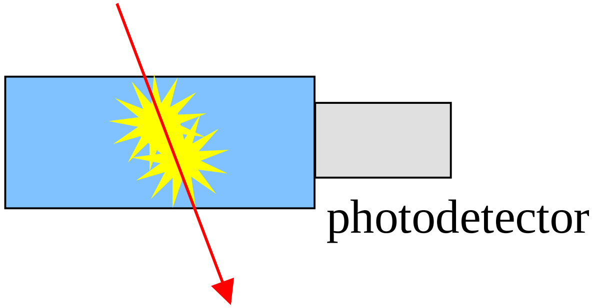
Photon Detection

- ☐ Scintillators
  - – organic
  - – inorganic
  - – wavelength shifters
- ☐ Scintillating Fibre Trackers
- ☐ Photon detectors
  - – photo multipliers
  - – diodes
  - – position sensitive devices
  - – multianode PMTs
  - – GAPD (SiPM)
  - – hybrid photo diodes

Scintillation



- ☐ Luminescence:
  - – materials absorb energy
    - light, heat, radiation, …
  - – reemit energy
    - as visible light
- ☐ Fluorescence:
  - – reemission within 10^{-8} s
    - atomic transitions
- ☐ Phosphorescence:
  - – slow reemission
    - afterglow

- ☐ Scintillators:
  - – luminescent
  - – light output:
    - very fast rise time: O(100ps)
    - exponential decay: O(ns)
    - proportional to energy deposition

$$N(t) = N_0 G(\sigma, t) \exp\left(\frac{-t}{\tau_d}\right)$$

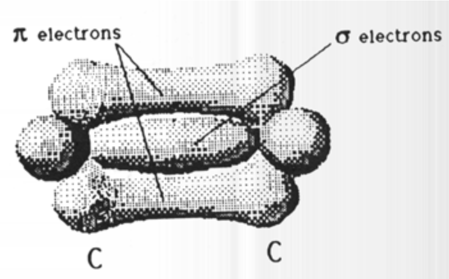
$$N_0 \propto E$$

- ☐ Usage:
  - – time-of-flight measurements
  - – trigger counter
  - – veto counter
  - – tracking

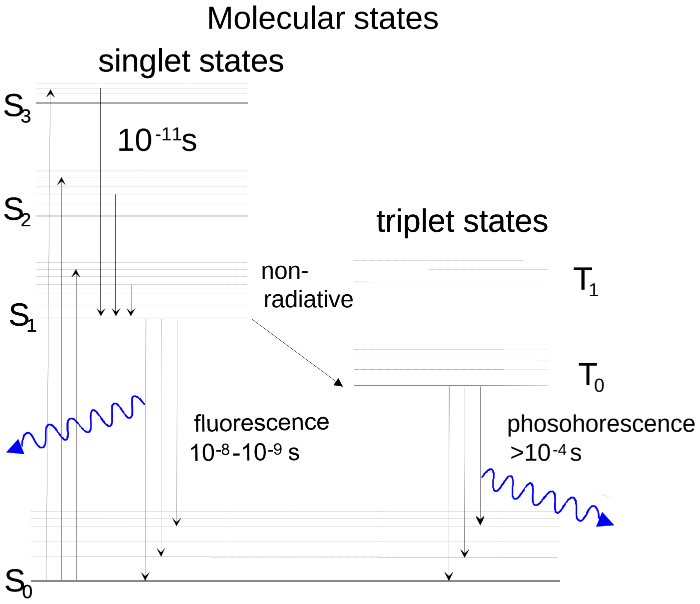
  - – energy measurements
  - – calorimetry

Organic Scintillators - Processes

- Organic scintillation:
  - arises from electrons in π-orbitals



  - energy level diagram



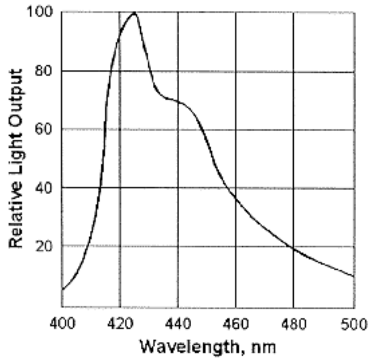
- Absorption:
  - to singlet states S_{1+}* (vibration bands)
- Decay (fluorescence):
  - fast internal degradation to S_1: $O(10^{-11}$ns)
  - radiative decay $S_1 \rightarrow S_0$*: $O(10^{-8}$-10^{-9}ns)
  - UV to blue wavelengths
  - scintillator is transparent to its own light!!
  - transition to triplet states $S_0^* \rightarrow T_1$ forbidden

    → no re-absorbtion
- Decay (phosphorescence):
  - non-radiative decay: $S_1 \rightarrow T_1$ *

    → delayed / slow radiative decay:

    $T_0 + T_0 \rightarrow S_0 + S^*$ + phonons
  - $O(>10^{-4}$ns) visible, IR

BC-400



Organic Scintillators - Materials

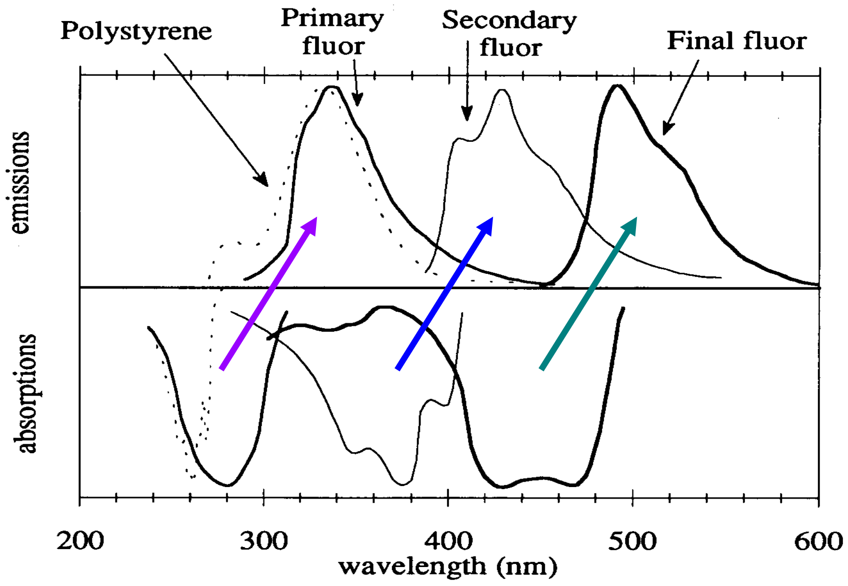
- Organic Crystals:
  - anthracene ($C_{14}H_{10}$), stilbene ($C_{14}H_{12}$), naphthalene ($C_{10}H_8$)
  - high photon, yield but slower
- Organic Liquids:
  - O(3%) solutions of one or more scintillators in solvent
  - absorption by solvent → pass of E to scintillator
  - for large volumes

	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

- Plastic Scintillators:
  - solid polymerised solutions
  - flexibility: various sizes and shapes
  - relatively cheap

  → most widely used

- Wave-length shifting:
  - shifted re-emission to longer λ
  - better match to photo multiplier
  - less absorption (by the matrix…)



Scintillator Properties I

- Properties:
  - low density
  - similar index of refraction
  - anthracene (crystal):
    - highest light yield
    - slowest: ~30ns
  - plasics:
    - fast: ~1ns
    - lower light yield: ~10-50% of anthracene
  - two developers for plasics:
    - Bicron
    - Nuclear Enterprises (gone bust…)
      - was resident to Edinburgh…

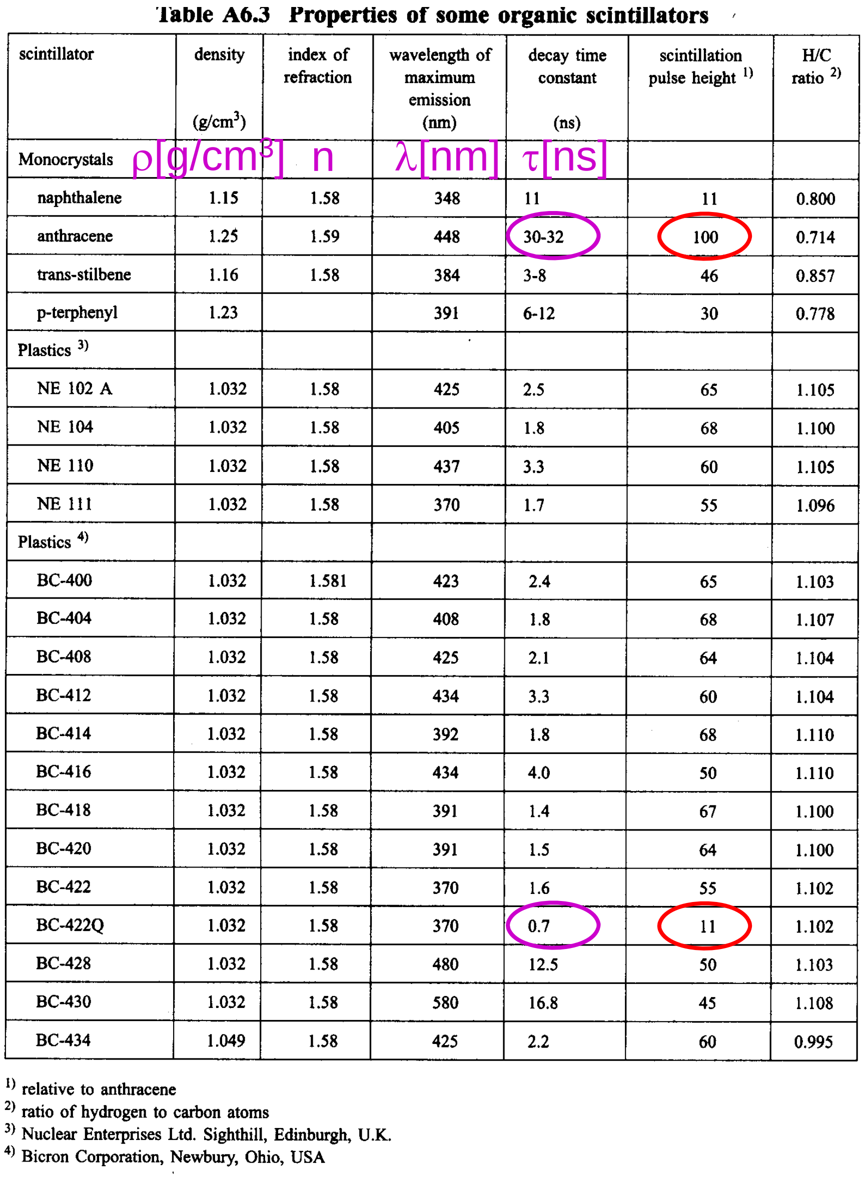


Table A6.3 Properties of some organic scintillators

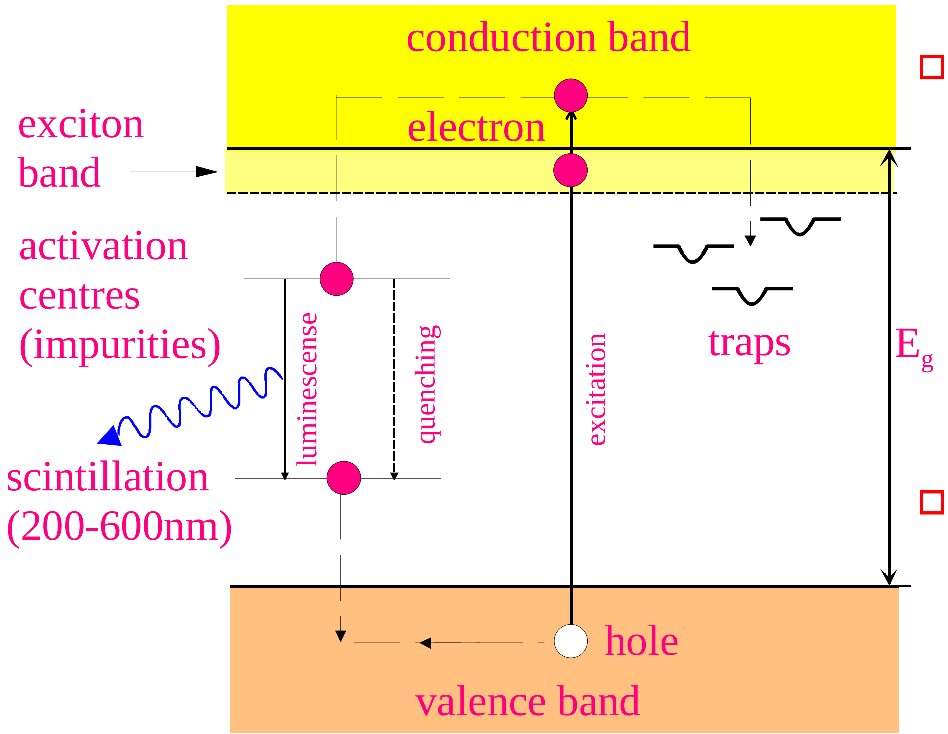
scintillator	density (g/cm^3)	index of refraction	wavelength of maximum emission (nm)	decay time constant (ns)	scintillation pulse height [1]	H/C ratio [2]
Monocrystals	ρ[g/cm^3]	n	λ[nm]	τ[ns]		
naphthalene	1.15	1.58	348	11	11	0.800
anthracene	1.25	1.59	448	30-32	100	0.714
trans-stilbene	1.16	1.58	384	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

Inorganic Scintillators - Processes

- Inorganic Scintillating Crystals:
  - alkali halides (NaI(Tl), CsI(Tl), …) and non-alkali materials ($Bi_4Ge_3O_{12}$=BGO, ZnS(Ag), …)
  - exciton = free e^- -hole pair or exiton
  - causes emission of photon in activation centres
  - small activator impurity (Tl, Na, Eu, Ag, Ga, …): radiative emission from activation centres
  - traps: impurities providing non-radiative recombination

$$N(t) = N_0 \exp\left(\frac{-t}{\tau_{d_1}}\right)\exp\left(\frac{-t}{\tau_{d_2}}\right)$$



- disadvantages:
  - time constants governed by band structure and drift times: ≥2 time constants
    → slower than organic scintillators: O(300ns)
  - traps: 100 ms
  - hygroscopic: NaI(Tl) very, CsI(Tl,pure) some

- advantages:
  - high light yield
  - high density and high Z
    → good for high energy e and γ

Inorganic Scintillators - Parameters

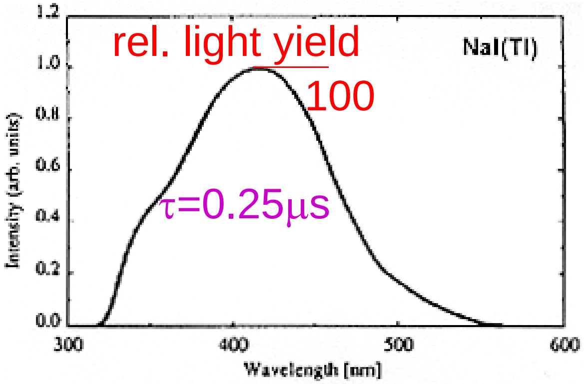


Figure 1. Scintillation emission spectrum of a canned NaI(Tl) crystal.

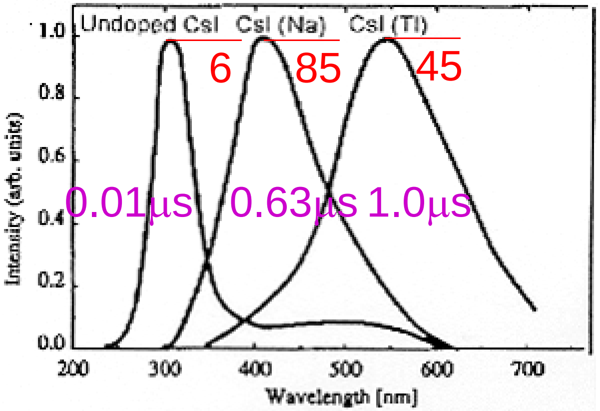


Figure 1. Scintillation emission spectrum of undoped CsI, CsI(Na) and CsI(Tl).

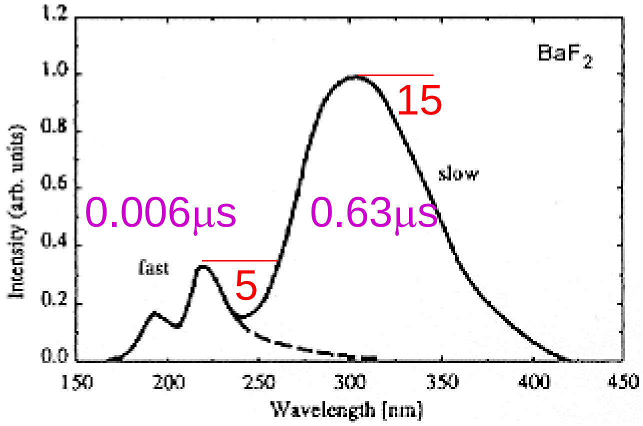


Fig. 1. Scintillation emission spectrum of BaF_2.

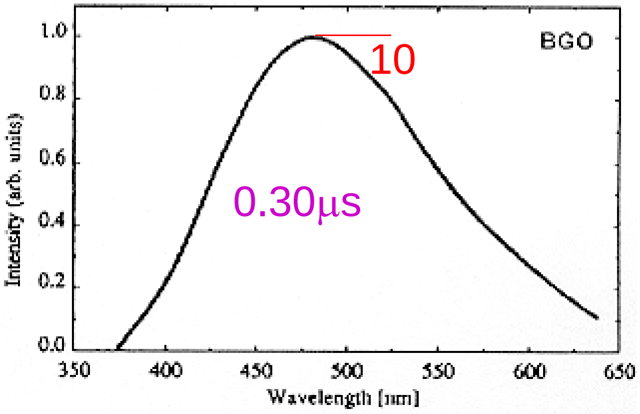
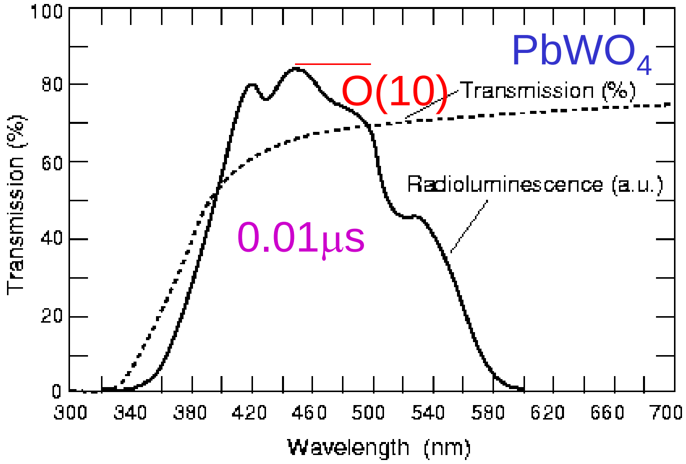


Fig. 1. Scintillation emission spectrum of BGO.



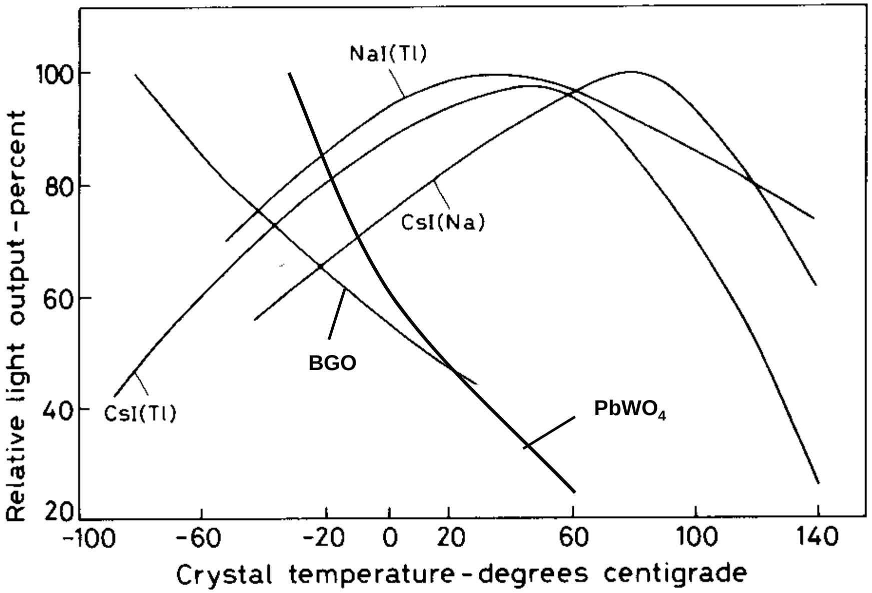
- Moliere radius:

$$R_M = 21\text{MeV} \cdot X_0 / E_C$$

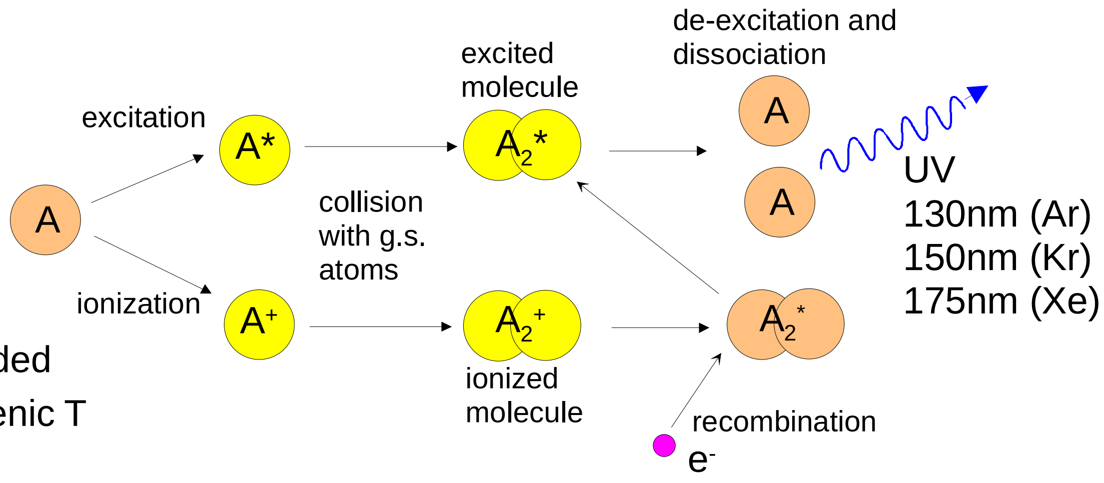
	R_M[cm]	X_0 [cm]
NaI	4.5	2.59
CsI	3.8	1.85
BaF_2	3.4	2.05
BGO	2.4	1.12
$PbWO_4$	2.2	0.89

Inorganic Scintillators (cont.)

- Temperature dependence of crystals:
  - light crystals (NaI, CsI):
    - weak dependence
  - heavy crystals (BGO, $PbWO_4$):
    - strong dependence
    - cooling helps



- (Liquid) Noble Gases:
  - Xe, He, (Kr, Ar, N_2)
  - advantages:
    - fast signals: few ns
    - linear in wide range of E and dE/dx
  - disadvantages:
    - low light yield (<10% of NaI)
    - UV radiation: wave length shifter needed
    - operation at high pressure and cryogenic T



UV
130nm (Ar)
150nm (Kr)
175nm (Xe)

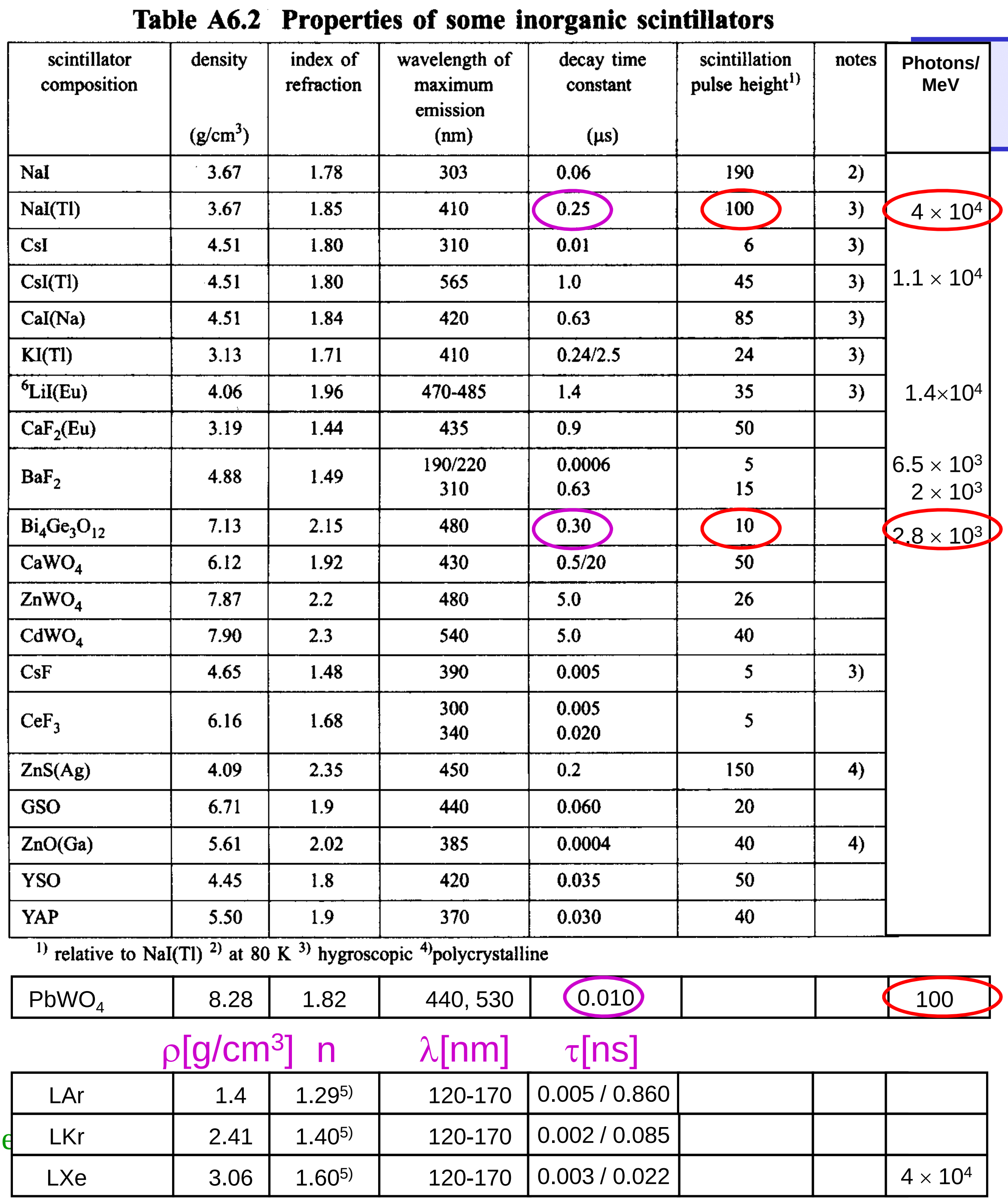


Table A6.2 Properties of some inorganic scintillators

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	0.010			100

ρ[g/cm^3] n λ[nm] τ[ns]

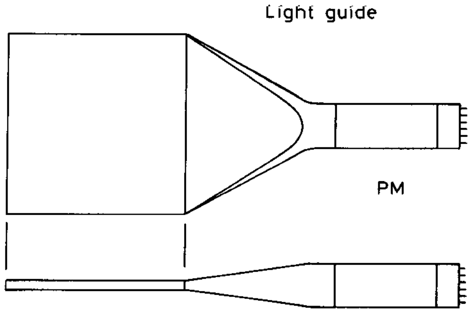
LAr	1.4	1.29$^{5)}$	120-170	0.005 / 0.860			
LKr	2.41	1.40$^{5)}$	120-170	0.002 / 0.085			
LXe	3.06	1.60$^{5)}$	120-170	0.003 / 0.022			4×10^4

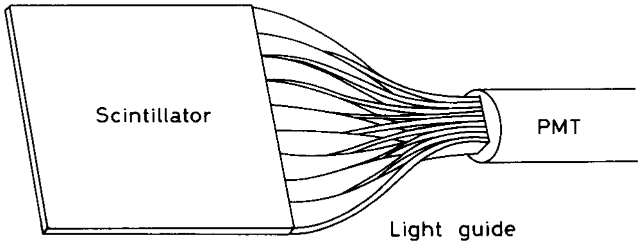
Scintillator Readout I

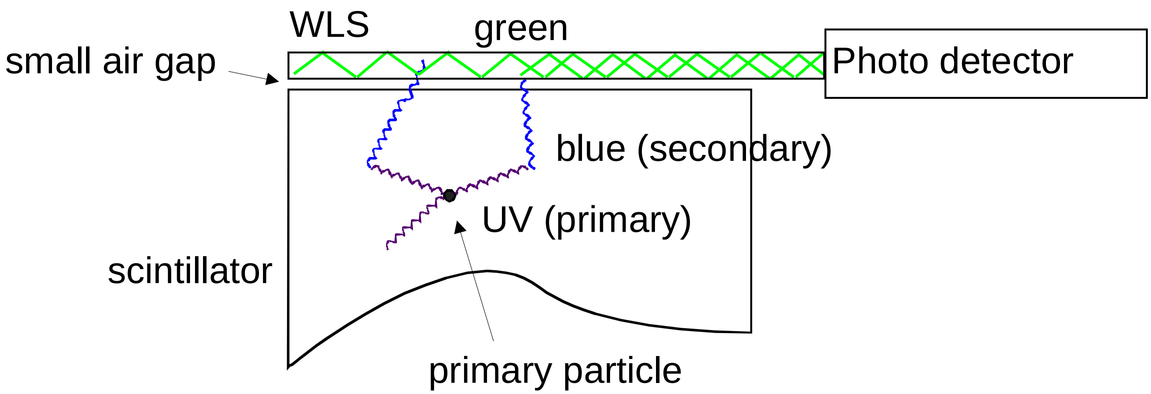
- Scintillator: light production
- Light guide: transmission
  - total internal reflection
  - attenuation length l
  - geometrical loss
- PMT: light detection
- Coupling:
  - optical glue
  - optical grease
  - air gap
- Shape adaptation:
  - Fish tail:
    - adiabatic shape adaptation
    - needs space
  - wavelength shifter:
    - 90° readout or as fibres
    - conversion efficiencies: ~10%
    - widely used for space advantage

$$N(x) = N_0 \exp\left(\frac{-x}{l}\right)$$

$$N_{\mathrm{PMT}} \leq \frac{A_{\mathrm{PMT}}}{A_{\mathrm{Sci}}} N_{\mathrm{Sci}}$$



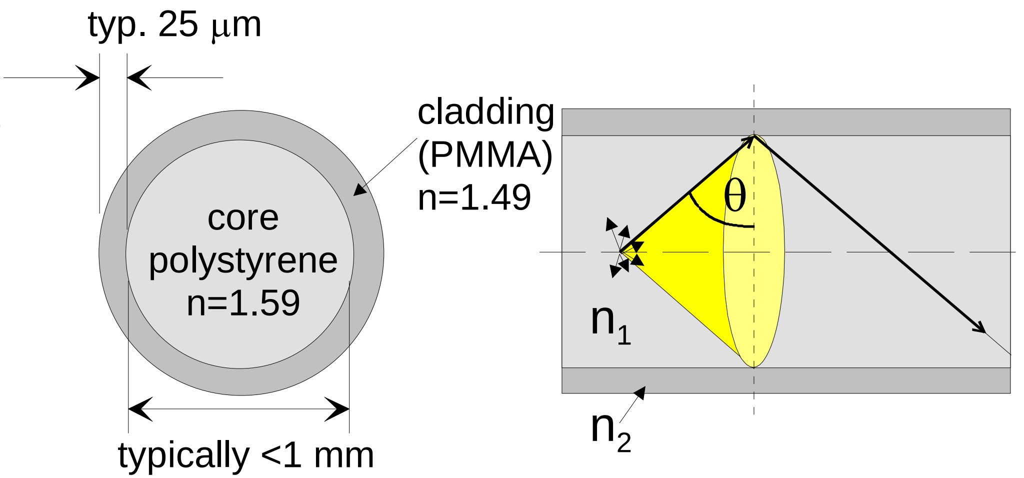




Scitillator Readout II

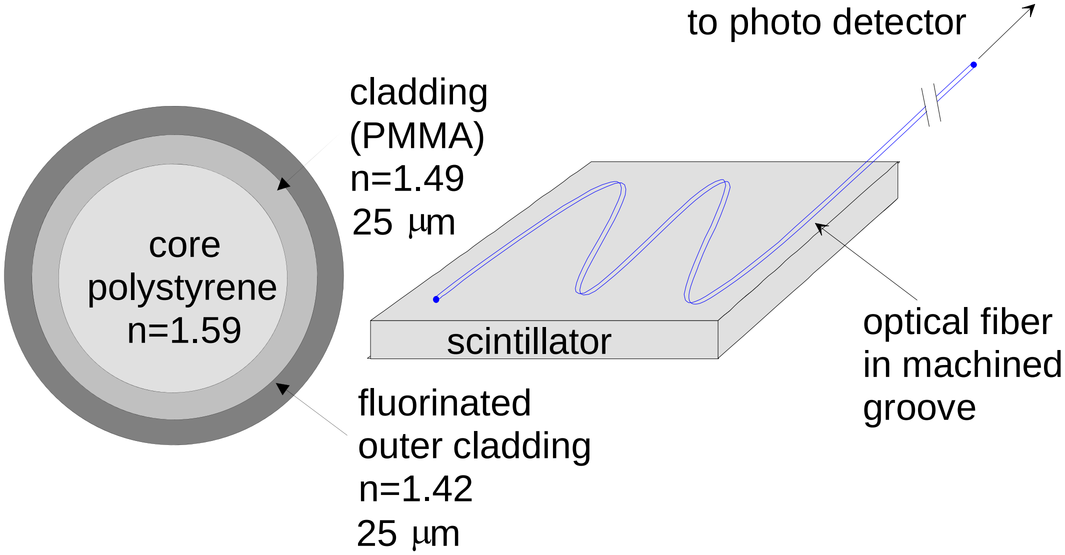
- ☐ Fibres:
  - – total internal reflection for light transport

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



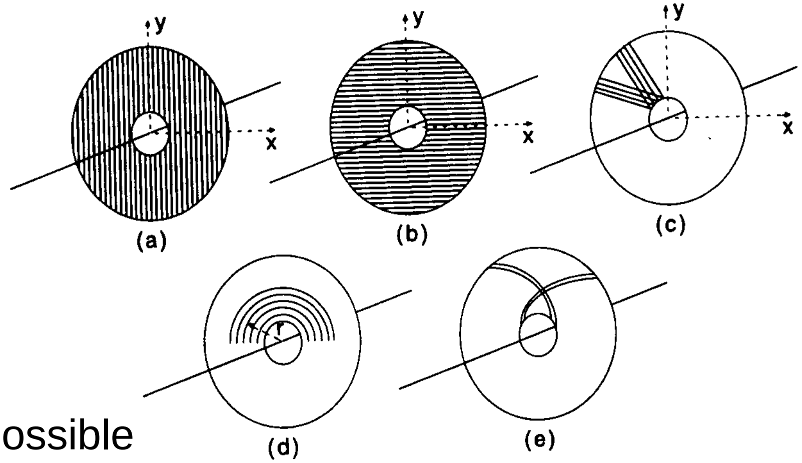
- ☐ Improved aperture:
  - – minimise $n_{cladding}$
  - – multi-clad fibres

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



Scintillating Fibre Trackers I

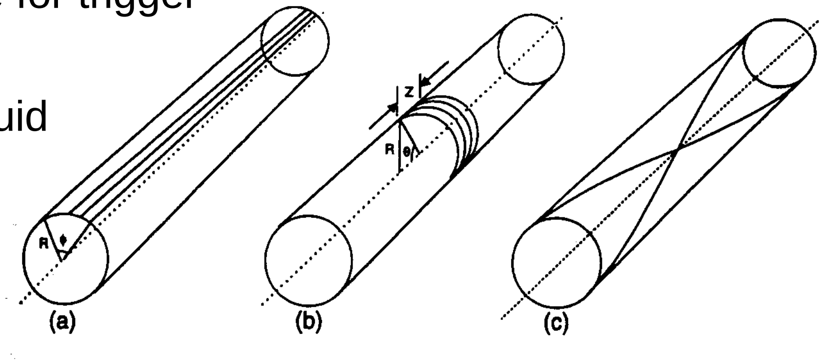
- Scintillating plastic fibres:
  - capillary fibres
  - filled with liquid scintillators



planar geometries
(end cap)

- Advantages:
  - fine granularity, various shapes possible
  - fast response time (ns) → usable for trigger
  - low mass
  - radiation hard: by exchanging liquid

circular geometries
(barrel)

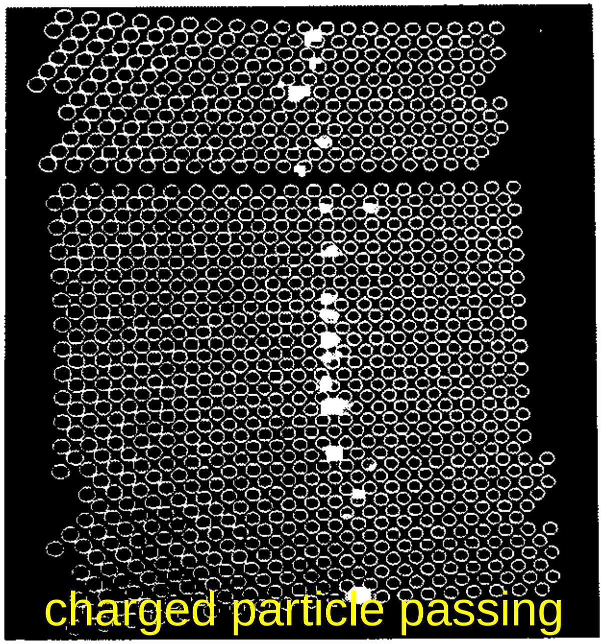


a) axial
b) circumferential
c) helical

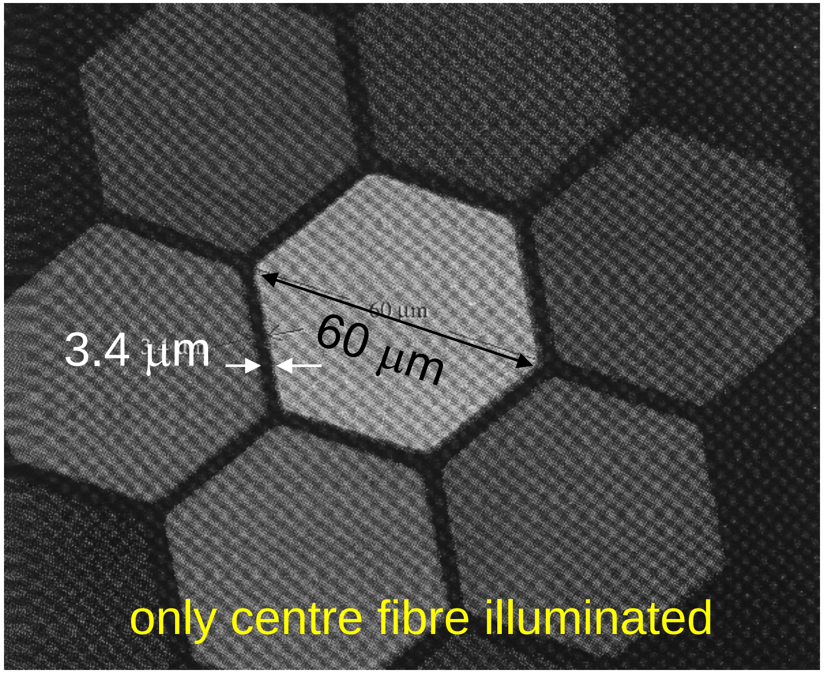
(R.C. Ruchti, Annu. Rev. Nucl. Sci. 1996, 46,281)

Scintillating Fibre Trackers II

- Scintillating fibres:
  - diameter: 1mm
  - close-packed stack



charged particle passing

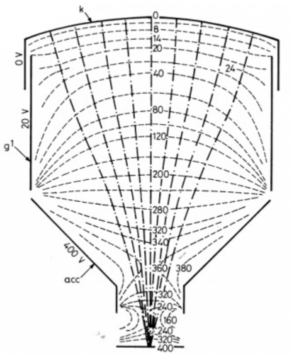


only centre fibre illuminated

- Hexagonal fibres:
  - double cladding
  - low cross-talk

Photo Multiplier Tubes - Basic Principle

- Photon emission from photo cathode:
  - Quantum Efficiency:
    $QE = N_{p.e.}/N_{photons}$

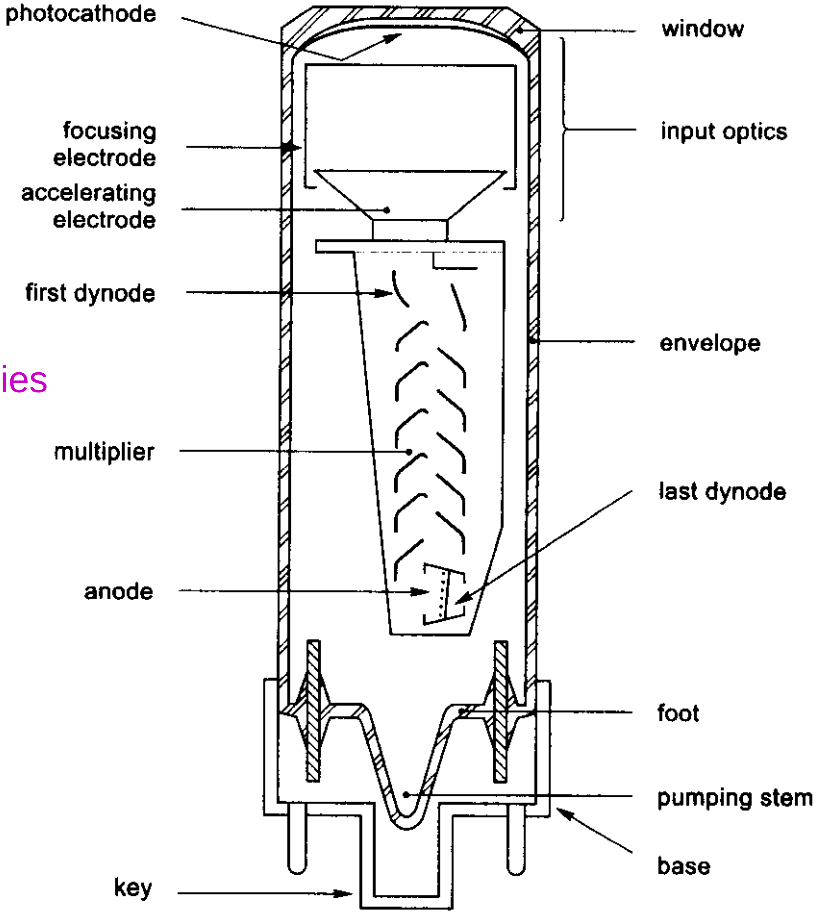


equi-potentials and trajectories
in a fast input system

- Single electron collection:
  - focusing optics
  - optimise efficiency
  - minimise transient time spread (<200ps)
- Secondary emission from dynodes:
  - electric potential
  - electron multiplication:
    dynode gain: g(E) = 3…50
- Total gain: $G = \Pi\, g_i$

  e.g. 10 dynodes with g=4
  ➔ $G = 4^{10} \approx 10^6$

1.25…50cm

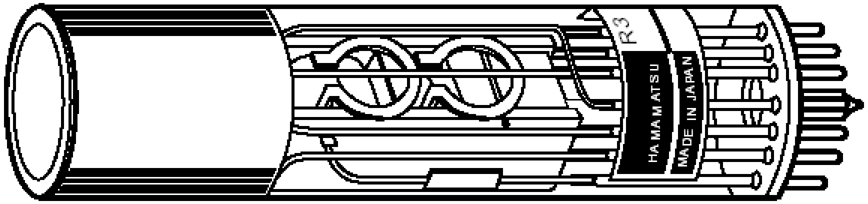


Schematic of Photomultiplier Tube
(Philips Photonic)

PMT - Extension of Vision

- Human eye:

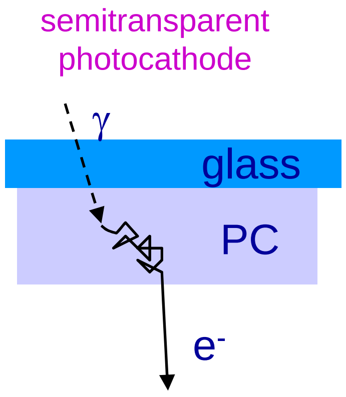
- Photomultiplier:

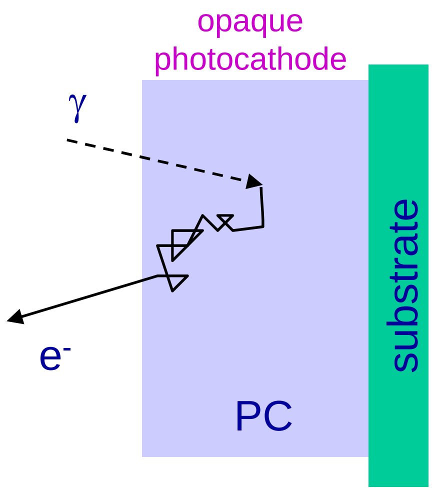


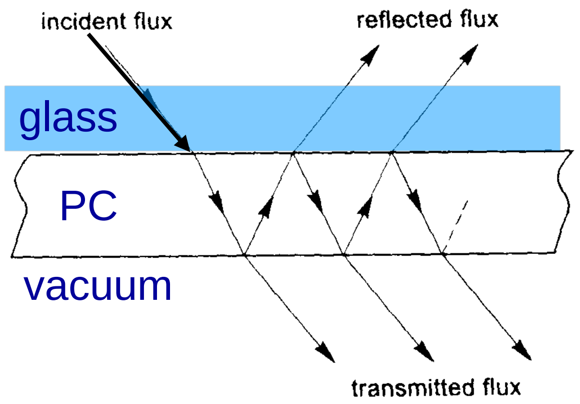
	Human eye:	Photomultiplier:
Spectral sensitivity:	$400<S(\lambda)<750$nm	$110<S(\lambda)<1600$nm
Time resolution:	~50ms	50ps…10ns
Spatial resolution:	~100 lines/mm (2500dpi)	1.25cm…50cm (new: 2mm)
Intensity range:	*O*($10^{16}\gamma/\text{mm}^2$s) (daylight) single photon sensitivity after adaptation	1γ … ~$10^8\gamma/\text{mm}^2$s (~1mA anode current for 1'' tube)
Life time:	*O*(10^5C/mm^2 =70yrs)	*O*(10C) for semi-transparent cathode

Photoemission

- 2-step process:
  - photo ionisation
  - escape of electron into vacuum
- Multiple reflection / interference:
  - due to high refractive index
  - bialkali: n(λ = 442 nm) = 2.7
- QE difficult to measure:
  - often only an effective detection efficiency determined, including:
    - internal reflection from a metallic surface
    - collection of the photoelectrons
    - electronic theshold…
- Photon Detection Efficiency:
  - PDE = ε_{geom} x QE x $\varepsilon_{photoel.\ detection}$
  - for comparison of detector systems

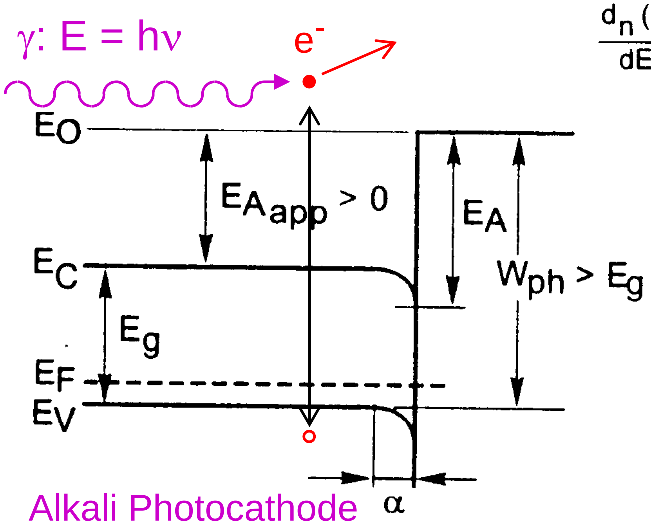




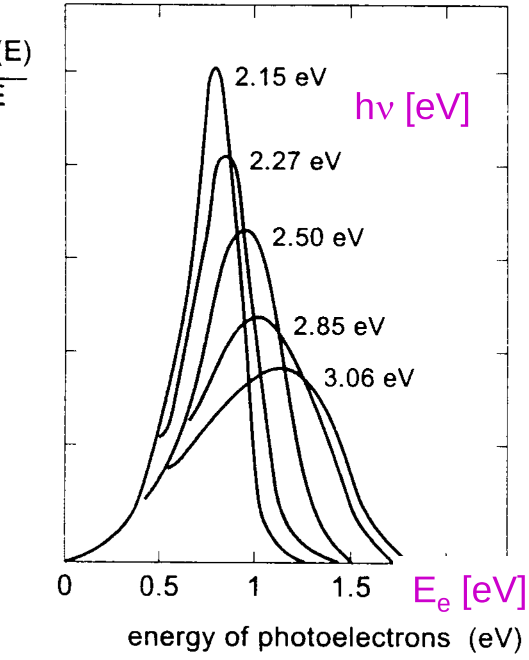


Spectral Response

- Photo cathode:
  - Alkali CsI, Sb-Cs
  - Bialkali Sb-K-Cs
  - Semiconductor Ga-As (negative E_A possible!)
- Band model:
  - E_A = electron affinity
  - W_{ph} = work function



- Photo electric effect:
  - $h\nu > E_g + E_A + dE/dx$
  - $E_e = h\nu - W - dE/dx$



- Spectral response:
  - Quantum efficiency:

$$QE(\lambda) = \frac{N_{p.e.}}{N_\lambda} = (1-R)\frac{P_\nu}{\alpha} P_S \left(\frac{1}{1+1/\alpha l}\right)$$

R = reflection coefficient

$\alpha = \gamma$ absorption coefficient

$l = e^-$ mean escape length

P_ν = excitation probability

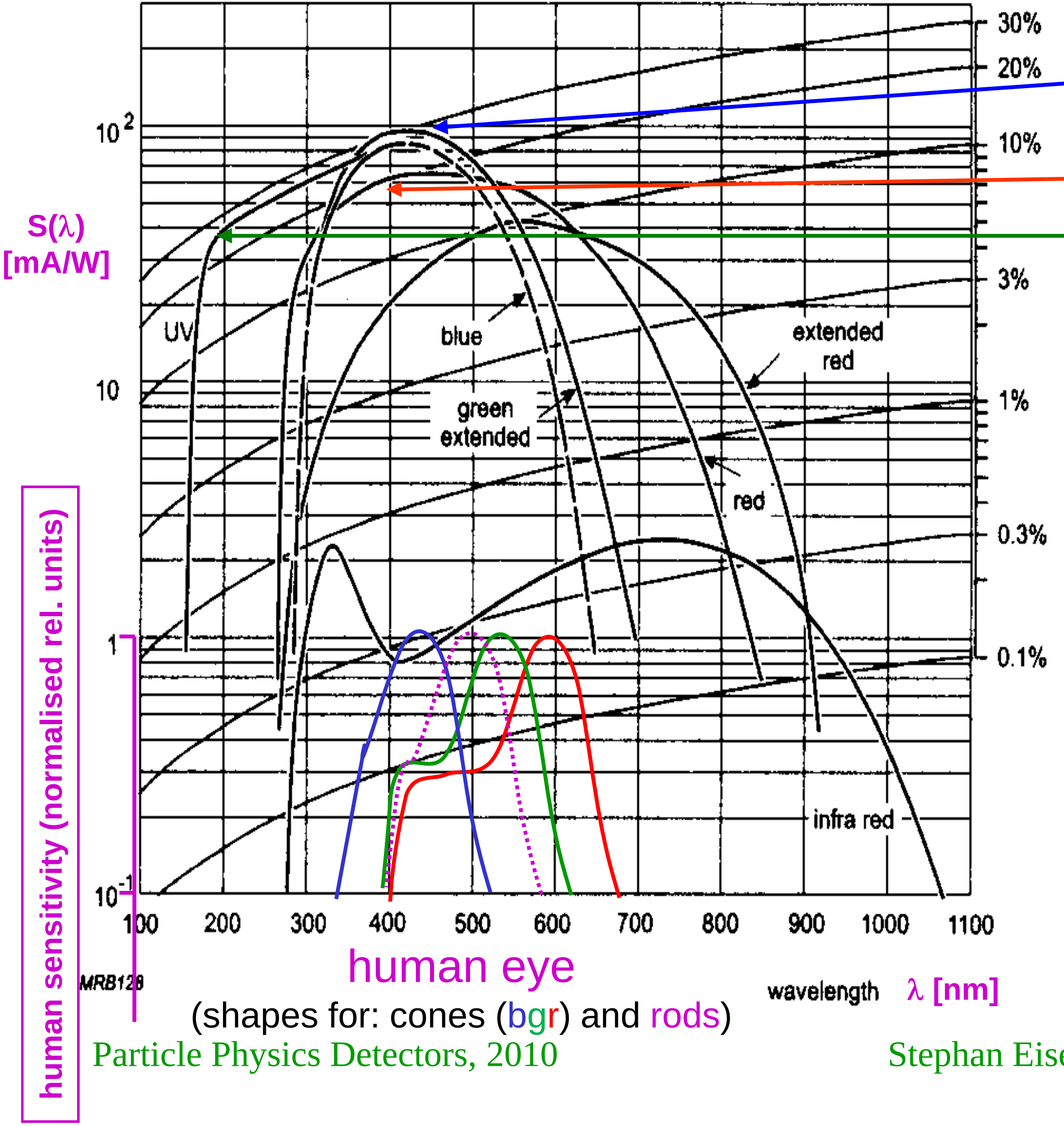
P_S = surface transition probability

- Cathode sensitivity:

$$S(\lambda) = \frac{I_C}{P(\lambda)} = \frac{\lambda\,[\mathrm{nm}]\,\mathrm{QE}(\lambda)}{1240}[\mathrm{A/W}]$$

Alkali Photocathodes

(Philips Photonic) semitransparent photocathodes



human eye

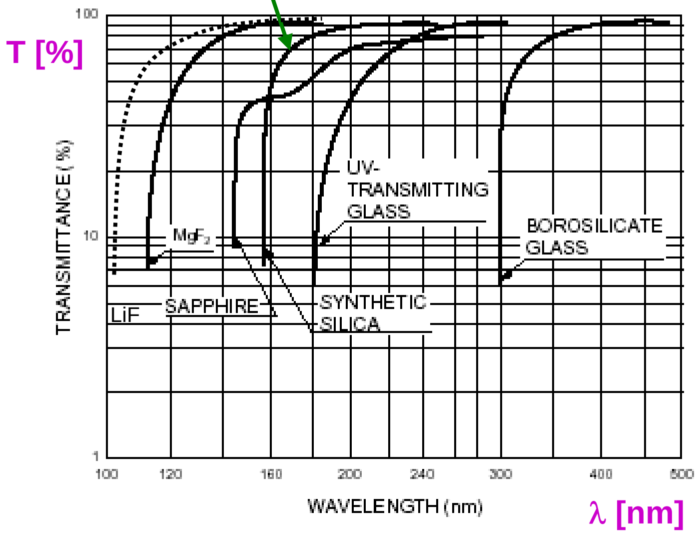
(shapes for: cones (bgr) and rods)

Bialkali : SbK_2Cs, SbRbCs

Multialkali : $SbNa_2KCs$

Solar blind : CsTe

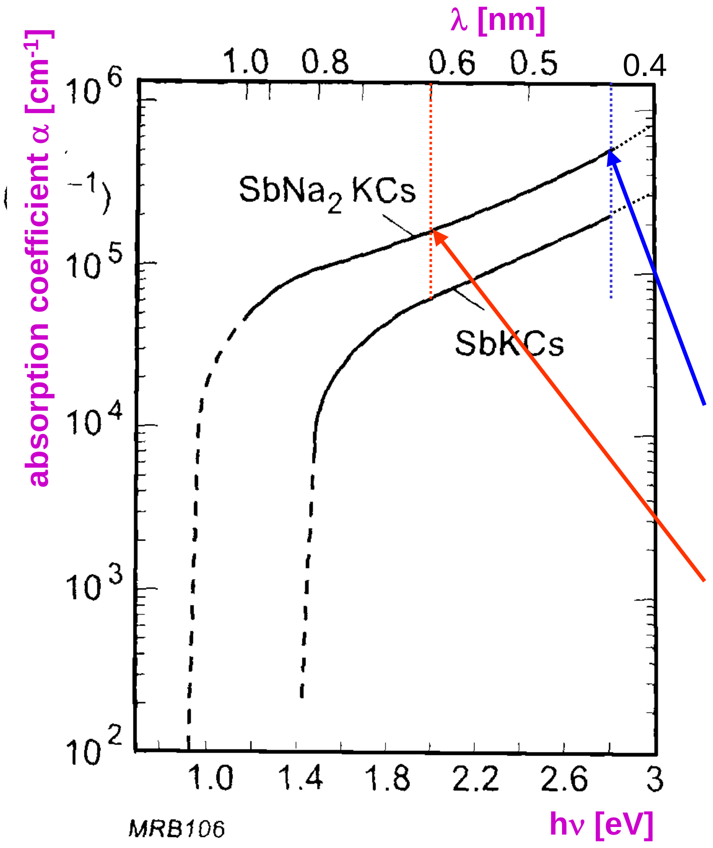
(cut by quartz window)



transmittance of window materials

Photocathode Thickness

Blue light is stronger absorbed than red light!



$\lambda_A = 1/\alpha$

$\alpha \approx 4 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 25$ nm

$\alpha \approx 1.5 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 60$ nm

- Semi-transparent cathodes:
  - best compromise for the thickness of the PC:
  - ↗ photon absorption length $\lambda_A(E_{ph})$
  - ↘ electron escape length $\lambda_E(E_e)$

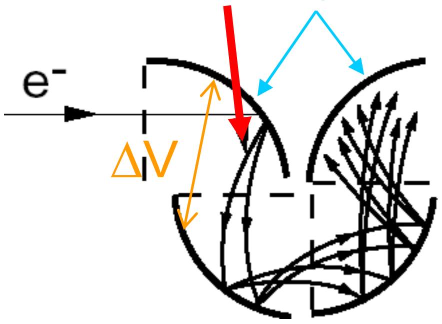
- Q.E. of thick cathode:
  - red response ↗
  - blue response ↘
- Q.E. of thin cathode:
  - blue response ↗
  - red response ↘

Secondary Emission

- Alloy of alkali or earth-alkali and noble metal
- Alkaline metal oxidises → insulating coating
  - large gain
  - stability for large currents
  - low thermal noise

$$\text{Gain } \delta = a(\Delta V)^k \quad \text{with } k = 0.7 \ldots 0.8$$

$$I = aT^2 \exp\left(\frac{-e\Phi}{kT}\right)$$



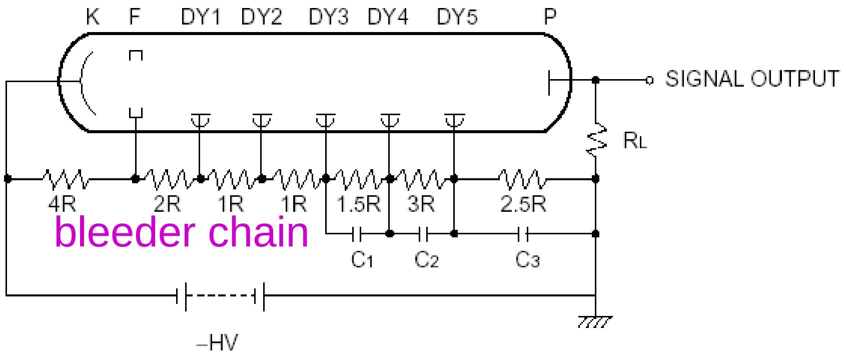
electron multiplication

- Statistical process: Poisson distribution
  - spread (RMS)
  - largest at 1st and 2nd dynode

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

$$\frac{\sigma_n}{\bar{n}} = \frac{\sqrt{\bar{n}}}{\bar{n}} = \frac{1}{\sqrt{\bar{n}}}$$

- Typically: 10 … 14 dynode stages
- Linearity limits:
  - pulse: space charge
  - DC: photo current << bleeder current

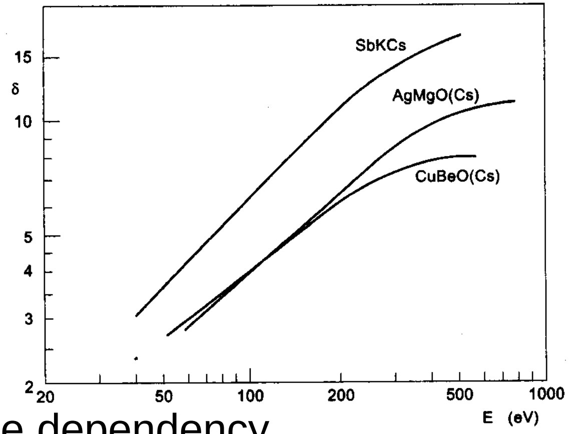


scheme of external circuit for dynode potentials

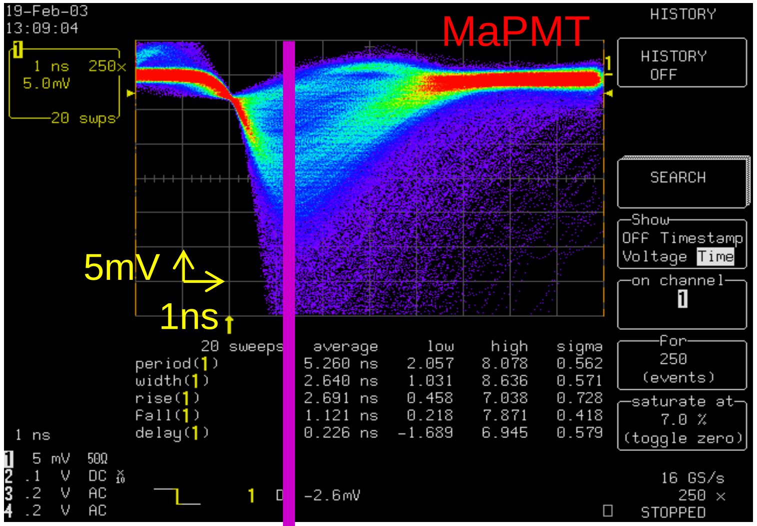
PMT Characteristics

- Fluctuations: (Poisson)
  - photo electron emission
  - secondary electrons
- Saturation: (bleeder chain)
  - space charge
  - large photon current
- Non-linearity: (PC)
  - at high gains
- Stability
  - drift, shift, temperature dependency
  - fatigue effects
  - ➔ Monitoring
- Sensitive to magnetic fields
  - Earth: 30-60 μT
  - ➔ requires μ-metal shielding

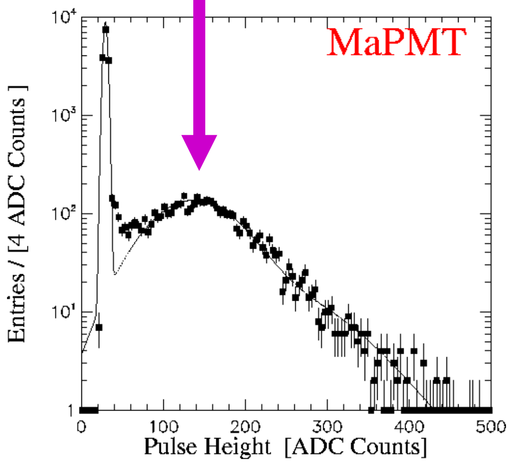
linearity on photo cathodes



- single photon events to oscilloscope (50Ω)



```
         20 sweeps   average      low     high    sigma
period(1)          5.260 ns    2.057    8.078    0.562
width(1)           2.640 ns    1.031    8.636    0.571
rise(1)            2.691 ns    0.458    7.038    0.728
Fall(1)            1.121 ns    0.218    7.871    0.418
delay(1)           0.226 ns   -1.689    6.945    0.579
```

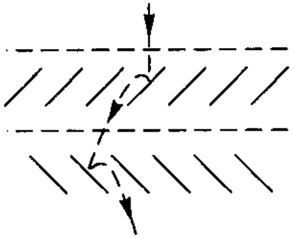


charge integration → pulse height spectrum

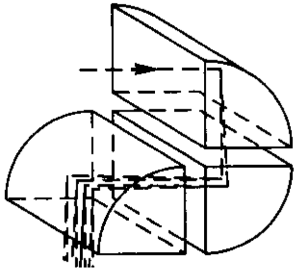
Classic Dynodes

- uniformity:
- photoelectron collection efficiency:

- simple design
- good for large PC ∅



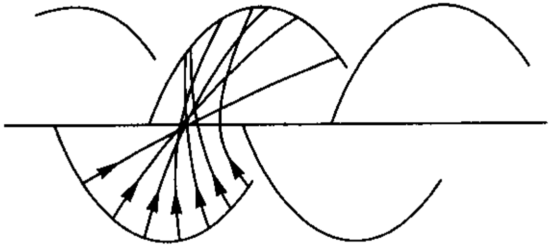
venetian blind ☺ ☹



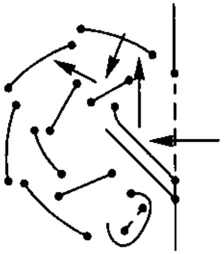
box and grid ☺ ☺☺

- best photoelectron collection efficiency
- good uniformity

- excellent linearity
- good time resolution
- fast time response



linear focusing ☹ ☺



circular cage ☹ ☺

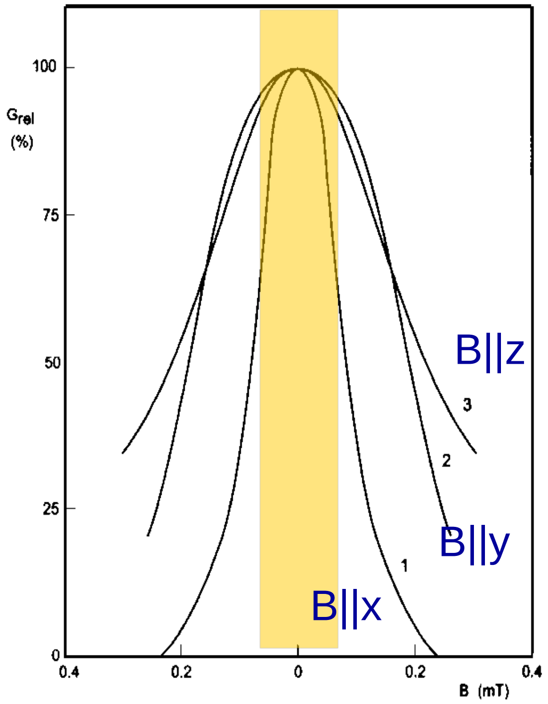
- compact
- fast time response

sensitive to Earth B-field (30-60μT)!

no spatial resolution

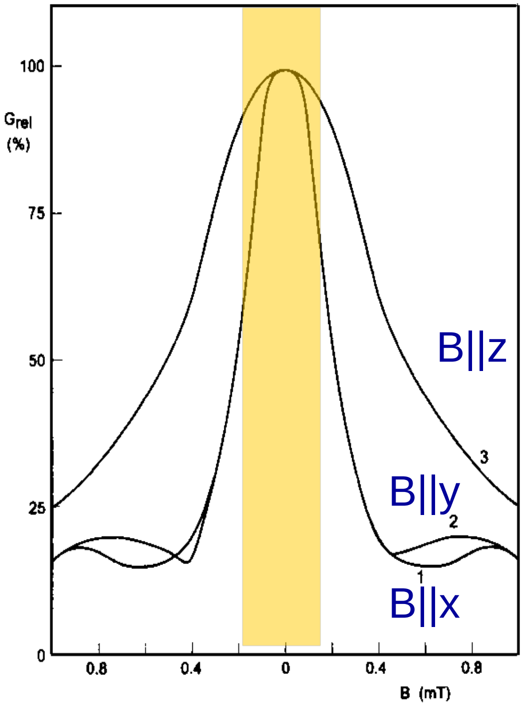
Sensitivity to Magnetic Fields

- linear focusing

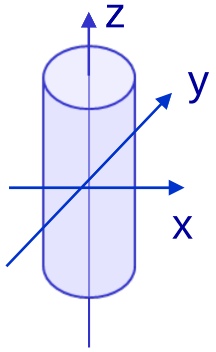


±50 μT
± 0.5 Gauss

- venetian blind



± 200 μT
2 Gauss



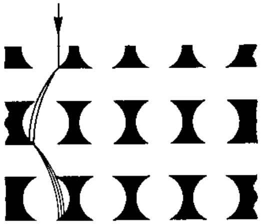
- Earth field: 30-60 μT

➔ requires μ-metal shielding

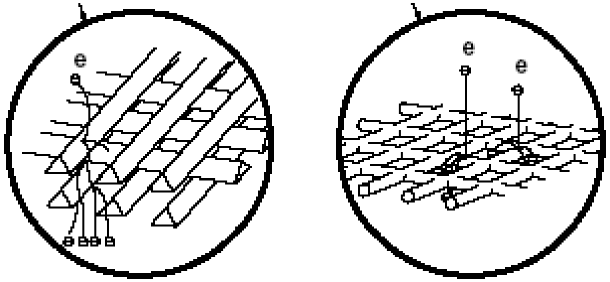
Modern Dynodes

- B-field immunity   up to 1.2T B-field
- spatial resolution   via segmented anode

- good uniformity
- poor e^- collection efficiency!

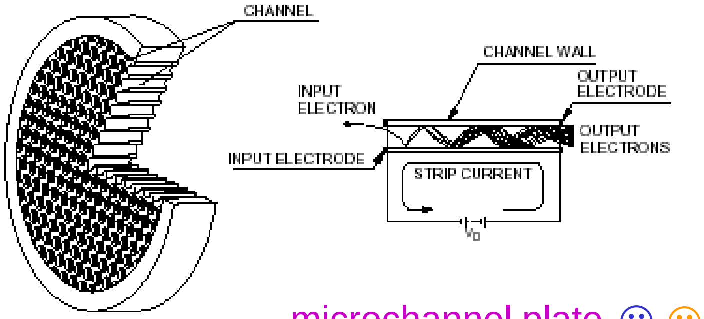


foil ☺ ☹



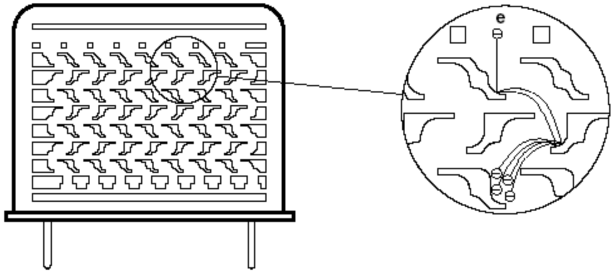
proximity mesh ☺ ☹

- excellent linearity



microchannel plate ☺ ☹

- excellent time resolution:
  transit time spread: 50ps

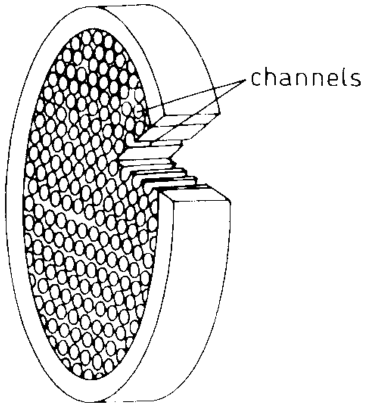


metal channel ☺ ☺

- good e^- collection efficiency
- excellent time characteristics
- stable gain
- …up to 20mT
- low cross-talk pixels

Micro Channel Plates

- Lead glass plate:
  - 10^4-10^7 tubes
  - diameter: 10-100µm
  - semi-conductor coating (high Ω)
  - HV to metallic electrodes on faces
  - electron multiplication in tubes
  - gain: 10^3-10^4
  - cascading possible
- Advantages:
  - very fast: transient time spread 50 ps
  - less sensitive to B-field
  - spatial resolution: 2-dim readout possible
- Disadvantages:
  - rate capability limit: ~ µA/cm^2
  - life time limit: ~ 0.5 C/cm^2
  - low active area fraction



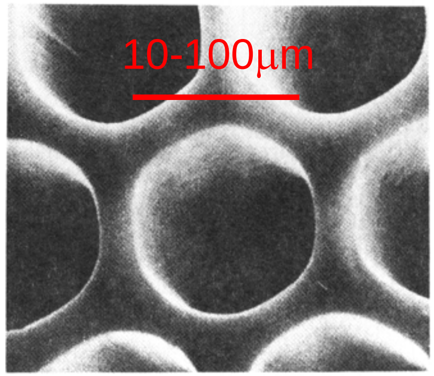
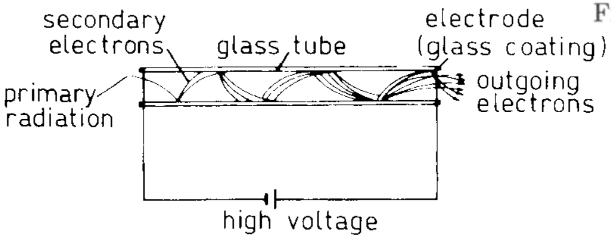
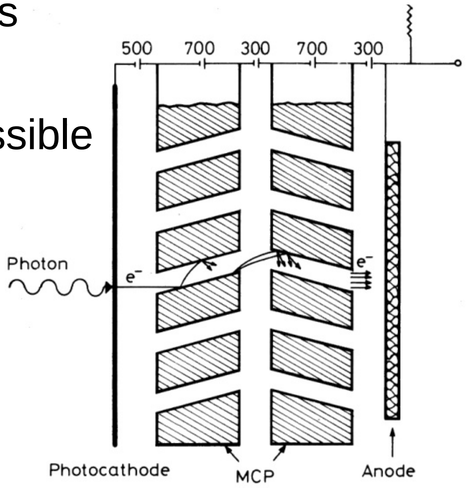
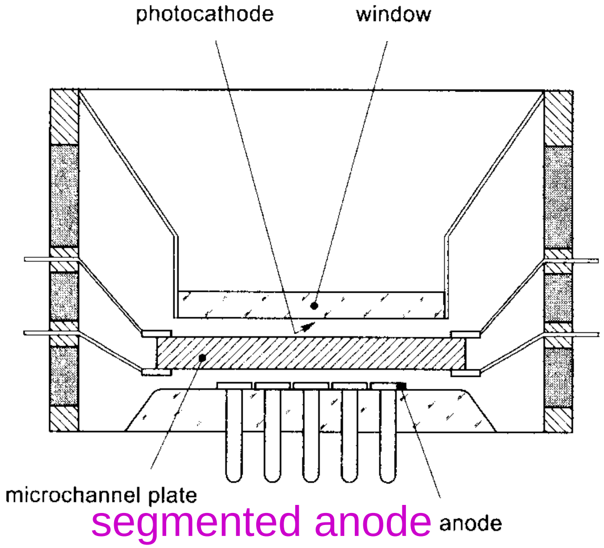


Fig. 5.6. Microphotograph of microchannels [384].





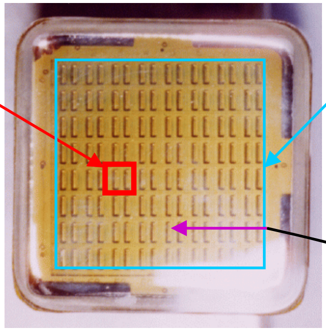
Chevron configuration



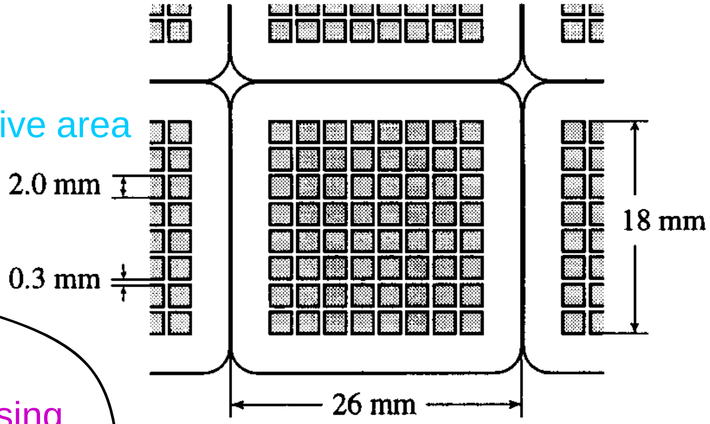
segmented anode

Multi-anode Photo Multiplier Tubes

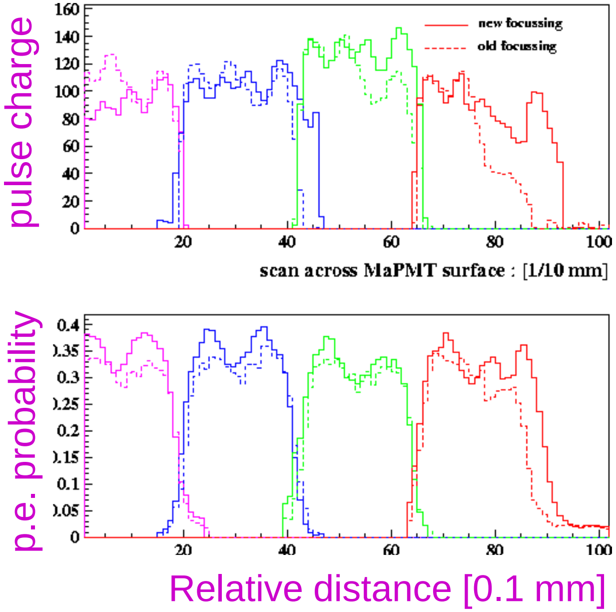
- Position sensitive PMT:
  - 8x8 metal channel dynode chains in one vacuum envelope (26x26 mm^2)
  - segmented anode: 2x2 mm^2
  - active area fraction: 48%
- UV glass window
- Bialkali photo cathode:
  - QE = 22…25% at λ = 380 nm
- Gain:
  - G = 3·10^5 at 800 V
- Uniformity, Crosstalk:
  - much improved wrt. first attempts
- Applications:
  - medical imaging
  - HERA-B, COMPASS: Ring Imaging Cherenkov counters

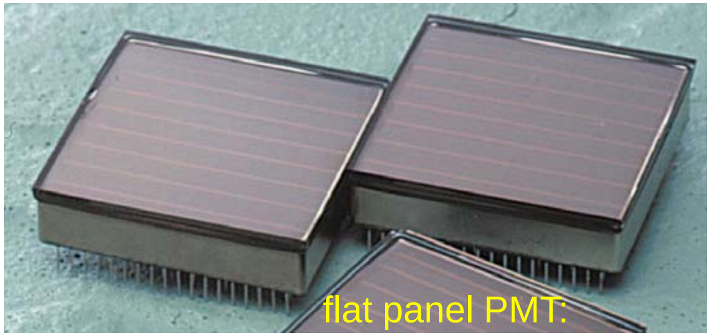


MaPMT window & electron focusing



segmented anode



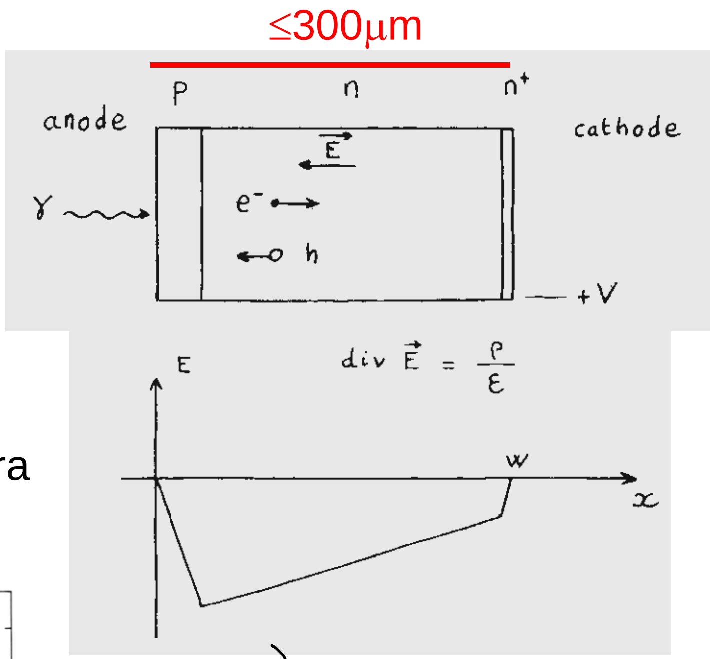


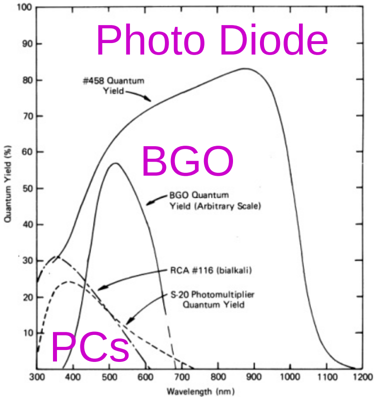
flat panel PMT:
next generation MaPMT

Photo Diodes & Triodes

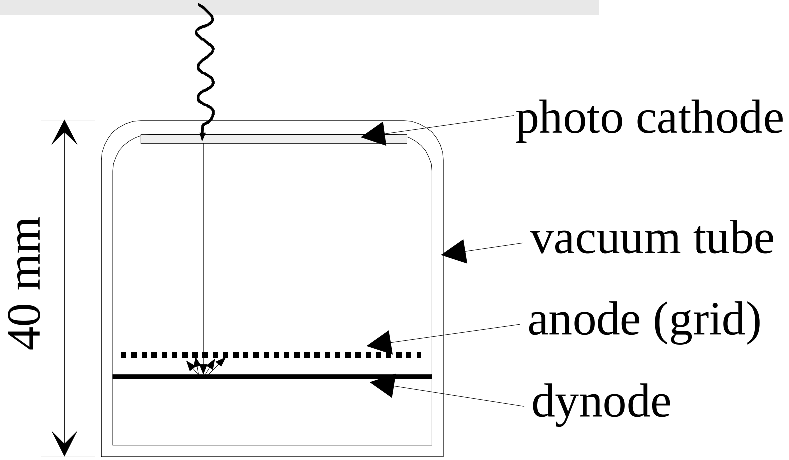
(sketches from J.P. Pansart, NIM A 387 (1997), 186)

- **Photo Diodes:**
  - P(I)N type
  - gain: G = 1 (hν = 3-4eV, band gap = 1-2eV)
  - high QE: 60-80% at λ = 500-900 nm
    → better E resolution than PMT
  - insensitive to B-fields, compact, low power, …
  - better match to CsI, BGO, $PbWO_4$ emission spectra
  - needs low noise: small area, cooling, large signal
  - example:
    - BaBar/CLEO: CsI Calorimeter



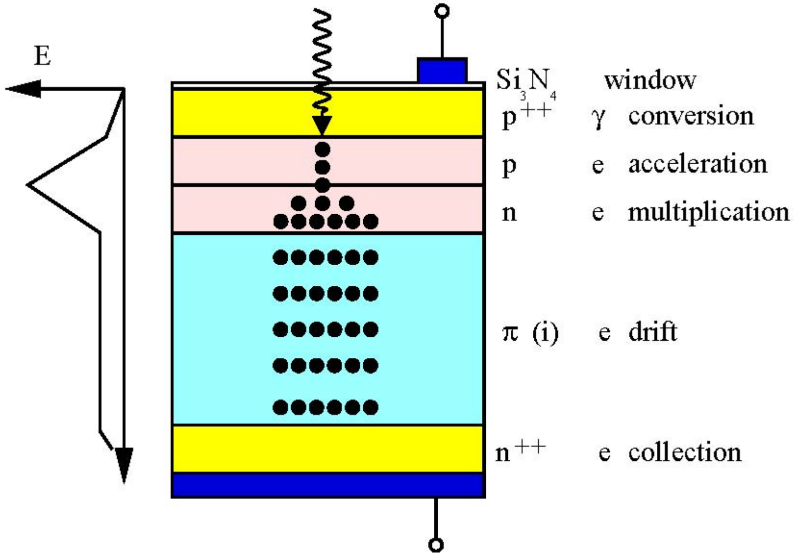


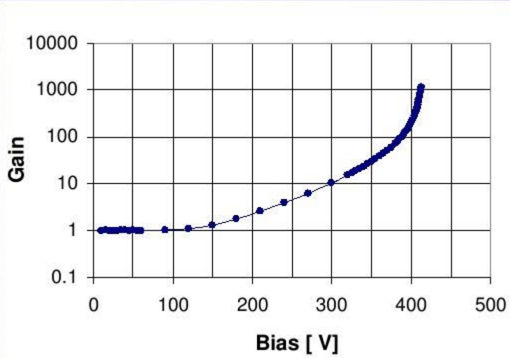
- **Photo Triodes:**
  - single stage PMT
  - gain: G ≈ 10
  - OK in axial B-fields up to 1T
  - examples:
    - DELPHI, OPAL: lead glass endcap calorimeter
    - L3 lead/scintillating fibre calorimeter

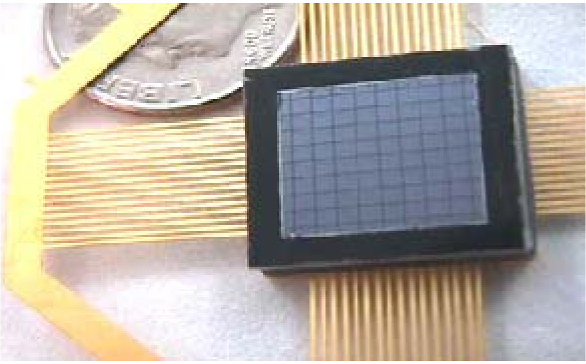


Avalanche Photo Diodes

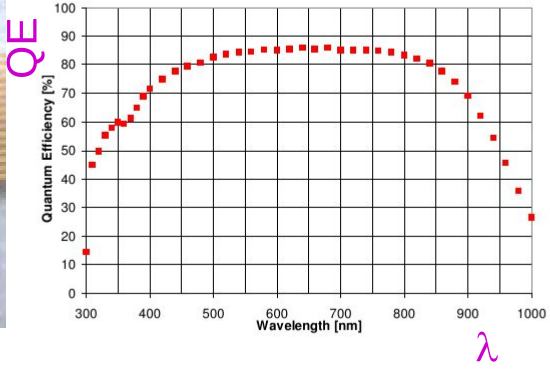
- Avalanche Photo Diodes (APD)
  - high reverse bias voltage
  - avalanche multiplication in high field region
  - gain: G ≈ 100 (even up to 1000)

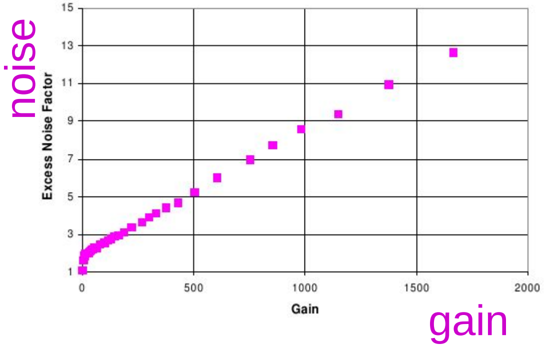






64-pixel APD array:
pixel size 0.9x0.9mm^2

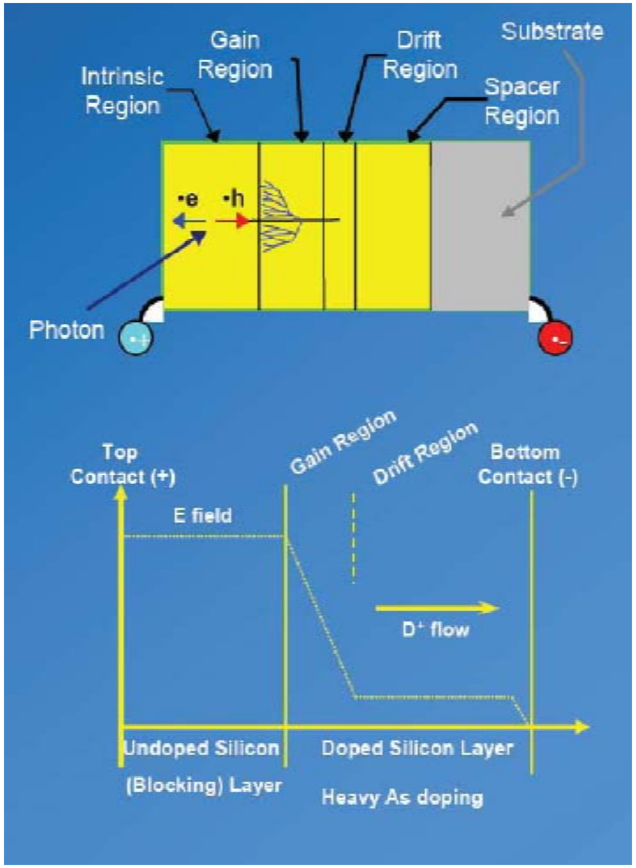


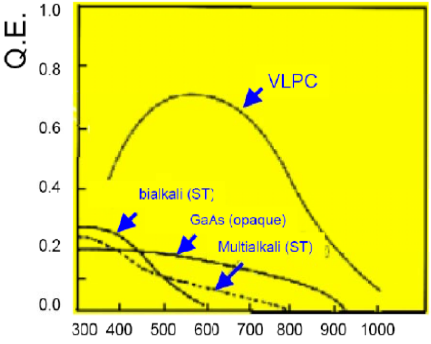


- needs very stable high voltage
- issues with uniformity (neutron transformation doping → good results)
- direct signal from ionising radiation → unwanted background
- noise scales with gain

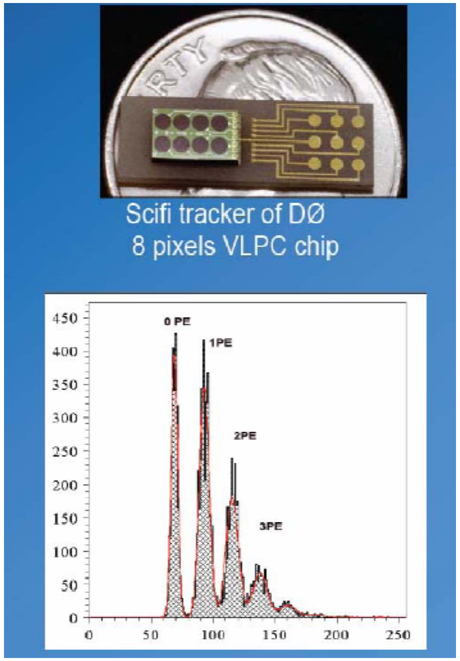
Visible Light Photon Counter

- VLPC layout:

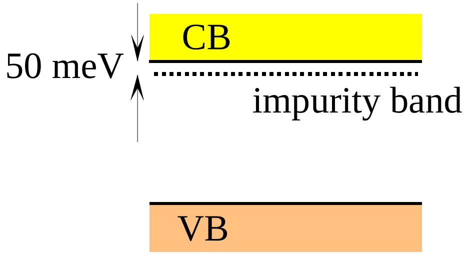




- Advantages:
  - low bias voltage: ~ 7V
  - sensitive to IR (@ T_{op}=6-9K)
  - Quantum efficiency: 70% at 520 nm
  - gain: G ~ 50000
- Disadvantages:
  - dark count rate: 20kHz/mm^2
- Example:
  - Fermilab E835 (D0): fibre tracker



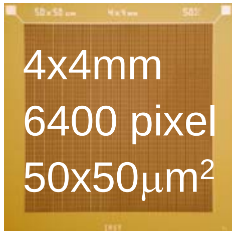
- Gain region:

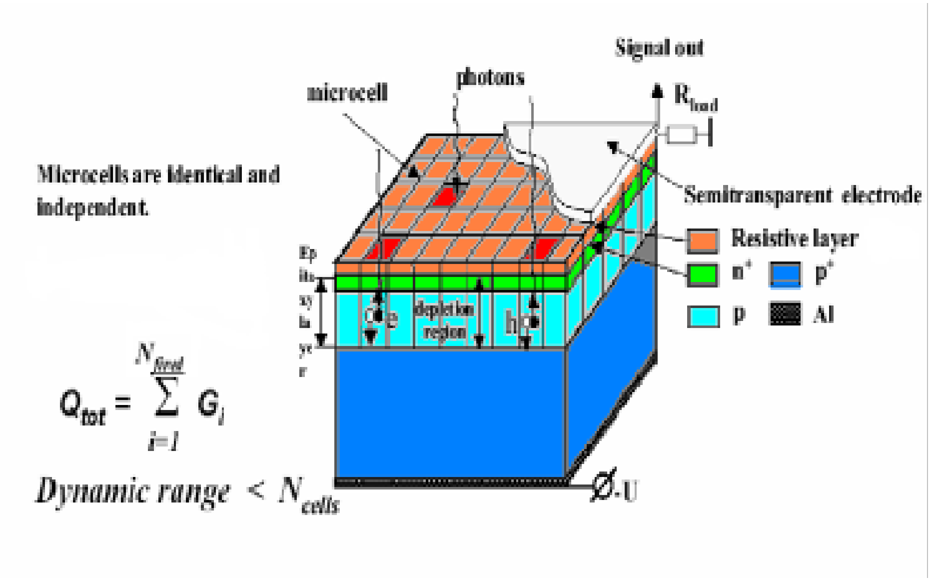


  - Si-As impurity band
  - drifting hole ionises donor atom → free e$^-$
- Avalanche
  - multiplication in highly doped gain region

Geiger-mode APDs (aka: SiPM, PixelPM)

- Main features:
  - Sensitive size: chips of 1…16mm^2 chip
  - up to 6400 pixel of size 50x50μm^2
  - Binary read-out for each pixel
  - Gain: 2×10^5
  - U_{bias} ~ 50V
  - Recovery time: ~ 100ns/pixel
  - Pixel-to-pixel signal uniformity quite good


4x4mm
6400 pixel
50x50μm^2



Microcells are identical and independent.

$$Q_{tot} = \sum_{i=1}^{N_{fired}} G_i$$

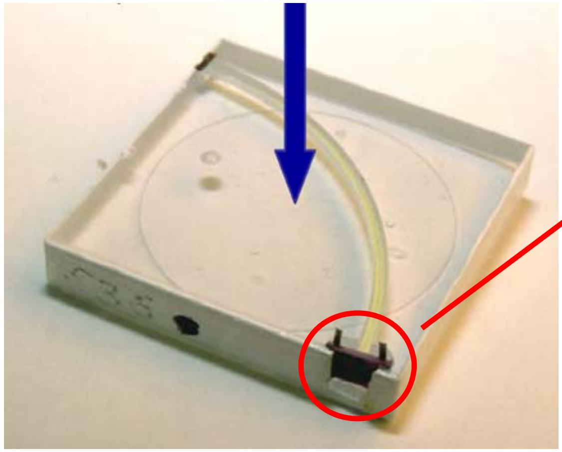
Dynamic range $< N_{cells}$

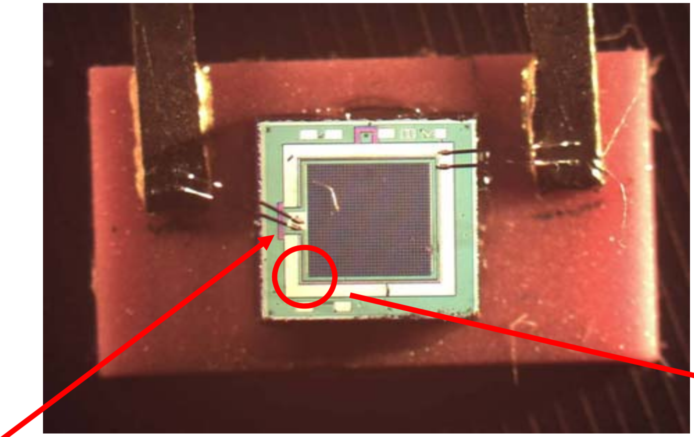
- Advantages:
  - PED: now 30-50%, 60-80% possible
  - low operation voltage: typical 30-100V
  - very fast signal rise-time
  - very compact, flexible geometry
  - very robust (survive daylight when biased!)
  - insensitive to magnetic fields
  - eventually low cost (not now…)

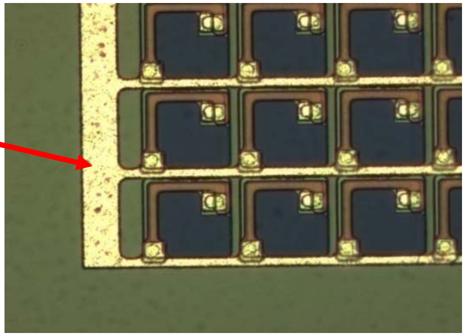
- Disadvantages:
  - limited area
  - high dark count rate (0.1-1MHz/mm^2)
  - optical cross-talk
  - temperature drift of gain/PDE
  - long signal decay time/pixel (recovery…)
  - limitation to dynamic range
  - still proto-types

Scintillating Tiles and GAPDs (SiPMs)

- Silicon “Photo Multipliers”:
  - Geiger-mode APD, 1mm^2
  - multi-pixel
  - gain: G= 10^6
  - bias: V ~ 50V

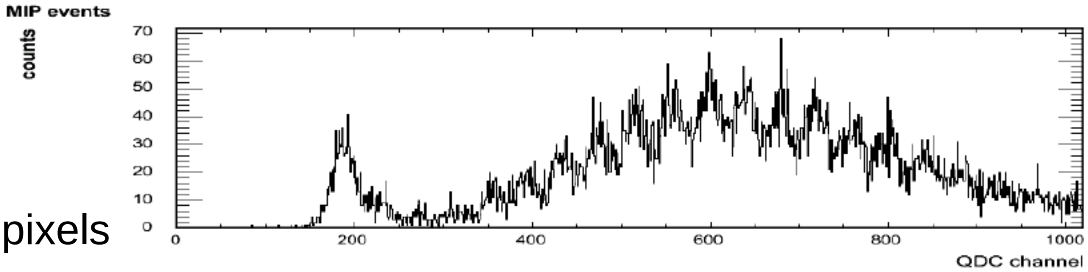






- Analog readout:
  - charge of pixels summed
  - allows autocalibration by counting pixel peaks
  - saturation (2+ hits in one pixel) → non-linearity

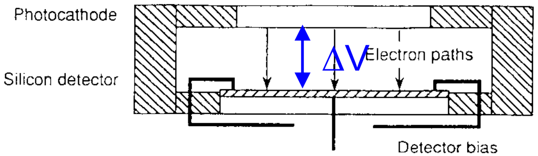
- Example: Calice pre-prototype
  - 3x3cm2 scintillator tiles
  - wavelength shifting fibre
  - directly couples to SiPM with 1156 pixels



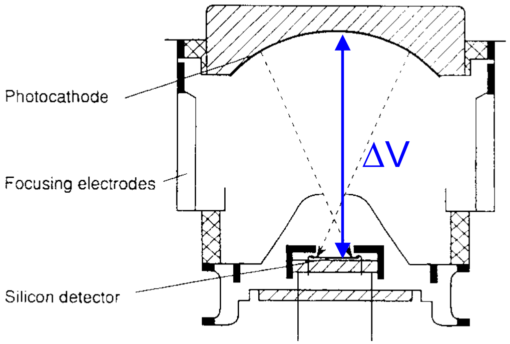
Hybrid Photon Diodes

- Hybrid technology:
  - photo cathode
  - p.e. acceleration
  - silicon detector

proximity focusing



cross focusing



- Gain: $G = \frac{e\Delta V}{W_{Si}} = \frac{20\text{ keV}}{3.6\text{ eV}} \approx 5000$

$$\boxed{\Delta V = 20\text{kV}}$$

- Resolution:
  - single photons resolved
- Active area fraction:
  - too small yet
- Bump bonding:
  - Si pixel arrays inside vacuum
  - technical challange

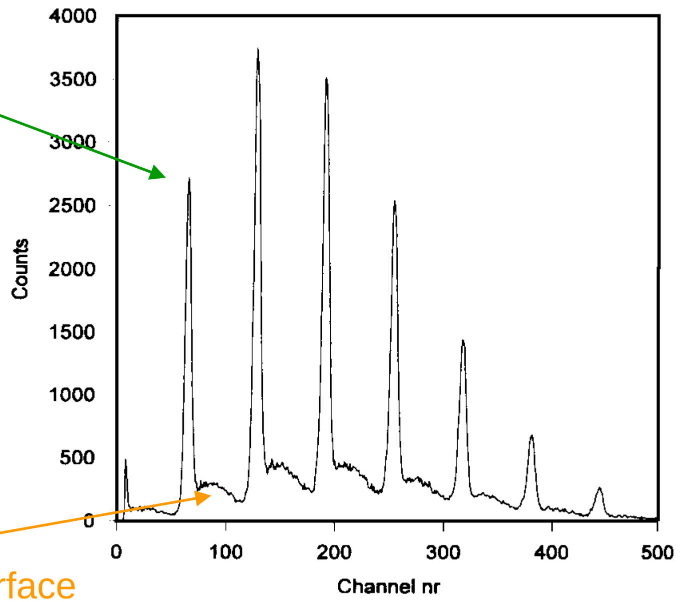
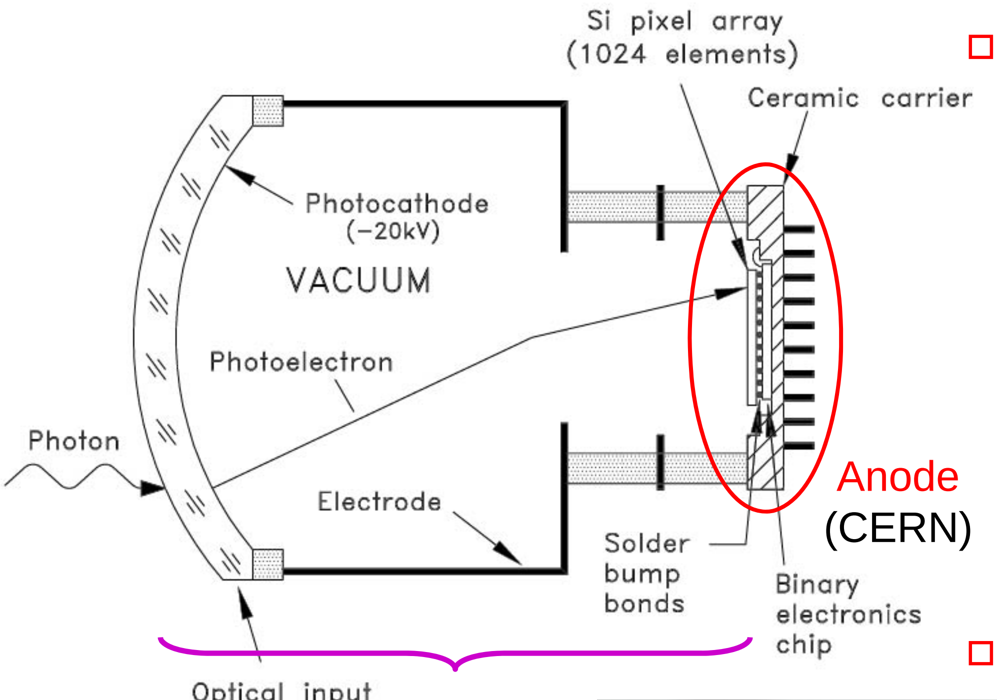


photo electron response

Background from electron backscattering from silicon surface

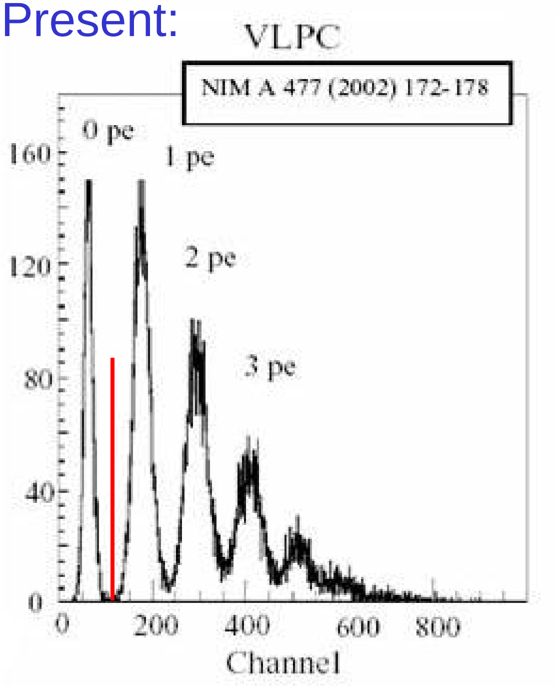
Pixel HPD

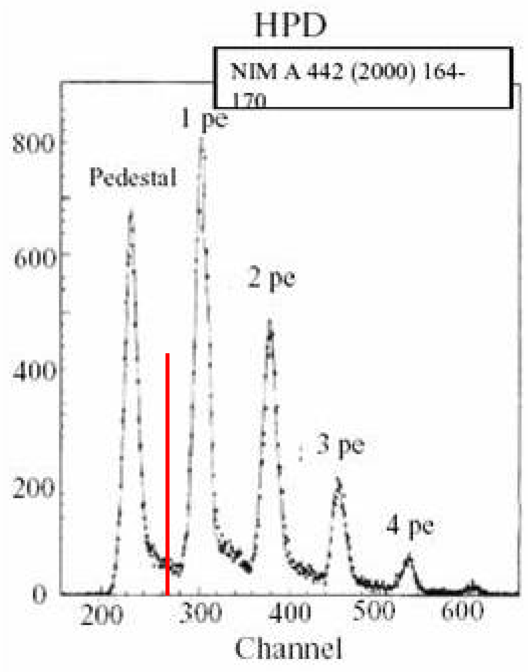


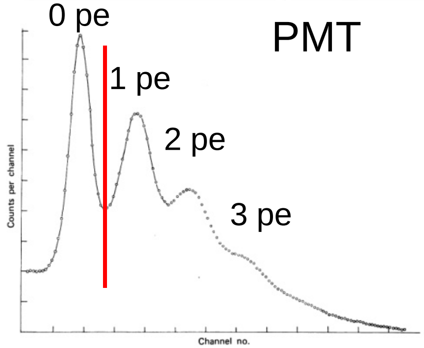
- Photon detector:
  - 7mm thick quartz window
  - S20 photocathode
    - typical ∫ QE dE > 0.7eV
  - Cross-focussing optics (tetrode structure):
    - de-magnification by ~5
    - 50 μm point-spread
    - active diameter 75mm
  - 20 kV operating voltage (~5000 e^- [eq. Si])
- Anode:
  - 256×32 pixel Si-sensor array
    small pixels → low noise
  - bump-bonded to binary readout chip
  - assembly encapsulated in vacuum tube
  - LHCb readout mode: 8-fold binary OR
    → effective 32×32 pixel array
  - pixel size 500μm×500μm sufficient

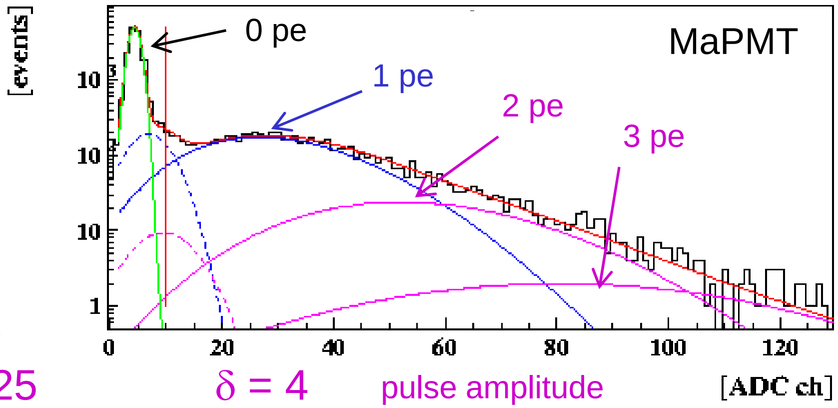
Single Photon Detection Performance

- Present:







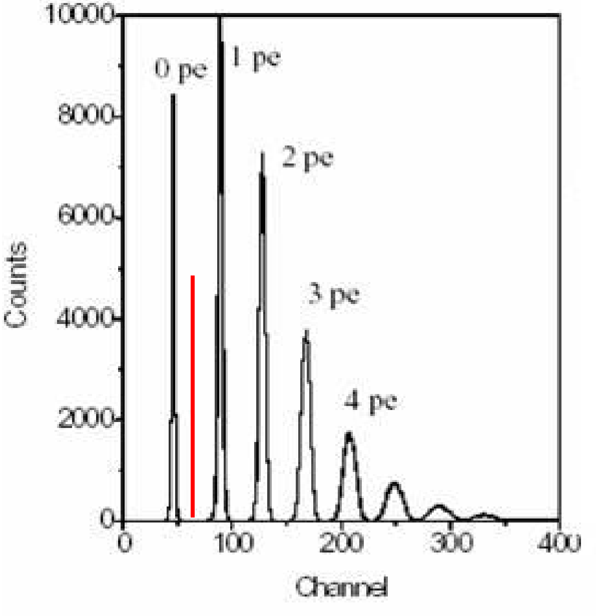


first dynode gain: $\delta = 25$

$\delta = 4$

- Future:

GAPD (SiPM)



nervous?

tense?

tired?