Significant increase of QE is opening new avenues for standard photodetectors

by C. Fontaine
PHOTONIS France
1. Interest of high QE
2. QE is key for new devices
3. Higher QE always existed
4. How to increase intrinsic photocathode QE?
5. Improving overall QE of photodetectors?
6. Conclusion
Visible light can react and become measurable by:

- **Eye** (*human: QE ~ 3 % & animal), plants, paints,...*
- **Photoemulsion** (*QE ~ 0.1 – 1 %*) *(photo-chemical)*
- **Photodiodes** *(photoelectrical, evacuated)*
  - Classical & hybrid photomultipliers (*QE ~ 25 %)*
  - *QE ~ 45 % (HPD with GaAsP photocathode)*
- **Photodiodes** *(QE ~ 70 – 80 %)* *(photoelectrical)*
  - PIN diodes, Avalanche diodes, SiPM,...
  - photodiode arrays like CCD, CMOS cameras,...
The photocathode is the first statistical process of the detection chain

For light detection:
- it is the first one to convert the photon statistics

For radiation detection:
- it is the first one to convert the photon statistics after the scintillator conversion of gamma rays into photons

It means QE is key for:
- Energy resolution
- Coincidence timing
- ... but there are other very important parameters not to forget
Definition is easy:

\[
QE = \frac{\text{\# Emitted Photoelectrons}}{\text{\# Insident Photons}} = \frac{N_{pe}}{N_{\gamma}}
\]

Many underlying factors:

\[
QE \approx \left(1 - P_{\text{rob of reflection}}\right) \left(1 - P_{\text{rob Absorption in Window}}\right) \\
\times \left(1 - e^{-\frac{d}{2\cos\alpha \cdot L_{\text{photon}}}}\right) \cdot P_{\text{rob of Electron Excitation}} \\
\times e^{-\frac{d}{2\cos\beta \cdot L_{\text{electron}}}} \cdot P_{\text{rob of Electron Emission}}
\]

\(d\): Thickness of Alkali Material  \\
\(\alpha\): Incident Photon Angle  \\
\(\beta\): Emitted Electron Angle

Ref: K. Arisaka
How to increase QE?

\[ QE \approx \left(1 - P_{\text{rob of refelection}}\right) \left(1 - P_{\text{rob of Absorption in Window}}\right) \times \left(1 - e^{-\frac{d}{2\cos\alpha L_{\text{photon}}}}\right) \times P_{\text{rob of Electron Excitation}} \times \frac{d}{2\cos\beta L_{\text{electron}}} \times e^{2\cos\beta I_{\text{electron}}} \times P_{\text{rob of Electron Emission}} \]

- **d**: Thickness of Alkali Material
- **\( \alpha \)**: Incident Photon Angle
- **\( \beta \)**: Emitted Electron Angle

Optimisation before photons reach the window

Optimisation when photons enter the window

Optimisation of photocathode material

Ref: K. Arisaka
Typical QE of photodetectors

- A: Borosilicate Glass
- B: UV Glass
- C: Synthetic Silica
- D: Bialkali Photocathode
- E: High Temp. Bialkali Photocathode
- F: Extended Green Bialkali Photocathode

**Bialkali:**
- Sb-Rb-Cs
- Sb-K-Cs
\[ DQE = \frac{\# \text{PE\_captured\_by\_1st\_Dynode}}{\# \text{Insident\_Photons}} \]

\[ = QE \cdot CE \]

It is not only important to convert photons into electrons: QE but also not to lose them before multiplication effect: CE.

Note: there is no longer a mesh in the electron path. We get 10% improvement.
\[ DQE = \frac{\text{\#PE\_captured\_by\_1st\_Dynode}}{\text{\#Insident\_Photons}} \]

\[ = QE \cdot CE \]

Another tube comparison:
XP1807 (12\" – 11 stage) and R8055 (13\" – 10 stages):
New recent comparison from BAIKAL
but QE is not everything ...

DQE in pixellated detectors ...

For these detectors, another strong parameter kicks in:

the actual active area

It is important to know how the QE is measured:
- Dead area around Perimeter
- Dead area inside the active area
  (for example active area for SiPM is in the range 30% to 80% depending on design)
- **QE**: quantum efficiency: as high as possible (> 30 \%)
- **$C_{ol}$**: collection efficiency: as close as possible to 100 \% (> 0.9)
- **ENF**: « Excess Noise Factor »: as close as possible to 1.0 (<1.2)
- **G**: Gain (>> 10^4)
- **ENC**: Electronic noise (1000 e^-)
- **$N_{bg}$**: (noise in photons of the detector) << $N_\gamma$ (number of photons to detect)

\[
\frac{\sigma}{E} = \sqrt{\frac{\text{ENF} \cdot QE \cdot C_{ol} (N_\gamma + N_{BG}) + (ENC/G)^2}{QE \cdot C_{ol} \cdot N_\gamma}} \\
\approx \sqrt{\frac{\text{ENF}}{QE \cdot C_{ol} \cdot N_\gamma}}
\]
Excess Noise Factor and energy resolution for PMT ...

- Definition:
  \[ ENF \equiv \frac{\sigma_{\text{Output}}^2}{\sigma_{\text{Input}}^2} \quad \text{Observed variance} \]
  \[ \text{Poisson predicted variance} \]

- In case of PMT:
  \[ ENF = 1 + \frac{1}{\delta_1} + \frac{1}{\delta_1 \cdot \delta_2} + \cdots + \frac{1}{\delta_1 \cdot \delta_2 \cdots \delta_n} \]

PHR can also be improved by high D1 secondary emission

Other key parameters:
- Gain stability
- Afterpulse
- Linearity
Energy resolution and non-linearity

Key PMT characteristics for good PHR: (1) high QE of PC, (2) high and uniform secondary gain ...

2 PMTs type XP5200 with the QE of 37% and 30% for 420 nm
### PMT size <-> cost

- **Diameter**  
  - 20“  <= >  (20“) 17“  <= >  12“

- **Projected area**  
  - 1660  1450  615  cm²

- **QE(typ)**  
  - 20  20  24  %

- **CE**  
  - 60  60  70  %

- **Cost**  
  - 2500  2500  800  €

- **Cost/cm² per useful** $PE_U = \frac{\text{cost}}{(\text{cm}^2 \times \text{QE} \times \text{CE})}$
  - 12.6  14.4  7.7  €/PEₕ/cm²

\textbf{Optimise!}

\textit{Cost/cm² per useful area}

\[PE_U = \frac{\text{cost}}{(\text{cm}^2 \times \text{QE} \times \text{CE})}\]

Talk from NNN 05:
Need to invest in high QE tube
Many applications require timing performance improvements:

Example 1: HEP

Timing is key for particle identification in Cerenkov counters by J. VAVRA

Example 2: TOF - PET

Time-of-Flight in PET
By W. MOSES
New trends in PET instrumentation
Sept 18, 2006

- Use time-of-flight to localize source along line of flight.
- Time of flight information reduces noise in images.
- Variance reduction given by $2D/c\Delta t$.
- 500 ps timing resolution (equivalent to 7.5cm localisation) $\Rightarrow$ 5x reduction in variance!

Need to go into psec time resolution … MCP-PMT / SiPM

- Time of Flight Provides a Huge Performance Increase
- Biggest Improvement in Large Patients
Many applications require timing performance improvements:

Parameter 1 of timing is photon statistics (small dependence of wavelength):
- time resolution is defined as FWHM of the probability distribution of the fluctuations ...
- proportional to $1/\sqrt{N}$ where $N$ photoelectrons

Parameter 2 of timing is TTS specified by its standard deviation sigma:
- distribution of the FWHM between PK locations
- it includes the TTD between different PK locations

- TTS between PK and D1 (CE)
- TTS of the multiplier structure
- Effect of the voltage
- Anode design

See talk from M. Moszynski at IEEE 2007
Interest: Additional noise while for PMTs noise is multiplying (no « Fano » factor)

Weakness of PMT & HPD: photocathode \(\rightarrow\) high QE!

Affinité électronique négative \(\rightarrow\) Semi-conducteur

Multiple réflexion (filtre interférentiel).

Pair creation by ionisation (3.6 eV / electron-hole pair for Si)
Another example of emerging new devices putting high QE photocathodes at the forefront of photodetection: EBCMOS.

Hybrid PMT R&D @ INFN Genova (Marco Battaglieri et al; NEMO/KM3Net)
Status on high QE photocathodes:

Higher QE photocathodes exist since long...
A few examples of high QE GaAs photocathodes:
QE above 40% at 420 nm are possible
Third generation imaging tube: high QE vs S/N ratio (lifetime drawback)
High QE material exist in standard devices but strong link to technology … and cost:

These materials require transfer photocathode processing which induces higher cost

Interest in lower technological cost high QE solutions … not transfer with the least technical drawbacks
Proximity focussed designs allow only 2 types of PK process:

1. **Transfer photocathode**
   (PK processing separate from the tube and then seal ... high cost)
   - PK process
   - Tube process
   - Tube sealing under vacuum

2. **Pre-deposited**
   (Sb predeposition before processing ... low QE)
   - Sb deposition outside
   - Tube building outside
   - In situ PK process under vacuum
Multipixel tubes (2, 4, 9 channels)

- Widely used in high performance PET and PET-CT scanners
- High resolution, Excellent sensitivity, cost effective channels, Easy to tile
- WIP to reduce length by HALF
  ... these designs allow standard PMT processing

also available in PHOTONIS XP912064:
11stage - 25mm square - 8 x 8 anodes
... these designs allow only lower QE
... high QE possible with transfer process

also available in PHOTONIS PLANACON XP85011:
MCP-PMT - 51mm square – many read-out designs
... high QE possible because of transfer process
How to improve intrinsic QE in photomultiplier processing?
QE always include transmittance of Glass Window for vacuum devices.

OPTIMISATION by industry (inside the tube) of:

- Window Thickness
- Window transmission
- Window optical coupling to PK
What are the key parameters to increase photocathode QE?

1. Surface structure and cleanliness:
   Impact on photocathode growth & diffusion of impurities

2. Photocathode interface:
   Optical coupling with entrance window

3. Photocathode material:
   Purity of basic materials (dispensers) - Composition

4. Photocathode growth:
   Growth defects – Uniformity – Band bending

5. Photocathode thickness:
   Compromise absorption of photons – recombination of electrons
Coefficient d'absorption (micron-1) en fonction de l'énergie des photons (eV) pour différents matériaux:
- SbNaK
- GaAs
- Si
Depending on electron transport:

- Semiconductors with negative affinity:
  - Quick thermalisation of electrons to the bottom of the energy band
  - Thermal diffusion: long lifetime
  - Diffusion length of a few μm

- Semiconductors with positive affinity:
  - Escape in vacuuum has to occur before complete thermalisation
  - Time to be thermalised << lifetime at bottom of energy band
  - Escaping depth ~ 1000 nm
Surface barriers and band bending of multialcali photocathodes

Band bending required to reach > 50% QE
Different generations of bialkali PK and related QE performance level

Super² bialkali allow Above 40% QE at 400 nm

Super bialkali allow 35 – 40% QE at 400 nm
Super bialkali process
(400 nm 30 – 40%)

Super² bialkali process
(400 nm 40 – 50%)

Comparisons de QE% : super bialkalis Photocathode

QE% on XP5302 Sn 104754
Super$^3$ bialkali process
(400 nm 50 – 60%)
The challenge is to master parameters and reduce production spread in order to produce a high ratio of high QE tubes.

These high QE bialkali photocathodes are available on SPECT tubes and are being tuned to other types (dimensions, glass, metal can ...)

**More production data on super² bialkali cathodes at IEEE in Hawai in October 07**
CONCLUSION:

1. QE is key for energy and time resolutions but other parameters participate

2. Intrinsic QE can reach above 50% at 420 nm

3. High QE availability require process adaptation and high manufacturability

4. There are many other key factors to consider and that must be also optimised in this process change

5. Overall QE can also be improved by TIR by 30 – 40% at no dark current expense

6. Together with the very efficient active area as well as other key parameters improvements, high QE PMTs are opening new limits for detection, energy and time resolution
PHOTODAC program proposal from Photonis:

A. Improving performance of current products:
   1. High QE PMT for CTA (target 50% QE at 420 nm)
   2. High QE hemispherical PMT for KM3NeT (target 40% at 420 nm)
   3. High QE SMART (may also include directionality information design)

B. Assessing potential of new technologies
   1. SiPM detectors for large area detection
   2. SMART tube with SiPM read-out for directionality information
PHOTODAC program proposal from Photonis:

Questions:

1. What are the selected subjects?
2. Project team for each selected subject (contacts)
3. R&D program for each selected subject (to be defined)