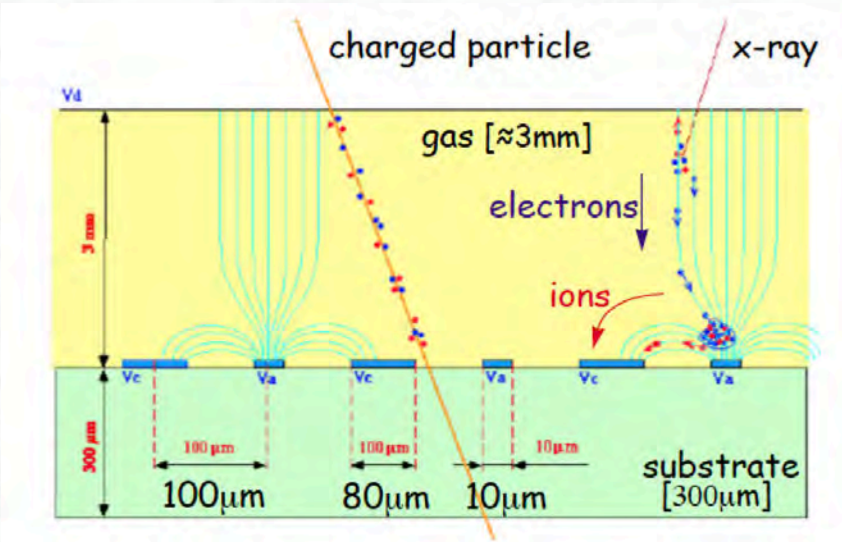
Advantages:

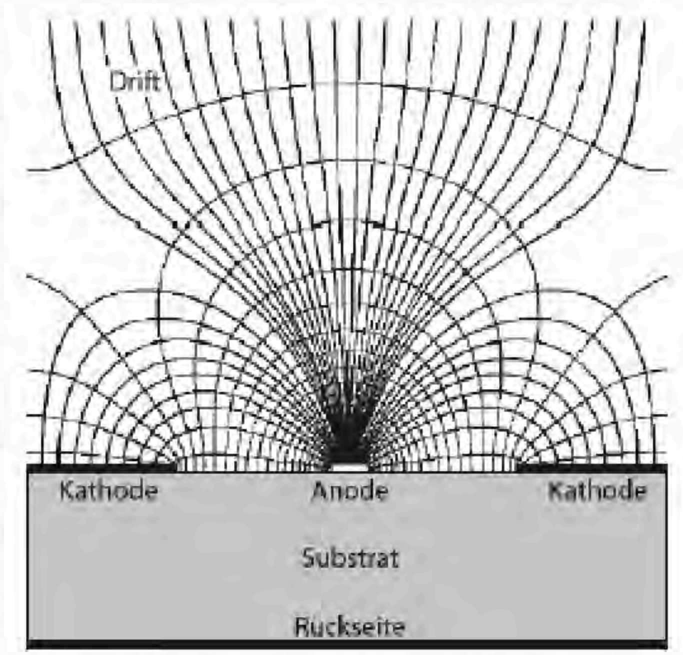
- Very precise and small anode / cathode structures
  (typical dimensions: 15 x 15 cm^2)

  → very good position resolution (~50 µm (200 µm / √12))

- Small drift distance for positive ions, therefore high rate capability

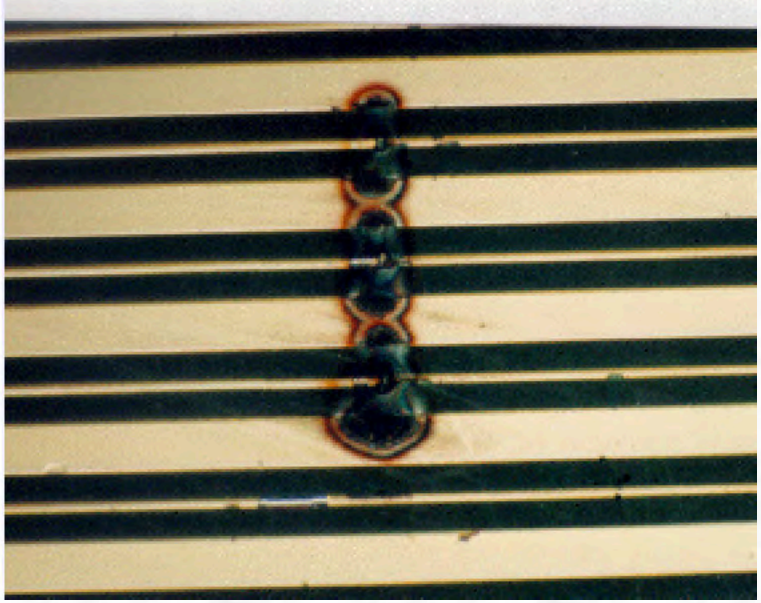
- High mechanical stability, simple construction



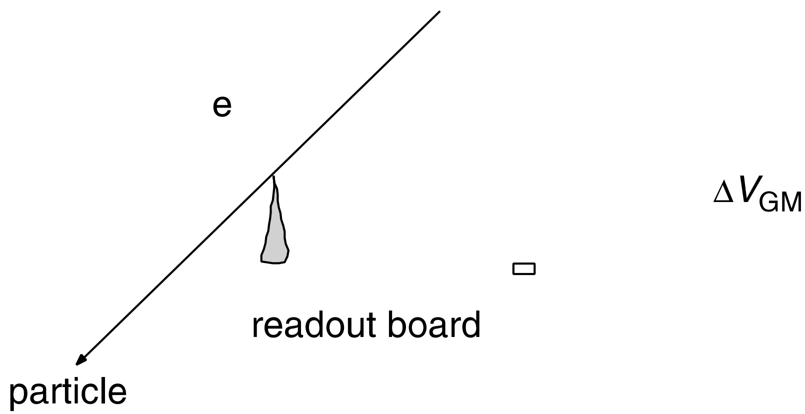


Disadvantages (after some experience: (HERA-B experiment, CMS, 1990s)

- MSGCs are prone to damaging sparks, when highly ionizing nuclei occur
- Regions in the detector with large E-fields can lead to sparks and to a break-down of the detector.
- Insulators can charge up and produce high E-fields.

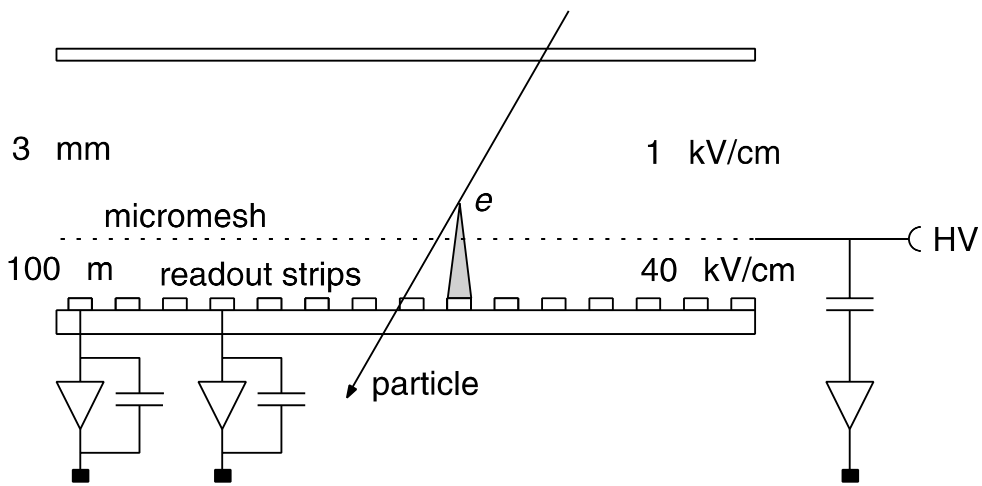


Solution: Introduce intermediate grid(s) to separate ions and gas amplification from the anode strips



GEM (Gas Electron Multiplier)
F. Sauli (CERN, 1997)

Thin isolated capton foil, coated with a metal film and (100 – 200 μm) holes, to allow electrons to penetrate into the anode region
(electric field at holes)
Gas amplification in holes, separated from anode strips

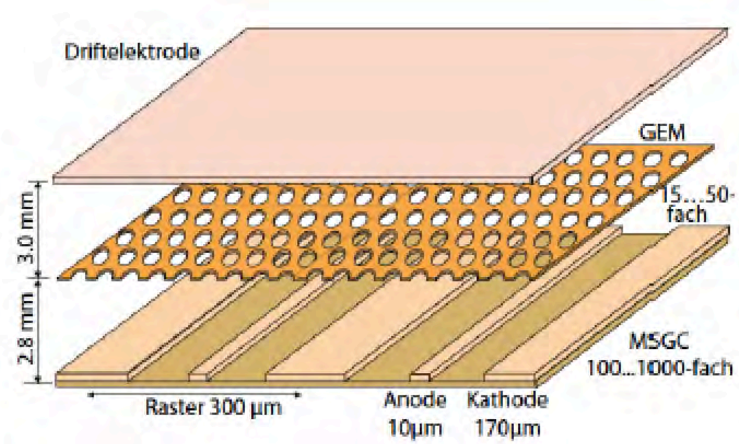


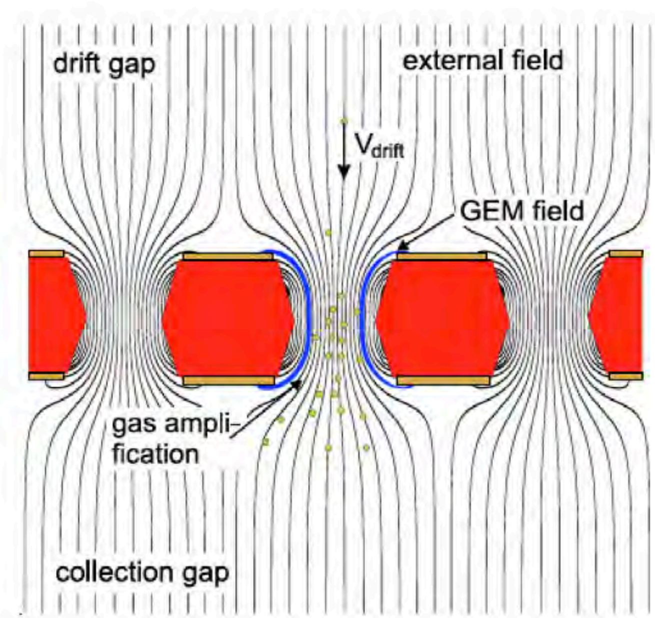
Micromegas (Micromesh gaseous structure)

micromesh (Frish grid) to decouple drift region from a very short amplification region

MSGCs with GEMs (Gas Electron Multiplier)

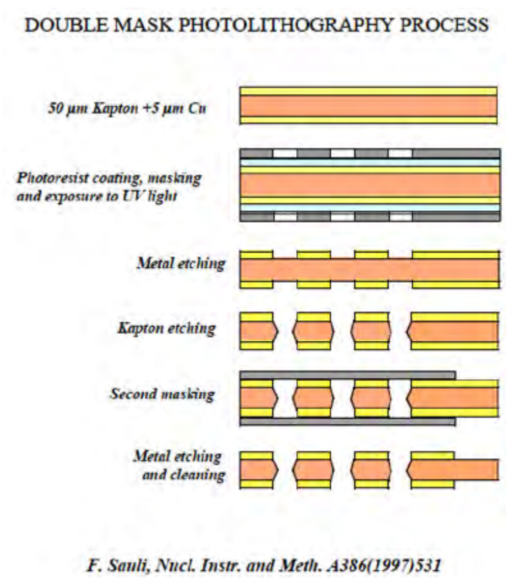
(i) A two step gain reduces the spark probability

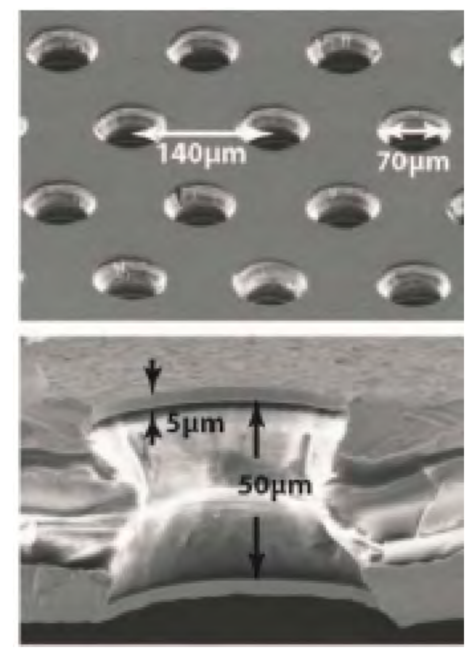




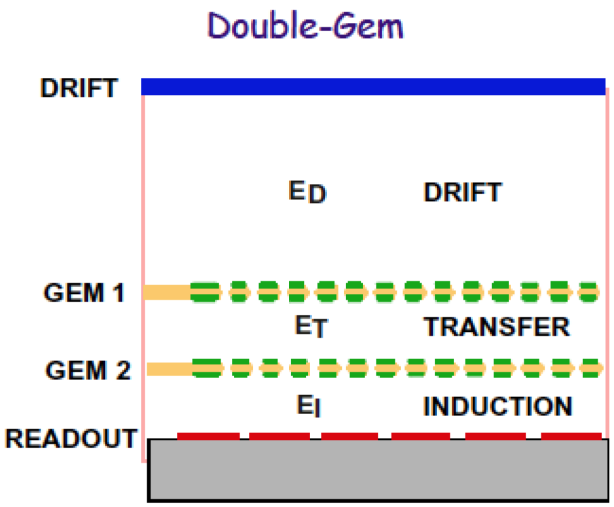
- Electrons are collected on anodes → signal

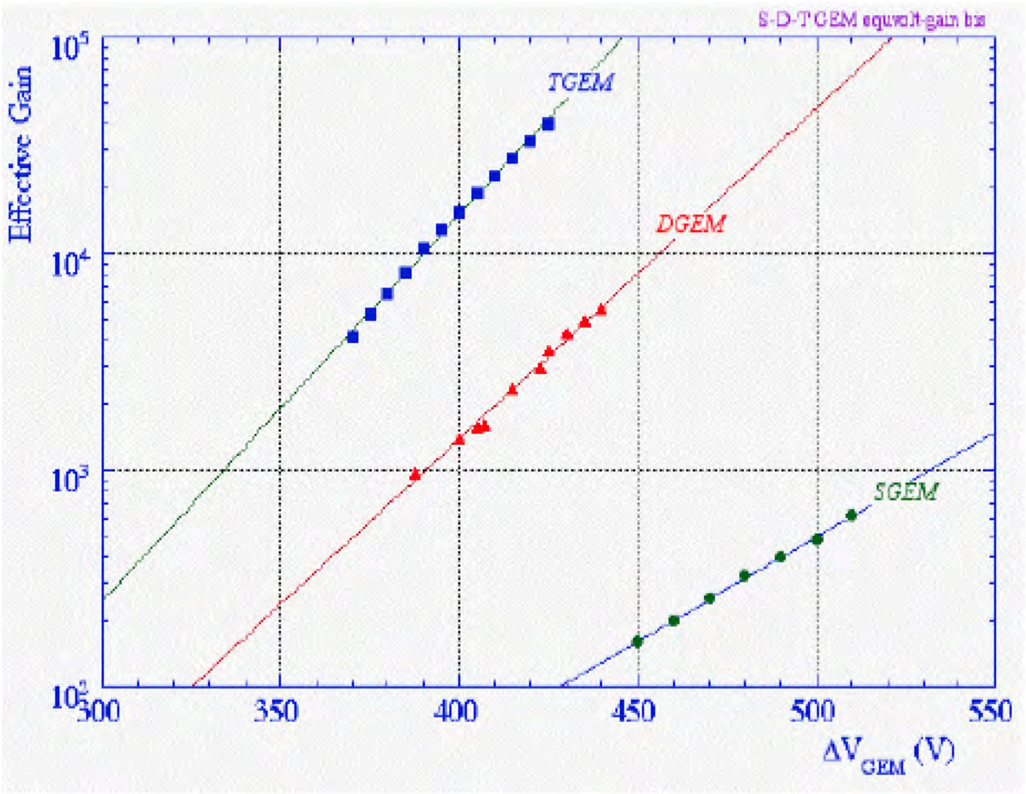
- Positive Ions are partially collected on the GEM electrodes





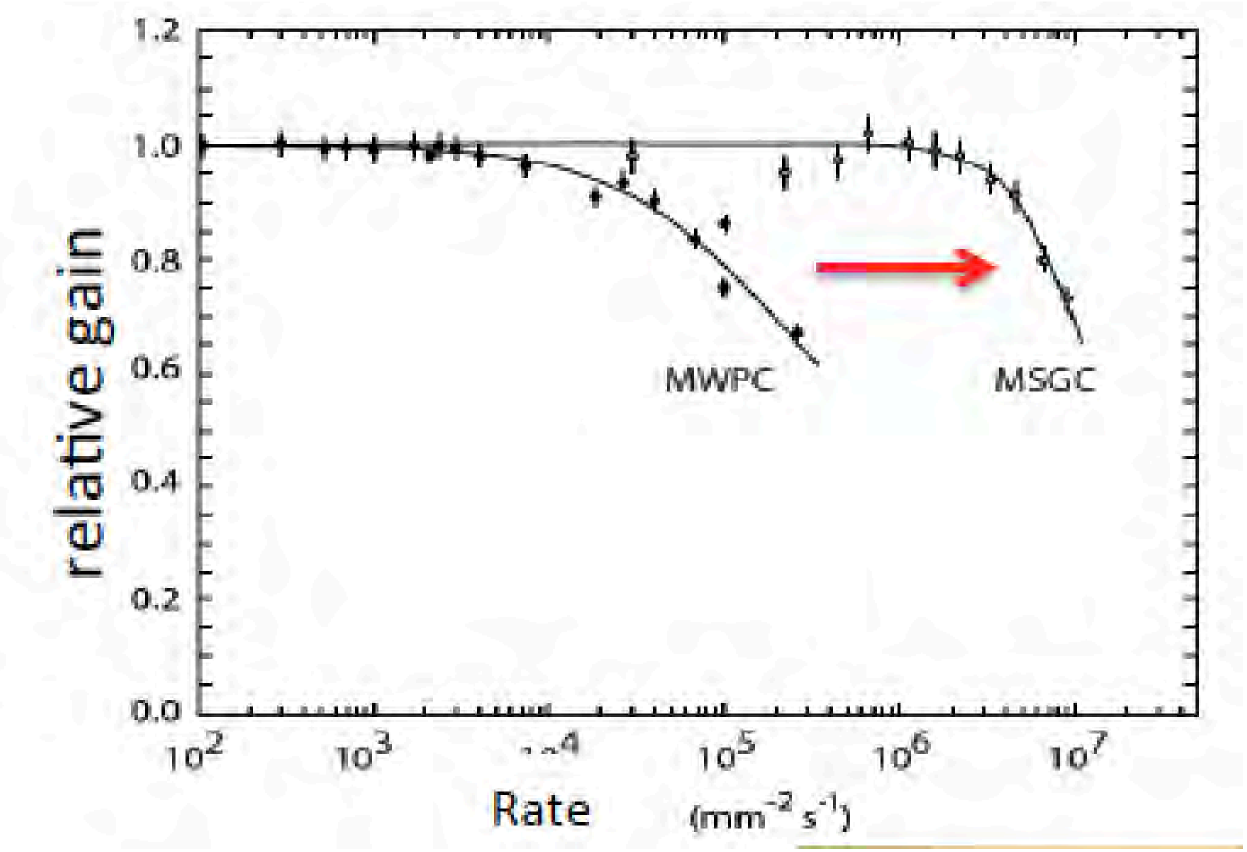
(ii) Today Double and Triple GEM detectors exist





- Such devices show large signals
- Good spatial resolution (σ ~ 60 μm)
- Good rate capability (1 MHz / mm^2)
- Radiation tolerant (> 100 mC / mm^2) (corresponds to 10^{14} MIPs / cm^2)

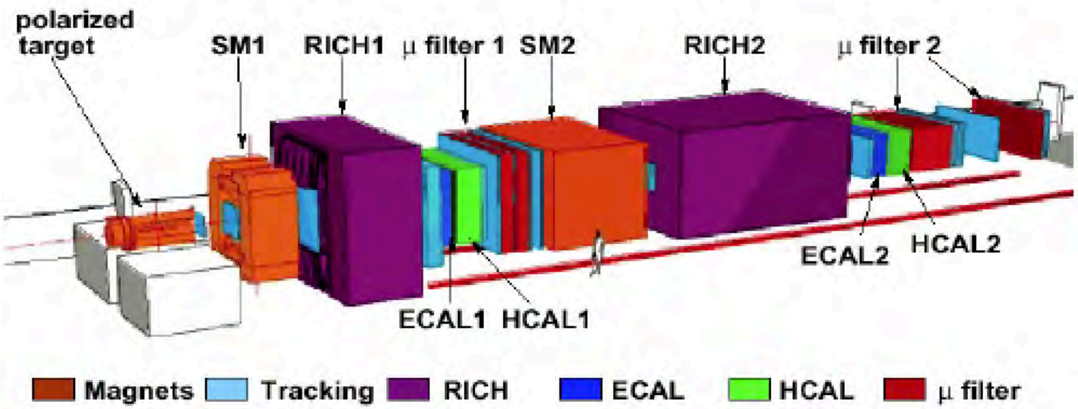
→ applications in today's particle physics experiments

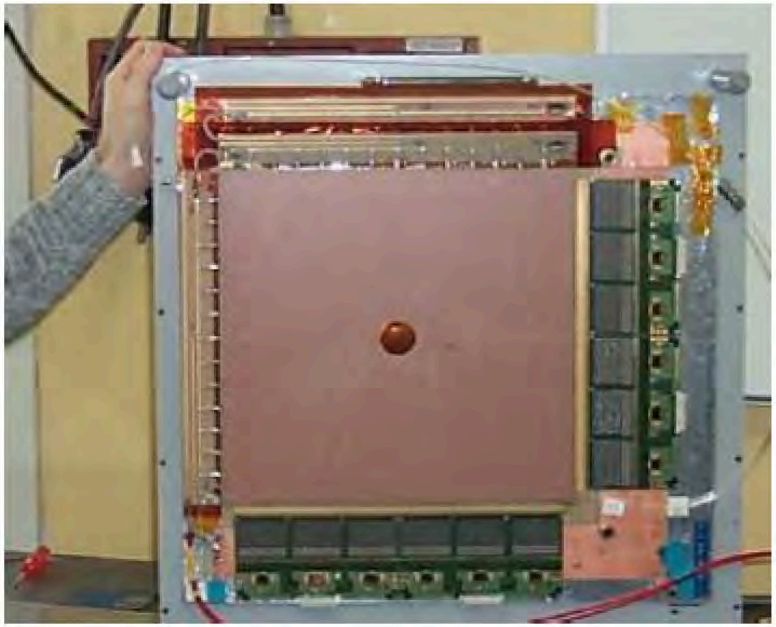


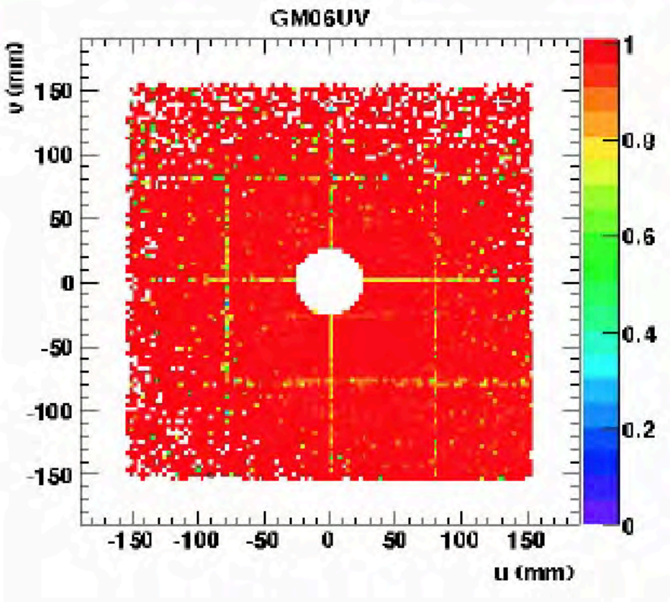
Significant progress on rate capability for gas-based detectors by MSGCs

GEM Tracker in the COMPASS experiment

COMPASS Magnetic Spectrometer
22 TRIPLE GEMs

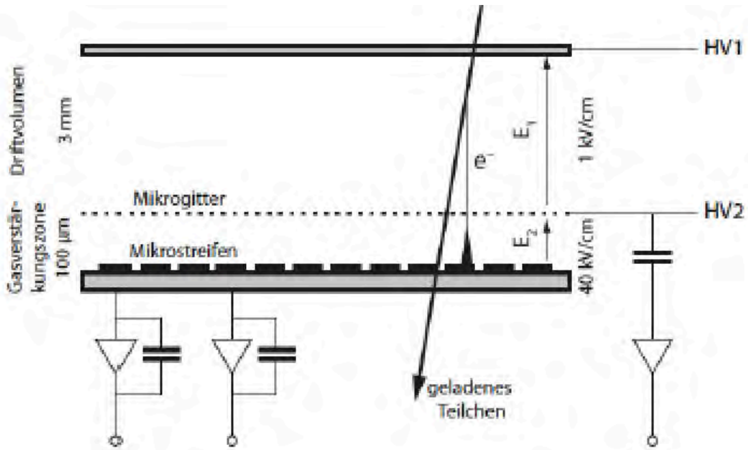




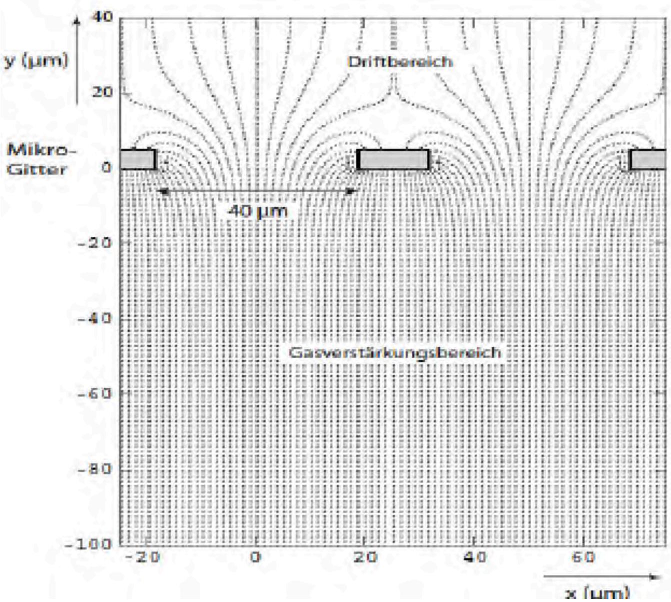


Uniformity of tracking efficiency

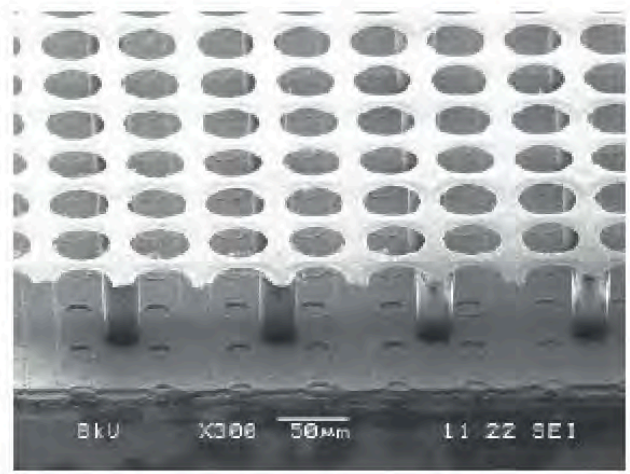
MICROMEGAS (MICRO MEsh GASeous Structure)



- Separation of drift region and a short amplification region by a micro grid
- Readout of the induced charges by patterned electrode (gas gain much lower)
- Fast induced signals
- New development: INGRID structure obtained by "post processing" of grid directly on readout structure



INGRID structure

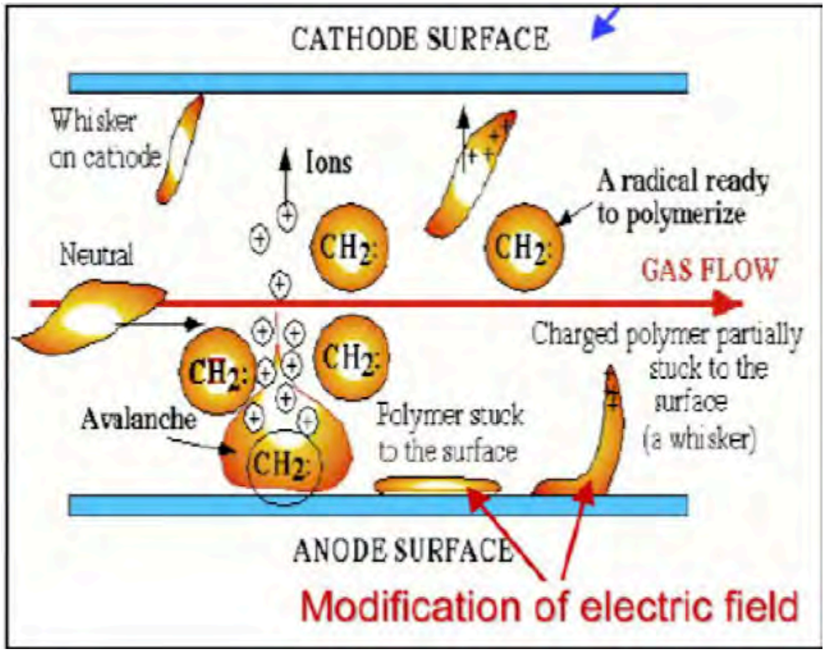


5.7 The Ageing of Gas detectors

- Avalanche processes in gas + radiation

  → gas molecules in particular those from heavier quench gases are disintegrated

  → free radicals (chemically aggressive) can form long molecule chains, polymerization



- Polymers attach to electrodes (growing of so called whiskers, + non-conducting anode coating, positive polymers affect cathode)

  → change of electric field

  → change of gas gain

  → increased dark currents (Malter effect, polymers on cathode extract electrons from cathode in high E-fields → continuous discharge currents)

- Avalanche processes in gas + radiation

  → gas molecules in particular those from heavier quench gases are disintegrated

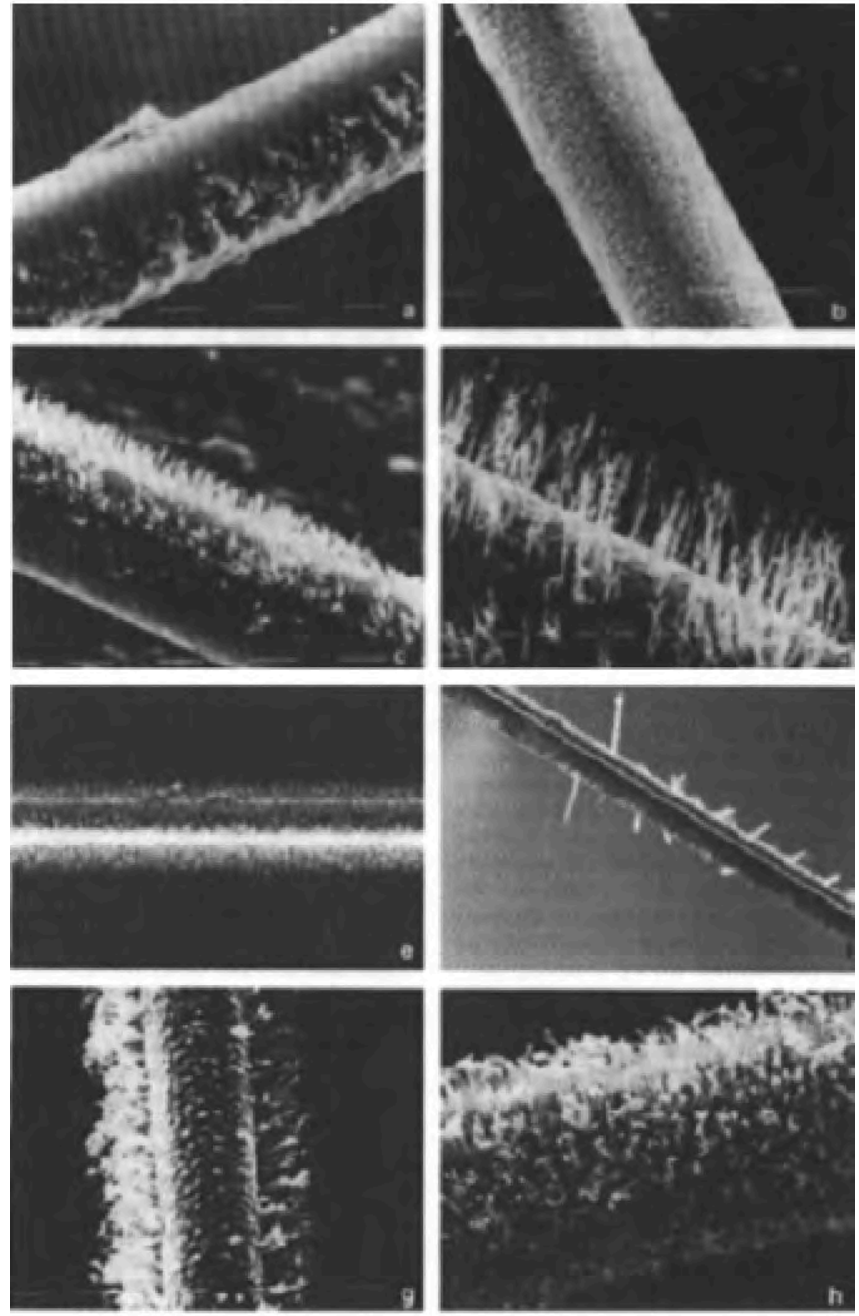
  → free radicals (chemically aggressive) can form long molecule chains, polymerization

- Polymers attach to electrodes (growing of so called whiskers, + non-conducting anode coating, positive polymers affect cathode)

  → change of electric field

  → change of gas gain

  → increased dark currents (Malter effect, polymers on cathode extract electrons from cathode in high E-fields → continuous discharge currents)

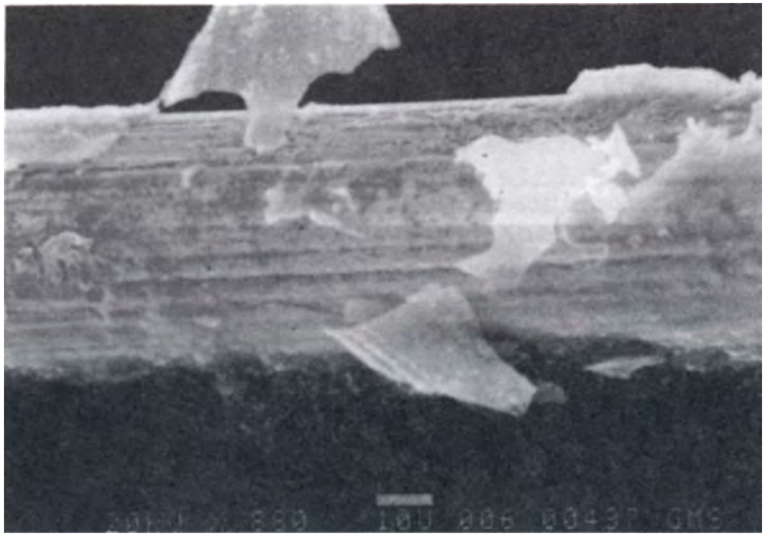


- In general: The detailed understanding of ageing in gas detector is very complex,;

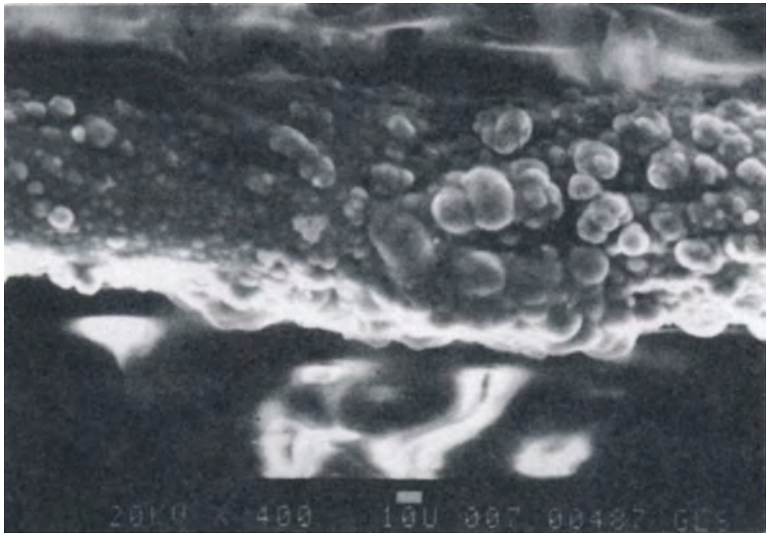
  No reliable theory, however, ageing effects will occur, they are proportional to the deposited charge and will eventually limit the operation of gas chambers

  Ageing depends on the deposited charge [C/cm]

  → *to minimize ageing effects: work in a clean environment, avoid certain materials (e.g. oil, carbon, carbon-polymers, silicon, SiO_2, halogens, ….)*



Silicon deposits on an anode wire (from Ref. [3])



Deposits of silicon, chloride and cupper on a cathode wire in a drift chamber (from Ref. [3])

Recipes to delay ageing:*

Material for construction:

- Use only material, which is certified in ageing test (high irradiation). Don't rely on manufacturers.
- Avoid glue, some type of plastic, PVC
- Be careful with O-rings (can contain silicone), printed circuit boards.
- Absolutely no silicone grease (often found in gas valves).

During construction:

- Absolute cleanliness
- No finger prints
- Clean all components before assembly, do not rely on cleaning by manufacturer.
- Perform aging tests with highly ionizing particles as early as possible, before mass production starts.

Operation:

- Use gas, which does not polymerize (noble gas, CO_2, ..)
- Gas additives ca help (water, alcohol, ...)
- Avoid high currents (low gas gain)

Don't expect immortality:

B. Schmidt: " Detectors are like us: aging is unavoidable, surviving in good shape is the main issue.

*) from G. Herten, Lectures at CERN school