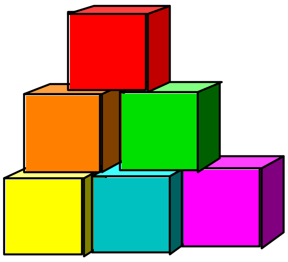
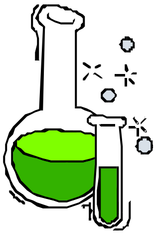
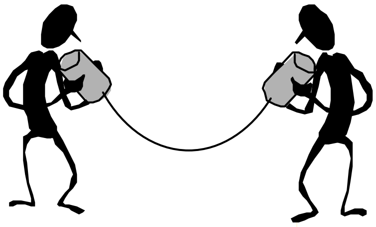
Scintillation + Photo Detection



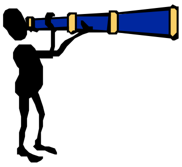
- Inorganic scintillators

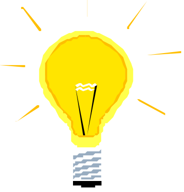


- Organic scintillators
- Geometries and readout



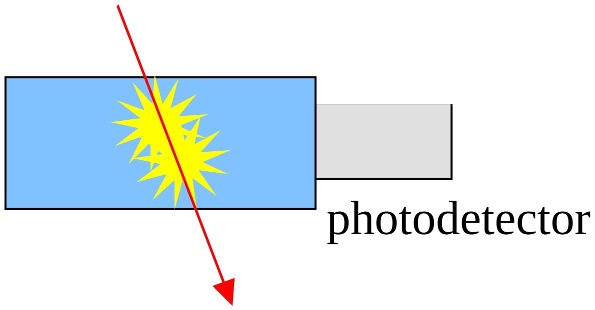
- Fiber tracking





- Photo detectors

Scintillation



Energy deposition by ionizing particle
→ production of scintillation light (luminescense)

Scintillators are multi purpose detectors

- calorimetry
- time of flight measurement
- tracking detector (fibers)
- trigger counter
- veto counter

.....

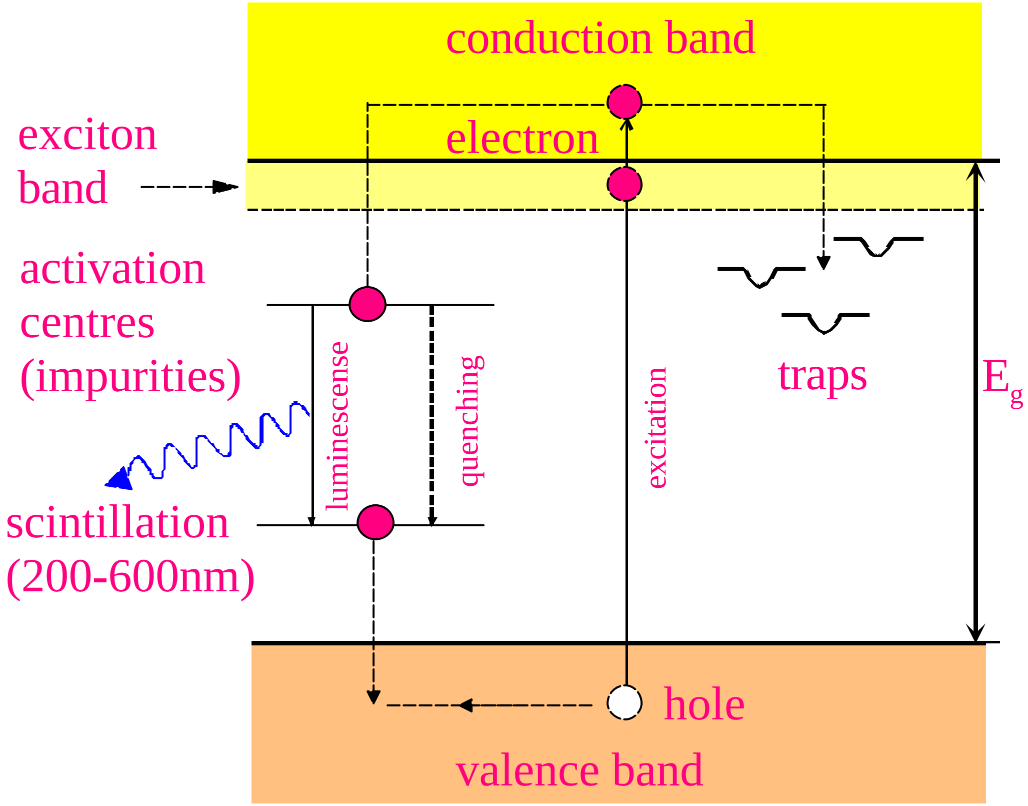
Two material types: Inorganic and organic scintillators

Inorganic ↓ high light output but slow

Organic ↓ lower light output but fast

Three different scintillation mechanisms:

1a. Inorganic crystalline scintillators (NaI, CsI, BaF_2...)

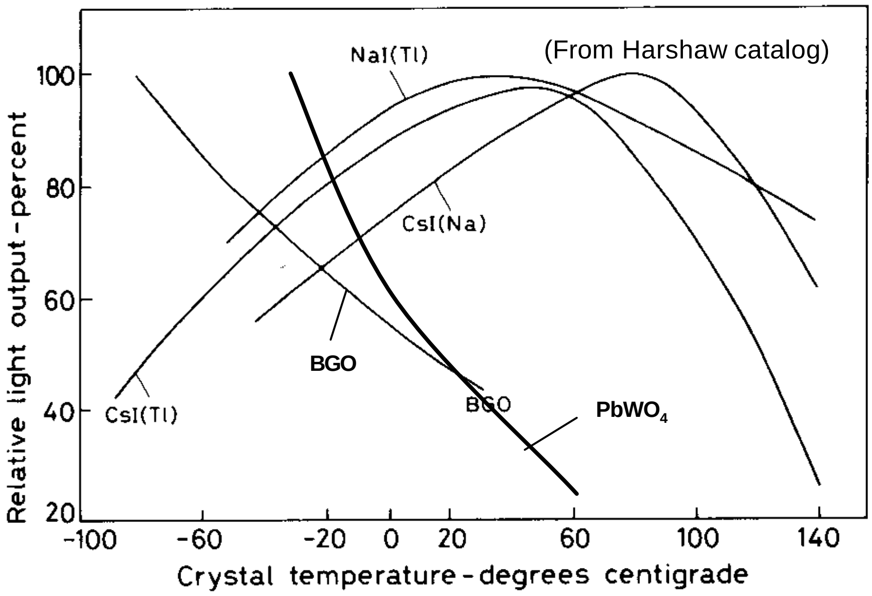


often ≥ 2 time constants:

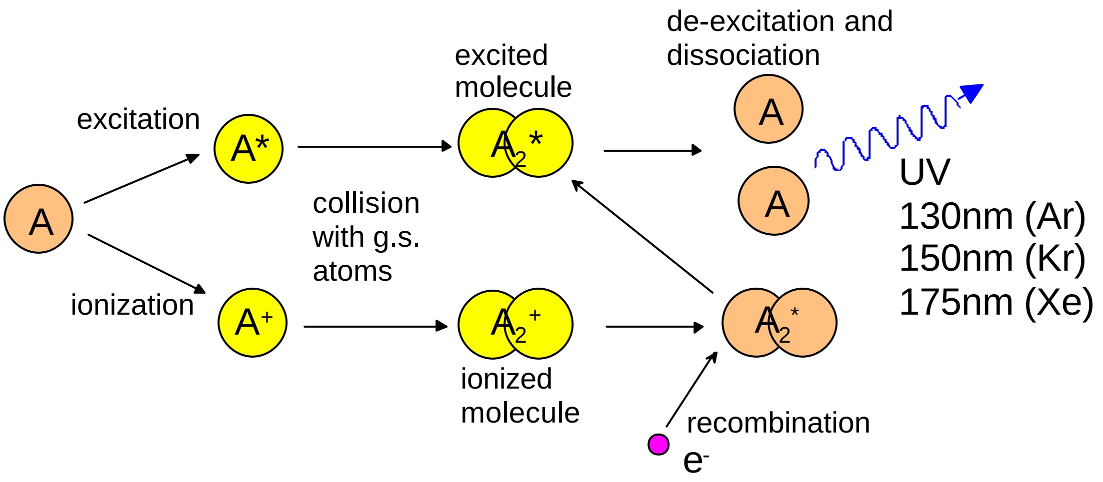
- fast recombination (ns-µs) from activation centre
- delayed recombination due to trapping (≈ 100 ms)

Due to the high density and high Z inorganic scintillator are well suited for detection of charged particles, but also of γ.

Light output of inorganic crystals shows strong temperature dependence



1b. Liquid noble gases (LAr, LXe, LKr)


excitation

ionization

A

A*

A$^+$

collision with g.s. atoms

excited molecule

A_2^*

ionized molecule

A_2^+

de-excitation and dissociation

A

A

UV

130nm (Ar)

150nm (Kr)

175nm (Xe)

A_2^*

recombination

e$^-$

also here one finds 2 time constants: few ns and 100-1000 ns, but same wavelength.

Properties of some inorganic scintillators

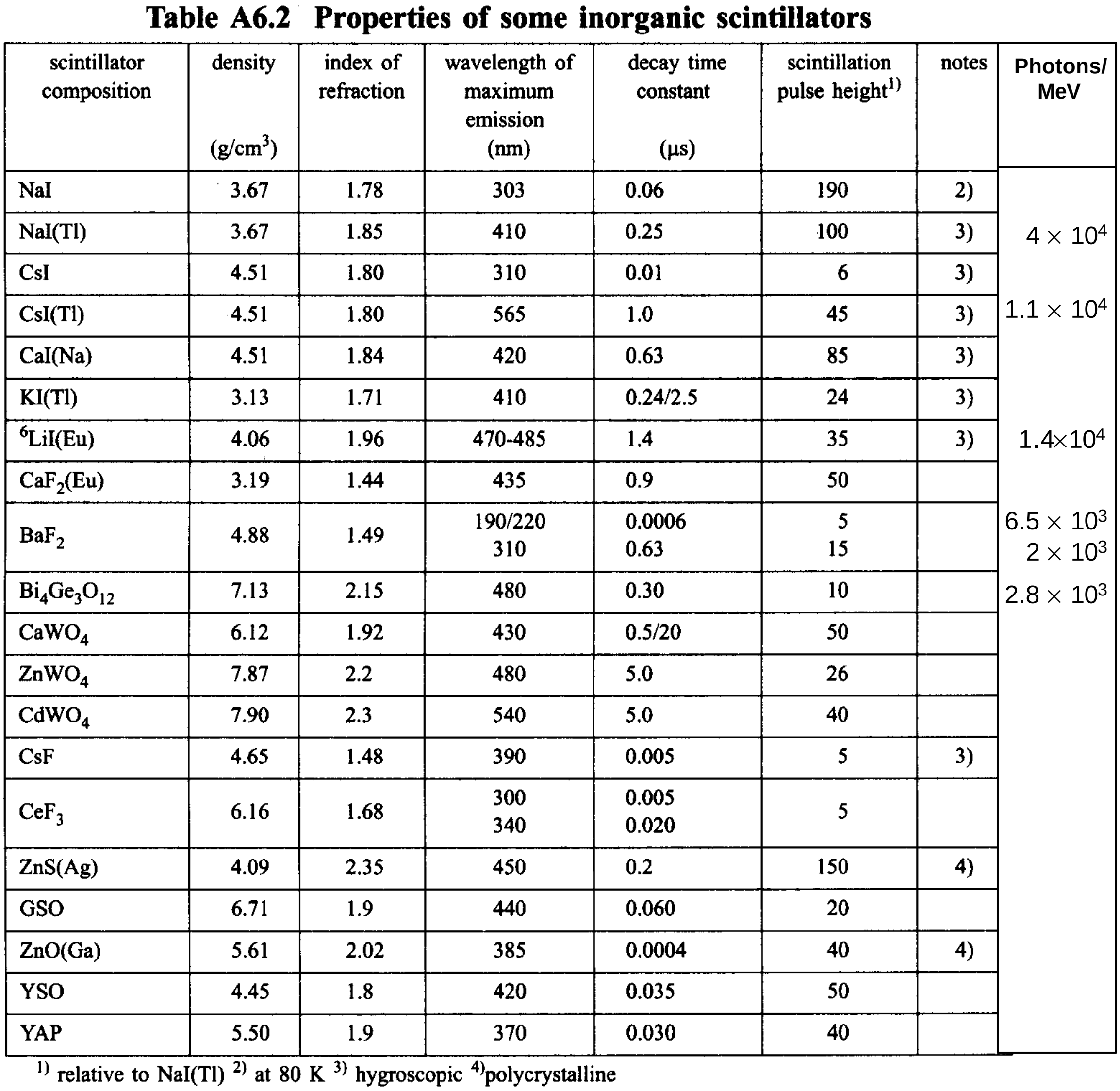


Table A6.2 Properties of some inorganic scintillators

scintillator composition	density (g/cm^3)	index of refraction	wavelength of maximum emission (nm)	decay time constant (μs)	scintillation pulse height$^{1)}$	notes	Photons/ MeV
NaI	3.67	1.78	303	0.06	190	2)	
NaI(Tl)	3.67	1.85	410	0.25	100	3)	4 × 10^4
CsI	4.51	1.80	310	0.01	6	3)	
CsI(Tl)	4.51	1.80	565	1.0	45	3)	1.1 × 10^4
CaI(Na)	4.51	1.84	420	0.63	85	3)	
KI(Tl)	3.13	1.71	410	0.24/2.5	24	3)	
^{6}LiI(Eu)	4.06	1.96	470-485	1.4	35	3)	1.4×10^4
CaF_2(Eu)	3.19	1.44	435	0.9	50		
BaF_2	4.88	1.49	190/220 310	0.0006 0.63	5 15		6.5 × 10^3 2 × 10^3
$Bi_4Ge_3O_{12}$	7.13	2.15	480	0.30	10		2.8 × 10^3
$CaWO_4$	6.12	1.92	430	0.5/20	50		
$ZnWO_4$	7.87	2.2	480	5.0	26		
$CdWO_4$	7.90	2.3	540	5.0	40		
CsF	4.65	1.48	390	0.005	5	3)	
CeF_3	6.16	1.68	300 340	0.005 0.020	5		
ZnS(Ag)	4.09	2.35	450	0.2	150	4)	
GSO	6.71	1.9	440	0.060	20		
ZnO(Ga)	5.61	2.02	385	0.0004	40	4)	
YSO	4.45	1.8	420	0.035	50		
YAP	5.50	1.9	370	0.030	40		

$^{1)}$ relative to NaI(Tl) $^{2)}$ at 80 K $^{3)}$ hygroscopic $^{4)}$polycrystalline

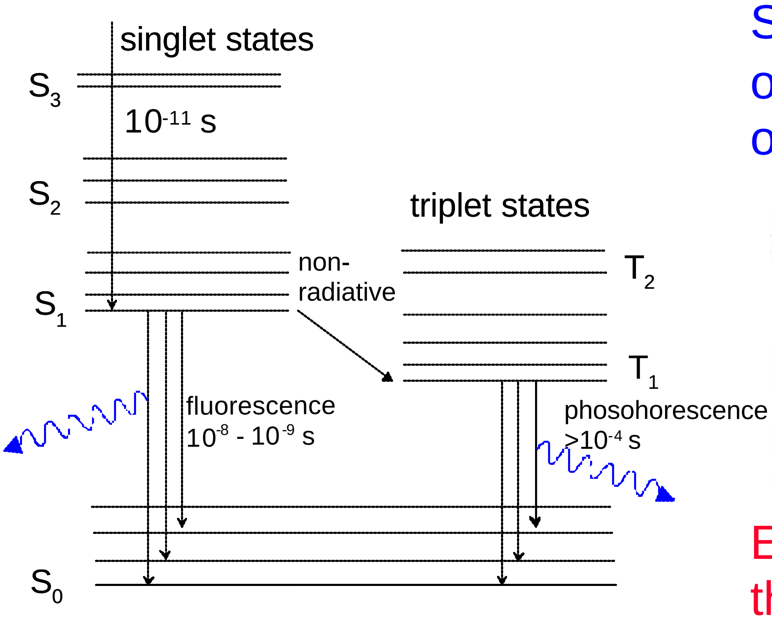
$PbWO_4$	8.28	1.82	440, 530	0.01			100

LAr	1.4	1.29$^{5)}$	120-170	0.005 / 0.860			
LKr	2.41	1.40$^{5)}$	120-170	0.002 / 0.085			
LXe	3.06	1.60$^{5)}$	120-170	0.003 / 0.022			4 × 10^4

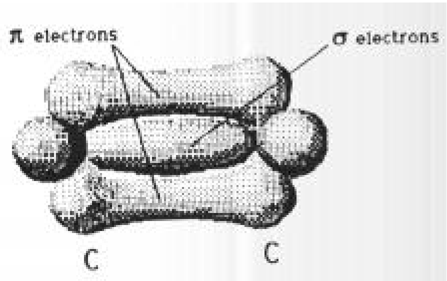
$^{5)}$ at 170 nm

2. Organic scintillators: Monocrystals or liquids or plastic solutions

Molecular states



Scintillation is based on the 2 π electrons of the C-C bonds.



Emitted light is in the UV range.

Monocrystals: naphtalene, anthracene, p-terphenyl….

Liquid and plastic scintillators

They consist normally of a solvent + secondary (and tertiary) fluors as wavelength shifters.

Fast energy transfer via non-radiative dipole-dipole interactions (Förster transfer).

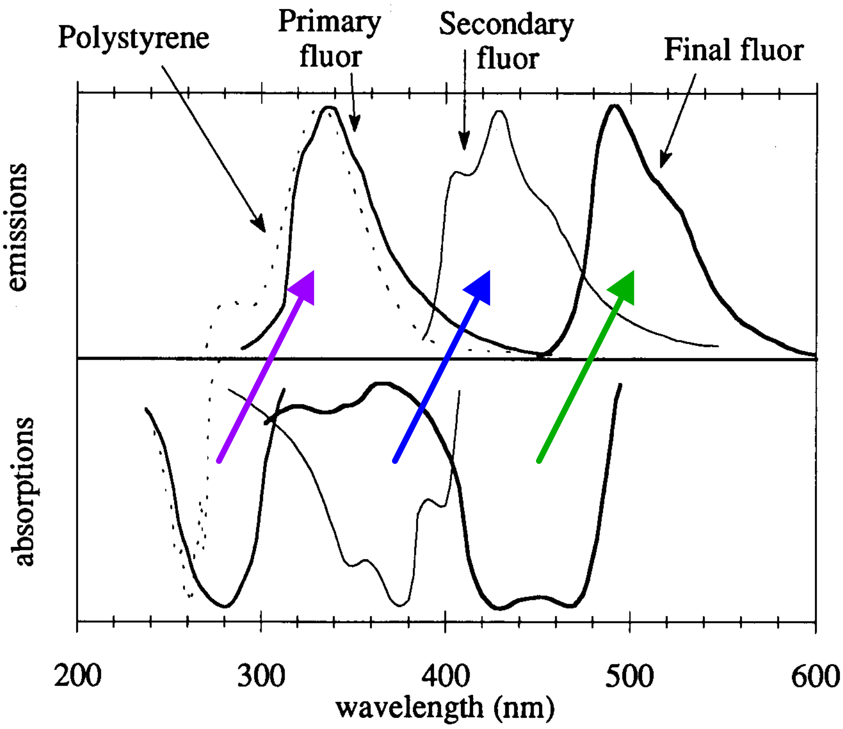
→ shift emission to longer wavelengths

→ longer absorption length and efficient read-out device

Organic scintillators (backup)

Schematic representation of wave length shifting principle

(C. Zorn, Instrumentation In High Energy Physics, World Scientific,1992)



Some widely used solvents and solutes

	solvent	secondary fluor	tertiary fluor
Liquid scintillators	Benzene Toluene Xylene	p-terphenyl DPO PBD	POPOP BBO BPO
Plastic scintillators	Polyvinylbenzene Polyvinyltoluene Polystyrene	p-terphenyl DPO PBD	POPOP TBP BBO DPS

After mixing the components together plastic scintillators are produced by a complex polymerization method.

Some inorganic scintillators are dissolved in PMMA and polymerized (plexiglas).

Organic scintillators

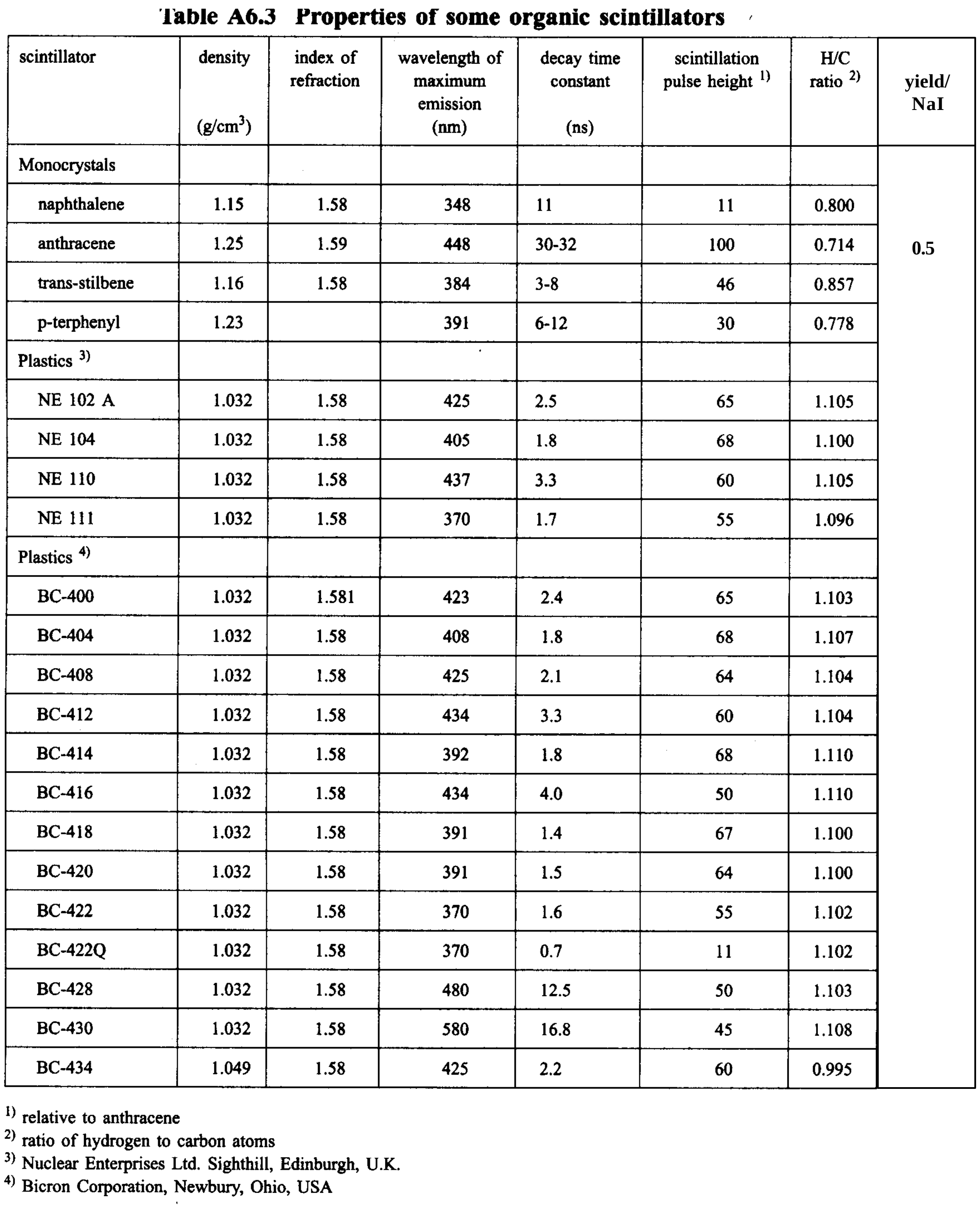


Table A6.3 Properties of some organic scintillators

scintillator	density (g/cm^3)	index of refraction	wavelength of maximum emission (nm)	decay time constant (ns)	scintillation pulse height 1)	H/C ratio 2)	yield/ NaI
Monocrystals							0.5
naphthalene	1.15	1.58	348	11	11	0.800	
anthracene	1.25	1.59	448	30-32	100	0.714	
trans-stilbene	1.16	1.58	384	3-8	46	0.857	
p-terphenyl	1.23		391	6-12	30	0.778	
Plastics 3)							
NE 102 A	1.032	1.58	425	2.5	65	1.105	
NE 104	1.032	1.58	405	1.8	68	1.100	
NE 110	1.032	1.58	437	3.3	60	1.105	
NE 111	1.032	1.58	370	1.7	55	1.096	
Plastics 4)							
BC-400	1.032	1.581	423	2.4	65	1.103	
BC-404	1.032	1.58	408	1.8	68	1.107	
BC-408	1.032	1.58	425	2.1	64	1.104	
BC-412	1.032	1.58	434	3.3	60	1.104	
BC-414	1.032	1.58	392	1.8	68	1.110	
BC-416	1.032	1.58	434	4.0	50	1.110	
BC-418	1.032	1.58	391	1.4	67	1.100	
BC-420	1.032	1.58	391	1.5	64	1.100	
BC-422	1.032	1.58	370	1.6	55	1.102	
BC-422Q	1.032	1.58	370	0.7	11	1.102	
BC-428	1.032	1.58	480	12.5	50	1.103	
BC-430	1.032	1.58	580	16.8	45	1.108	
BC-434	1.049	1.58	425	2.2	60	0.995	

1) relative to anthracene
2) ratio of hydrogen to carbon atoms
3) Nuclear Enterprises Ltd. Sighthill, Edinburgh, U.K.
4) Bicron Corporation, Newbury, Ohio, USA

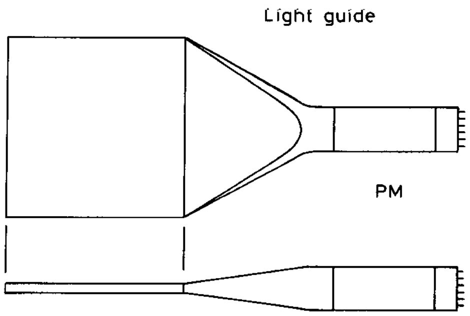
Organic scintillators have low Z (H,C). Low γ detection efficiency (practically only Compton effect). But high neutron detection efficiency via (n,p) reactions.

Scintillator readout

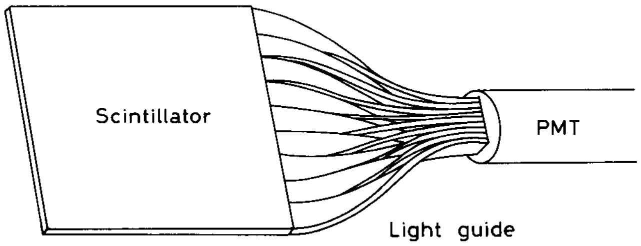
Readout has to be adapted to geometry and emission spectrum of scintillator.

Geometrical adaptation:

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

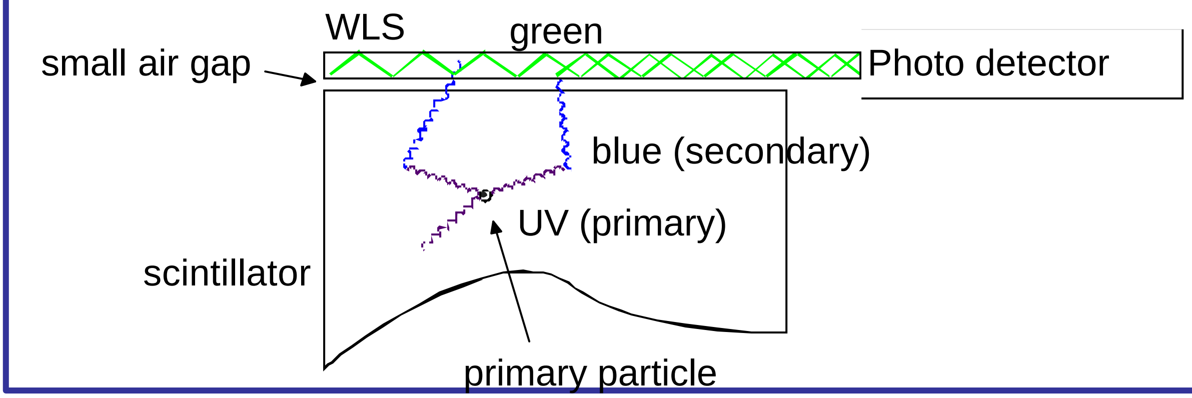


“fish tail”



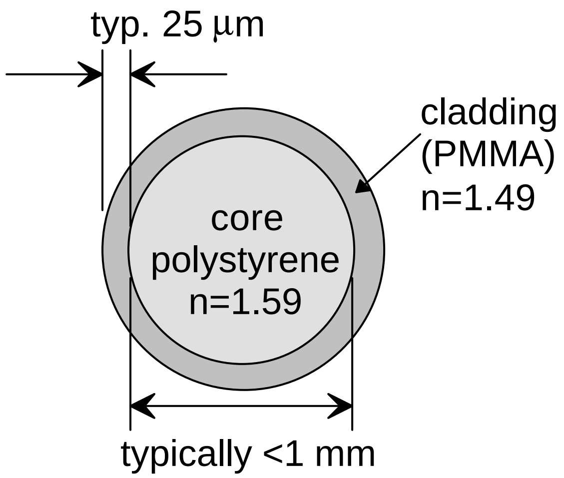
adiabatic

- wavelength shifter (WLS) bars

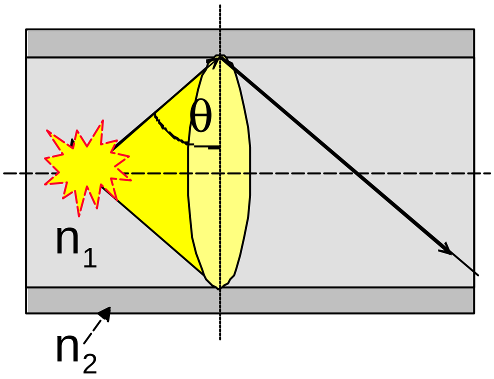

WLS
green
small air gap
Photo detector
blue (secondary)
UV (primary)
scintillator
primary particle

Scintillator readout

◆ Optical fibers



light transport by total internal reflection



$$\theta \geq \arcsin \frac{n_2}{n_1} \approx 69.6^\circ \qquad \frac{d\Omega}{4\pi} = 3.1\%$$ in one direction

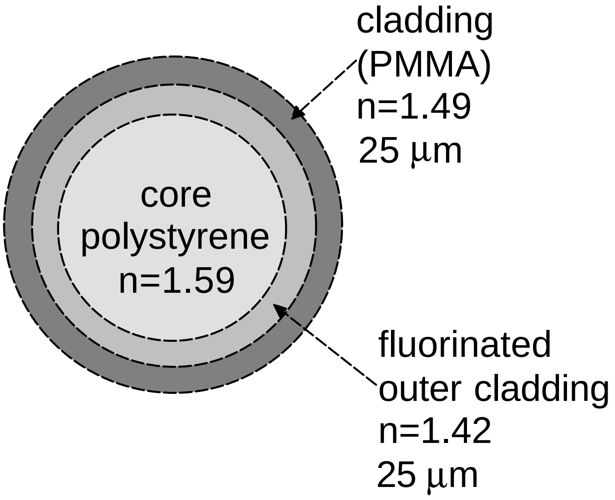
minimize $n_{cladding}$.

Ideal: air (n=1), but impossible due to surface imperfections

multi-clad fibres
for improved
aperture

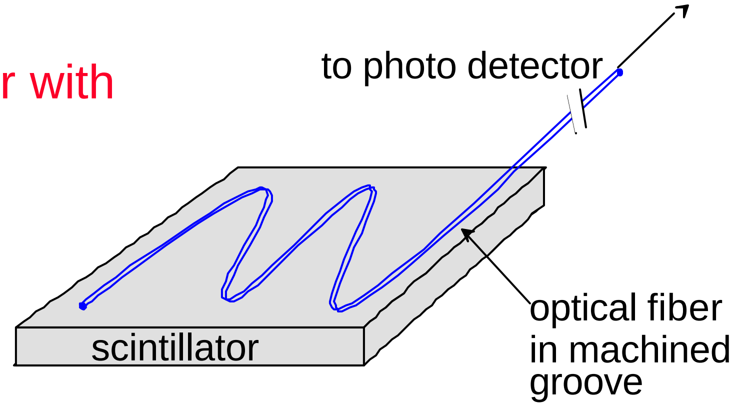
$$\frac{d\Omega}{4\pi} = 5.3\%$$

and absorption
length: λ>10 m for
visible light



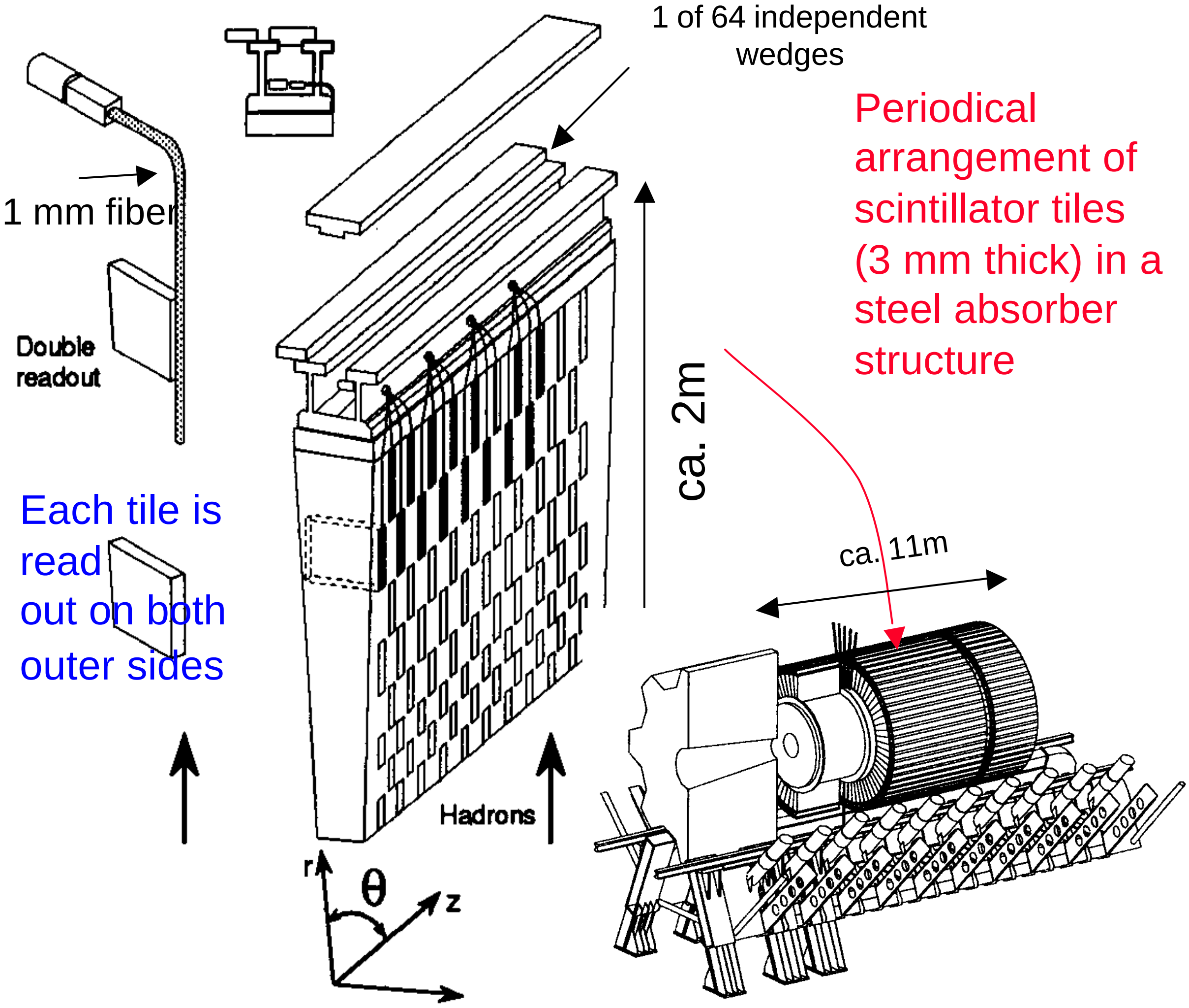
Scintillator readout

readout of a scintillator with a fiber (schematically)



ATLAS Hadron Calorimeter: (ATLAS TDR)

Scintillating tile readout via fibers and photomultipliers

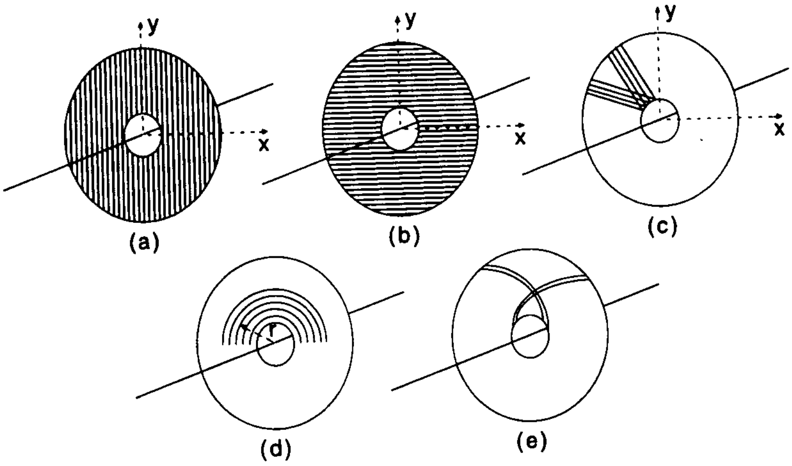


Periodical arrangement of scintillator tiles (3 mm thick) in a steel absorber structure

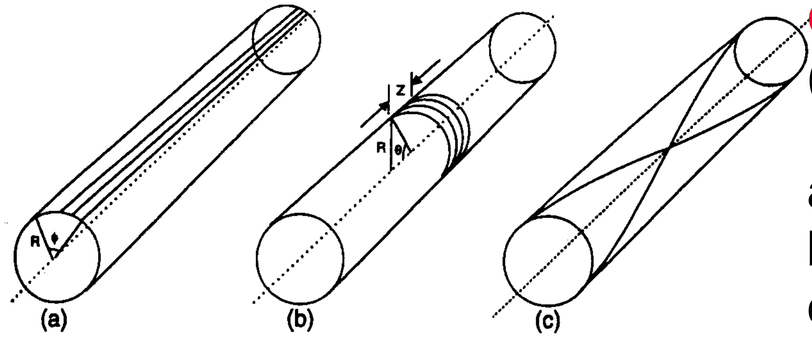
Each tile is read out on both outer sides

Scintillating fiber tracking

- Scintillating plastic fibers
- Capillary fibers, filled with liquid scintillator



Planar geometries
(end cap)



Circular geometries
(barrel)

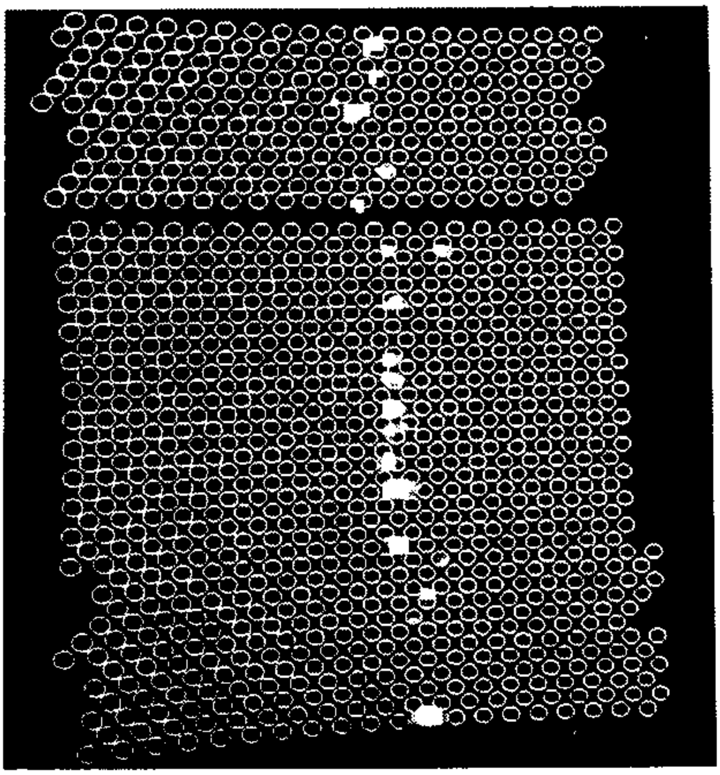
a) axial
b) circumferential
c) helical

(R.C. Ruchti, Annu. Rev. Nucl. Sci. 1996, 46,281)

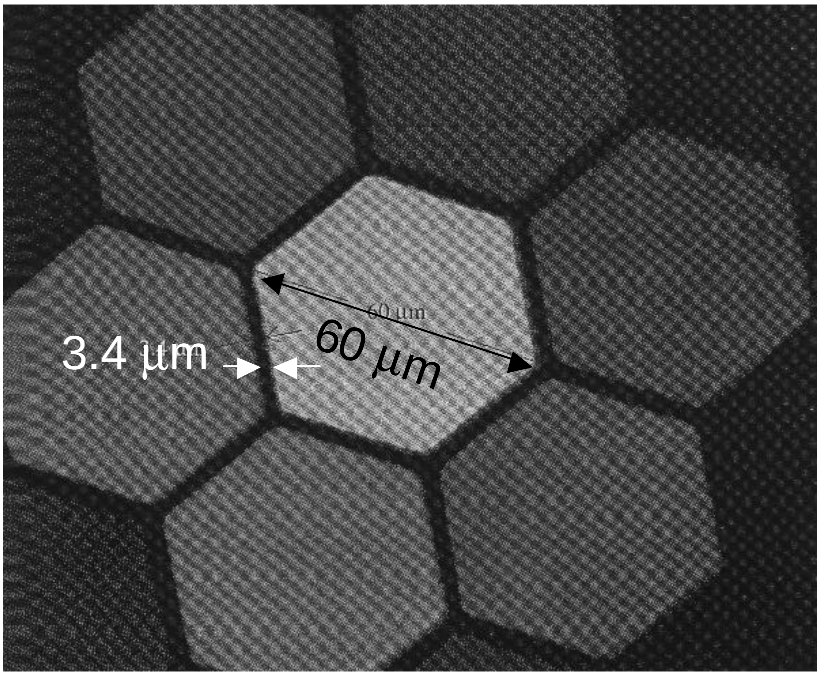
- High geometrical flexibility
- Fine granularity
- Low mass
- Fast response (ns) (if fast read out) → first level trigger

Scintillating fiber tracking

Charged particle passing through a stack of scintillating fibers (diam. 1mm)



UA2 (?)



Hexagonal fibers with double cladding.

Only central fiber illuminated.

Low cross talk !

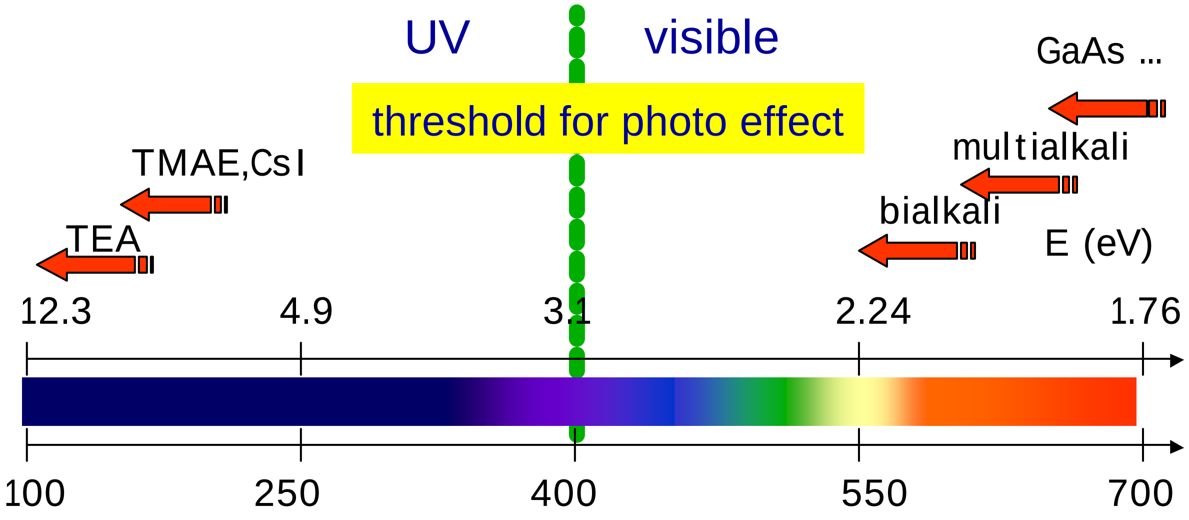
(H. Leutz, NIM A 364 (1995) 422)

Photo Detectors

Purpose: Convert light into detectable electronics signal

In HEP we are usually interested in visible and UV spectrum

Threshold of some photosensitive material



standard requirement

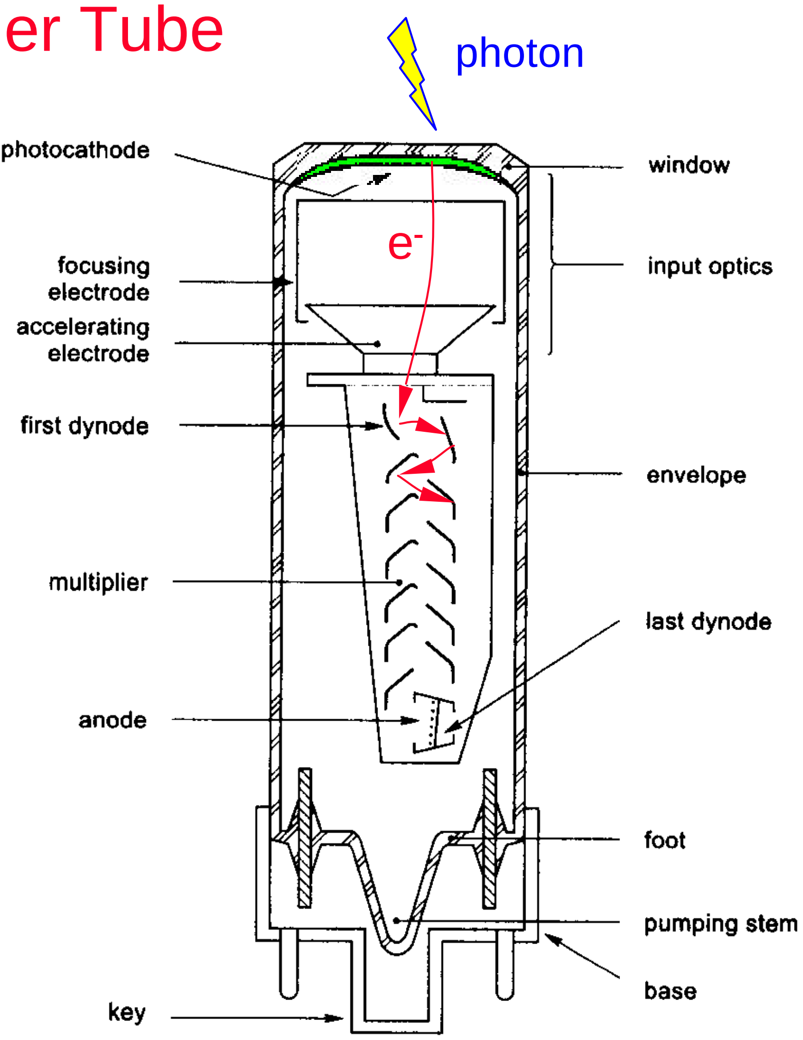
- high sensitivity, usually expressed as quantum efficiency $Q.E. = N_{p.e.} / N_{photons}$

Main types

- gas based devices (see RICH detectors)
- vacuum based devices
- solid state detectors

Photo Multiplier Tube (PMT)

(Philips Photonic)



main phenomena:

- photo emission from photo cathode.
- secondary emission from dynodes.

  dynode gain g=3-50 (f(E))

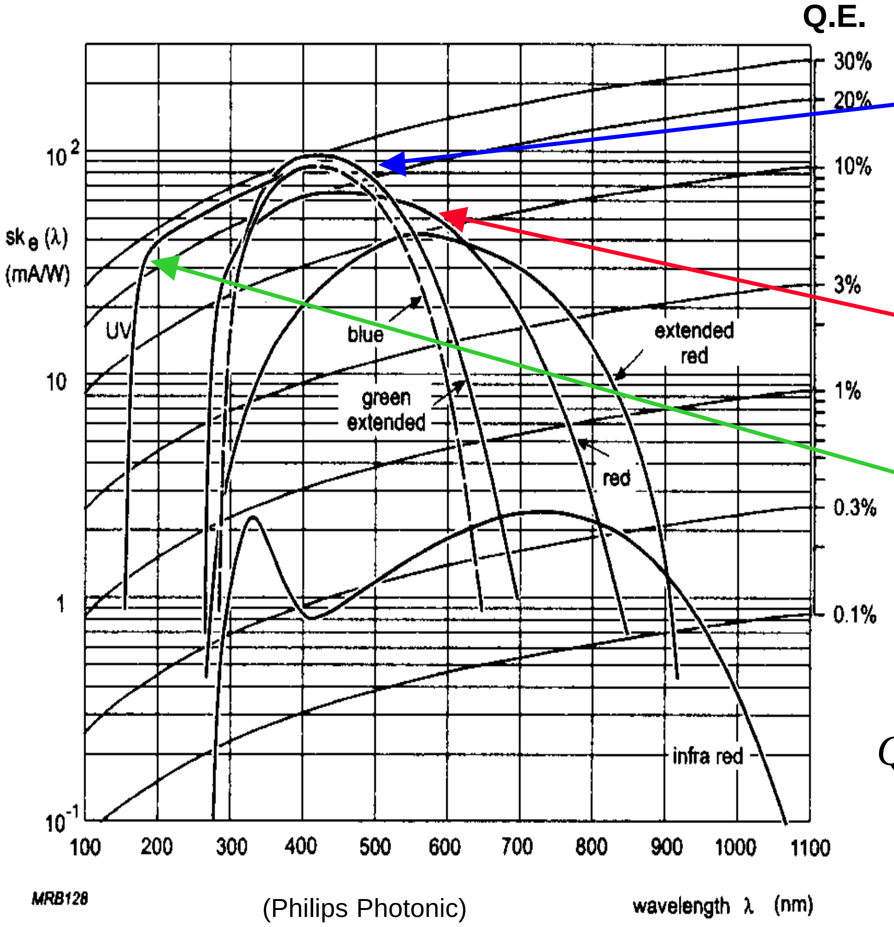
  total gain $M = \prod_{i=1}^{N} g_i$

  10 dynodes with g=4

  $M = 4^{10} \approx 10^6$

PM's are in general very sensitive to B-fields, even to earth field (30-60 μT). μ-metal shielding required.

Quantum efficiencies of typical photo cathodes



(Philips Photonic)

Bialkali

SbK_2Cs

SbRbCs

Multialkali

$SbNa_2KCs$

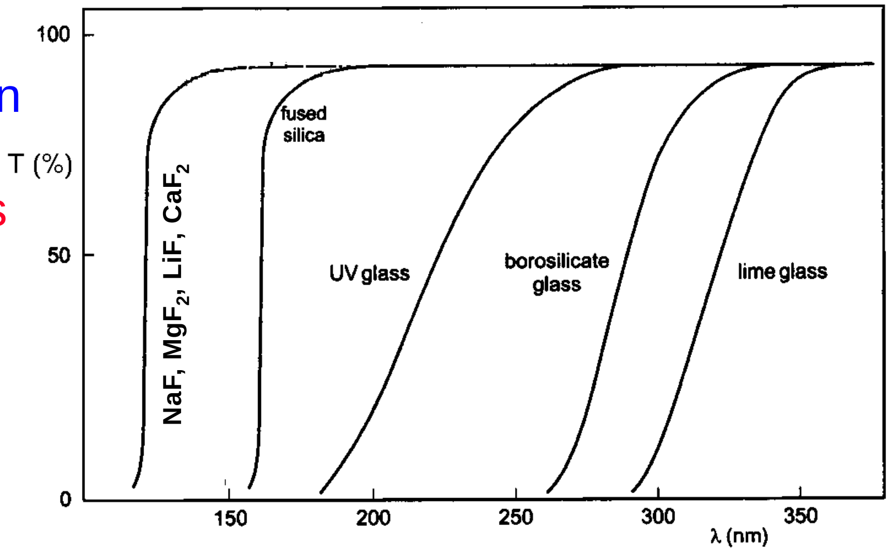
Solar blind

CsTe

(cut by quartz window)

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

Transmission of various PM windows



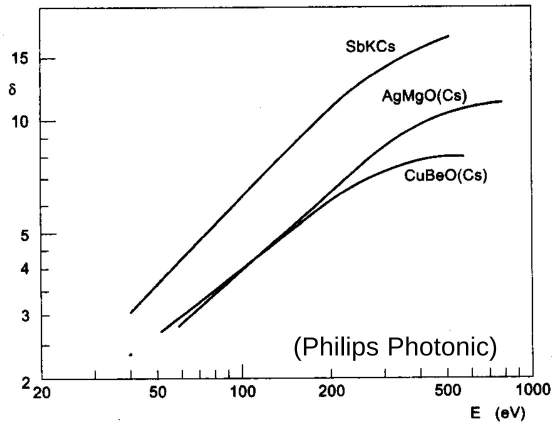
Energy resolution of PMT’s

The energy resolution is determined mainly by the fluctuation of the number of secondary electrons emitted from the dynodes.

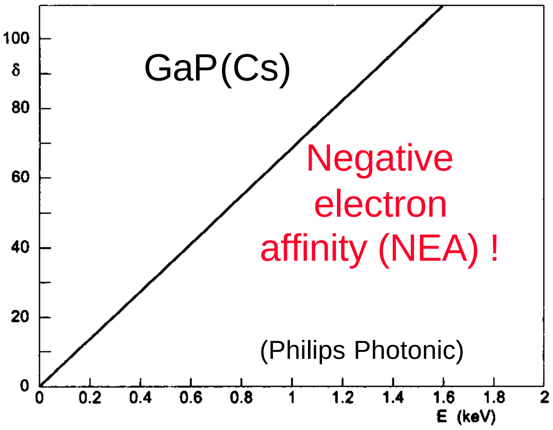
Poisson distribution: $$P(\bar{n},m)=\frac{\bar{n}^{m}e^{-m}}{m!}$$

Relative fluctuation: $$\frac{s_n}{\bar{n}}=\frac{\sqrt{\bar{n}}}{\bar{n}}=\frac{1}{\sqrt{\bar{n}}}$$

Fluctuations biggest, when $\bar{n}$ small ! → First dynode !



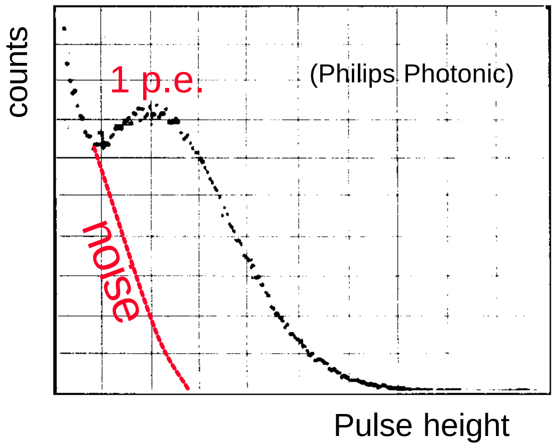
(Philips Photonic)



Negative electron affinity (NEA) !

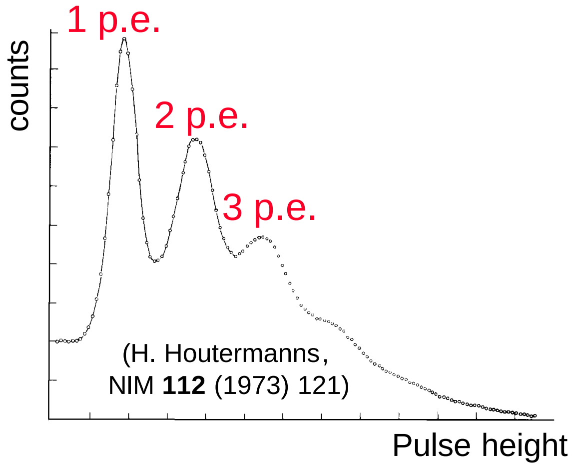
(Philips Photonic)

Single photons.
Pulse height spectrum of a PMT with Cu-Be dynodes.



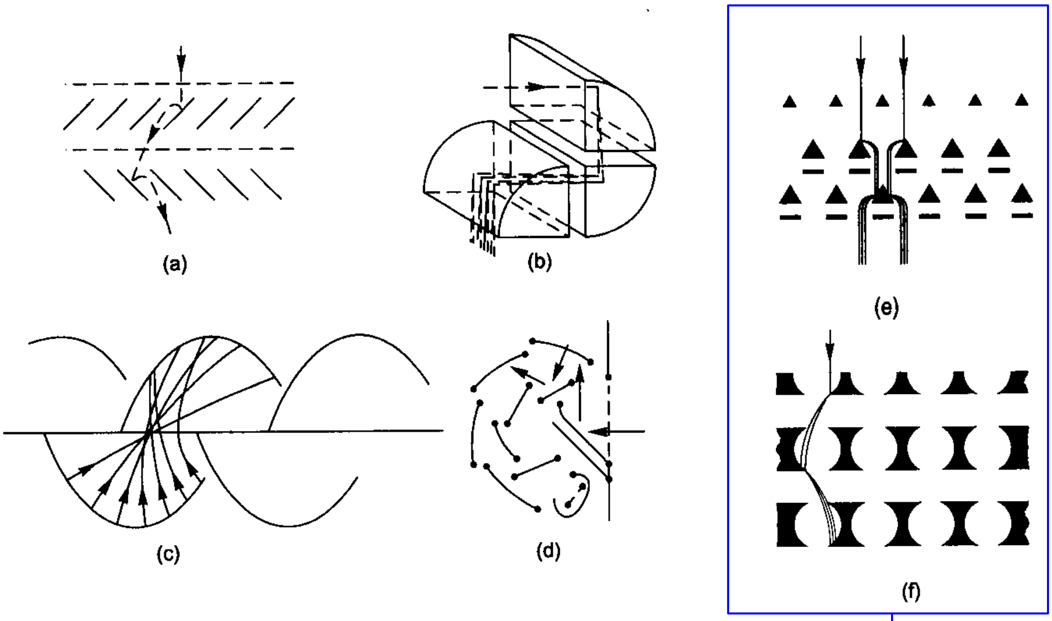
(Philips Photonic)

Pulse height spectrum of a PMT with NEA dynodes.



(H. Houtermanns, NIM **112** (1973) 121)

Dynode configurations



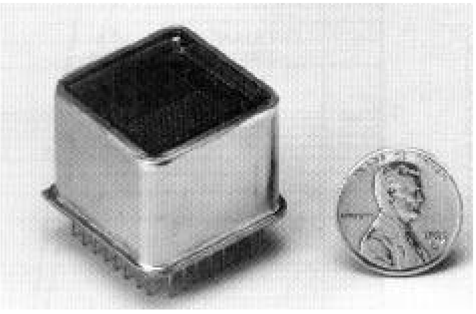
(Philips Photonics)

Dynode configurations: (a) venetian blind, (b) box, (c) linear focusing, (d) circular cage, (e) mesh and (f) foil

position sensitive PMT’s

Multi Anode PM

example: Hamamatsu R5900 series.



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.

Gain uniformity and cross-talk used to be problematic, but recently much improved.

- Hybrid photo diodes (HPD)

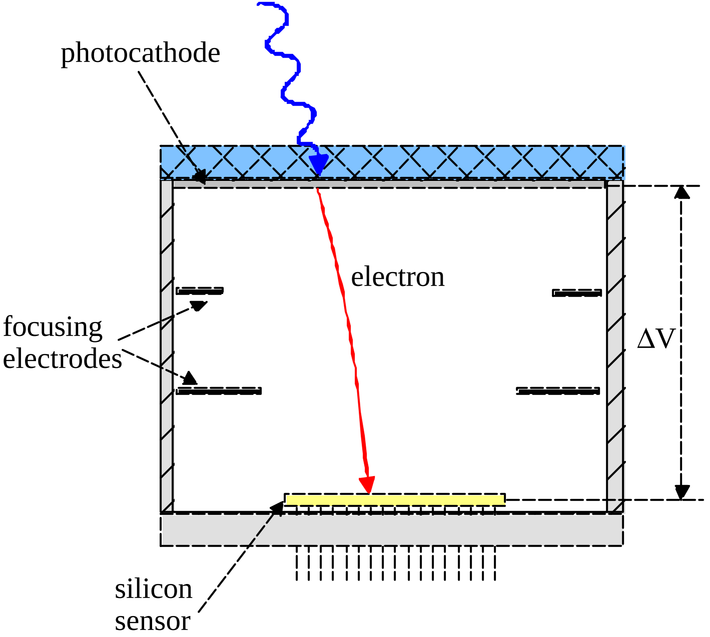


photo cathode + p.e. acceleration + silicon det. (pixel, strip, pads)

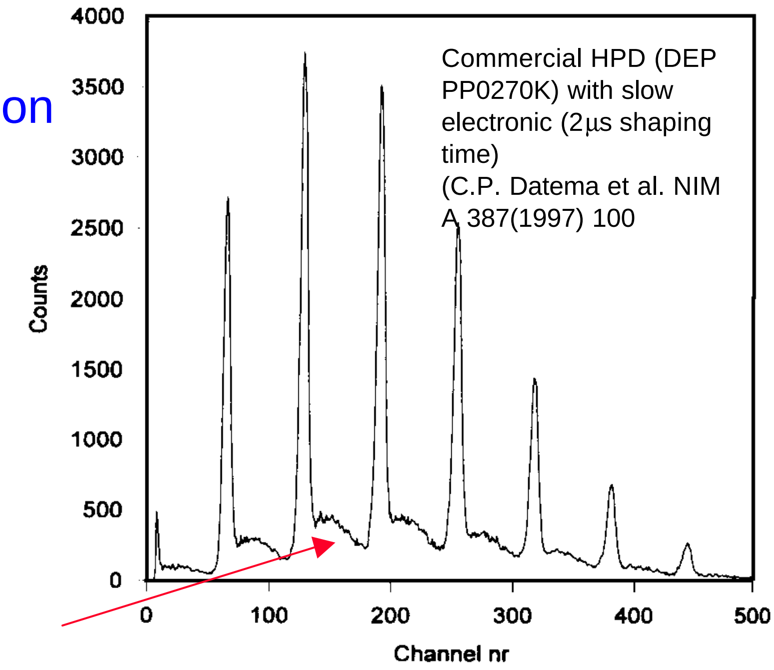
Photo cathode like in PMT, ΔV 10-20 kV

$$G = \frac{e\Delta V}{W_{Si}} = \frac{20\,keV}{3.6\,eV} \approx 5 \cdot 10^3$$ (for ΔV =20 kV)

Single photon detection with high resolution

Poisson statistics with $\overline{n}$ =5000 !

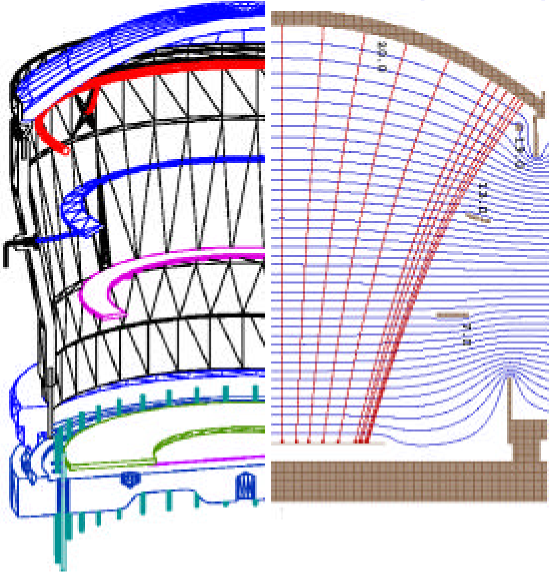
Background from electron backscattering from silicon surface



Commercial HPD (DEP PP0270K) with slow electronic (2µs shaping time)
(C.P. Datema et al. NIM A 387(1997) 100

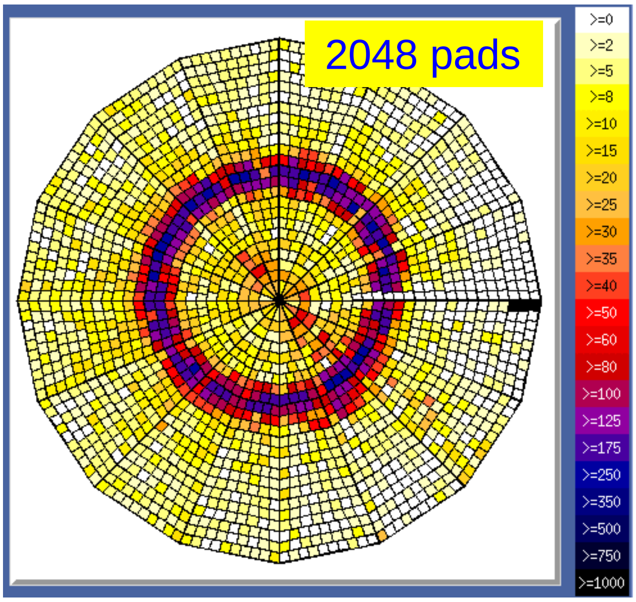
Cherenkov ring imaging with HPD's

(CERN)



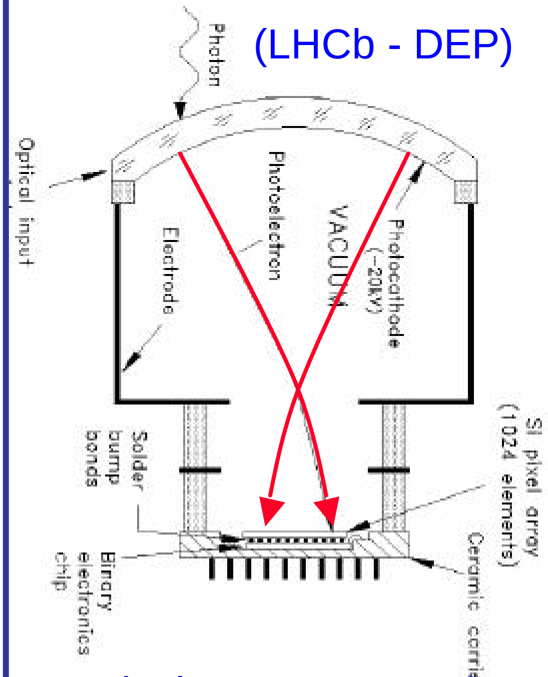
Pad HPD, Ø127 mm,

fountain focused



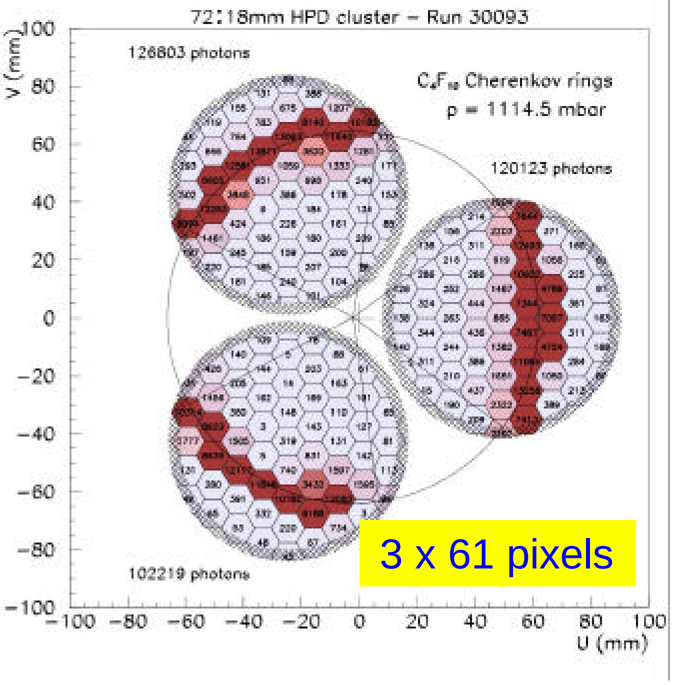
test beam data, 1 HPD

(LHCb - DEP)



Pixel-HPD, 80mm Ø

cross-focused

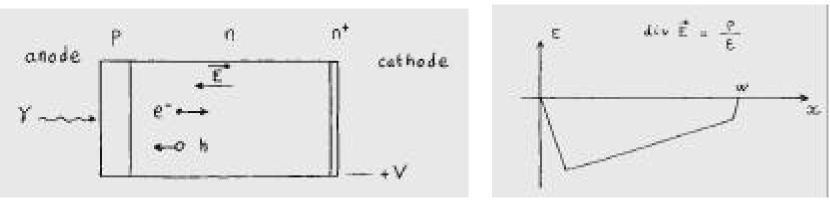


test beam data, 3 HPDs

Photo Detectors

◆ Photo diodes

P(I)N type



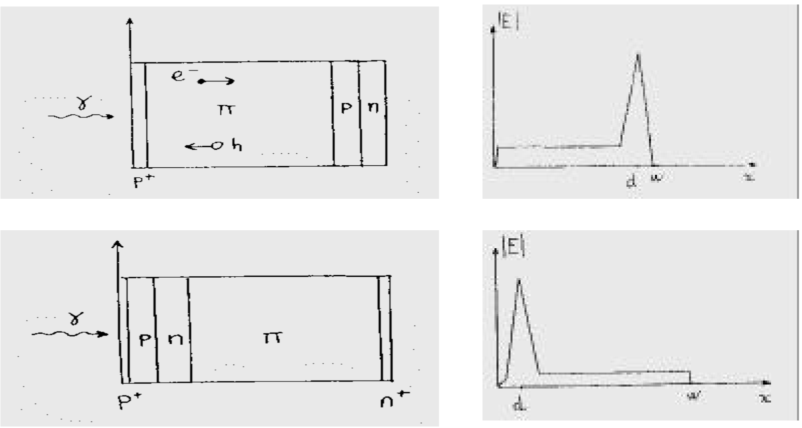
(sketches from J.P. Pansart, NIM A 387 (1997), 186)

High Q.E. (≈80% at λ ≈ 700nm), gain G = 1.

◆ Avalanche Photo diodes (APD)

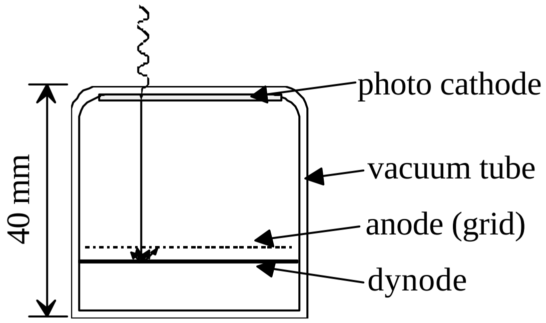
(J.P. Pansart, NIM A 387 (1997), 186)

High reverse bias voltage ≈ 100-200V. High internal field → avalanche multiplication.
G ≈ 100(0)



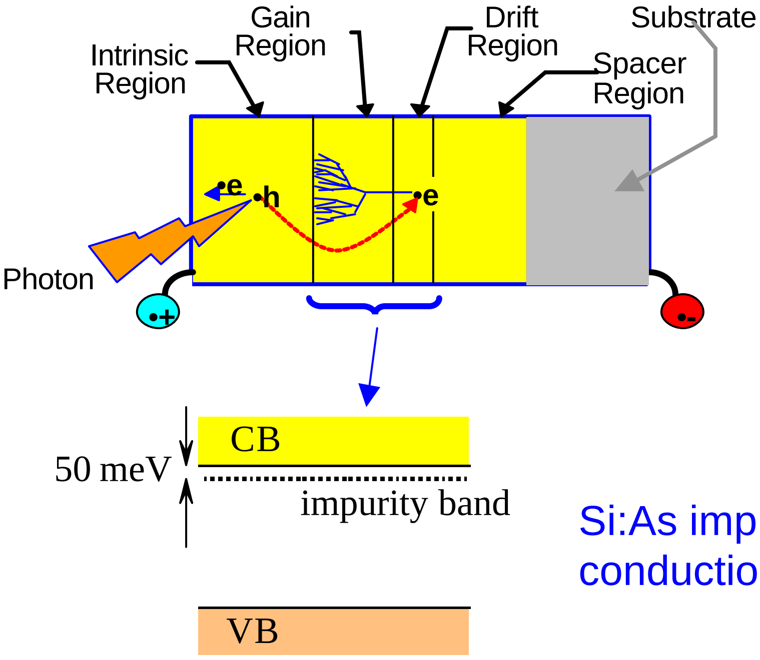
◆ Photo triodes = single stage PMT (no Silicon !)

G ≈ 10.
work in axial B-fields of 1T
OPAL, DELPHI: readout of lead glass in endcap calorimeter
G at 1T ≈ 7-10



IEEE NS-30 No. 1 (1983) 479

◆ Visible Light Photo Counter VLPC

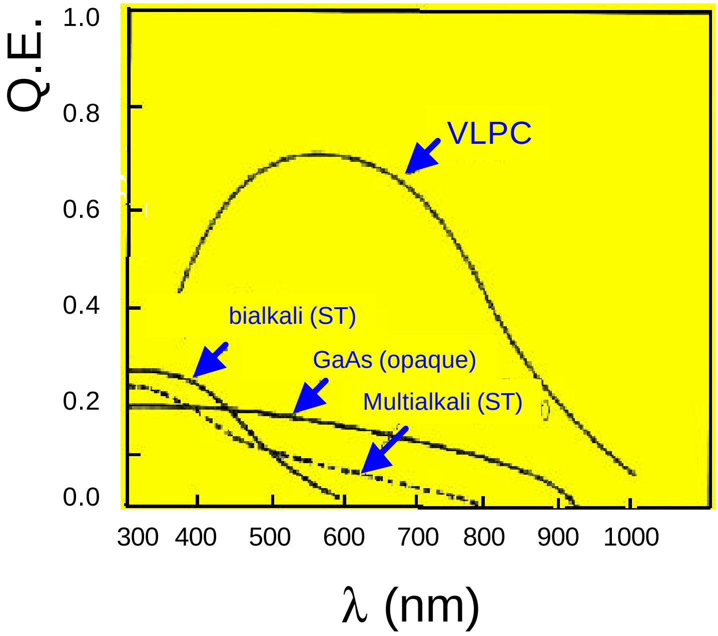


Hole drifts towards highly doped drift region and ionizes a donor atom → free electron. Multiplication by ionization of further neutral donor atoms.

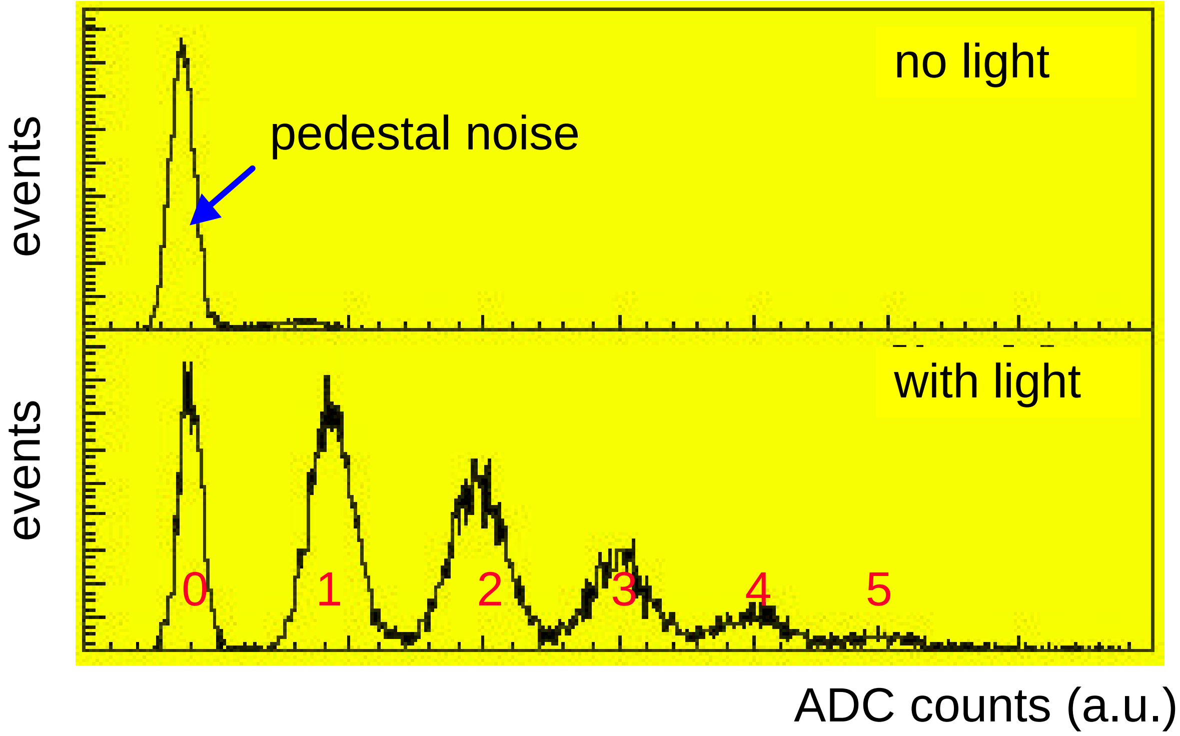
Si:As impurity band conduction avalanche diode

- Operation at low bias voltage (7V)
- High IR sensitivity → Device requires cooling to LHe temperature.

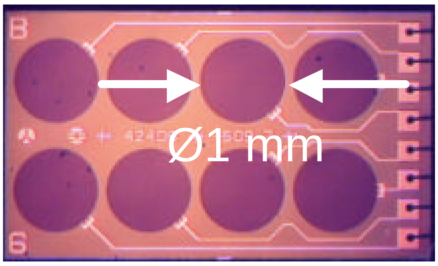
- Q.E. ≈ 70% around 500 nm.
- Gain up to 50.000 !



High gain → real photon counting as in HPD



Fermilab: D0 (D zero) fiber tracker (72.000 channels)



8 pixels per chip
(vapour phase epitaxial growth)