Photo – Multiplier Technologies

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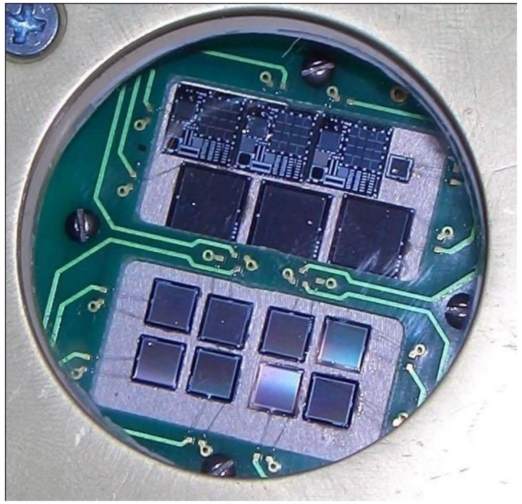
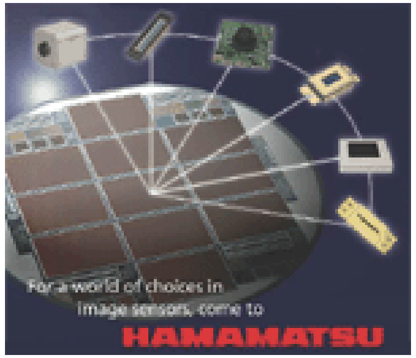
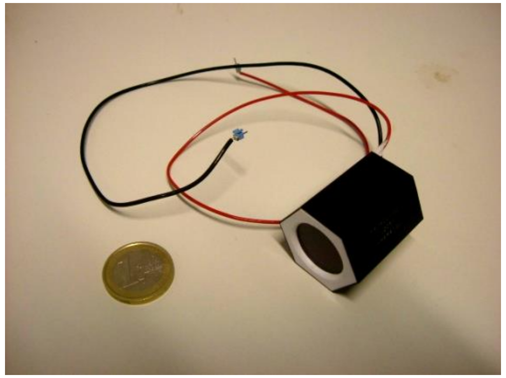
The „zoo“ of LLL sensors







Vacuum Light Sensor Types

- Quantum Efficiency
- Photo-multipliers (including large area ones, e.g. SuperK)
- Multianode (MaPMTs)
- HAPDs
- hybrid HPDs
- Ways to further enhance the QE

Quantum Efficiency

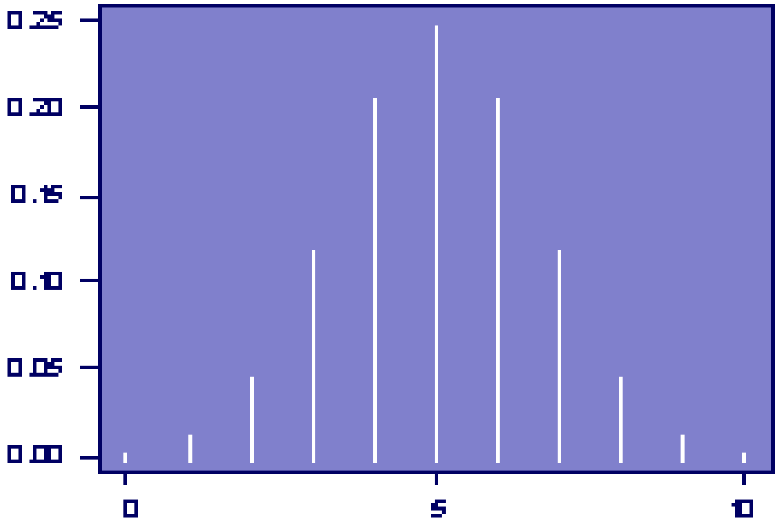
Quantum efficiency (QE) of a sensor is defined as the ratio

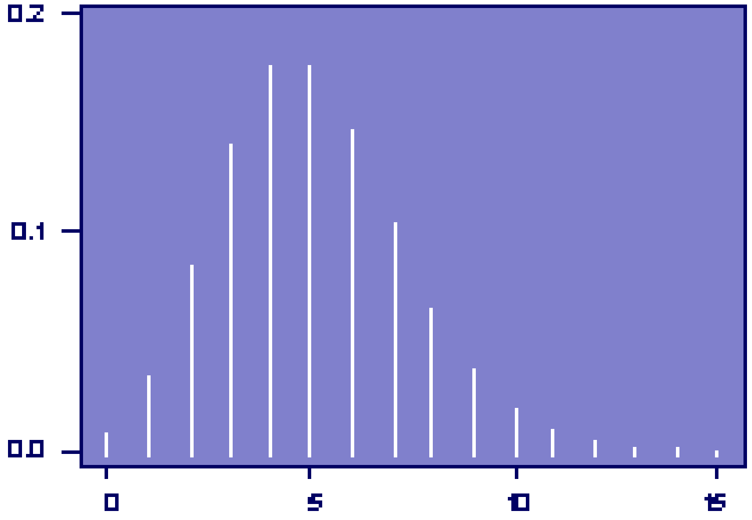
$$QE = N(ph.e.) / N(photons)$$

Conversion of a photon into ph.e. is a purely binomial process (and not poisson !)

Light sources of thermal origin can be described by the poisson distribution (including LED)

Differences between binomial and poisson distributions


Binomial (n=10, p=0.5)
Probability Density Function


Poisson (mean=5)
Probability Density Function

SNR = 3.16

mean/σ = 2.24

Signal to noise ratio

The signal-to noise ratio of a light sensor can be calculated as

$$\mathbf{SNR = [N \times P/(1 - P)]^{1/2}}$$

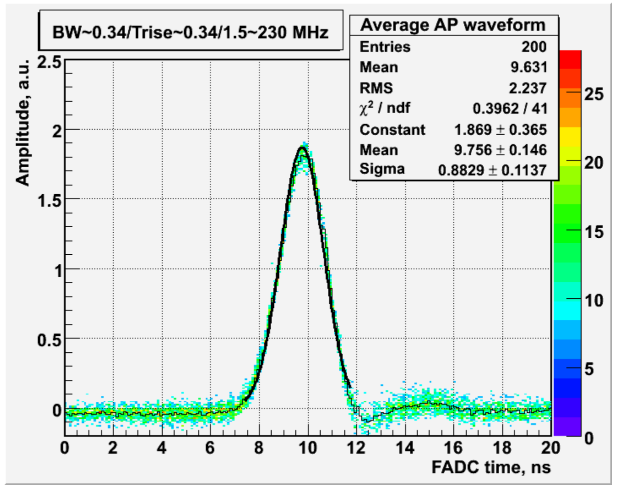
For example, if N = 1 (single impinging photon):

P	0.1	0.3	0.9
SNR	0.33	0.65	3

One of the best known light sensors: the classical PMT

- The impinging photons kick out e- from the thin photo cathode (~25nm)
- e- are accelerated in a static electric field (~100V) and hit dynodes arranged in a sequential topology
- Every dynode enhances the number of e- by a factor 4-5
- The net gain of a PMT could be $3x10^4 – 10^9$
- That allows measuring single photons

PMTs for MAGIC developed by ETE, Hamamatsu, Photonis

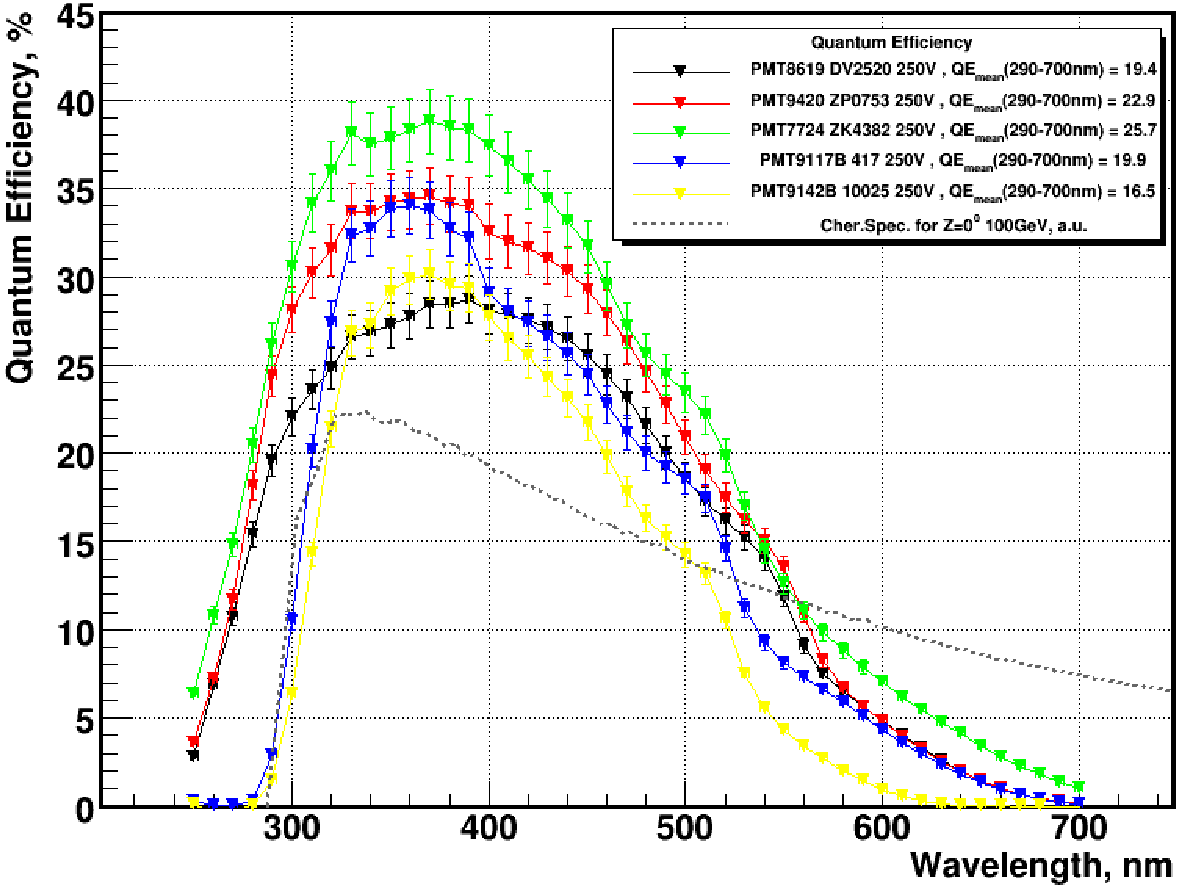


1-inch hemispherical MAGIC-type PMTs:

- ultra-fast resonse; ETE PMT: rise tome 600ps, fall time 700ps, FWHM = 1.2ns
- possible due to 6 dynodes
- hemisperical shape photo cathode
- providing double crossing of photons (the highest probability of the semi-transparent photocathode is ~60% @ 400nm) with light guides
- low gain → slow ageing in time

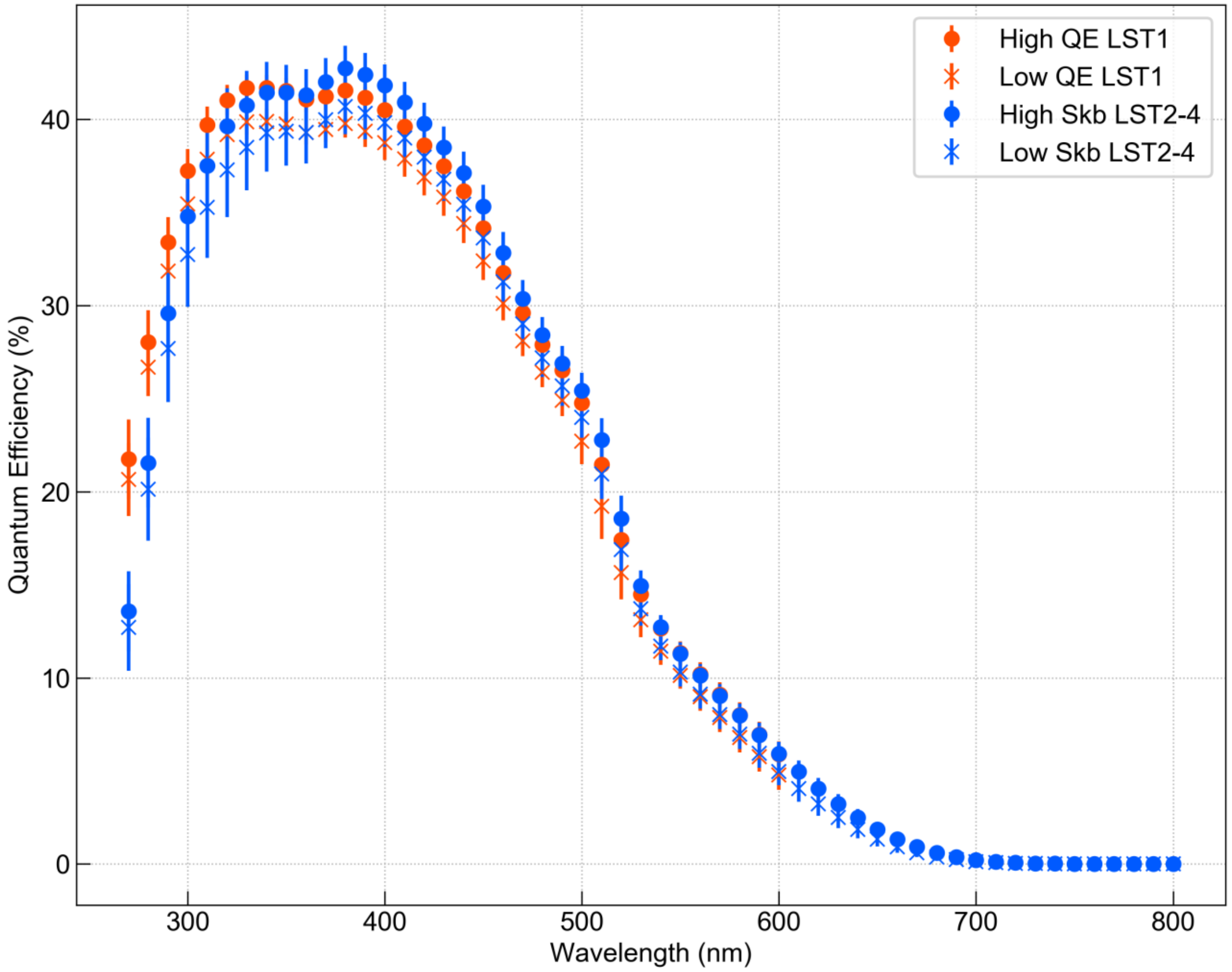
Instrumental/technological improvements

Running target: light sensor improvements. Successfully pushing the PDE higher up. Shown for several types of PMTs



- Some 16 years ago we have launched a QE improvement program with manufacturers Hamamatsu (Japan), Photonis (France) and Electron Tubes Enterprises (England).
- The results were very encouraging, → superbialkali PMTs
- About 11 ago years we launched a new improvement program for CTA PMTs

QE for novel 1.5 inch PMTs from Hamamatsu (~1200 PMTs)



credit: M. Takahashi

Type: R12992-100-05

PMT Light Emission

Ahnen, et al., IEEE TNS, 2015

2.3.1 Set-Up

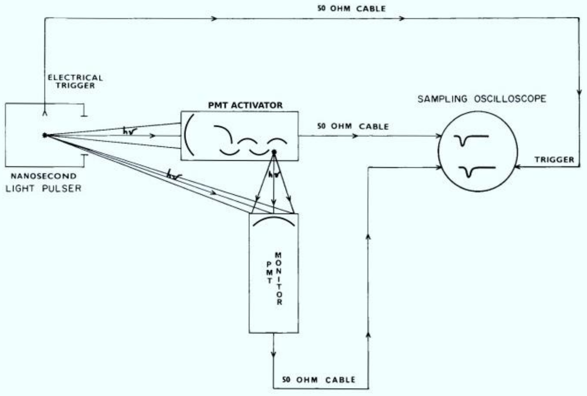
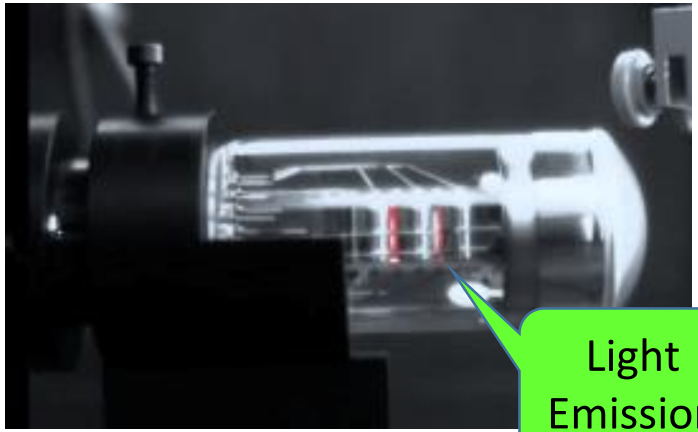


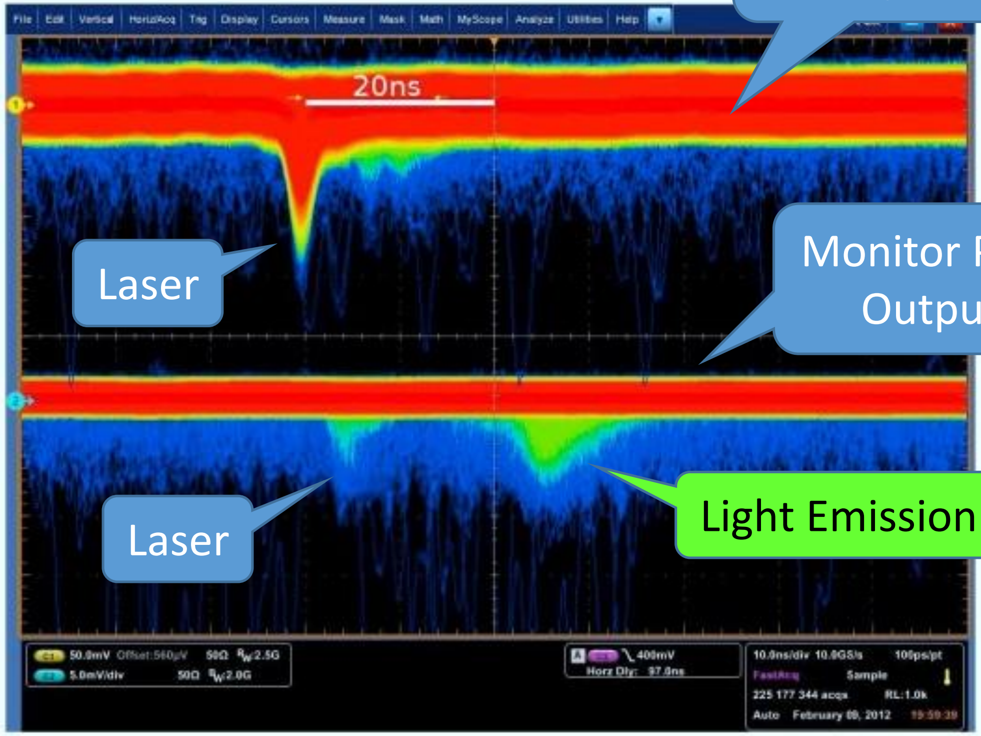
Figure 2.2: The photomultiplier dynode glow test apparatus, sketch adapted from [10]



Light Emission

2.3.3 Results

A screen capture of the oscilloscope with more than 200 million
Fig.2.3. The individual peaks on the activator photomultiplier are



R11920-100 Output

Laser

Monitor PMT Output

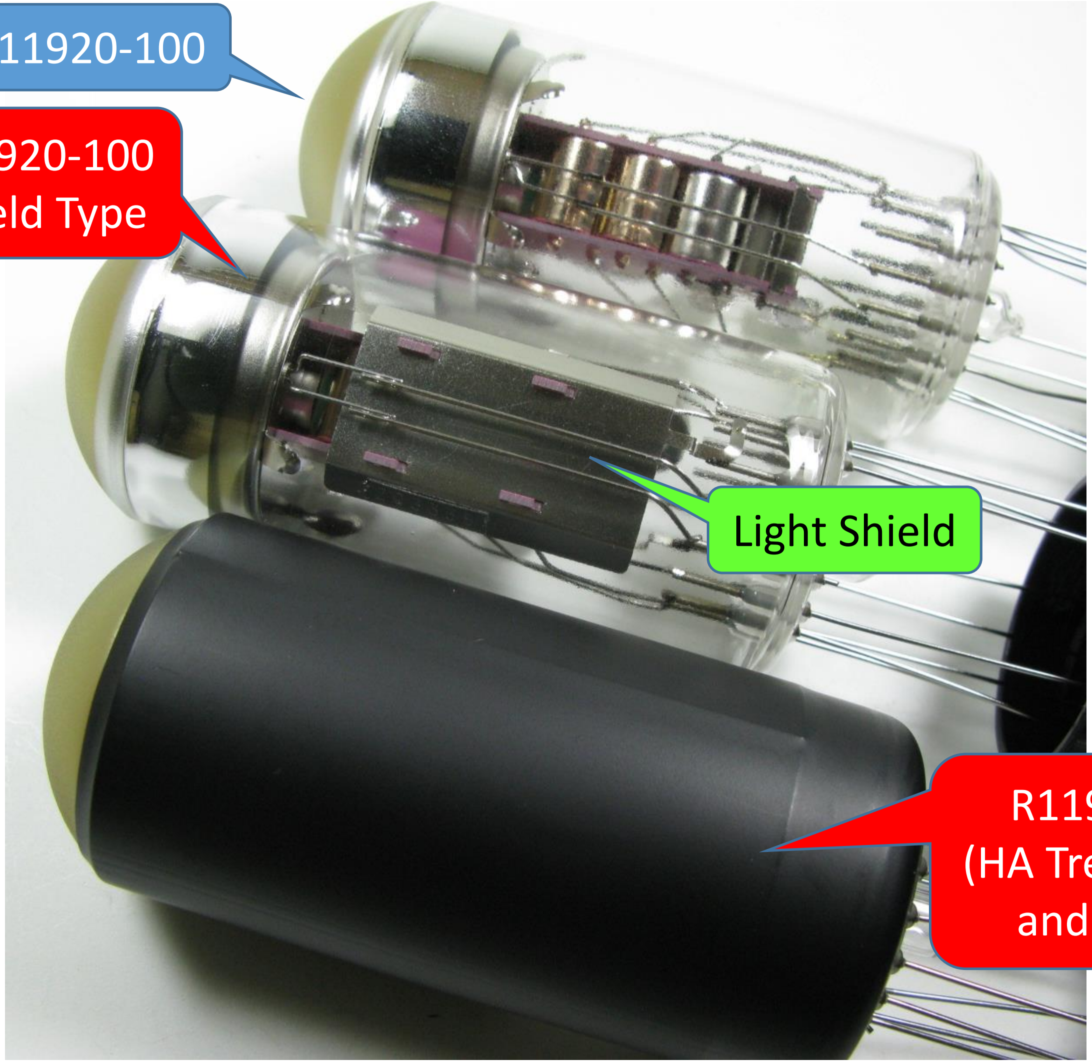
Laser

Light Emission

Figure 2.3: Measurement of the activator photomultiplier (top) and the monitor photomultiplier (bottom).

Hamamatsu Solution to Block the Light Emission

Ahnen, et al., IEEE TNS, 2015

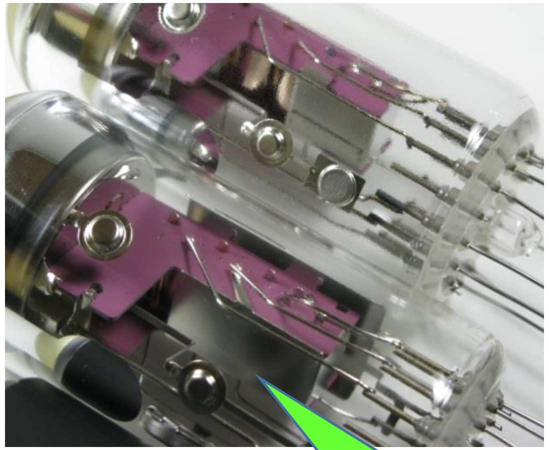


R11920-100

R11920-100
Shield Type

Light Shield

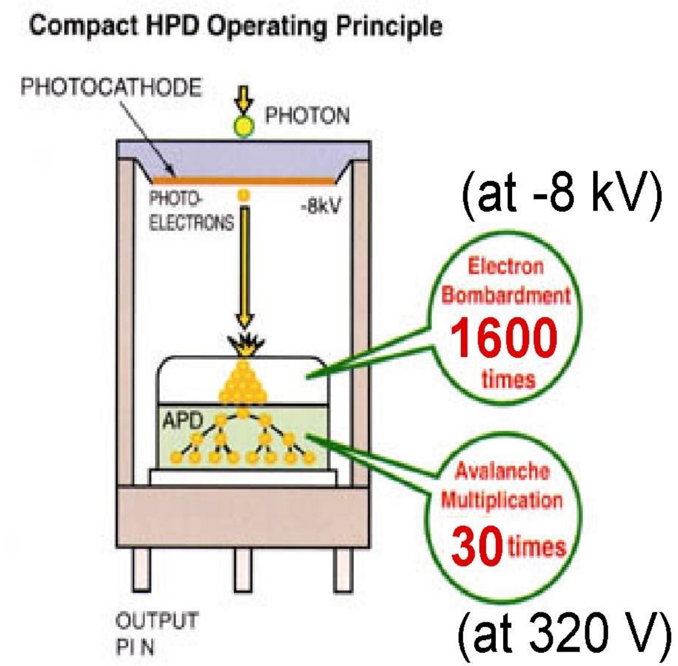
R11920-100-05 Shield type
(HA Treatment, Magnetic Shield
and Heat Shrinkable Tube)



Light Shield

HPD Structure

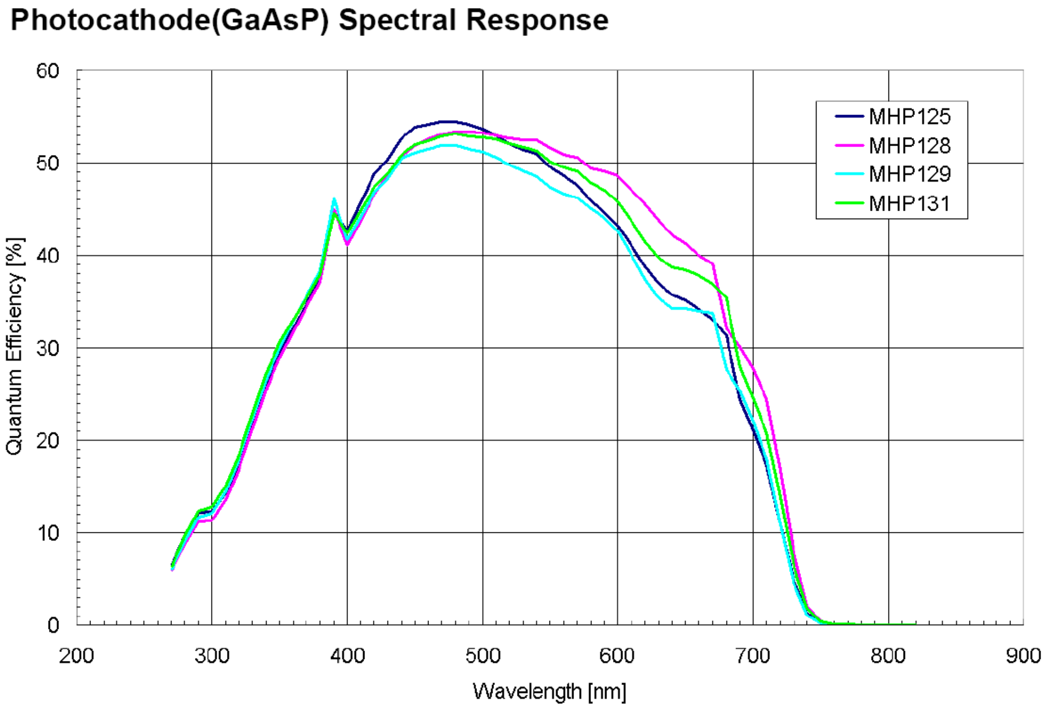
- HPD (Hybrid Photo Diode).
- Structure
  - Photo cathode
  - Avalanche diode as anode.
  - High vacuum tube (∼10^{-7} Pa)
- Gain mechanism (2 stages)
  - Electron bombardment ~(x 1600)
  - Avalanche effect ~(x 30-50)

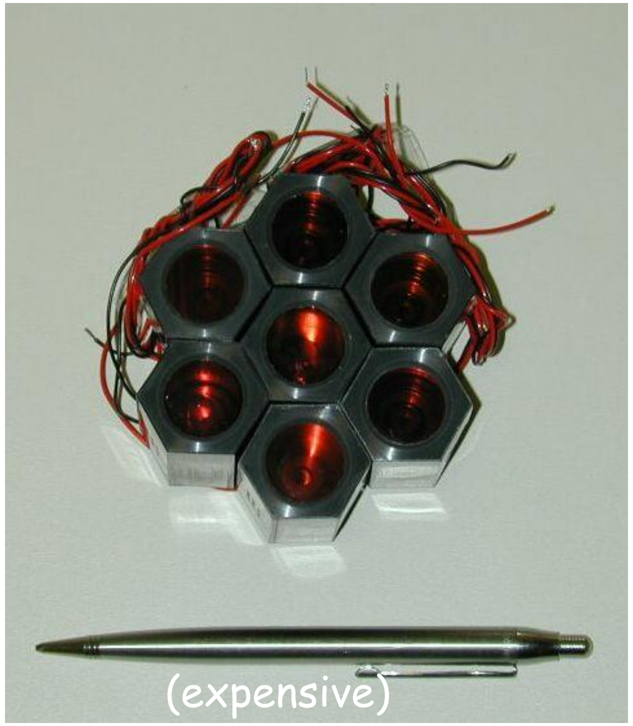


Much better pulse height resolution than PMT.

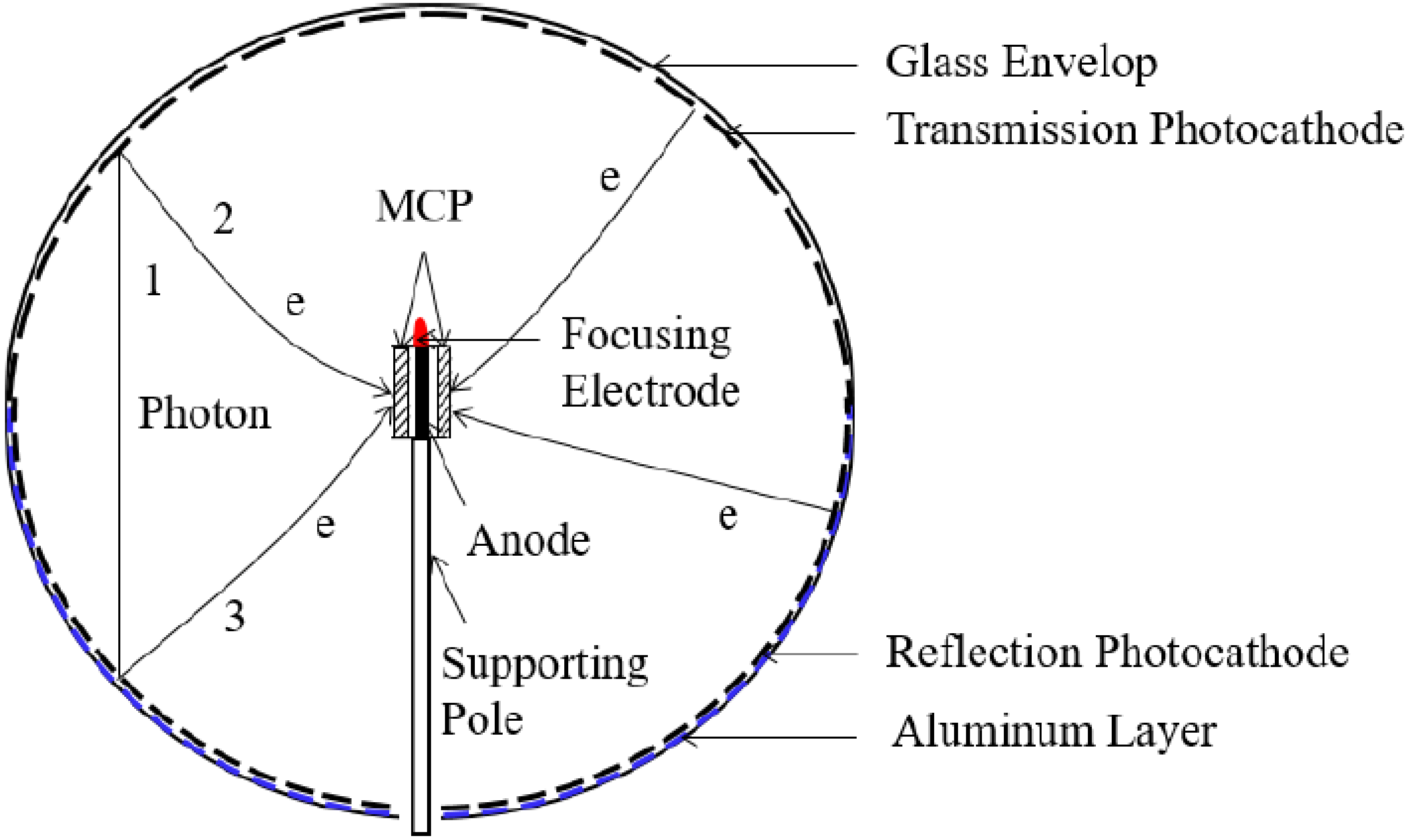
18-mm GaAsP HPD (R9792U-40) (development started ~15 years ago)

Designed for MAGIC-II telescope camera;
(developed with *Hamamatsu Photonics*)

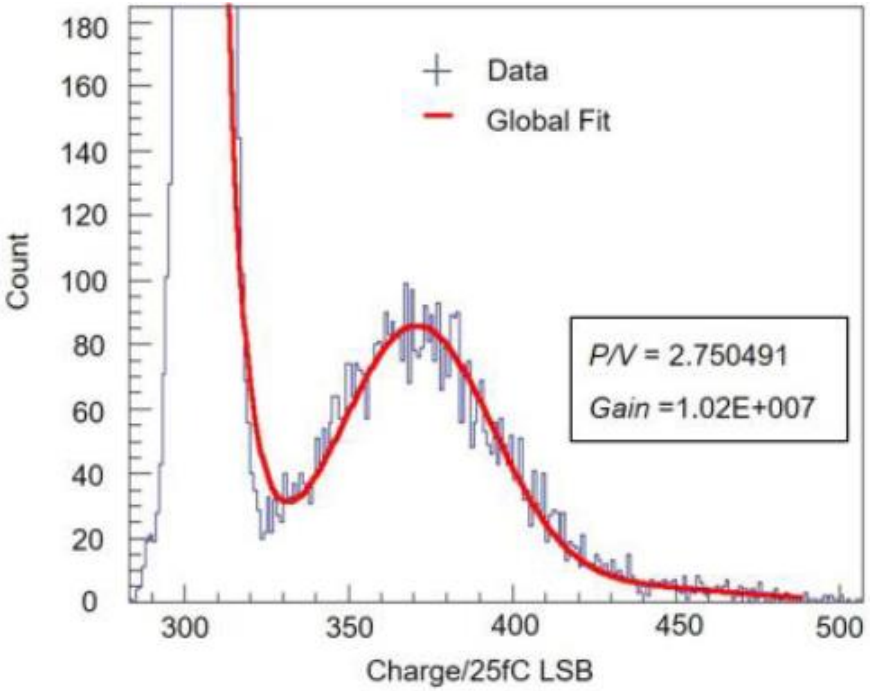




8-inch spherical MCP-PMT from China



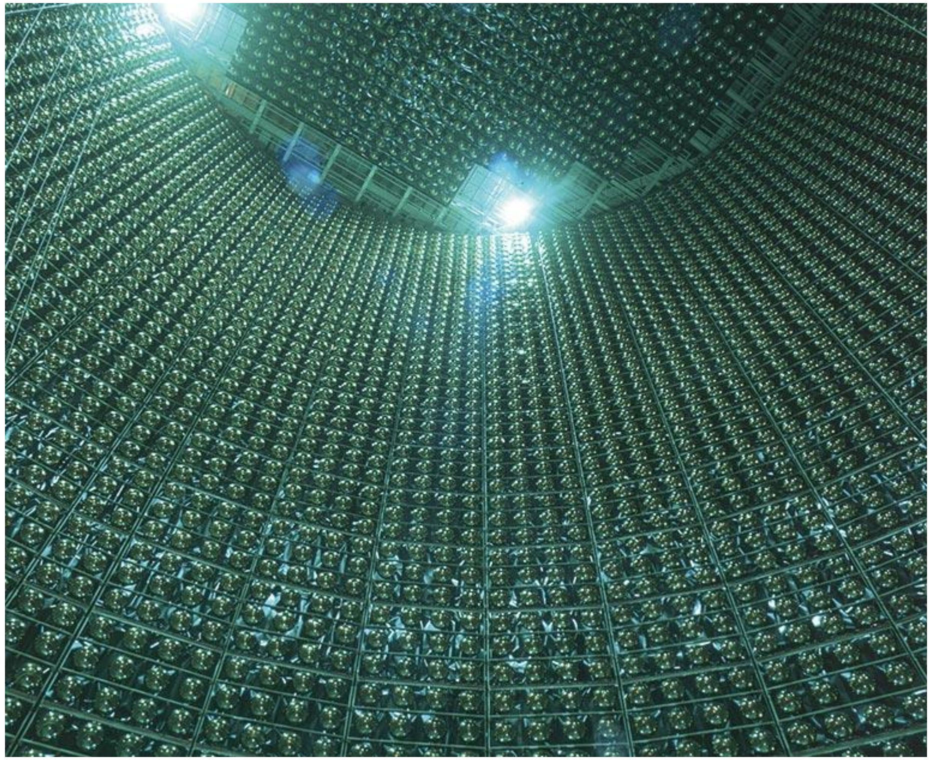
Picture of the 8-inch spherical MCP-PMT prototype



Hamamatsu 20 inch size PMT

Hamamatsu R1449 PMT; further improved model under the name R3600-05.

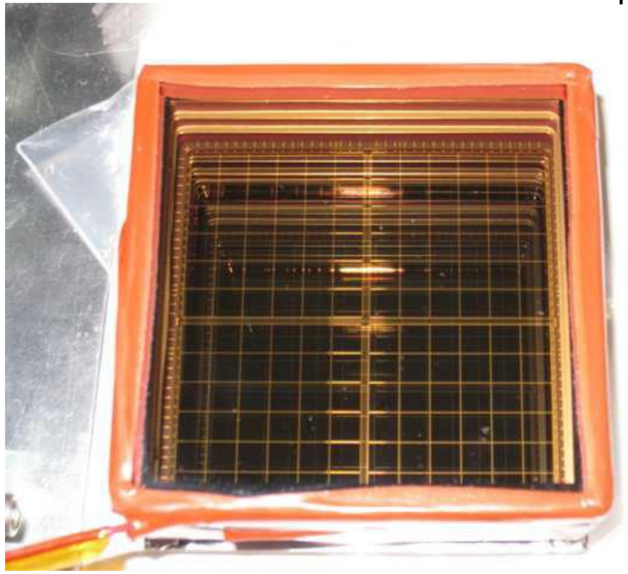
Credit: ICRR, Univ. Tokyo

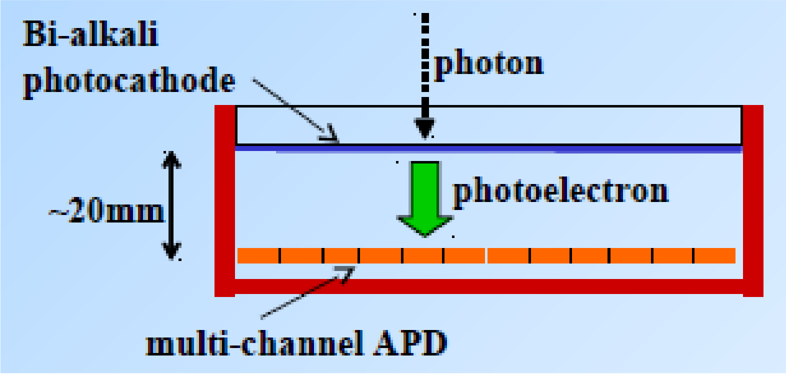


144-channel HAPD
for aerogel RICH at Belle II

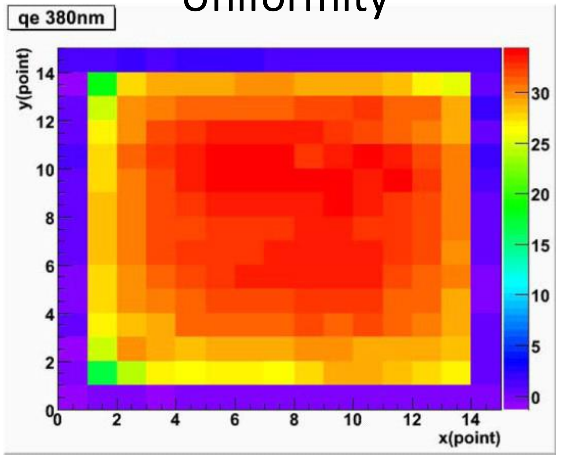
- Hybrid avalanche photo detector developed in cooperation with Hamamatsu, proximity focusing type
- 12 x 12 channels (5 mm x 5mm); physical size 72mm x 72 mm
- ~65 % effective area
- Net gain: 4.5 x 10^4 (e- bombardment: x 1500, APD: x 30)
- Superbialkali photocathode, peak QE ~28 %
- Capable to work under the condition of ~perpendicular to entrance window strong magnetic field of 1.5 T
- Output capacitance: ~80 pF/ch.

Credit: S. Korpar

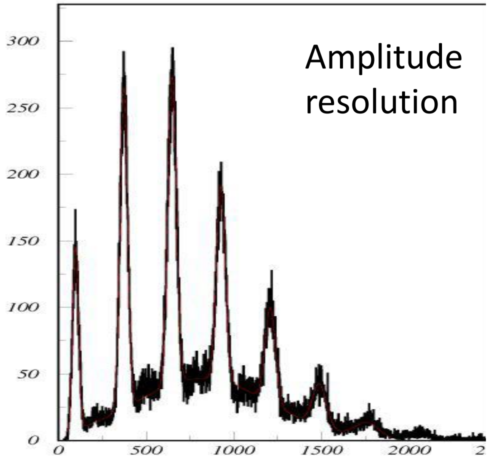




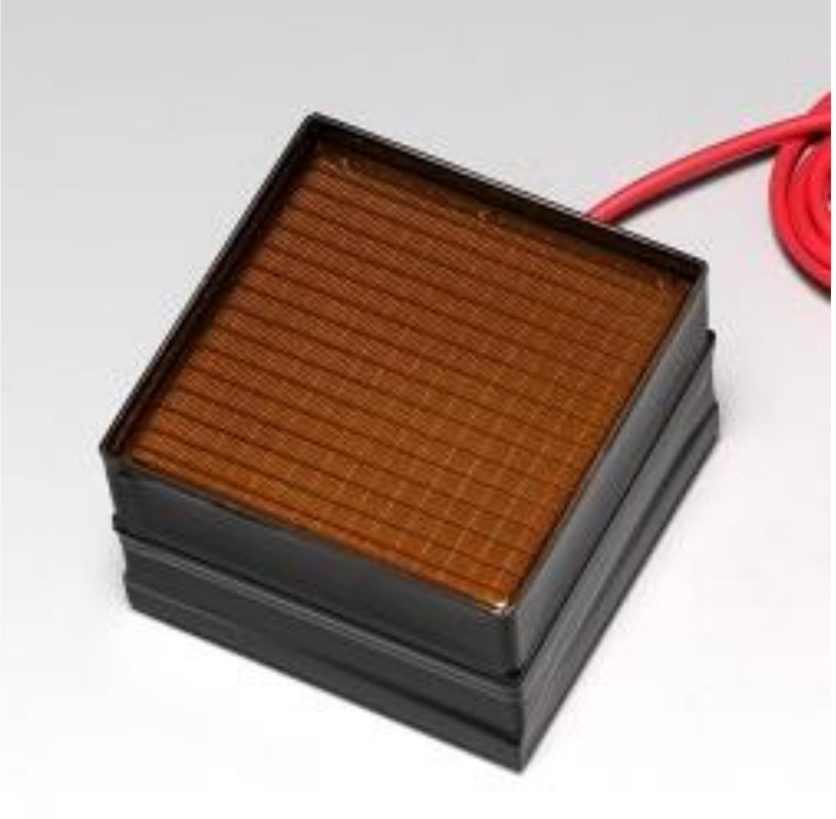
Uniformity



Amplitude resolution



Flat Panel Multi-anode PMT Hamamatsu H9500



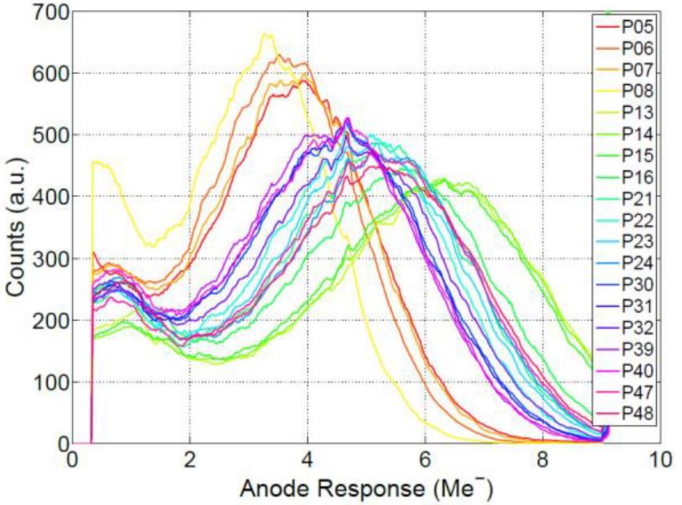
- Large effective area: 49 mm × 49 mm
- 16 × 16 multianode
- Anode pixel size: 2.8 mm × 2.8 mm / anode
- Small dead space
- Fast time response
- Metal channel dynodes
- Number of stages: 12
- Maximum supply voltage: 1.1 kV

MaPMTs

On the example of Hamamatsu R13742 (1’’) & R13743 (2’’)

Credit: M. Fiorini

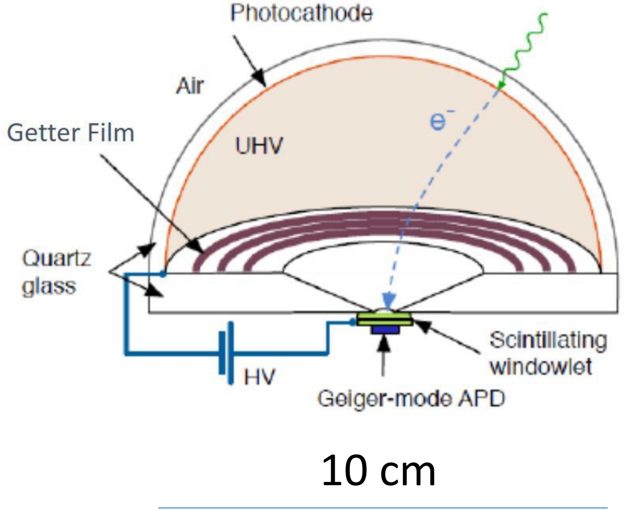
- Super-bialkali photo cathode, peak QE ~ 35 %
- UV-glass window
- Gain ≥ 10^6 @ 1 kV
- Channel-to channel gain spread in a given MaPMT: 3:1
- Spread among different MaPMTs: 3:1
- Usual for PMTs low dark count rate
- Single photo-electrons well separated from noise
- Sensitive to magnetic fields, at field strngth ~30 G edge pixles show ~50% loss of efficiency



Abalone

D. Ferenc, et al., NIM A 2020

- @ 25 keV a single ph.e. generates ~650 photons in LYSO scintillator (6x6x1.5 mm³)
- 100 of those detected by SensL J-type G-APD (6x6 mm²) with a gain of ≈$6.1x10^6$
- Combined gain ≈ $6x10^8$
- Cs3Sb photocathode
- After-pulsing rate ~$5x10^{-3}$ ions (mostly helium) per photo-electron
- Sub-nanosecond timing resolution
- Single-photon sensitivity
- Very high radio-purity
- UV sensitivity due to fused silica

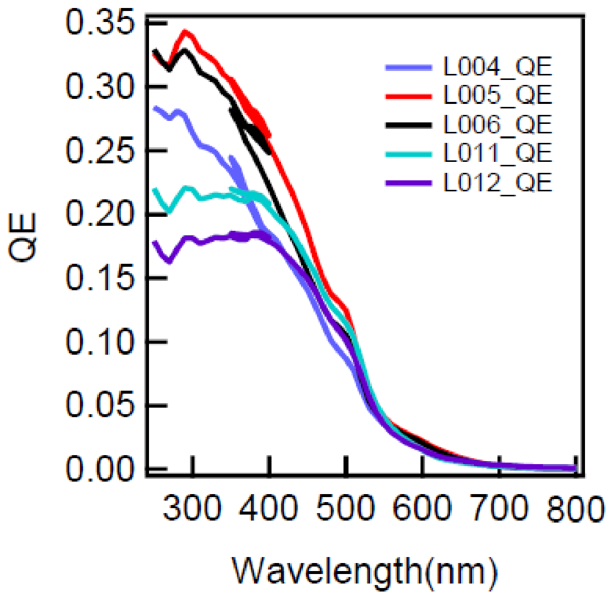


Schematics

Prototype for IceCube extention

Surface roughness and the QE

J. Smedley, Light-17

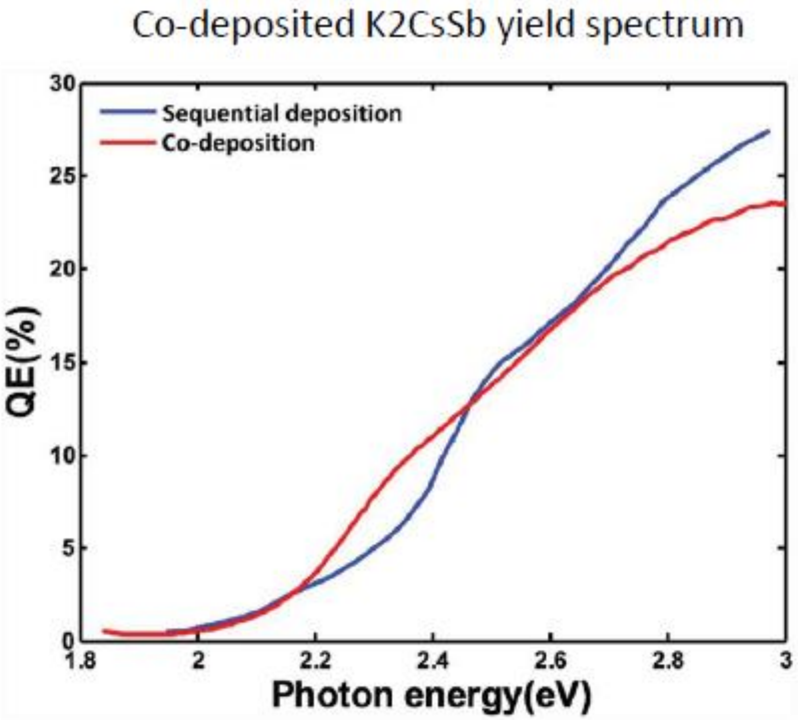


- Simultaneous evaporation of all constituents results in no crystal phase transformation
- Smooth, and high crystal quality
  => provides High QE

	QE@532nm(%)	Roughness(A)	Thickness (A)	Grain size (A)
L004 Si	4.9	3.5	234	155
L005 Si	5.8	11.5	815.3	277
L006 Si	5.4	13.8	757.5	202

Co-deposition of the photo cathode materials leads to very smooth surface quality as well as to high QE

J. Smedley, Light-17



Triple co-evaporation at LBNL