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MCP-PMT development for Belle-II TOP counter

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Abstract

We have developed a multiple-anode square-shape MCP-PMT for the Belle-II Time-Of-Propagation (TOP) counter. This detector is a hybrid cherenkov ring imaging and timing detector for particle identification in the barrel region of the upgraded detector. The Belle-II experiment will operate at high event rates and needs to withstand the correspondingly high background environment. MCP-PMT's have demonstrated excellent single photon timing resolution. However, the lifetime of photocathode is a known issue. Recently, we successfully improved the lifetime of a square-shape MCP-PMT by a factor of about 10, which is adequate for estimates of the nominal Belle-II background rates in the TOP counter. We have also developed a new MCP-PMT with Hamamatsu photonics, that adopts a super bialkali photocathode. Currently a peak quantum efficiency of 28 % for 400 nm photons has been achieved.

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Keywords: MCP-PMT, Cherenkov, photon

1. Introduction

The TOP counter has been developed to upgrade the barrel particle-identification (PID) detector at the super-KEKB/Belle-II experiment, in order to improve the $K^{\pm}/\pi^{\pm}$ separation power, even under a high beam background environment, in which the peak luminosity is about 50-times higher than that of current KEKB/Belle experiment. The TOP counter utilizes the total internal reflection of Cherenkov photons produced in a quartz radiator, and measures the position and precise arrival time of propagated photons at the radiator ends [1]. In order to separate the $K^{\pm}$ and $\pi^{\pm}$ accurately, we need to measure the particle's velocity, β, very precisely. To measure β, the TOP counter uses two kinds of information. One is the difference of the Cherenkov angle, θ_c; θ_c depends on β as $\cos\theta_c = 1/(n\beta)$, where n is the refractive index of the radiator. The difference of θ_c causes a difference in the path length of the Cherenkov photons inside the radiator, i.e., a difference in the time of propagation (TOP). Another is the time of flight (TOF) from the interaction point to the counter, which affects the difference in the photon's arrival time additively in most cases. The performance depends on the timing resolution for the single photon detection and the square root of the number of detected photons. Because a typical time difference is about 200 ps for 2 GeV/c $K^{\pm}$ and $\pi^{\pm}$, the time resolution for single-photon detection needs to be about 50 ps. To meet the requirement, we selected a micro-channel plate (MCP) photo-multiplier tube (PMT) as a photon detector.

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An MCP-PMT uses micro-channel plates as an electron multipliers, which realize the high gain of 10^6 for two stage type and shows the fast time response. The pulse raise time is < 400 ps and the transit-time-spread (TTS) is < 50 ps for single photon detection. We have developed new square-shaped multi-anode MCP-PMT with Hamamatsu Photonics, named SL10. The characteristics and performance are satisfactory as shown in Table 1 and reported in Ref.[2]. The time resolution for single photon detection is around σ = 35 ps, even under 1.5T magnetic fields.

Table 1. Basic characteristics of SL10.

items	SL10
photocathode	multialkali $Na_2KSb(Cs)$
window	borosilicate glass
effective area	22×22 (mm^2)
quantum efficiency @ λ = 400 nm	~ 20 (%)
channel-diameter of MCP	10 (μm)
length-to-diameter ratio of MCP	40
MCP aperture	~ 60 (%)
bias angle	13(^{o})
Al prevention layer	ON
anodes	4, 4×4
	gap (mm) / voltage (kV) $^\flat$
photocathode - 1st MCP	2.0 / 0.2
1st MCP in - out	0.4 / 1.0
1st - 2nd MCP's	1.0 / 1.0
2nd MCP in - out	0.4 / 1.0
2nd MCP - anodes	1.0 / 0.6
HV supplied	3.4-3.8 (kV)
gain	$(1-3)\times 10^6$
σ_{TTS}	30-40 (ps)
dark counts	$O(10-10^4)$ (Hz)
collection efficiency	60 (%)

$\flat$ Placing the Al prevention layer on the 2nd MCP yields a distance of 1 mm between MCP's.

2. Lifetime test

The basic performance of SL10 meets our requirements, however the MCP-PMT needs to work stably under high background environment. The photon hit rate on the MCP-PMT surface is evaluated to be $\sim 7\times 10^5$ Hz/cm^2. Under such high counting rate, the most difficult R&D item is to settle the subject for protecting the photocathode from its quantum efficiency (QE) degradation for a long experimental period. We previously found [2, 3] that an aluminum prevention layer from ion-feedbacks plays an essential role for this problem, and a round-shape MCP-PMT (Hamamatsu Photonics K.K. (HPK) R3809U-50-11X) with a multialkali photocathode kept its performance up to the integrated amount of output charge of $Q > 2.6$ C/cm^2, corresponding to more than a 14-year time duration under our supposed Super-KEKB/Belle-II [4].

We then have checked the lifetime of photocathode for SL10. An aluminum (Al) layer is put on second MCP, to prevent ion-feedbacks and to improve the collection efficiency (CE) from 35 % to 60 %. We can expect that the number of ions produced in first MCP is small, because of $1/10^3$ smaller number of secondary electrons in first MCP compared to second MCP. The QE degradation of PMT's is measured in terms of an integrated amount of output charge, $\sum_{\mathrm{Q}}$. The measurement system consists of an LED, a light pulser, a filter, a standard PMT for calibration, and PMT's tested, in a black box. An LED ($\lambda \simeq 400$

nm) was pulsed (10 ns-wide) at repetition rates of $f = 1 - 20$ kHz, which yielded the number of observed photo-electrons, $N_{\mathrm{p.e.}} = 20-50$ per pulse, corresponding to the output charge from an anode of $\sum_{\mathrm{Q}} = 2-10$ mC/cm^2/day under an expected Belle-II condition, $\sum_{\mathrm{Q}}$=0.16 C/cm^2 per year. During continuous irradiation, the performance of SL10's for single photons was monitored every 1-3 days, using a light pulser PLP (λ = 408 nm with a duration of 50 ps (FWHM) and a jitter of ±10 ps). For our convenience, we define the lifetime, τ_{Q}, in terms of $\sum_{\mathrm{Q}}$, at which the QE drops to 80 % ($\simeq -1$ dB) of the beginning.

Figure 1 shows the observed QE as a function of $\sum_{\mathrm{Q}}$ for the round-shape MCP-PMT (CT0790) and square-shape MCP-PMT (YJ0011). The CT0790 exhibits a long life of $\tau_{\mathrm{Q}} > 3$ C/cm^2, as expected from previous measurements. Concerning the YJ0011, one of the most corner located (ch1) and one of the central (ch6) anodes among the 4×4 configuration (numbered in sequence from a corner) are plotted. In spite of adopting the Al-layer, the YJ0011 exhibited a much shorter lifetime of $\tau_{\mathrm{Q}} = 0.03-0.05$ C/cm^2, compared to the CT0790. The fact that the 1st-anode drops QE faster than the 6th-anode is also observed for the similar type of MCP-PMT.

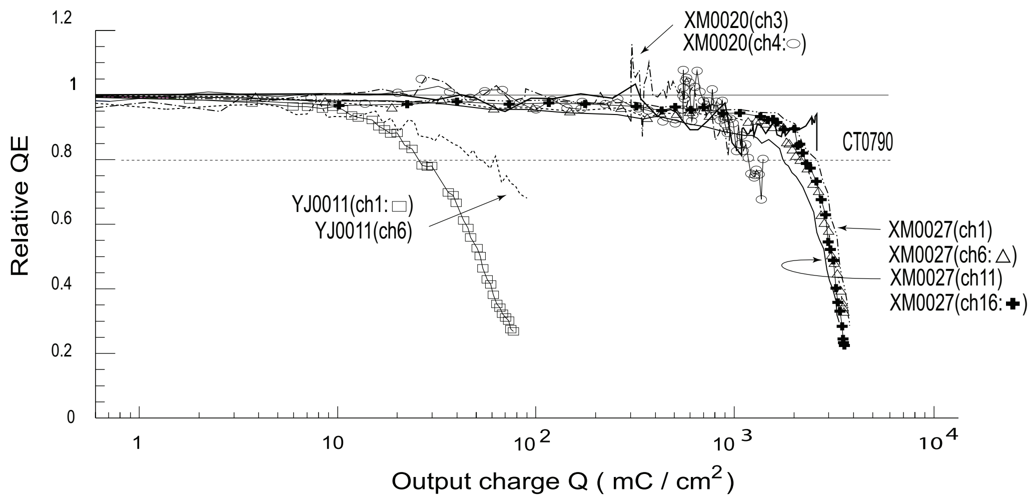

Fig. 1. Relative QE as a function of $\sum_{\mathrm{Q}}$. Plotted are for R3809U-50-11X (CT0790) and SL10's (YJ0011, XM0020 and XM0027).

We measured the QE distribution over the photocathode surface on YJ0011 by scanning with a slit of 1×1 mm^2-size using a monochromator system at λ = 400 nm. Figure 2 shows the observed distributions before and after full irradiation of $\sum_{\mathrm{Q}} \simeq 0.065$ C/cm^2. The QE distribution is quite homogeneous at the beginning, while it degrades, especially, further along the surrounding. For instance, it varies from QE$\simeq 23-24$ % to $\simeq 10-17$ % at around the center and from $20-24$ % to ~ 5 % along the sides.

For the CT0790, the Al-layer essentially functions to protect the photocathode, however this is not the case for the SL10. There might exist another source(s) of deterioration.

3. Inner structure

Figure 3 illustrates the inner structure of two kinds of PMT's. The CT0790 holds MCP-layers adhered to a cylindrical ceramic container. On the other hand, the container of the SL10 is made of a cubic shape of metal in order to have sufficient mechanical strength to sustain a wider effective area, and its MCP-layers are held with pins that supply high voltages for YJ0011.

We speculate that some neutral molecular residual gases exist on MCP surface, and are unsticked from the surface due to the multiplication process of the secondary electrons. Those production rate is proportional to the $\sum_{\mathrm{Q}}$, just the same as the production rate of the positive-ions, which will damage the photocathode. Even so, it is expected that the residual gases are prevented by the Al-layer, just as the positive-ions are.

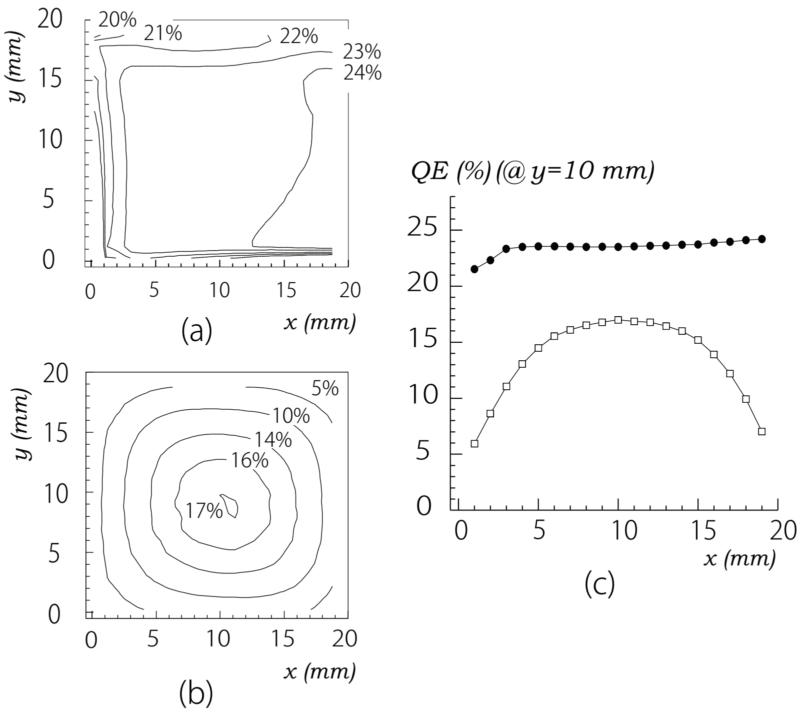

Fig. 2. QE distributions (a) before and (b) after full radiation for YJ0011, measured using a monochromator system with λ = 400 nm, and (c) QE values at y=10 mm along x position before (●) and after (□).

It is inferred that the Al-layer can prevent the gases passing through the MCP channels to the photocathode, but can not for the gases making a detour through the side-ways between the MCP's and the metallic wall. Gases such as carbon dioxide and monoxide, oxygen, and water, which can be the main ingredients of the residual gases, are reported to affect the work function, ϕ, of the photocathodes [5, 6].

For the early SL10 sample, we attained a lifetime of $\tau_Q = 0.1 - 1$ C/cm^2. The QE drops to 70-80% after irradiation of $\sum_Q \simeq 0.2$ C/cm^2 (see, Fig.4(a)). Since then, half of its photocathode-surface ($y \geq 12$ mm) is shielded from irradiating light. If the QE drop can be attributed, regardless of the Al-layer presence, to positive-ions or something else produced in the multiplication process and feedback through the MCP channels, the degradation over the shielded surface will stop. We, of course, do not observe the output signals for the shielded anodes at the rates of the LED triggered. Observation for a consecutive irradiation of $\sum_Q \simeq 0.16$ C/cm^2 results in a quite similar QE degradation, as can be seen in Fig.4(b), with the former one. The QE drops ~ 20% more in the surrounding than that in the center area.

This fact supports our speculation that the residual gases taking the roundabout route, not directly through the MCP channels, to the photocathode would cause QE deterioration.

4. Lifetime of modified SL10

First, we have manufactured various different SL10's (its structure is essentially the same as that of YJ0011, as listed in Table 1, but with 4 anode-channels), each of which replaces some elements that attempt to suppress the residual gases. Among many trails, for examples, MCP's are replaced with ones of different material-property; MCP's are electron-scrubbed to further remove the residual gases; getters are furnished close to the photocathode to adsorb out-gases, and so on. No significant improvement in the lifetime has been obtained for any of the PMT's: $\tau_Q < 0.1$ C/cm^2.

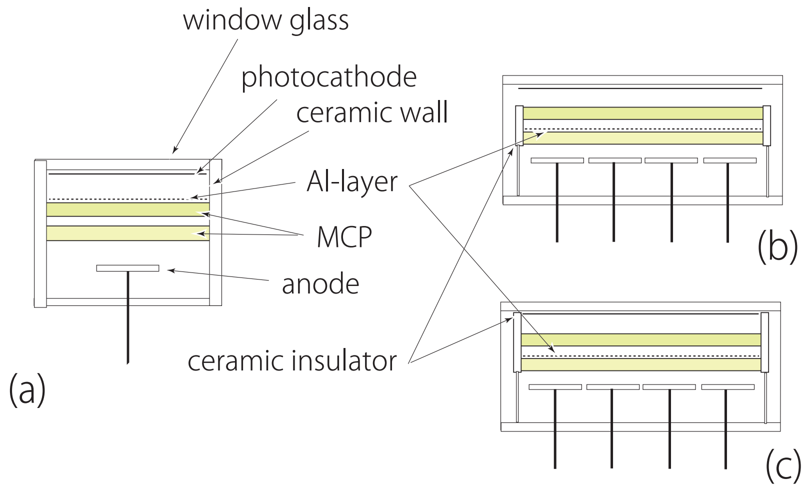

Fig. 3. Schematic drawing of inner structure of PMT's. (a) CT0790, (b) YJ0011 and (c) XM-versions. Arrows for common items are omitted for (b) and (c).

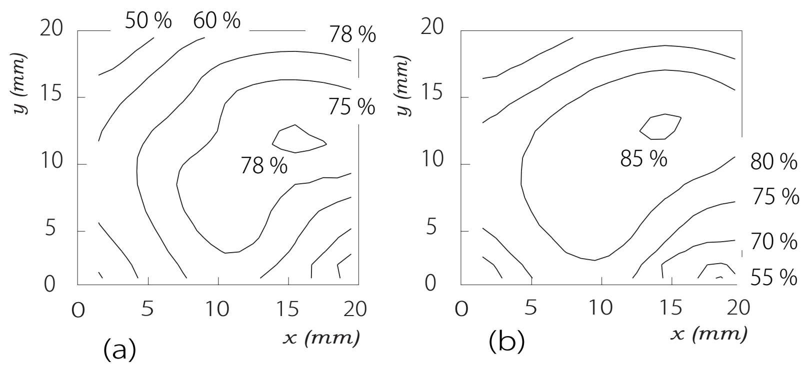

Fig. 4. Contours of QE drops for early SL10 version, measured with $\lambda = 400$ nm. The integrated output charge, $\sum_{\rm Q}$, over the irradiation period is (a) $\simeq 0.2$ C/cm^2 and (b) $\simeq 0.16$ C/cm^2. For (b) half of the photocathode surface ($y \geq 12$ mm), corresponding to the 3rd and 4th anodes, is shielded from the light.

Next, we employed ceramic elements, on the one hand, to support MCP-layers (Fig. 3(b) and (c)) and, on the other hand, to isolate the photocathode from the gap-space between the MCP's and metal-walls where the gases would be supposed to pass through (Fig. 3(c)). These SL10's are named "XM-version", and the insulation becomes tighter with the XM-version number. The lifetime extends to $\tau_{\rm Q} \sim 0.1$ C/cm^2 by XM0001. Supposing that the MCP's are the source of residual gases outbreaking, MCP's are further treated to the highest degree of cleanliness, as mentioned above, in addition to furnishing the Al prevention layer between the MCP's. Along with steady progress by improving the individual elements and mechanical structure, we have obtained insulation-tight SL10's, the XM0020 and XM0027 with 4 and 4×4 anodes, respectively, which attain $\tau_{\rm Q} \simeq 1$ and $2 - 3$ C/cm^2, as can be seen in Fig. 1. The lifetime of the XM0027 is the longest one ever achieved, which corresponds to $12 - 19$ equivalent-years at the planed Super-KEKB / Belle-II.

Figure 5 shows their performance. The output signals for single photons, the ADC and TDC histograms for the XM0020, and the relative gain variation and the time resolutions, $\sigma_{\rm TTS}$, for the XM0027 during the irradiation. The gain is $G \sim (1-3) \times 10^6$ in the beginning, but it linearly drops with $\sum_{\rm Q}$. For instance, it is reduced to 60% at $\sum_{\rm Q} = 3.8$ C/cm^2 for the XM0027 (HV=3.8 kV). Although it is sufficient gain to detect the single photon, the gain can be recovered by applying higher HV. The σ_{TTS} value is stable, and exhibits a similar value between the two XM's. It varies within a range of 41 ± 4 (ps) for the XM0027 and within 46 ± 4 (ps) for the XM0020.

Dark counts of the XM0020 (HV=3.8 kV) are ∼ 18 kHz at the 2nd anodes, but ∼ 1 kHz at the other 3 anodes in the beginning, while they are ∼ 3 kHz, but ∼ 10 Hz, respectively, after the irradiation period. A similar situation also occurs for the XM0027. They are 16, 36, 160 and 330 Hz at the 1st, 2nd, 3rd and 4th anodes in the beginning, and 0.2, 3, 4 and 17 Hz after irradiation.

5. Photocathode improvement

The PID performance directly depends on the number of detected photons. To increase the QE, we adopted the super bialkali technique to the MCP-PMT, in place of multialkali photocathode. The technique have been realized by HPK with conventional PMT's and achieved the QE of about 35 % at peak. Figure 6 shows the QE distribution for recent SL10 samples. The obtained peak QE is about 28 % for bialkali photocathode, while it is about 20 % for multialkali photocathode. Although the QE improvement is underway, the obtained QE increases the number of detected photons by 20 % in the TOP counter.

The lifetime of bialkali photo-cathode have been measured with the same system. The result is shown in Fig. 1. The initial samples achieved $\tau_Q > 1$ C/cm^2, which corresponds to > 6 years operation.

6. Summary

As a photon device for the TOP counter, planned for the second generation of the high-luminosity B-factory, Super-KEKB/Belle-II, we have developed an MCP-PMT, SL10, having considerable endurance under high rates of counting for a long experimental period. It is found that in addition to positive ion-feedbacks, residual gases had substantial influences on the lifetime of the PMT photocathode. The QE variation with the integrated amounts of the output charge, $\sum_{\mathrm{Q}}$, was measured, and the QE(λ) spectra before and after irradiation were examined for about 30 different versions of SL10's.

Both the furnishments of the Al-layer and the ceramic-insulation largely suppress the ions and gases from damaging the photocathode, and then resulting in a long lifetime of $\tau_{\mathrm{Q}} \simeq 2-3$ C/cm^2, which is equivalent to well more than 10 years of operation at the supposed Super-KEKB/Belle-II [7].

New bialkali photocathode is adopted to MCP-PMT and we successfully obtained the improved QE of 28 % at peak. The lifetime is also confirmed to be sufficient level of $\tau_{\mathrm{Q}} > 1$ C/cm^2.

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References

[1] M. Akatsu *et al.*, Nucl. Instr. and Meth. **A 440** (2000) 124-135; T. Ohshima, Nucl. Instr. and Meth. **A 453** (2000) 331-335; T. Ohshima, ICFA Instr. Bull. **20** (2000) 2, (15pages); M. Hirose *et al.*, Nucl. Instr. and Meth. **A 460** (2001) 326-335; S. Matsui *et al.*, Nucl. Instr. and Meth. **A 463** (2001) 220-226; Y. Enari *et al.*, Nucl. Instr. and Meth. **A 494** (2002) 430-435; T. Hokuue *et al.*, Nucl. Instr. and Meth. **A 494** (2002) 436-440; Y. Enari *et al.*, Nucl. Instr. and Meth. **A 547** (2005) 490-503.

[2] K. Inami *et al.*, Nucl. Instr. and Meth. **A 592** (2008) 247.

[3] N. Kishimoto *et al.*, Nucl. Instr. and Meth. **A 564** (2006) 204.

[4] S. Hashimoto, (ed) *et al.*, Letter of Intent for KEK Super B Factory, KEK-REPORT-2004-4 (jun 2004).

[5] T. Wada, T. Nitta, T. Nonura, M. Miyao and T. Nomura, Jap. Jour. App. Phys., **29** (1990) 2087-2091.

[6] P. Michelato, C. Pagani, D. Sertore and S. Valeri, EPAC 94, Fourth European Particle Accelerator Conf., London, 1994, Poster Sessions, 1456.

[7] T. Jinno *et al.*, Nucl. Instr. and Meth. **A 629** (2011) 111.

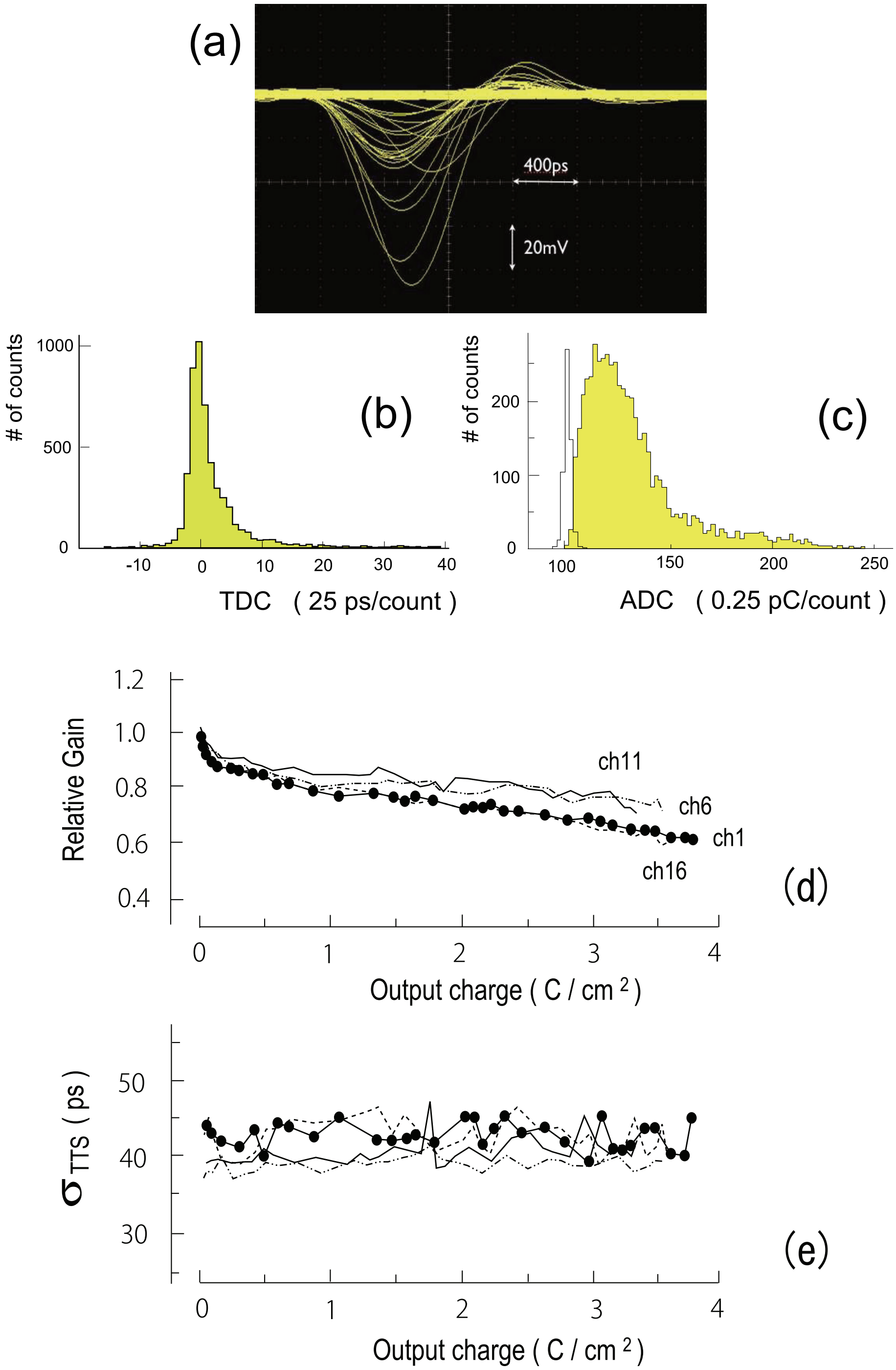

Fig. 5. Performance of XM0020 and XM0027. (a) output signals, (b) TDC and (c) ADC distributions for XM0020, measured with HV=3,400 kV. (d) and (e) are the relative gain variation and the time resolution for single photons for XM0027.

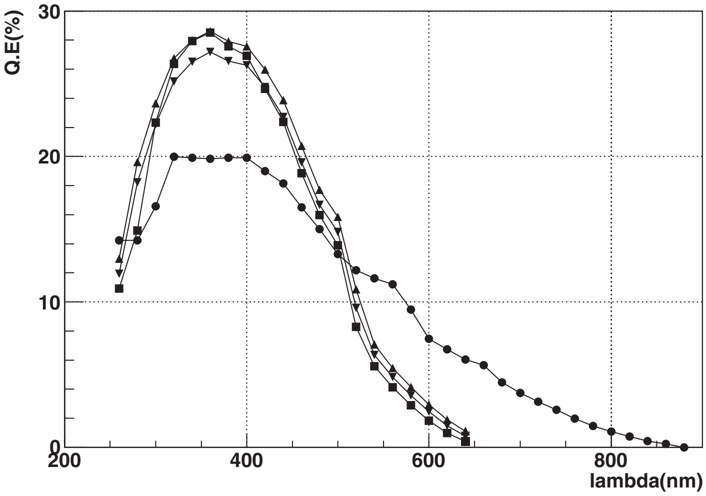

Fig. 6. QE distributions as a function of wavelength for typical multialkali photocathode (●) and bialkali photocathode for recent samples (■, ▲, ▼).