Significant increase of QE

is opening

new avenues

for standard photodetectors

by C. Fontaine
PHOTONIS France

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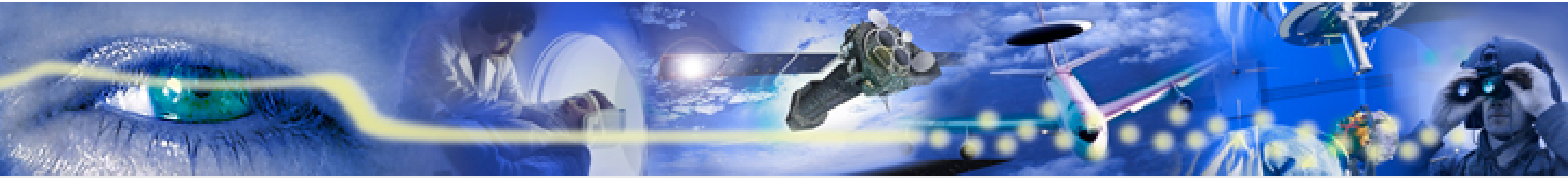
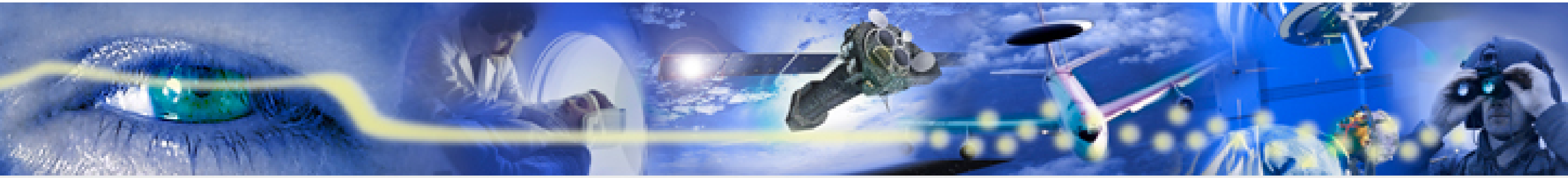
Overview of the talk ?



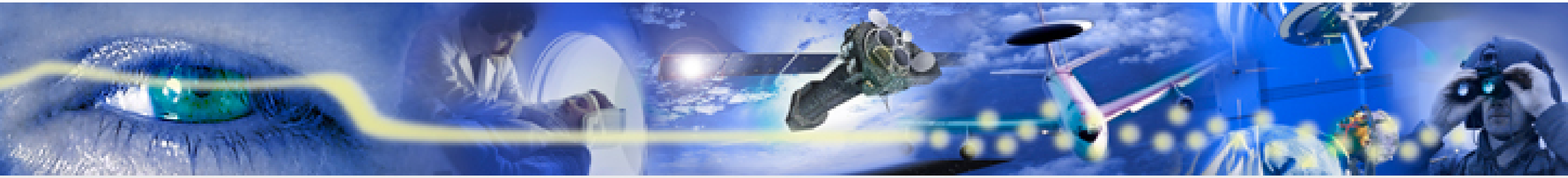
1. Interest of high QE
2. QE is key for new devices
3. Higher QE always existed
4. How to increase intrinsic photocathode QE ?
5. Improving overall QE of photodetectors ?
6. Conclusion



- 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,…

Why QE is key ?



The photocathode is the first statistical process of the detection chain

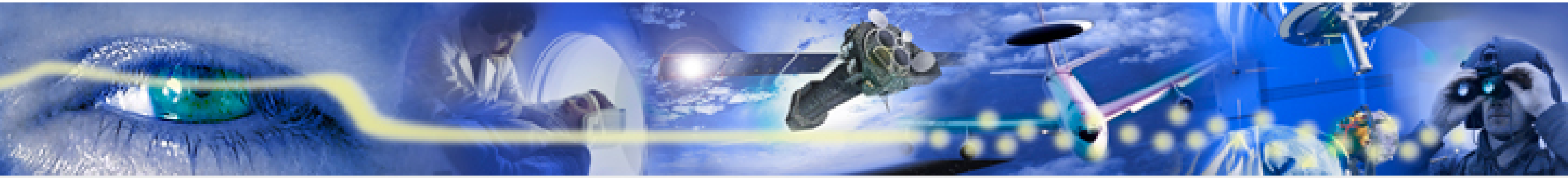
For light detection :
it is the first one to convert the photon statistics

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

What is Quantum Efficiency ?



Definition is easy :

$$QE \equiv \frac{(\#\,Emitted\_Photoelectrons)}{(\#\,Insident\_Photons)} = \frac{N_{pe}}{N_{\gamma}}$$

Many underlying factors :

$$QE \approx \left(1 - P_{rob\_of\_refelection}\right)\left(1 - P_{rob\_Absorption\_in\_Window}\right) \times \left(1 - e^{-\frac{d}{2\cos\alpha \cdot L_{photon}}}\right) \cdot P_{rob\_of\_Electron\_Excitation} \times e^{-\frac{d}{2\cos\beta \cdot L_{electron}}} \cdot P_{rob\_of\_Electron\_Emission}$$

d: Thickness of Alkali Material
α: Incident Photon Angle
β: Emitted Electron Angle

Ref : K. Arisaka

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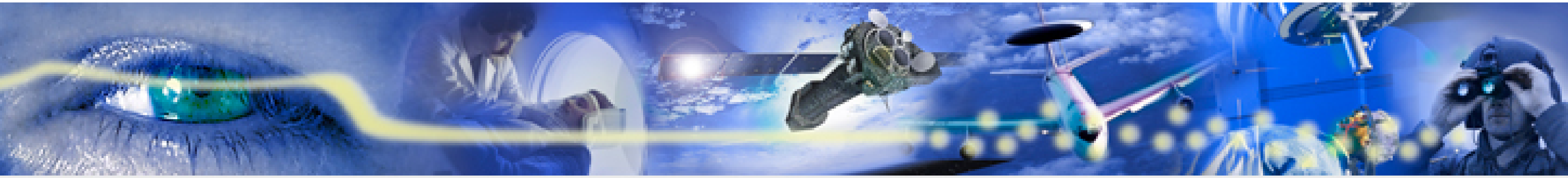
How to increase QE ?



d: Thickness of Alkali Material - α: Incident Photon Angle - β: Emitted Electron Angle

Optimisation before photons reach the window

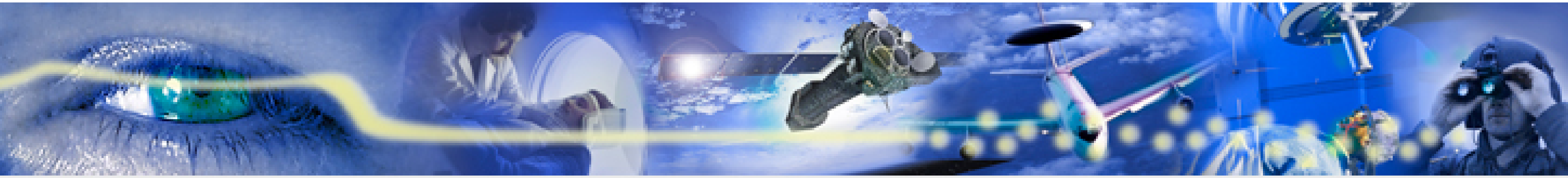
Optimisation when photons enter the window

$$QE \approx \left(1 - P_{rob\_of\_refelection}\right)\left(1 - P_{rob\_Absorption\_in\_Window}\right)$$
$$\times \left(1 - e^{-\frac{d}{2\cos\alpha \cdot L_{photon}}}\right) \cdot P_{rob\_of\_Electron\_Excitation}$$
$$\times e^{-\frac{d}{2\cos\beta \cdot L_{electron}}} \cdot P_{rob\_of\_Electron\_Emission}$$

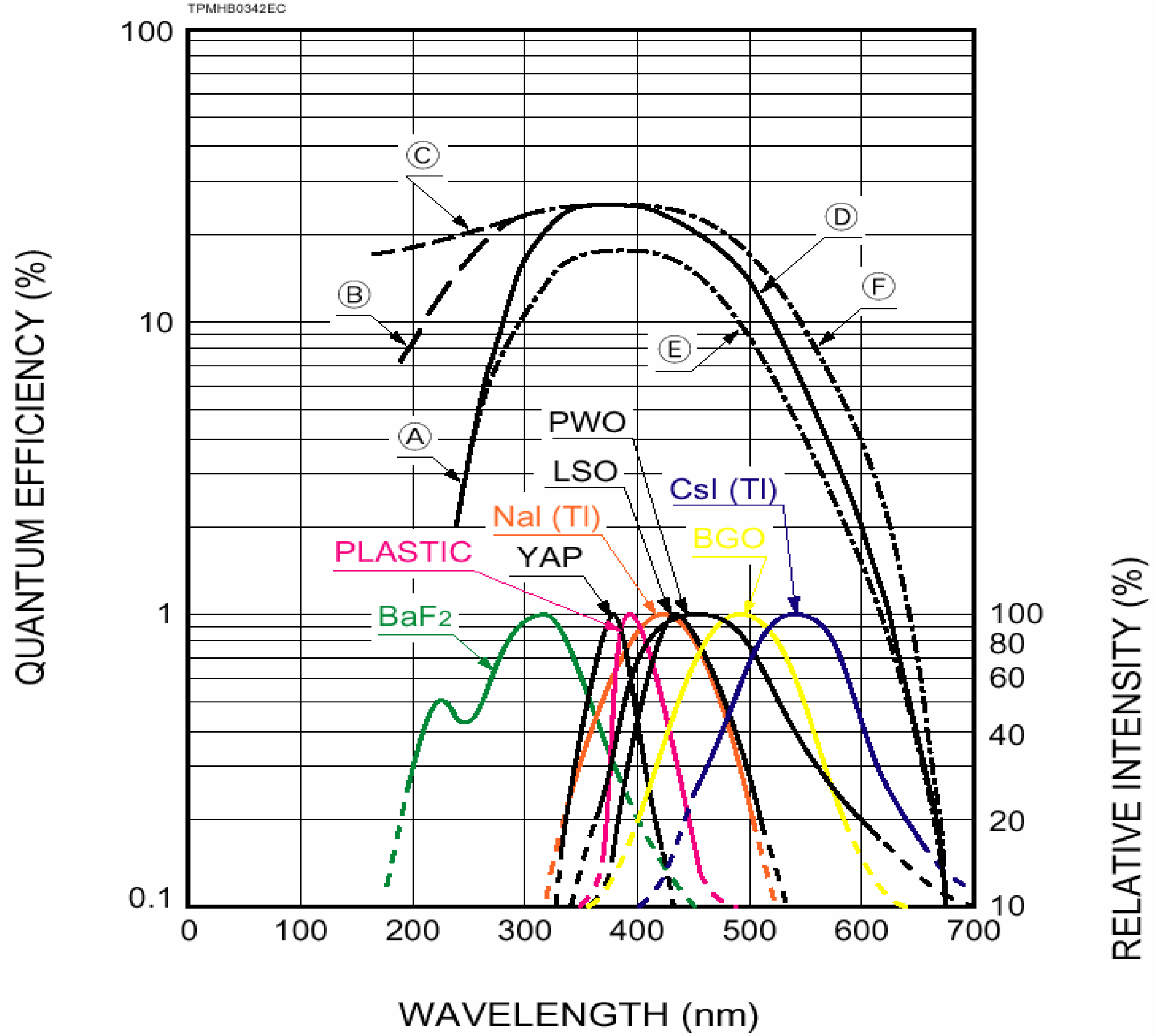
Optimisation of photocathode material

Ref : K. Arisaka

Typical QE of photodetectors ?

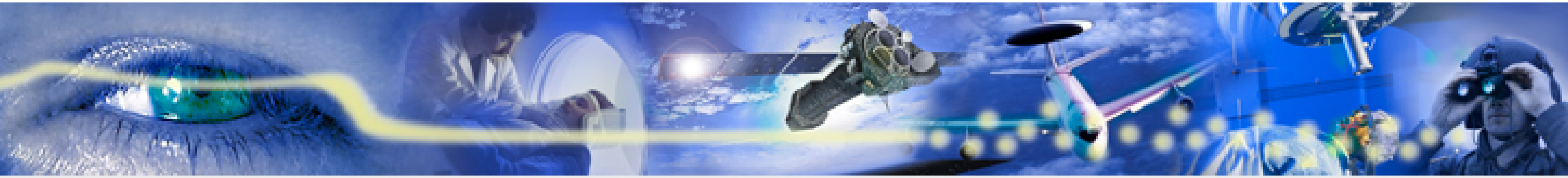


Ⓐ: Borosilicate Glass
Ⓑ: UV Glass
Ⓒ: Synthetic Silica
Ⓓ: Bialkali Photocathode
Ⓔ: High Temp. Bialkali Photocathode
Ⓕ: Extended Green Bialkali Photocathode

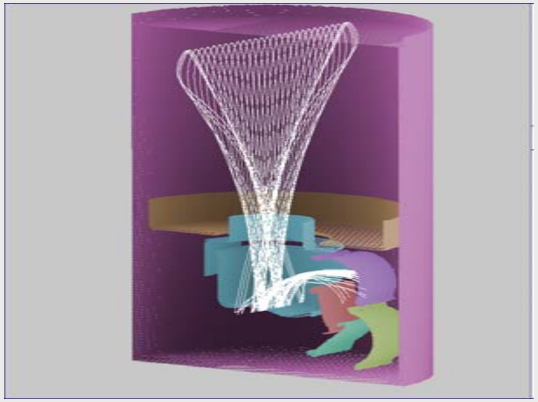


Bialkali:
Sb-Rb-Cs
Sb-K-Cs

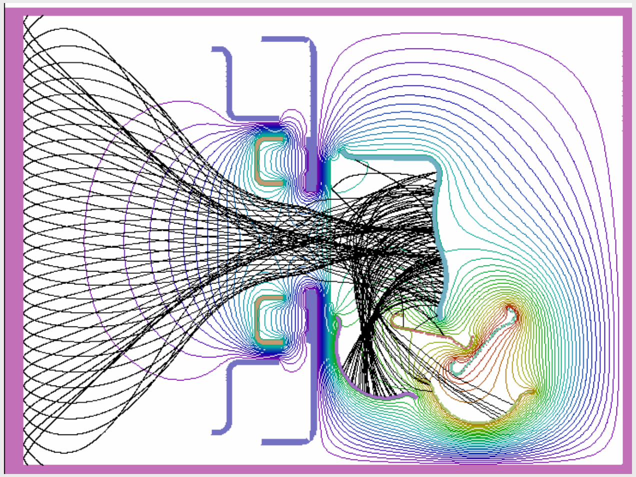
QE vs DQE : a key difference …

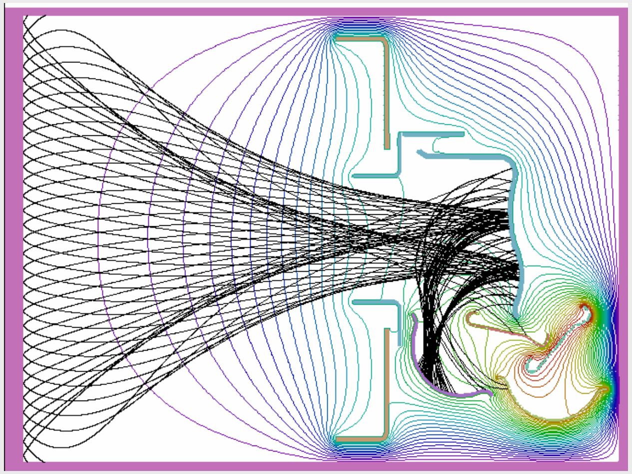


$$DQE \equiv \frac{(\#\,PE\_captured\_by\_1st\_Dynode)}{(\#\,Insident\_Photons)} = QE \cdot CE$$



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.

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$$DQE \equiv \frac{(\#PE\_captured\_by\_1st\_Dynode)}{(\#Insident\_Photons)} = QE \cdot CE$$

Another tube comparison :

XP1807 (12“ – 11stage) and R8055 (13“ – 10 stages):

New recent comparison from BAIKAL

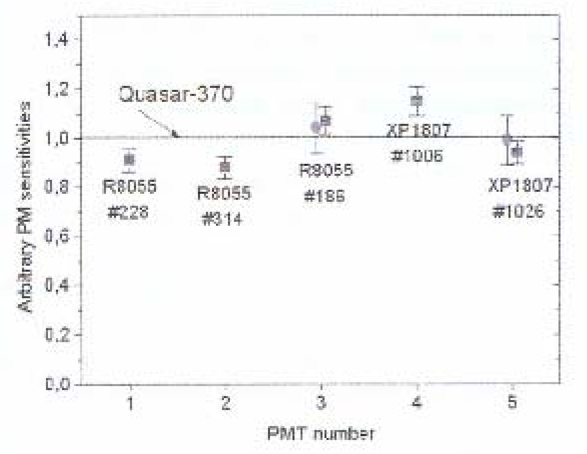
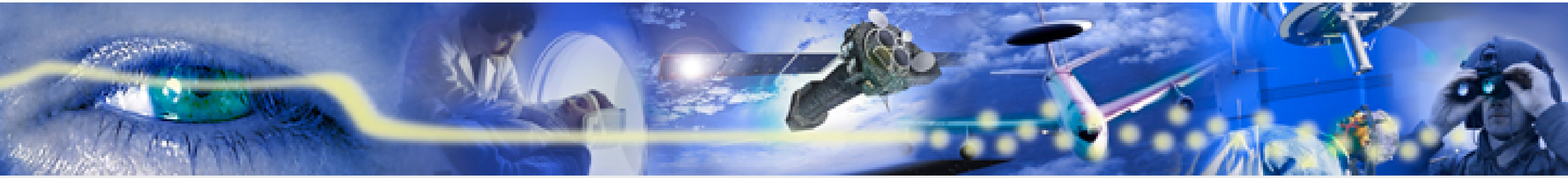
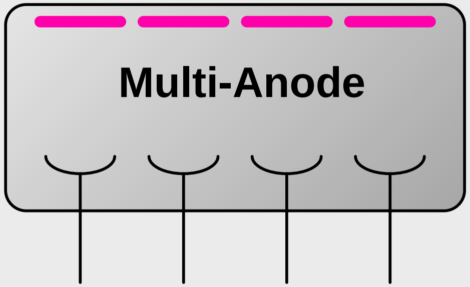
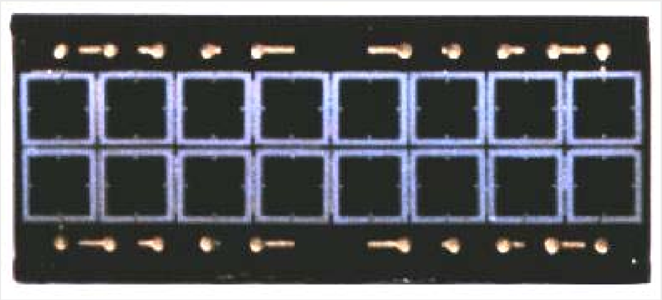


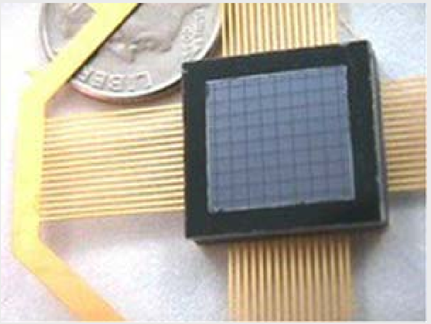
Figure 4: Ratio of effective sensitivity of large area PMs R8055/13" and XP1807/12" to QUASAR-370/14.6". Laboratory (squares), in-situ (dots).



DQE in pixellated detectors …







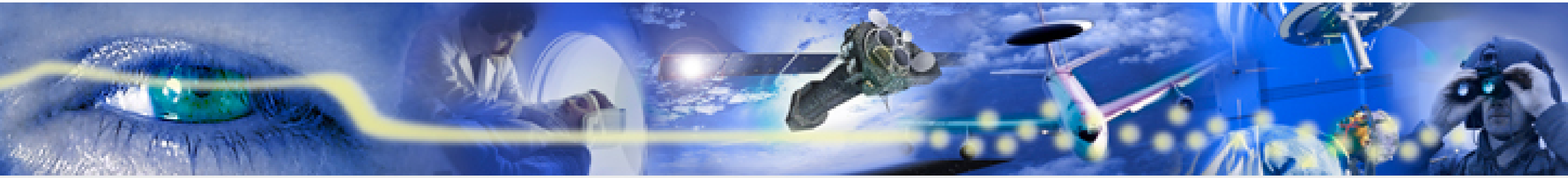
For these detectors, another strong parameter kicks in :

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)

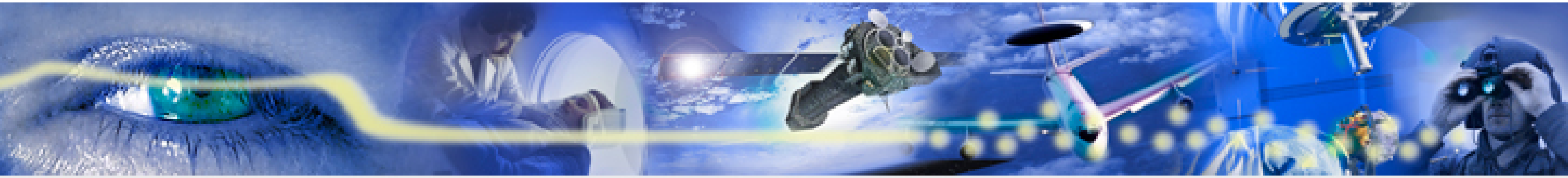
QE and energy resolution …



- QE : quantum efficiency : as high as possible (> 30 %)
- C_{ol} : collmection efficiciency : 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) << $N\gamma$ (noumber of photons to detect)

$$\frac{\sigma}{E} = \frac{\sqrt{ENF \cdot QE \cdot C_{ol}(N_\gamma + N_{BG}) + (ENC/G)^2}}{QE \cdot C_{ol} \cdot N_\gamma}$$

$$\approx \sqrt{\frac{ENF}{QE \cdot C_{ol} \cdot N_\gamma}}$$



- Definition:

$$ENF \equiv \frac{\sigma^2_{Output}}{\sigma^2_{Input}}$$

$$\frac{\text{Observed variance}}{\text{Poisson predicted variance}}$$

- 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

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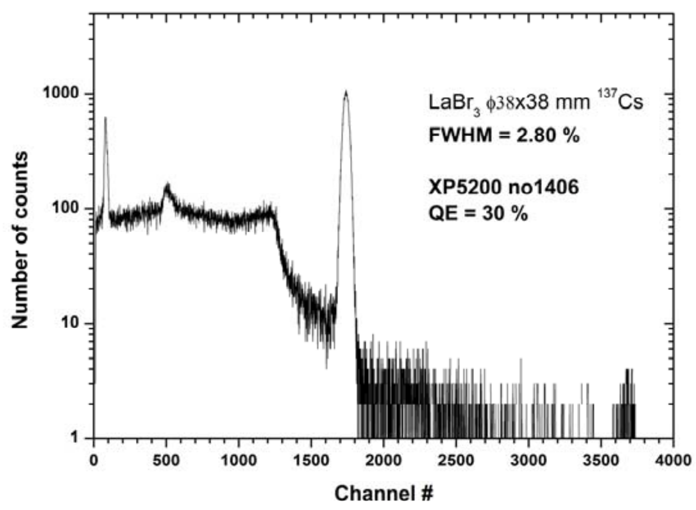
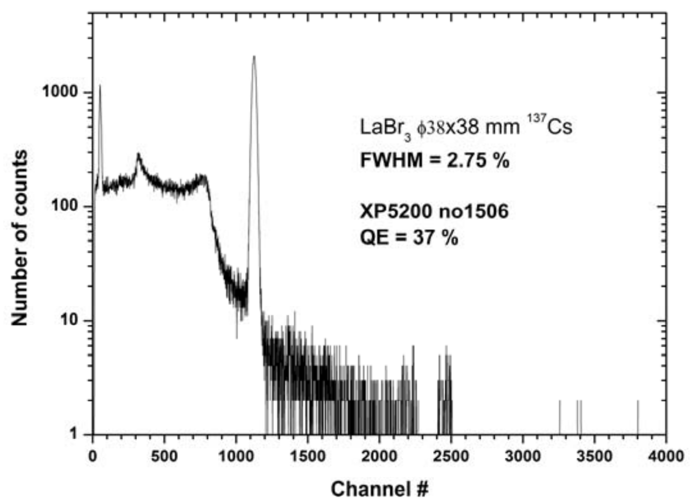
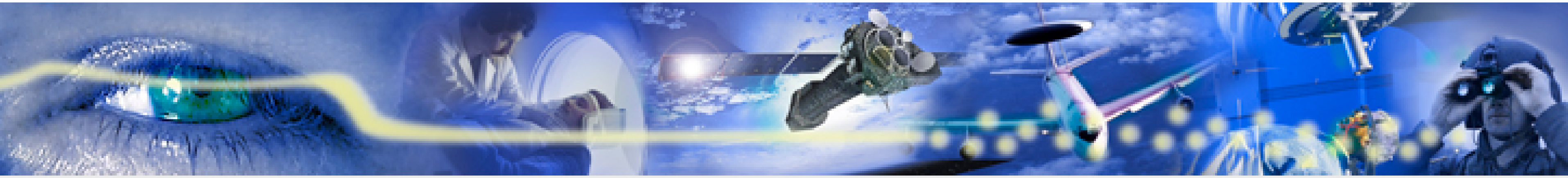
Energy resolution and non-linearity

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 **= cost/(cm²*xQExCE)***

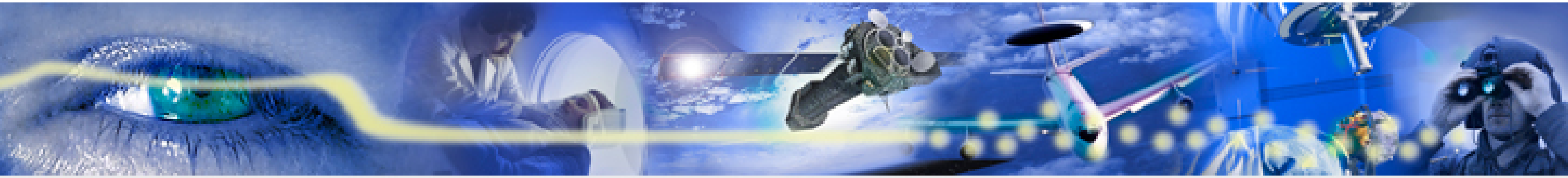
12.6	**14.4**	**7.7**	**€ / PE_U/cm²**

Optimise !

Cost/cm² per useful area

PE_U=cost/(cm²xQExCE)

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

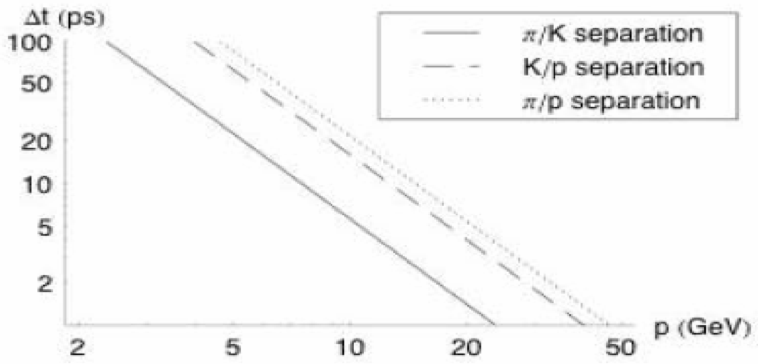


Fig. 1. The separations of pions, kaons, and protons, the difference in the time it takes two different particles with the same momentum to travel 1.5 m, as a function of momentum. Large time-of-flight detector systems have a time resolution on the order of 100 ps [2]-[4].

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

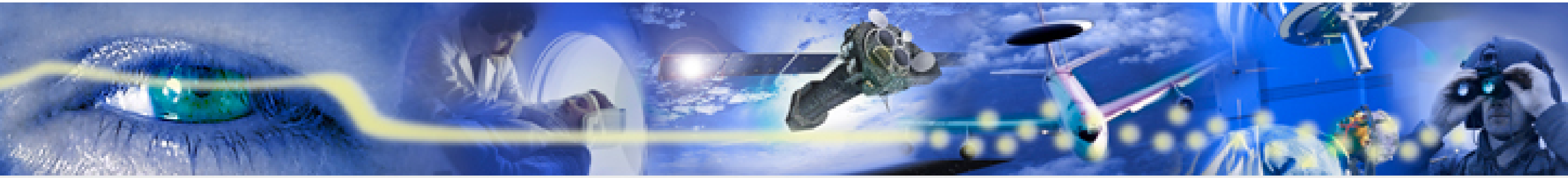
Example 2 : TOF - PET

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*Δt.**
- **500 ps timing resolution**
  (equivalent to 7.5cm localisation)
  ⇒ 5x reduction in variance!

- **Time of Flight Provides a *Huge* Performance Increase**
  - **Biggest Improvement in Large Patients**

QE is key for timing performances …



Many applications require timing performance improvements :

Parameter 1 of timing is photon statistics
(small dependance of wavelength) :

QE

when light hitting the same photocathode location
time resolution is defined as FWHM of the probability distribution of the fluctuations …
proporitional to 1 / sqrt (N) where N photoelectrons

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

Detector design

- 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

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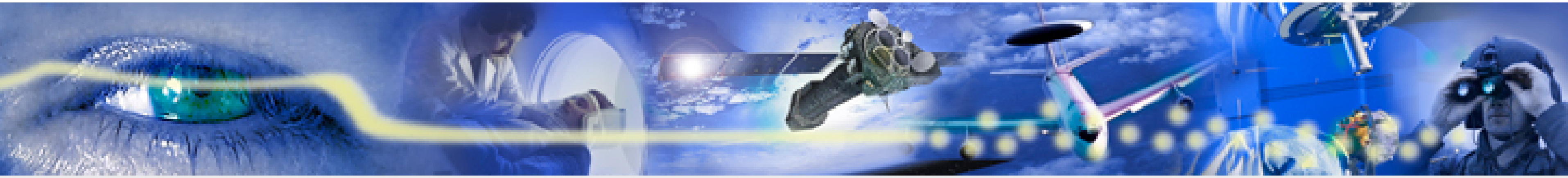
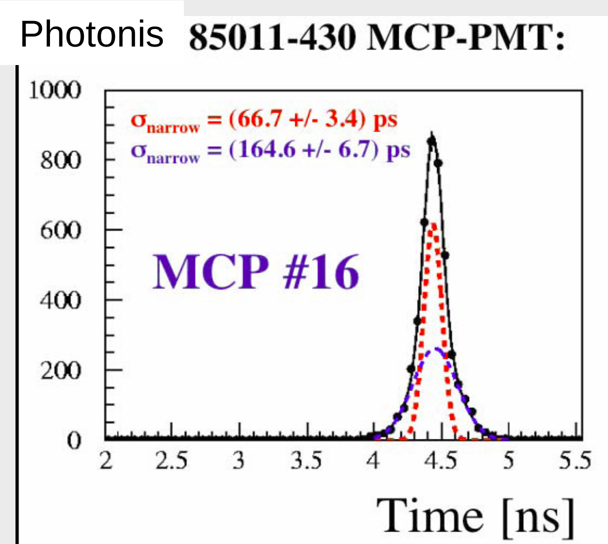
TTS improvement in PMT …



Newest designs from Photonis allow reaching < 300 ps TTS
for tubes 1’’ (XP1020) and 1.5’’ (XP3060)

For TOF PET; limitations of time resolution are now coming from scintillator statistics rather than PMT performance
with leading edge trigger

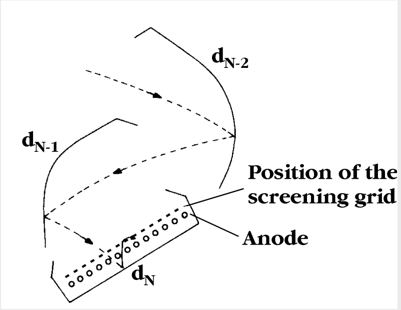


2’’ round, 8 stage for very fast timing :

XP20D0

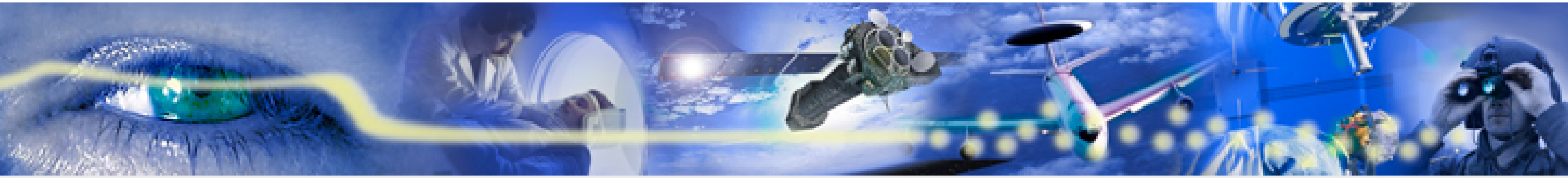
TTS = 520 ps, 13.7 µA/lmF, screening grid

- **$LaBr_3$ 154±5 ps**
- **LSO 166±5 ps**

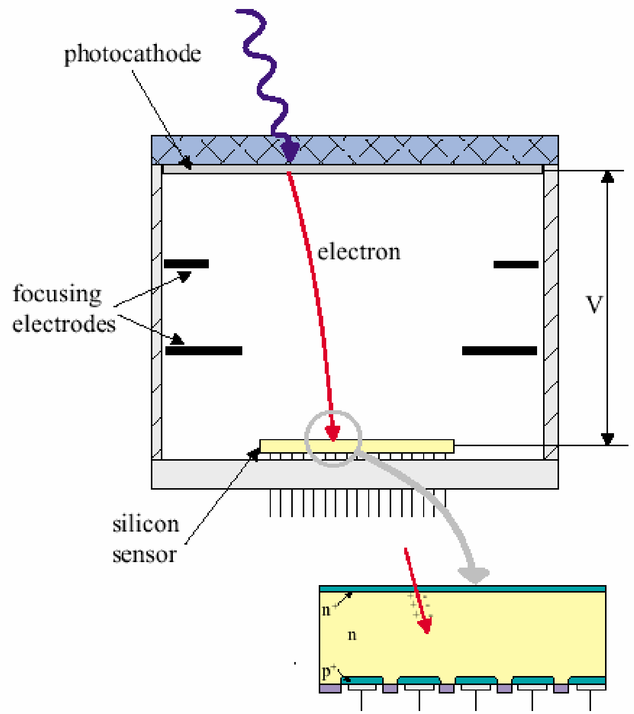


Beaune 2005 talk Photonis

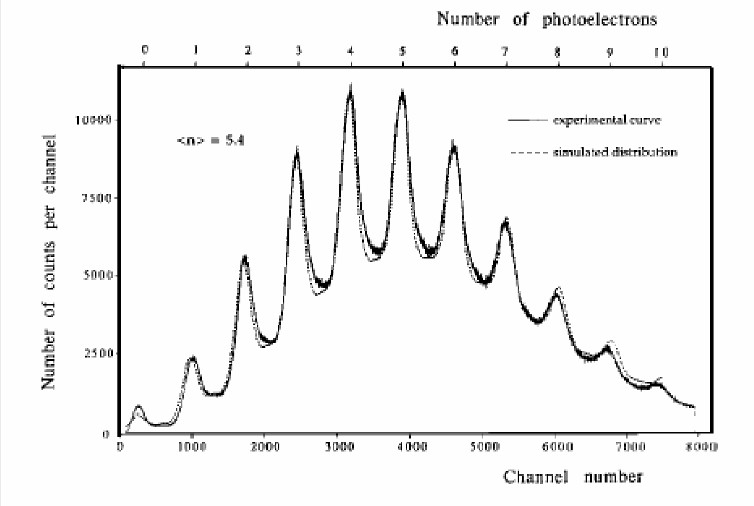
QE is key for hybrid devices …

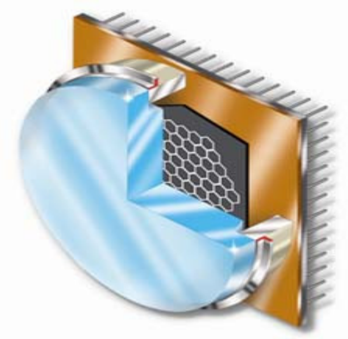


Interest : Additional noise while for PMTs noise is multiplying (no « Fano » factor)



Pair creation by **ionisation**
(3,6 eV / electron-hole pair for Si)





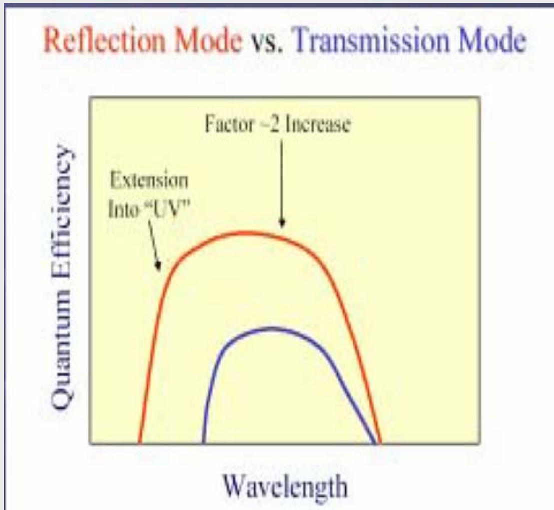
From JC VANEL
Prospectives IN2P3

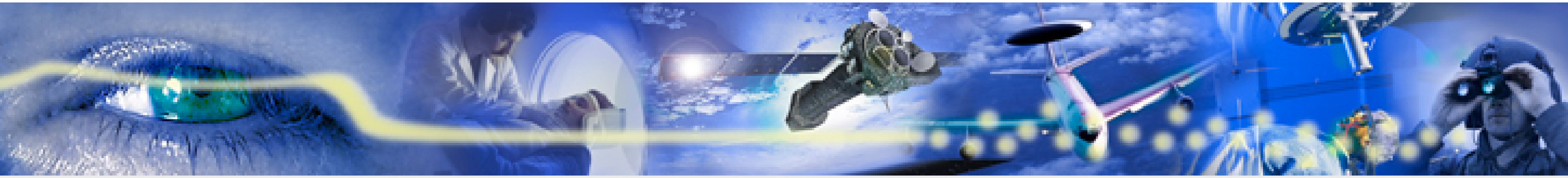
Weakness of PMT & HPD : photocathode → high QE !

Affinité électronique
négative → Semi-conducteur

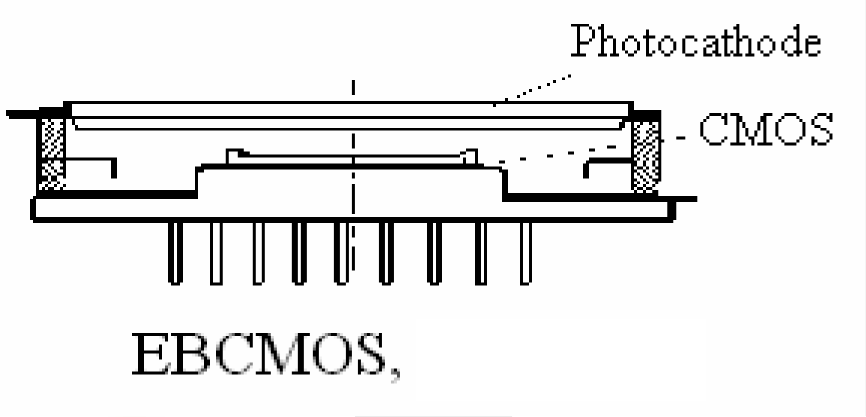
Multiple réflexion (filtre
interférentiel).

R&D

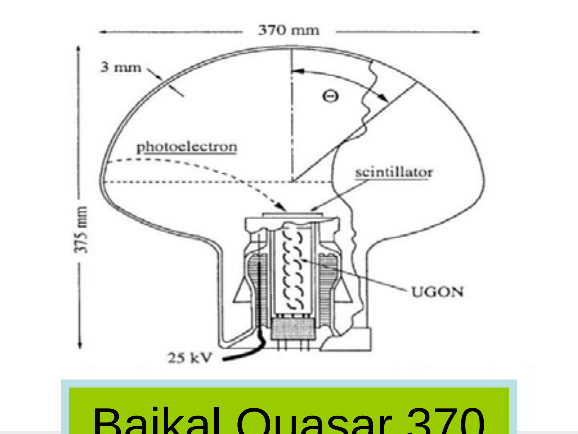




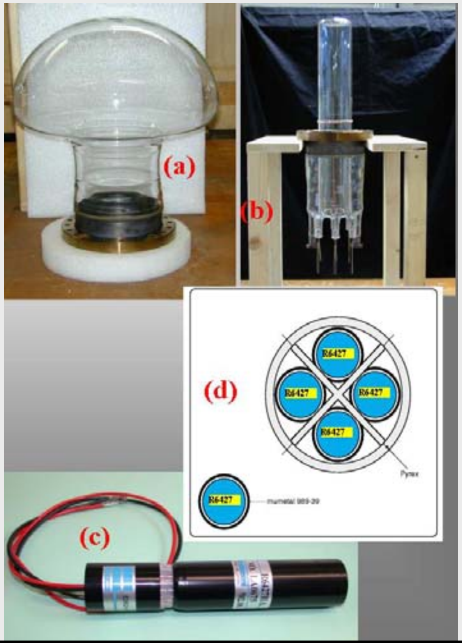
Another example of emerging new devices putting high QE photocathodes at the forefront of photodetection : EBCMOS



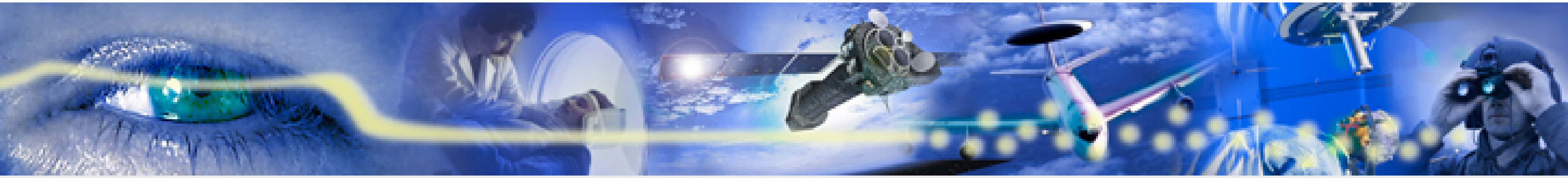
HPD for LHCb RICH counter



Baikal Quasar 370



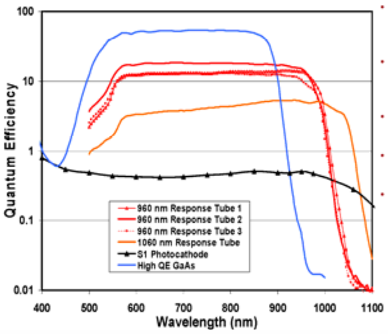
Hybrid PMT R&D @ INFN Genova (Marco Battaglieri et al; NEMO/KM3NeT)



Status on high QE photocathodes :

Higher QE photocathodes exist since long …

Results of Extended NIR Photocathodes



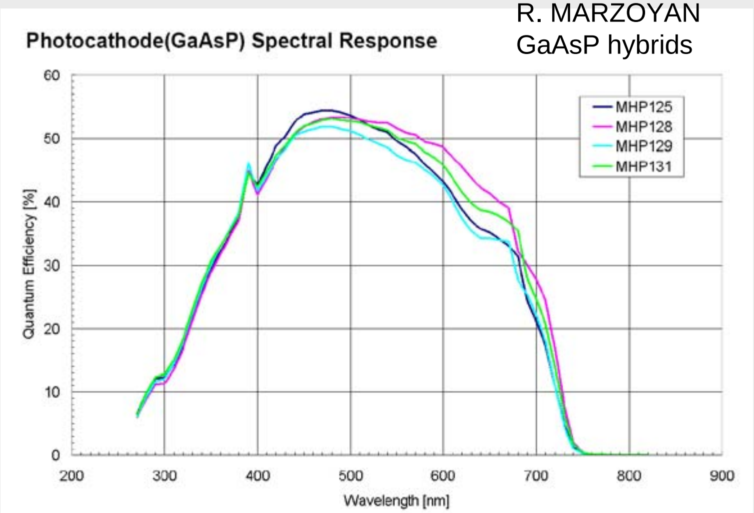
- Peak QE of 18% on 960 nm photocathode structure (13% at 960 nm)
- Peak QE of ~5% on 1060 nm photocathode structure (1% at 1060 nm)
- Further InGaAs material optimization possible
- UHV processing optimization possible
- Lower band gap and low lifetime affecting performance
  - Switching to lattice matched material could improve minority carrier properties
  - Lattice matched material would also remove visible cross hatch pattern

Night Vision KM 17 ITT Industries *Engineered for life*

A few examples of high QE GaAs photocathodes :

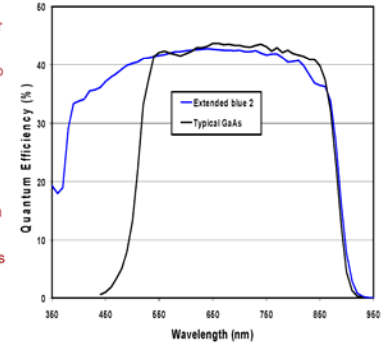
QE above 40% at 420 nm are possible

R. MARZOYAN
GaAsP hybrids

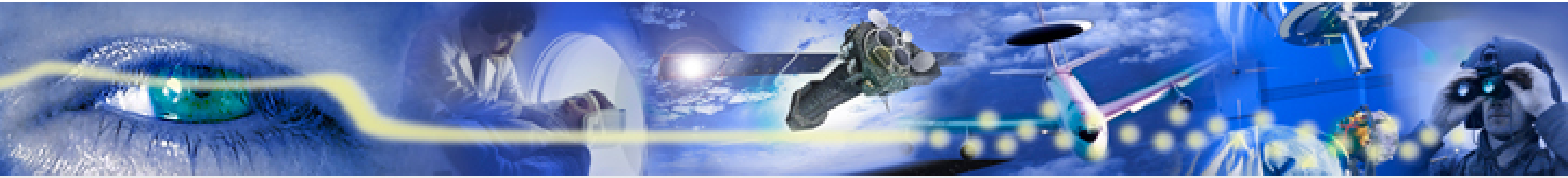


Extended Blue GaAs Photocathode

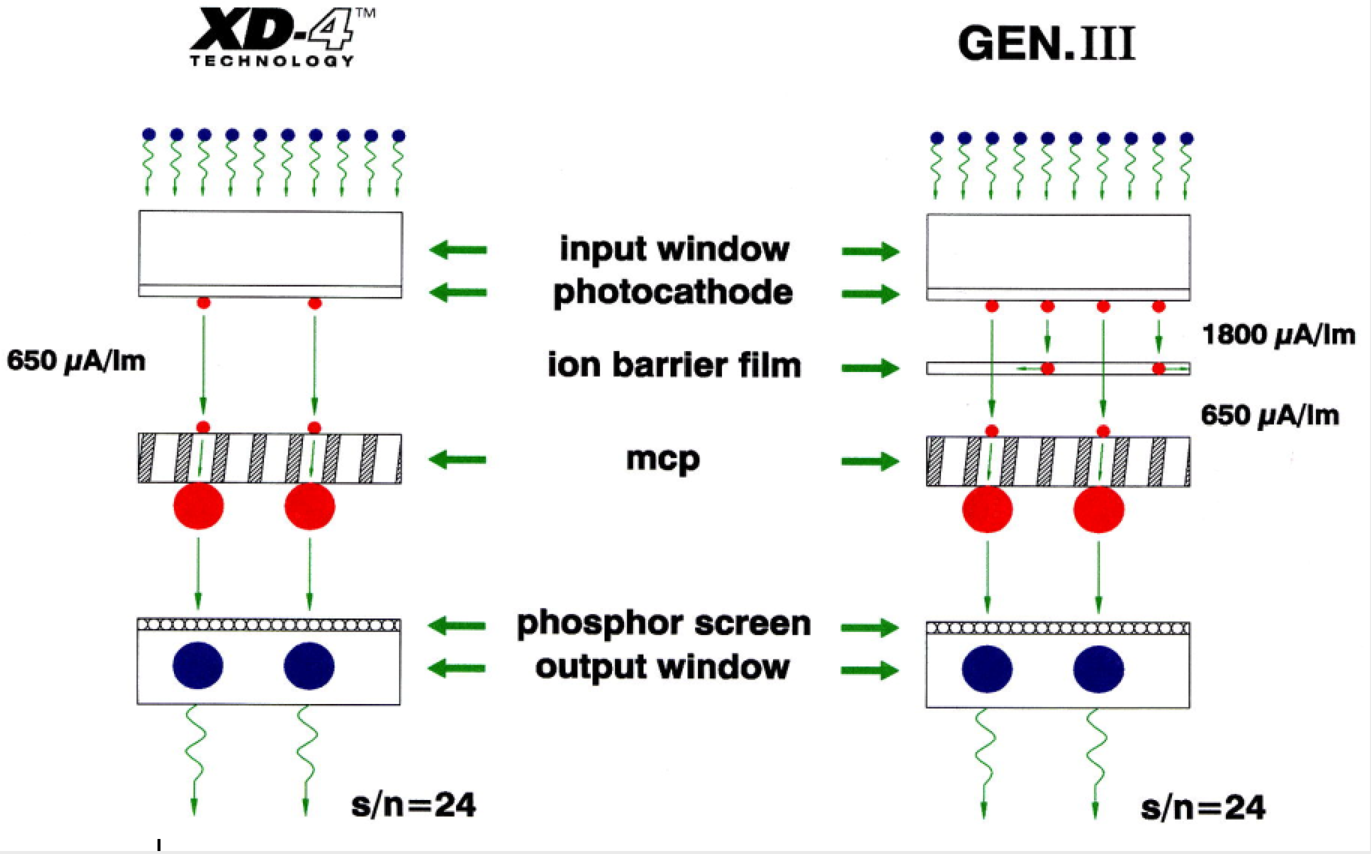
- Thinned the AlGaAs window layer for improved blue transmission
  - Thickness can not be reduced to zero as FSRV increases
- Applied most of the lessons learned from best GaAs photocathodes
- Used production process
  - Lower response but repeatable
- Lower red response is due to using a thinner photocathode
- Still not getting to cutoff of 7056 glass
  - Fall off in blue is 50 nm to soon

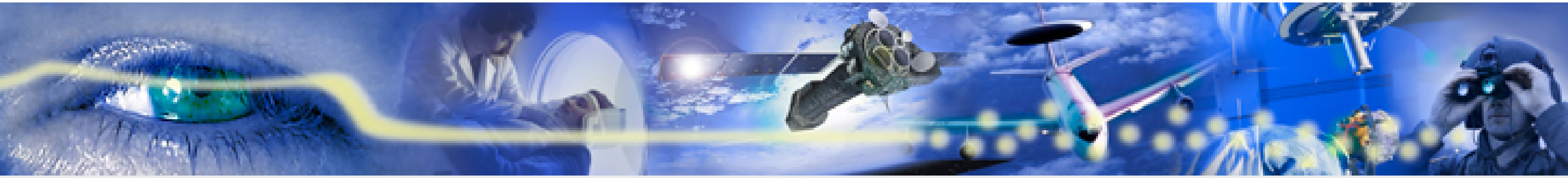


Night Vision KM 10 ITT Industries *Engineered for life*

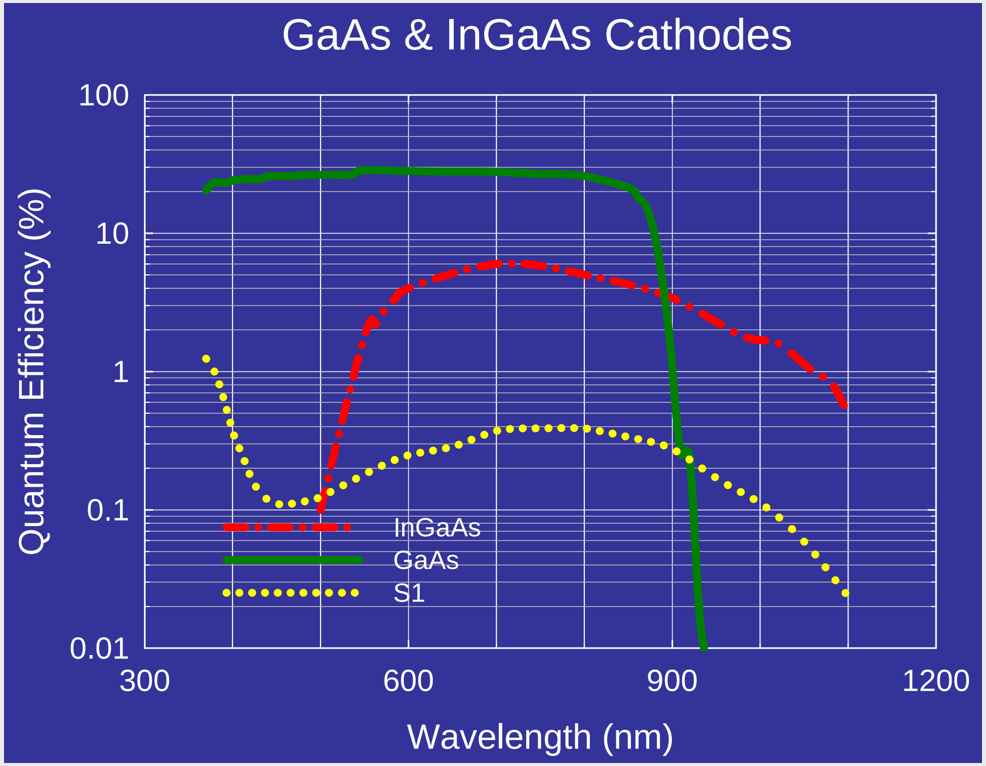


Third generation imaging tube : high QE vs S/N ratio (lifetime drawback)



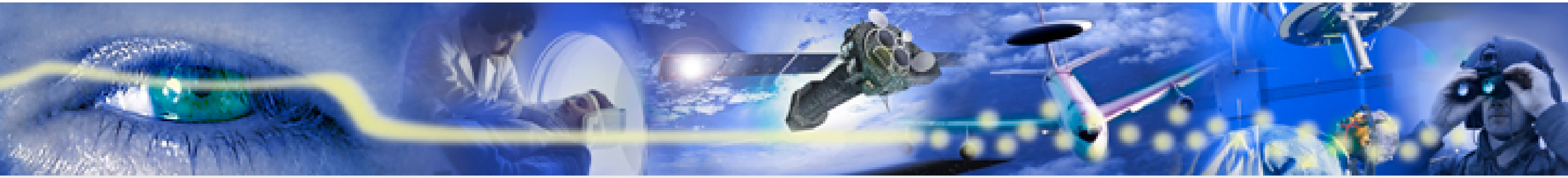


High QE material exist in standard devices but strong link to technology … and cost :



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)

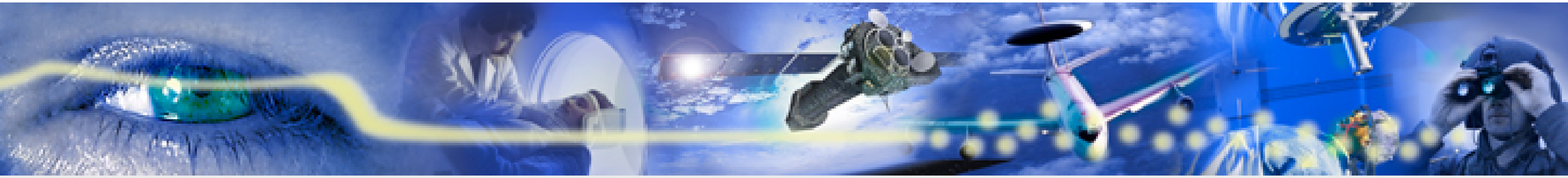
PK process → Tube sealing under vaccuum

Tube process → Tube sealing under vaccuum

2. Pre-deposited (Sb predeposition before processsing … low QE)

Sb deposition outside → In situ PK process under vaccuum

Tube building outside → In situ PK process under vaccuum



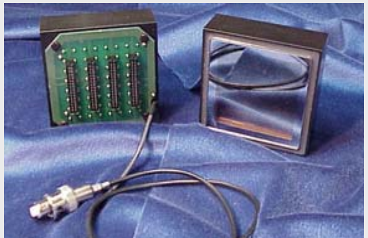
Multipixel tubes (2, 4, 9 channels)

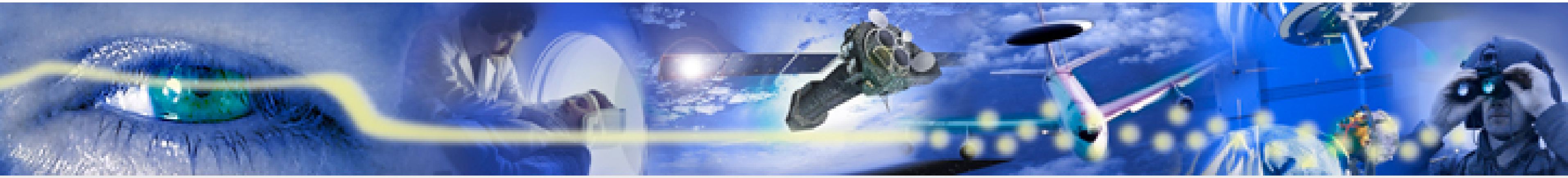
XP1422 XP1432 XP1452 XP1470

- 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
  … <u>these designs allow standard PMT processing</u>

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

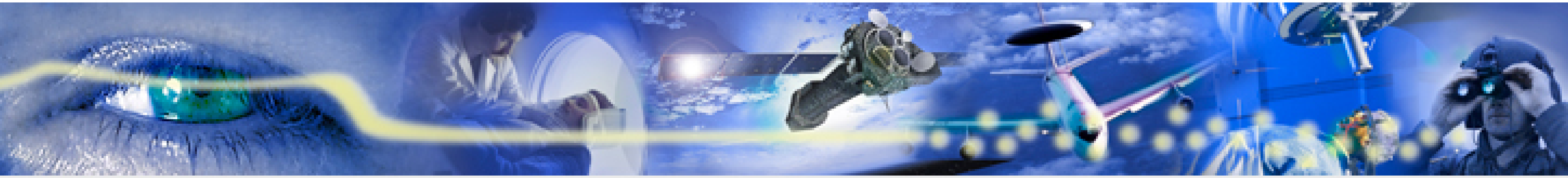




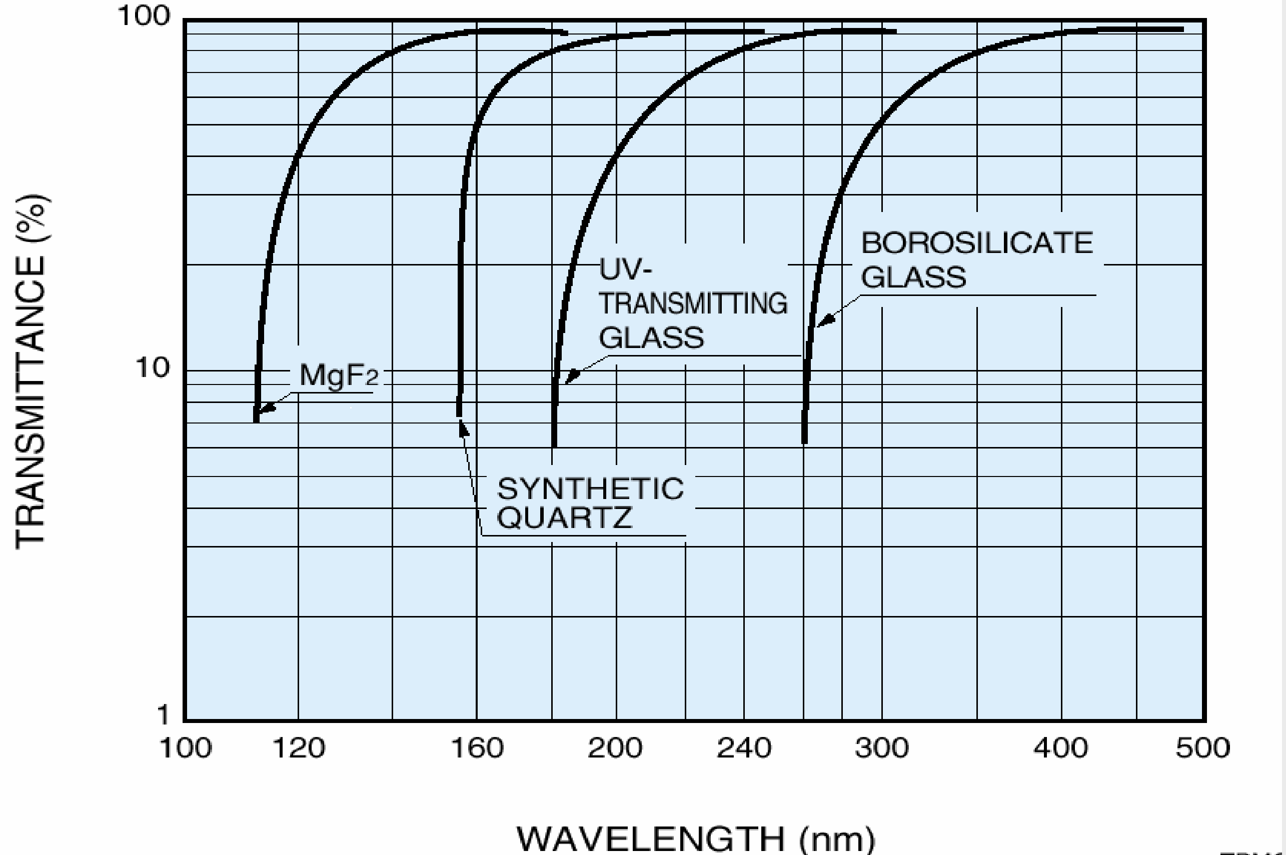
How to improve intrinsic QE in photomultiplier processing ?

PHOTONIS

First way to Improve QE of photodetectors ?



QE always include transmittance
of Glass Window for vacuum devices

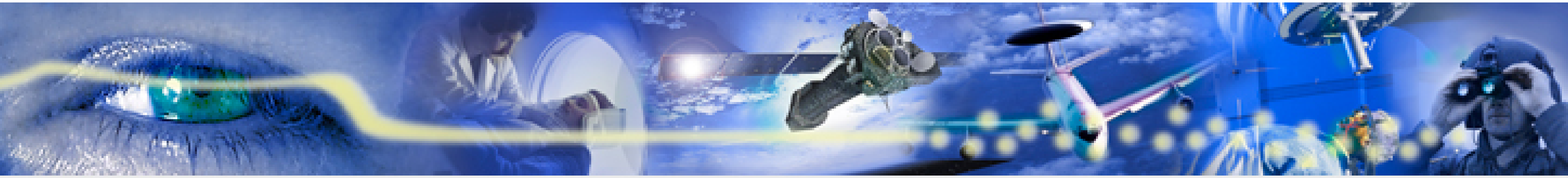


OPTIMISATION by industry (inside the tube) of :

Window Thickness

Window transmission

Window optical coupling to PK



What are the key parameters to increase photocathode QE ?

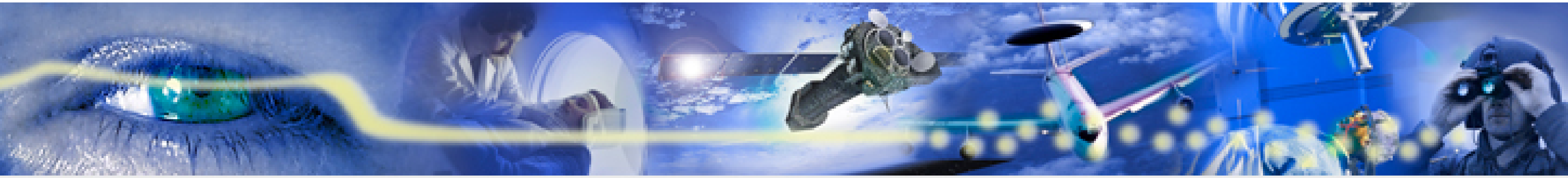
1. Surface structure and cleanliness :
Impact on photocathode growth & diffusion of impurities

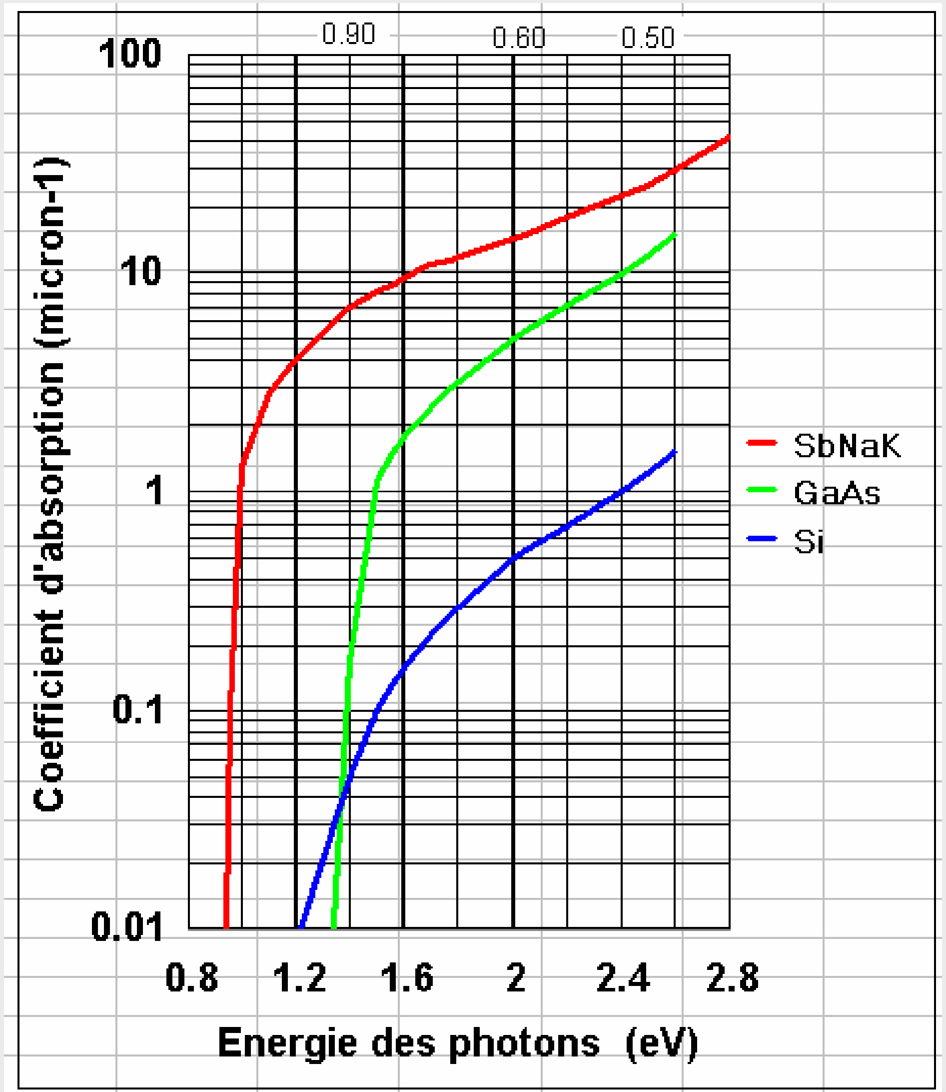
2. Photocathode interface :
Optical coupling with entrance window

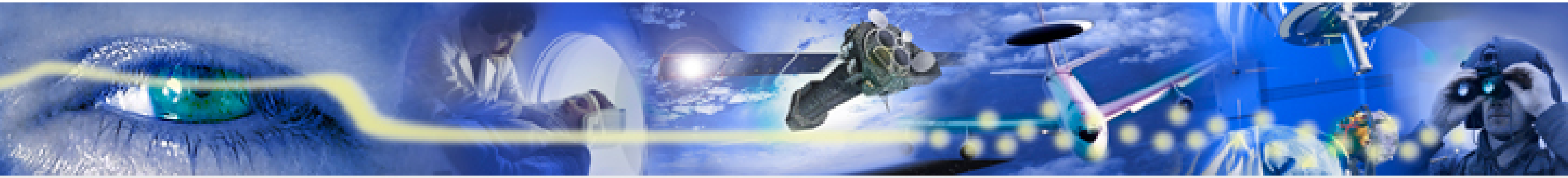
3. Photocathode material :
Purity of basic materials (dispensers) - Composition

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

5. Photocathode thickness :
Compromise absorption of photons – recombination of electrons



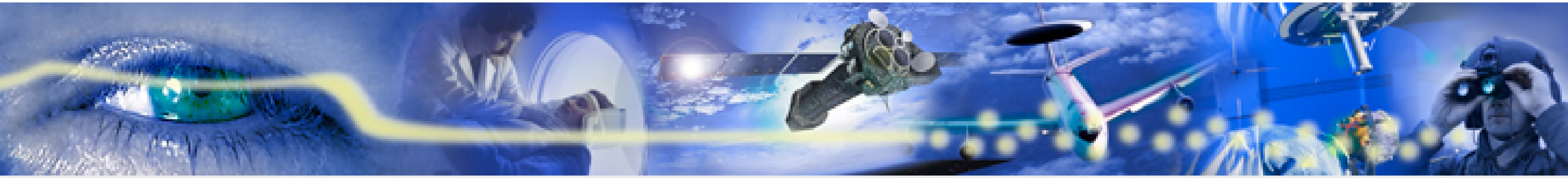

0.90
0.60
0.50
100
10
1
0.1
0.01
Coefficient d'absorption (micron-1)
0.8
1.2
1.6
2
2.4
2.8
Energie des photons (eV)
SbNaK
GaAs
Si



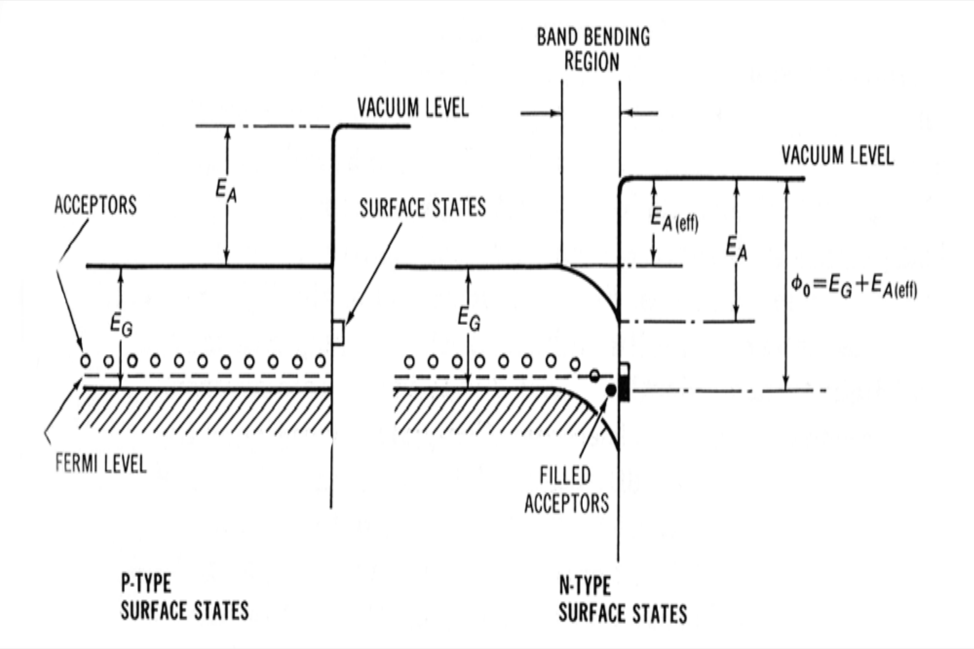
Depending on electron transport :

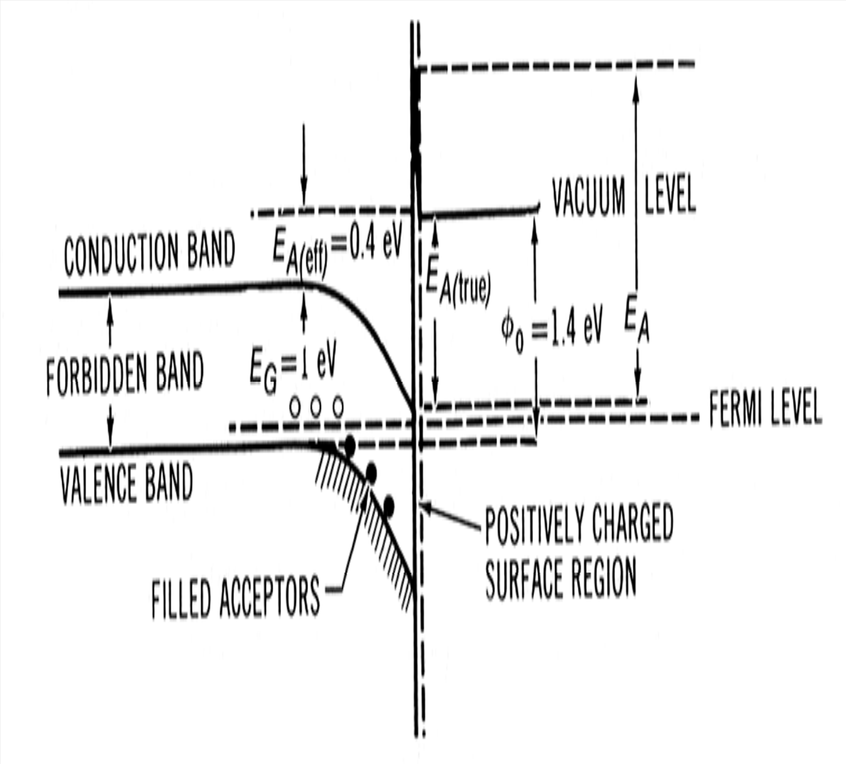
- Semiconductors with negative affinity :
  - Quick thermalisation of electrons to the bottom of the energy band
  - Thermal diffusion : long lifetime
  - ⇨ Diffusion length of a few µm

- Semiconductors with positive affinity :
  - Escape in vaccuum has to occur before complete thermalisation
  - Time to be thermalised << lifetime at bottom of energy band
  - ⇨ Escaping depth ~ 1000 nm

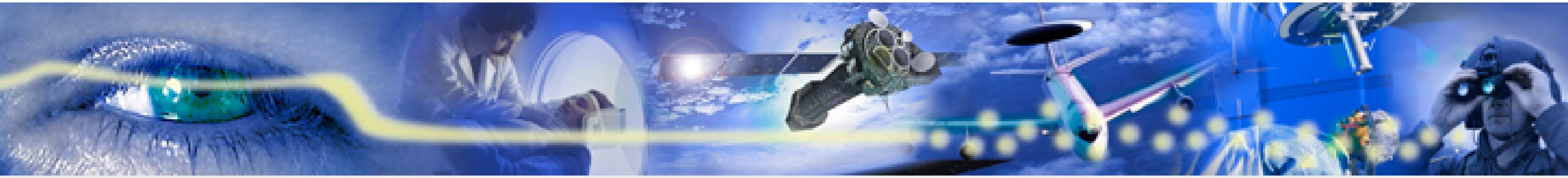


Surface barriers and band bending of multialcali photocathodes

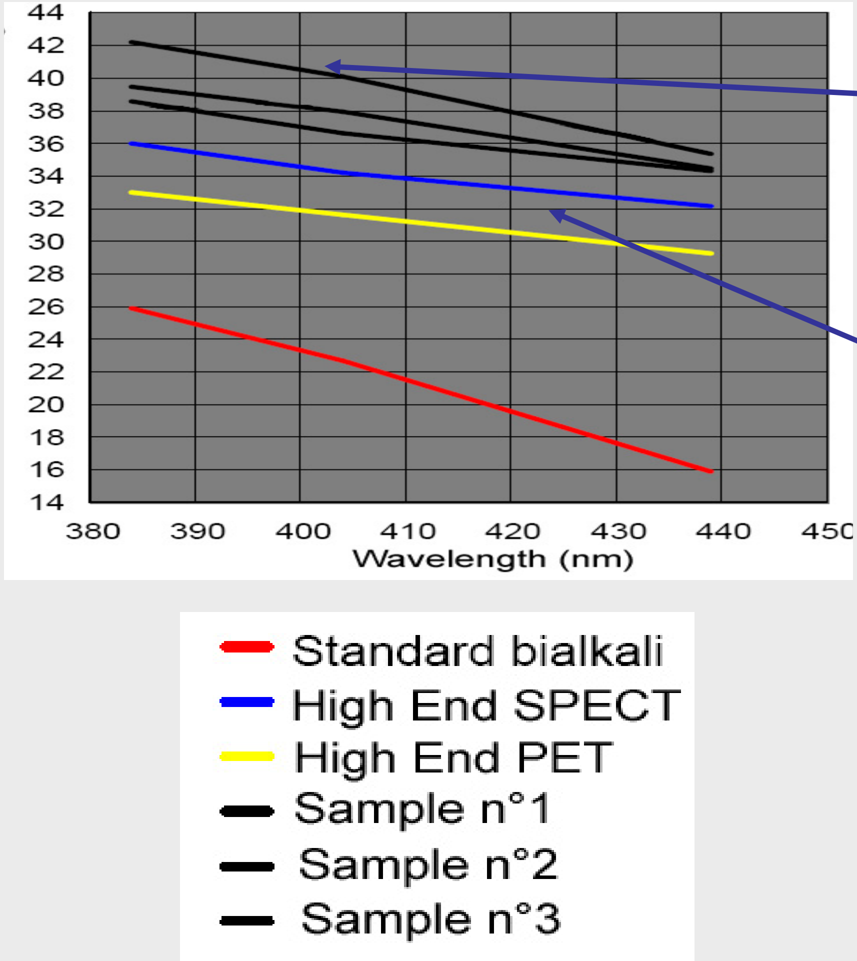




Band bending required to reach > 50% QE



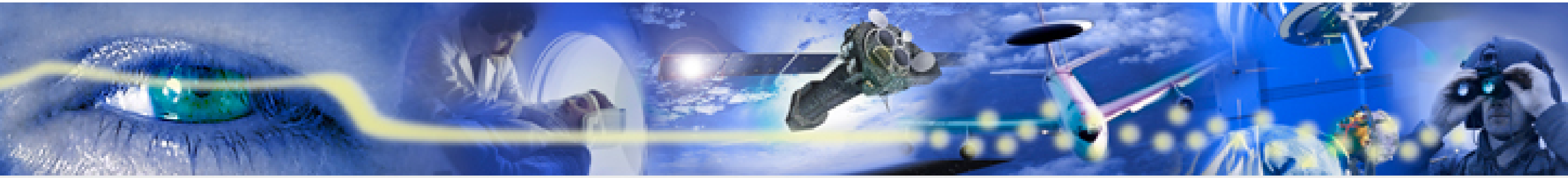
Different generations of bialkali PK and related QE performance level



Super[2] bialkali allow
Above 40% QE at 400 nm

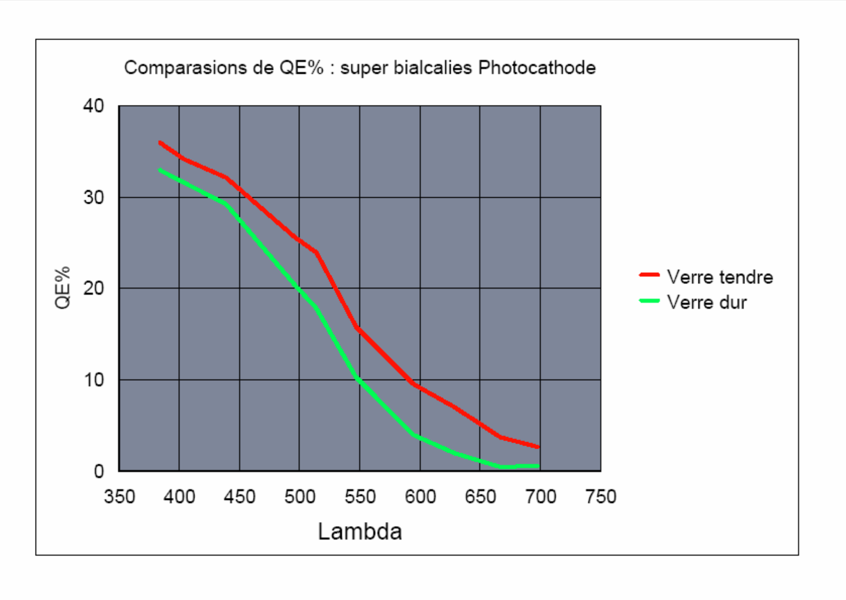
Super bialkali allow
35 – 40% QE at 400 nm

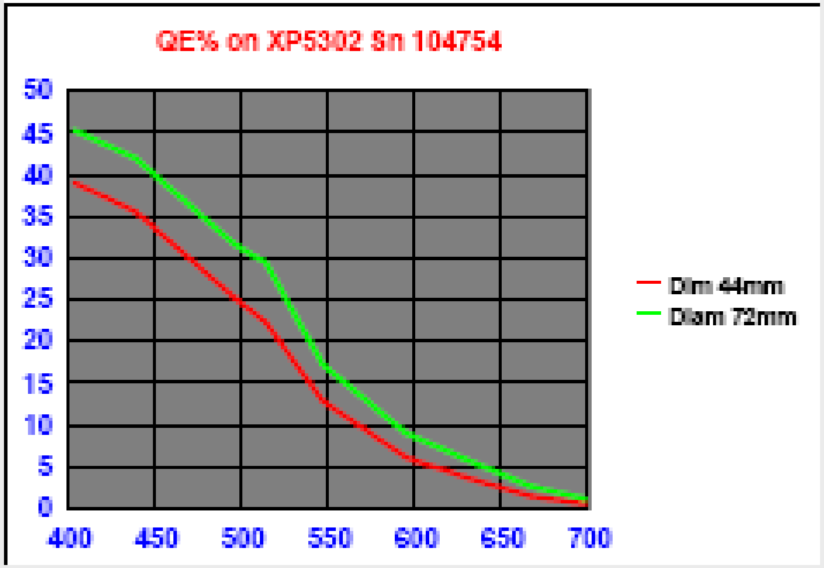
PHOTOCATHODE : the key factor is yield

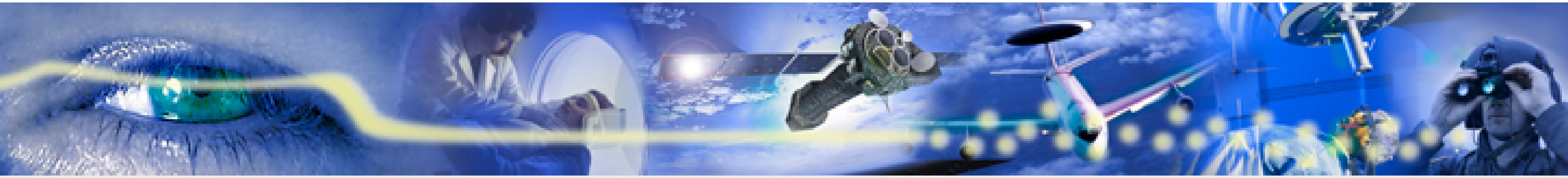


Super bialkali process
(400 nm 30 – 40%)

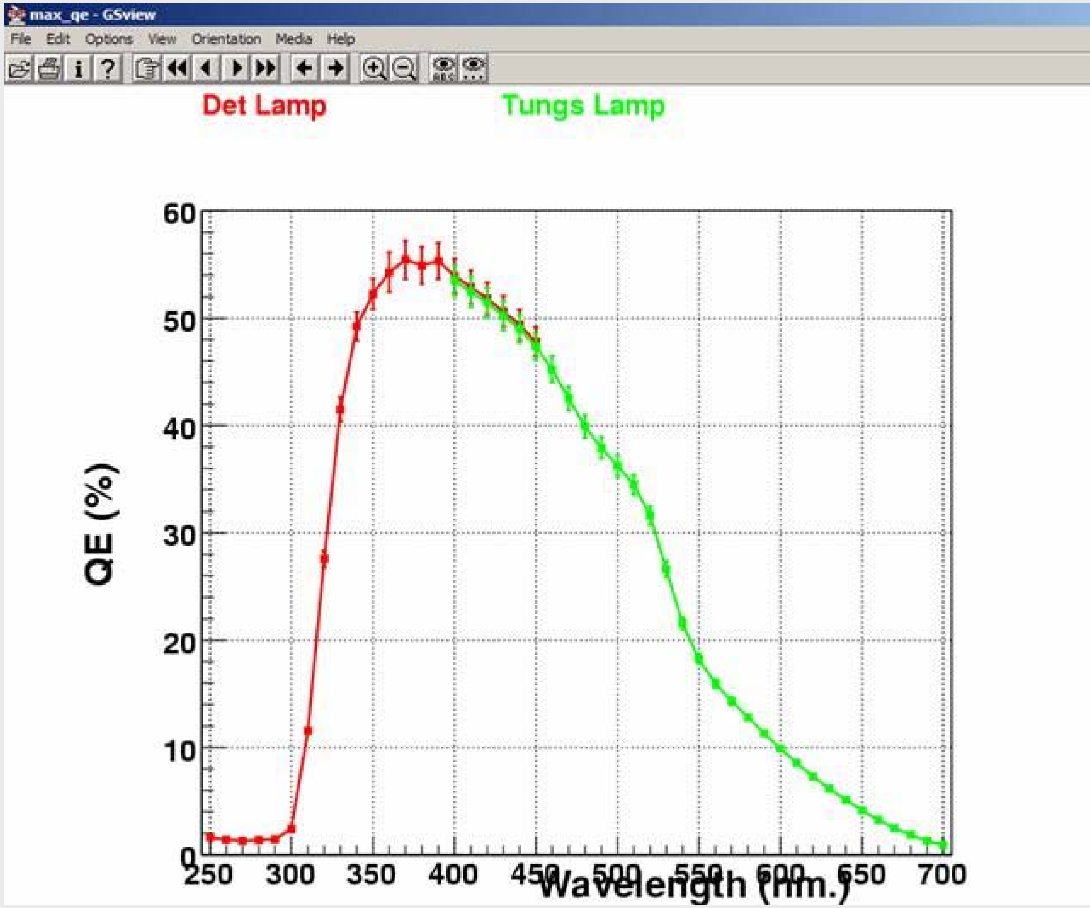
Super² bialkali process
(400 nm 40 – 50%)

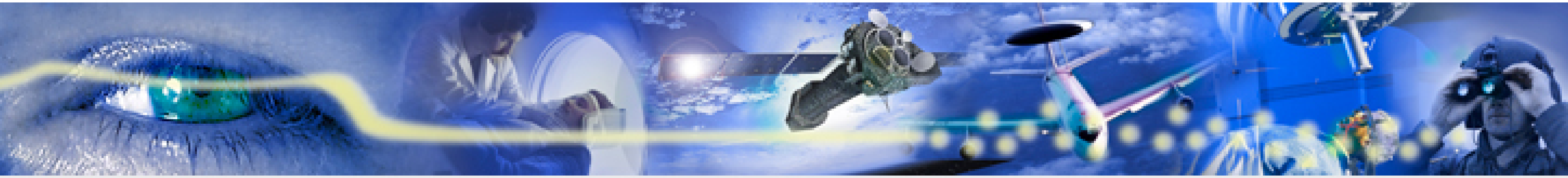




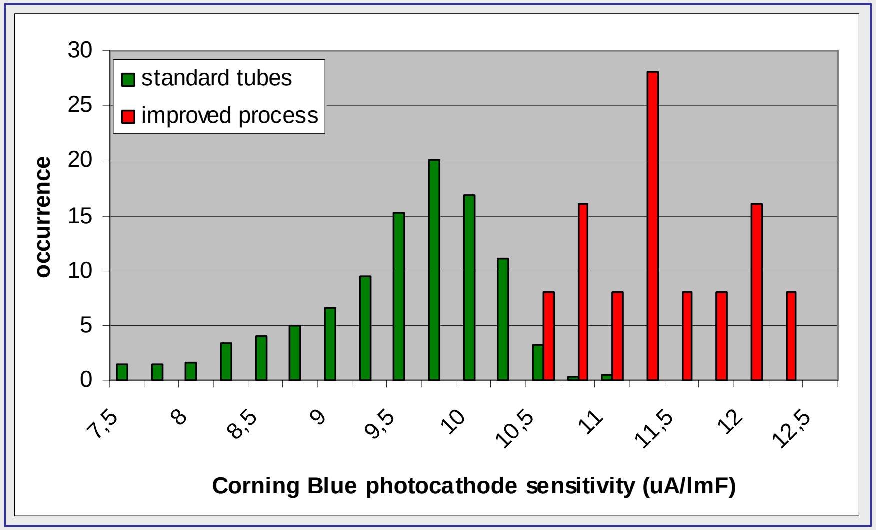


Super³ bialkali process
(400 nm 50 – 60%)





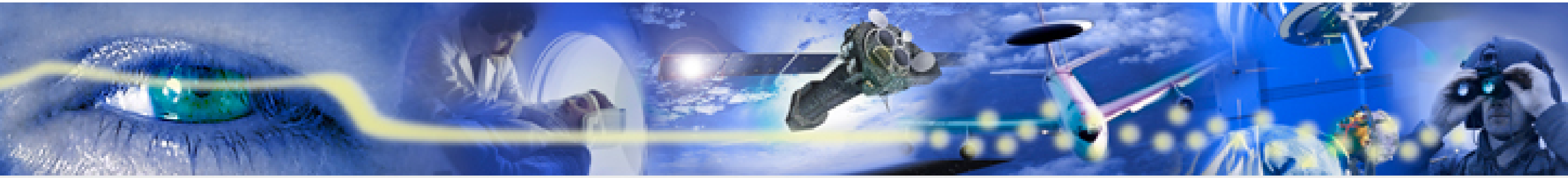
The challenge is to master parameters and reduce production spread in order to produce a high ratio of high QE tubes



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

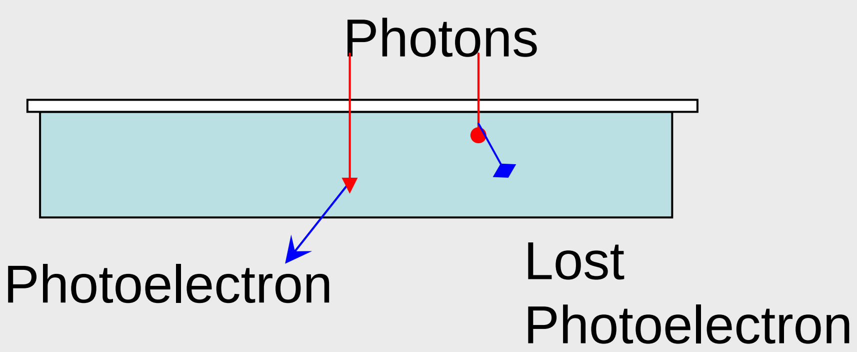
More production data on super² bialkali cathodes at IEEE in Hawai in October 07

PHOTONIS

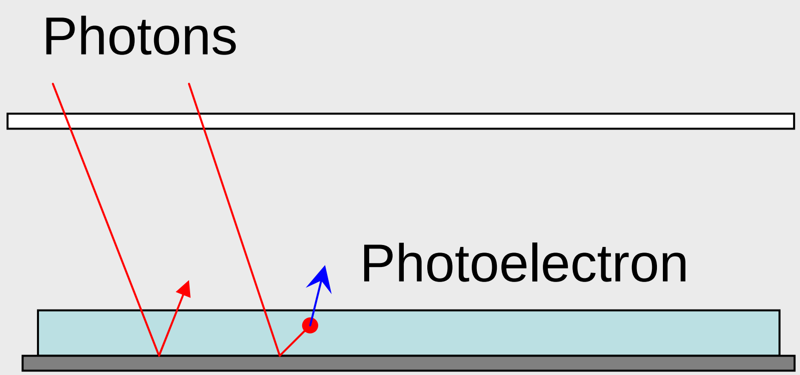


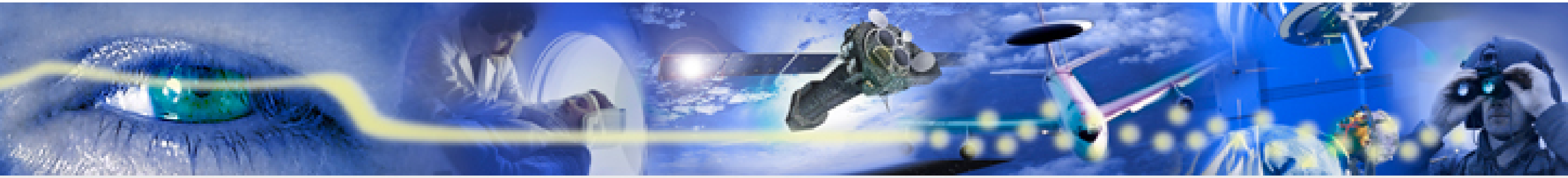
Improving overall QE of photodetectors ?

Thick Transmission mode photocathode

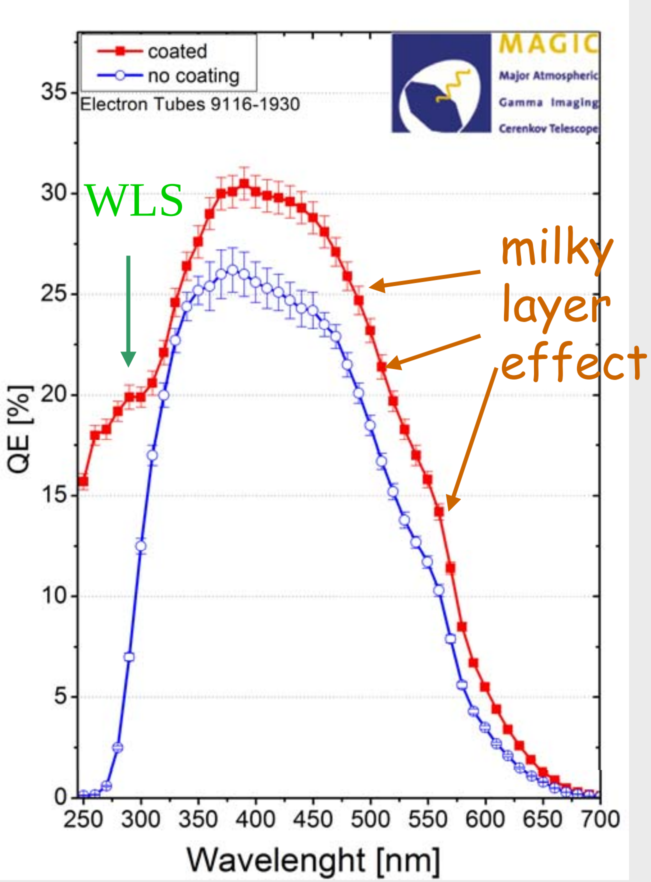


Reflection mode photocathode





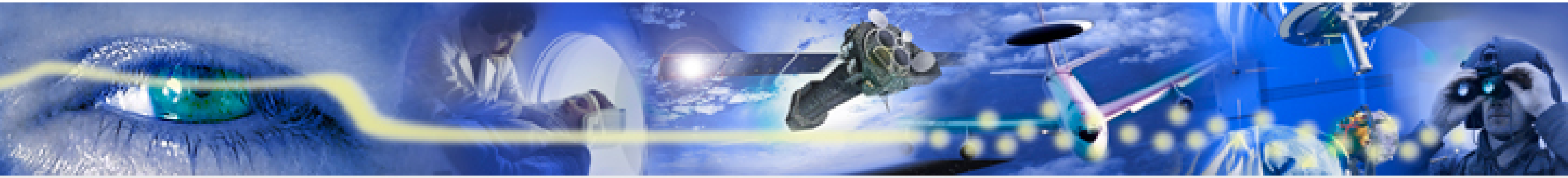
One example from physicists : PMTs of MAGIC-I



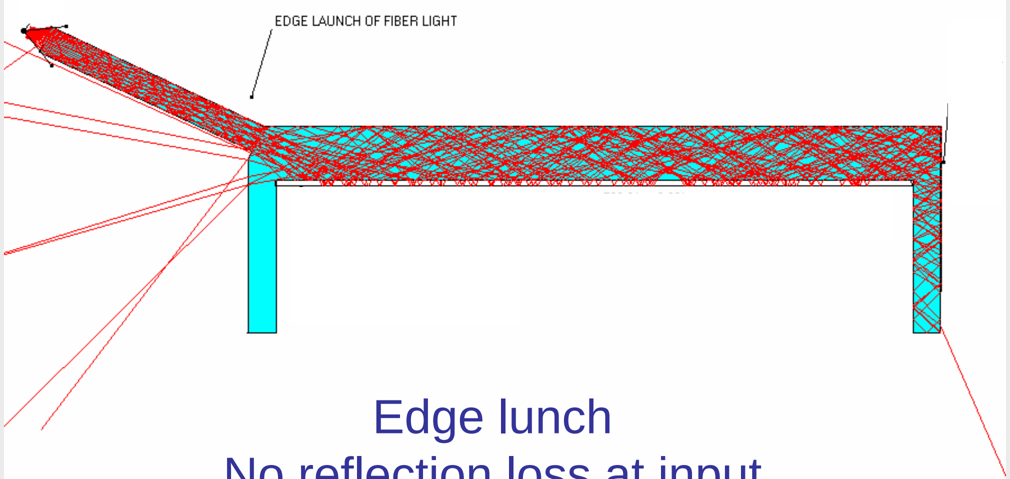
QE ⬆ by a diffuse scattering coating, +WLS

(D. Paneque, et al., 2002)

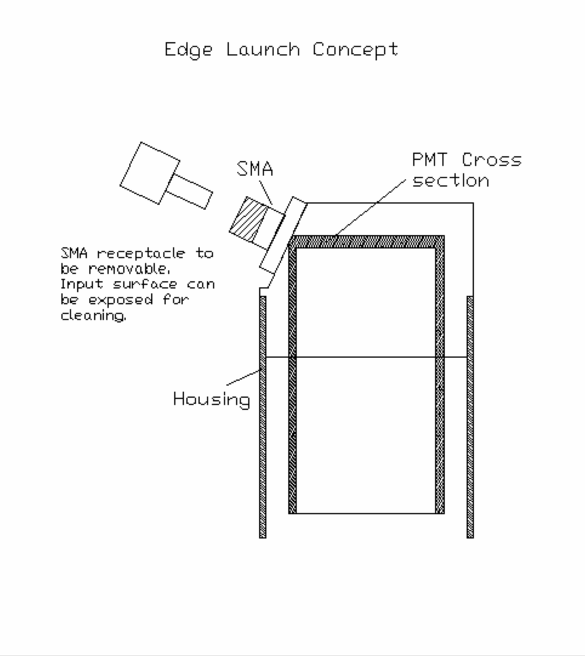
Effective QE ⬆ ~ 15 %



RED new PMT for spectrometers by TIR

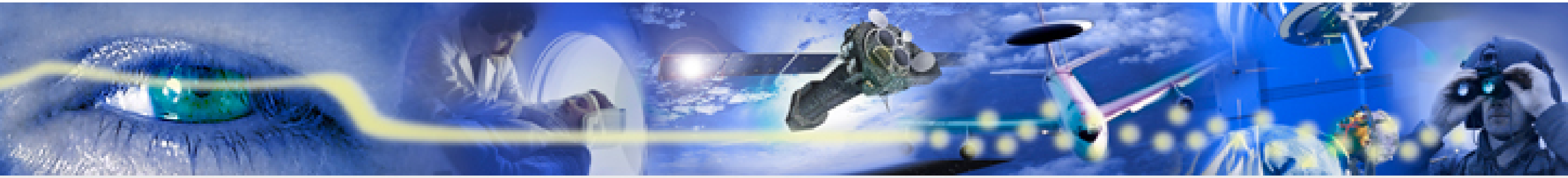


Edge lunch
No reflection loss at input



It is characterized by broad spectral response covering the 300-850 nm wavelength range due to its unique fiber-optic input.

This sensor has improved signal-to-noise ratio.

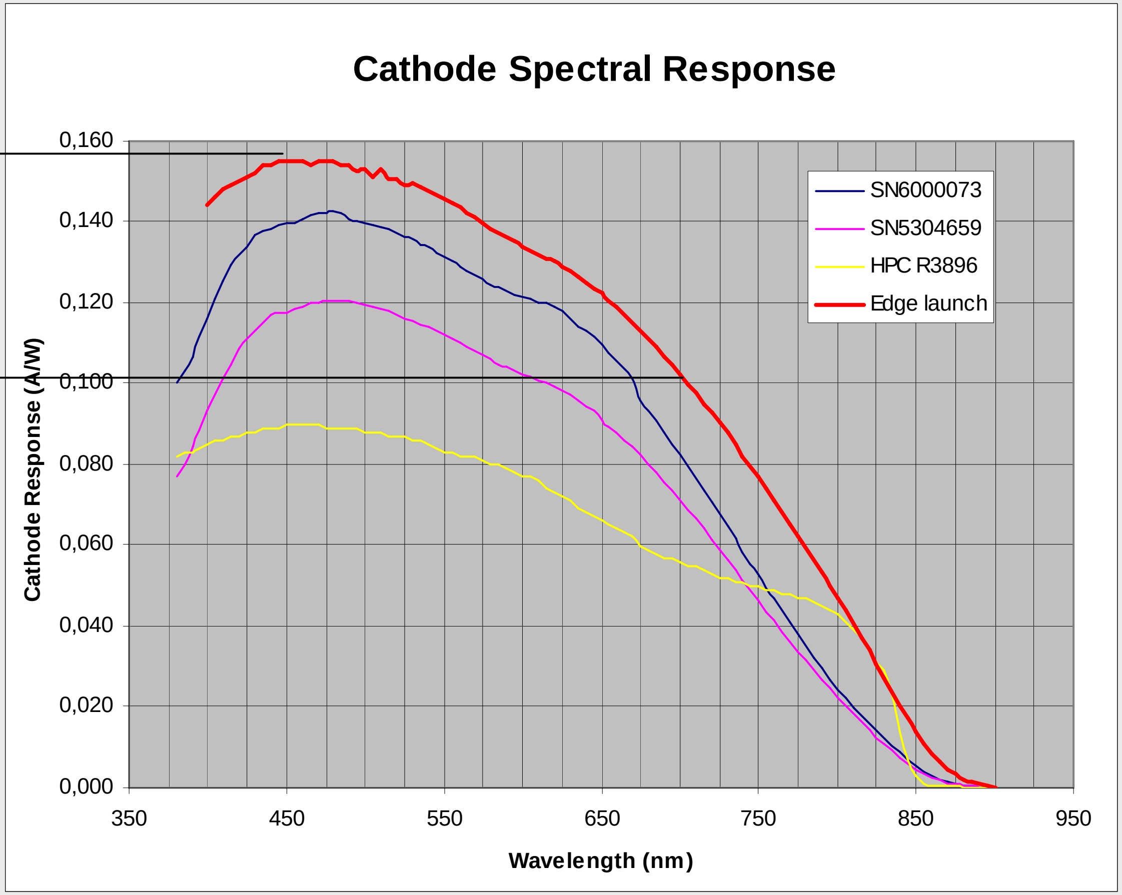


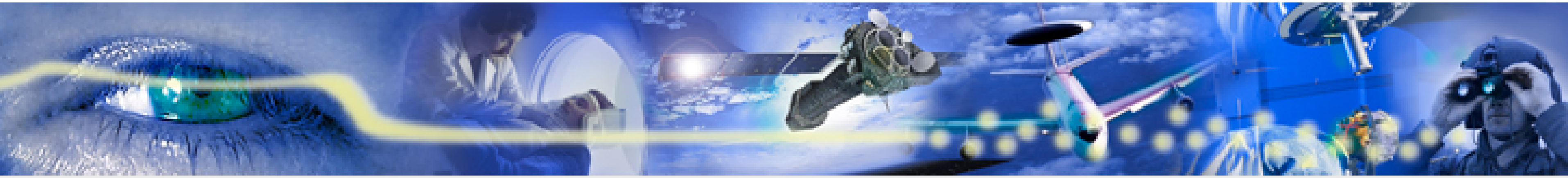
Improved Response with Edge Launch

QE of 43% at 450 nm

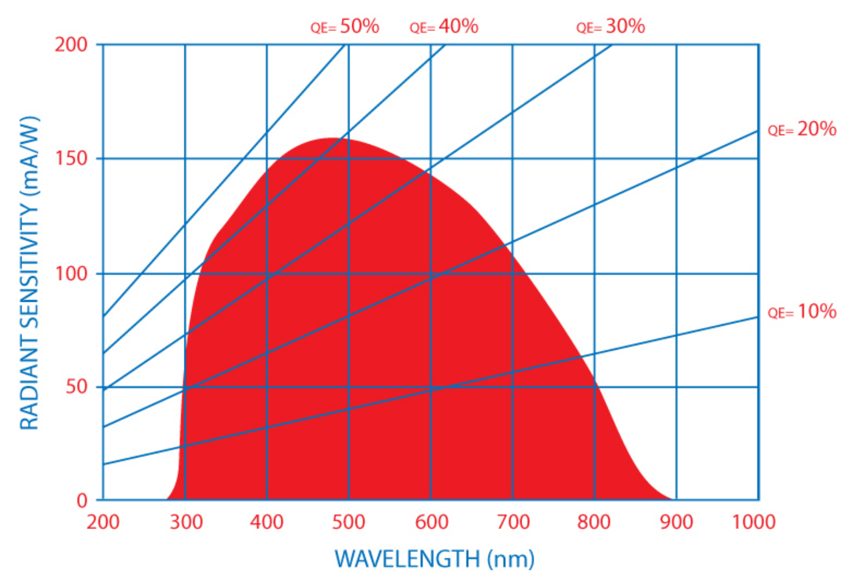
QE of 18% at 700 nm

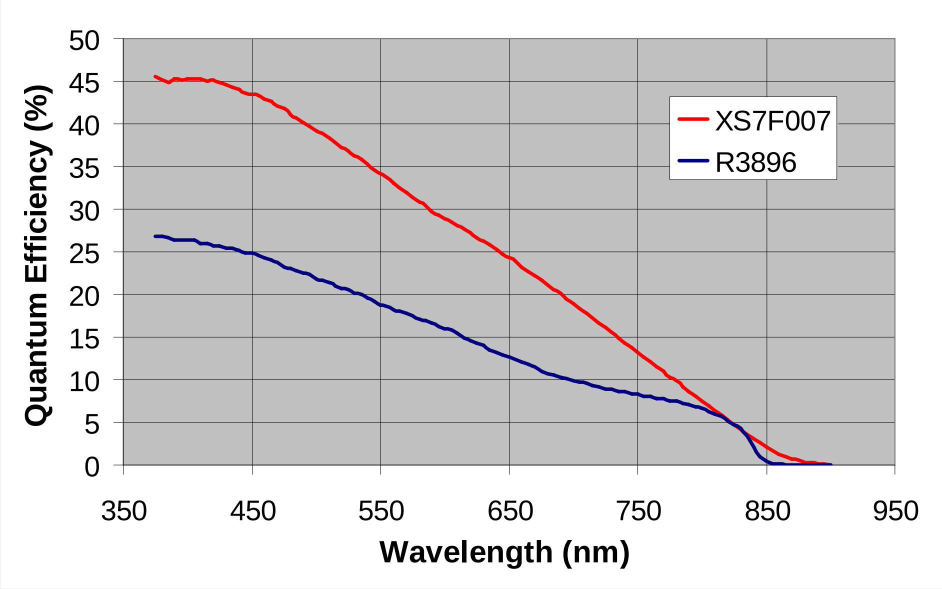
Estimated White Light = 820 uA/lm





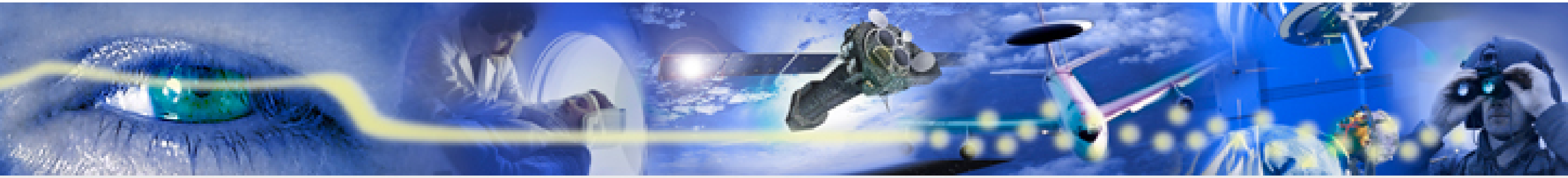
XS7F007 cathode spectral response





Important note :
QE increase by 30 to 40% by increasing the probability of interaction with PK
<u>while dark current remained the same.</u>

PHOTONIS



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 availibility 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 curent 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