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Enhanced quantum efficiency bialkali photo multiplier tubes

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Abstract

Currently, the classical PMTs with semitransparent bialkali photo cathode show peak quantum efficiency (QE) of ~25–27%. Although the above-mentioned peak QE was achieved already ~40 years ago, nevertheless one cannot report any significant increase since then. A couple of years ago we started a development program with the main PMT manufacturers Photonis, Electron Tubes and Hamamatsu, aiming to boost-up the peak QE of the (1–2)″ size bialkali PMTs. Today we want to report that our efforts were successful: all of the three above-mentioned companies succeeded to boost the peak QE of bialkali PMTs to the level of 30–35%. In this report, we want to show the QE measurements of different tubes and discuss the future prospects. For example, it shall be possible to use the diffuse-scattering matt lacquer coating technique in order to enhance further the QE. In our previous experience application of that coating provided ~15% increase in QE for 1–1.5″ hemispherical tubes.

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1. Introduction

The classical PMTs were invented in the mid-1930s. Since the very beginning they have revolutionized the physics experiments. Also, they had a strong impact on other disciplines or applications where it was necessary to measure very fast low light level (LLL) signals. Initially, the photo cathodes had very low peak QE on the order of ~1% but in the following 20–25 years it was increased to the level of ~25%. It may sound surprising but one cannot report any significant increase of the peak QE value after that. One possible explanation could be the fact that most PMT users (including industrial applications, like for example, in γ-cameras and in positron emission tomography (PET) in medical diagnostics) are working in conditions when there is "enough" light. Those who are working with LLL signals are in minority (these are mostly scientists working in astronomy and astroparticle physics). Especially in the case of LLL applications, it is becoming important to provide high signal-to-noise ratio. As one can see from formula (1) below, the signal-to-noise ratio depends on the QE value η and on the number of incident photons N as

$$\text{signal/noise} = \sqrt{\mathrm{N} \cdot \eta/(1-\eta)}. \quad (1)$$

In order to provide a relatively high signal-to-noise ratio, especially at low number of incident photons, one needs to provide high QE.

2. Short historical review

Below we want to list the main historical milestones that made it possible to develop and produce state-of-the-art PMTs:

- 1889: Elster and Geitel [1] discovered that in alkali metals a photo-electric effect can be induced by visible light (the existence of the e^- was yet unknown).
- 1905: Einstein [2] put forward the concept that photo-emission is the conversion of a photon into a free e^-.
- 1910: Photoelectric effect on K–Sb compound was found [3].

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- 1923: found that thermionic emission of W is greatly enhanced when exposed to Cs vapour [4].
  It was found that the work function in the above case was lower than of Cs metal in bulk.
- Until ~1930 QE of available materials was $<10^{-4}$.
- 1929: discovered Ag–O–Cs photo-emitter (Koller; Campbell) improved the QE to the level of $\sim 10^{-2}$ [5,6].
- First important commercial application: reproduction of sound for film.
- 1936: discovered high efficiency of Cs–Sb (Görlich) [7].

Improved photo cathode materials were discovered later on but it was a combination of a good luck with "intelligent guessing".

A very important step was to realize that the photo cathode materials are semiconductors. By comparing the metallic versus nonmetallic materials one can say that

1. the yield of metallic photo cathodes is very low because of initial very high reflectivity,
2. semiconductors have less reflection losses and correspondingly higher yield (see below).

The main loss process in metals is the e^- scattering; e^- escape depth of only few atomic layers is possible. The losses in semiconductors because of phonon scattering (interaction with lattice) are much less, i.e. e^- from deeper layers can reach the surface. The measured escape depth was 10–20 atomic layers for K, Rb, Cs. It is interesting to mention that for photon energies $\geqslant 12$ eV QE values of 1–10% were reported for Ni, Cu, Pt, Au, W, Mo, Ag and Pd [8]. More concrete, for example, 7% QE was reported for Au at 15 eV and 2% for Al at 17 eV.

In 1955–1958 Sommers found the "multialkali" effect: combination of Cs–K–Na–Sb has high QE in the visible spectrum (see for a historical review and for details [9]).

Also were discovered

- Cs_3Sb on MnO (S11, QE_{peak} ~20% at 400 nm),
- $(Cs)Na_2KSb$ (S20, QE_{peak} ~30% at 400 nm),
- K_2CsSb (QE_{peak} ~30% at 400 nm),
- $K_2CsSb(O)$ (QE_{peak} ~35% at 400 nm).

One can see from the above list that peak QE values in the range of 20–30% were reported already at the end of the 1950s and at the beginning of the 1960s. Nevertheless, until very recently the commercially available PMTs had QE values of ~25%.

3. Increase of the QE of PMTs

Below we want to list the main factors that can allow one to enhance the QE of PMTs:

- Use of highly purified materials for the photo cathode composition (for example, change from 99.999% purity of materials to 99.9999% or even higher).
- Optimal tuning of the photo cathode thickness.
- Optimal tuning of the material composition and their treatment.
- Optimal tuning of the anti-reflective layer.
- Recycling of the photons that pass through the semitransparent photo cathode without interaction.

The first of the above points shall have a dominant effect. For the given thickness this will provide less scattering length for e^- (low recombination probability). Under this condition the e^- released from deeper layers can reach the photo cathode-vacuum junction and can contribute into photo current.

Tuning of the photo cathode thickness shall be decisive for the peak position of the QE curve. The given thickness shall define the wavelength range where light interference is important that can be used to enhance the QE. Perhaps there is not much freedom in the selection of photo cathode materials, their composition and used technologies. Still an optimal composition shall be important in order to provide a possibly wide and high spectral response. Optimal tuning of the anti-reflective layer is related with the photo cathode thickness as well as with the possibility to use special layers in the junction between the photo cathode and the glass envelope. Our earlier measurements have shown that ~10–30% of incident light (correspondingly the lower value in the blue, increasing towards the higher one in the red part of the spectrum) is reflected back from the photo cathode because of its high refractive index. Optimally tuned anti-reflective layer could reduce the reflection losses and increase the QE. The last point in the above list can also contribute into the increase of QE on a few percent level: one needs to make (coat) the surrounding surfaces of the PMT input chamber from a highly reflective material.

4. The measurements

In our measurements we used a spectrophotometer assembled from commercial parts. As a reference we used a 10 × 10 mm calibrated diode from Hamamatsu that has a calibration precision of 2%. The spectrophotometer and the diode were driven and read out via Lab-View under the computer control. A central 5–15 mm diameter of the photo cathode area of PMTs were illuminated. Usually, a potential difference of 200 V was applied between the photo cathode and the first dynode and then the photo current was measured by using a picoammeter Keitley 485. All the other dynodes were shorted with the first one.

4.1. Hamamatsu PMTs

Earlier we have reported about QE measurements of few 2″ size flat window bialkali PMTs from Hamamatsu of type R878 [10]. They showed peak QE values of 33–36% (see, for example, the measured QE of PMT #WS7454 in Fig. 1). The PMT #WS7454 shows a QE curve that is above 30% in the wavelength range of 330–460 nm with a peak value 33% at 370 nm.

In Fig. 2 are shown the measured QE curves for three 1″ size PMTs with hemispherical windows: two from Hamamatsu (type R7373, #5038 and #5043) and one from Electron Tubes (type ET9116 A, PMT #1930). The latter PMT stems from a few years ago production cycle and was used for reference purposes. As one can see the PMT from Electron Tubes shows a relatively low peak QE of about 25% while the PMTs from Hamamatsu show peak QE values of 31% and 33%. While the QE peak position for the Electron Tubes PMT is at ~380 nm, it has a flat shape in the wavelength range 330–390 nm for the Hamamatsu PMT #5043 and again, it has a (rather unusual) relatively flat shape in the wavelength range 290–380 nm for the PMT #5038. While the PMT from Electron Tubes shows only a QE of 11% at 300 nm (this relatively low value is also due to the light absorption in the used BK-7 type of glass for the entrance window), the PMTs from Hamamatsu show correspondingly 28% (#5043) and 31% (#5038) QE at the same wavelength. One can see some other striking difference in Fig. 2, namely that the PMTs have rather different QE values for wavelengths above 450 nm. Both Hamamatsu PMTs, in spite of their different QE values at shorter wavelengths, show essentially the same QE for wavelengths >450 nm. The PMT from Electron Tubes shows systematically higher QE than those of Hamamatsu for wavelengths >450 nm. For example, while the Hamamatsu PMTs show a QE of only 6% for the wavelength 550 nm, the Electron Tubes PMT shows a QE of 12%.

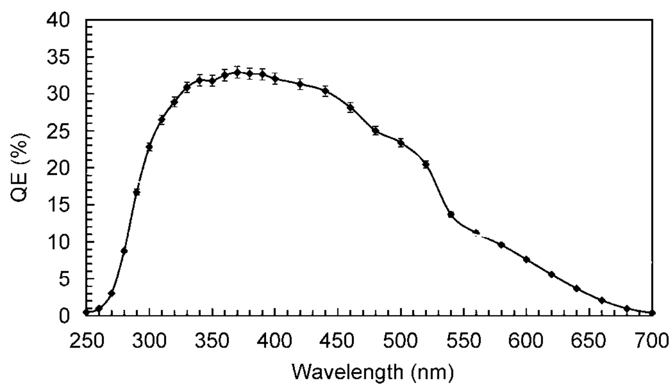

Fig. 1. Measured QE of 2″ size PMT R878 (serial #WS7454) from Hamamatsu.

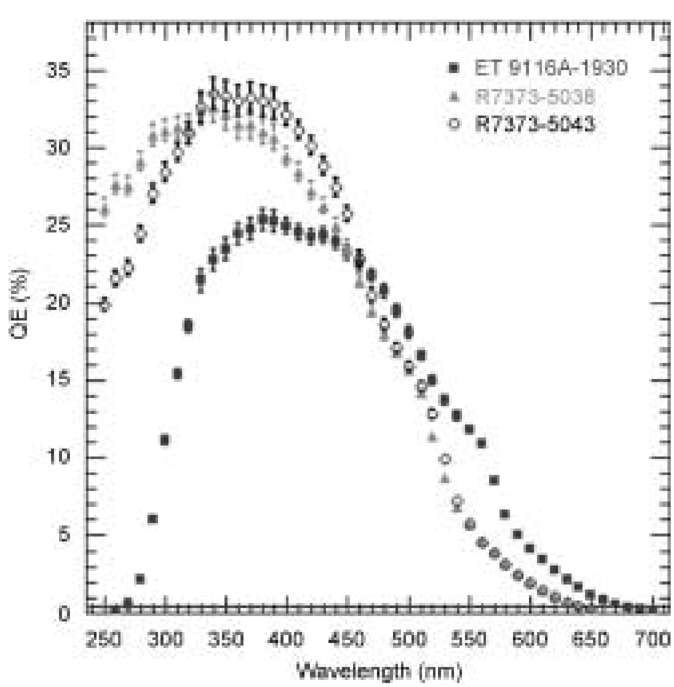

Fig. 2. Measured QE curves for three 1″ size PMTs with hemispherical windows: two from Hamamatsu and one from Electron Tubes.

4.2. Electron tubes PMTs

In Fig. 3 are shown measured QE curves for five PMTs with hemispherical windows, again of 1″ size, from Electron Tubes. Looking into the QE curves from right to the left, one can see that the peak QE value of these PMTs is shown in increasing order. The lowest peak QE of

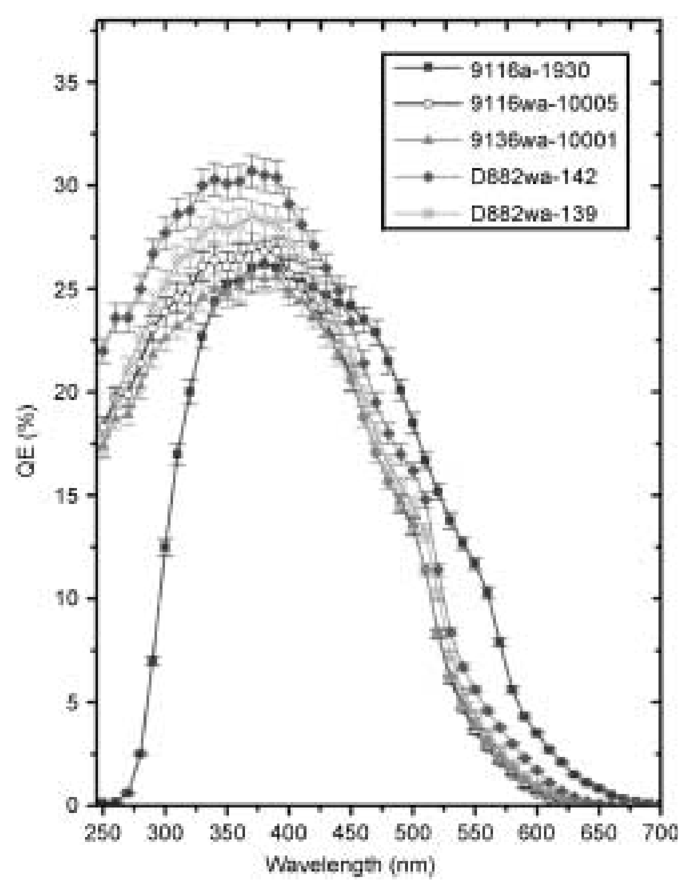

Fig. 3. Measured QE curves of five 1″ size PMTs with hemispherical windows from Electron Tubes from different production iterations.

26% (at 360 nm) has the PMT of type ET9116A (serial #1930) and the highest QE of (30–31)% (in the wavelength range of 330–390 nm) has the PMT of the type D822WA (serial #142). It is interesting to note that if the peak QE of a given PMT is higher, then its entire curve is shifted towards the shorter wavelengths. One may speculate that when thinning the photo cathode, the response in the short-wavelength part shall increase because of the light interference in the photo cathode and neighbouring junctions, while the response at longer wavelengths shall drop.

4.3. Photonis PMTs

Also several PMTs from few production iterations were obtained from Photonis. While the measurements of two PMTs of type XP5312 (3″ size, with flat entrance window) showed a peak QE of ~30%, an experimental PMT of the type XP3422 (flat window, 2″ size, #82410) showed a peak QE of 34% [10]. The QE curve of this latter PMT had somewhat unusual, narrow shape: one could observe a steep drop of QE for wavelengths >400 nm. Also, several PMTs of type XP31T2 of 1″ size (with hemispherical window, but about twice as long as the 1″ PMTs from Electron Tubes and Hamamatsu) were obtained from Photonis. Our measurements showed only "modest" 27–28% peak QE for these tubes. We have obtained information from Photonis that they succeed to produce a few batches of bialkali PMTs with peak QE values well in excess of 30%. We will be looking for an opportunity to measure those PMTs.

5. Coating of PMTs with a milky scattering layer

Earlier we have reported on the increase of the QE value of bialkali PMTs from Electron Tubes with hemispherical entrance windows, when they were coated with a milky scattering layer of paraloid [11].

Application of the milky lacquer has increased the QE value of 1″ PMTs of type ET9116A on ~15% in a wide spectral range above 330 nm.

We have applied the milky lacquer coating technique on the Hamamatsu hemispherical PMTs, shown in Fig. 2.

For control reasons we also coated the PMT #1930 from Electron Tubes (see Fig. 2). The results of QE measurements are shown in Fig. 4. Both Hamamatsu PMTs show peak QE of ~35% (in the wavelength range 340–390 nm) after coating. The Electron Tubes PMT shows a peak QE of ~30% at ~390 nm. Comparing the Fig. 4 with the Fig. 2 one may conclude that while we succeeded to increase strongly, as "usual" [11], the QE for the Electron Tubes PMT, we could obtain only a modest increase with the Hamamatsu PMTs. It is interesting to note, that while the QE curves of Hamamatsu PMTs show different shapes for wavelengths below 450 nm (see Fig. 2), they are becoming very similar after coating with a milky layer

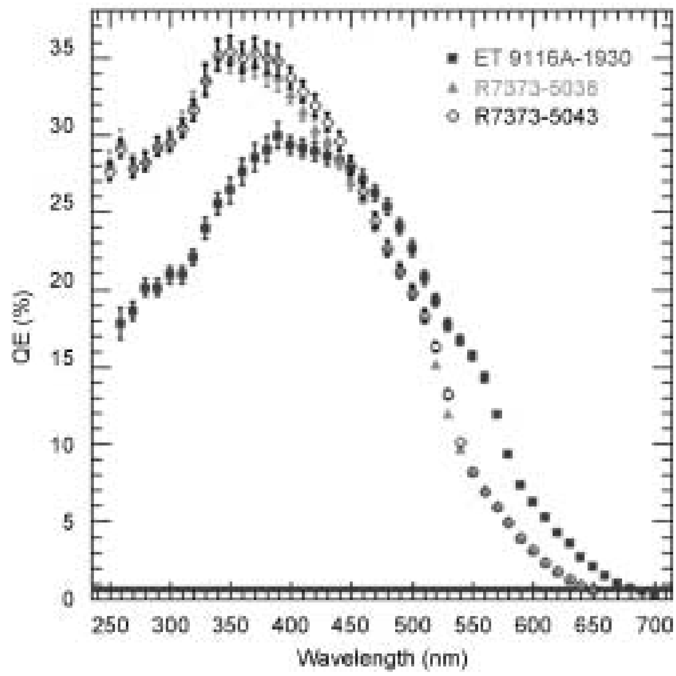

Fig. 4. The measured QE curves of two PMTs from Hamamatsu and one from Electron Tubes after coating them with a milky lacquer. All the three tubes are of 1″ size and have hemispherical input windows.

(see Fig. 4). Also, by comparing the PMTs #5043 and #5038 in Figs. 2 and 4 one may notice that the PMT with lower original QE gets stronger enhancement in QE due to the coating. The relatively low increase of the QE of Hamamatsu PMTs after coating could be due to their low back-reflection of photons from the photo cathode.

6. Conclusions

In the last couple of years we were working with the PMT manufacturers Hamamatsu, Electron Tubes and Photonis on increasing the QE of 1–2″ bialkali PMTs. We can report that all the three companies succeeded to produce PMTs with enhanced QE. Especially successful is Hamamatsu who could produce PMTs with QE in excess of 32–33%. When applying the milky lacquer coating technique to few Hamamatsu PMTs we could obtain peak QE values of ~35%. It seems that for producing bialkali PMTs with enhanced QE the manufacturers are using technologies that are not much different from the usual ones. Correspondingly their cost shall not differ much from the usual ones.

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