7. Scintillators, Photomultiplier and Time measurements

7.1 Principle of scintillators

7.2 Inorganic scintillators

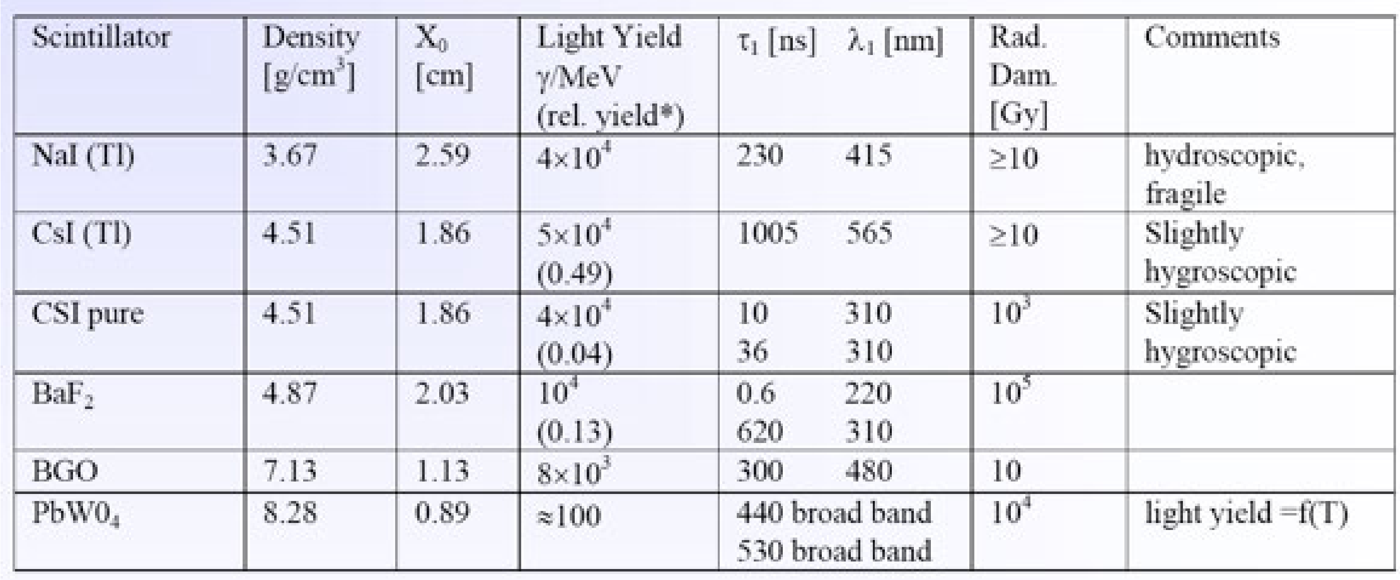
7.3 Organic scintillators

7.4 Photomultiplier

7.5 Applications in detector systems

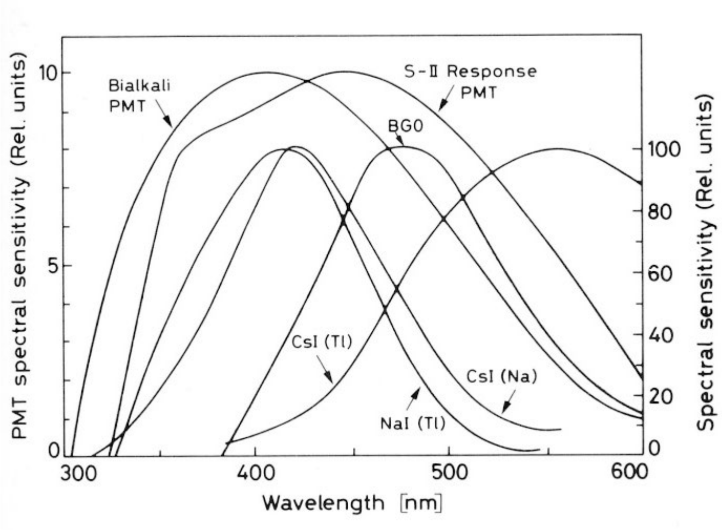
7.6 New devices:
- Avalanche Photo Diodes
- Silicon Photomultiplier

Figures to Chapter 7.2



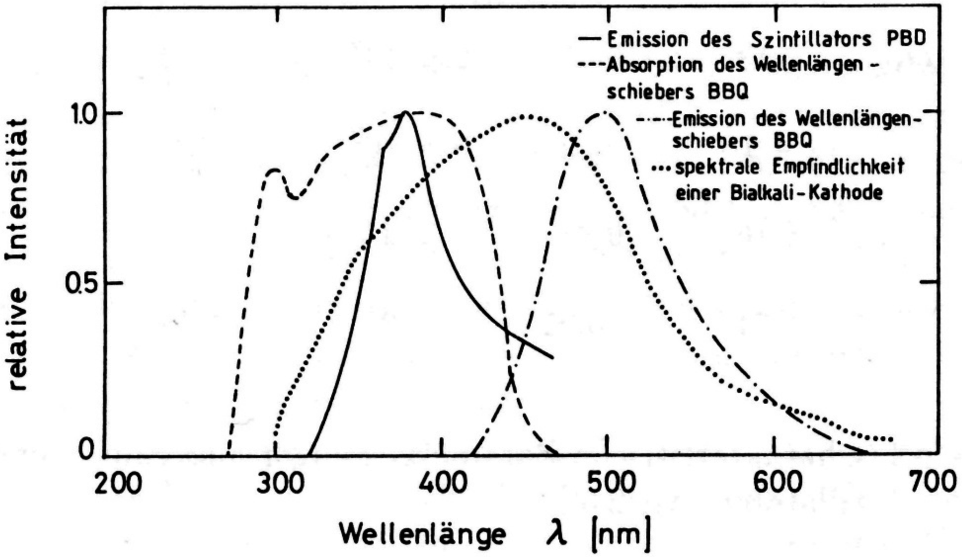
Scintillator	Density [g/cm^3]	X_0 [cm]	Light Yield γ/MeV (rel. yield*)	τ_1 [ns] λ_1 [nm]	Rad. Dam. [Gy]	Comments
NaI (Tl)	3.67	2.59	4×10^4	230 415	≥10	hydroscopic, fragile
CsI (Tl)	4.51	1.86	5×10^4 (0.49)	1005 565	≥10	Slightly hygroscopic
CSI pure	4.51	1.86	4×10^4 (0.04)	10 310 36 310	10^3	Slightly hygroscopic
BaF_2	4.87	2.03	10^4 (0.13)	0.6 220 620 310	10^5	
BGO	7.13	1.13	8×10^3	300 480	10	
$PbW0_4$	8.28	0.89	≈100	440 broad band 530 broad band	10^4	light yield =f(T)

Characteristic parameters of some inorganic scintillators



Light emission spectra for some inorganic scintillator crystals [Ref. W.R. Leo]

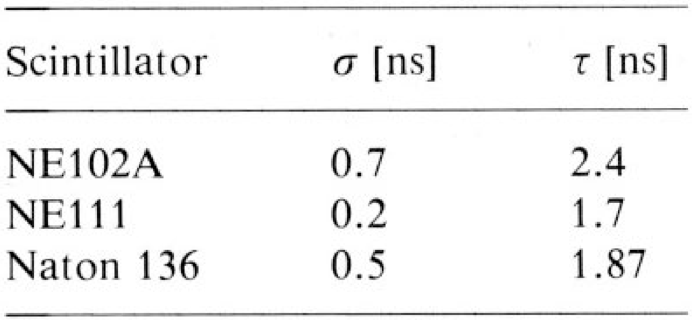
Figures to Chapter 7.3



Fluoreszenzstoffe	$\lambda_{\mathrm{max}}[nm]$ Emission	Abklingzeit $[ns]$	$\frac{\text{Ausbeute}}{\text{Ausbeute } NaJ}$
Naphtalen	348	96	0.12
Anthracen	440	30	0.5
p-Therphenyl	440	5	0.25
PBD	360	1.2	
Wellenlängenschieber			
POPOP	420	1.6	
bis-MSB	420	1.2	

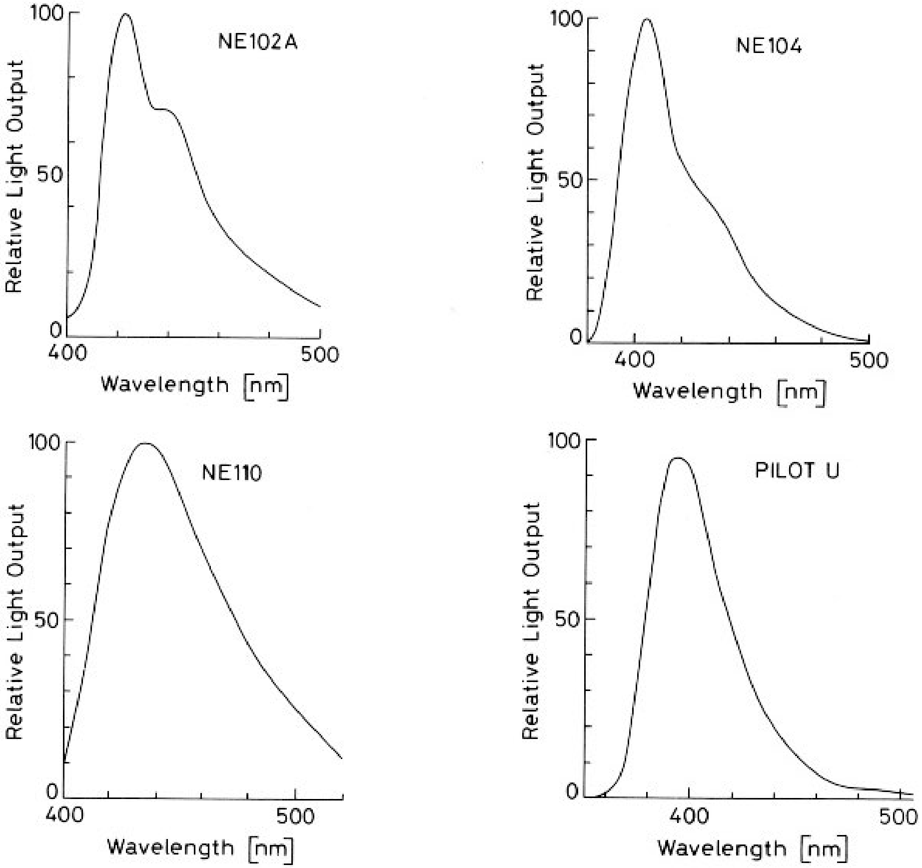
Emission spectra of a primary fluorescence material and a wavelength shifting material in comparison to the spectral sensitivity of the photo-cathode of a common photomultiplier [Ref. C. Grupen]

Important parameters of organic fluorescence materials and wavelength shifting materials. The quoted light yield is normalized to the one of NaJ (sodium iodide). [Ref. C. Grupen]



Scintillator	σ [ns]	τ [ns]
NE102A	0.7	2.4
NE111	0.2	1.7
Naton 136	0.5	1.87

Gaussian standard deviation and exponential decay constant for light pulses of frequently used plastic scintillators.
[Ref. W.R. Leo]



Light emission spectra of several frequently used plastic scintillators of the company *Nuclear Enterprises.*
[Ref. W.R. Leo]

Figures to Chapter 7.4

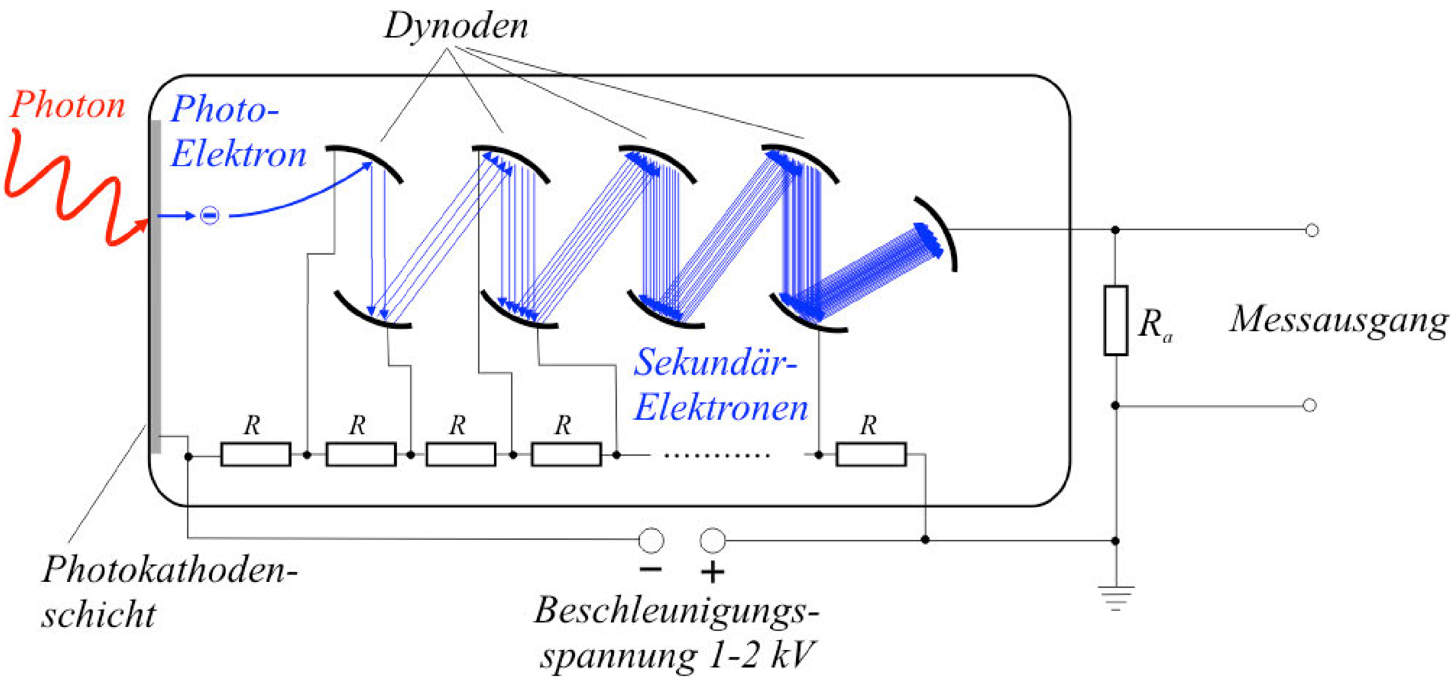
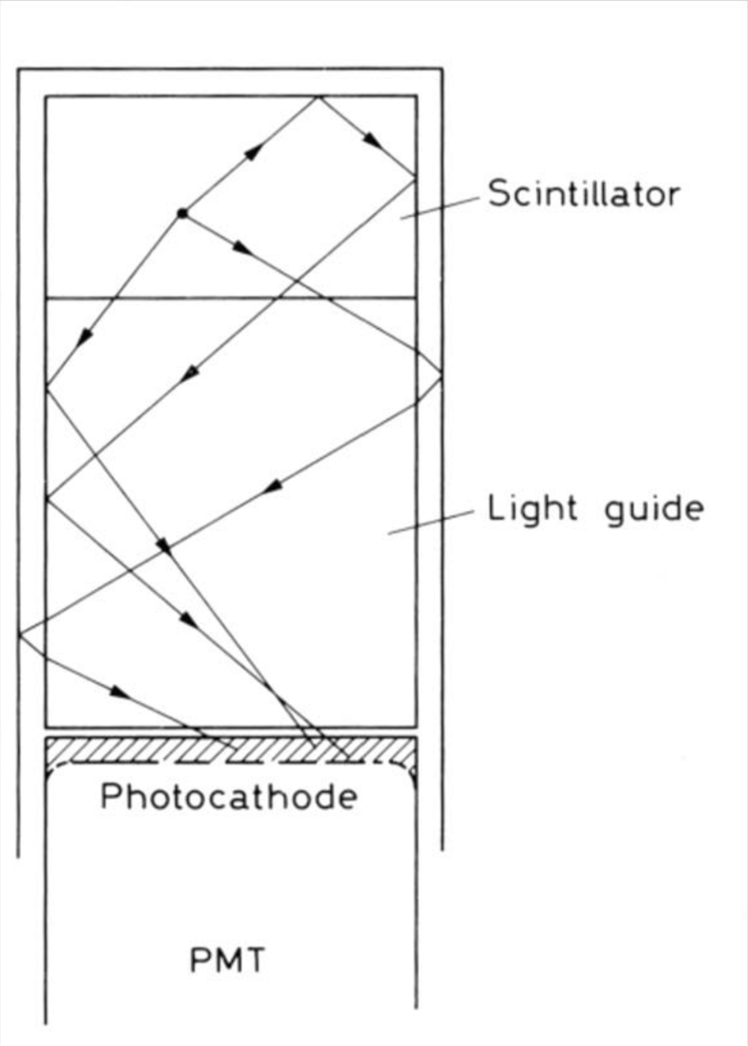


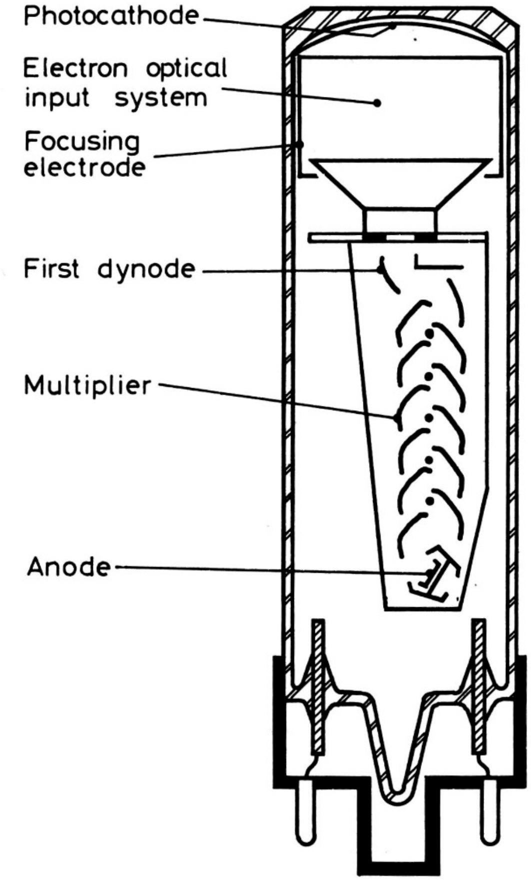
Illustration of the principle layout and of the mode of operation of a photomultiplier


[redacted]

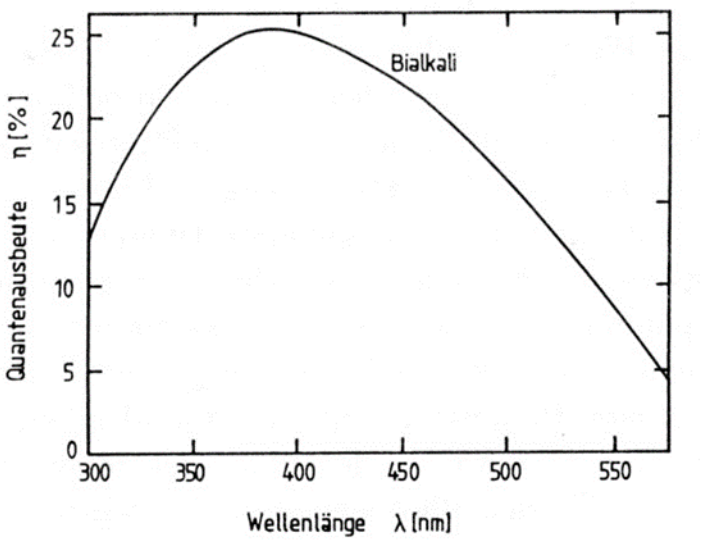
„Standard photomultiplier“ for applications in detector physics

Variety of photomultipliers of the company *Hamamatsu Photonics (Japan)*


Scintillator
Light guide
Photocathode
PMT

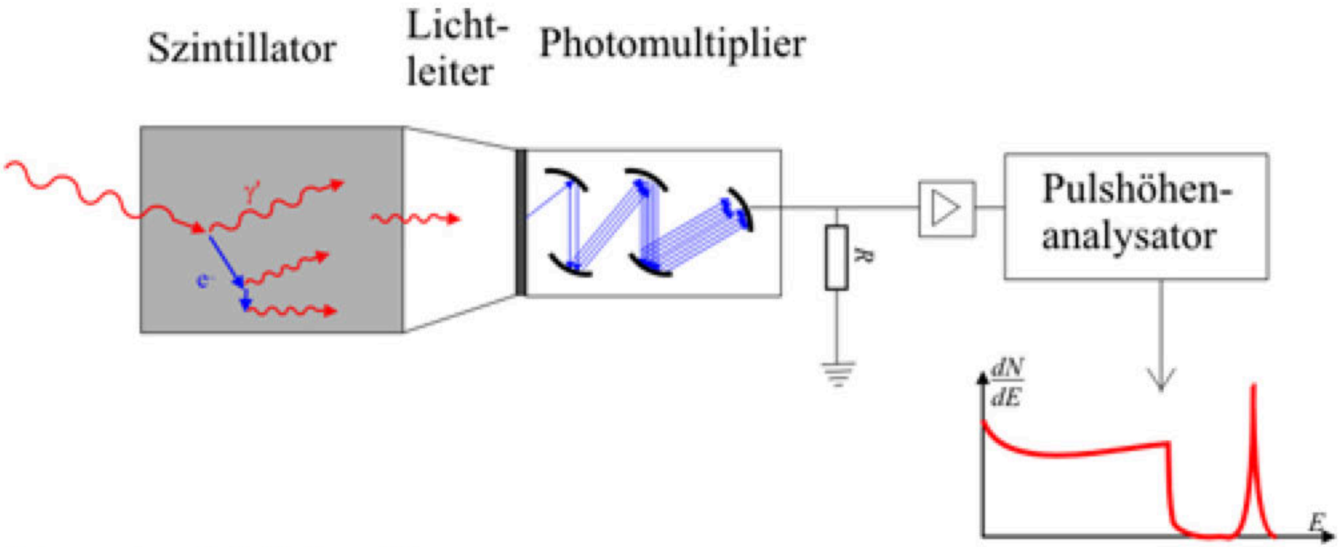


Schematic drawing of the layout of a photomultiplier [Ref. W. R. Leo]



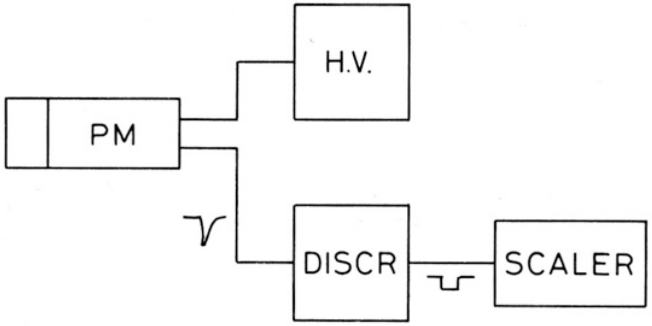
Quantum efficiency of a bi-alkali-cathode as a function of the wavelength [Ref. C. Grupen]

Figures to Chapter 7.5

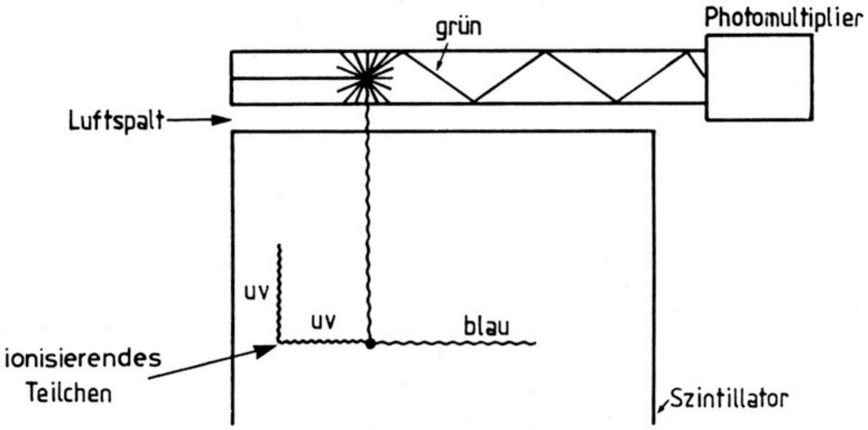


Schema eines Szintillationszählers

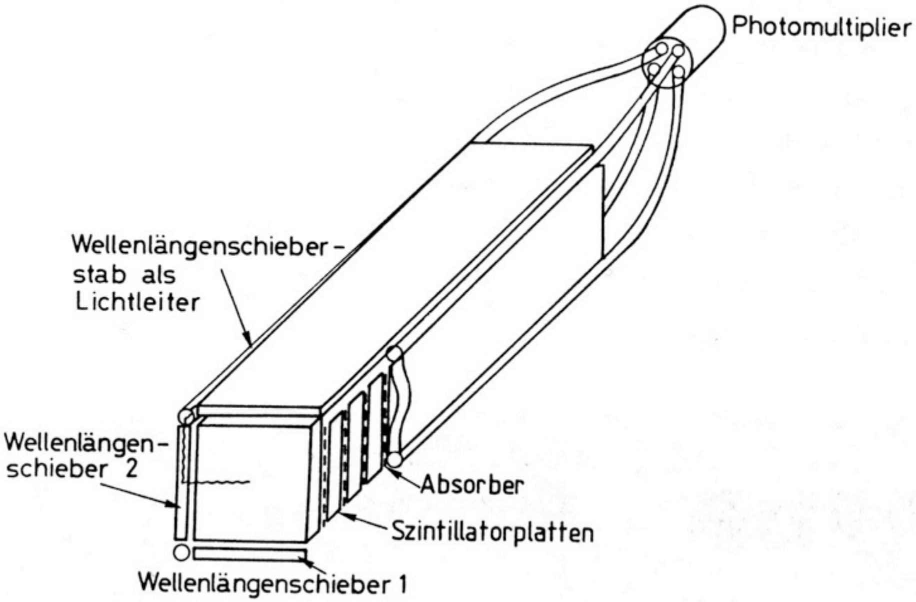
Typical setup for γ-spectroscopy using a scintillator and photomultiplier

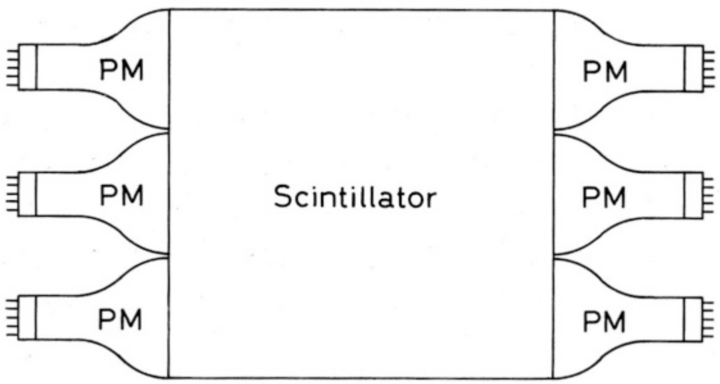


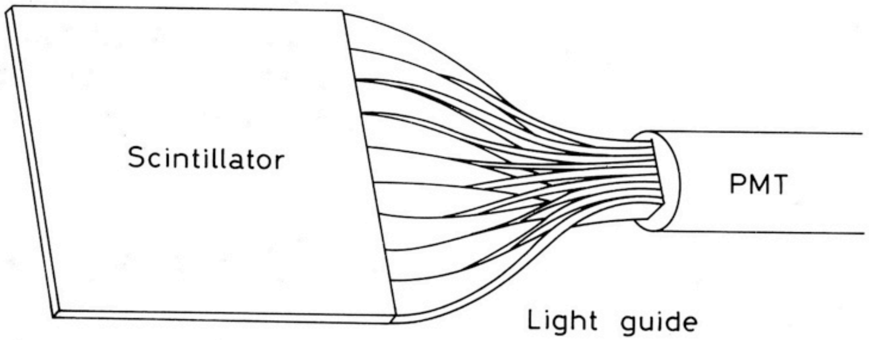
Setup of a counter to register particles using a scintillator

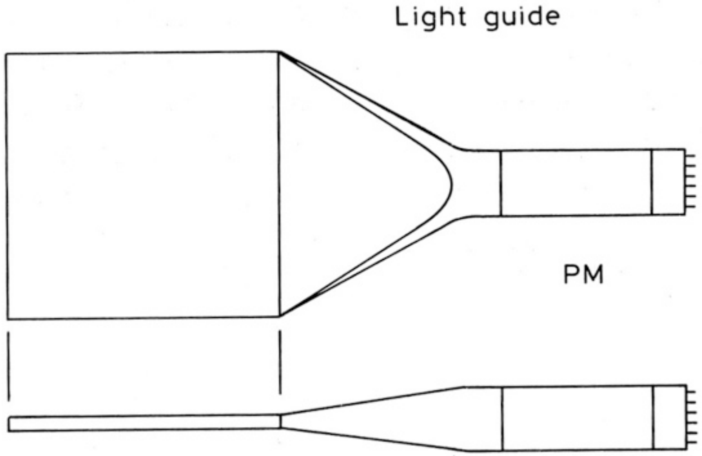


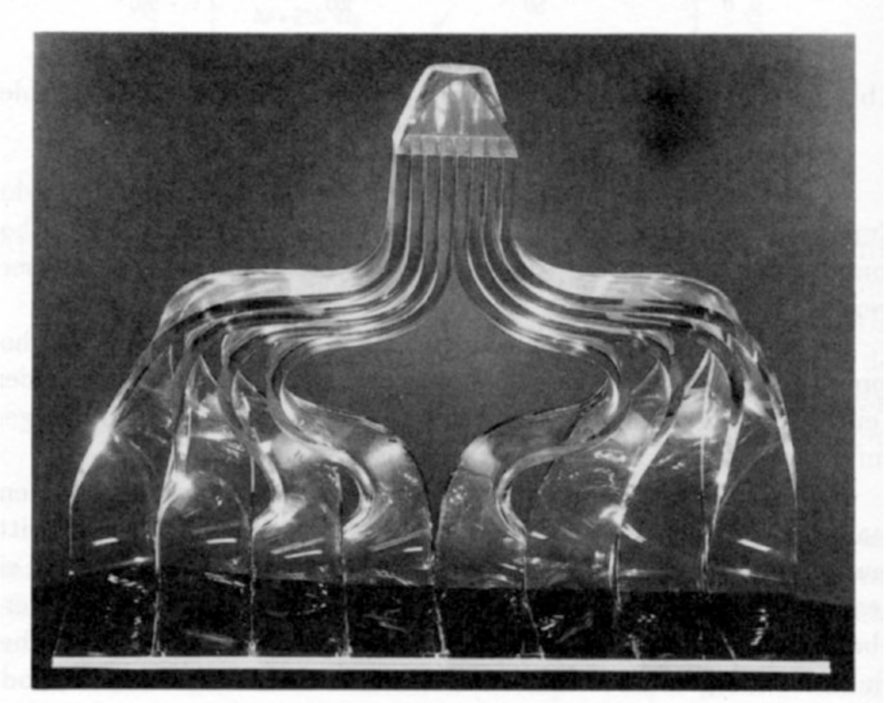
Principle of a calorimeter readout with a scintillator and a wavelength shifters



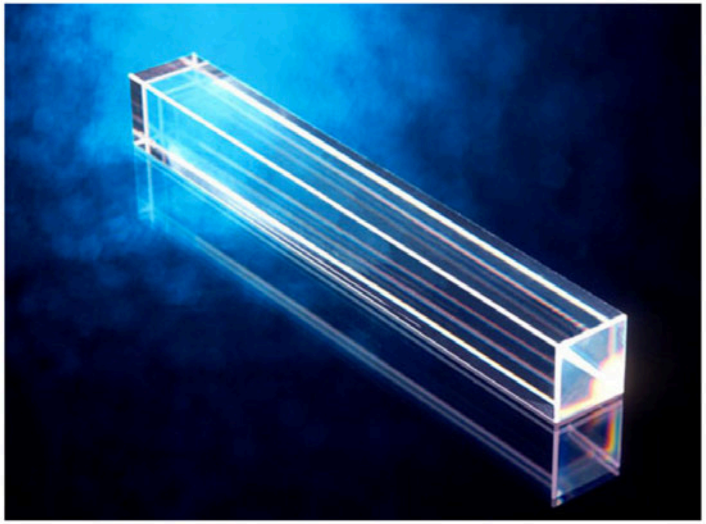








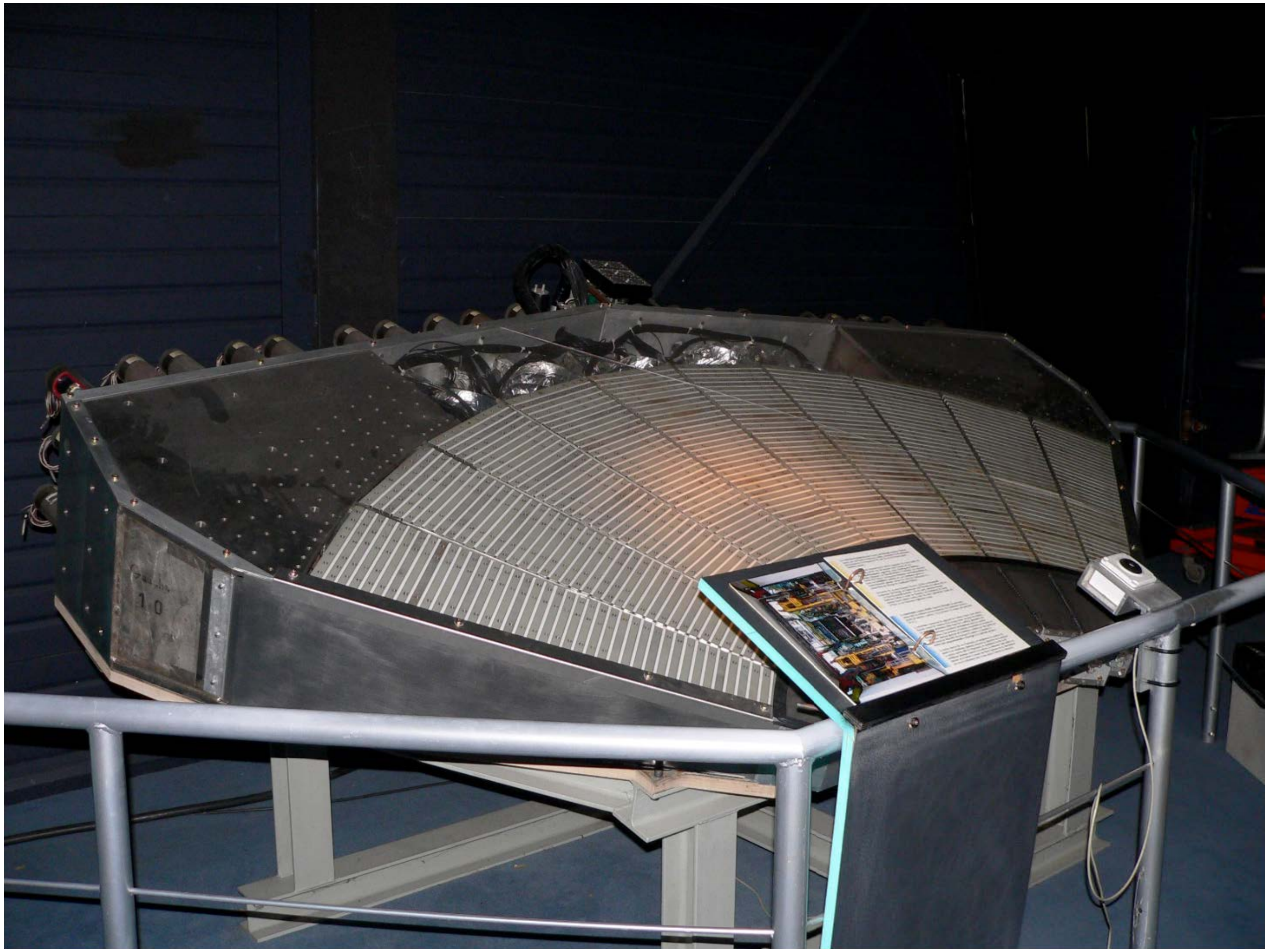
Examples for the coupling of photomultipliers and scintillators via light guides



Blei-Wolframat Kristall

Quelle: CERN

Lead-tungstate scintillator crystal for the energy measurement in the calorimeter of the CMS experiment at the LHC



Calorimeter module of the UA2 experiments with plastic scintillators as active material

7.6 New photon-sensitive devices

- Avalanche Photon Diode (APD)
- Silicon Photomultiplier (SiPM)

Why new devices?

Pros and Cons for conventional photomultipliers

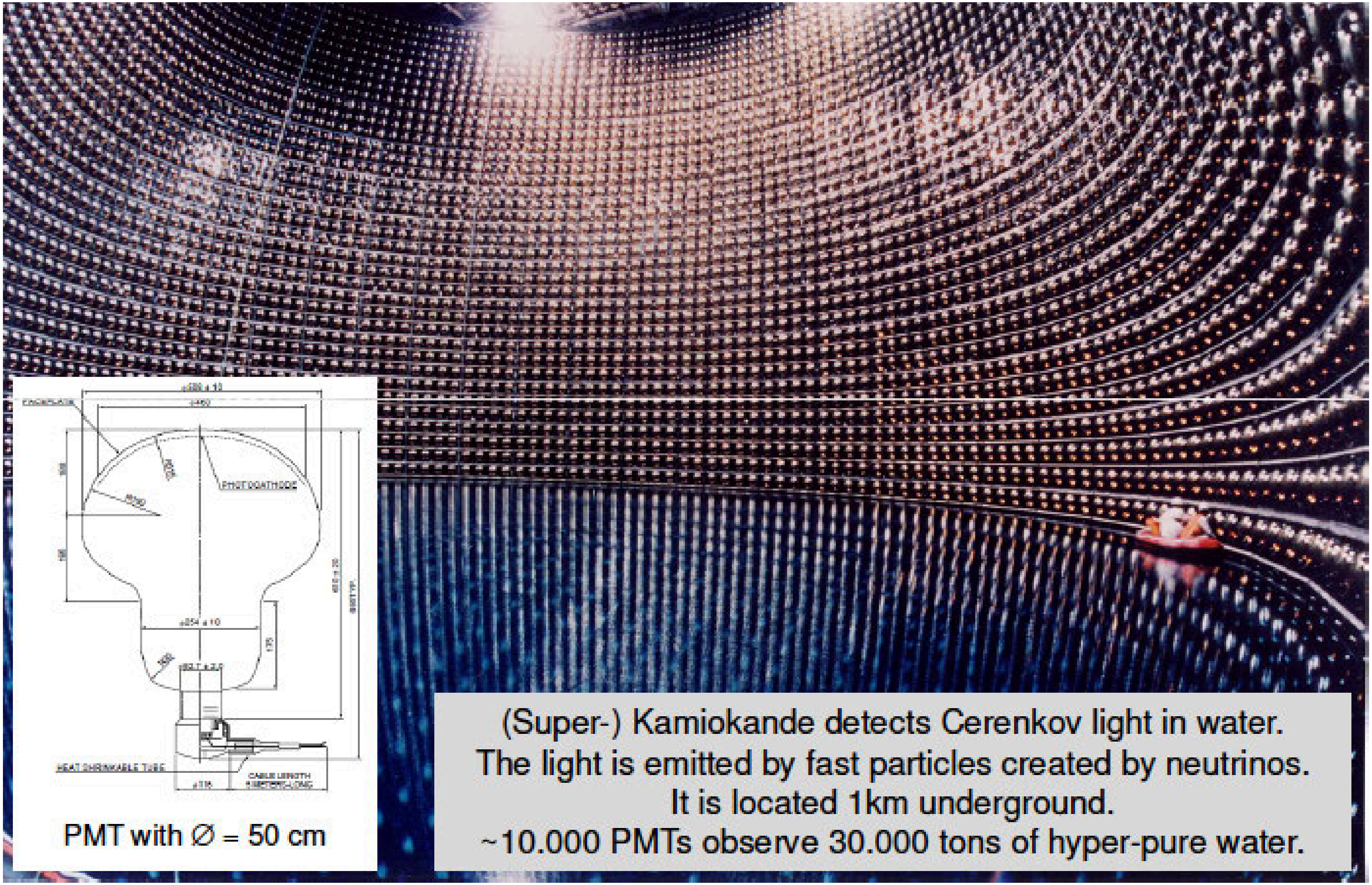
Pros:

- Single photon sensitivity
- Low dark noise (signals with no photons)
- Sensitive from UV to IR light (depends on window and photocathode)
- Fast (rise time ~ns)
- Large areas can be covered (example: Super-Kamiokande, Japan)

Cons:

- Mechanically sensitive (large, glass windows)
- Expensive / but not per area
- Need high voltage (kV) / large power (divider for dynode voltage)
- Large
- Sensitive to magnetic fields
  (effect depends on orientation of the PM w.r.t. field)

Very large photomultipliers at Super-Kamiokande



PMT with Ø = 50 cm

(Super-) Kamiokande detects Cerenkov light in water.
The light is emitted by fast particles created by neutrinos.
It is located 1km underground.
~10.000 PMTs observe 30.000 tons of hyper-pure water.

Avalanche Photodiode (APD)

Basic Function:

-pn diode in reverse bias (partially or fully depleted)

-Some potential for photon absorption

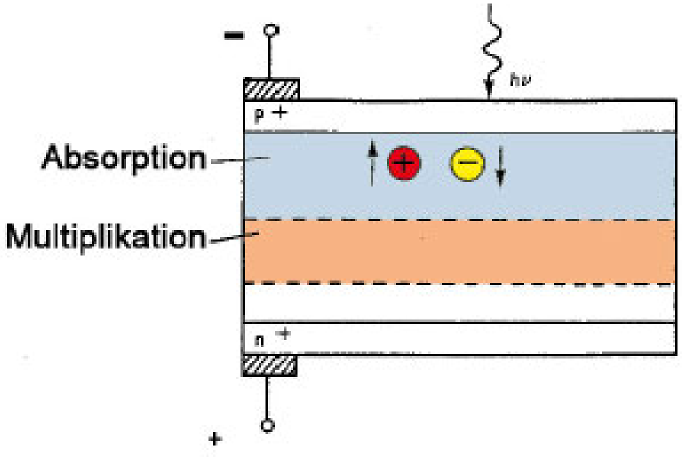
(The efficiency clearly depends on the material, layer thickness and wavelength; proper materials for absorption in the range from 350 nm – 100 μm exist)

-Per photon: electron-hole pair is created

-Charge carriers are separated and drift to electrodes

SPECIAL: a very high field accelerates the charge carriers so much that secondary carriers are created

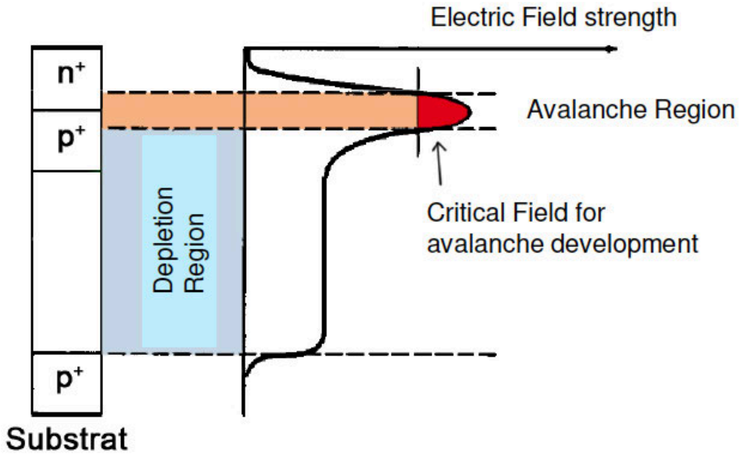
→ an avalanche develops → amplification, large signals



Avalanche Photodiode (APD) (cont.)

- The absorption / drift region should be thick
  → sensitivity increases with thickness

- A high-field region is created by a strongly doped pn-junction
  * High field must still be below Si-breakdown (3 x 10^7 V/m)
  * Typical field: ~10^7 V/m = 10^5 V/cm = 10 V/µm



- Difficult design / layout issues (high electric fields might appear at edge structures, guard rings (lower doped regions at the edge) needed

Operation modes of APDs

-Linear (Proportional) Mode

- * Bias is below the breakdown voltage
- * Moderate gain ~10 - 10^3
- * The signal is proportional to the number of photons; required e.g. in calorimetry (measured scintillation light)

-Geiger Mode

- * Bias voltage is (slightly) above the breakdown voltage
- ***** Very high gain ~10^6
- * Signal becomes independent of primary number of photons
- * Needs a so-called quenching circuit to lower the bias voltage after a hit to stop the avalanche
- * APD (in this mode of operation) is insensitive after “quenching”

Silicon Photomultiplier (SiPM)

- Problem of APD: the gain is low in linear mode
  (which is often preferred, e.g. in calorimeter readout)

- → Use Geiger mode and use many APDs in parallel with separate quench circuits
  (essentially go to pixel structures of 50 x 50 μm^2 areas)

  → Each Single Photon APD (SPAD) works in Geiger mode

- Breakdown of a single SPAD creates only a small signal

- The total signal is proportional to the number of fired cells,
  (i.e. equal to the number of photons for low numbers, however,
  saturation effects expected)

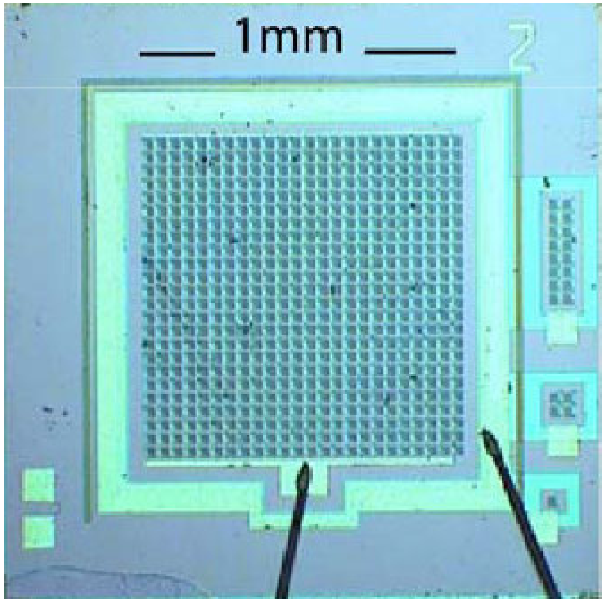
- Such devices are called: SiPM (Silicon Photo Multipliers)
  MPPC (Multiple-Photon Pixel Counter)
  Si-SSPM (Silicon Solid State PMT)

Silicon Photomultiplier (SiPM) (cont.)

- SPAD cell size is in the order of 50 x 50 μm^2
  → $10^2 – 10^3$ SPADs per mm^2

- Bias voltage typically 30-60 V

- Device area can be up to 8 x 8 mm^2
  → more than 10.000 SPADs



Photon detection efficiency of SiPMs

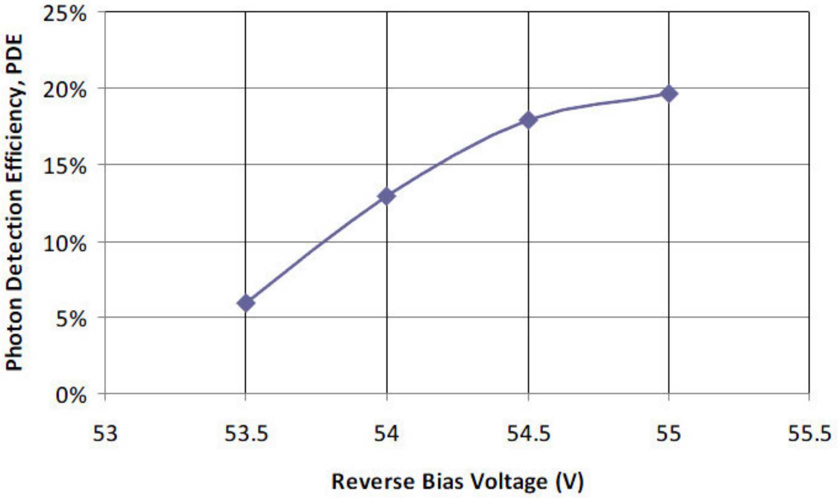
The fraction of detected photons depends on:

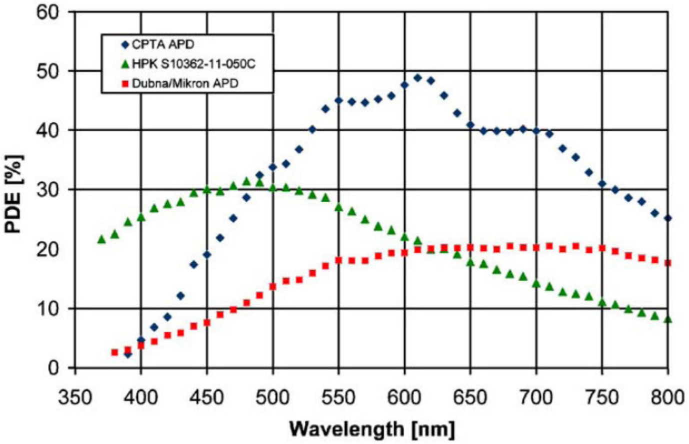
- Fraction of really sensitive area
  (cell boundaries, isolation, ..)

- Reflectivity of the surface (anti reflex coating ARC)

- Probability of photon absorption (depends on wavelength)

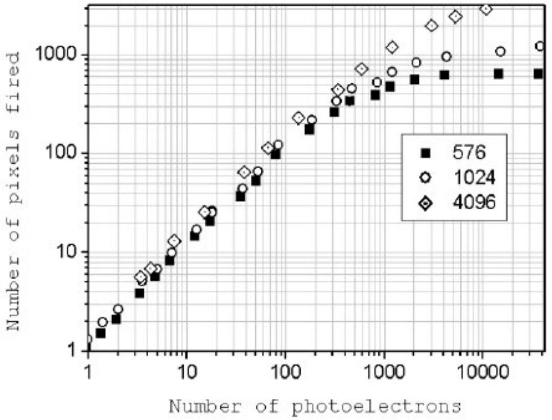
- Dead time after a pulse or a dark hit





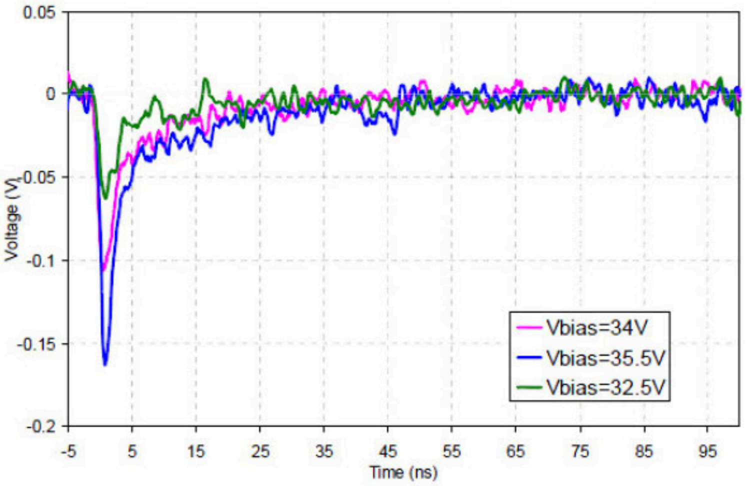
Additional features of SiPMs

- Non-linearities for large number of photons
  - Fired cells cannot fire again (within a short time)
    → reduction of detected signal for many photons;
    largest signal is obviously = # of SPAD cells



- Temperature sensitivity: Breakdown voltage depends on temperature, temperature has to be controlled

- Very fast !
  Rise time < 1 ns
  however, recovery time ~70 ns



Summary on SiPMs

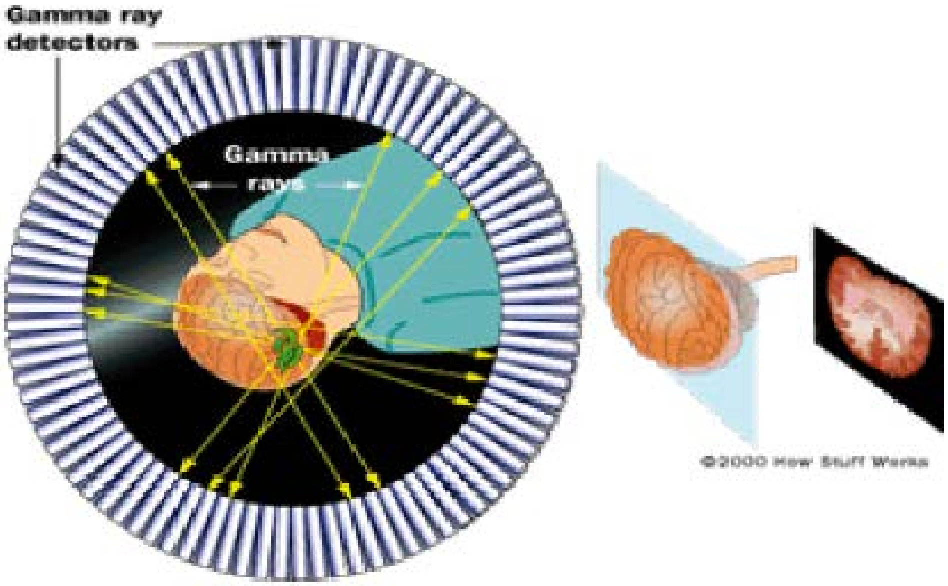
- Interesting new development
  First applications promising, however, more experience need to be gained

- Good sensitivity, however, lower than PMT
- Signal linear, however, saturation effect for large number of photons
- Insensitive to magnetic fields, low bias voltage, small devices and relatively cheap

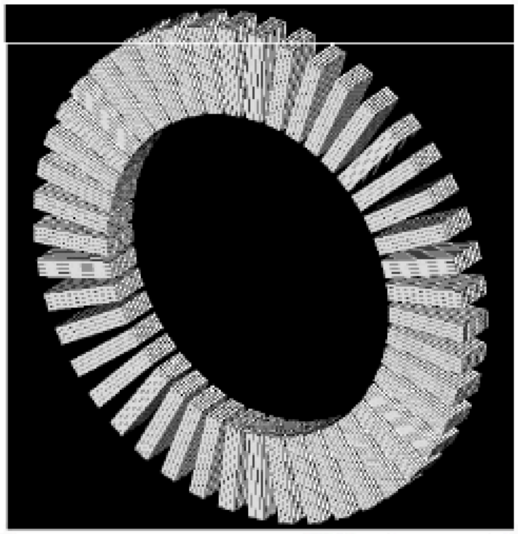
- Larger dark noise as compared to PMT
- Control of temperature required

A major application of SiPMs: Tomography (PET)

- Detection of scintillation photons (from 511 keV γ) required
- Time resolution required
  - for coincidence: ~ 5 – 10 ns
  - for time of flight: ~100 ps
- Compact
- Need to be operated in presence of large magnetic fields



©2000 How Stuff Works



Tomograghgeometrie mit 45 Detektormodulen