Summary of previous slides :

We now know how most particles (i.e all particles that live long enough to reach a detector; e,u,p,π,k,n,γ, neutrinos,etc) react with matter.

We now know how to identify particles to some extend, how to measure E and p, v, and how to measure lifetimes using secondary vertices, etc

Lecture set 2 : but we skipped one essential step in the process .....

How are reactions of the various particles with detectors turned into electrical signals. We would like to extract position and energy information channel by channel from our detectors.

Three effects are usually used :

1 Ionisation

2 Scintillation

3 Semi Conductors

and these are used in either for tracking, energy measurements, photon detectors for Cherenkov or TRT, etc

4 Finally we will have a quick look at how electrical signals are amplified in FE electronics

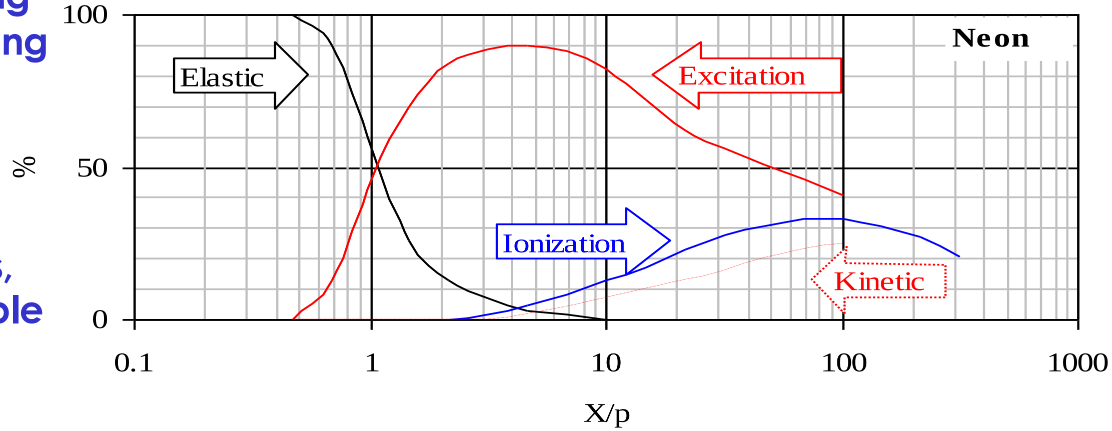
and from then on it is all online (trigger, DAQ) and offline treatment and analysis ....

Ionisation Detectors

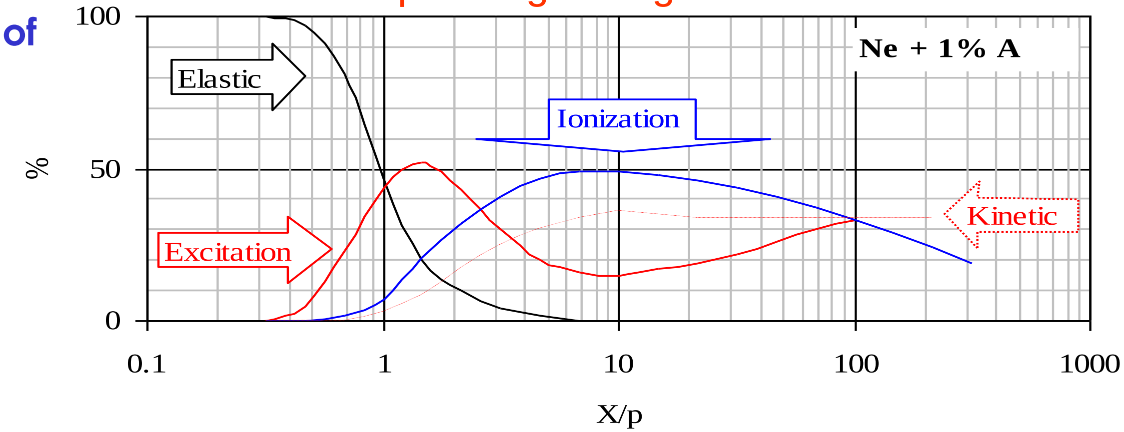
From CERN-CLAF, O.Ullaland

Approximate computed curves showing the percentage of electron energy going to various actions at a given X/p (V/cm/mmHg)

Elastic: loss to elastic impact
Excitation: excitation of electron levels, leading to light emission and metastable states
Ionization: ionization by direct impact
Kinetic: average kinetic energy divided by their "temperature"
Vibration: energy going to excitation of vibrational levels

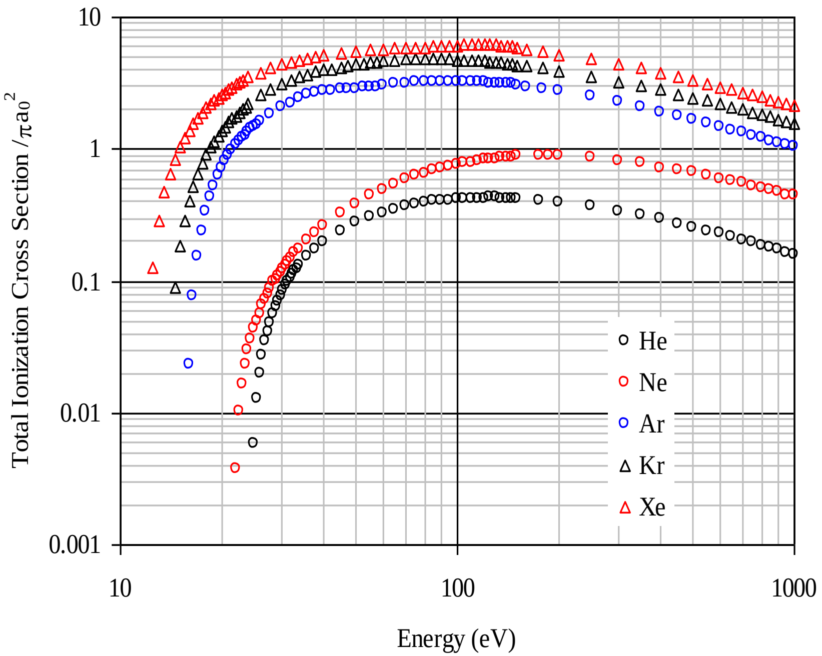


Add a sprinkling of argon

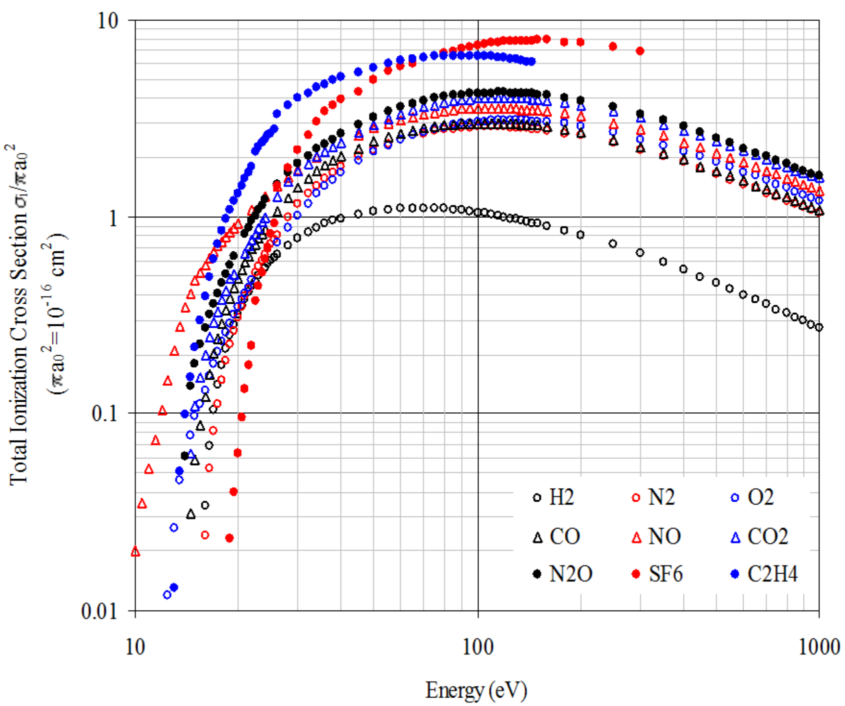


L. B. Loeb, Basic Processes of Gaseous Electronics

Experimental results. Rare gases.



Experimental results. Diatomic molecules.

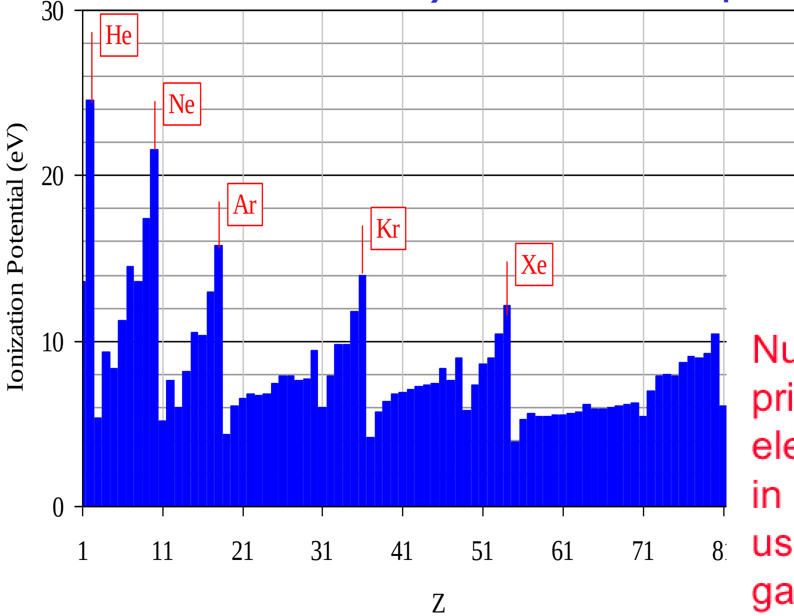


D. Rapp et al., Journal of Chemical Physics, 43, 5 (1965) 1464

Fig 1. Ionisation potiential. The work required to remove a given electron from its orbit and place it at rest at an infinite distance.

Fig 2. Note that limited number of primary electrons/ions.

Fig 3 (table). Taking into account that some of the primary electrons will ionise further (factor 3-4 increase); nevertheless keep in mind that electronics noise can be 300-500 ENC.

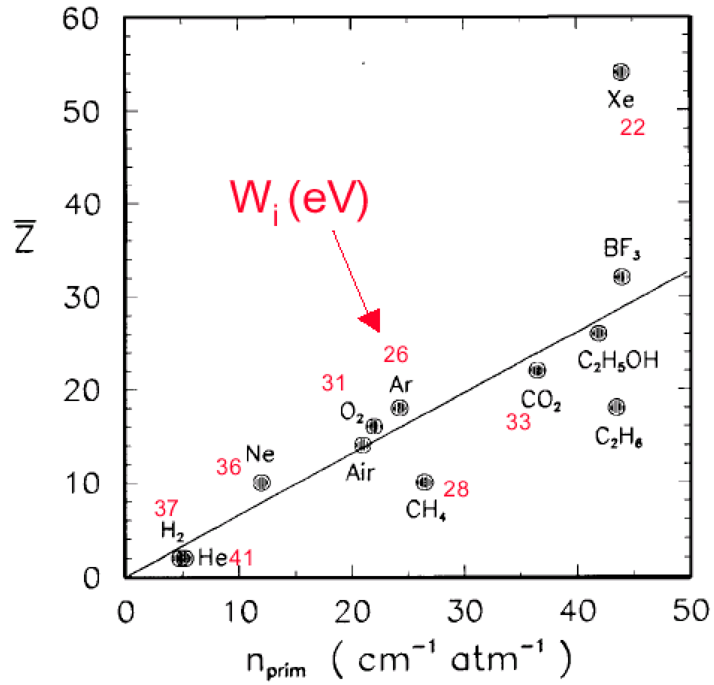


CRC Handbook 63 ed.

Number of primary electron/ion pairs in frequently used (detector) gases.

	Encounters/cm	t_{99}(mm)	Free electrons/cm
He	5	9.2	16
Ne	12	3.8	42
Ar	25	1.8	103
Xe	46	1.0	340
CH_4	27	1.7	62
CO_2	35	1.3	107
C_2H_6	43	1.1	113

(Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific,1992)



From C.Joram

Ionisation Detectors

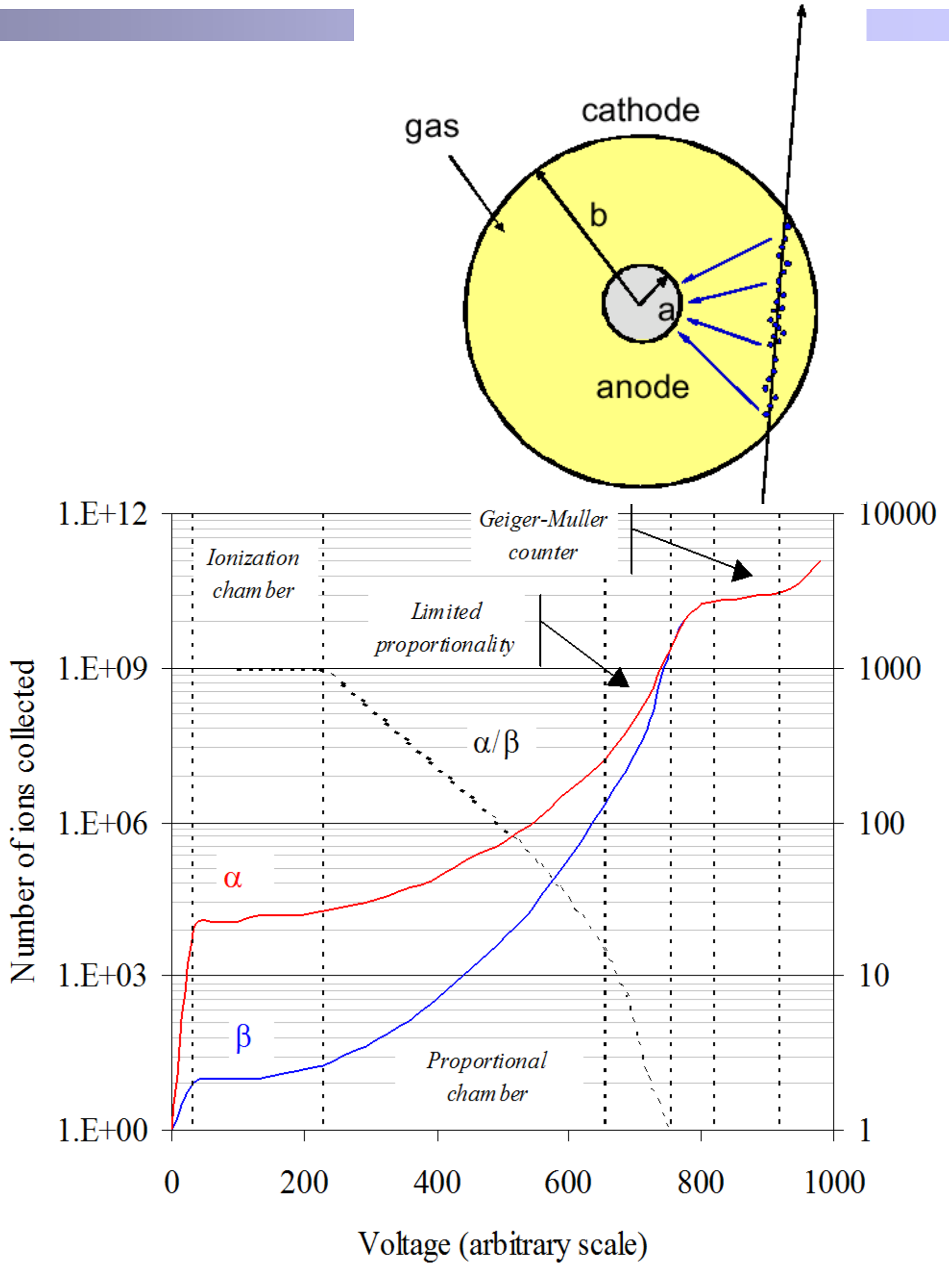
The different regions :

Recombination before collection.

Ionisation chamber; collect all primary charge. Flat area.

Proportional counter (gain to 10^6); secondary avalanches need to be quenched.
Limited proportionality (secondary avalanches distorts field, more quenching needed).

Geiger Muller mode, avalanches all over wire, strong photoemission, breakdown avoided by cutting HV.



From C.Joram

No external fields:

Electrons and ions will lose their energy due to collisions with the gas atoms → thermalization

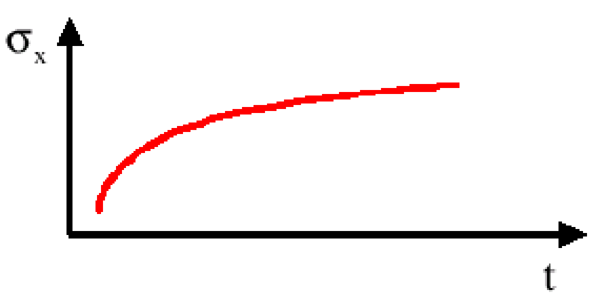
$$\varepsilon = \frac{3}{2} kT \approx 40 \text{ meV}$$

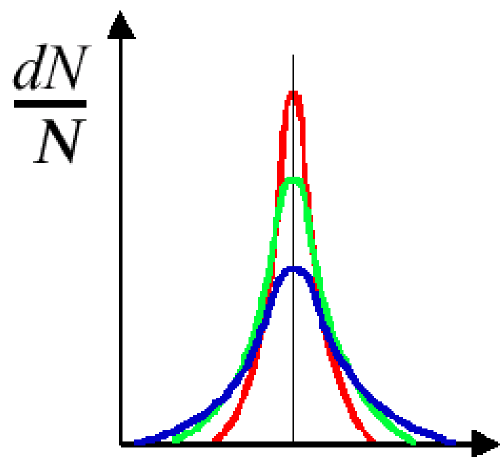
Undergoing multiple collisions, an originally localized ensemble of charges will diffuse

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-(x^2/4Dt)} \, dx$$

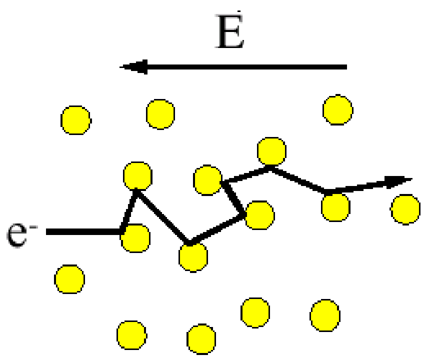
D: diffusion coefficient

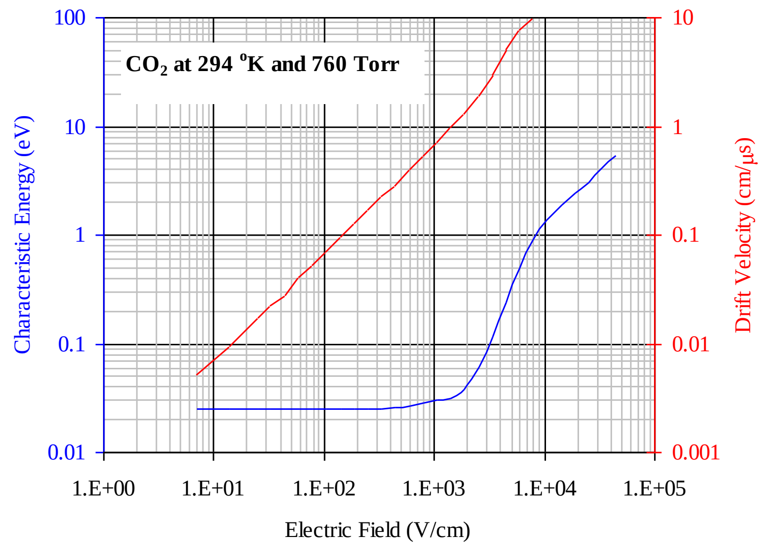
$$\sigma_x(t) = \sqrt{2Dt} \quad or \quad D = \frac{\sigma_x^2(t)}{2t}$$





Drift of electrons under the action of the electric field (superimposed on thermal movements) :





The drift velocity of the positive ions under the action of the electric field is linear with the reduced electric field (E/pressure) up to very high fields.

$v^{+ions} = \mu^{+ions} E$ where $\mu^{+} \propto 1/p$ and diffusion $D^{+ions} \propto \mu^{+ions} T$

$$\frac{v_{electron}}{v_{ion}} \approx 10^3$$

in CO_2 with $E=10^4$ V/cm

From CERN-CLAF, O.Ullaland

From CERN-CLAF, O.Ullaland

The amplification process :

Let α^{-1} be the mean free path (also called the first Townsend coefficient) between each ionization, in other words dn = nadx.

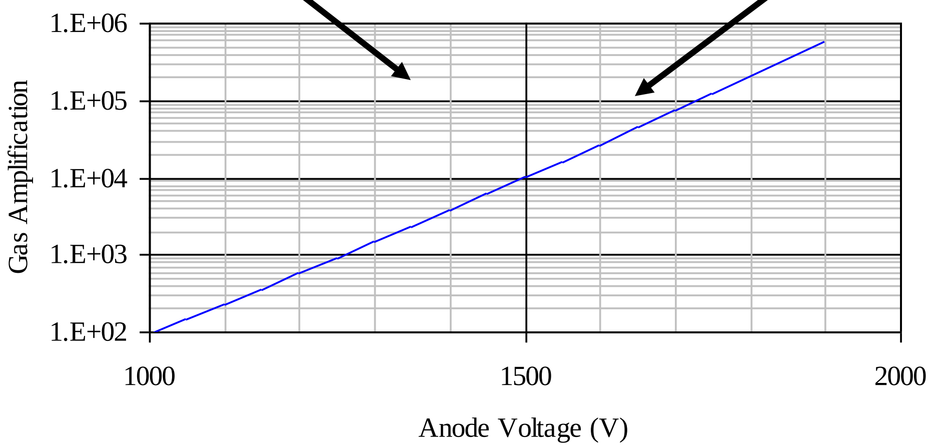
The gas amplification is then given by :

$$M = e^{\int_{x_1}^{x} \alpha(x)dx}$$

Korff's approximation (model) $\frac{\alpha}{p} = Ae^{-Bp/E}$ where *A* and *B* are gas dependent constants and *p* is the pressure.

$$M = \exp\left[\frac{A}{B}\frac{V_0}{\ln\frac{R}{r_0}} e^{-\frac{Bpr_0 \ln\frac{R}{r_0}}{V_0}}\right]$$

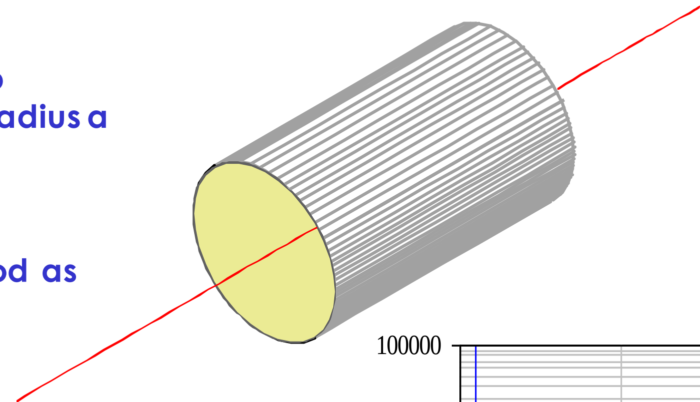
	A	B
	(Torr/cm)	(V Torr/cm)
He	3	34
Ne	4	100
Ar	14	180
Xe	26	350
CO2	20	466



for a gas mixture of Ar/CO_2 : 80/20

Ionisation Detectors

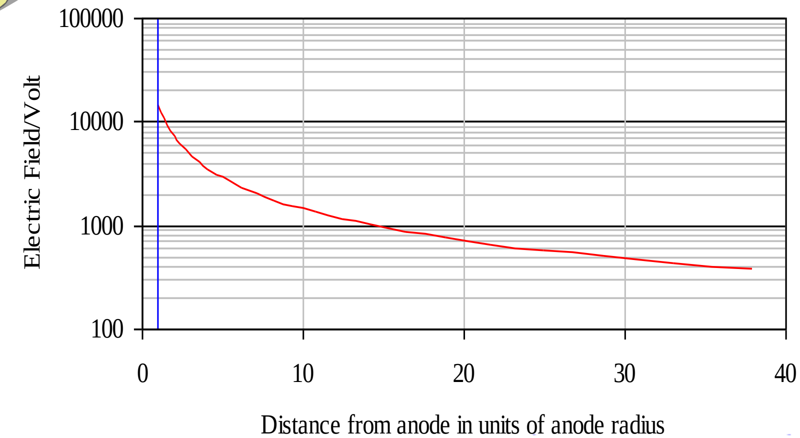
Cathode :A metallic cylinder of radius b
Anode : A gold plated tungsten wire of radius a
a = 10^{-5} m
b/a = 1000



$$E = \frac{1}{r}\frac{V_0}{\ln\left(\frac{b}{a}\right)}$$

The formation of signal can be understood as follows. The electrostatic energy of the configuration is :

$$W = \frac{1}{2} lCV_0$$



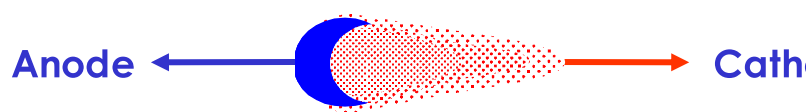
where C is the capacitance per unit length of the configuration and l is the length.
The potential energy of a charged particle at radius r is given by the charge times the potential :

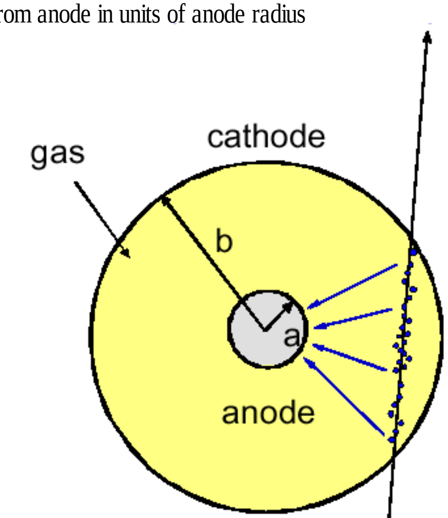
$$W = -q\frac{CV_0}{2\pi\varepsilon}\ln\frac{r}{a}$$

The result is an equation for how the voltage (signal) changes when the particle moves in the electric field :

$$dW = lCV_0 dV = q\frac{d\varphi(r)}{dr}dr$$

$$\varphi(r) = -\frac{CV_0}{2\pi\varepsilon}\ln\frac{r}{a}$$





Signal induced by (mainly) the positive ions created near the anode.
Assume that all charges are created within a distance λ from the anode.
λ is of the order of a few 10's of μm → $v_{electron}$ = v_{ion} /100 which can be seen from the equations below setting in the correct values for a and b :

$$v_{electron} = -\frac{Q}{lCV_0}\int_a^{a+\lambda}\frac{dV}{dr}dr = -\frac{Q}{2\pi\varepsilon l}\ln\frac{a+\lambda}{a}$$

$$v_{ion} = +\frac{Q}{lCV_0}\int_{a+\lambda}^{b}\frac{dV}{dr}dr = -\frac{Q}{2\pi\varepsilon l}\ln\frac{b}{a+\lambda}$$

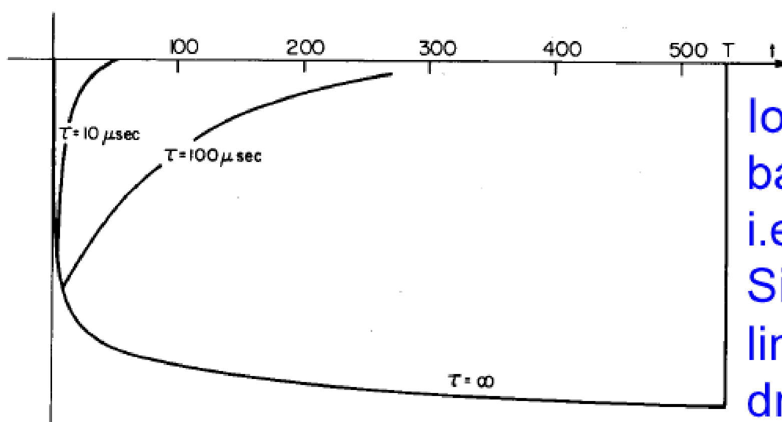
Assuming a=0 and all the signal comes from the ions we can write:

$$v(t) = +\frac{Q}{lCV_0}\int_{r(0)}^{r(t)}\frac{dV}{dr}dr = --\frac{Q}{2\pi\varepsilon l}\ln\frac{r(t)}{a}$$

r(t) can be taken from :

$$\frac{dr}{dt} = \mu E(r)$$

The final result for v(t) :



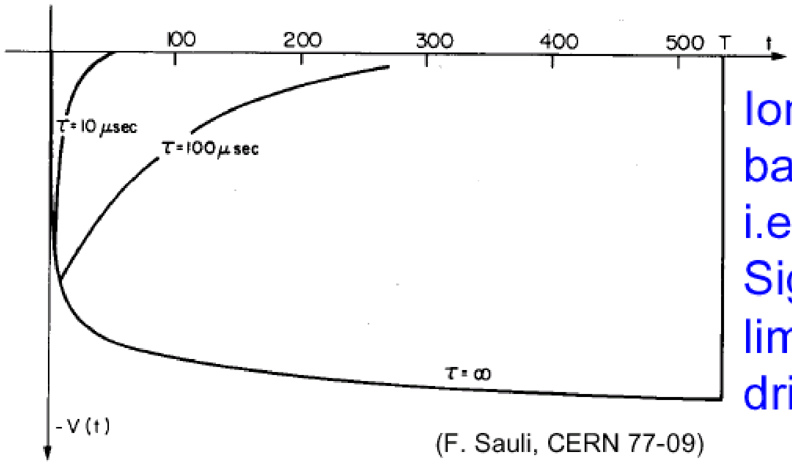
(F. Sauli, CERN 77-09)

Ions have to drift back to cathode, i.e. *dr* is big. Signal duration limited by total ion drift time !

Need electronic signal differentiation to limit dead time.

In modern fast ionisation detectors the electrons are used (faster) as well as the beginning of the ion signal.

For example if we use 5% of the signal with a gain 10^4 we still have a healthy signal compared to the noise – and we can operate mostly with the fast part of the signal (electrons) and differentiate away the tails ….



(F. Sauli, CERN 77-09)

Ions have to drift back to cathode, i.e. *dr* is big. Signal duration limited by total ion drift time !

Need electronic signal differentiation to limit dead time.

With these tools, we can now make :

Straw Tube

Multiwire Proportional Chambers

Drift Chambers

Time Projection Chambers

Thin Gap Chambers

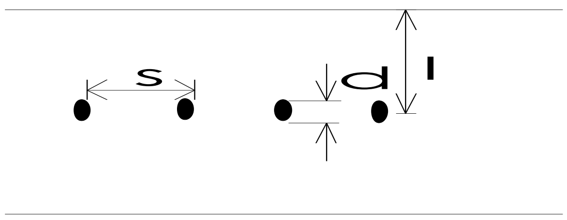
Jet Chambers

etc

From CERN-CLAF, O.Ullaland

Classic Multi-Wire Proportional Chamber (MWPC)
Typical parameters :

- **l : 5 mm**
- **s : 2 - 4 mm**
- **d : 20 mm**



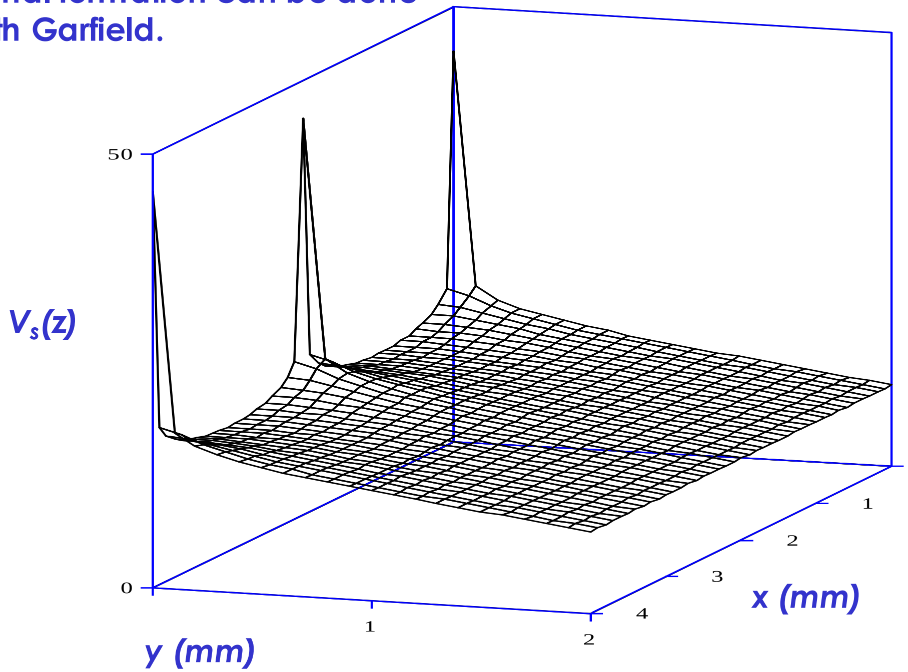
Still possible to calculate by hand (leave as exercise for you) :

$$V_s(z) \underset{d \to 0}{\approx} \frac{2\pi l}{s} - \ln\left\{4\sin^2\left(\frac{\pi x}{s}\right) + 4\sinh^2\left(\frac{\pi y}{s}\right)\right\}$$

$$Q = \frac{V_0}{\frac{2\pi l}{s} - 2\ln\frac{\pi d}{s}}$$ **and** $$E_0 = \frac{sV_0}{\frac{\pi d}{2}\left[l - \frac{s}{\pi}\ln\frac{\pi d}{s}\right]}$$

Ionisation Detectors

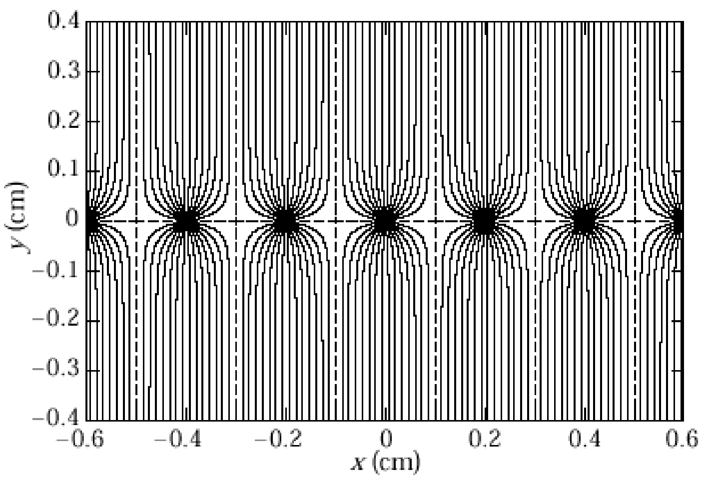
Advanced calculations of electric field, drift, diffusion and signal formation can be done with Garfield.

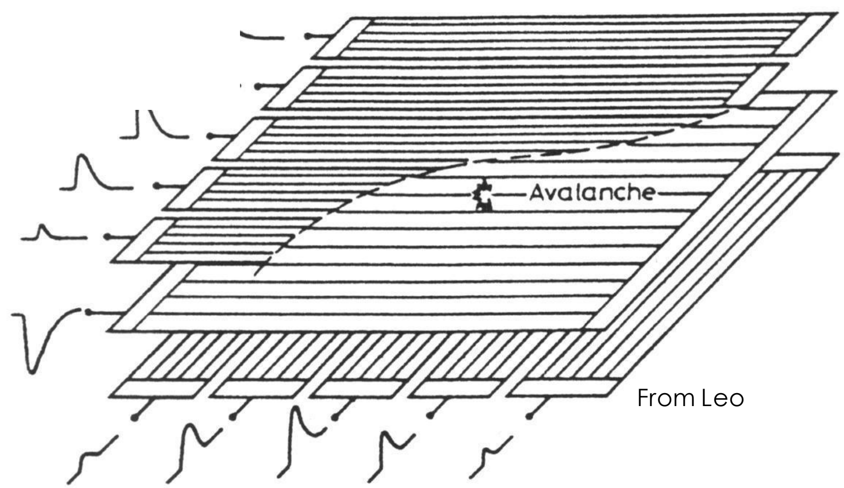


Two dimensional readout can be obtained by; crossed wires, charge division with resistive wires, measurement of timing differences or segmented cathode planes with analogue readout

Resolution given by (binary readout): $\sigma = d/\sqrt{12}$

Analogue readout and charge sharing can improve this significantly when the left/right signal size provide more information about the hit position.

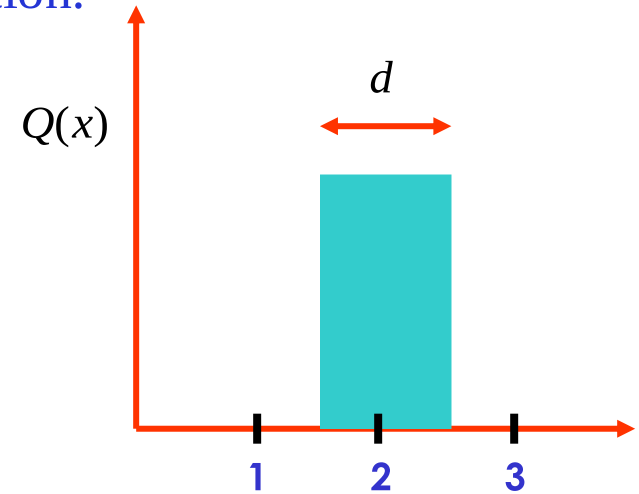




From Leo

$$y = \frac{\sum (Q_i - b) y_i}{\sum (Q_i - b)},$$

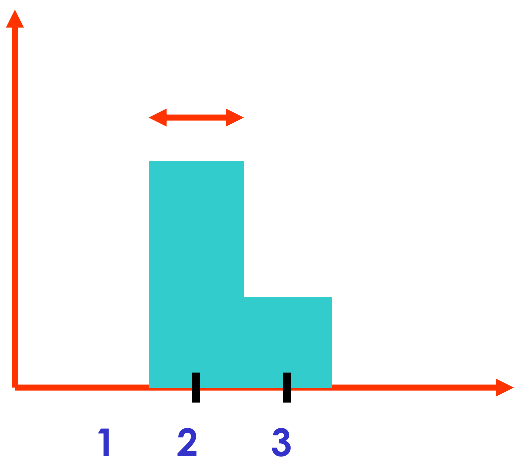
Charge on a single wire/strip is the worst possible situation for the resolution:



$$\sigma^2(x) = \int Q(x)\,(x-\bar{x})^2\,dx = d^2/12$$

where $Q(x)$ is charge readout in position x

(in this case a box with width equal to the pitch)



With analogue readout and charge sharing we improve the information content significantly – on the left we know that the hit was between the second and third readout electrode and closest to the 2nd, so we can make a probability function which is much more narrow (some times pitch/10).

Another way of saying it: For every point between wire/strip 2 and 3 there is a unique value of : $(Q_2-Q_3)/(Q_2+Q_3)$, so by measuring this quantity we can reconstruct the position.

From C.Joram

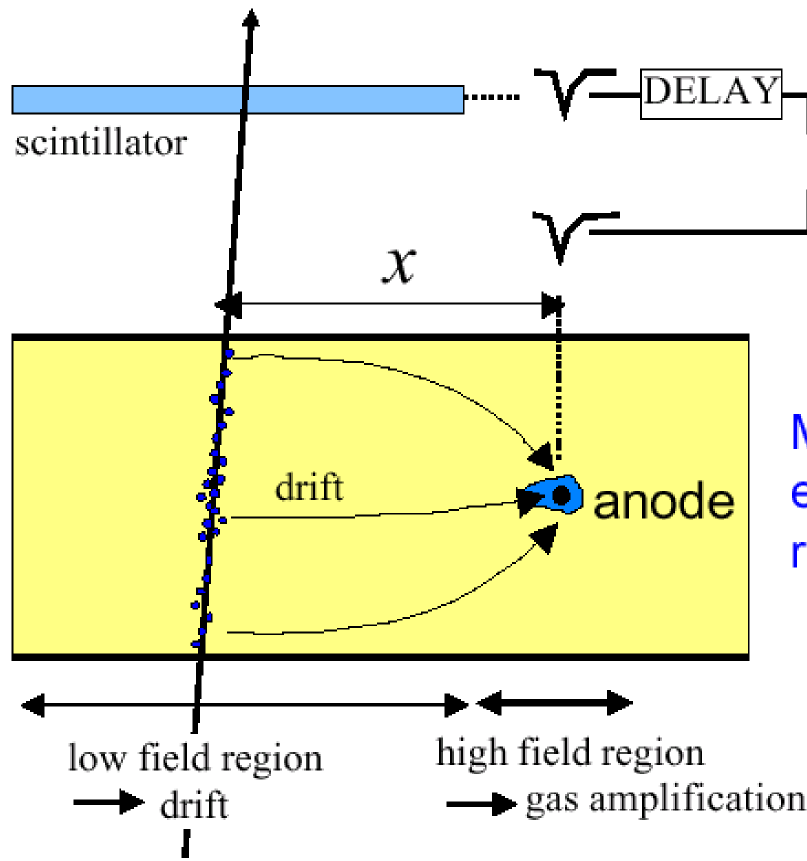
Drift Chambers :

Reduced numbers of readout channels

Distance between wires typically 5-10cm giving around 1-2 μs drift-time

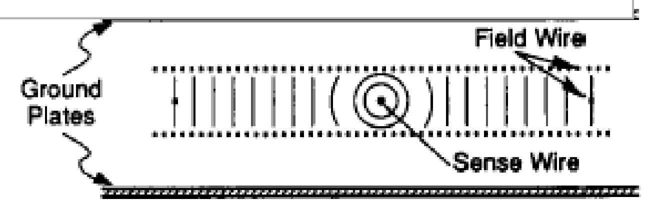
Resolution of 50-100μm achieved limited by field uniformity and diffusion

More problems with occupancy



Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t)dt$$



Ionisation Detectors

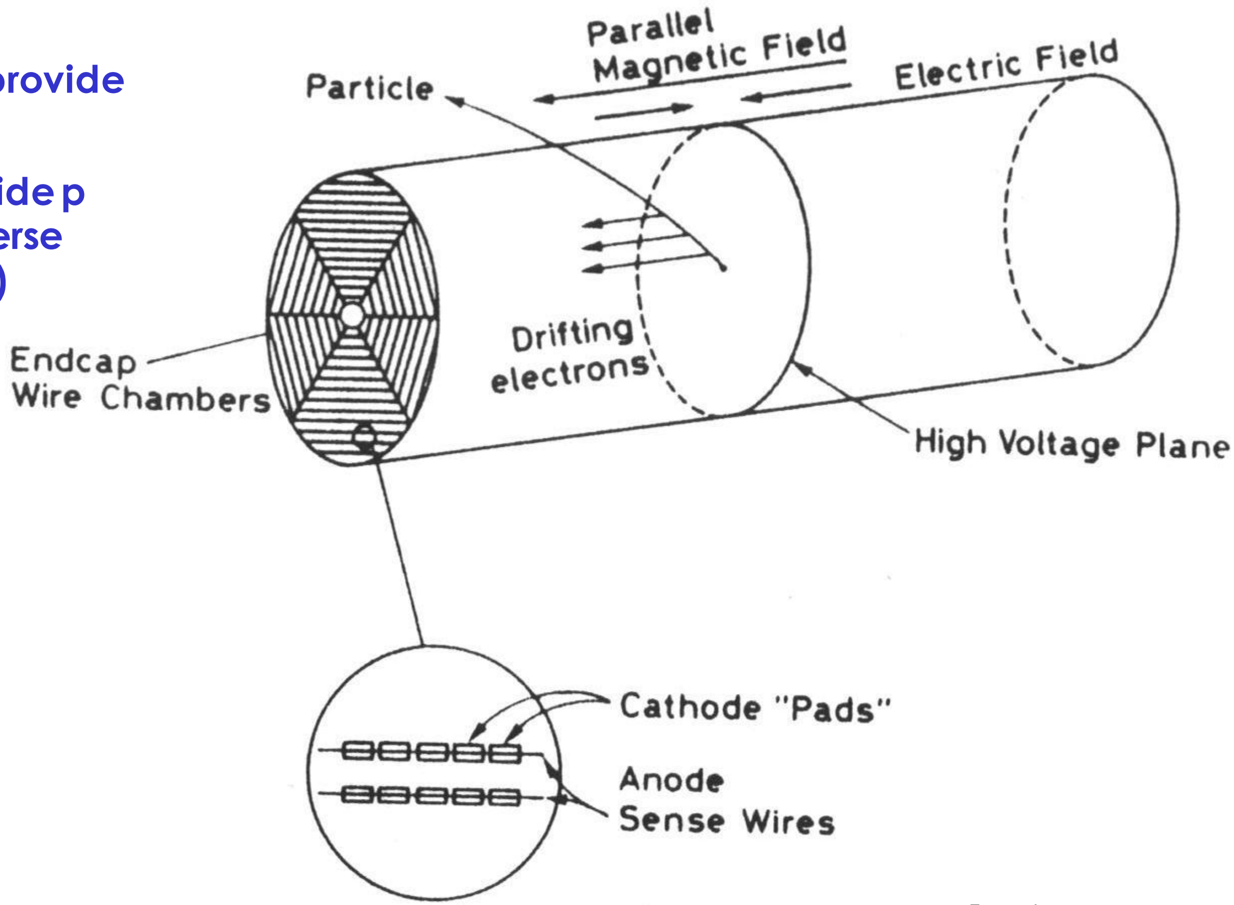
Time projection chamber :

Drift to endplace where x,y are measured

Drift-time provides z

Analogue readout provide dE/dx

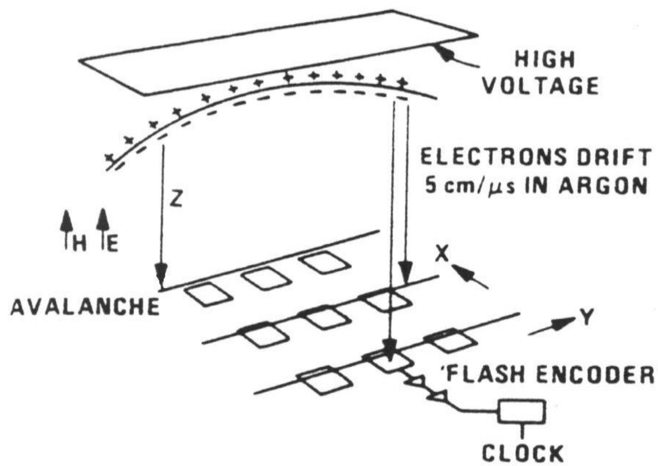
Magnetic field provide p (and reduce transverse diffusion during drift)

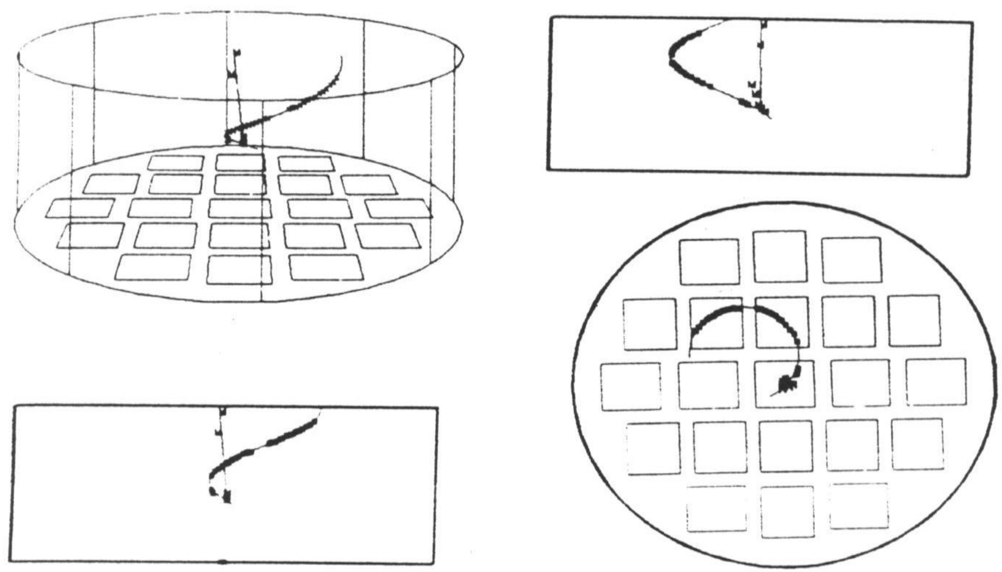


From Leo

Ionisation Detectors

The Time Projection Chamber (TPC)





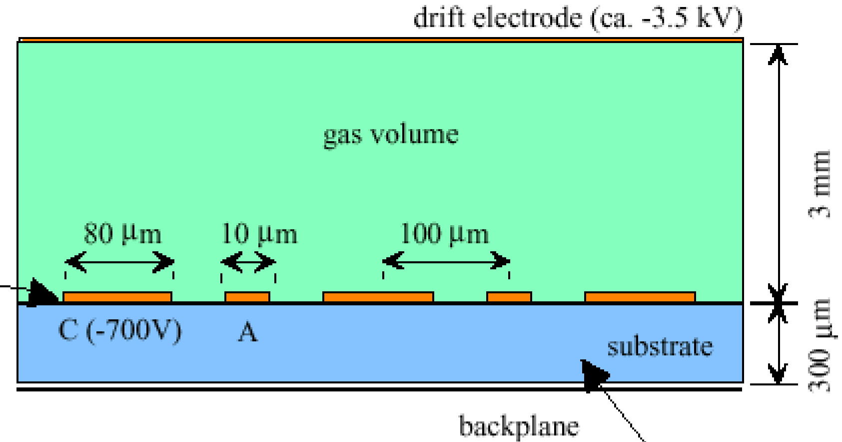
From Leo

In recent years there has been several developments directed towards making gas detectors more suitable for high rate applications (inner detectors components for LHC). I will mention only two (C.Joram; CERN summer student lectures 2002) :

◆ Microstrip gas chambers

(A. Oed, NIM A 263 (1988) 352)

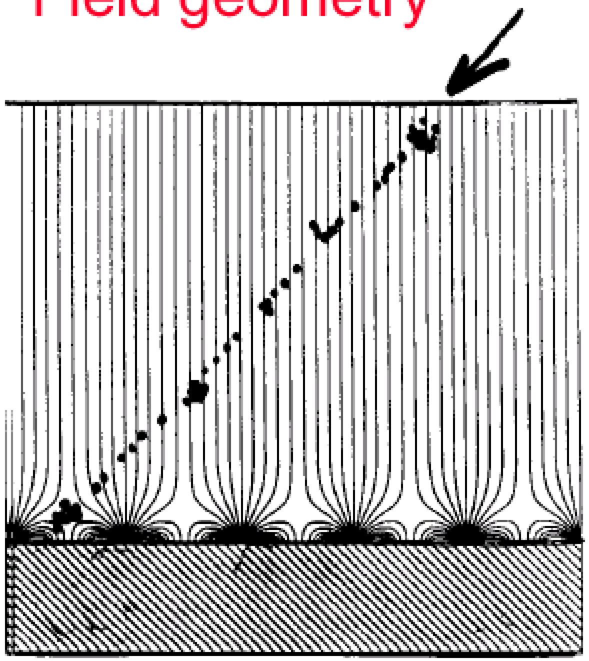
geometry and typical dimensions
(former CMS standard)

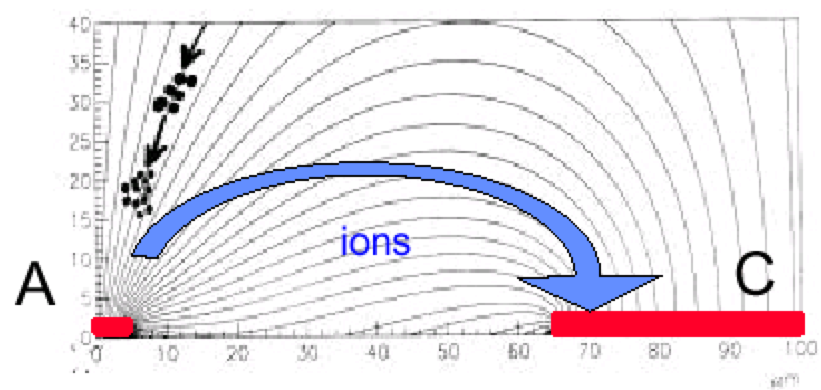


Gold strips
+ Cr underlayer

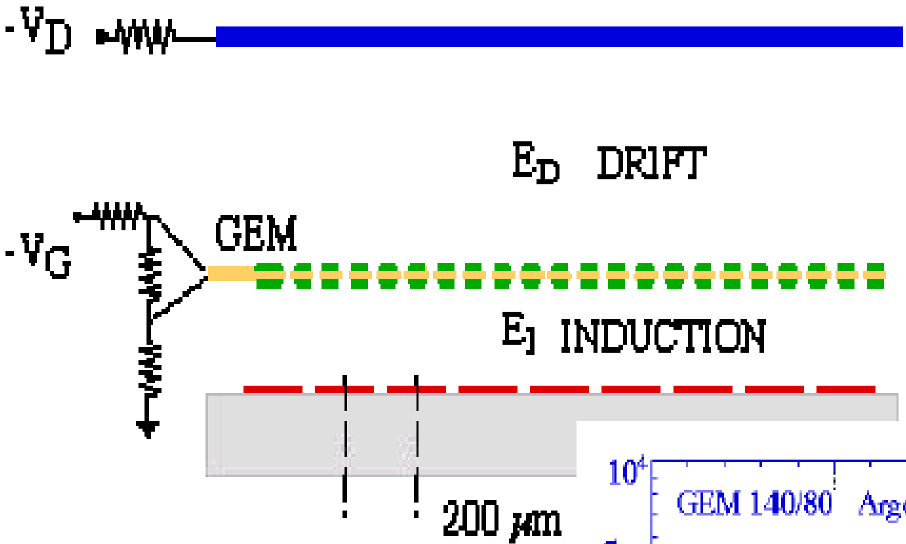
Glass DESAG AF45 + S8900
semiconducting glass coating,
$\rho = 10^{16}\ \Omega/\Box$

Field geometry



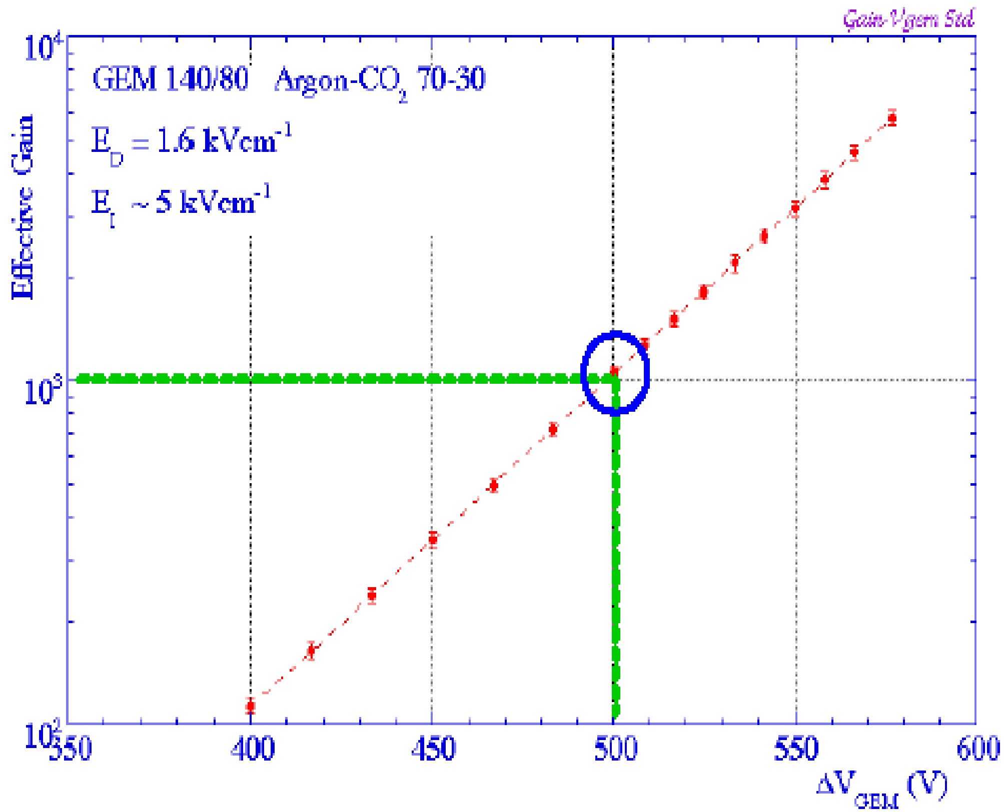


Fast ion evacuation → high rate capability
$\approx 10^6$ /(mm^2·s)



Single GEM

+ readout pads

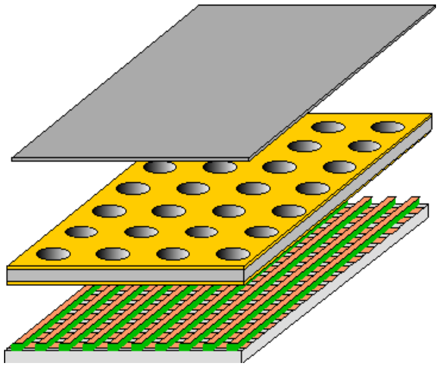


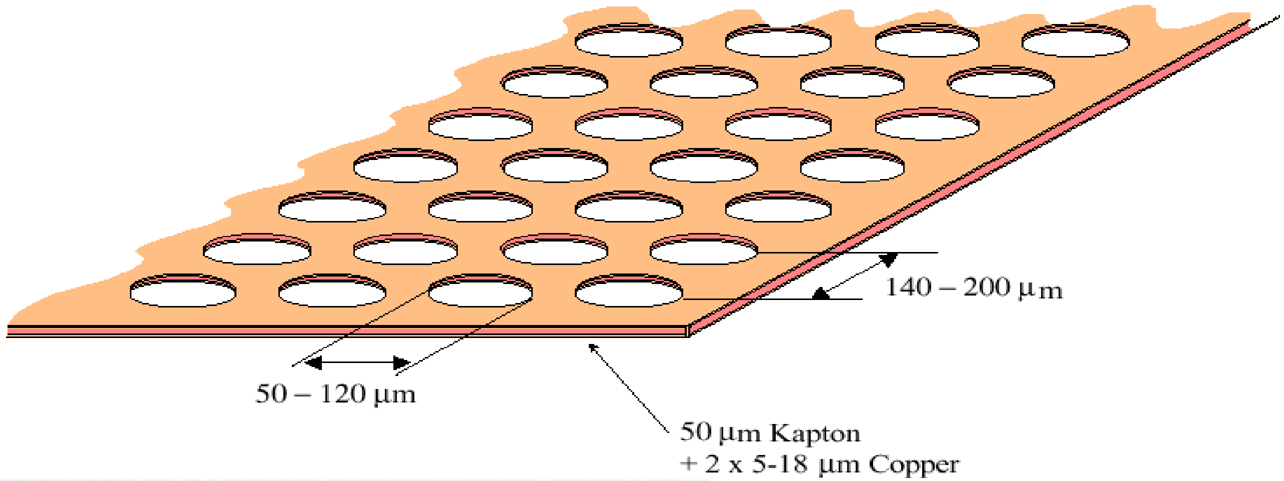
GEM : Gas Electron Multiplier

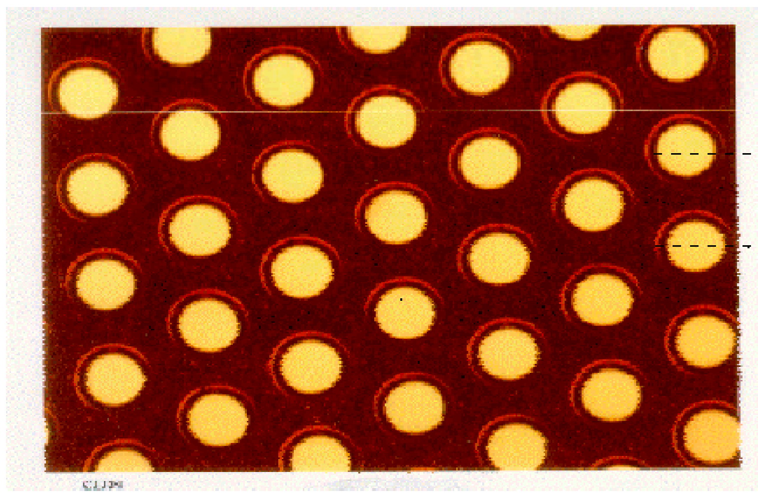
Can be used as a detector on its own or as amplifier stage in multiple structure

GEM: The Gas Electron Multiplier

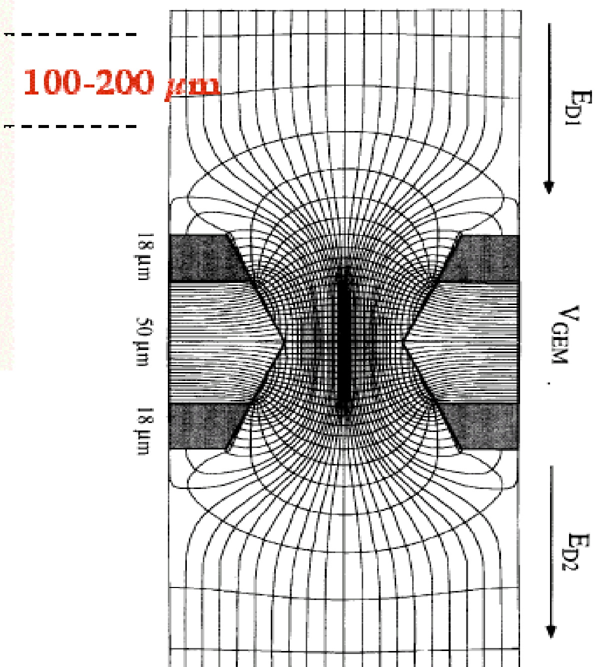
(R. Bouclier et al., NIM A 396 (1997) 50)







Micro photo of a GEM foil



Scintillators

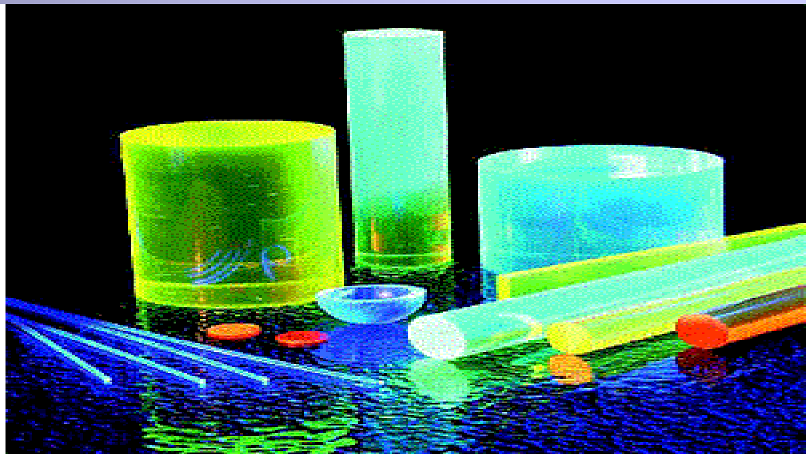
Scintillators are used in many connections :

- Calorimetry (relatively cheap and good energy resolution)
- Tracking (fibres)
- Trigger counters
- Time of flight
- Veto Counters

Will discuss mainly inorganic (often used in calorimeters due to high density and Z; slow but high light output and hence good resolution) and organic (faster but less light output)

Will discuss readout (wavelength shifters, photon detectors and new developments to increase granularity of the readout).

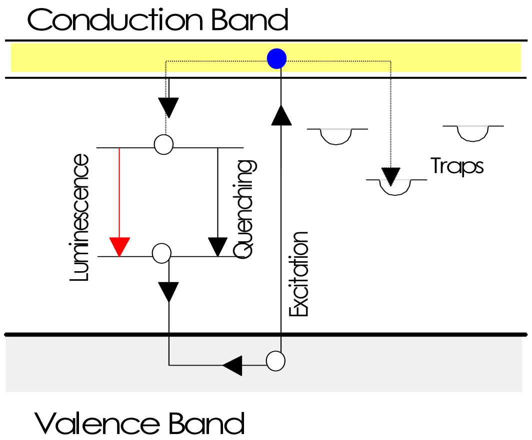
Scintillators

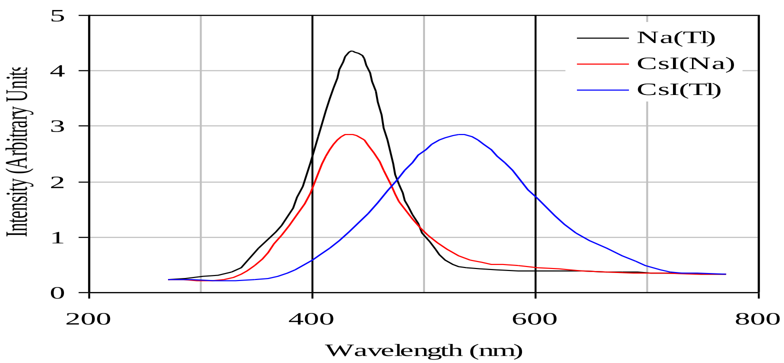


http://www.bicron.com.

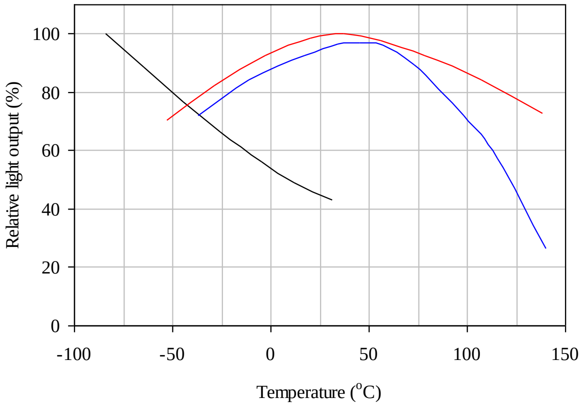
Inorganic Crystalline Scintillators
The most common inorganic scintillator is sodium iodide activated with a trace amount of thallium [NaI(Tl)],

Energy bands in impurity activated crystal





Strong dependence of the light output and the decay time with temperature.



Parameters for some common scintillator materials

Crystal	ρ (g/cm^3)	X_0 (cm)	$r_{\text{Molière}}$ (cm)	dE/dx (MeV/cm)	λ_I (cm)	τ_{decay} (ns)	λ_{max}	n_D	Rel. output*	Hygro?
NaI(Tl)	3.67	2.59	4.5	4.8	41.4	250	410	1.85	1.00	very
BGO	7.13	1.12	2.4	9.2	22.0	300	410	2.20	0.15	no
BaF_2	4.89	2.05	3.4	6.6	29.9	0.7^f	220^f	1.56	0.05^f	slightly
						620^s	310^s		0.20^s	
CsI(Tl)	4.53	1.85	3.8	5.6	36.5	1000	565	1.80	0.40	some
CsI(pure)	4.53	1.85	3.8	5.6	36.5	$10, 36^f$	305^f	1.80	0.10^f	some
						$36^f, 620^s$	$\sim 480^s$		0.20^s	
$PbWO_4$	8.28	0.89	2.2	13.0	22.4	5–15	420–440†	2.3	0.01	no
CeF_3	6.16	1.68	2.6	7.9	25.9	10–30	310–340	1.68	0.10	no

NaI has a light output of typically 40000 photons per MeV; keep in mind that light collection, and the quantum efficiency of the photo detector will reduce the signal significantly.

The detector response is fairly linear (see Leo).

Scintillators

Organic Scintillators

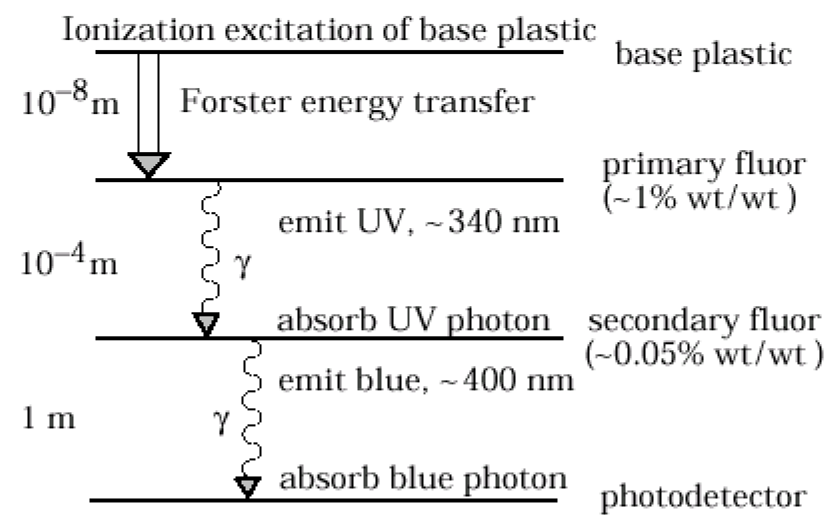
These are fast and with typical light output around half of NaI.

Practical organic scintillators uses a solvents; typically organic solvents which release a few % of the exited molecules as photons (polystyrene in plastic for example, xylene in liquids)

+ large concentration of primary fluor which transfers to wavelengths where the scintillator is more transparent (Stokes shift) and changes the time constant

+ smaller concentration of secondary fluor for further adjustment

+ ......



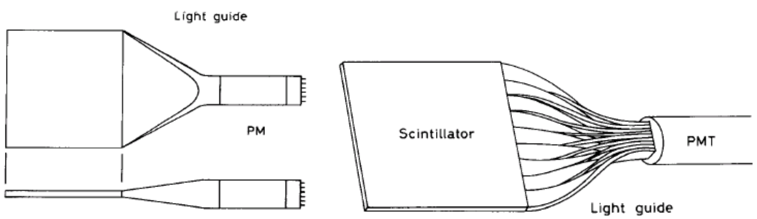
List of materials and solvents can be found in most textbooks

Generally the final light output has two time constants and the relative contributions from them depend on the energy deposition (particle type); this can be used for particle identification (pulse shape discrimination). This is for example used for neutron counting; the detectors are sensitive to proton recoils (contain hydrogen) from neutrons.

Scintillators

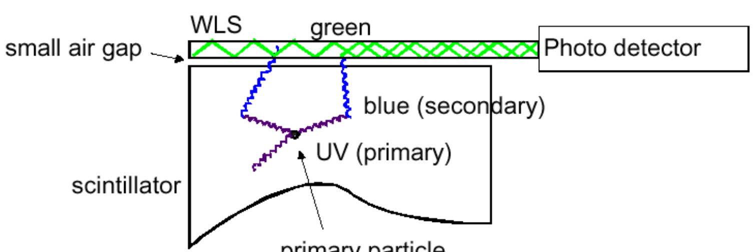
External wavelength shifters and light guides are used to aid light collection in complicated geometries; must be insensitive to ionising radiation and Cherenkov light. See examples.

- Light guides: transfer by total internal reflection
  (+outer reflector)



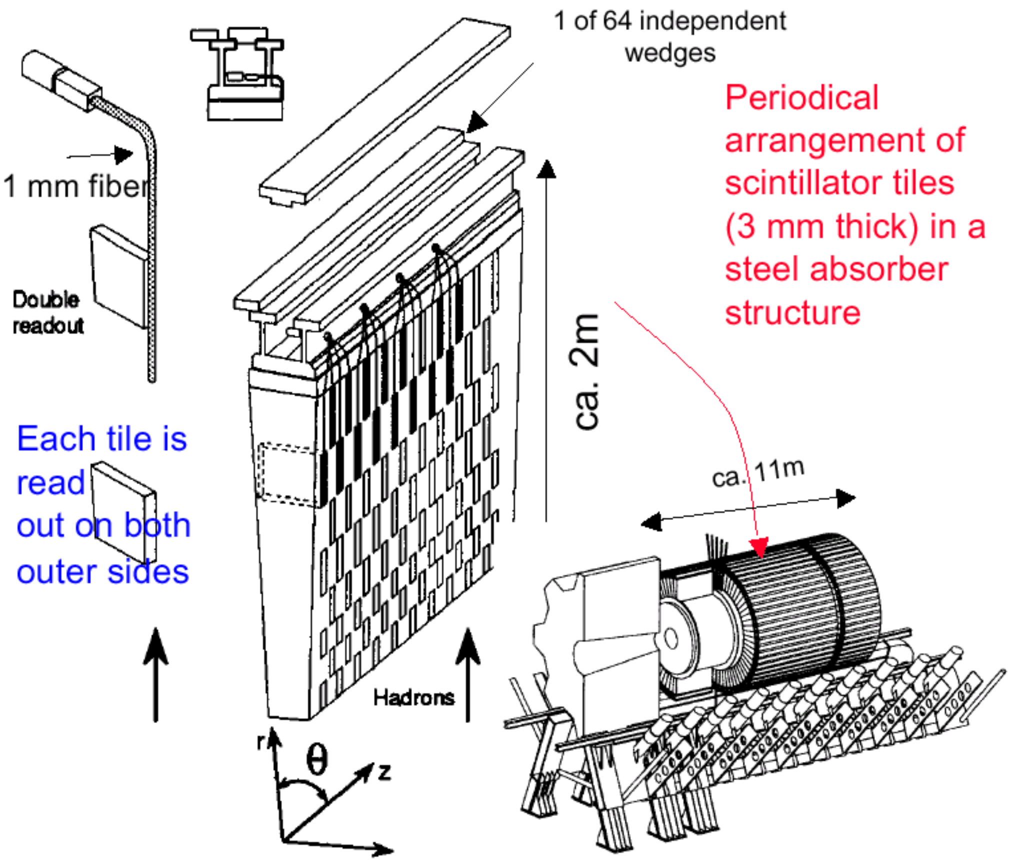
"fish tail" **adiabatic**

- wavelength shifter (WLS) bars



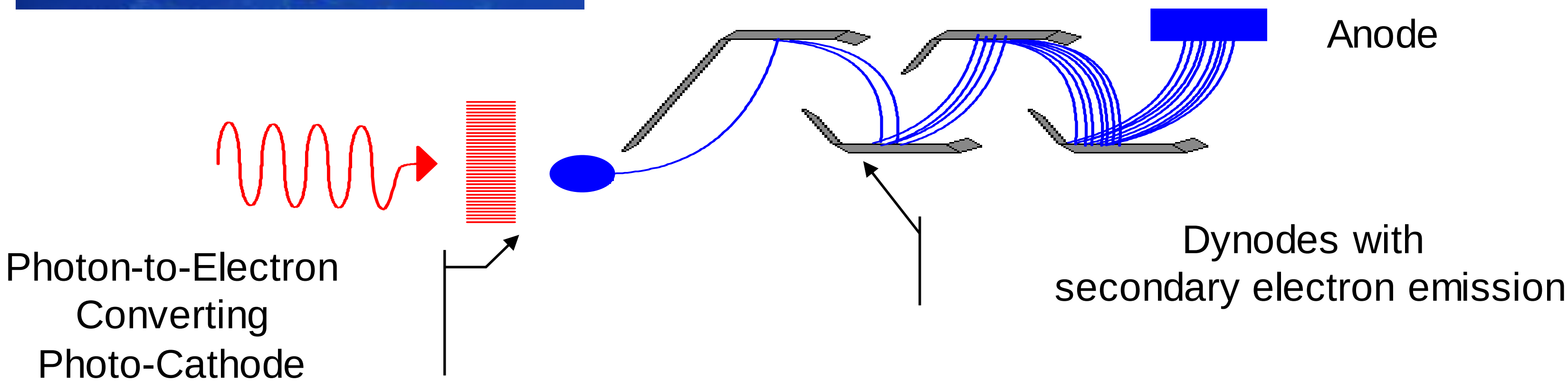
ATLAS Hadron Calorimeter: (ATLAS TDR)

Scintillating tile readout via fibers and photomultipliers



From C.Joram

Photo Multiplier Tube for readout

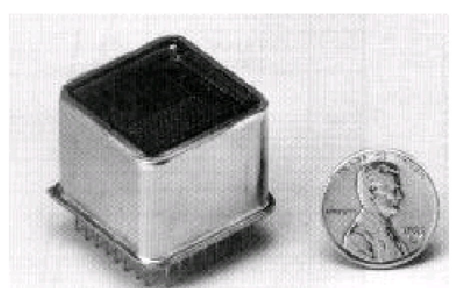


Multi Anode PM

example: Hamamatsu R5900 series.

Typical gain ≈ 10^6
Transient time spread ≈ 200 ps
Limited space resolution

http://www.hamamatsu.com/



Up to 8x8 channels.
Size: 28x28 mm^2.
Active area 18x18 mm^2 (41%).
Bialkali PC: Q.E. = 20% at λ_{max} = 400 nm. Gain ≈ 10^6.

From CERN-CLAF, O.Ullaland

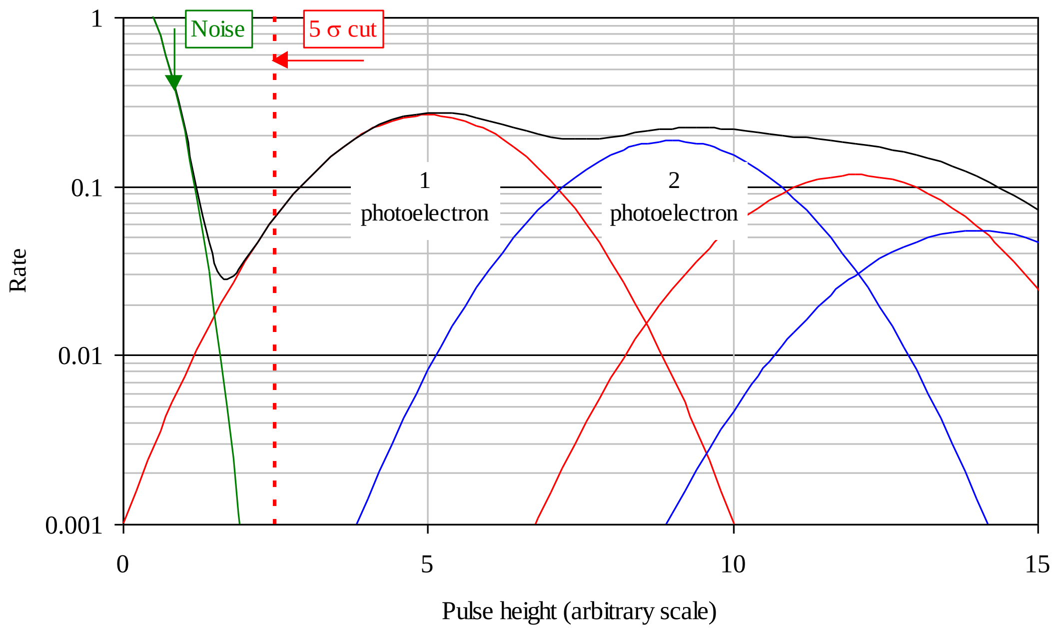
The energy resolution is determined mainly by the fluctuation of the number of secondary electrons emitted at each dynode.

Poisson distribution

$$P(r,\mu)=\frac{\mu^r e^{-\mu}}{r!}$$

where
m = mean number
= the variance
r = 1, 2 , 3 ...

Fluctuations mainly induced at the first dynode where the number of primary electrons are small

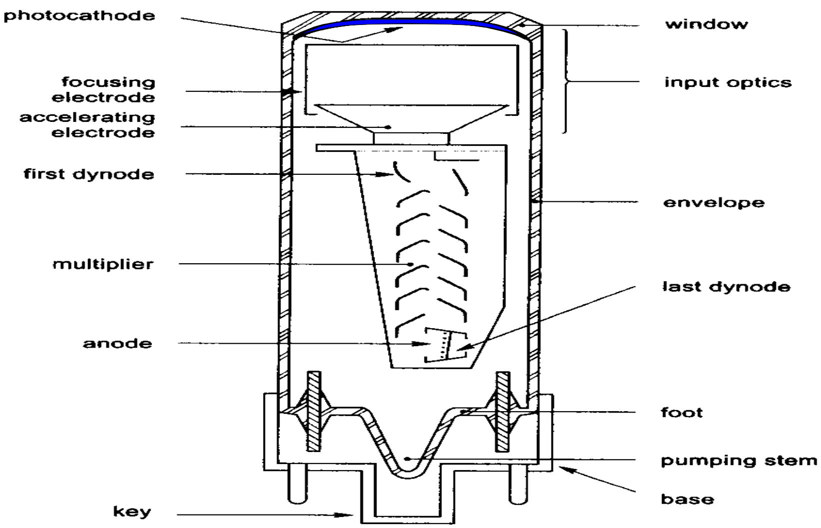


Physical principles of Hybrid Photo Diodes

From CERN-CLAF, O.Ullaland

Take one

Photo Multiplier Tube

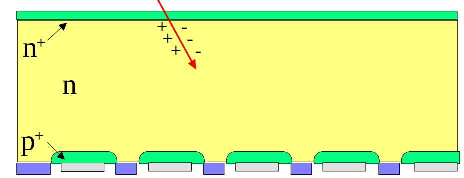


Remove dynodes and anode

Add

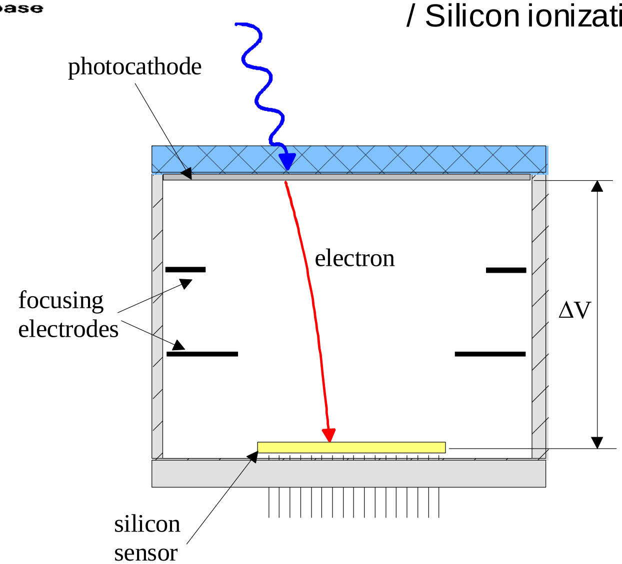
Silicon Sensor

inside tube



Electron-hole pairs:
Kinetic energy of the impinging electron / Silicon ionization energy

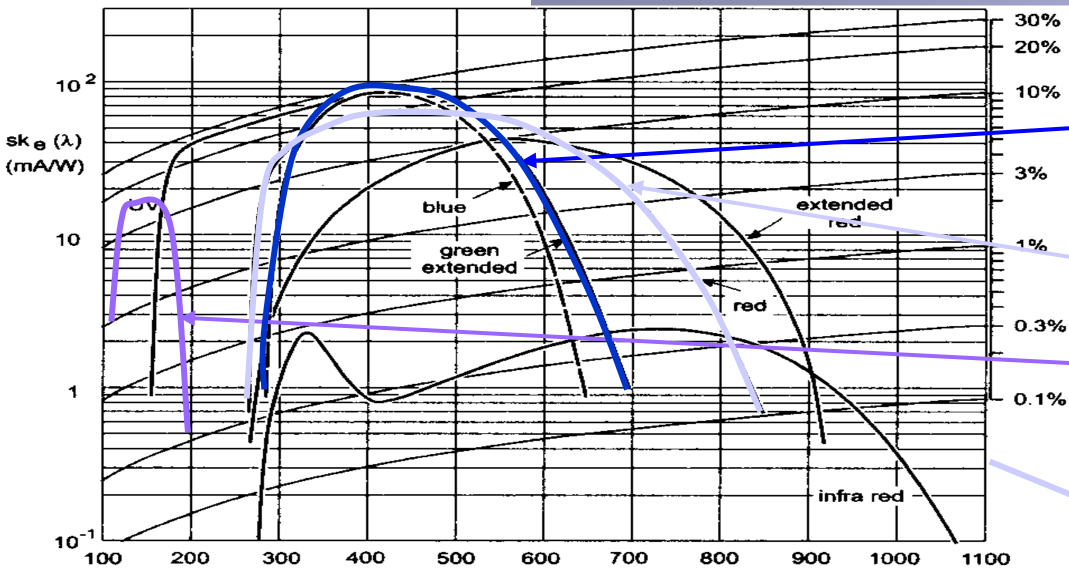
Hybrid Photo Diode



~ 20 kV; i.e 4 - 5000 electron-hole pairs → Good energy resolution

Hybrid Photo Diode

From CERN-CLAF, O.Ullaland



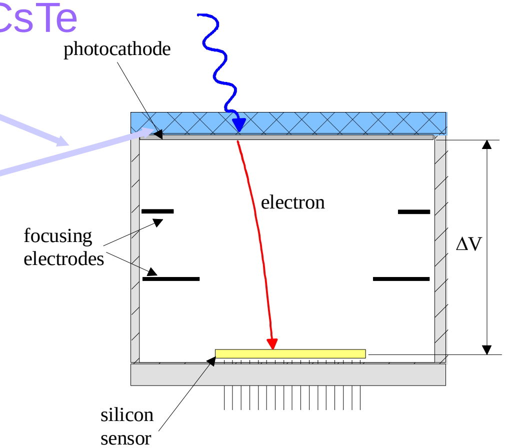
(Philips Photonic)

Q.E.

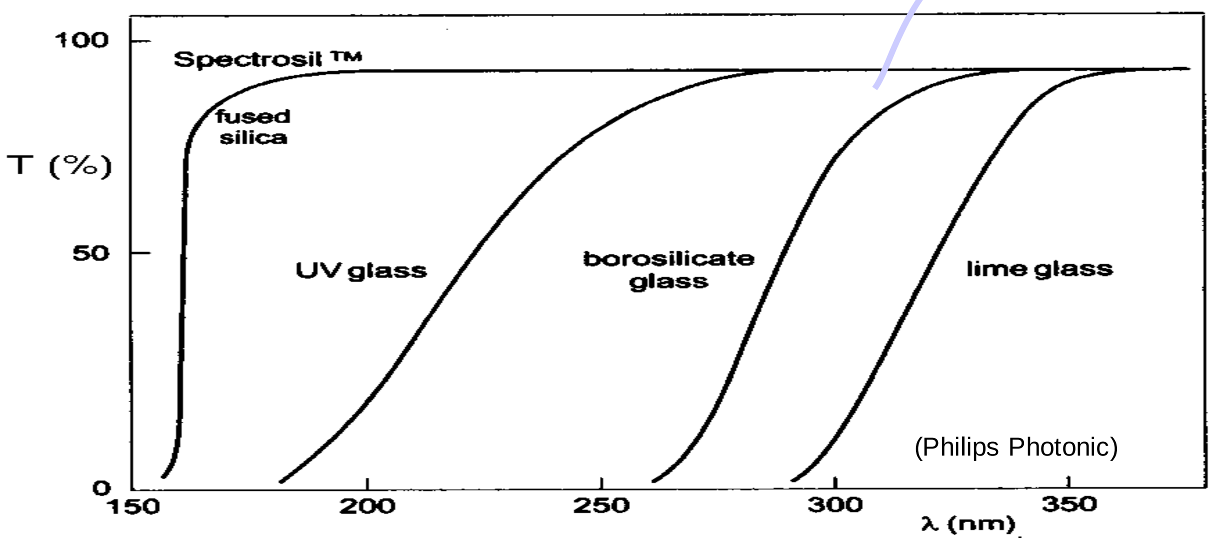
Bialkali
SbK_2Cs

Multialkali
$SbNa_2KCs$ (S20)

Solar blind
CsTe



$$Q.E.(\%) \approx 124 \cdot \frac{sk_e(mA/W)}{\lambda(nm)}$$



Transmission of various windows materials

not shown:
MgF_2: cut @115 nm
LiF: cut @105 nm

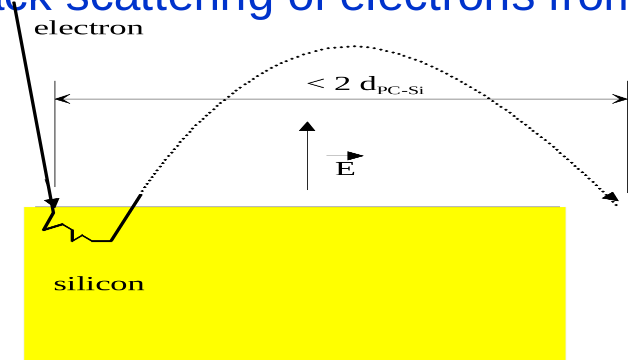
But…

From CERN-CLAF, O.Ullaland

- Electronic noise, typically of the order of ≥ 500 e

$$\sigma^2_{total} = \sigma^2_{int.} + \sigma^2_{E_{loss}} + \sigma^2_{elec.} >> \sigma^2_{int.}$$

- Back scattering of electrons from Si surface

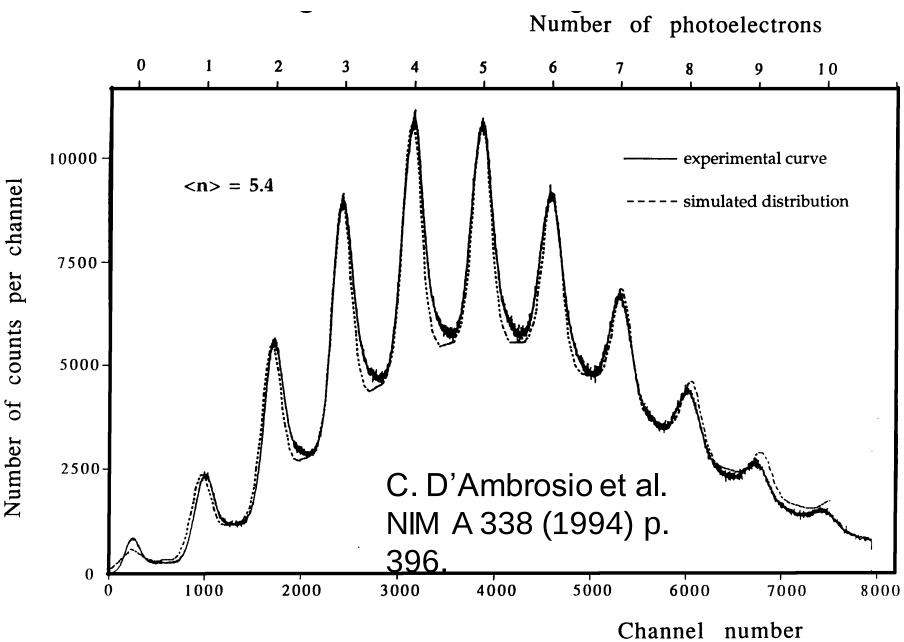


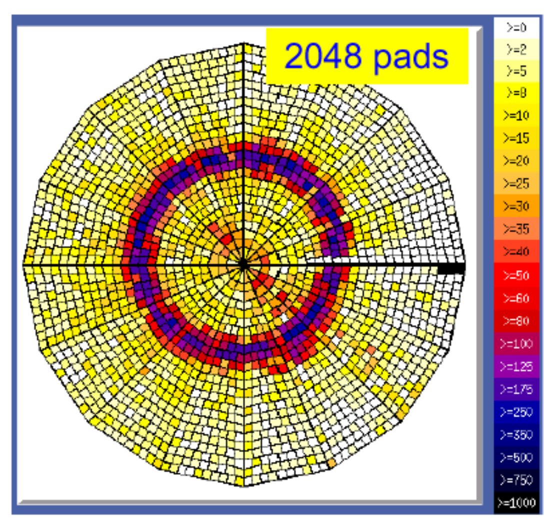
back scattering probability at E ≈ 20 kV

$$\alpha_{Si} \approx 0.18$$

20% of the electrons deposit only a fraction 0≤ε<1 of their initial energy in the Si sensor .

→ continuous background (low energy side)





test beam data, 1 HPD

Semi-Conductors

Solid state detectors have been used for energy measurements a long time (Si,Ge…). It takes a few eV to create an e/h pairs so the energy resolution is very good.

Nowadays silicon detectors are mostly used for tracking.

From C.Joram

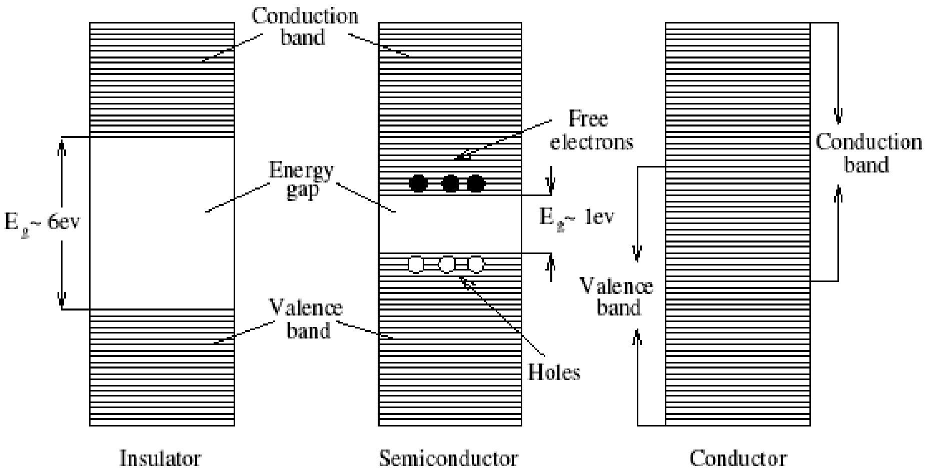
Some characteristic numbers for silicon

- Band gap: E_g =1.12eV.
- E(e^--hole pair) = 3.6 eV, (≈ 30 eV for gas detectors).
- High specific density (2.33 g/cm^3) → ΔE/track length for M.I.P.'s.: 390 eV/µm ≈ 108 e-h/ µm (average)
- High mobility: μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs
- Detector production by microelectronic techniques → small dimensions → fast charge collection (<10 ns).
- Rigidity of silicon allows thin self supporting structures. Typical thickness 300 µm → ≈ 3.2 ·10^4 e-h (average)
- But: No charge multiplication mechanism!

Semi-Conductors

When isolated atoms are brought together to form a lattice, the discrete atomic states shift to form energy bands as shown below.

From E.Cortina, A.Sfyrla, Univ. of Geneva



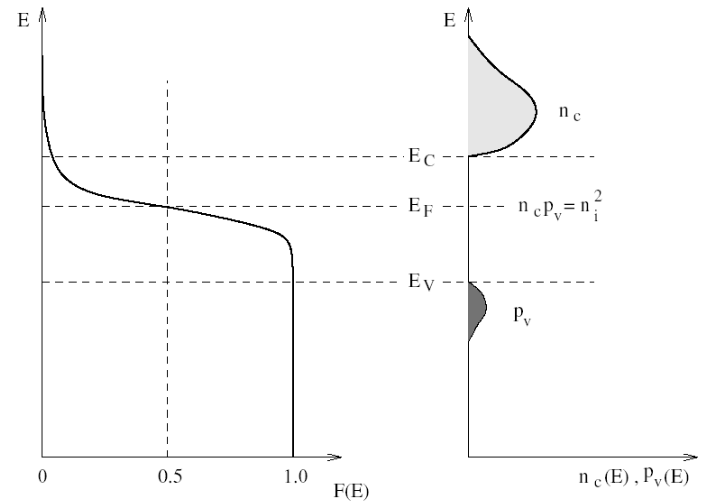


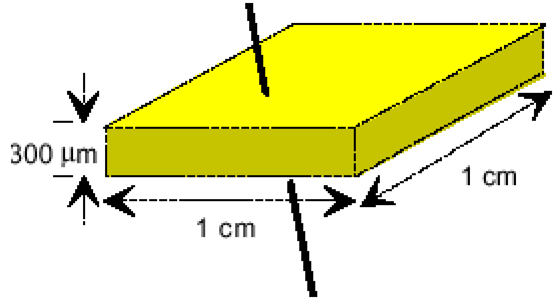
Figure 2: Occupation probability and carrier concentration for intrinsic semiconductors.

The number of states per volume and energy can be calculated – from this we can derive the number of electrons in the conduction band and holes in the valence band – per unit volume (as a function of temperature)

$$P(W) \propto \exp\left[-\frac{W - W_F}{kT}\right]$$

W_F = Fermi Level = the Energy where P(W)=1/2

For basic semi-conduction physics see :
http://jas.eng.buffalo.edu/index.html
Text, illustrations, models and online diagrams, etc …



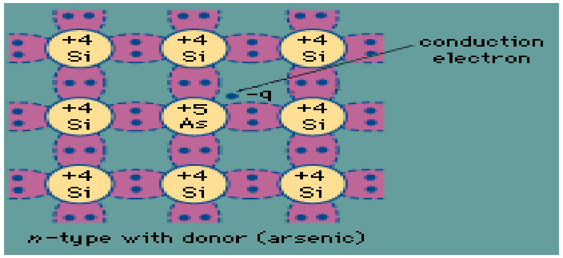
Intrinsic silicon will have electron density = hole density; 1.45 10^{10} cm^{-3} (from basic semiconductor theory).

In the volume above this would correspond to 4.5 10^{8} free charge carriers; compared to around 3.2 10^{4} produces by MIP (Bethe Bloch loss in 300um Si divided by 3.6 eV).

Need to decrease number of free carriers; use depletion zone (reduce temperature would also help but one would need to go to cryogenic temperatures)

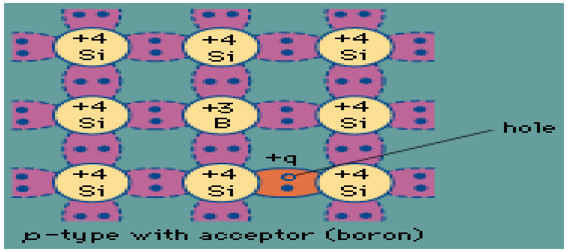
Doping of semiconductors.

N-Type



P, As, Sb
5 electrons in the M-shell
→1 electron with binding energy 10-50 *meV*

P-Type



B, Al, Ga
3 electrons in the M-shell
→1 electron missing

The zone between the N and P type doping is free of charge carriers, forms an capasitor, have an electric field and is well suited as detector volume; need to increase by applying reverse biasing

From E.Cortina, A.Sfyrla, Univ. of Geneva

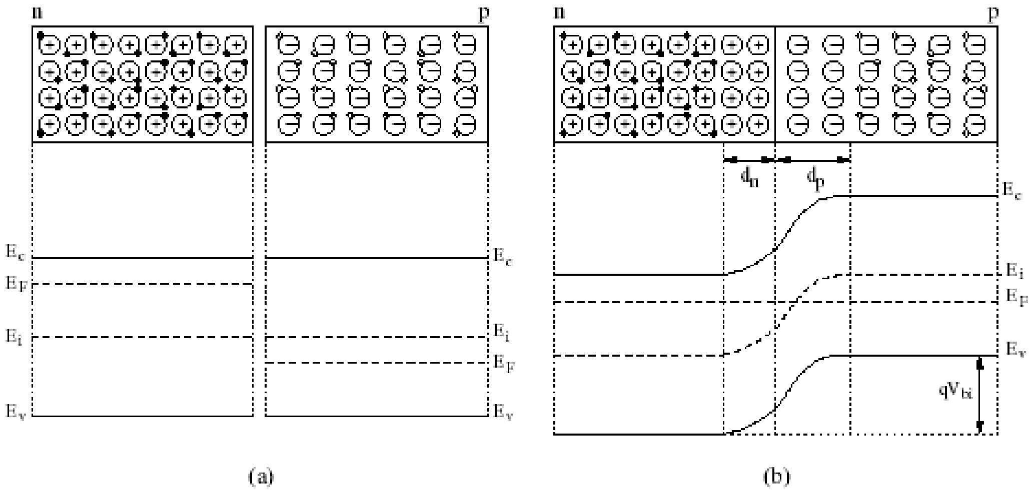
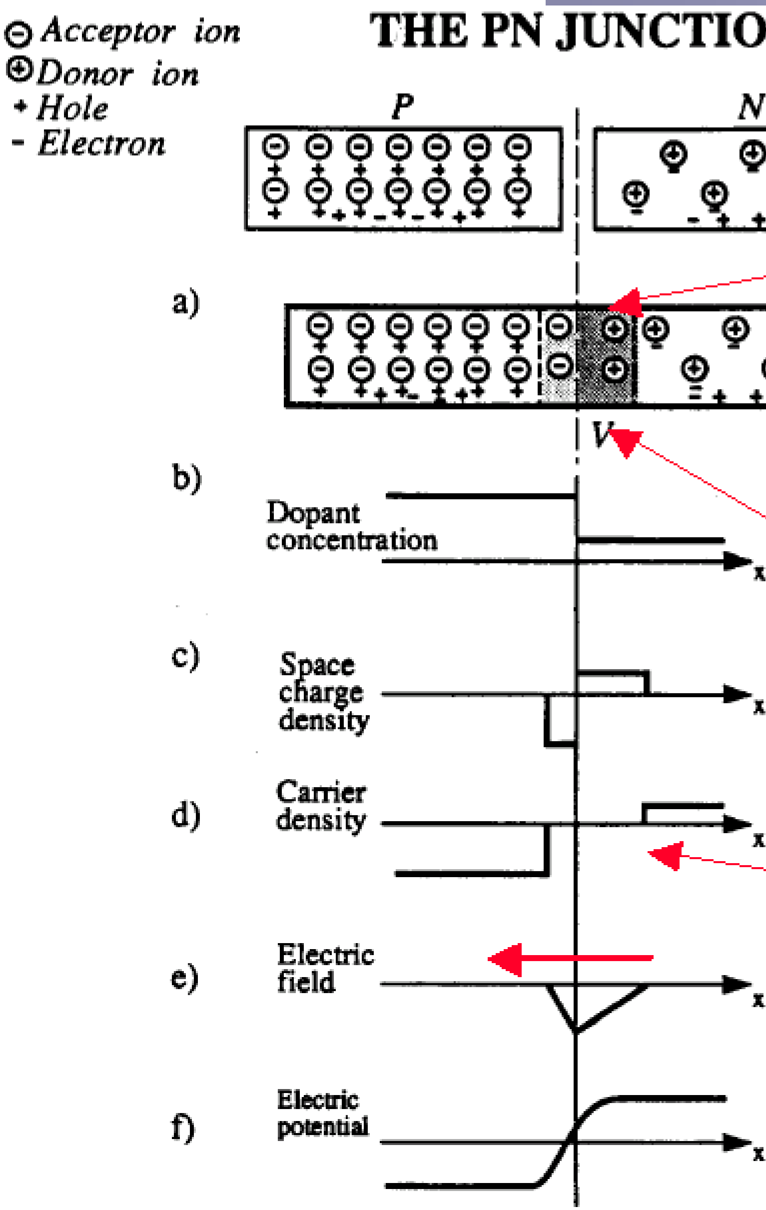


Figure 4: A $p-n$ junction in thermal equilibrium, with its parts separated (a) and brought together (b) forming a potential barrier.

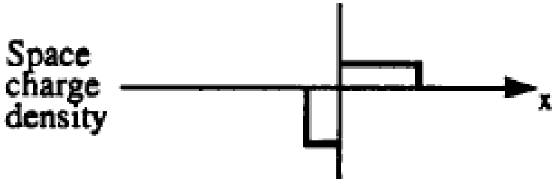


diffusion of e^- into p-zone, h^+ into n-zone
→ potential difference stopping diffusion

thin depletion zone

no free charge carriers in depletion zone

(A. Peisert, Instrumentation In High Energy Physics, World Scientific)



Semi-Conductors

One can quickly establish the most critical parameters for a silicon detector by looking at the p,n junction above :

Poisson's equation :

$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\varepsilon}$$

With charge density from $-x_p$ to 0 and from 0 to x_n defined by :

$$\rho(x) = \pm eN_{D/A}$$

N_D and N_A are the doping concentrations (donor, acceptor).

$$N_D x_p = N_A x_n$$

The depletion zone is defined as :

$$d = x_p + x_n$$

By integrating one the E(x) can be determined, by integrating twice the following two important relations are found :

$$V \propto d^2$$

$$C = \varepsilon \frac{A}{d} \propto V^{-1/2}$$

By increasing the voltage the depletion zone is expanded and C (capasitance) decreased – giving decreased electronics noise.

Signal formation in general terms

For ionisation detectors we used energy balance to look at how a voltage signal was created due to charge drifting in the device.
More general we have to use the Shockley-Ramo theorem for induced charge:

$$i = q\vec{v} \cdot \vec{E}_0$$

or

$$Q = q\Delta\varphi_0$$

where $\vec{E}_0$ is the weighting field and $\Delta\varphi_0$ the potential difference from the beginning to the end of the path.
The weighting potential is found by solving Laplace equation with some artificial boundary conditions (for the electrode under study (= unity) and for all other electrodes (= 0)).

The main message is that the signal is induced by the motion of charge after incident radiation (not when the charge reach the electrodes).

References:
Appendix D in ref (7) or chapter 5 of Particle Detection with Drift Chambers, W.Blum and L.Rolandi, Springer Verlag, ISBN 3-540-58322-X

For ionisation chambers it can be used to study not only the signal on the primary anode but also for the neighbours, or the cathode strips (if these are read out). For silicon detectors to study charge sharing between strips or pixels.

Let us have look at the signal formation using the same simple model of the detector as two parallel electrodes separated by d.
A electric charge q moving a distance dx will induce a signal dQ on the readout electrode :

dQ d = q dx

As in the case of the proportional chamber we use : $\frac{dx}{dt} = \mu E(x)$

giving $x(t) = x_0 \exp(\frac{\mu_e t}{\mu_h \tau})$

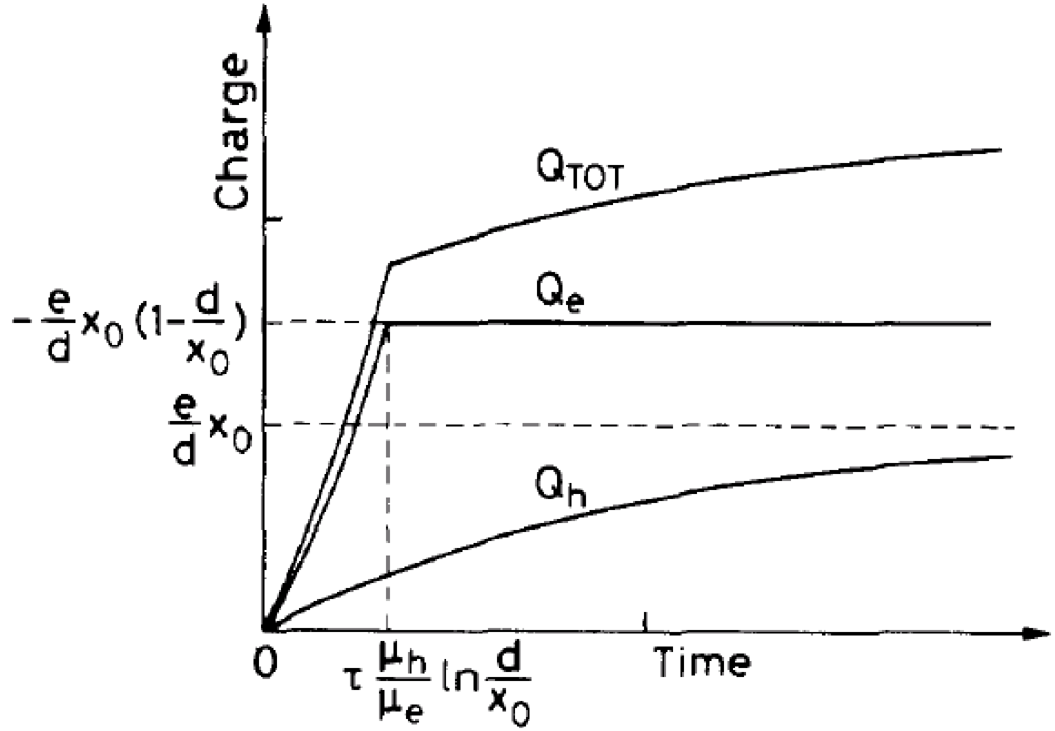
where $\tau = \varepsilon / eN_A \mu_h$

The time dependent signal is then : $Q_e(t) = -\frac{e}{d}\int \frac{dx}{dt} dt$

Semi-Conductors

The final result showing (when entering real numbers and using a more complete model) time-scales of 10/25 ns for electron/hole collection :

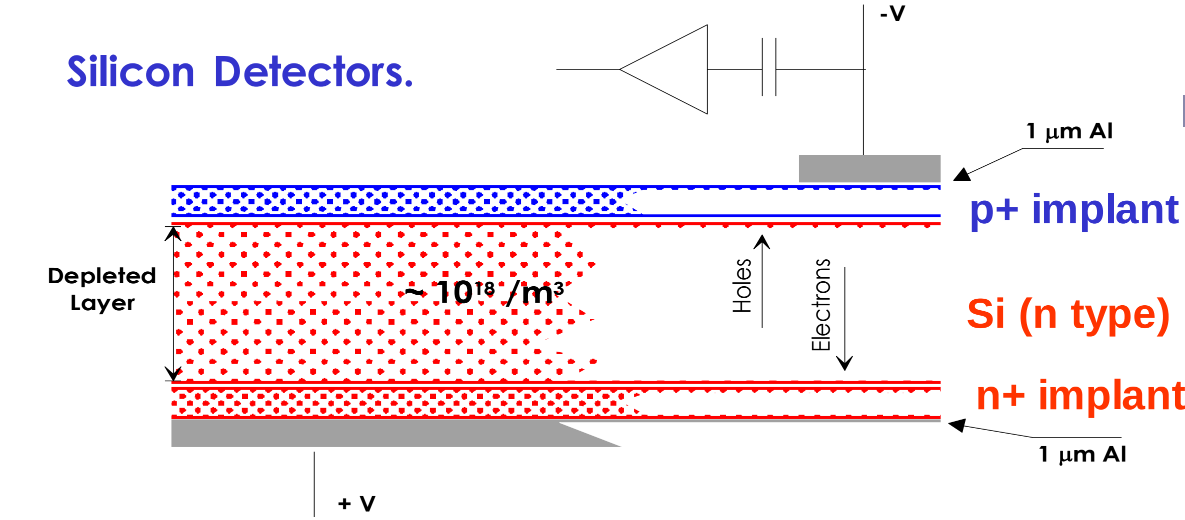
However, there are many caveats:
In reality one as to start from the real e/h distribution from a particle.
Use a real description of E(x) taking into account strips and over-depletion.
Traps and changes in mobility can also come in, etc

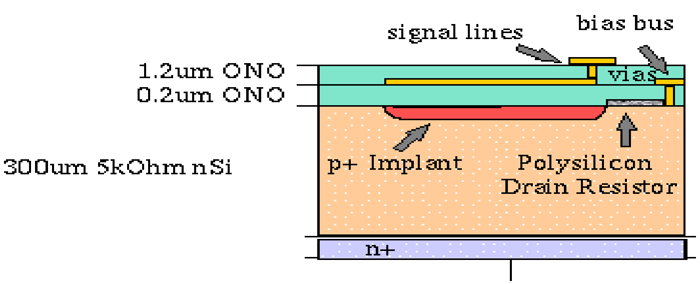


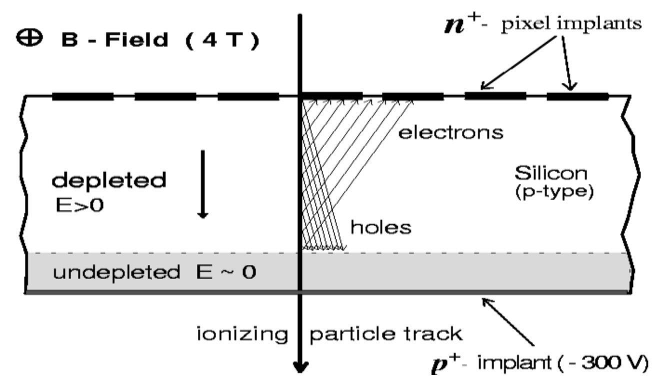
From Leo

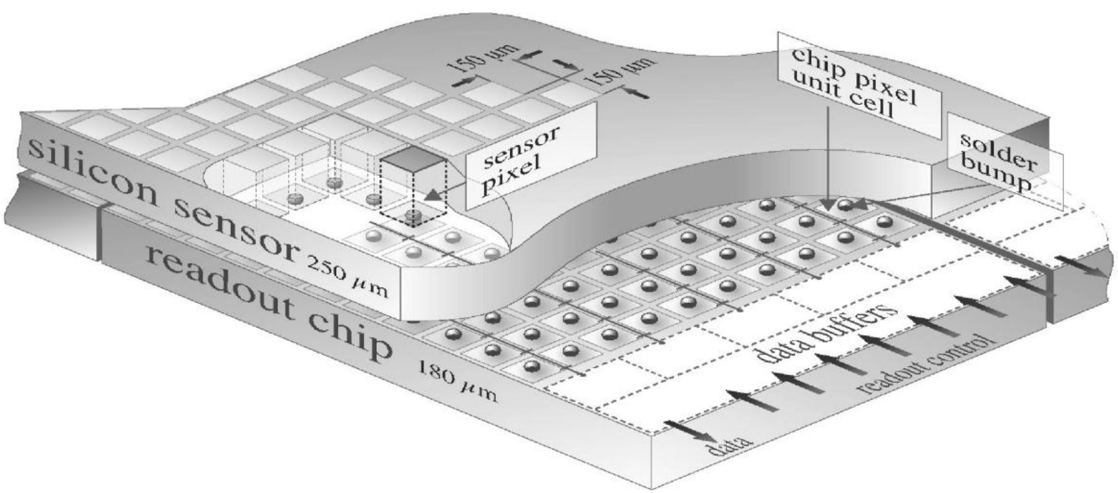
Silicon Detectors.

From CERN-CLAF, O.Ullaland





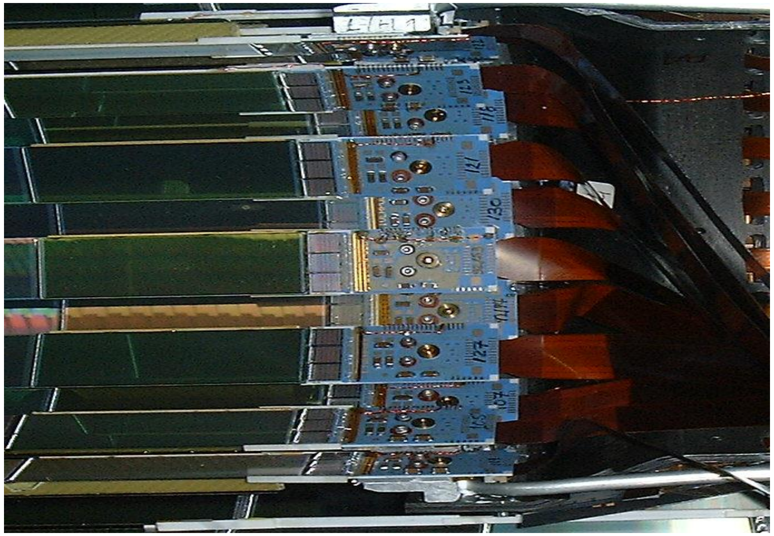




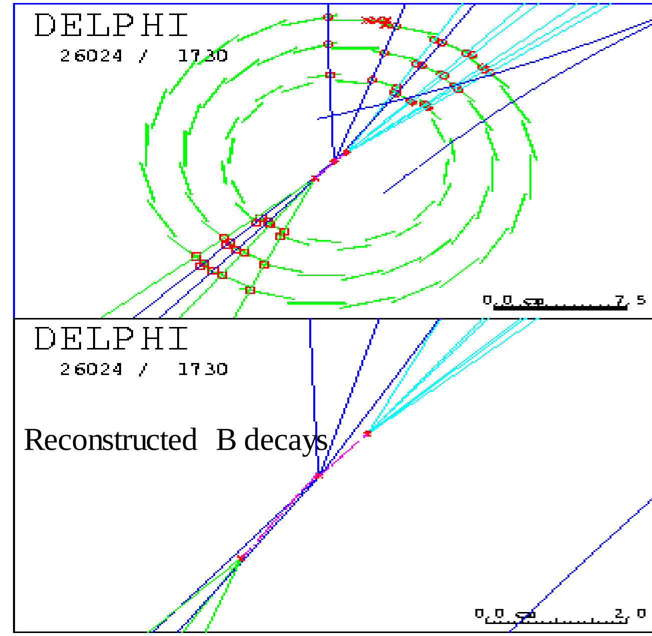
H. Pernegger - CERN
G. Bagliesi - INFN Pisa

Semi-Conductors

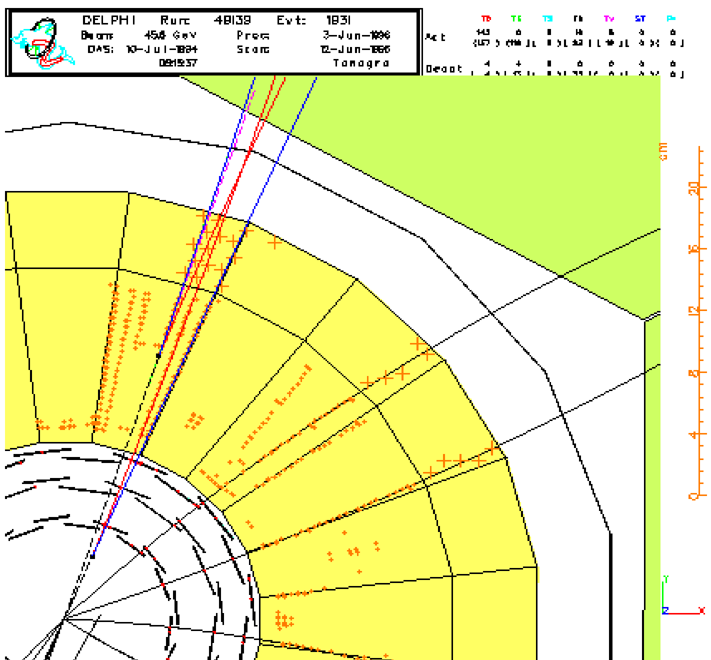
The DELPHI Vertex Detector



From CERN-CLAF, O.Ullaland



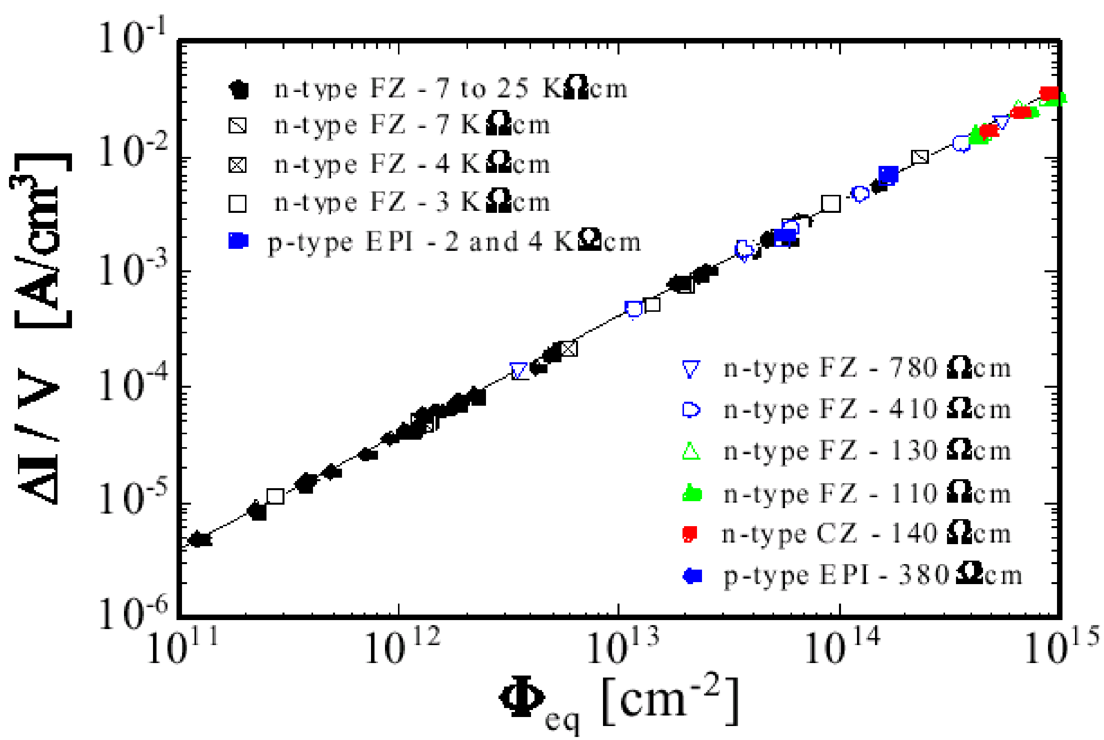
K0 and Lambda reconstruction



At the moment silicon detectors are used close to the interaction region is most collider experiments and are exposed to severe radiation conditions (damage).

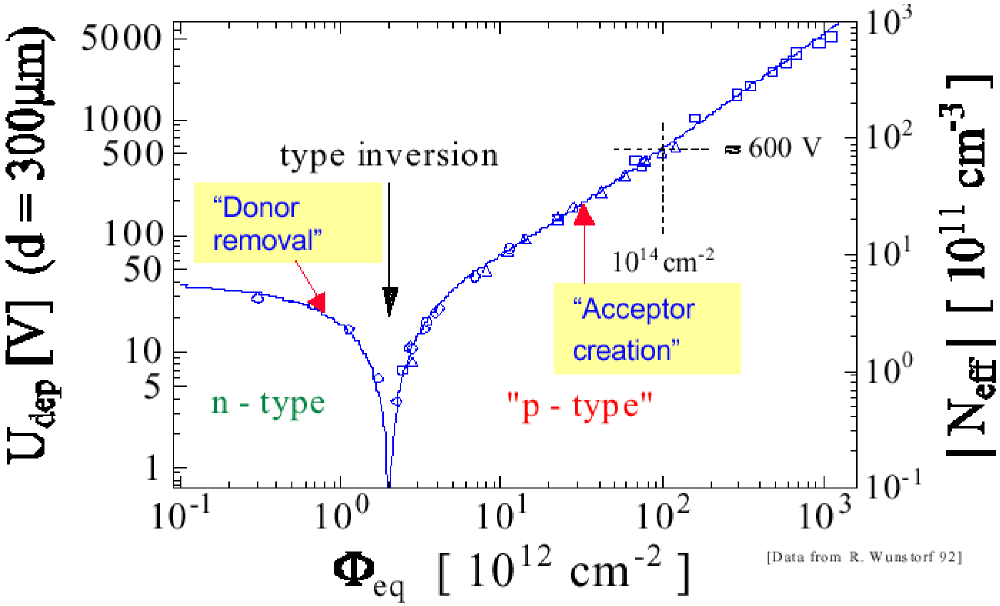
The damage depend on fluence obviously as well particle type (π,γ,e,n,etc) and energy spectrum and influences both sensors and electronics. The effects are due to bulk damage (lattice changes) and surface effects (trapped charges). Three main consequences seen for silicon detectors (plots from C.Joram) :

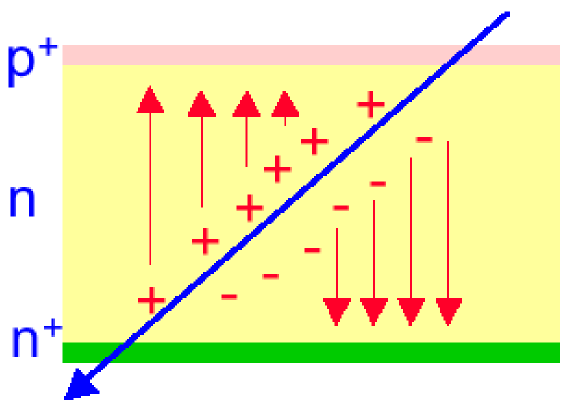
(1) Increase of leakage current with consequences for cooling and electronics

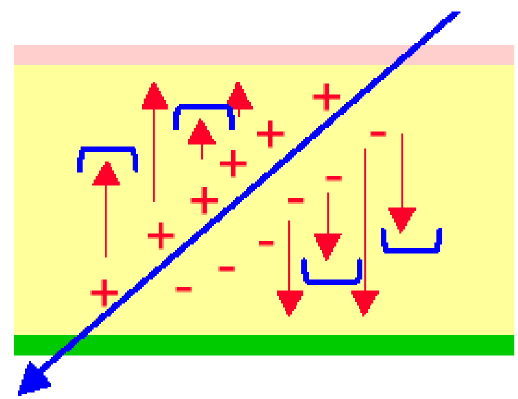


(2) Change in depletion voltage, high at end of lifetime of detector; combined with increased leakage current this leads to cooling problems again

(3) Decrease of charge collection efficiency (less and slower signal)



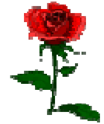




Charge trapping in defects

Semi-Conductors

More fun: some of the ongoing R&D (C.Joram)



ROSE / RD48
http://cern.ch/rd48

- Defect engineering.

  Introduce specific impurities in silicon, to influence defect formation. Example Oxygen.

  Diffusion Float Zone Oxygenated (DOFZ) silicon used in ATLAS pixel detector. Gain a factor 3.

RD39
http://cern.ch/rd39

- Cool detectors to cryogenic temperatures (optimum around 130 k)

  "zero" leakage current, good charge collection (70%) for heavily irradiated detectors ($1 \cdot 10^{15}$ n/cm^2). "Lazarus effect"

RD42
http://cern.ch/rd42

- New materials

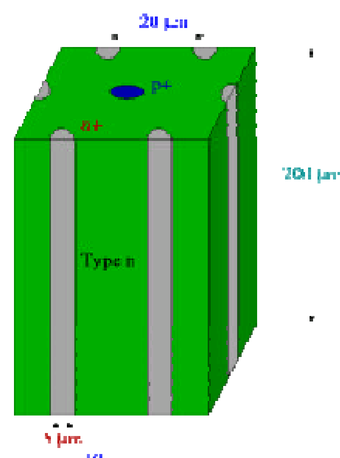
  Diamond. Grown by Chemical Vapor Deposition. Very large bandgap (≈ 6 eV). No doping and depletion required! Material is still rather expensive. Still more R&D needed.

- New detector concepts

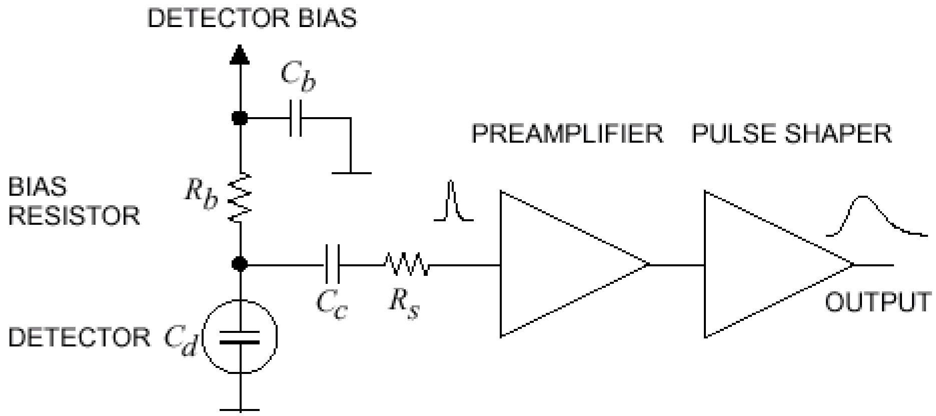
  "3D detectors" → "horizontal" biasing

  faster charge collection

  but difficult fabrication process

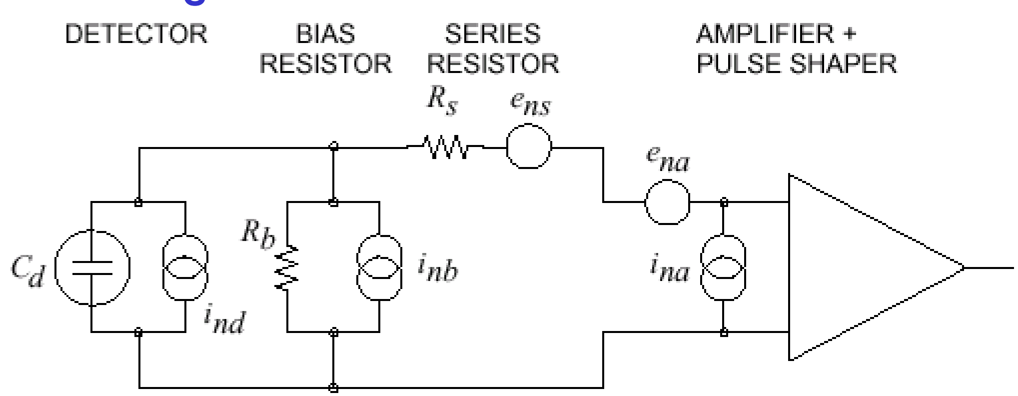


Most detectors rely critically on low noise electronics. A typical Front End is shown below :

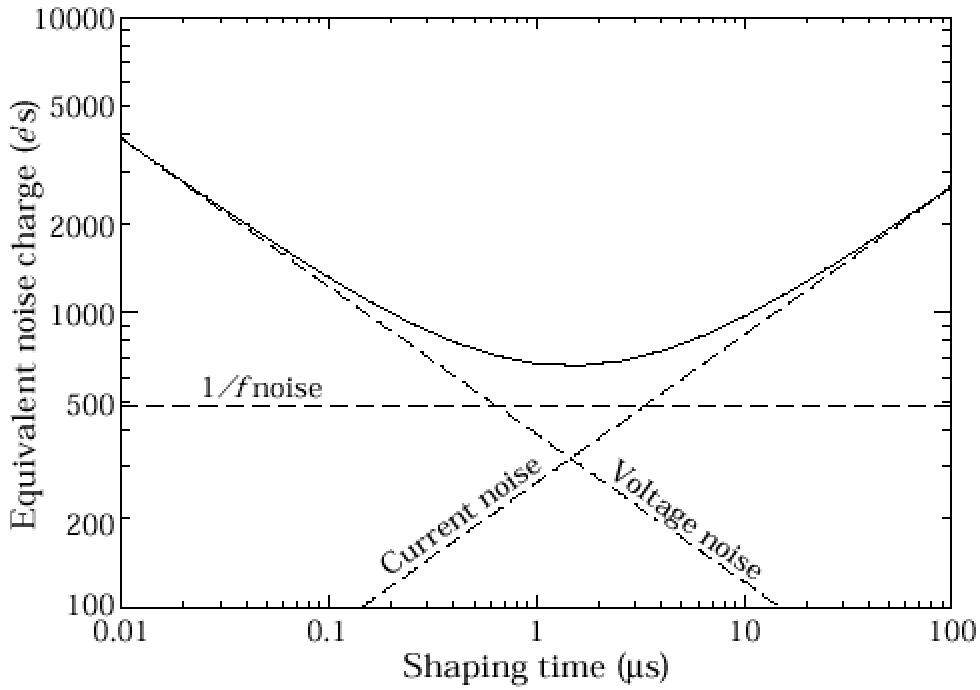


where the detector is represented by the capasitance C_d, bias voltage is applied through R_b, and the signal is coupled to the amplifier though a capasitance C_c. The resistance R_s represent all the resistances in the input path. The preamplifier provides gain and feed a shaper which takes care of the frequency response and limits the duration of the signal.

The equivalent circuit for noise analysis includes both current and voltage noise sources labelled i_n and e_n respectively. Two important noise sources are the detector leakage current (fluctuating -some times called shot noise) and the electronic noise of the amplifier, both unavoidable and therefore important to control and reduce. The diagram below show the noise sources and their representation in the noise analysis :



While shot noise and thermal noise has a white frequency spectrum (dP_n/df constant), trapping/detrapping in various components will introduce an 1/f noise. Since the detectors usually turn the signal into charge one can express the noise as equivalent noise charge, which is equivalent of the detector signal that yields signal-to-noise ratio of one. For the situation we have described there is an optimal shaping time as shown below :



Increasing the detector capasitance will increase the voltage noise and shift the noise minimum to longer shaping times.

For quick estimates, one can use the following equation, which assumes an FET amplifier (negligible i_{na}) and a simple CR–RC shaper with time constants τ (equal to the peaking time):

$$(Q_n/e)^2 = 12\left[\frac{1}{\mathrm{nA}\cdot\mathrm{ns}}\right] I_d\tau + 6\times10^5\left[\frac{\mathrm{k}\Omega}{\mathrm{ns}}\right]\frac{\tau}{R_b} + 3.6\times10^4\left[\frac{\mathrm{ns}}{(\mathrm{pF})^2(\mathrm{nV})^2/\mathrm{Hz}}\right] e_n^2\frac{C^2}{\tau}\ . \qquad (27.26)$$

which shows that the critical parameters are detector capasitance, the shaping time τ, the resistances in the input circuit, and the amplifier noise parameters. The latter depends mostly on the input device (transistor) which has to optimised for the load and use. One additional critical parameter is the current drawn which makes an important contribution to the power consumption of the electronics.

Practical noise levels vary between 10^2-10^3 ENC for silicon detectors to 10^4 for high capasitance LAr calorimeters (10^4 corresponds to around 1.6fC).

We now know how most particles (i.e all particles that live long enough to reach a detector; e,u,p,π,k,n,γ, neutrinos,etc) react with matter.

We now know how to identify particles to some extend, how to measure E and p, v, and how to measure lifetimes using secondary vertices, etc

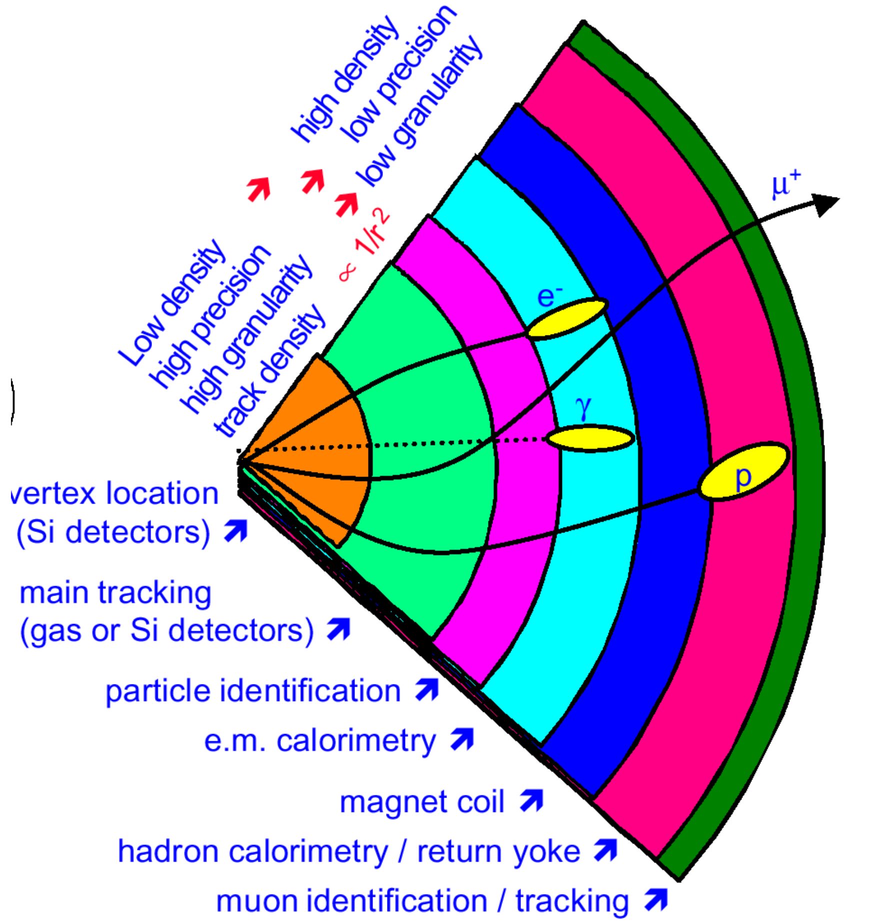
Essential three detector types are used :

1 Ionisation detectors

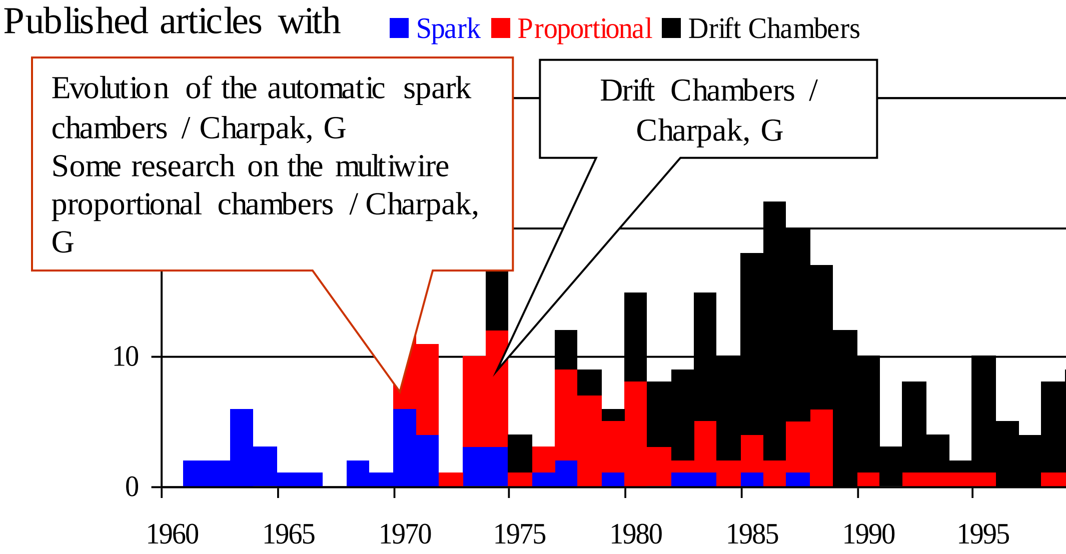
2 Scintillators

3 Semi Conductors

4 Finally we have looked briefly at how electrical signals are treated in FE electronics



The detector-types mentioned are either for tracking, energy measurement, photon detectors for Cherenkov or TRT, etc in various configurations.

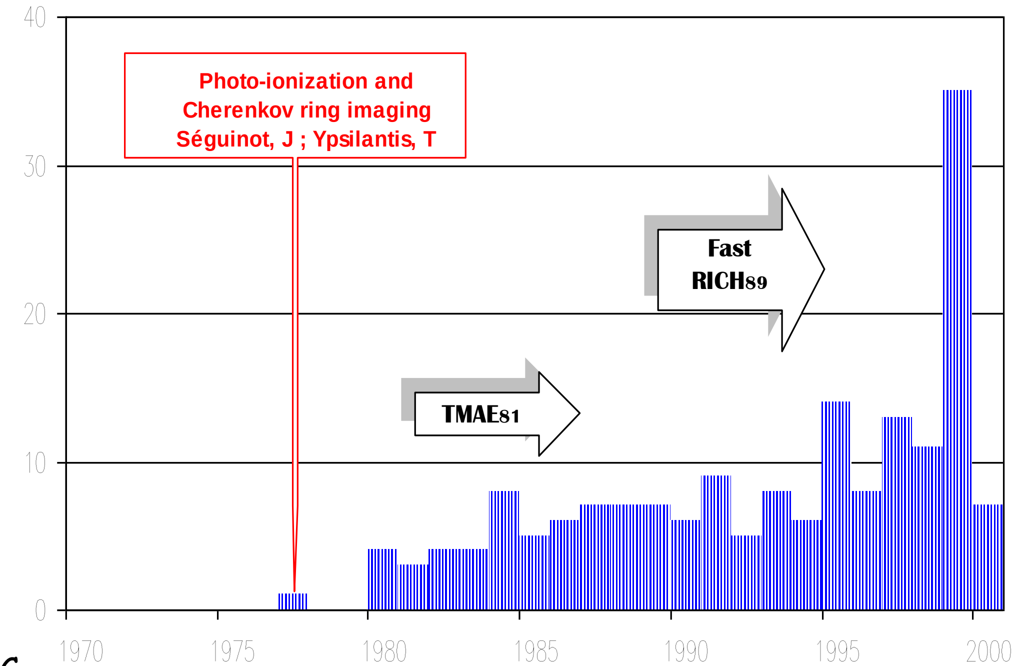


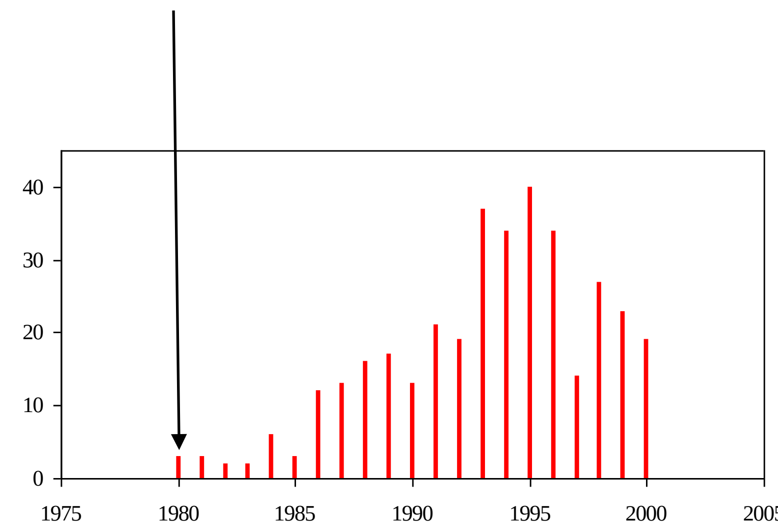
Capacitative charge division read-out with a silicon strip detector /
England, J B A ; Hyams, B D ; Hubbeling, L ; Vermeulen, J C ; Weilhammer, P ; Nucl. Instrum. Methods Phys. Res. : 185 (1981)

.A silicon surface barrier microstrip detector designed for high energy physics /
Heijne, E H M ; Hubbeling, L ; Hyams, B D ; Jarron, P ; Lazeyras, P ;Piuz, F ; Vermeulen, J C ; Wylie, A ; Nucl. Instrum. Methods Phys. Res. : 178 (1980)

A multi electrode silicon detector for high energy physics experiments /
Amendolia, S R ; Batignani, G ; Bedeschi, F ; Bertolucci, E ; Bosisio, L ; Bradaschia, C ; Budinich, M ; Fidecaro, F ; Foà, L ; Focardi, E ; Giazotto, A ; Giorgi, M A ;Givoletti, M ; Marrocchesi, P S ; Menzione, A ; Passuello, D ; Quaglia, M ; Ristori, L ; Rolandi, L ; Salvadori, P ; Scribano, A ; Stanga, R M ; Stefanini, A ; Vincelli, M L ; IFUP-TH-80-2.

Published articles with "Cherenkov Ring Imaging"





From O.Ullaland

Improved detectors will certainly be needed. Linear colliders, TESLA and LHC upgrades will drive this development and things are already happening.

I would identify some main areas of research :

- Radiation hardness will remain a headache. Both for trackers and calorimeters, detector elements, materials and electronics.
- Reduce power or deliver power in a more intelligent way (trackers at LHC need of order 100kW at less than 5V, current are huge, cables the same to keep losses acceptable). The services complicate the detector integration and compromises the performance.
- Reduce costs for silicon detectors (strip and various pixels). Today at PIXEL detector cost 5-10 MChf per m^2, strip trackers around 0.3-1 MChf per m^2. Similar arguments apply to large muon chambers.