Gaseous detectors

- Very important class of detectors with many applications

    charged particle, x- & gamma rays, visible light detection

- applications in many areas of research, & commercial

    particle & nuclear physics

    space-borne astro-particle physics

    medical imaging

    x-ray crystallography

    environmental monitoring

- long history

    Investigations of ionisation of gases and spark discharges

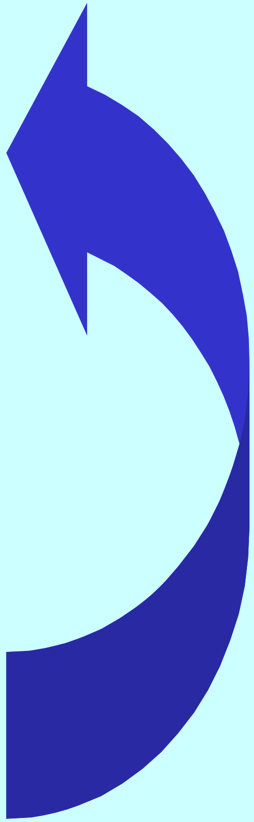
    Crookes (?), Townsend *(fluorescent light)*

    Geiger-Muller tube

    Very large systems in particle physics experiments

- Position sensitive detectors most useful kind

    rapid progress following developments in 1960's [Nobel: G. Charpak 1992]



Principle of gas detector

- Ionisation of gas -> electron-ion pair
- Drift of charges in electric field
- Avalanche multiplication of charges by electron-atom collision in high E field

  applying voltage across gas - geometry dependent
- Signal induction via motion of charges

- Typical properties

  signal sizes are for a high energy particle crossing the detector

  for photons use absorption length (photoionisation cross-section)

Gas	$E_{average}$ per ion pair (eV)	Ionisations per cm	Free electrons per cm
He	28	5	16
Ne	36	12	42
Ar	25	25	103
Xe		46	340
CH_4	28	27	62
CO_2	33	35	107

Signal vs applied field

E range	Behaviour	
I	recombination of part or all of signal	
II	constant signal = total ionisation deposited no recombination	Ionisation chamber
III	impact ionisation during charge collection signal proportional to initial ionisation linear response $\Delta V = Anq/C$ A > 10^4 - depends on gas	Proportional region
IV	impact ionisation but gain depends on initial signal size A = A(n)	Limited proportional region
V	Pulse size independent of initial ionisation	Geiger region
VI	Continuous discharge	
C = chamber capacitance n = initial no e-ion pairs		

- For high fields ion (space) charge builds up around anode

    reduces gain - eventually saturates

- Geiger region - photon emission spreads avalanche throughout chamber

    longer recovery time between pulses

Signal vs applied field

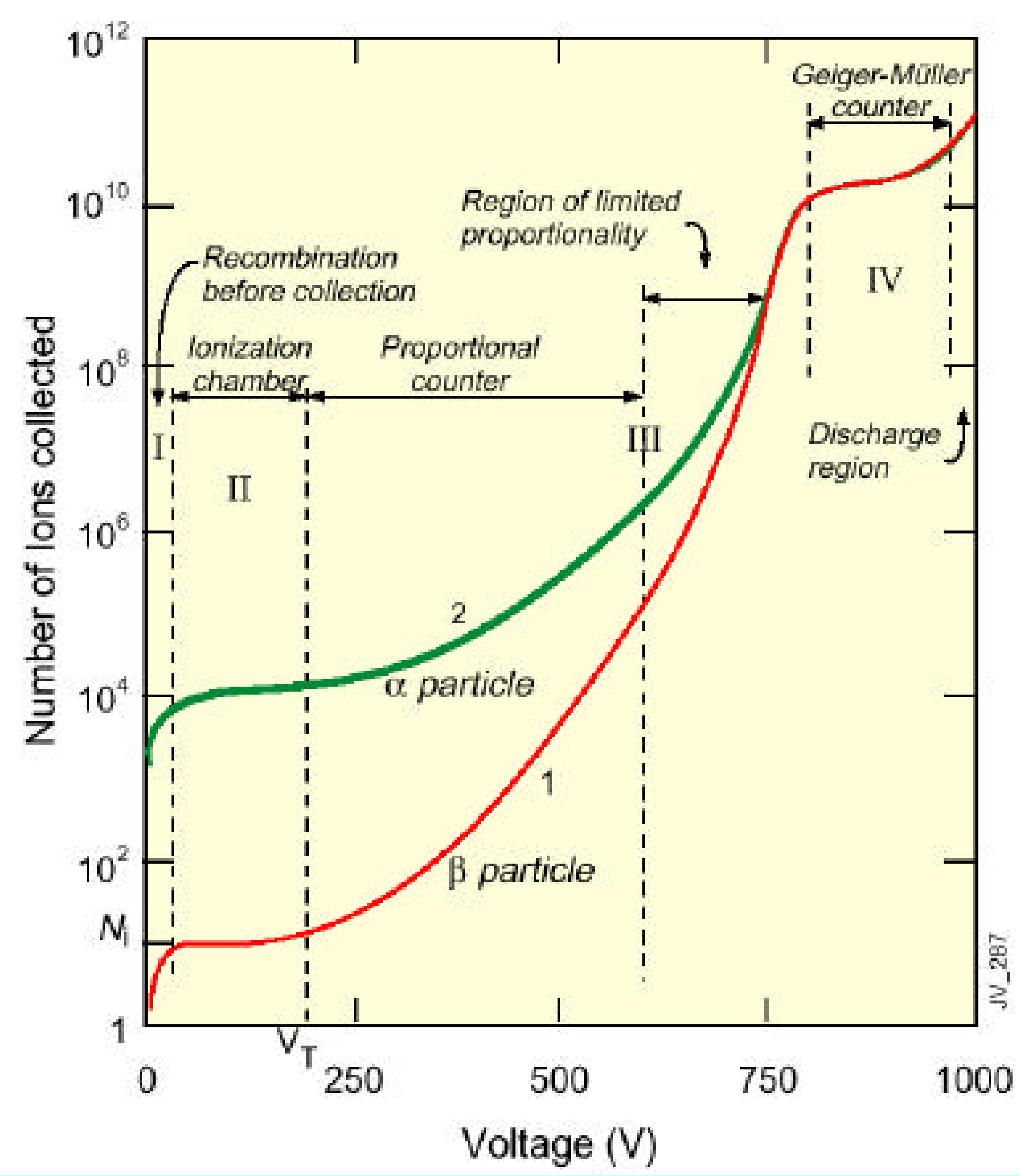
- NB

  Although the figure shows behaviour vs voltage, it is actually the electric field which determines the behaviour,

  ie. these results are for a particular geometry:

  cylindrical (?)

- It is the general form which counts, not the absolute voltage



Amplification process

- Electrons acquire kinetic energy from E field, so gain velocity

  but subject to collisions with gas molecules where energy lost

  mean free path between collisions typically ~ few µm

- If KE gained > ionisation energy -> impact ionisation = amplification

  $dN = \alpha N dx$ $\alpha = f(E, \text{pressure}) \sim Ape^{-Bp/E}$ *first Townsend coefficient*

  $N \sim N_0 e^{\alpha x}$

- Impact ionisation also often produces photons

  can spread and produce further ionisation, far from original site

  organic "quenchers" absorb photons well

  molecules have many excited states (vibration/rotation)

- Choice of gas for detector - wide choice & big subject

  low working voltage, high gain operation, good proportionality, drift speed,...

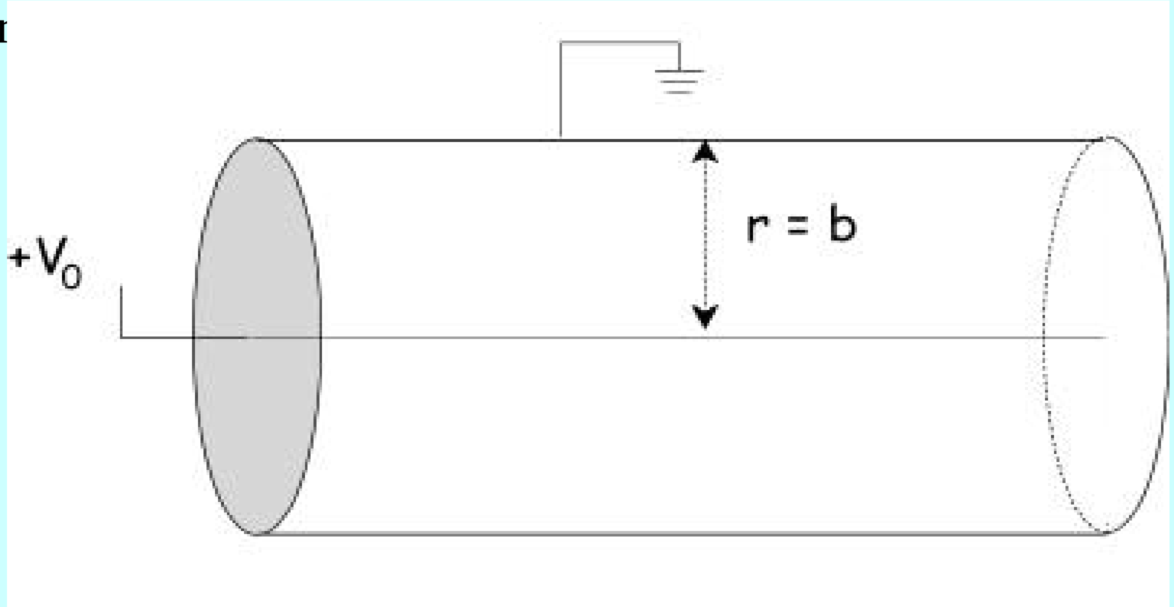
  noble gases + organic quencher

  some elements have strong affinity for electrons (O_2, Cl, F) - avoid

Cylindrical chamber

- Simplest design - long wire (r=a), with surrounding conducting cylinder (r=b)

  q = charge per unit length of wi



- Gauss' law $\int \mathbf{E.n}.dS = q/\varepsilon_0$

  $E(r) = q/2\pi\varepsilon_0 r = -d\varphi/dr$

  solve for q, with $\varphi(b) = 0$

  $\varphi(r) = V_0 - (q/2\pi\varepsilon_0)\ln(r/a)$

- possible values

  $V_0 = 4000V$ b = 1cm a = 50µm

  Argon mixture with $E_{ion} = 30eV$

  $E(r) = 755V/r$

  if mfp ≈ 10µm then eE(r) x mfp > 30eV at r = 250µm

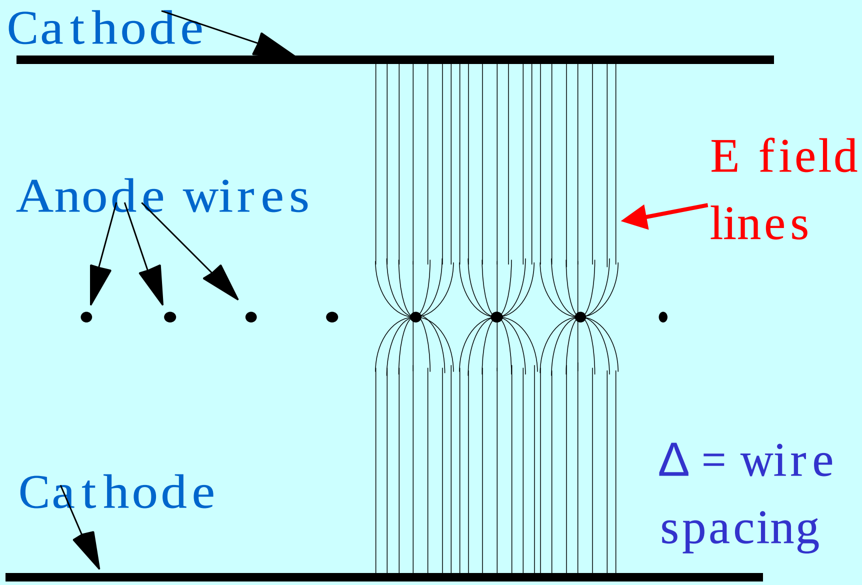
- although ionisation only begins close to the wire there are still ~ 20 mfp

  so each electron can multiply many times, in ~ nsec

  $dN = \alpha N dx \quad N \sim N_0 e^{20} \quad \alpha \sim 1 \quad A \sim 10^8$

- Many variants on design possible, including multi-wire designs

Multi-Wire Proportional Counter MWPC



- anode wires equally spaced at few mm
  - spatial resolution of few x100µm
- operated in proportional region
- each anode acts as independent counter
  - measure many particles simultaneously
- confinement of charge by field
  - energy measurements possible
  - very often used as binary position detector => $\sigma_{meas} = \Delta/\sqrt{12}$
  - measure signal amplitudes on each wire and form weighted sum
    - *centre of gravity method*
- care in construction needed to place wires accurately
  - displacements lead to field distortions
  - multiple (y/z/u) layers in single chamber give coordinate measurements

Drift chamber

- constant (low) electric field in region to ensure constant velocity

  avalanche begins only close to single wire

  time measurement -> distance

  $t_{avalanche} - t_0 = L/v$

- external "trigger" defines t_0

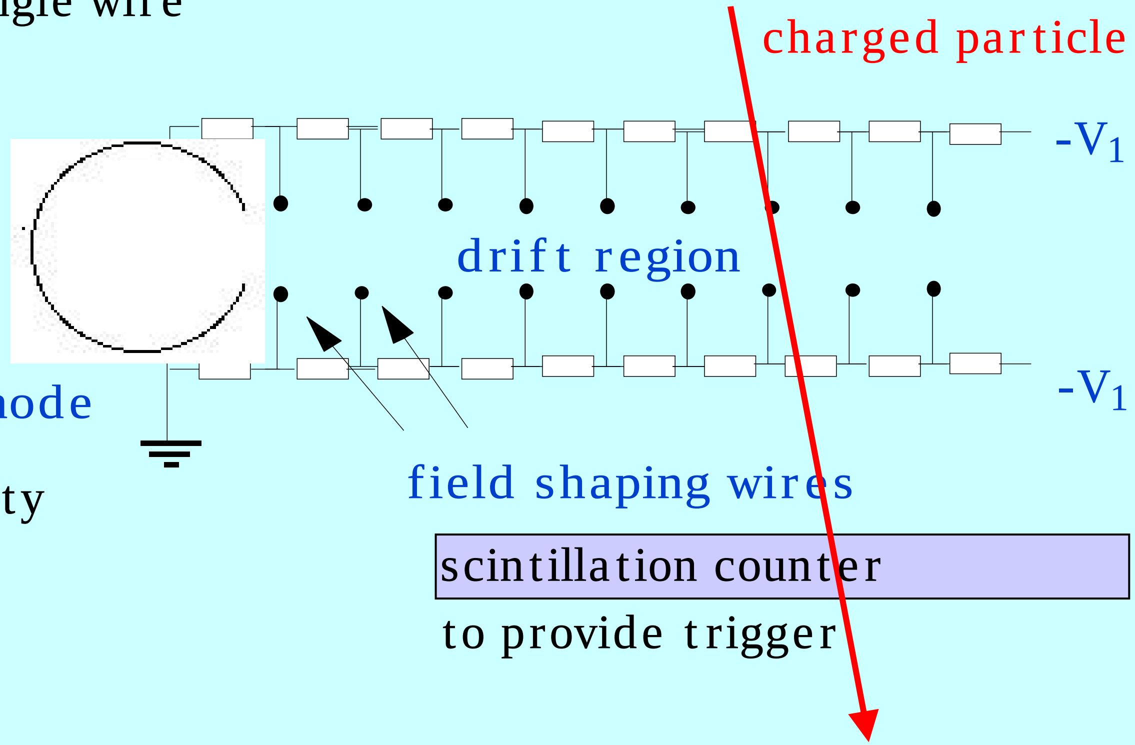
- for accurate measurement

  in-situ calibration of drift velocity

  typical $v_e \sim 5$ cm/μs

  $v_{ion} \sim v_e/1000$

  measurements σ < 100μm achieved over few cm drift path



- Large chambers

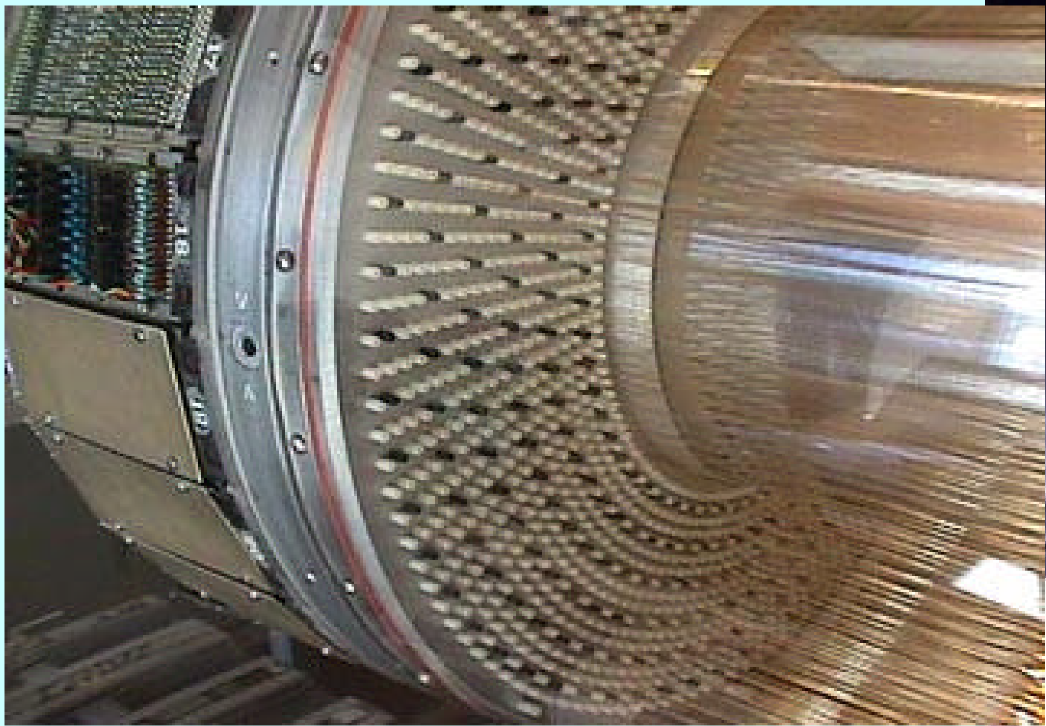
  wires configured in electrostatic "cells"

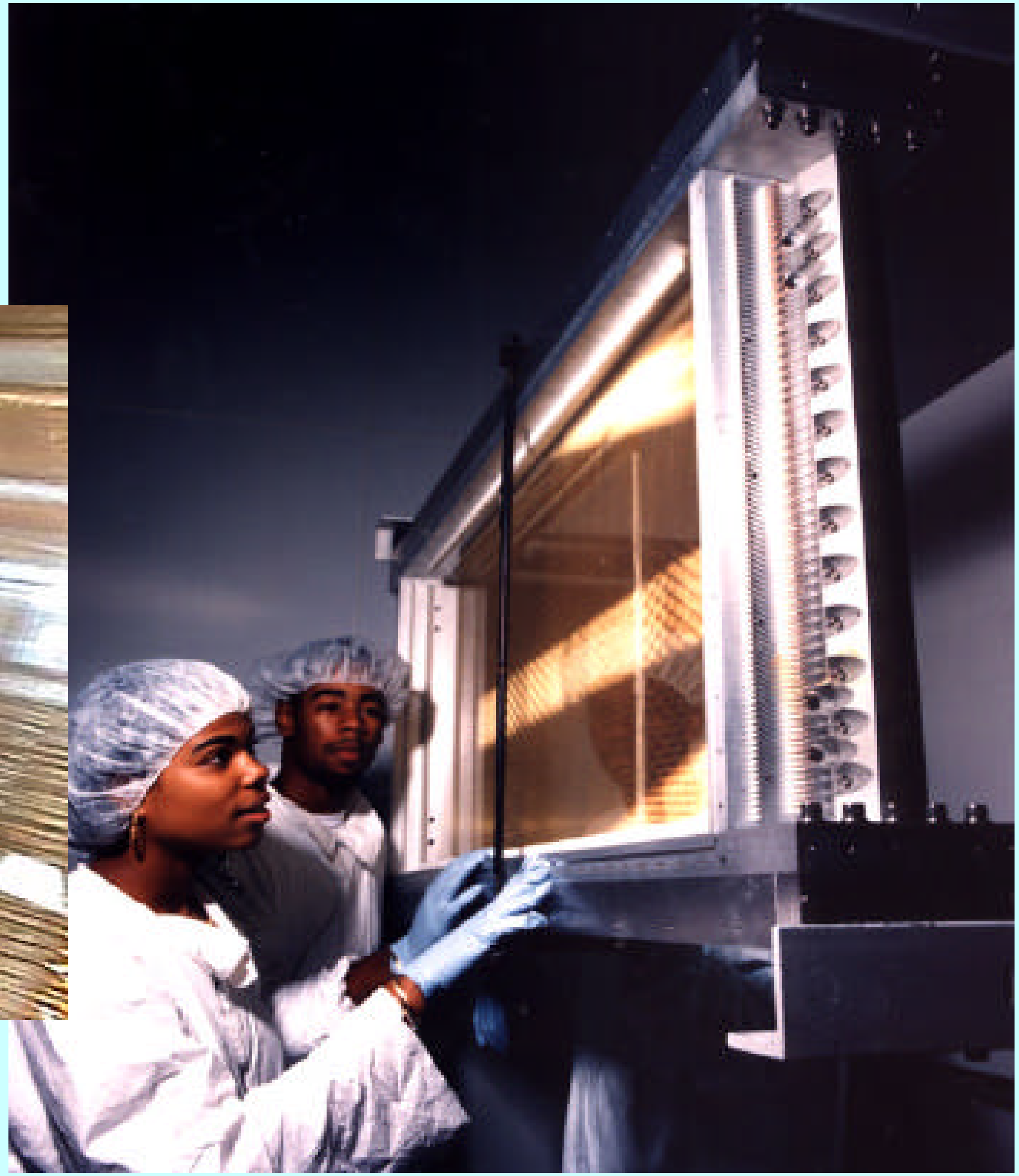
  small cells maximise capability to operate in high intensity conditions

Actual chambers

- Manufacture under clean conditions

  wide range of designs and geometries





Time Projection chamber

- chamber is large cylindrical volume with high voltage at central plane

  electrons drift to ends - up to few m

  diffusion via molecular collisions would spread signal over wide area

- apply B-field parallel to E-field - 3-d measurement

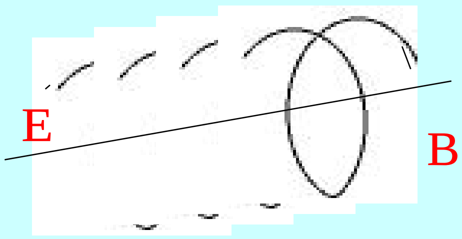
  wanted anyway for momentum measurements

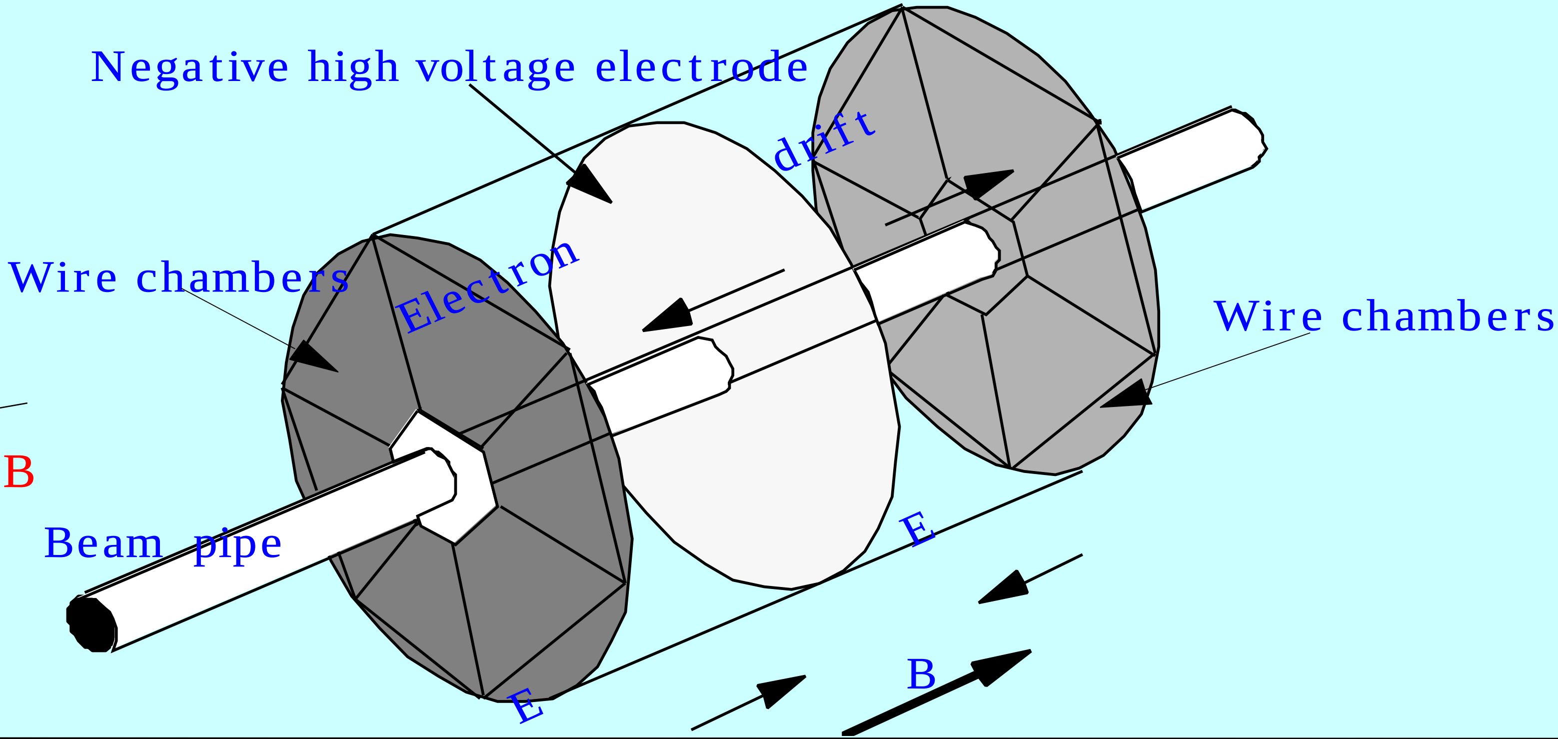
  limits diffusion, e⁻s follow helical paths

achieved in very large volumes

σ_T < 200µm

σ_L < 500µm





Pulse formation in gas detectors

- Signal is due to induction - positive ions dominate - why?

  charge Ne migrates toward anode, crosses voltage drop $\Delta\varphi$

  Work done transporting charge => charge movement in external circuit

  $Ne\,\Delta\phi = V_0\Delta q$ $\quad$ V_0 = *bias voltage - constant*

  since avalanches form close to anode, electrons do not experience large $\Delta\varphi$

  ions drift across whole chamber so feel full bias voltage applied to chamber

- Ion velocity is much less than electrons

  fast rise to signal pulse

  drift time to cathode to induce full signal charge: pulse duration ~ µs - ms

- This is a drawback for some applications

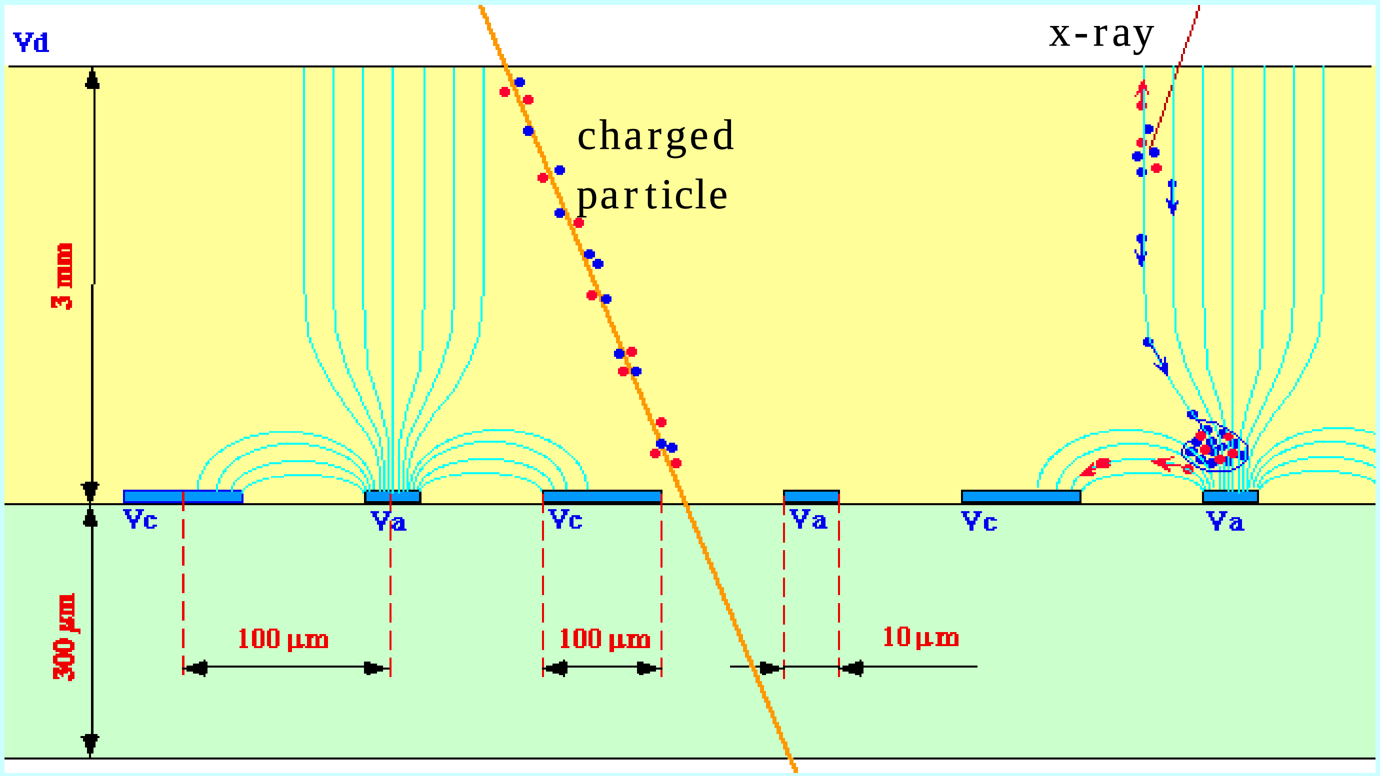
  => designs to shorten ion drift paths while operating at the same voltage

  amplifiers with pulse shaping so slow part of signal can be ignored or cancelled

MicroStrip Gas Chambers (MSGC)

- Etch anode and cathode strips on same glass substrate
  - avalanche region near glass surface
  - very accurate postions of strips   *control gain*
  - short distance for e^- & ions to travel   *fast signal, with short tail*
  - duration (for charged particle signals) due to drift time in gas

Note uniform E field in drift region

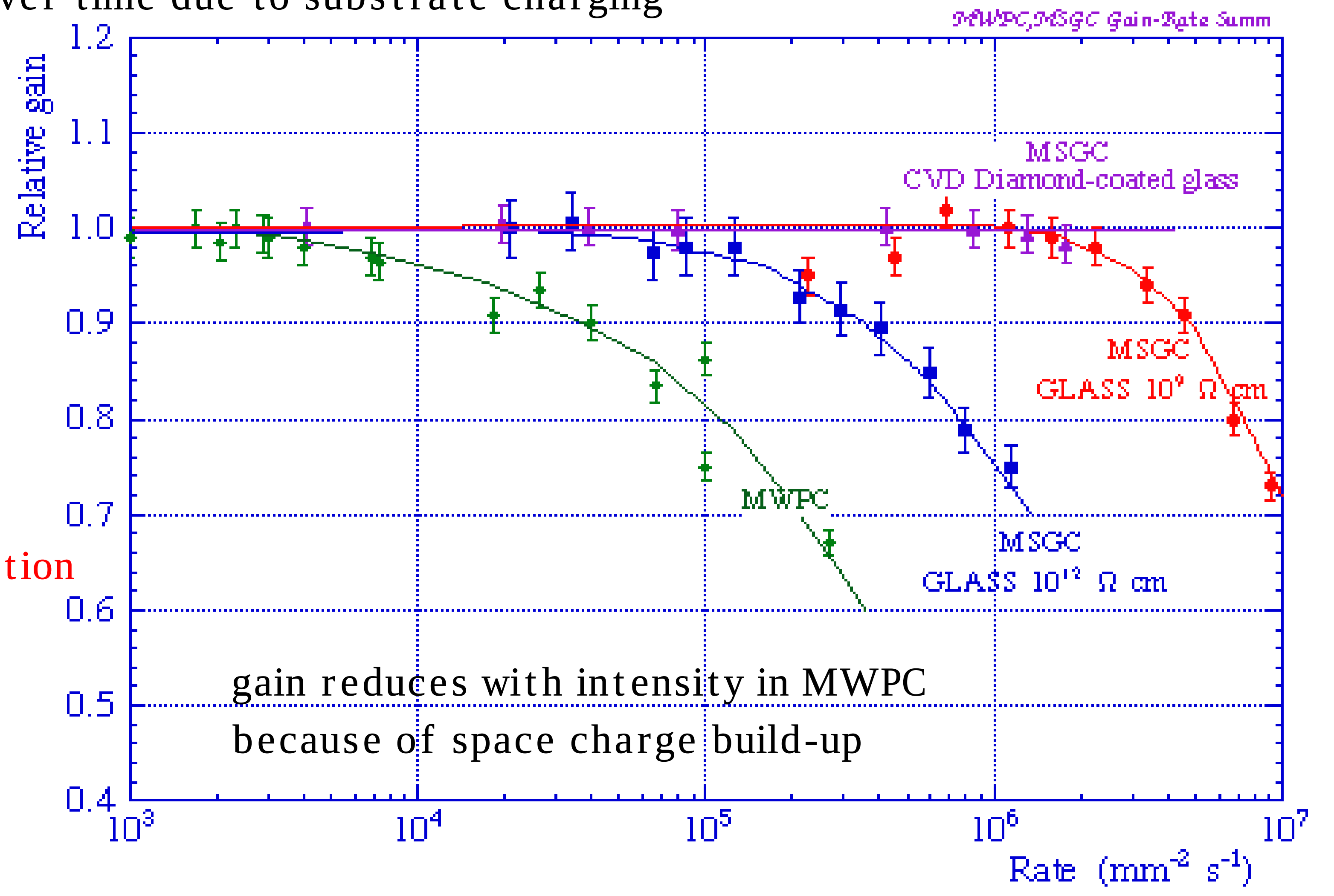


MSGC properties

- Excellent performance in high intensity (rate) conditions

gain reduction over time due to substrate charging

coatings and low resistivity to avoid

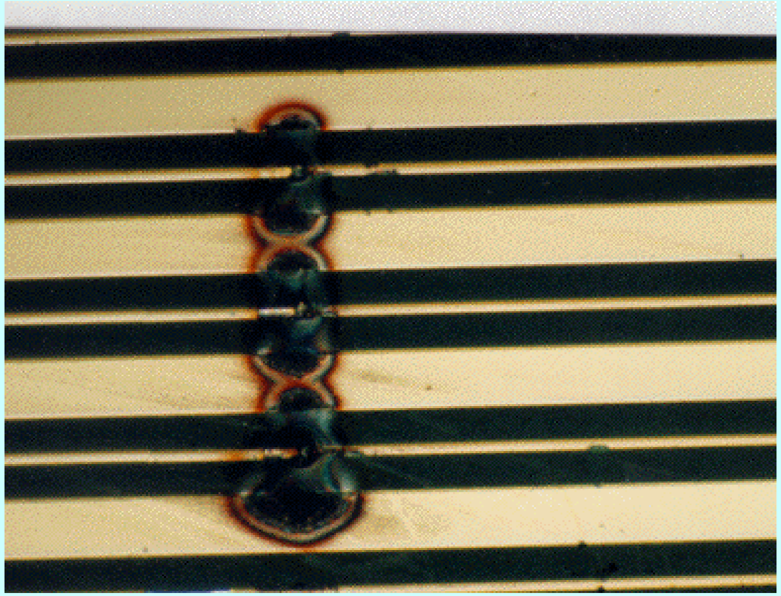


gain reduces with intensity in MWPC
because of space charge build-up

- also
- good energy resolution

Gas discharges

- bane of all gas detectors and troublesome for MSGC
  - charge is stored in capacitances
  - high E fields present
- discharge typically initiated by
  - heavily ionising nuclear events
  - manufacturing defects
  - deposits on electrodes
- discharge is very fast
  - ~ns
  - difficult to predict
  - or prevent



Gas Electron Multiplier GEM

- Principle

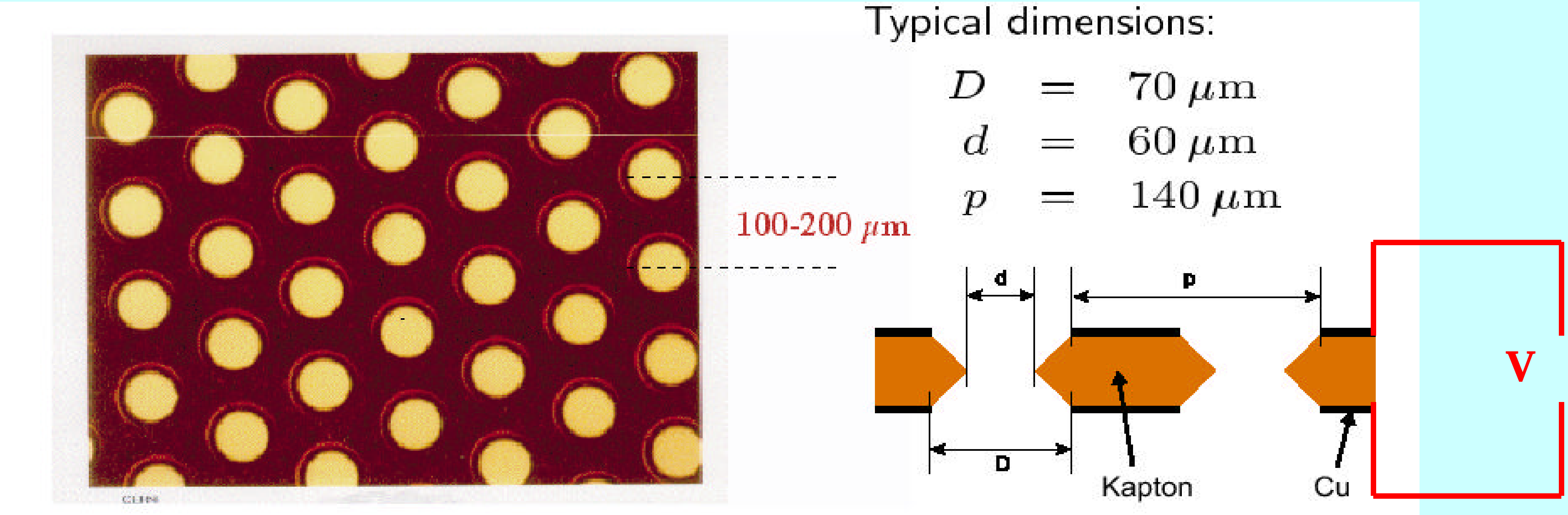
  Thin polymer (kapton) foil ~50µm thick,

  metal clad on both sides

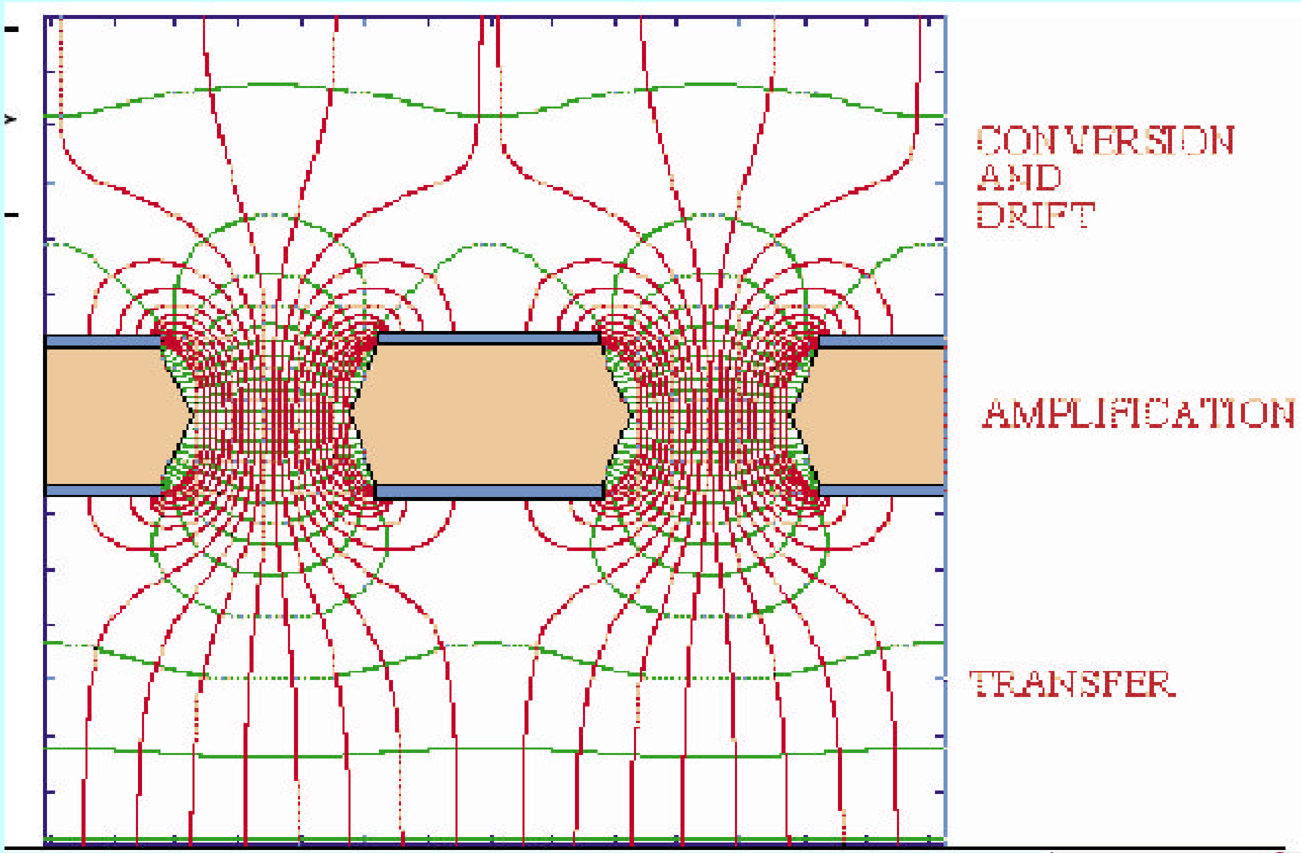
  perforated by large number of holes, ~$10^4.cm^{-2}$,

  using photolithographic process & etching

- Apply voltage ~500V across foil

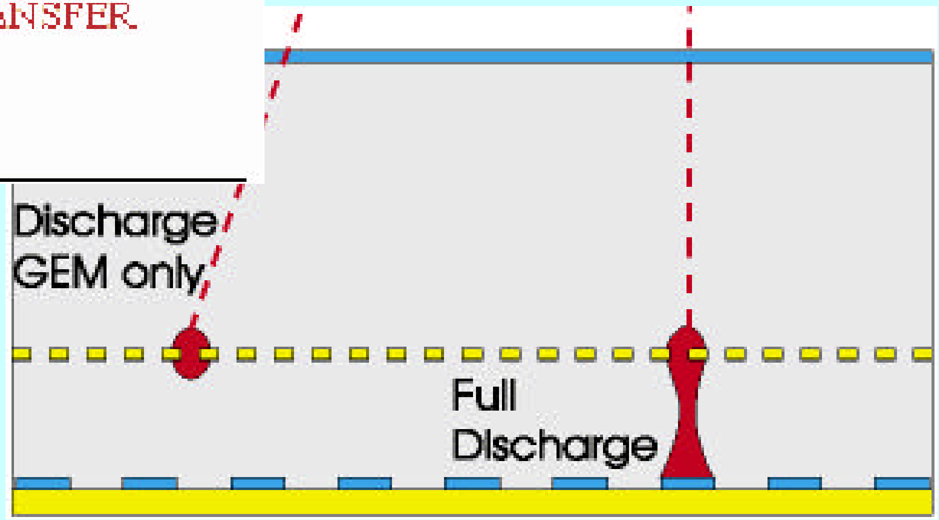


GEM electric field



amplification field is mainly confined to holes

- reduces risk of complete discharge between electrodes



GEM operation

- Operated in proportional region

  amplification in holes in foil but gain is property of foil, so

  little dependence on external fields

  good mechanical tolerance

- signal on readout electrode due only to electron collection

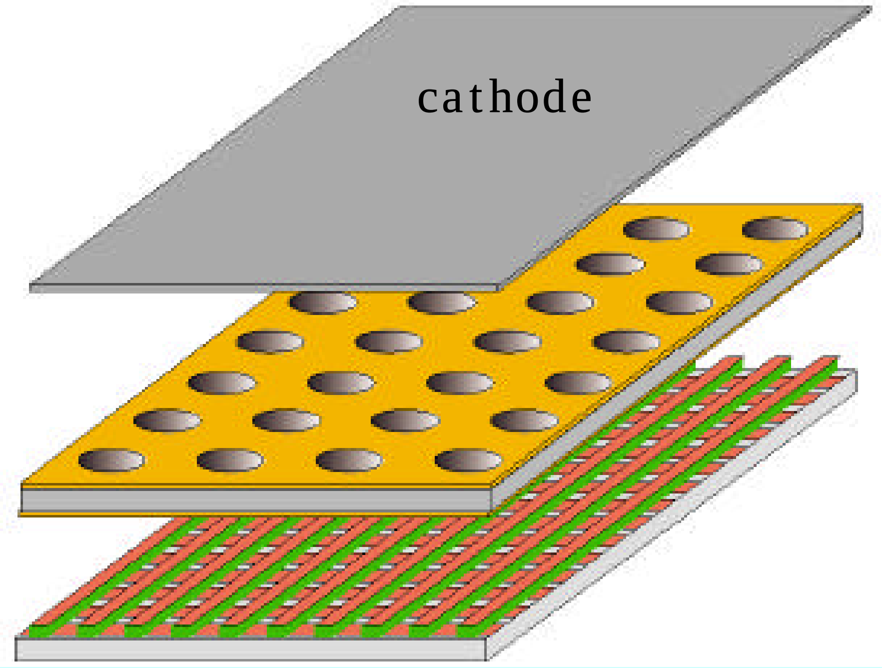
  no slow ion tail or ion feedback

- can cascade several GEM foils to increase gain

- separation of gas amplification and readout

  = flexible design

- readout electrodes at OV



Problems with gaseous detectors

- Excellent and widely used detectors, but some drawbacks

- Detectors with built-in amplification need careful attention

  small voltage changes can produce large variations in gain

  gas quality must be carefully monitored

    impurities can affect operation or, worse, cause long term damage

    sparking, if chamber enters discharge region - noise and damage

  gas amplification has inherent instability - for long term use

    organic molecules break into new polymers

    deposits in gas can build up on wires

  radiation damage

  wires strung in chambers must be maintained under tension

    gravitational displacement can distort field in multi-wire systems

    long thin wires subject to stress, particularly at connection points

- Nevertheless, large chambers with 10^4 wires or more have been operated successfully for many years