Particle Identification at High Energies

Part 2

- RICHes with vacuum based photodetection
- Auxiliary systems for RICHes
- Alternative particle ID methods

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CERN / EP

This lecture is dedicated to our colleague and friend Tom Ypsilantis 1928 - 2000

Vacuum based Photo detectors

Introduction

Photocathodes in the visible range

- Basics about PC
- Characterization of PC
- Types of PC (bialkali, multi-alkali, solar blinds, semi-conductors)

Photomultiplier Tubes

- Basics about PMT (gain, gain spread, magnetic field)
- PMT types (head on, side on, multi anode, flat panel)
- Examples

Hybrid Photodiodes

- Basics about HPD (gain, gain spread, magnetic field)
- HPD types
- Examples

Photocathode fabrication

- Basics of vacuum deposition / epitaxial growth
- Phototube processing

Applications

- HERMES
- LHCb
- DIRC

Auxiliary systems

- Fluids circulation systems (radiator liquids and gases, detector gases)
- Fluids cleaning
- T measurement (monochromator)
- N measurement (prism spectrograph, Fabry-Perot interferometer)

Alternative Particle ID methods

- dE/dx (Bethe-Bloch, gaseous detectors, solid state detectors)
- TOF
- Lifetime (impact parameter measurement in micro-vertex detectors)

Literature:

See Peter Križan's selection

Additional literature…

Philips Photomultiplier Handbook, French version "Photomultiplicateurs" (Available from Photonis, France http://www.photonis.com)

Proceedings of the Beaune Photosensor conferences (1996 and 1999), NIM A 387 (1997) and NIM A 442 (2000)

A.H. Sommer. Photoemission materiale, J.Wiley & Sons (1968)

Particle Detectors, CERN Academic Training Lecture series (C. Joram) http://training.web.cern.ch/Training/ACAD/acad0_E.html

Thanks for providing very useful material to …

E. Aschenauer, T. Bellunato, M. Davenport, W. Klempt, D. Liko, M. Mayer (Hamamatsu), V. Shelkov, O. Ullaland, J. Va´vra

Ring Imaging CHerenkov Detectors with vacuum based photodetection

Introduction

What is a vacuum based photo detectors ?

A device which detects light by means of a photocathode in an evacuated volume. No gas amplification involved !

Why vacuum based photo detectors ?

A RICH aims to detect the maximum number of photons with the best angular resolution.

Number of detected photoelectrons $N_{p.e.}$

$$N_{p.e.} = L \sin^2 q \underbrace{\frac{a}{\hbar c} \int_{E_1}^{E_2} e_Q(E) \prod_i e_i(E) dE}$$

$$N_0 = 370 \cdot eV^{-1} \cdot cm^{-1} \langle e_{total} \rangle \Delta E$$

$DE = E_2 - E_1$ is the width of the sensitive window of the photodetector. $N_{p.e.} \propto \langle \varepsilon_{total} \rangle \cdot DE$ → to be maximized.

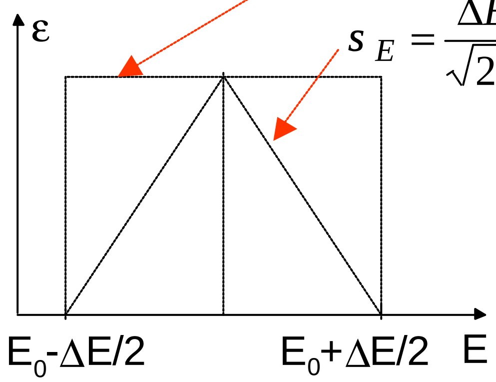
A large dE increases however the chromatic error

$$\sigma_\theta = \frac{1}{n\tan\theta}\sigma_n = \frac{1}{n\tan\theta}\frac{dn}{dE}\sigma_E$$

dn/dE is the dispersion of the radiator medium.

$$\sigma_E = \frac{\Delta E}{\sqrt{12}}$$

$$\sigma_E = \frac{\Delta E}{\sqrt{24}}$$

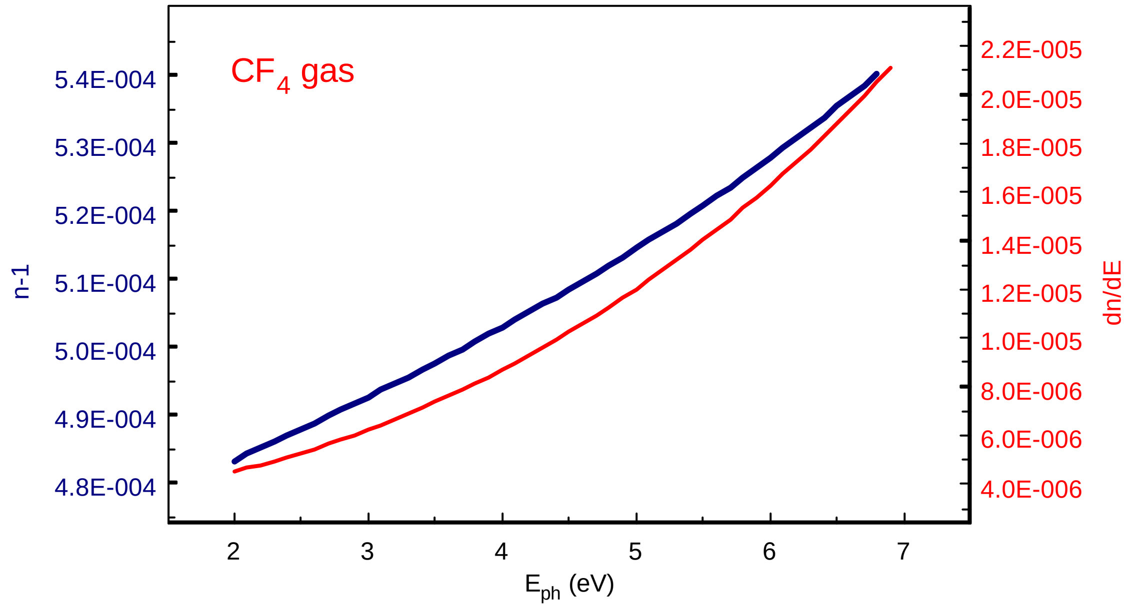


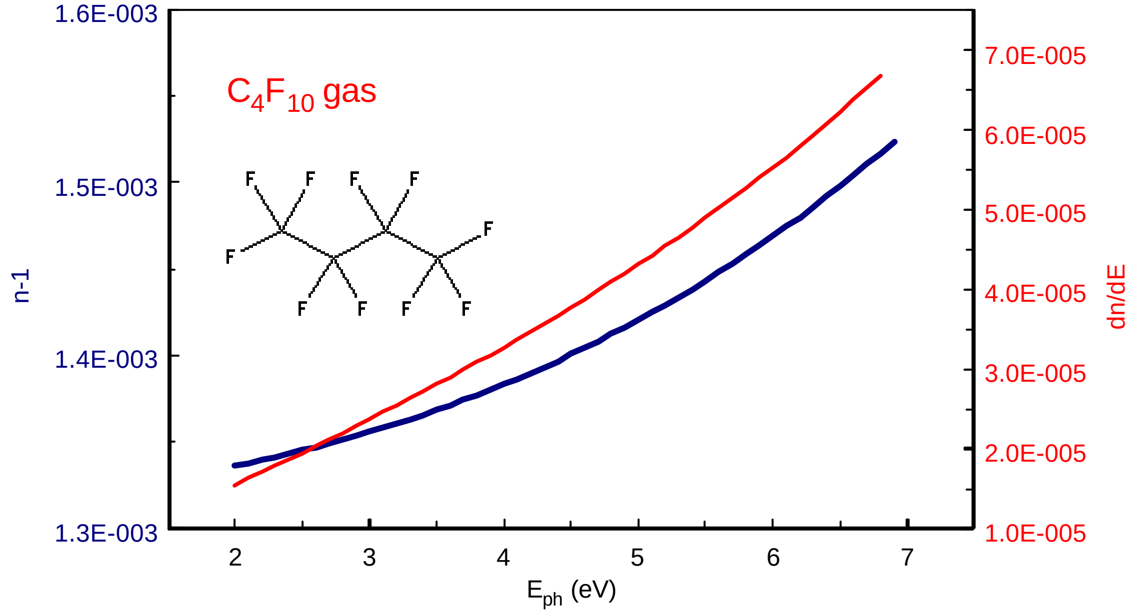
$\sigma_\theta \propto dn/dE \cdot \Delta E$ → to be minimized.

A RICH should provide a good compromise between $N_{p.e.}$ and σ_θ

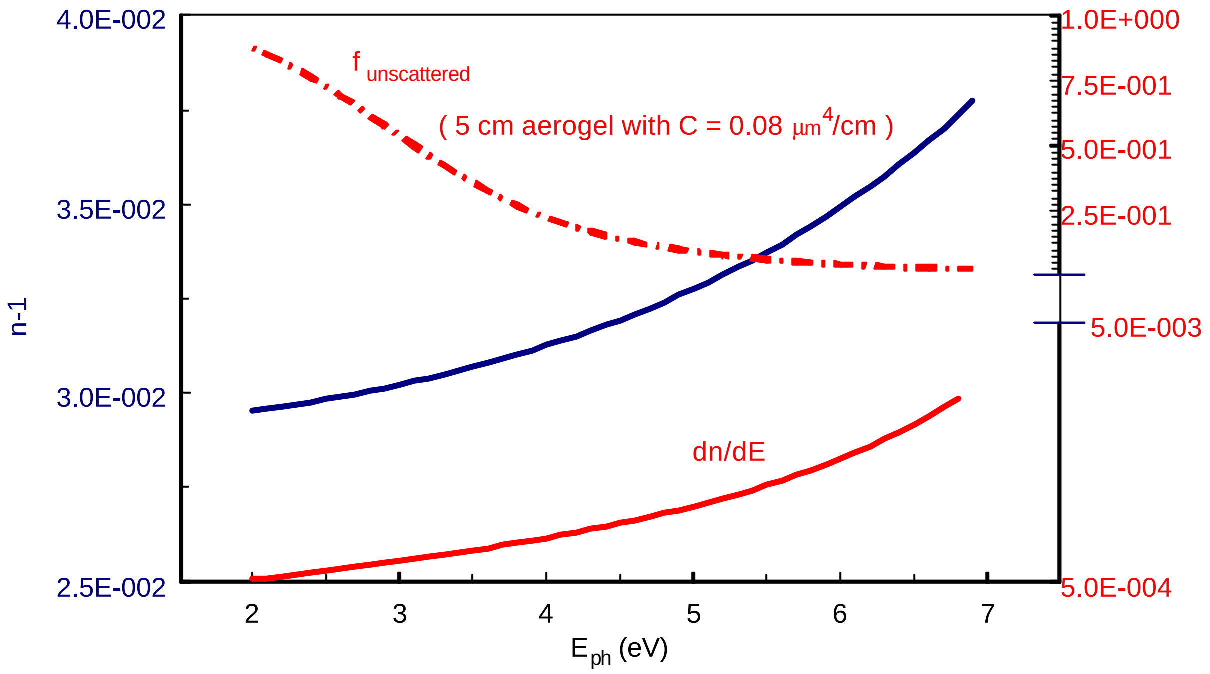
➔ Look for a photodetector with large ΔE which can be combined with a radiator with small dn/dE.

Refractive index and dispersion of CF_4 and C_4F_{10} gas gases





Refractive index (n-1) and dispersion dn/dE increase with the photon energy.



Aerogel can reduce the gap between gases (n-1 <≈ 0.002) and liquids (n-1 > ≈ 0.25)

n-1_{aerogel} ≈ 1.01 - 1.10

However: aerogel is a colloidal form of quartz, a extremely light microporous material. Light suffers scattering coherent from the micro bubbles, Rayleigh scattering. The probability for not being scattered is

$$P = e^{-CL/l^4}$$

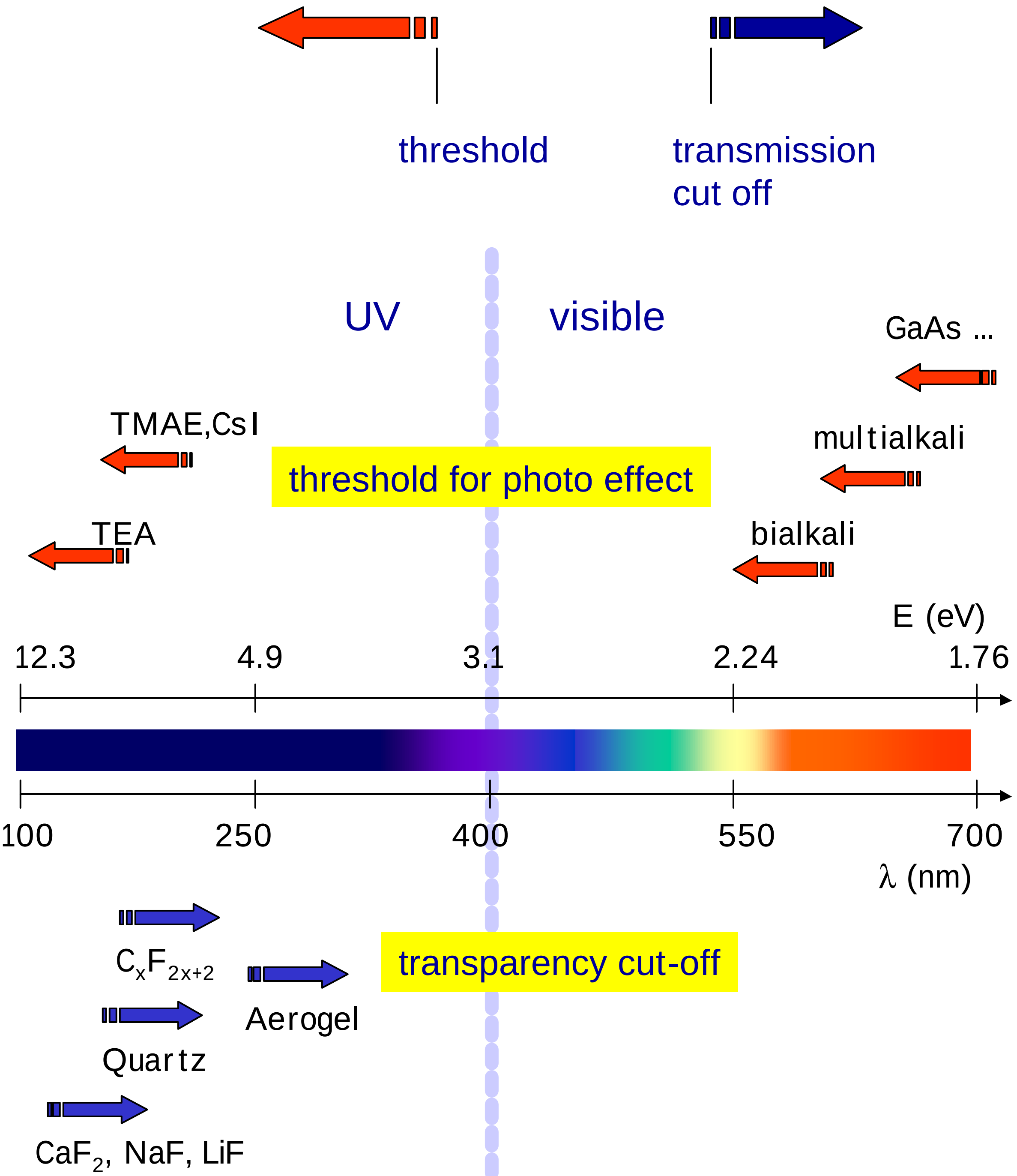
C = clarity coefficient. 0.05 - 0.1 μm^4/cm

The unscattered fraction of Cherenkov light being uniformly emitted over the length L is

$$f_{unscattered} = \frac{l^4}{CL}\left(1 - e^{-CL/l^4}\right)$$

Photocathodes in the the visible range

Overview: Photocathodes and Cherenkov radiators



Advantages - Disadvantages

Vacuum based detectors...

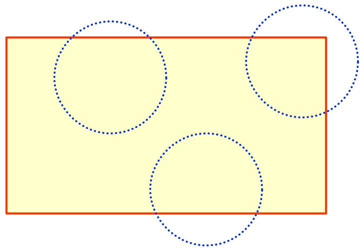
- work in the visible and near UV range. Dispersion dn/dE much smaller than in deep UV
- cover a large energy / wavelength range ΔE = 3-4 eV
- can be combined with a large variety of radiator and window materials (incl. aerogel radiators).
- are easy to operate

But...

- are housed in small fragile glass tubes
- are quite expensive
- fairly difficult to fabricate

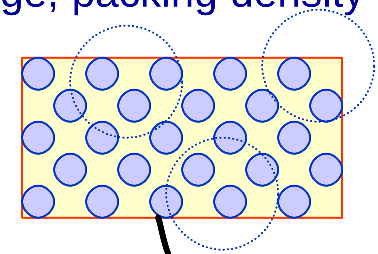
Basic requirements of photo detectors in RICH counters

- total surface



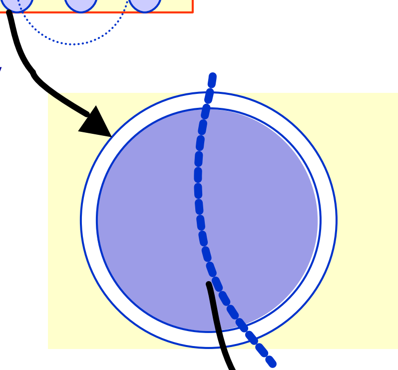
→ $N_{p.e.}$

- surface coverage, packing density



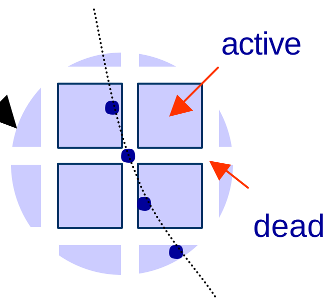
→ $N_{p.e.}$

- active area, granularity



→ $N_{p.e}$
→ σ_θ

- quantum efficiency → $N_{p.e}$



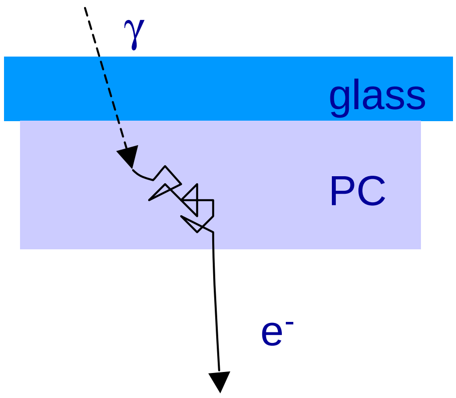
- wavelength range → $N_{p.e,}$, σ_θ
- speed, dead time
- noise
- cost
- ...

Photoemission

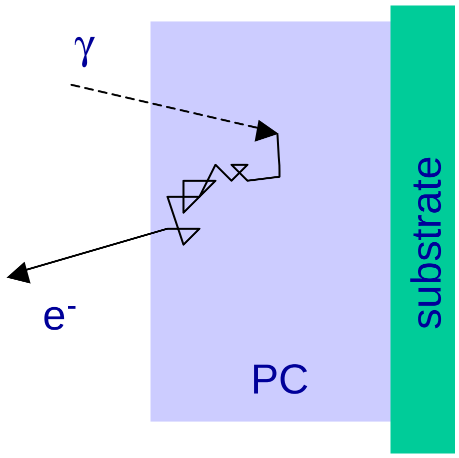
2-step process

- photo ionization of molecule
- escape of electron back into the vacuum

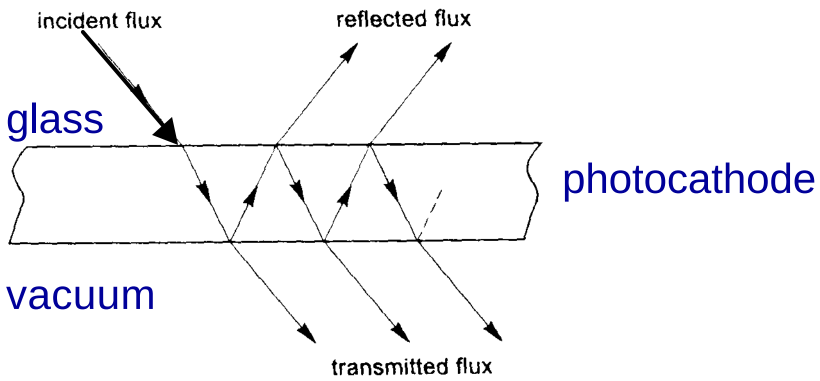
Semitransparent photocathode



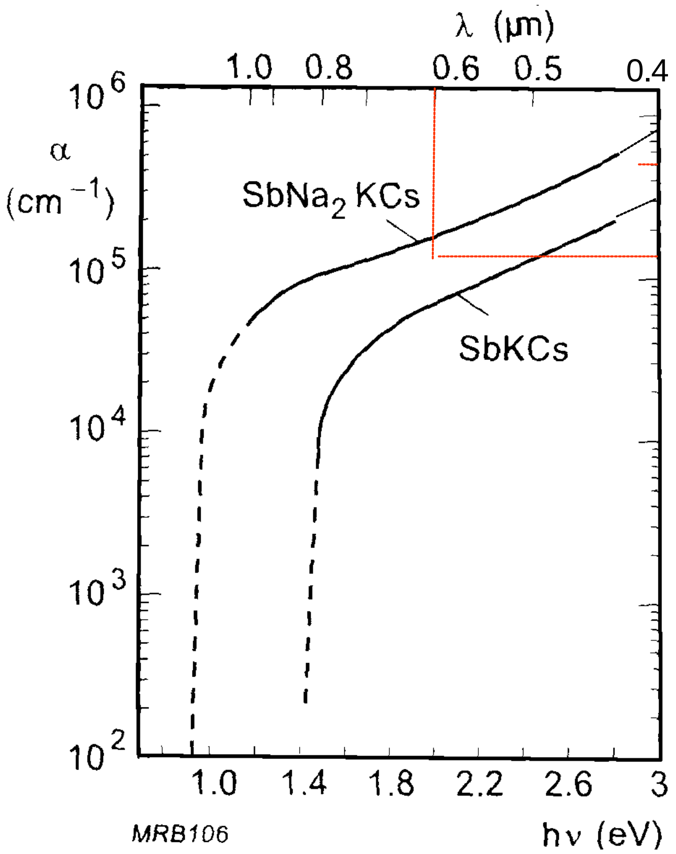
Opaque photocathode



In reality the situation is more complex: Due to the high refractive index of the photocathode (example bialkali: $n(\lambda = 442\ nm) = 2.7$) we get a multi reflection / interference situation



Experimentally...



$\lambda_A = 1/\alpha$

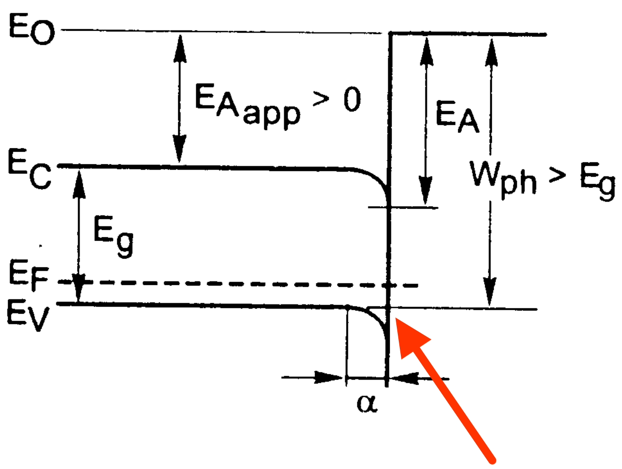
Red light ($\lambda \approx 600$ nm)
$\alpha \approx 1.5 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 60$ nm

Blue light ($\lambda \approx 400$ nm)
$\alpha \approx 4 \cdot 10^5$ cm^{-1}
$\lambda_A \approx 25$ nm

Blue light is stronger absorbed than red light !

In the band model:

Photocathodes are semiconductors:
$E_V < E_F < E_C$



Photon energy has to be sufficient to bridge the band gap E_g, but also to overcome the electron affinity E_A, so that the electron can be released into the vacuum.

p-doping (Cesium) deforms bands at surface and results in a lower apparent electron affinity. Lower threshold for photoeffect.

The 'hot' photoelectron in the conduction band has to reach the PC surface. Energy loss due to electron-phonon collisions. $\Delta E \approx 0.05$ eV per collision. Free path between 2 collisions

$\lambda \approx 2.5 - 5$ nm.

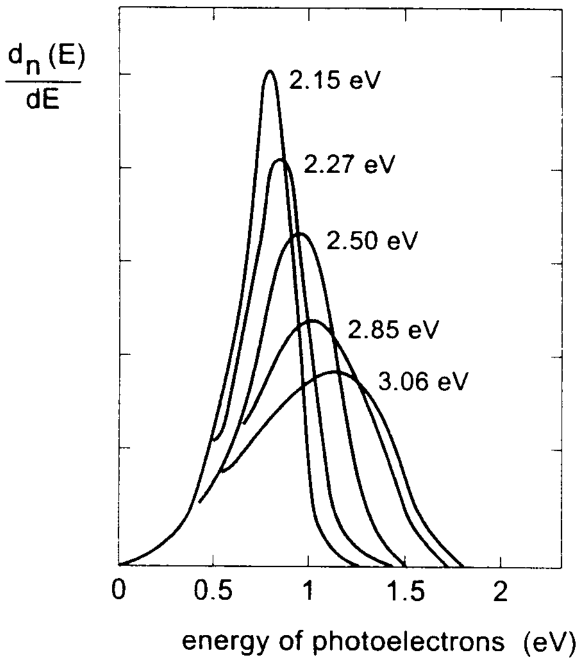
➔ escape depth $\lambda_E \approx$ some tens of nm.

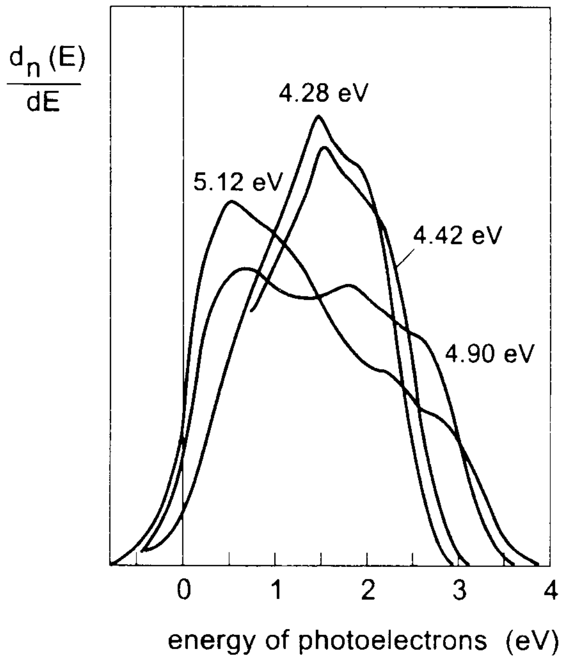
➔ Particularly for semi-transparent cathodes one has to find the best compromise for the thickness of the PC: photon absorption length $\lambda_A(E_{ph})$ ⇔ electron escape depth $\lambda_E(E_e)$

thick cathode: high red response - low blue response

thin cathode: low red response - high blue response

The energy of the emitted photoelectron still depends a bit on the energy of the photon. Typical energies are 0.5 - 2 eV.





Sensitivity characteristics

- Quantum efficiency

$$e_Q = \frac{N_e}{N_g}$$

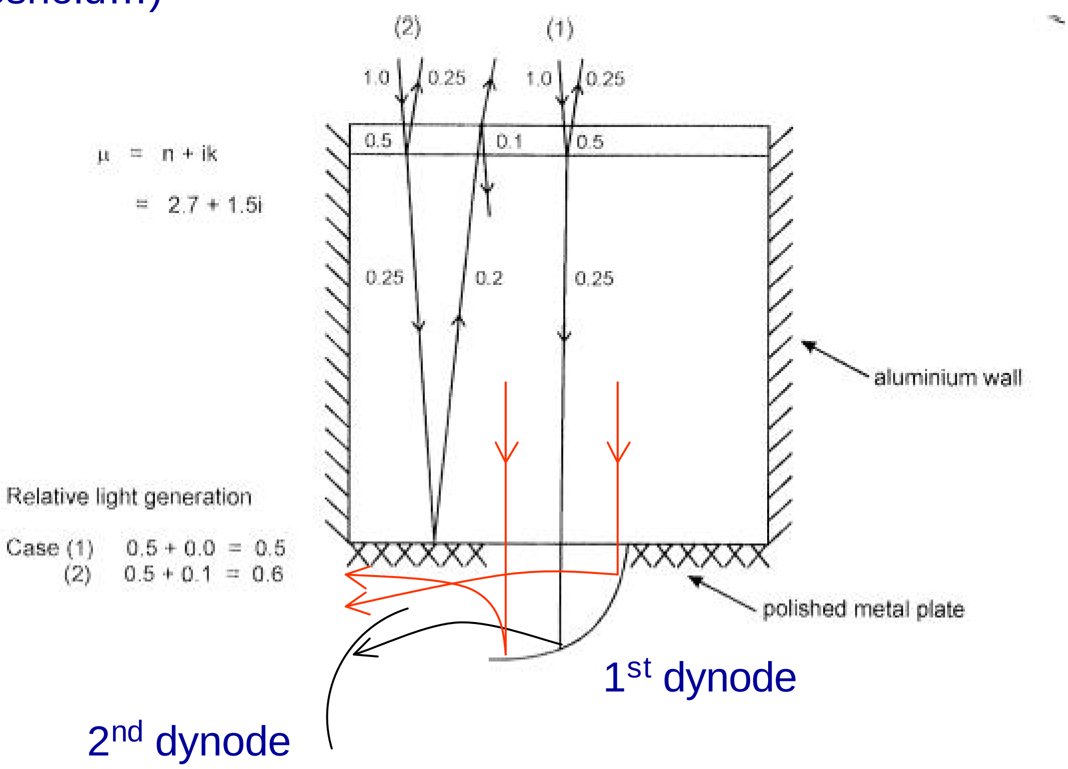
- Cathode radiant sensitivity

$$S_k(mA/W) = \frac{I_k(mA)}{\Phi_g(W)}$$

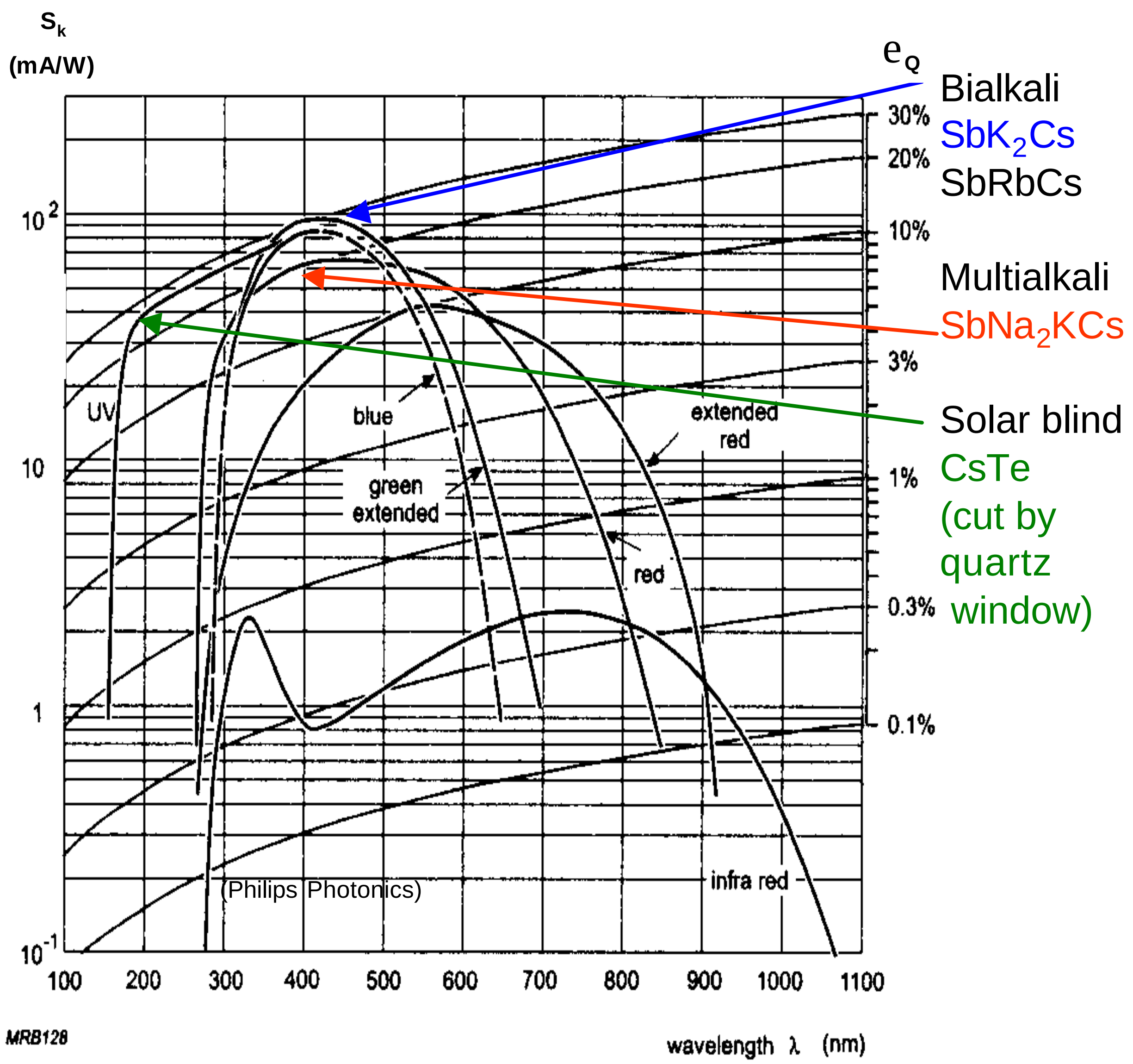
$$e_Q = S_k \frac{hn}{e} = S_k \frac{hc}{l e} \qquad e_Q(\%) \approx 124 \cdot \frac{S_k(mA/W)}{l\,(nm)}$$

ε_Q is relativley difficult to measure with high precision.

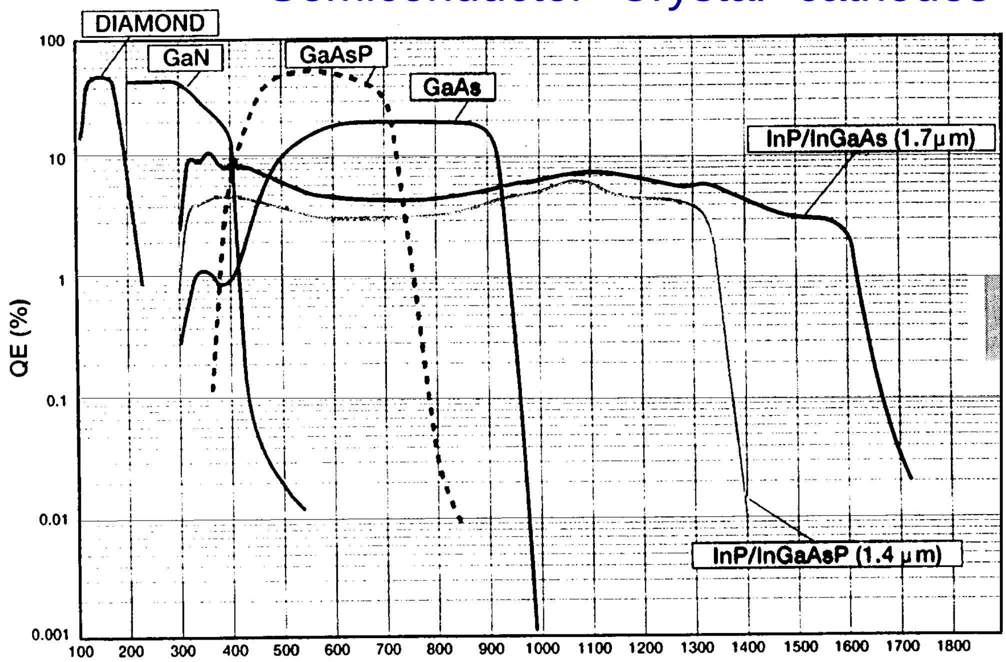
Often one determines only an effective detection efficiency, where other effects are folded in (e.g. internal reflection from a metallic surface, collection of the photoelectrons, electronic threshold…)



Sensitivity of “standard” photocathodes

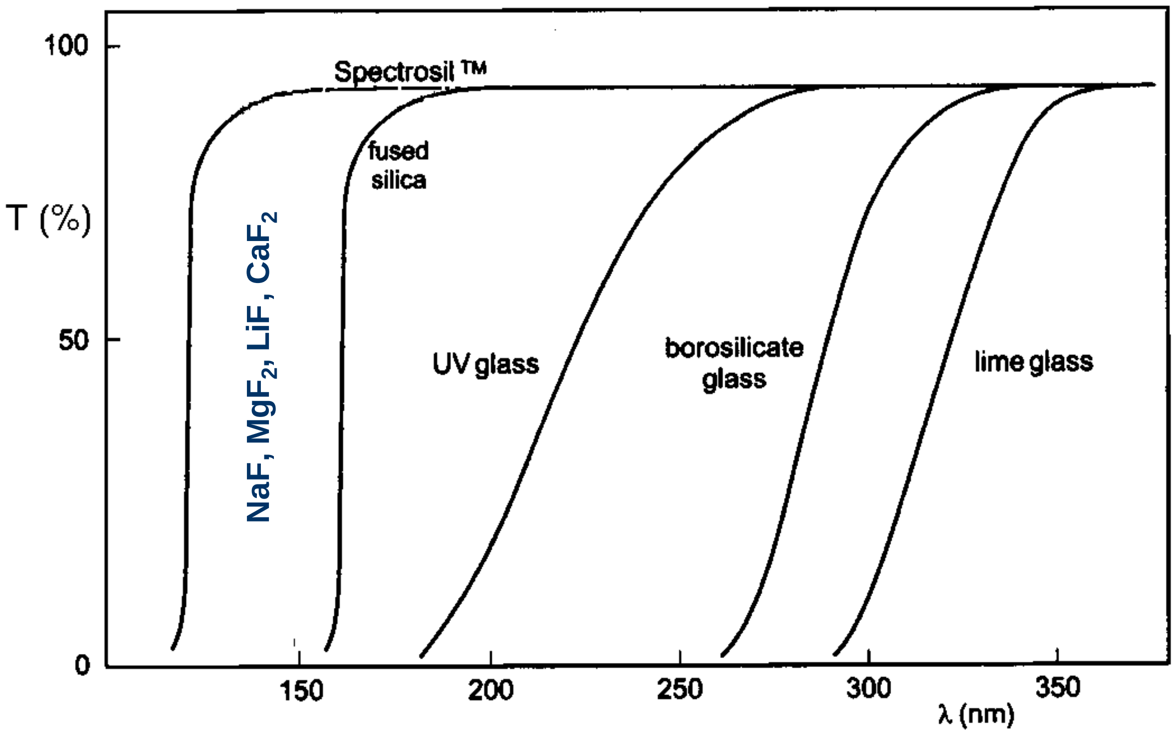


Semiconductor "Crystal" cathodes



(Hamamatsu)

Transmission of frequently used windows



Photocathode fabrication

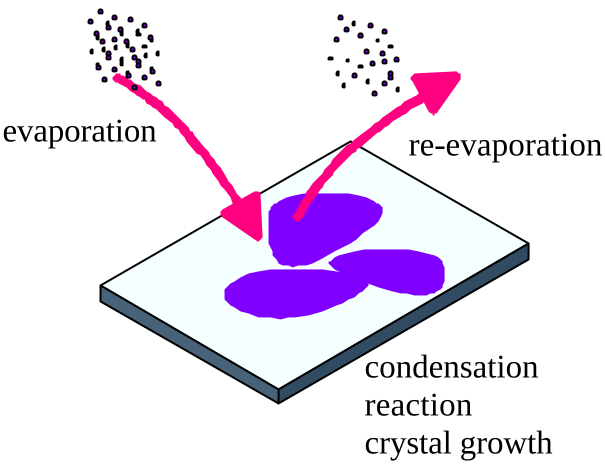
“Metallic” cathodes (alkali)
(SbK_2Cs, SbNaKCs,...)

↓

Vacuum evaporation

Evaporation of metals in a ultra high vacuum. Condensation of vapour and chemical reaction on entrance window.

Relatively simple technique



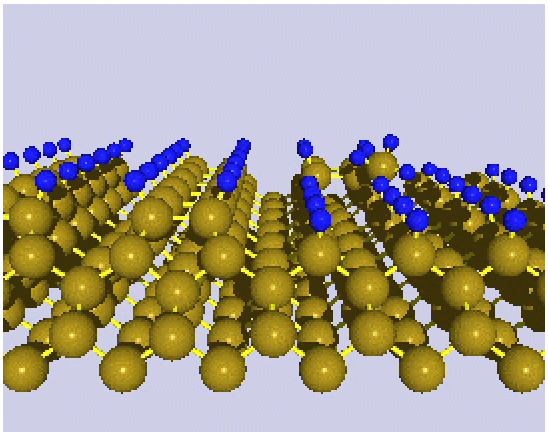
Semiconductor cathodes
GaAs, GaInAs,...

↓

Molecular beam epitaxial growth

Bombardement of a substrate crystal (similar lattice dimensions) with a molecular beam → formation of a crystalline semiconductor

Fairly difficult technique



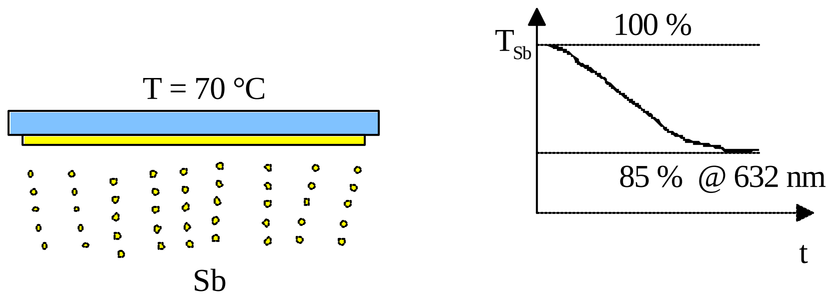
Alkali photocathode fabrication

vacuum requirements

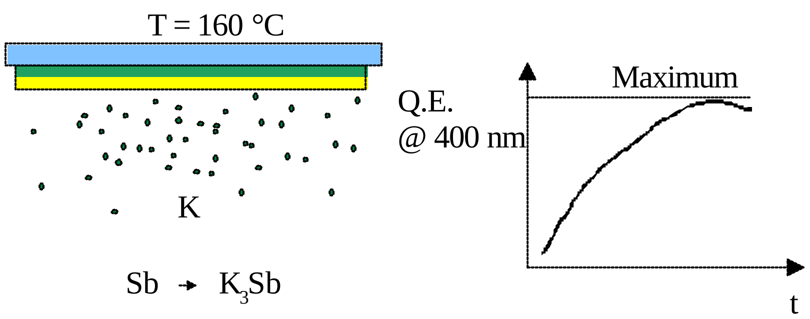
- < 10^{-7} mbar
- < 10^{-9} mbar H_2O partial pressure
- no other contaminants (CO, C_xH_y...)

- thorough bakeout of process chamber (>150°C) and substrate (>300°C) required. The higher the better.

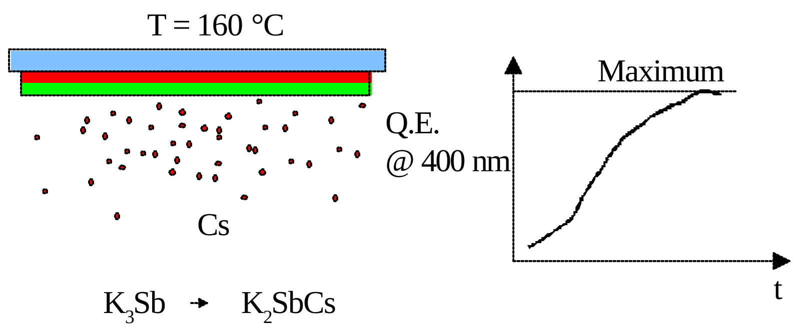
- Example: simplified sequential bialkali process (SbK_2Cs)



$d_{Sb} \approx 5$ nm



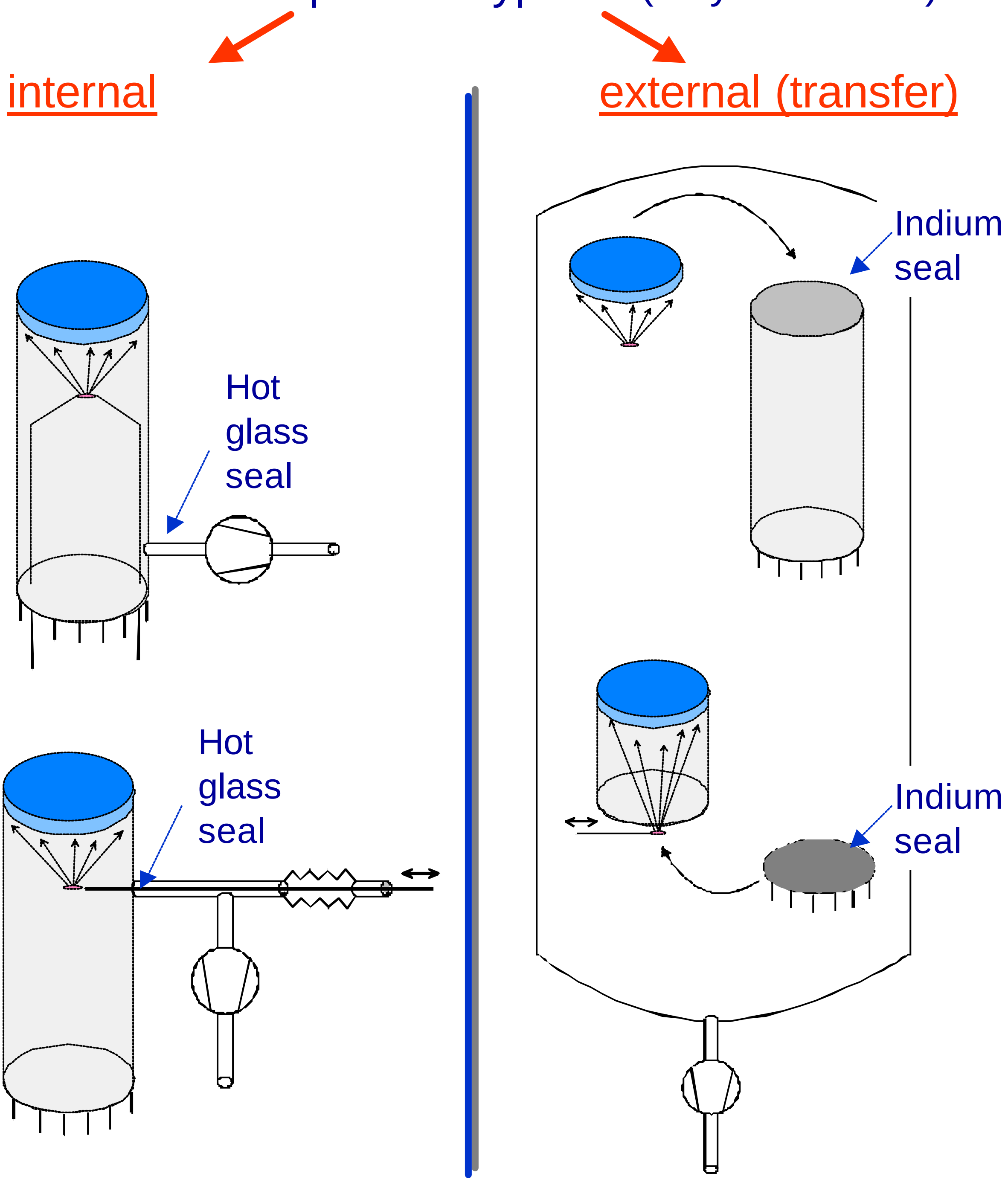
$\varepsilon_Q \approx 3 - 5$ %



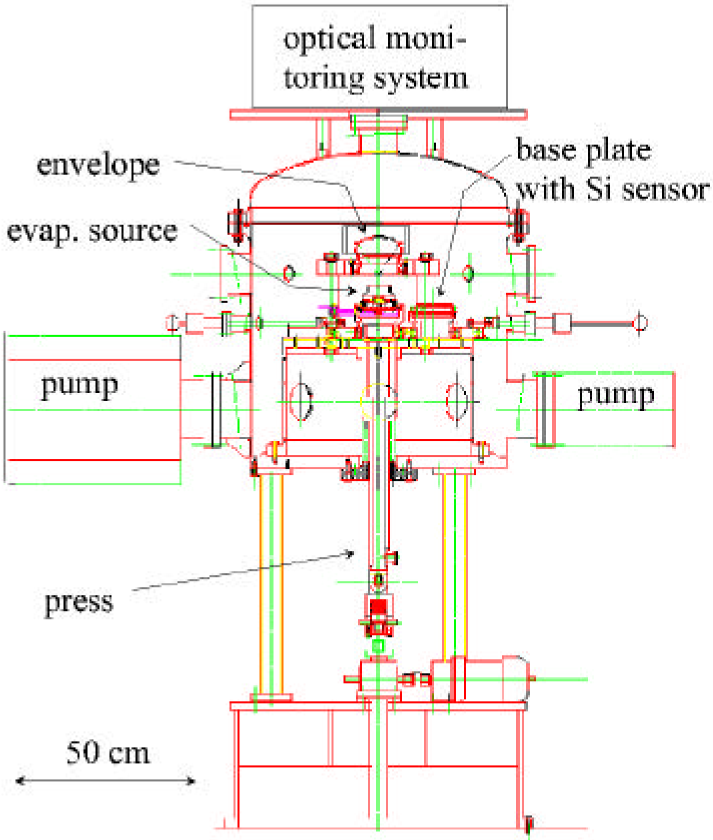
$\varepsilon_Q \approx 15 - 20$ %

Phototube fabrication
(very schematic)

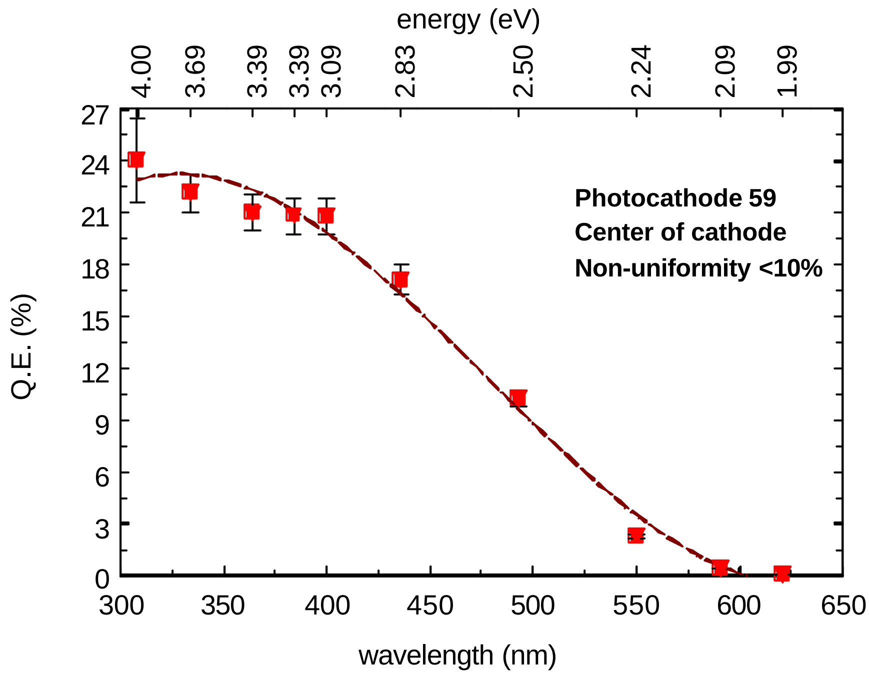
process types (very schematic)



Tube manufacturing (photocathode processing, sealing). CERN/LHCb

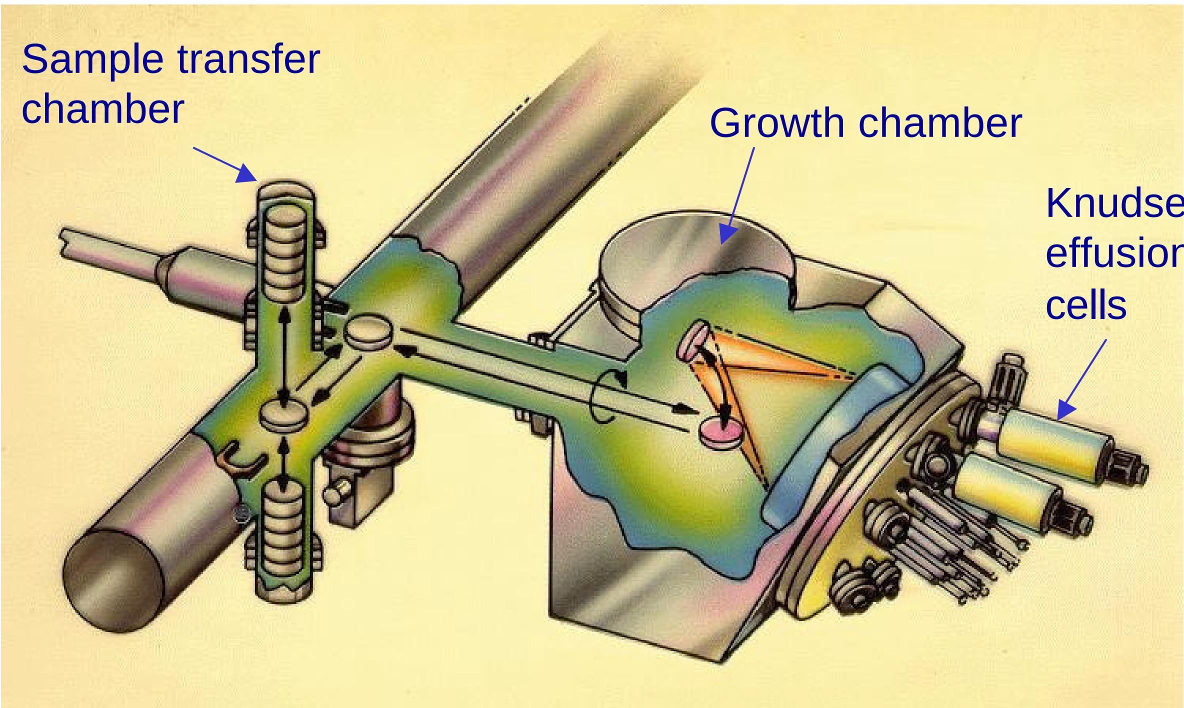


The evaporation and encapsulation facility



Semiconductor photocathode fabrication

Method: Molecular beam epitaxial growth.
Very stringent vacuum requirements (10^{-10} mbar)



How to produce semitransparent cathodes ? (very schematic)

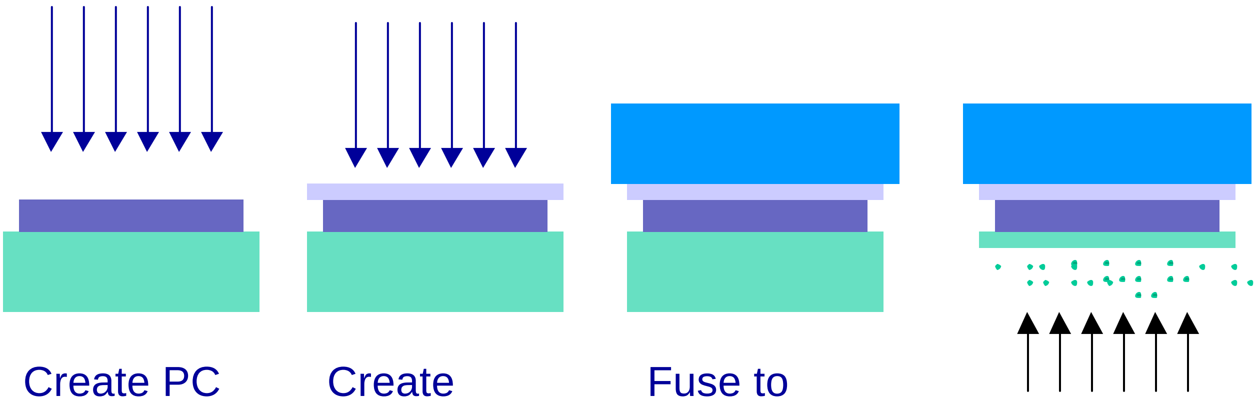
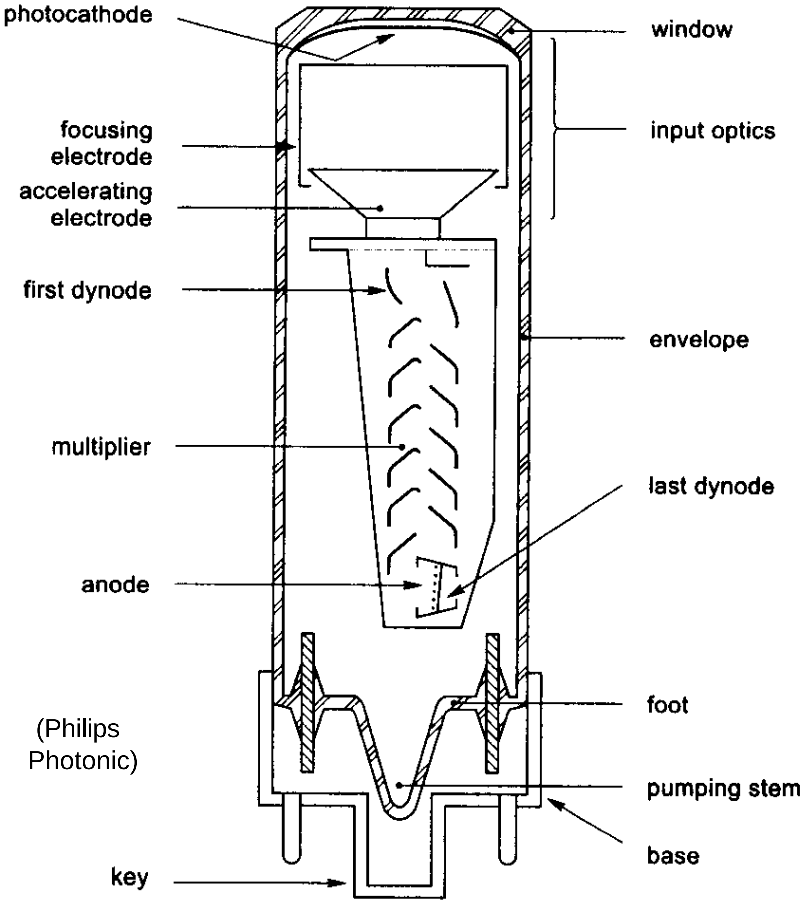


Photo Multiplier Tubes

basic principle:



(Philips Photonic)

- photo emission from photo cathode.
  $Q.E. = N_{p.e.}/N_{photons}$
- 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 $M = 4^{10} \approx 10^6$

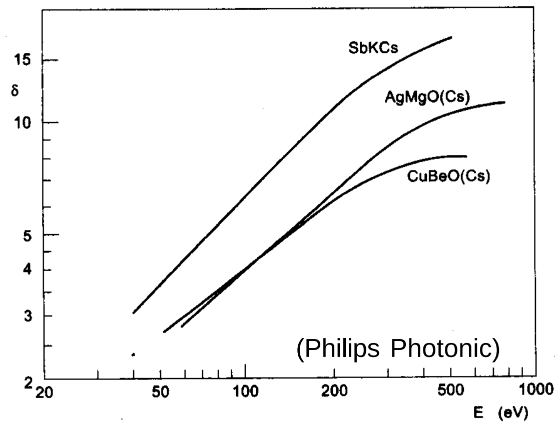
Gain spread / Energy resolution

Mainly by the fluctuation of the number of secondary electrons emitted from the first dynodes.

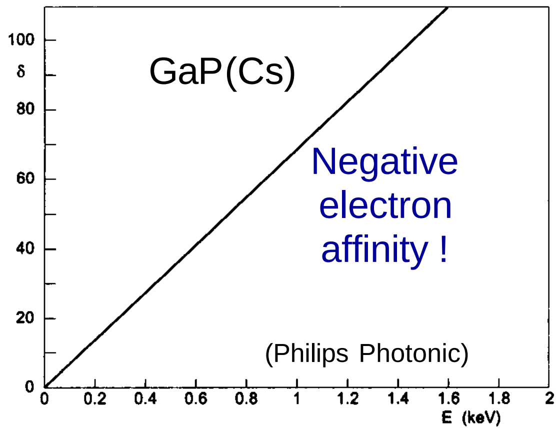
Poisson distribution: $P(\bar{n},m) = \frac{\bar{n}^m e^{-m}}{m!}$

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

Fluctuations biggest, when $\bar{n}$ small ! $\rightarrow$ 1st and 2nd dynode !

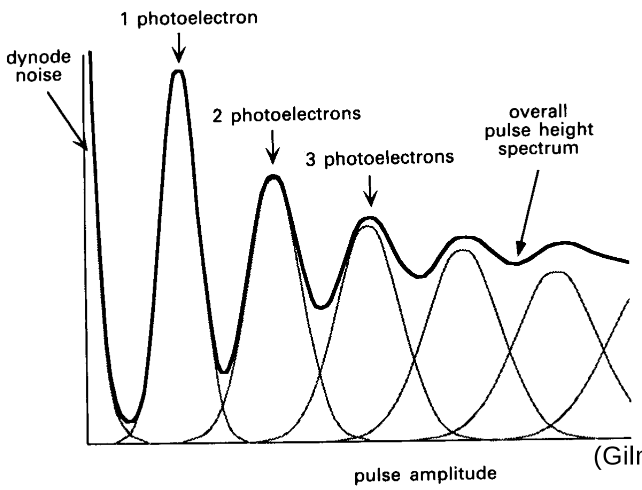


(Philips Photonic)



(Philips Photonic)

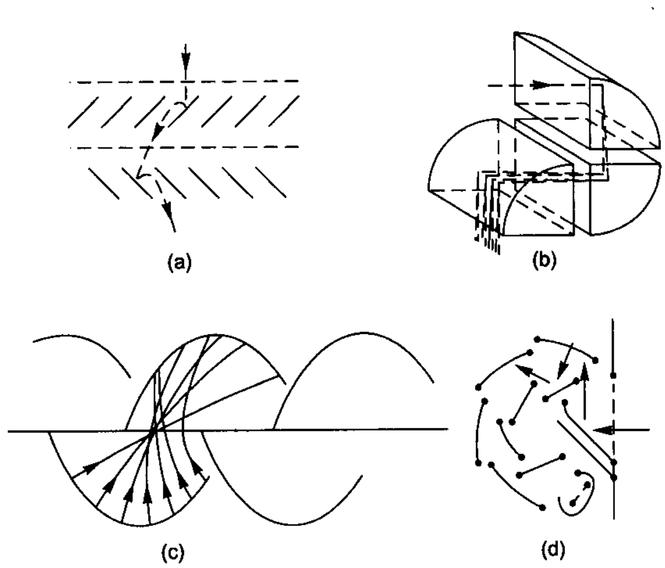
Backscattering ($\eta \approx 0.25$, $\propto Z_{dynode}$) reduces effective δ !



(Gilmore)

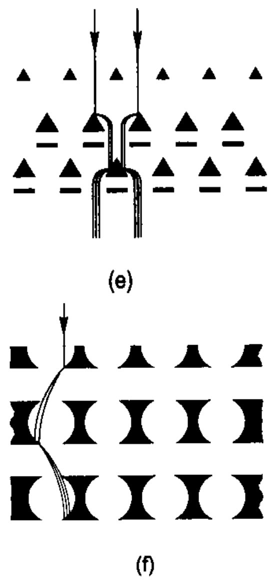
Illustration of a pulse height spectrum of a PM. First dynode: δ = 25

Dynode configurations

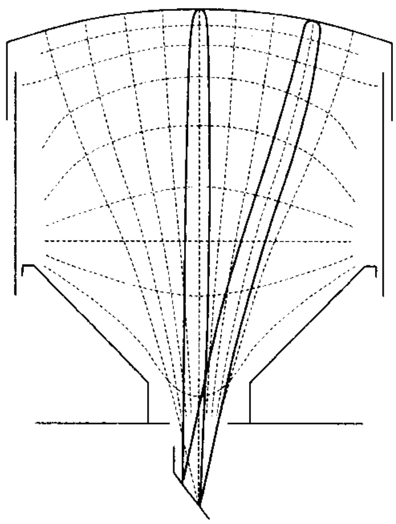


(Philips Photonics)

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



position sensitive PM's

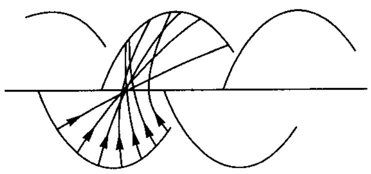


Equi-potentials and trajectories in a fast input system

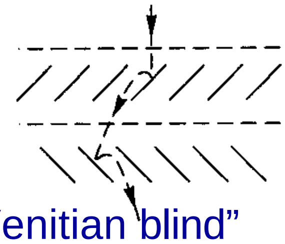
"Fast" PM's require well designed input optics to limit chromatic (energy spread) and geometric aberrations (path length)
→ transit time spread < 200 ps

Sensitivity to magnetic fields

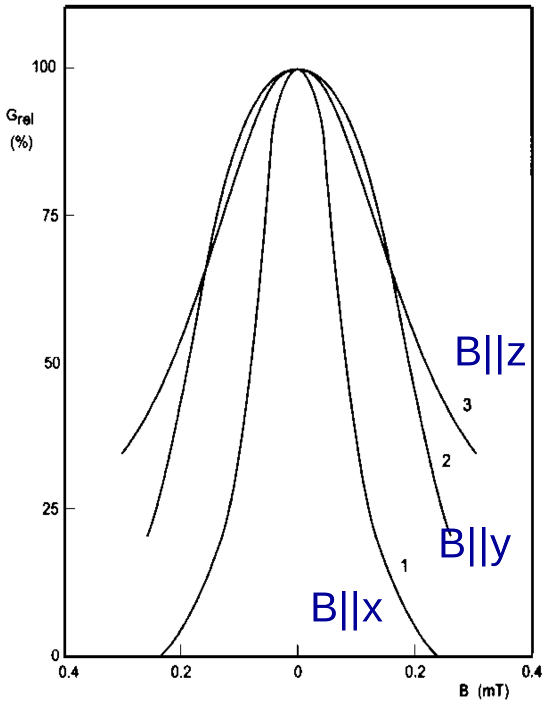
PM's are in general very sensitive to B-fields, even to earth field (30-60 μT). μ-metal shielding required.



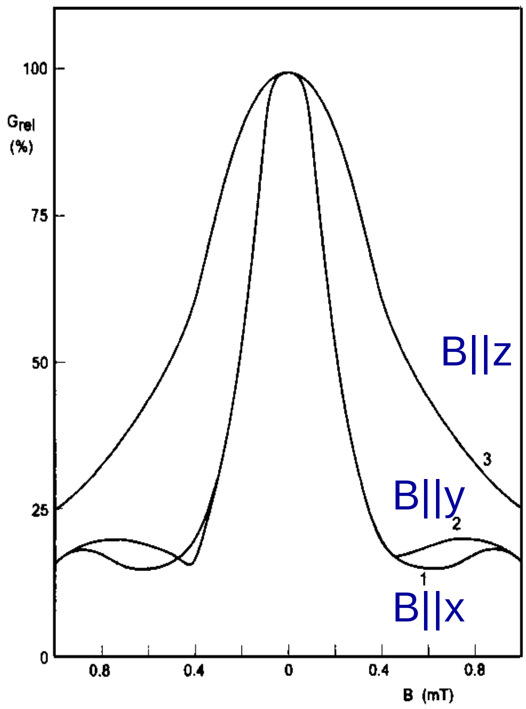
"Linear focusing"



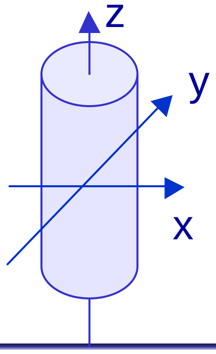
"Venitian blind"



±50 μT
± 0.5 Gauss



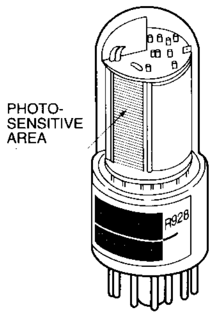
± 200 μT
2 Gauss

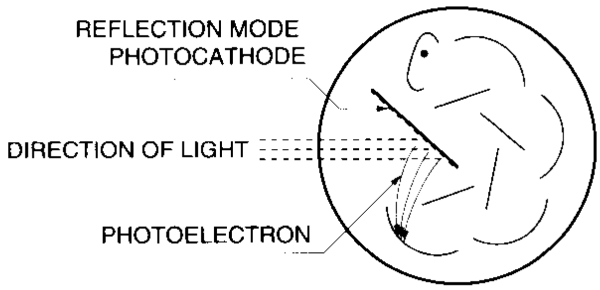


Photomultiplier types used in RICH detectors

- **Standard:** cylindrical head on multipliers
  exist in a large range of diameters (3/8”-5”)
  examples: DIRC (BaBar), HERMES

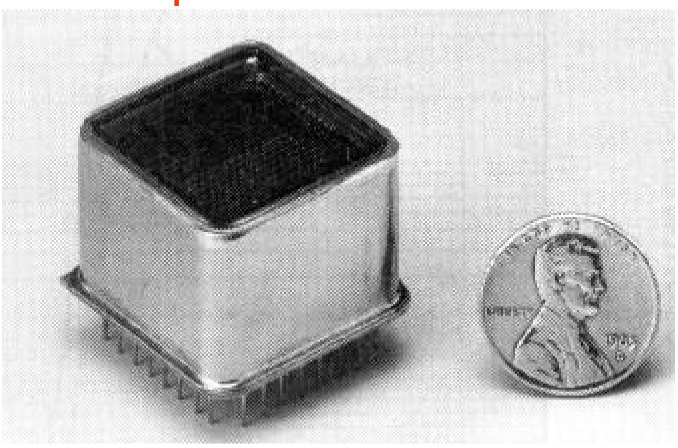
Side on PMTs (opaque PC) are not used for RICH applications.



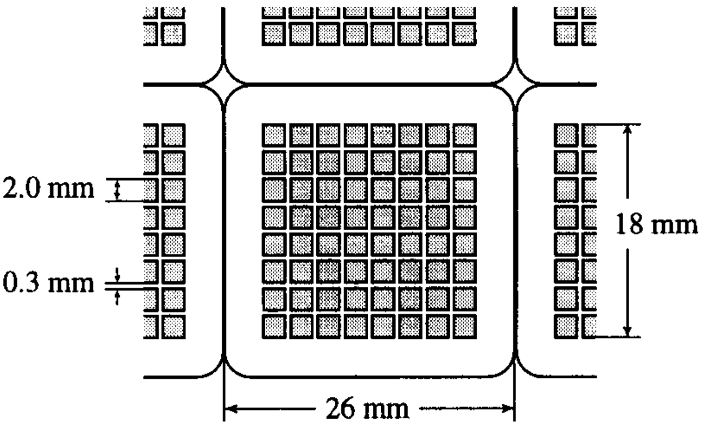


- **Position sensitive PMs**
  examples: HERA-B, LHCb (backup)

Position sensitive Multi Anode PM
example: Hamamatsu R5900 series.

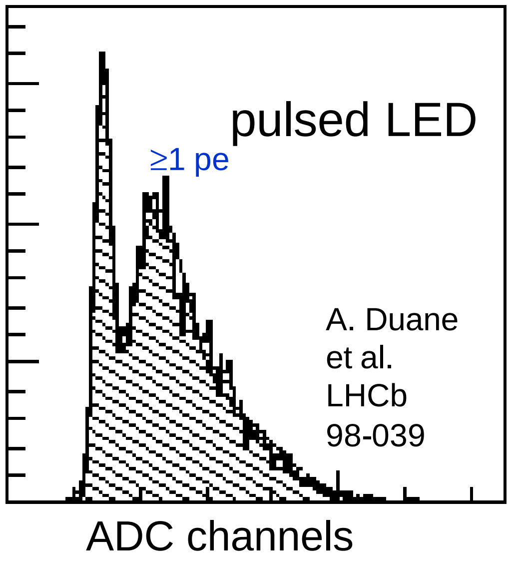


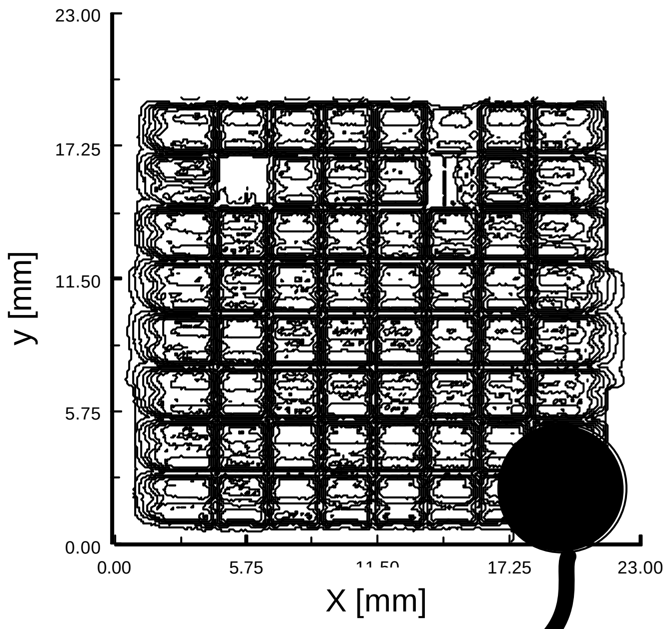
Up to 8x8 channels.
Size: 26x26 mm^2.
Bialkali PC:
Q.E. = 20% at
λ_{max} = 400 nm.
Gain $\approx 10^6$.



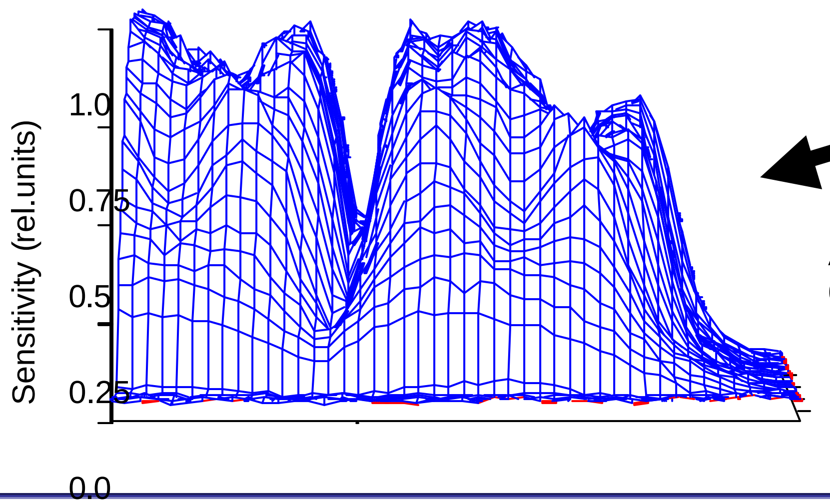
Active area fraction 38%.

Pulse height spectrum of Hamamatsu R5900



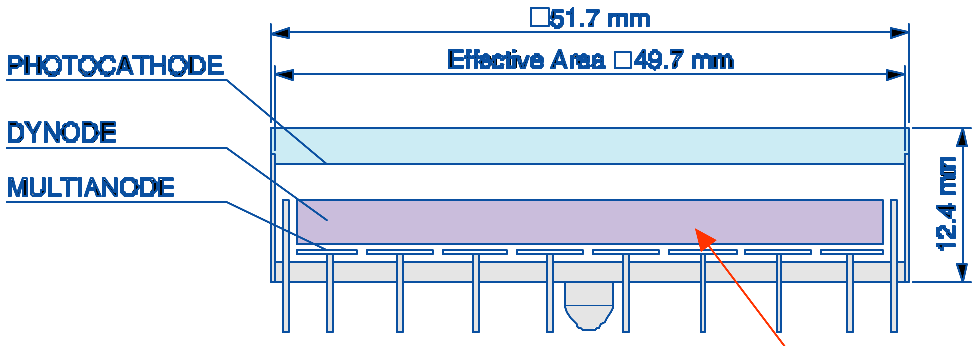


Collection efficiency of R5900-64 is not very uniform. Deep valleys between pixels.



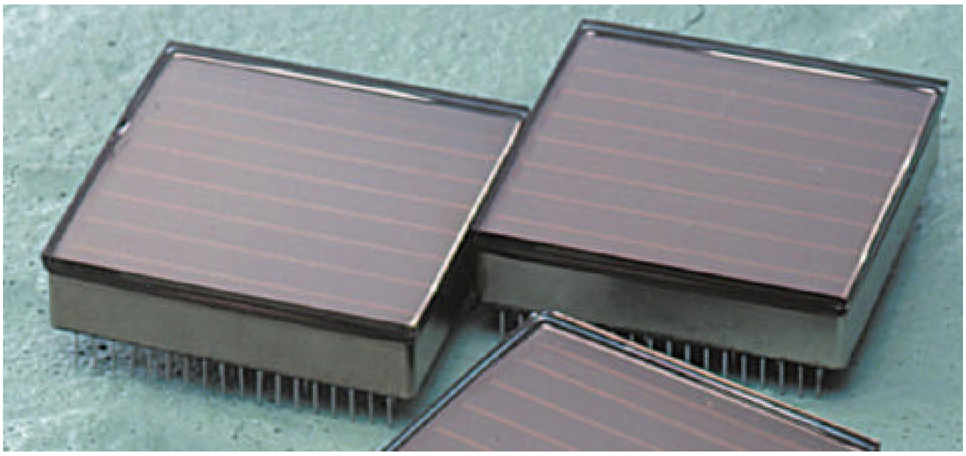
A. Duane et al. LHCb 98-039 and
N. Smale, Oxford Univ., private communication

Example:
Hamamatsu Flat Panel PMT (FPP)

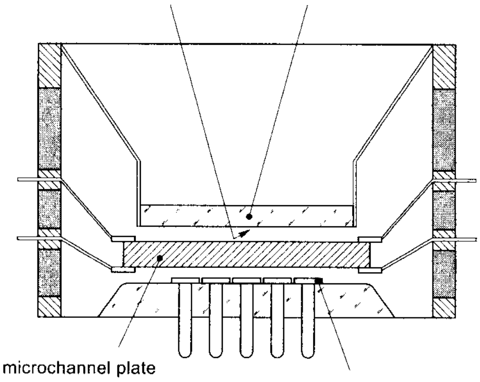


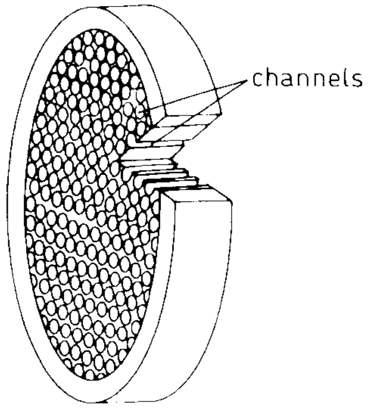
10 stage metal channel dynode ($G \approx 10^6$)

Excellent surface coverage (>90%)
Bialkali PC, $\varepsilon_Q \approx 20\%$ (blue)
Availability: Soon !?
Price: “cost/surface cheaper than for MaPMT”



Micro Channel Plates





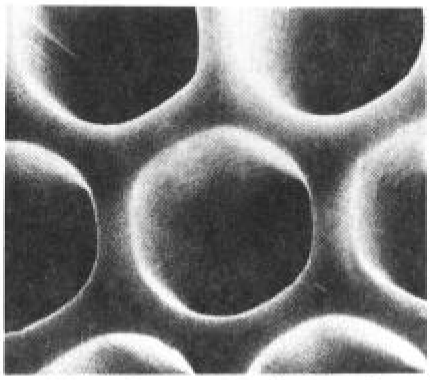
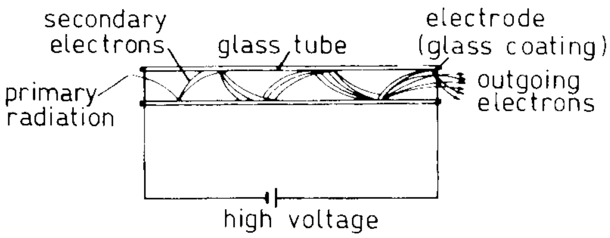


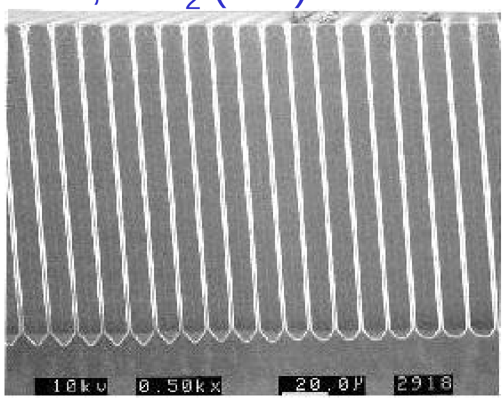
Fig. 5.6. Microphotograph of microchannels [384].



(Philips Photonics)

+ fast signal (transit time spread $\approx$ 50 ps),
+ little sensitive to B-field (0.1 T)
+ 2-dimensional readout possible
- limited life time (0.5 C/cm^2)
- limited rate capability (µA/cm^2)

New development: MCP on Si, SiO_2 (+…) basis

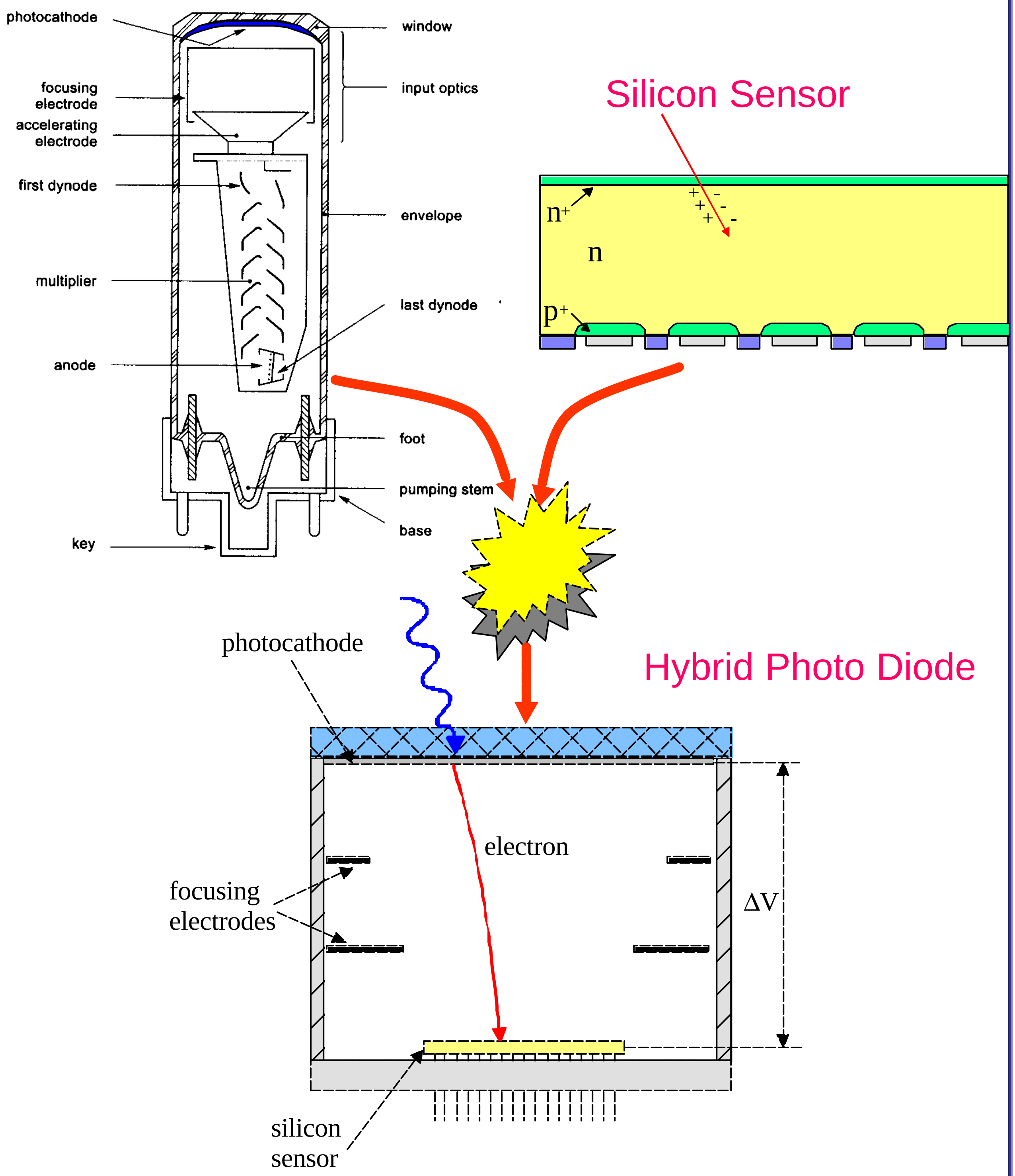


www.nanosciences.com

Precise photolithographic manufacturing
Very low background rate
chemically inert

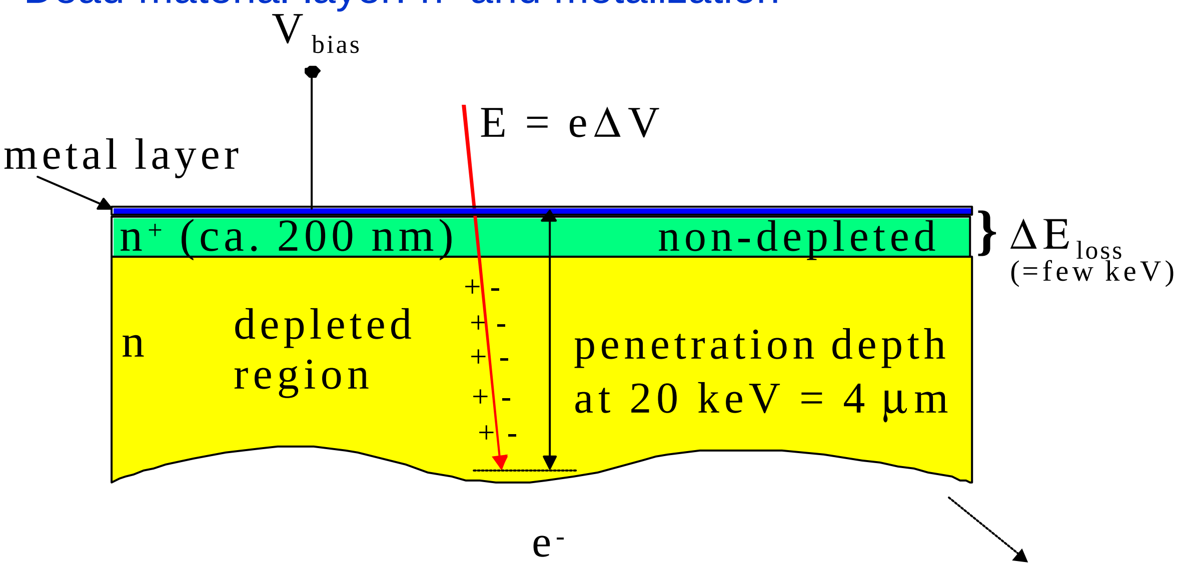
Hybrid Photo Diodes

Photo Multiplier Tube



Why use a Si sensor ?

- $W_{e/h}$(Silicon) = 3.6 eV
- But no internal amplification, i.e. gain $G_{Si} = 1$
- Dead material layer: n^+ and metalization

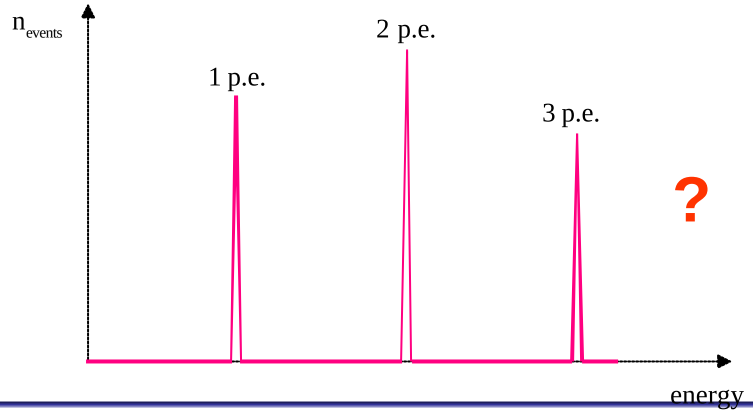


fast signals
$t_{rise} \leq 1ns$

- Gain of the HPD: $$G_{HPD} \approx \frac{e\Delta V - E_{loss}}{W_{e/h}}$$
- Example: $\Delta V = 20kV, E_{loss} = 2keV \rightarrow G_{HPD} = 5000$

→ Expected energy resolution (m photoelectrons):

$$s^{m}_{int.} = \sqrt{m \cdot F \cdot G_{HPD}} = \sqrt{m} \cdot 22\, e \quad with\ F_{Si} = 0.1$$

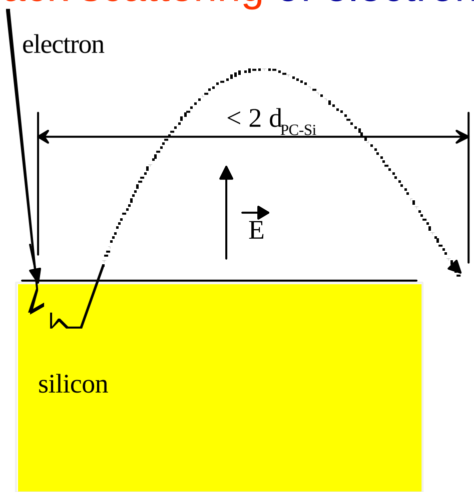


But…

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

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

- Back scattering of electrons from Si surface

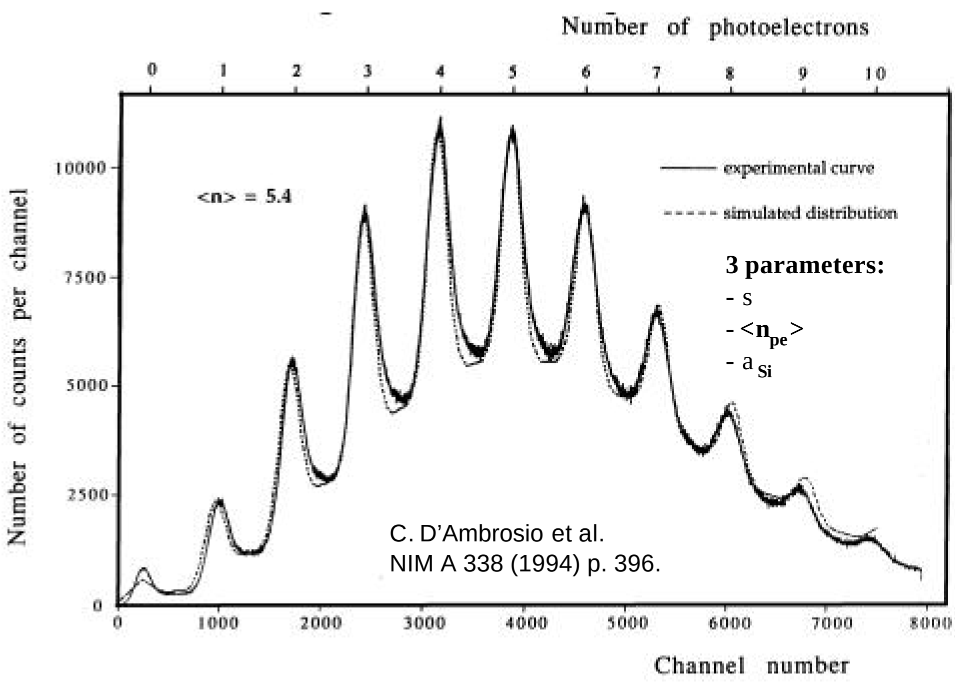


back scattering probability at E ≈ 20 kV

$$a_{Si} \approx 0.2$$

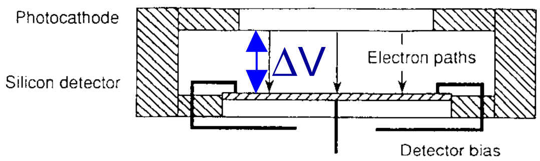
20% of the electrons deposit only a fraction o≤ε<1 of their initial energy in the Si sensor .

→ continuous background (low energy side)



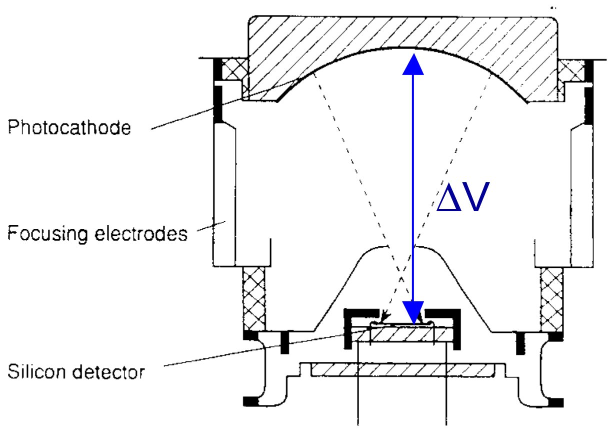
HPD Designs

proximity focusing (i.e. no focussing)



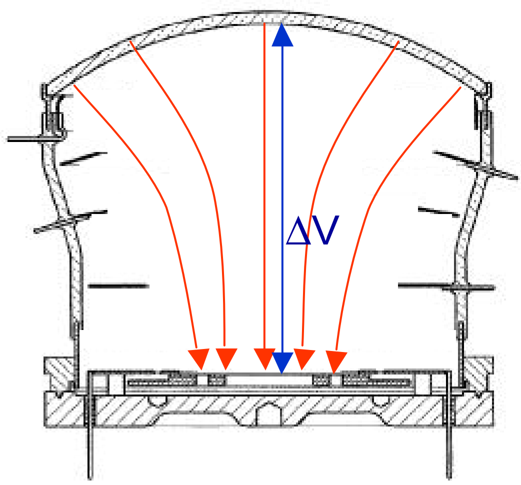
- demagnification = 1
- $A_{sensitive} = A_{silicon}$
- small gap → insensitive to B-field

cross focusing



- demagnification > 1
- $A_{sensitive} > A_{silicon}$
- optics allows very good spatial resolution
- typical small pin cushion distortion for large r
- large gap → sensitive to B-field

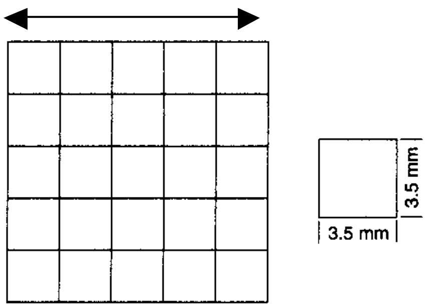
fountain focusing



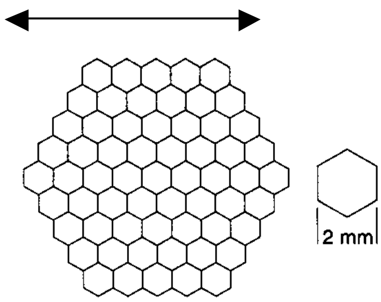
- demagnification > 1
- $A_{sensitive} > A_{silicon}$
- uniform mapping but lower spatial resolution
- large gap → sensitive to B-field

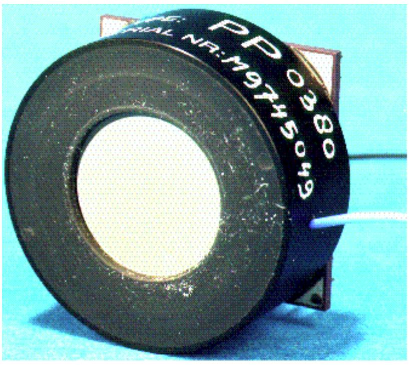
Commercially available HPD's

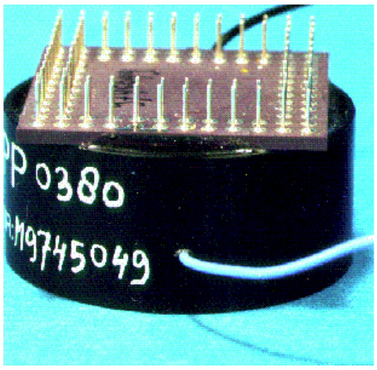
- DEP (Delft Electronic Products, NL)
  - ➔ various single pixel (upto 40 mm Ø)
  - ➔ and multi pixel (7, 25, 61) HPD's, prox. focused
  - ➔ electronics not enclosed in tubes



25 pixel structure



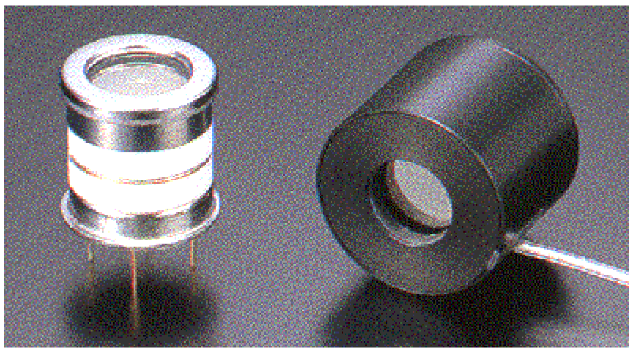




DEP 61 pixel HPD

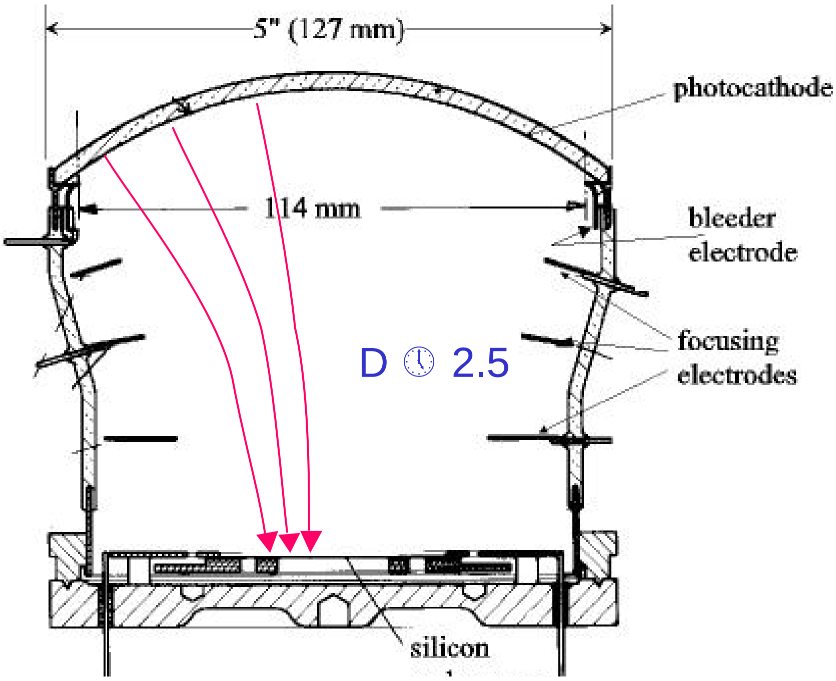
Problem: sensitive area fraction « 50%

- Hamamatsu (Japan)
  - ➔ only single pixel Si PIN diode or APD, proximity focused
  - ➔ S20 or GaAsP(Cs) photocathode
  - ➔ sensitive area: 8 mm Ø
  - ➔ gain: 1600 (PIN), 65000 (APD)
  - ➔ active area fraction: 16%

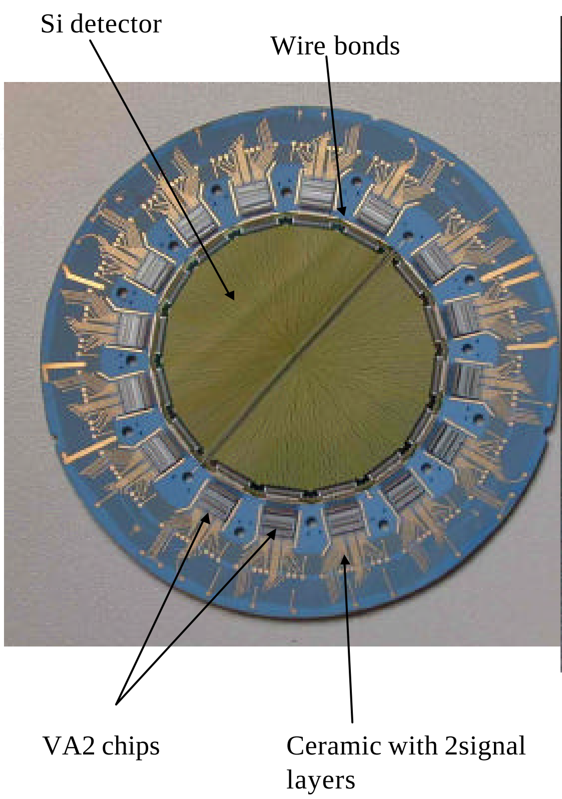


5'' Pad-HPD prototype

developed for the LHCb RICH



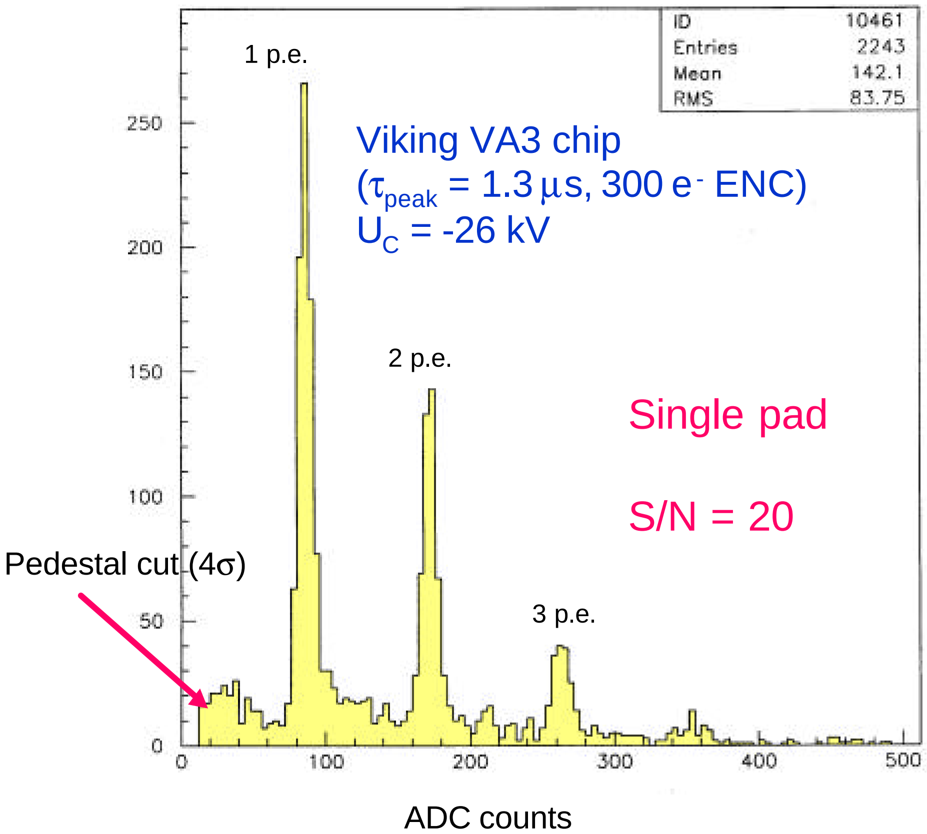
- fountain-focused
- 2048 pixels
- electronics enclosed in vacuum envelope.
- active area 91%

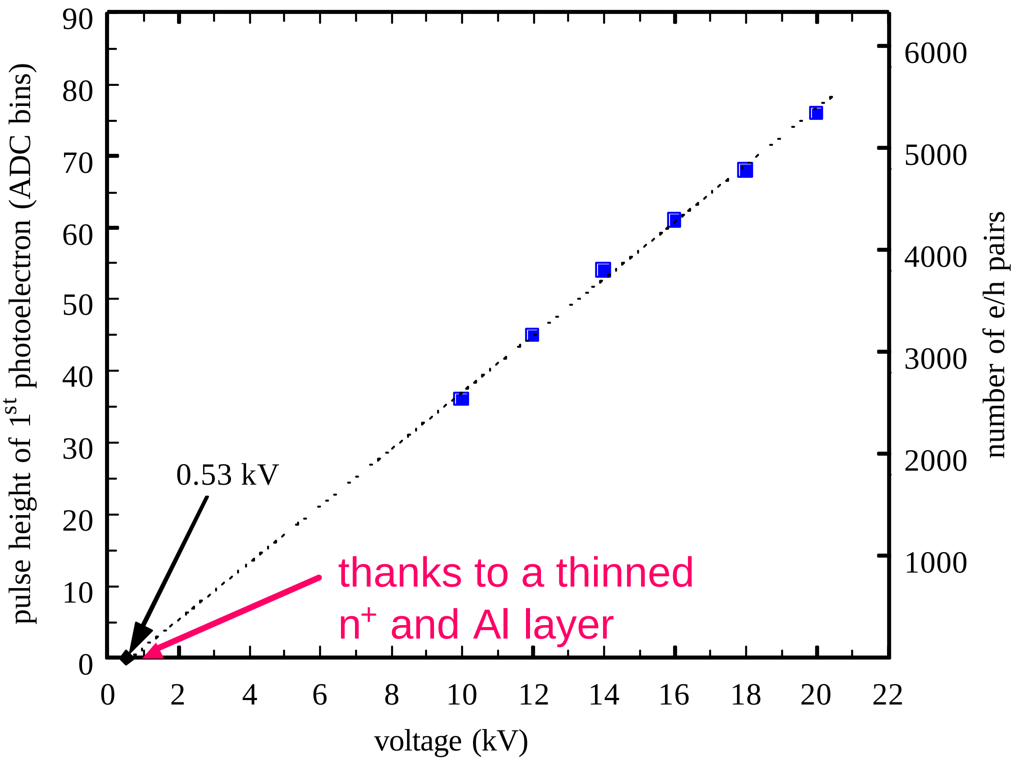


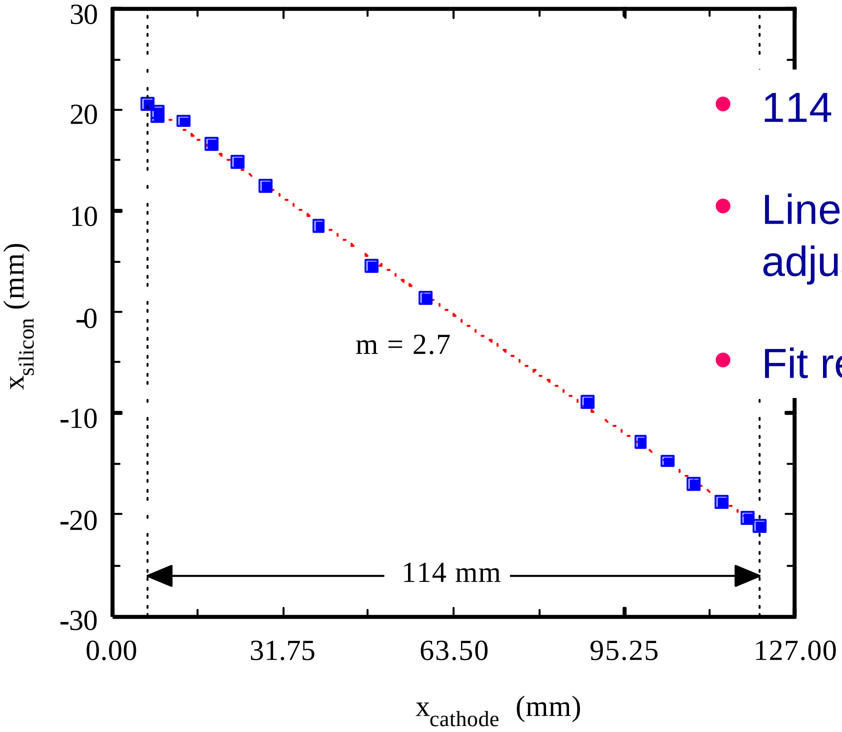
Pad size 1 x 1 mm^2

A. Braem et al., NIM A 442 (2000) 128

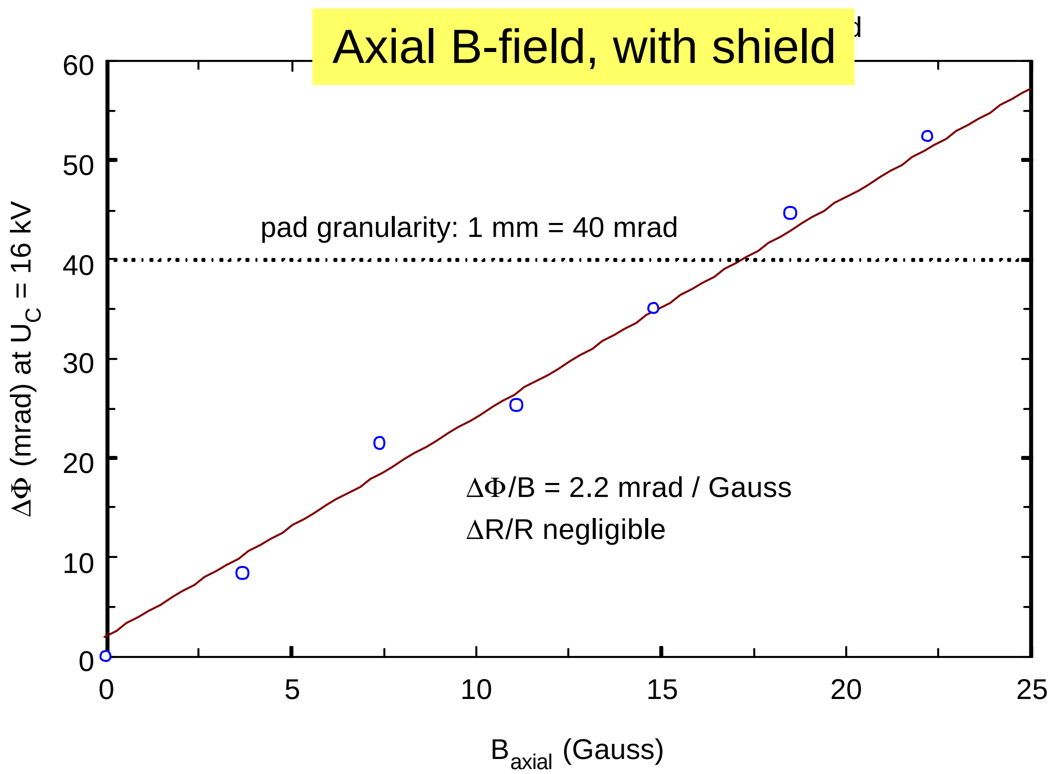
Signals on the Si sensor







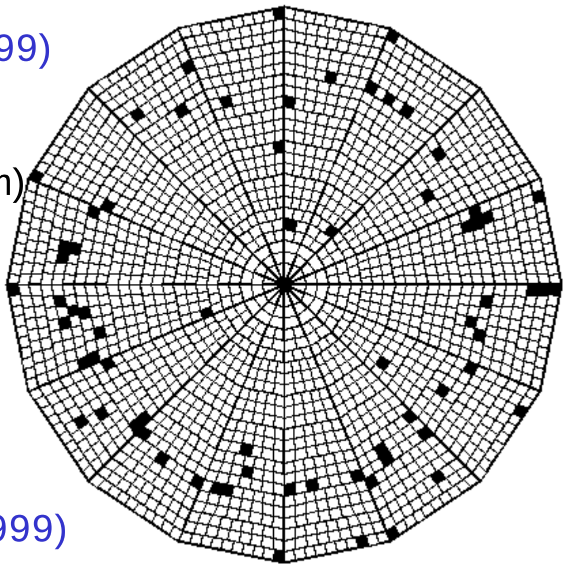
- 114 mm active ∅
- Linear demagnification, adjustable
- Fit residuals ≈200 µm



Testbeam (Sep. 1999)
1 Pad HPD

C_4F_{10} radiator (1.8m)

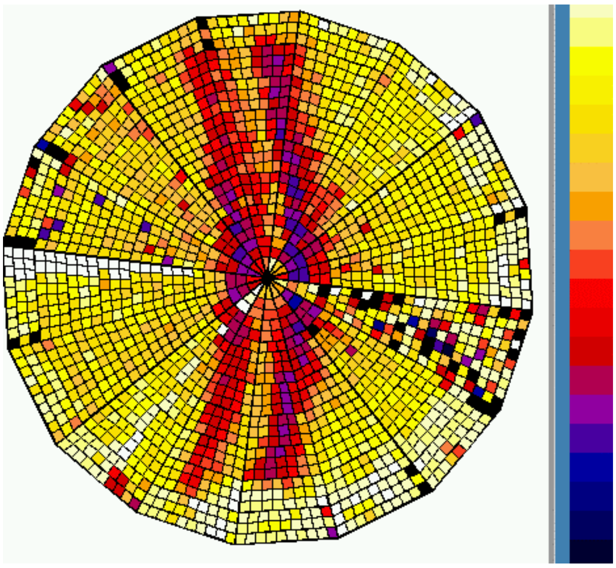
Single event



Testbeam (Nov. 1999)
2 Pad HPD

Aerogel radiator

Multi-event display
(π + p at 8 GeV)



M. Alemi et al., LHCb note 2000-76 RICH, in preparation