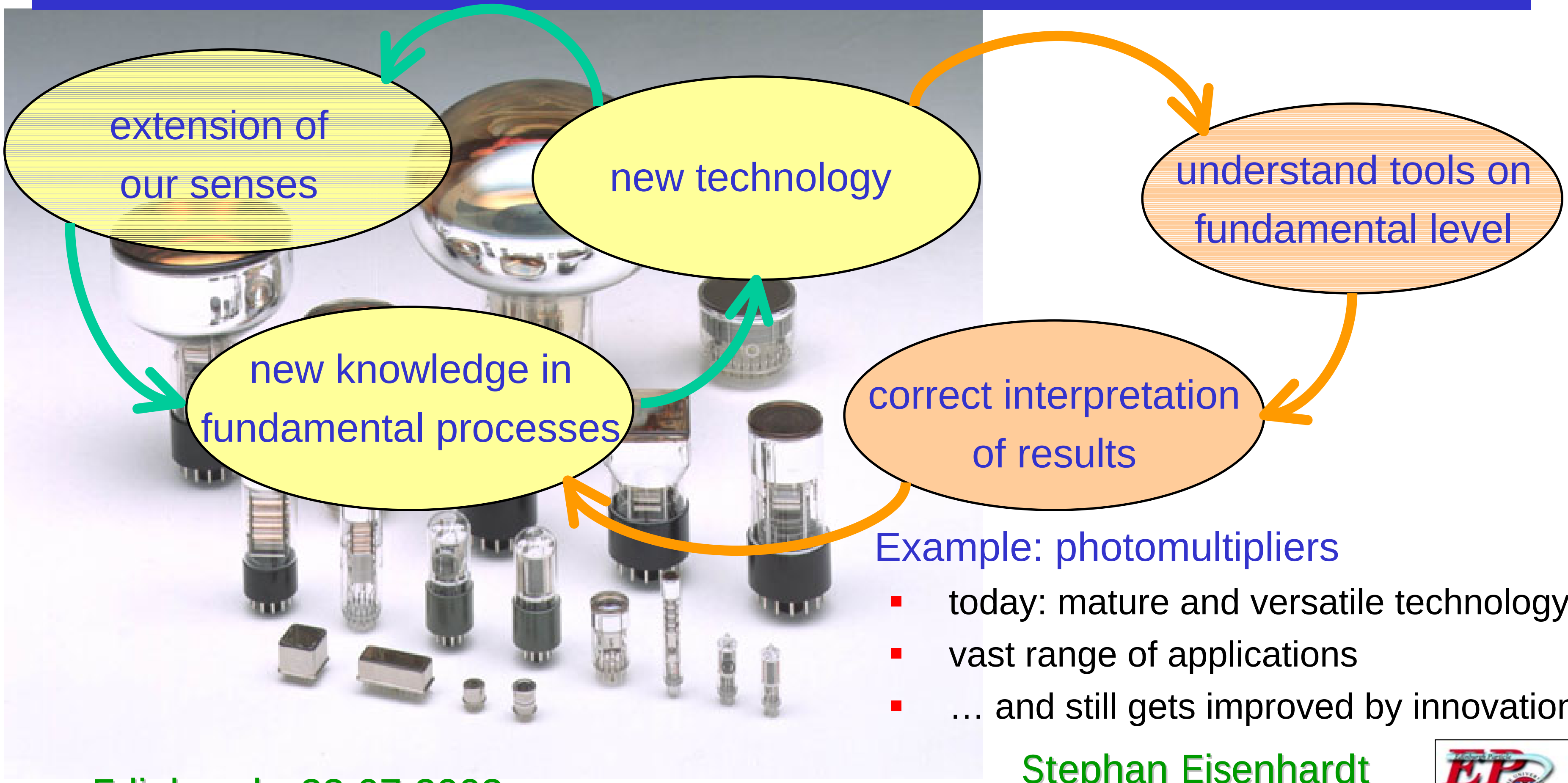
Photomultipliers:
Eyes for your Experiment



extension of our senses

new technology

new knowledge in fundamental processes

understand tools on fundamental level

correct interpretation of results

Example: photomultipliers

- today: mature and versatile technology
- vast range of applications
- … and still gets improved by innovations

Edinburgh, 23.07.2003

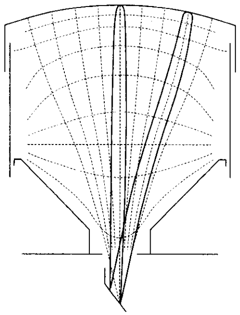
Stephan Eisenhardt
University of Edinburgh

Basic Principle

- Photo emission from photo cathode

  Q.E. = $N_{p.e.}/N_{photons}$

- Electron collection
  - Focusing optics
  - optimise efficiency
  - minimise transient time spread



Equi-potentials and trajectories in a fast input system

- Secondary emission from dynodes:

➔ Electric potential

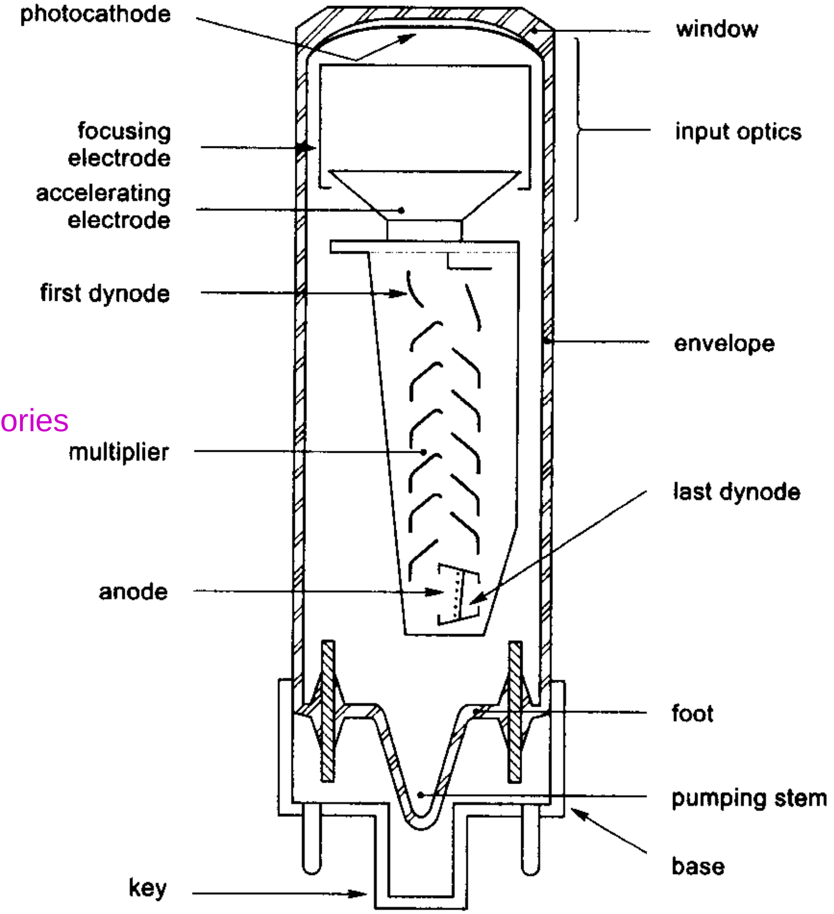
➔ Electron multiplication

dynode gain: g(E) = 3…50

- Total gain: $G = \Pi g_i$

e.g. 10 dynodes with g=4

➔ $G = 4^{10} \approx 10^6$



Schematic of Photomultiplier Tube

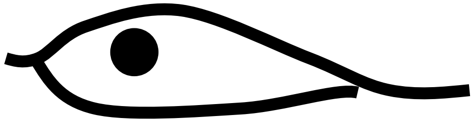
(Philips Photonic)

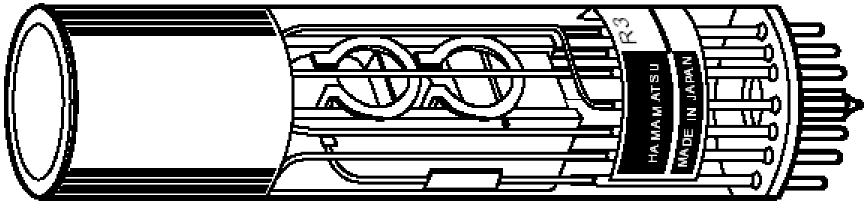
A Brief History

- 1887: photoelectric effect discovered by Hertz
- 1902: first report on a secondary emissive surface by Austin et al.
- 1905: Einstein: "Photoemission is a process in which photons are converted into free electrons."
- 1913: Elster and Geiter produced a photoelectric tube
- 1929: Koller and Campbell discovered compound photocathode (Ag-O-Cs; so-called S-1)
- 1935: Iams et al. produced a triode photomultiplier tube (a photocathode combined with a single-stage dynode)
- 1936: Zworykin et al. developed a photomultiplier tube having multiple dynode stages using an electric and a magnetic field
- 1939: Zworykin and Rajchman developed an electrostatic-focusing type photomultiplier tube
- 1949 & 1956: Morton improved photomultiplier tube structure

➔ commercial phase, but still many improvements to come

Extension of Vision





	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)	2mm…50cm
Intensity range:	$O(10^{16}\gamma/\text{mm}^2\text{s})$ (daylight) single photon sensitivity after adaptation	1γ … ~$10^8\gamma/\text{mm}^2\text{s}$ (~1mA anode current for 1'' tube)
Life time:	$O(10^5\text{C/mm}^2$ 70yrs)	O(10C) for semi-transparent cathode

Photoemission

- ☐ 2-step process:
  - – photo ionisation
  - – escape of electron into vacuum

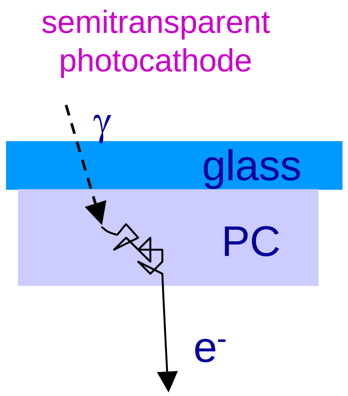
- ☐ Multi-reflection/interference due to high refractive index

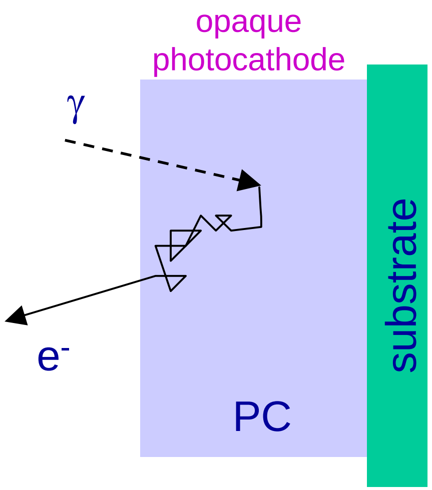
  bialkali: n(λ = 442 nm) = 2.7

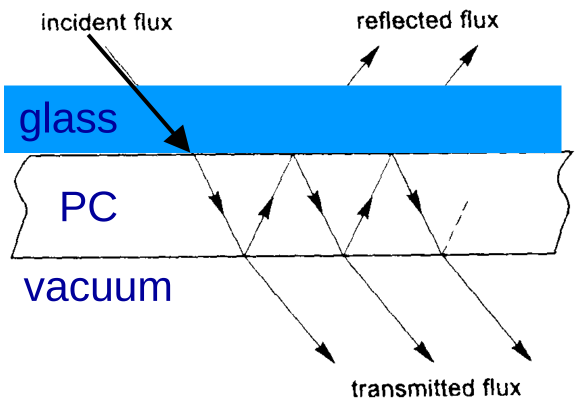
- ☐ Q.E. difficult to measure

➔ often only an effective detection efficiency determined:

  - + internal reflection from a metallic surface
  - + collection of the photoelectrons
  - + electronic theshold…


semitransparent photocathode

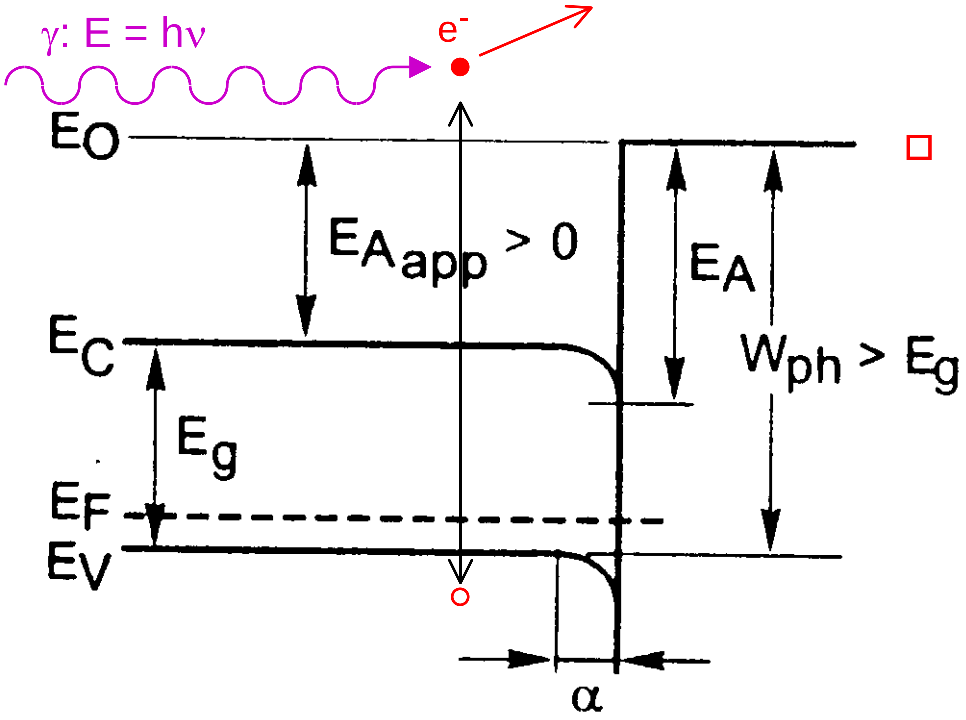

opaque photocathode



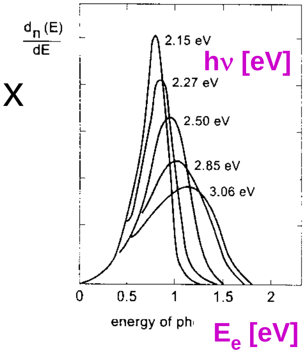
Spectral Response

- In the band model:

Alkali Photocathode



- Photo electric effect
  - hν > E_g + E_A + dE/dx
  - E_e = hν - 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

$P_{\nu} =$ excitation probability

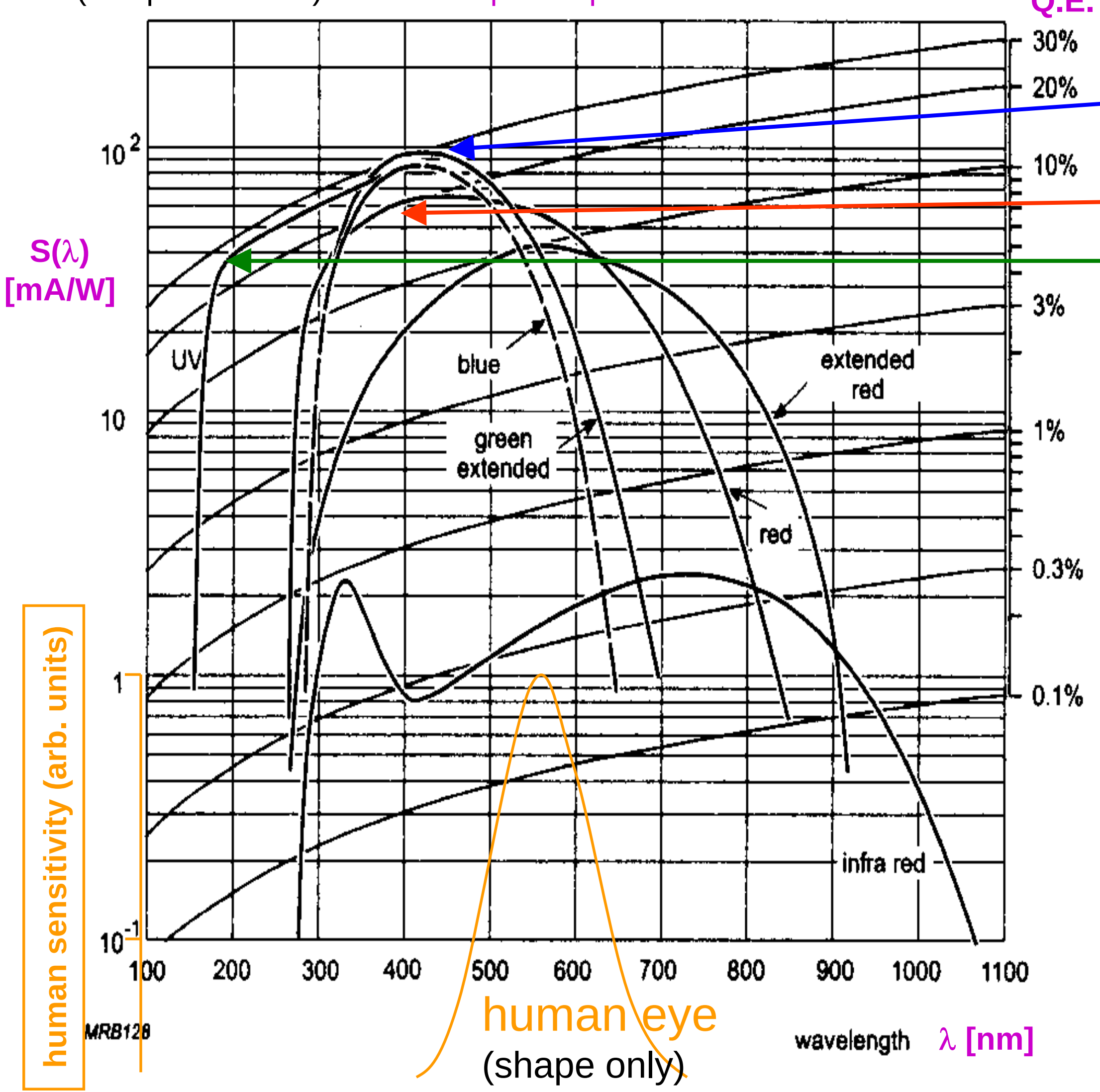
$P_{S} =$ surface transition probability

  - 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

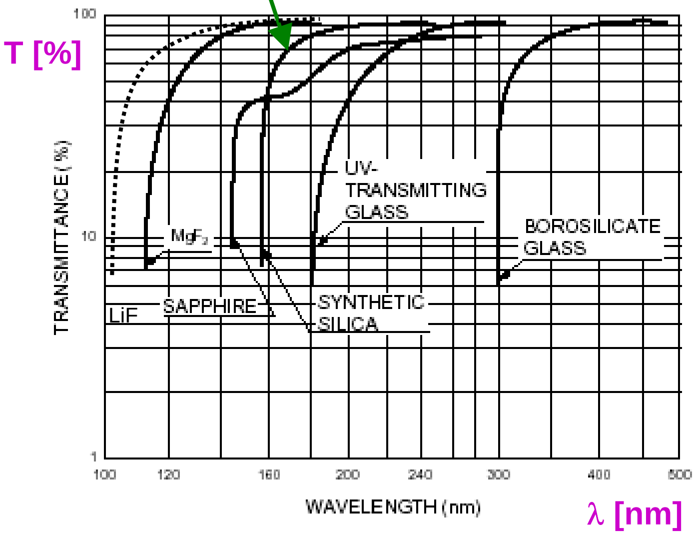


Bialkali : SbK_2Cs, SbRbCs

Multialkali : $SbNa_2KCs$

Solar blind : CsTe

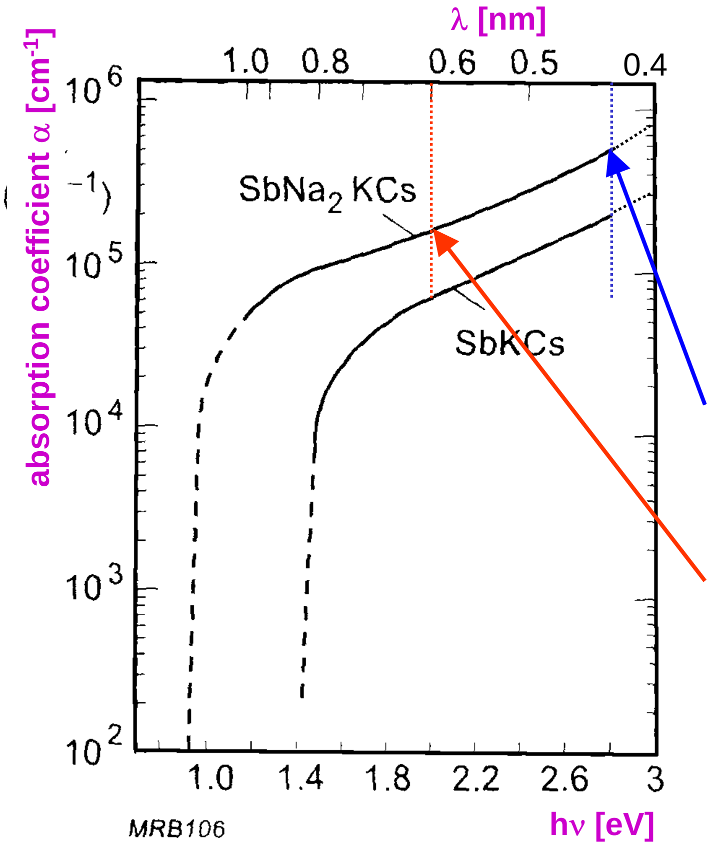
(cut by quartz window)



transmittance of window materials

Photocathode Thickness

Blue light is stronger absorped than red light!



$\lambda_A = 1/\alpha$

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

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

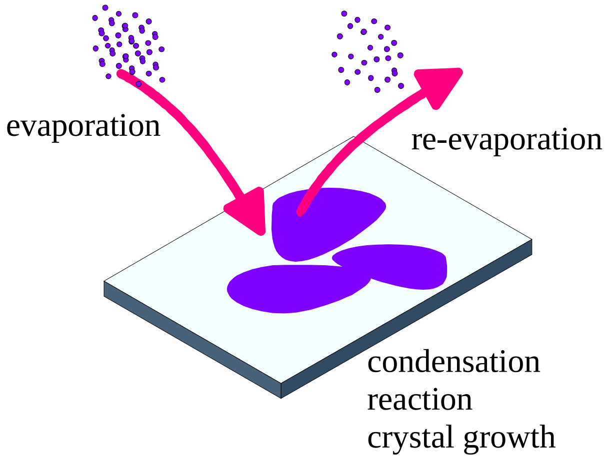
- semi-transparent cathodes

➔ 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 ↘

Alkali Photocathode Production

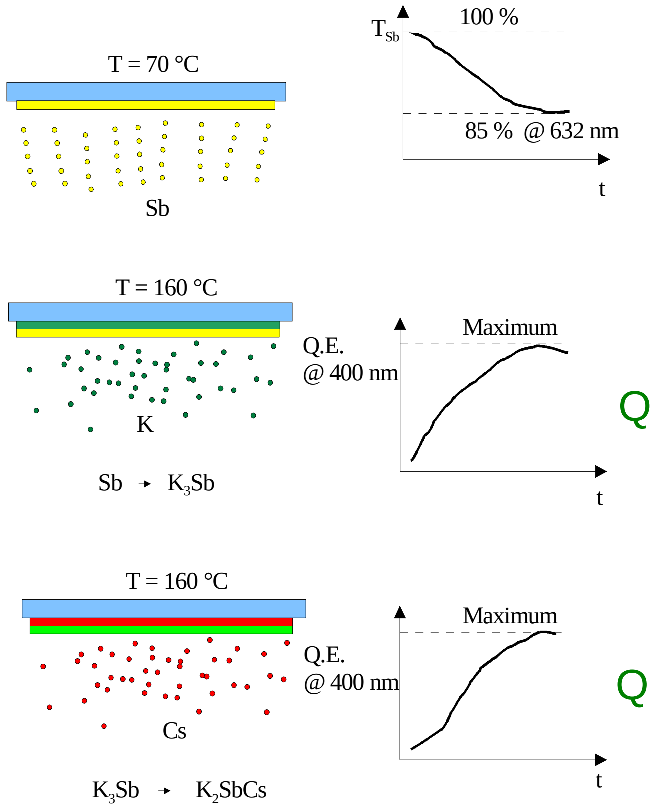
- evaporation of metals in high vacuum
  - – $< 10^{-7}$ mbar
  - – $< 10^{-9}$ mbar H_2O partial pressure
  - – no other contaminants (CO, C_xH_y...)
  - ➔ bakeout of process chamber (>150°C) and substrate (>300°C)
- condensation of vapour and chemical reaction on entrance window



➔ relatively simple technique

- Example: SbK_2Cs

simplified sequential bialkali process



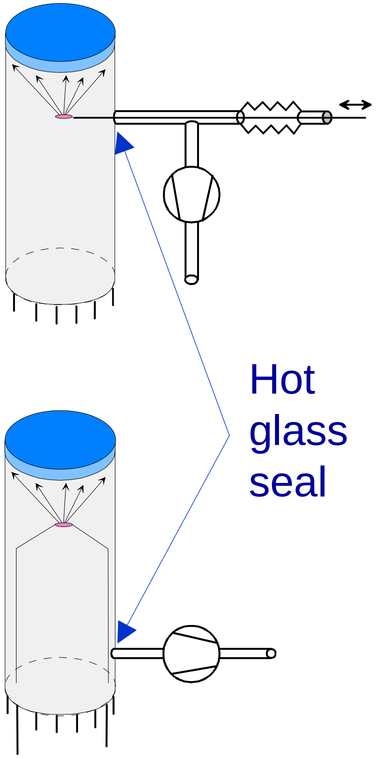
$d_{Sb} \approx 5$ nm

Q.E. ≈ 3 - 5 %

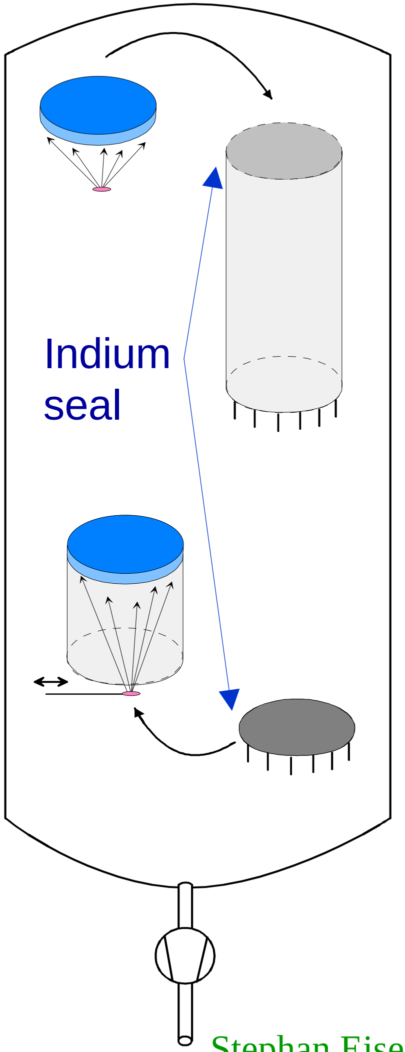
Q.E. ≈ 15 - 20 %

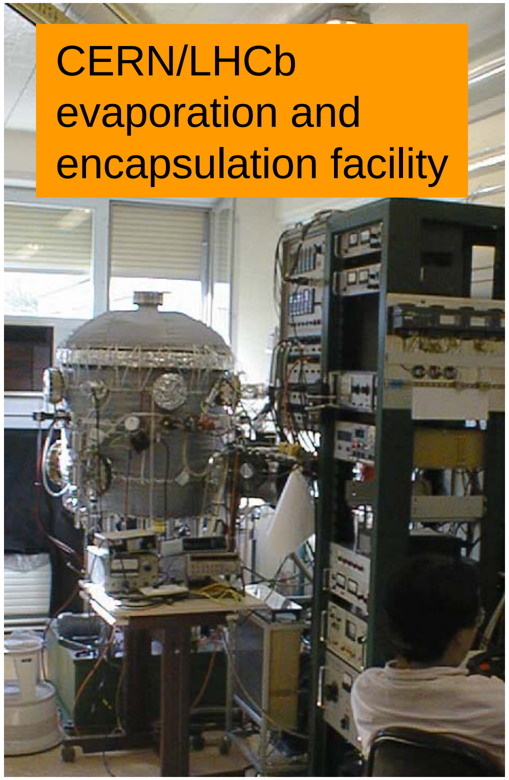
Phototube Fabrication

- internal:



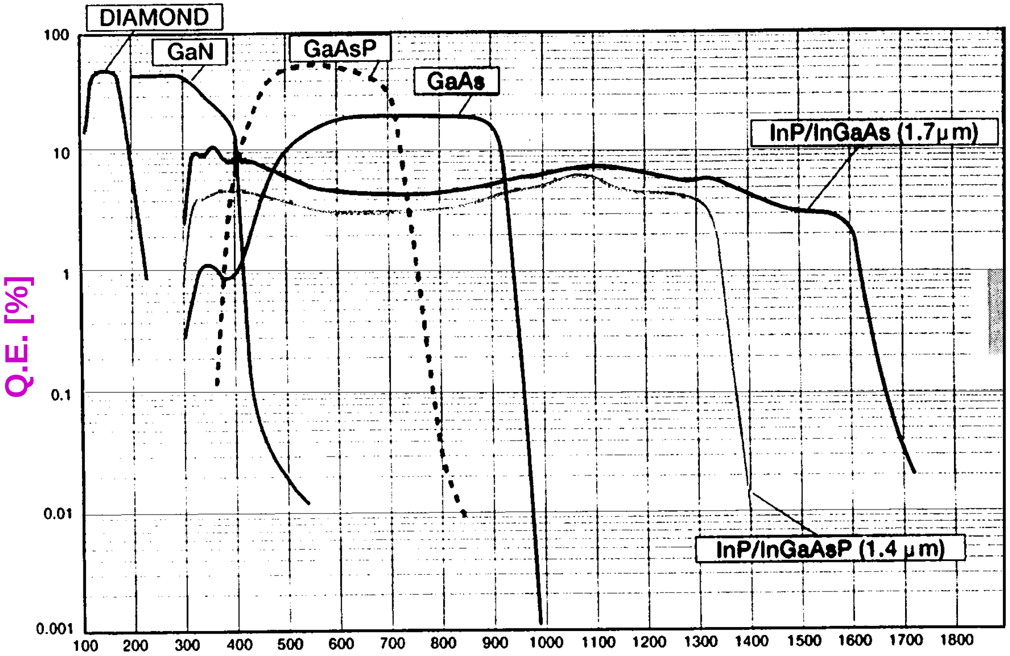
- external:





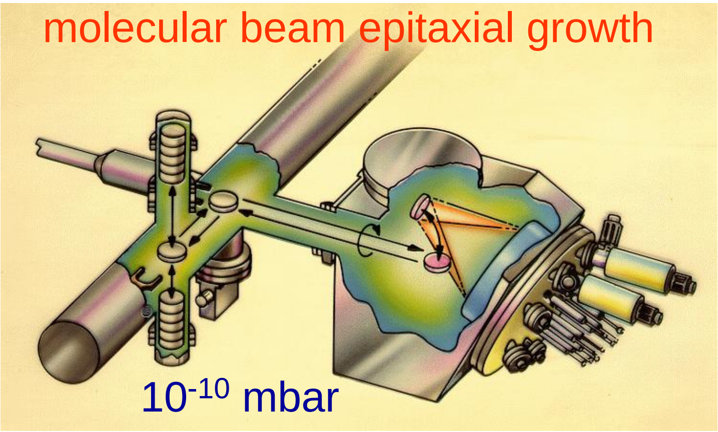
CERN/LHCb evaporation and encapsulation facility

Semiconductor Photocathodes



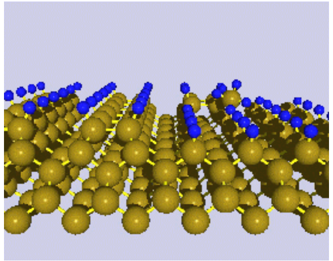
(Hamamatsu)

- ☐ ☺ high Q.E. and spectral width
- ☐ ☺ negative electron affinity
- ☐ ☹ complex production



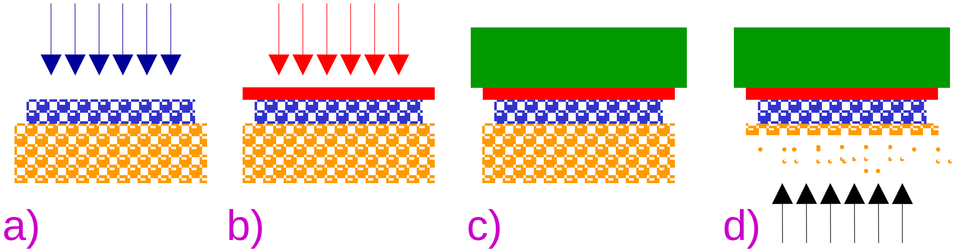
molecular beam epitaxial growth

10^{-10} mbar



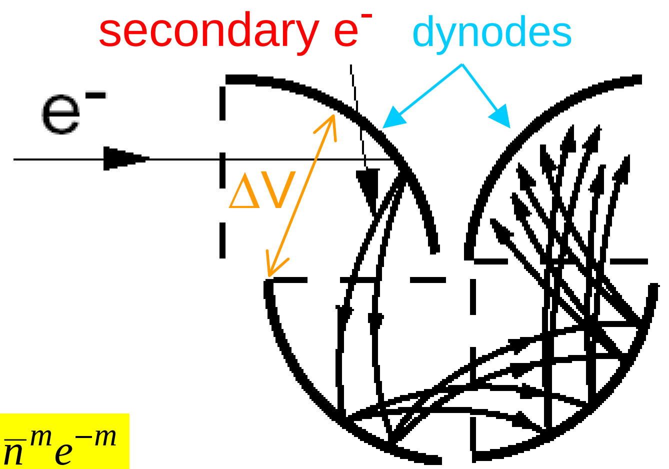
a) grow PC on
crystalline substrate

b) create interface layer
c) fuse to entrance window
d) etch substrate away



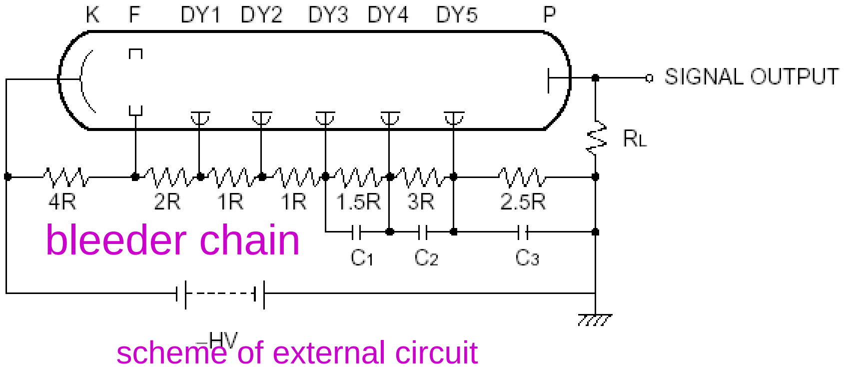
Secondary Emission

- alloy of alkali or earth-alkali and noble metal
- alkaline metal oxidises → insulating coating
  - Large gain   Gain $\delta = a(\Delta V)^k$ with $k = 0.7...0.8$
  - Stability for large currents
  - Low thermal noise $I = aT^2 \exp\left(\frac{-e\Phi}{kT}\right)$



electron multiplication

- Statistical process: Poisson distribution $P(\bar{n}, m) = \frac{\bar{n}^m e^{-m}}{m!}$
  - Spread (RMS)
  - Largest at 1st and 2nd dynode $\frac{\sigma_n}{\bar{n}} = \frac{\sqrt{\bar{n}}}{\bar{n}} = \frac{1}{\sqrt{\bar{n}}}$
- typically 10 … 14 dynode stages
- linearity limits:
  - pulse: space charge
  - DC: photo current << bleeder current

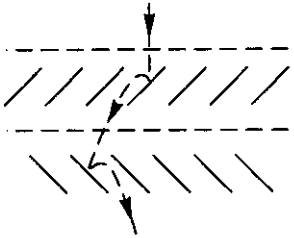


scheme of external circuit for dynode potentials

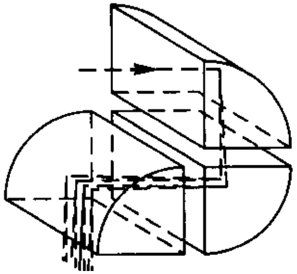
Classic Dynodes

- uniformity:
- photoelectron collection efficiency:

- simple design
- good for large PC ∅



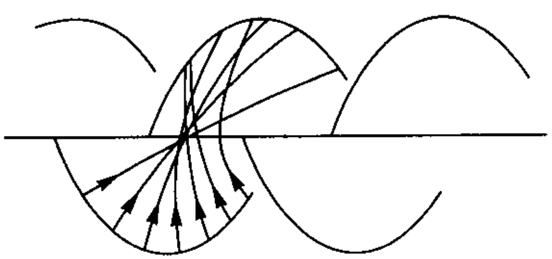
venetian blind ☺ ☹



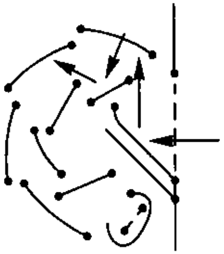
box and grid ☺ ☺☺

- best photoelectron collection efficiency
- good uniformity

- excellent linearity
- good time resolution
- fast time response



linear focusing ☹ ☺



circular cage ☹ ☺

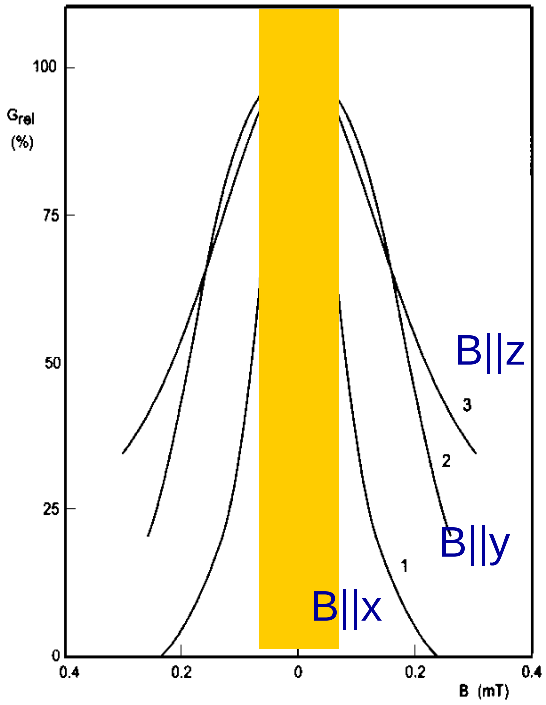
- compact
- fast time response

sensitive to Earth B-field (30-60μT)!

no spatial resolution

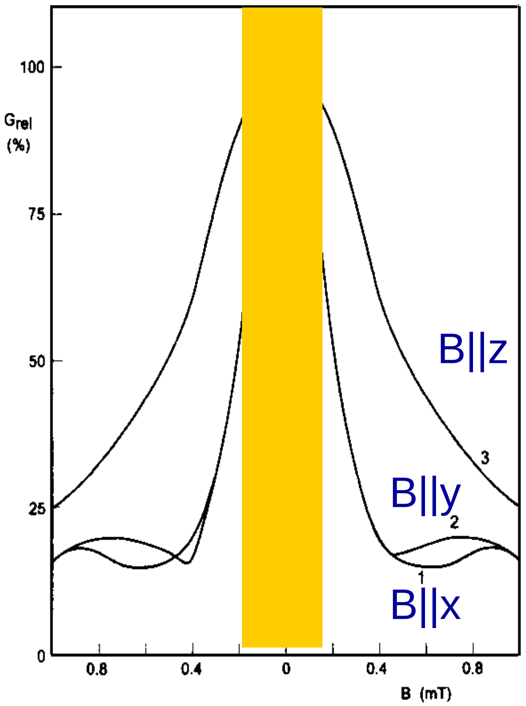
Sensitivity to Magnetic Fields

- linear focusing

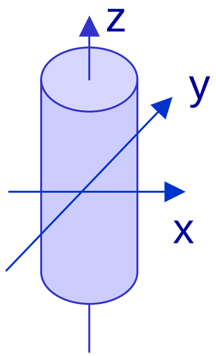


±50 μT
± 0.5 Gauss

- venetian blind



± 200 μT
2 Gauss

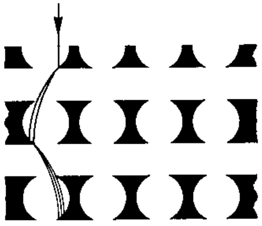


- Earth field: 30-60 μT
- ➔ requires μ-metal shielding

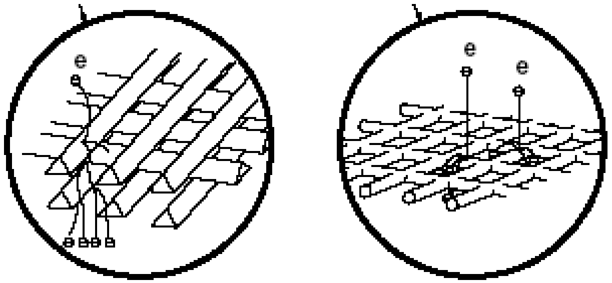
Modern Dynodes

- 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

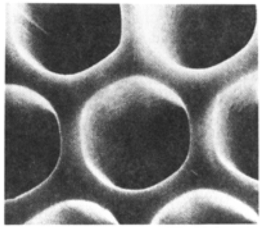
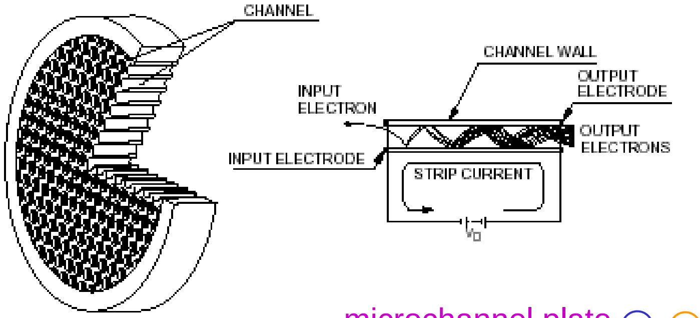


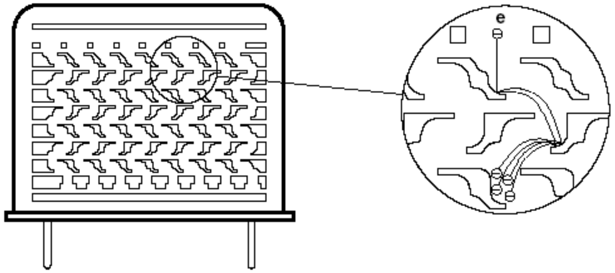
Fig. 5.6. Microphotograph of microchanne



microchannel plate ☺ ☹

- excellent time resolution:

  transit time spread: 50ps

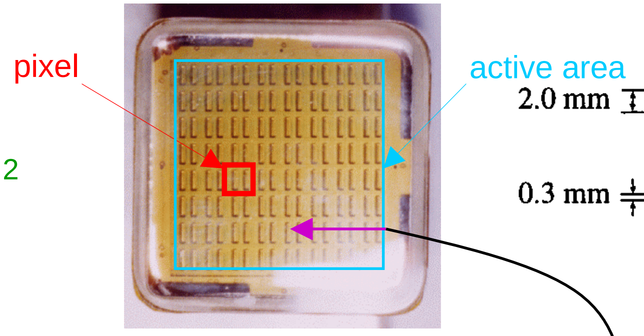


metal channel ☺ ☺

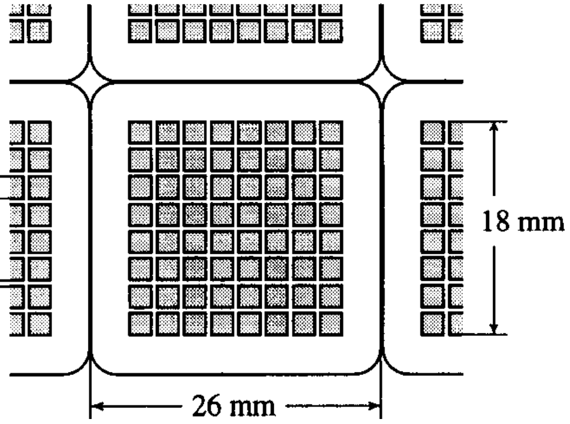
- good e^- collection efficiency
- excellent time characteristics
- stable gain
- …up to 20mT
- low cross-talk pixels

Multianode PMT

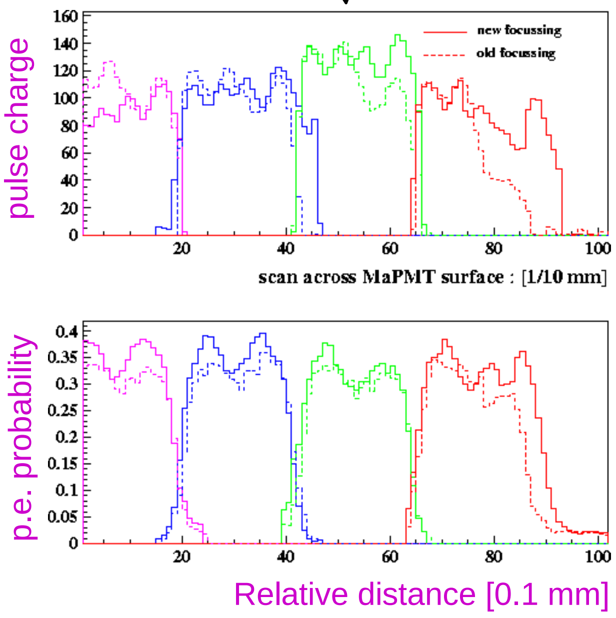
- Position sensitive PMT
  - 8x8 metal channel dynode chains in one vacuum envelope (26x26 mm^2)
  - segmented anode: 2x2 mm^2
  - active area fraction: 48%
- UV glass window
- Bialkali photo cathode
  - QE = 22…25% at λ = 380 nm
- Gain
  - $3 \cdot 10^5$ at 800 V
- Uniformity, Crosstalk
  - much improved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



MaPMT window & electron focusing



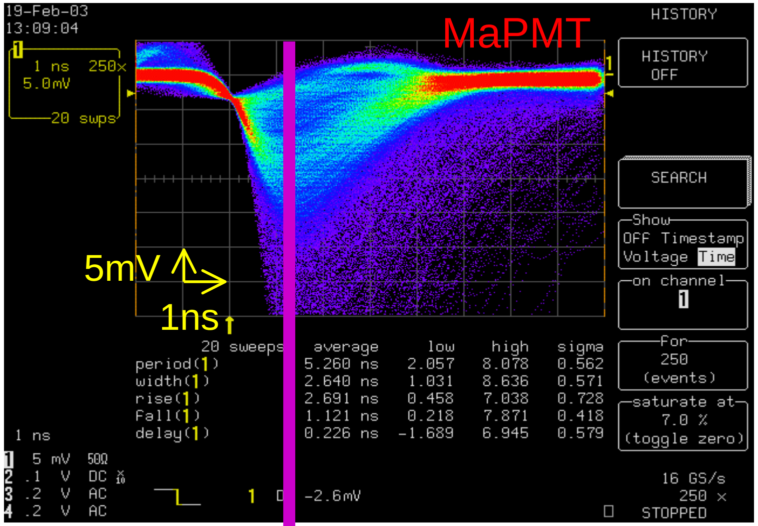
segmented anode



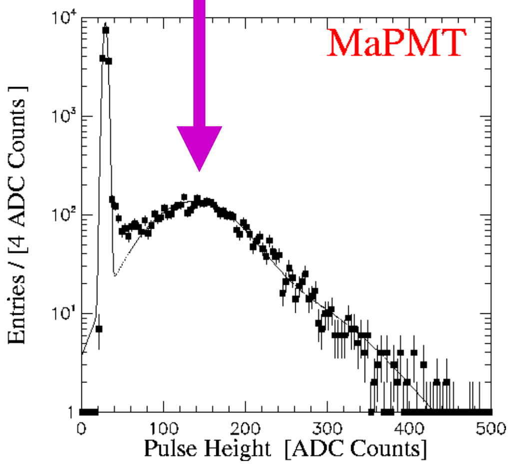
PMT Characteristics

- Fluctuations
  - number of secondary electrons
  - Poisson distribution
- Saturation
  - space charge
  - large photon current
- Non-linearity
  - at high gains
- Stability
  - drift, temperature dependency
  - fatigue effects
  - ➔ Monitoring
- Sensitive to magnetic fields
  - Earth: 30-60 μT
  - ➔ requires μ-metal shielding

- single photon events to oscilloscope (50Ω)



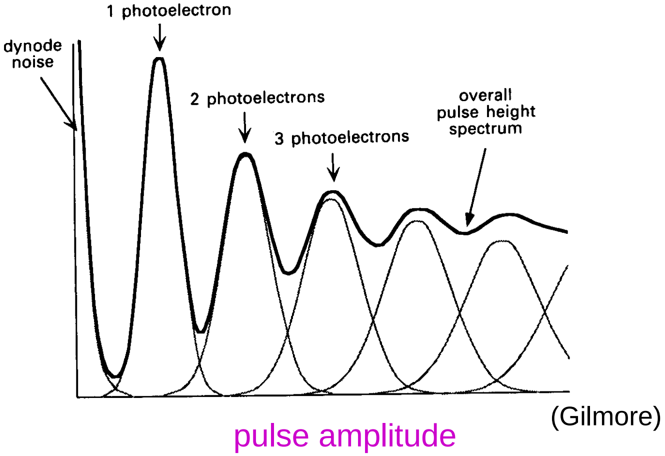
```
19-Feb-03
13:09:04
  1 ns   250x
 5.0mV
      20 swps

             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
 1 ns
1  5 mV  50Ω
2  .1  V  DC ×10
3  .2  V  AC
4  .2  V  AC          1  D  -2.6mV
```



charge integration ➔ pulse height spectrum

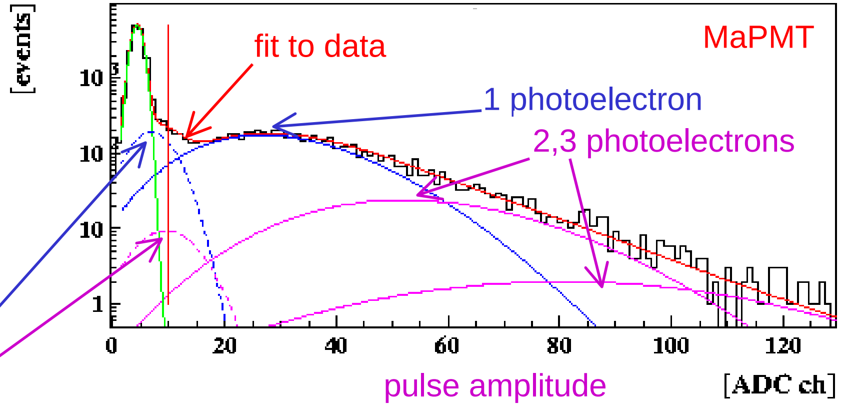
Pulse Height Spectrum

- first dynode gain: $\delta = 25$
  - clear separation of $n\gamma$ signals
  - Gaussian shape
  - Poisson for γ probability

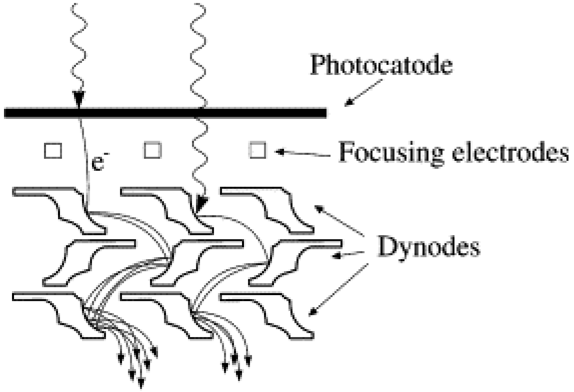


(Gilmore)

- first dynode gain: $\delta = 4$
  - broad signal distributions
  - Poisson shape for $n_{pe}=1,2$
  - significant signal loss below threshold cut

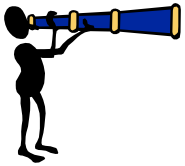


- Photo conversion possible at 1st dynode
  - Gain reduced by δ_1
  - ~~explains data between noise and 1 p.e.~~



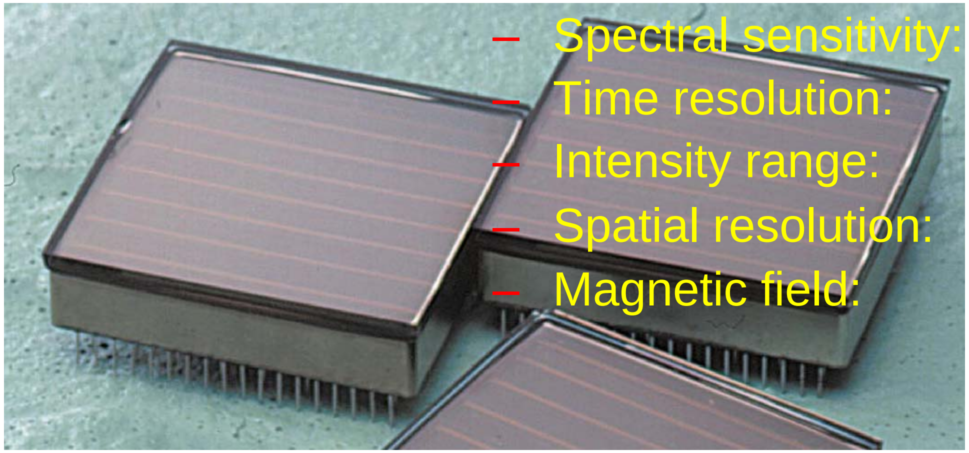
- contradiction when HV is changed!!
  - this data is contaminated with incompletely sampled charge pulses

Conclusion



- ☐ know your tools
- ☐ don't fool yourself with immature conclusions
- ☐ always cross-check as far as possible

- ☐ photomultipliers are a mature and versatile technology
- ☐ suitable for a vast range of applications in light detection:



  - Spectral sensitivity: 110<S(λ)<1600nm
  - Time resolution: down to 50ps
  - Intensity range: 1γ … anode current *O*(1mA)
  - Spatial resolution: down to 2mm with low cross-talk
  - Magnetic field: up to 1.2T

flat panel PMT: next generation MaPMT

- ☐ development goes on…

Super-Kamiokande: 20’’ tubes