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Effect of light flash on photocathodes

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Abstract

We have measured the discharge of the bi-alkali (high resistivity) photocathode of the 2 inch diameter Hamamatsu photomultiplier type R1828-01 when its surface is uniformly illuminated with 5×10^8 photons. The gain of the tube (when operated at -1800 V) is reduced by 7% immediately after the flash, and recovers with a time constant of about 50 μs. Time delays are also affected. Photomultipliers with multi-alkali (low resistivity) photocathodes do not show these effects.

1. Introduction

The photocathode surface of a bi-alkali photomultiplier tube (PMT) is of high resistance. Combined with its stray capacity to earth and the neighbouring internal electrodes this gives an RC time constant of order 50 μs [1]. Therefore the PMT does not respond rapidly to voltage changes applied to the photocathode connection. Moreover an intense flash of light can significantly alter the photocathode potential leading to a change of gain [2] and transit time. This can be important whenever particles are to be detected soon after an intense flash of radiation, for example in colliding beam accelerators and in the muon $(g-2)$ experiment [3].

It is estimated that during pion injection into the ring magnet of the muon $(g-2)$ experiment [3], under preparation at Brookhaven National Laboratory, there will be a light flash of 5×10^8 photons per PMT. For a PMT with an average quantum efficiency of 20% this corresponds to 10^8 photoelectrons leaving the photocathode in a very short time. This will cause a drop in the voltage between the photocathode and the first dynode D1 and influence both the gain and time response of the PMT until the charge is replenished by the external circuit. The strict requirements of the $(g-2)$ experiment in gain stability of 0.2% and timing stability of 20 ps between early (20 μs after pion injection) and late times (500 μs after injection) prompted us to study this effect. Other experiments with similar sensitivities might also benefit from this study, especially those deployed near the high intensity accelerators now coming on stream.

2. Experimental method

Our initial tests were made on the Hamamatsu PMT type R1828-01 which has a bi-alkali photocathode. In order to eliminate the discharge of the base capacitors when the PMT was illuminated we operated the tube at low gain using only -1100 V high voltage. As a light source we used a blue light emitting diode (LED), calibrated with a light power meter. We first illuminated the photocathode with 2.5×10^9 photons in a 100 μs time window and from the exponentially decaying output deduced the photocathode parameters. Next, we shortened the time window to 30 μs and illuminated the photocathode with 7×10^8 photons and observed the recovery time constant of the PMT. Finally, taking into account the experimental data, we make a more accurate estimate of the PMT gain change for our experimental conditions, 5×10^8 photons incident in a very short burst.

The PMT output recorded when it is illuminated uniformly with a square light pulse is shown in Fig. 1. The total number of photons from the LED, measured by a light power meter, was 2.5×10^9 in the 100 μs time period (implying a photon flux of $N_{P/S} = 2.5 \times 10^{13}$ photons per second). We see from Fig. 1 that the PMT current decays almost exponentially with a time constant of about 60 μs. Possible sources of the drop in signal are: (1) the LED itself, (2) the depletion of the base buffer capacitors and consequent changes in the dynode voltages, and (3) the change of voltage between the photocathode and D1 due to high photocathode resistivity.

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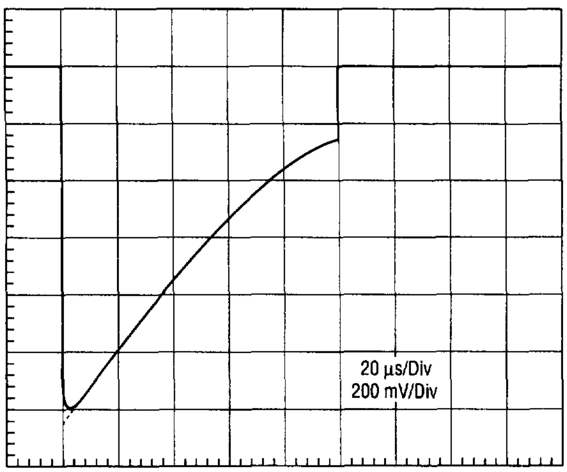

Fig. 1. PMT (R1828-01, bi-alkali) output when the photocathode is illuminated with 2.5×10^9 photons in 100 μs time period. The HV on the PMT base is −1100 V.

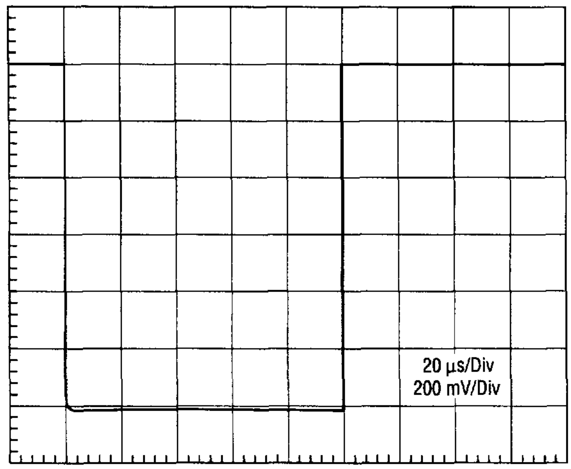

Fig. 2. PMT (R1828-01, bi-alkali) output when the photocathode is illuminated with 2.5×10^6 photons in 100 μs time period. The HV on the base is −2500 V to give the same output signal as in Fig. 1.

Fig. 2 shows the same output when there is a light attenuator of a factor of 10^3 in front of the LED and the gain of the PMT is raised by increasing the applied voltage to obtain the same output signal height as in Fig. 1. Now the output is flat showing that the LED output is constant and the PMT base capacitors in the final stages are not affected. The decay seen in Fig. 1 is therefore ascribed to a change of voltage on the photocathode.

We conclude that the effect is due to the high photocathode resistivity that is typical of bi-alkali tubes. When the electrons leave the photocathode it takes a long time before they are replenished from the external circuit. In the meantime the photocathode remains positively charged and the PMT gain drops due to two effects: less efficient focusing by the focusing electrode F1, and smaller multiplication at the first dynode D1.

To analyse the effect more quantitatively we modified a PMT base so that the photocathode potential (V_k) could be varied, while the voltages on F1, D1 and all other electrodes remained constant. The variation of output signal voltage with changes in V_k are plotted in Fig. 3 for various values of the applied high voltage. Two

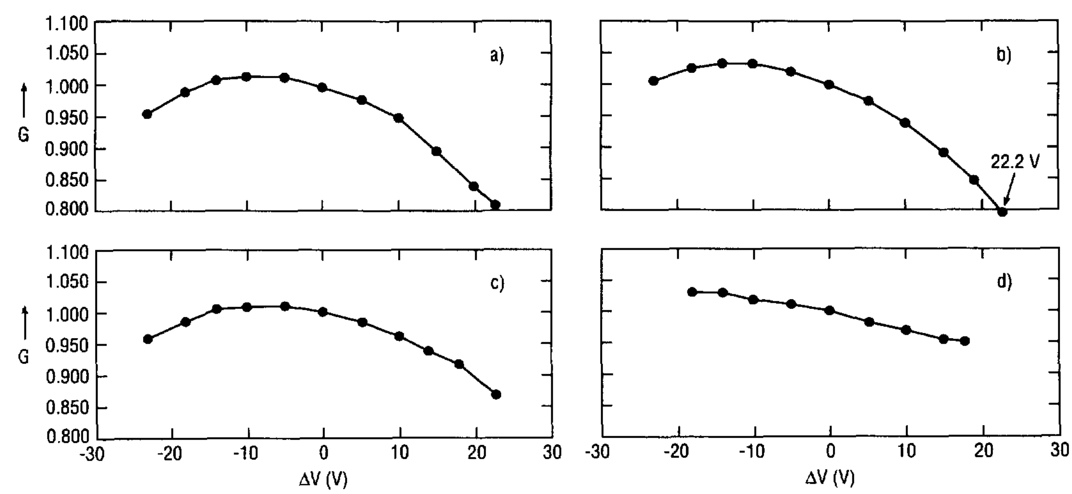

Fig. 3. PMT gain versus change of the photocathode potential in Figs. 3(a)–(d) for HV −1000, −1100, −1500 and −1800 V respectively.

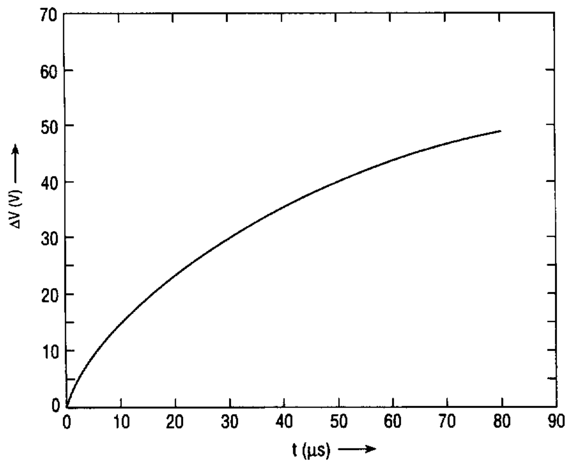

Fig. 4. The estimated photocathode voltage change inferred from the gain drop of Fig. 1 by using the calibration curve of Fig. 3(b).

effects are operating in parallel: (1) the multiplication at D1 increases as V_k goes more negative (presumably more or less linearly) due to the increased kinetic energy of the incident electrons, and (2) the focusing moves away from the preset optimum (presumably more or less parabolic). The combination gives a parabolic variation, but with the maximum displaced to negative values as seen in Fig. 3(a).

Using these calibration curves we can calculate the voltage change at the photocathode for each measured change in gain seen with the light flash in Fig. 1. The results are shown in Fig. 4.

We model the photocathode as a capacity C connected to the power supply through a resistor R. Then drawing a constant current i from the photocathode will produce a change of voltage

$$\Delta V = Ri(1 - e^{-t/RC}) \qquad (1)$$

and initially the rate of change of voltage is

$$dV = Q/C \qquad (2)$$

where $Q = i\,dt$ is the charge leaving the photocathode.

From Fig. 1 we see that $dG/G = 0.22$ in the first 20 μs, for which $Q = 5 \times 10^8 \times 1.6 \times 10^{-19} \times 0.21 = 17$ pC, where we have used the nominal quantum efficiency of the bi-alkali photocathode to the blue light of 21%, and 5×10^8 is the number of photons in the first 20 μs. The photocathode current $i = 0.85$ μA.

This measurement was done with − 1100 V applied to the PMT, in which case the voltage change dV is estimated from the fit of the calibration curve of Fig. 3(b) to be 24 V. Hence [4] using Eq. (2)

$$C = Q/dV = 17\text{ pC}/24\text{ V} = 0.7\text{ pF}. \qquad (3)$$

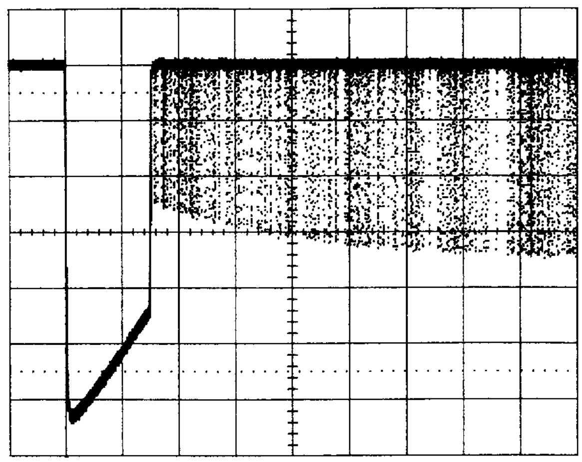

Fig. 5. The PMT (R1828-01, bi-alkali) output with a total of 7×10^8 photons hitting the photocathode in a 30 μs time period and − 1100 V at the base. We have used the persistence display mode and varied the time delay between the test signal and the end of the photon flash. The recovery time constant is approximately equal to 60 μs. When − 1800 V is used at the base, the recovery time constant is predicted to be closer to 50 μs (see text). The time and voltage scales are 20 μs and 200 mV per division respectively.

As the time constant of the signal in Fig. 1 is distorted, due to the second order dependence of the PMT gain on the photocathode voltage drop at − 1100 V, we have used Fig. 4 to deduce the average photocathode resistance value. Fitting Fig. 4 with Eq. (1) gave $R \approx 73$ MΩ, implying $RC \approx 50$ μs. These capacitance and resistance values are of course only approximate [5]. At − 1800 V the gain has more or less linear dependence on the photocathode voltage drop and therefore its time constant should be the same (≈ 50 μs) as the RC time constant of the photocathode voltage.

One must of course expect the effective resistance for recharging the photocathode to vary from one point on the surface to another, being largest at the center. On the other hand the stray capacity per unit area will also vary from point to point. So what we have observed is some average behaviour. It nevertheless seems to fit fairly well to a simple exponential, which can at least be used as a guide in estimating pulse height and timing errors.

To study the recovery of the PMT after the flash we next illuminated the photocathode with 7×10^8 photons in 30 μs and flashed another LED with a short pulse at later times. By varying the time delay and using the persistent mode of the sampling oscilloscope (LeCroy Series 9300), we display in Fig. 5 the PMT response versus time. This shows an initial drop in gain to 71% followed by an exponential recovery with time constant of order 60 μs consistent with the time constant observed in Fig. 1. With pion injection into the $(g-2)$ ring, the number of photons per PMT is estimated to be 5×10^8, arriving within 100 ns. In this case, assuming that the high voltage on the PMTs was − 1800 V and the tube was gated by switching the voltage on D7 to prevent overload in the later stages [6], the expected drop in gain will be 7% immediately after the flash. This will change to 4.5%, 20 μs after injection [7] which is still unacceptable [3].

One solution would be to run the experiment with less beam intensity (which would mean increasing the running time substantially) or to run with only muon injection, when the light flash will be much lower. Since we wish to keep open the option of running with pion injection, we have studied the behaviour of multi-alkali photomultiplier tubes which are known to have lower photocathode resistance.

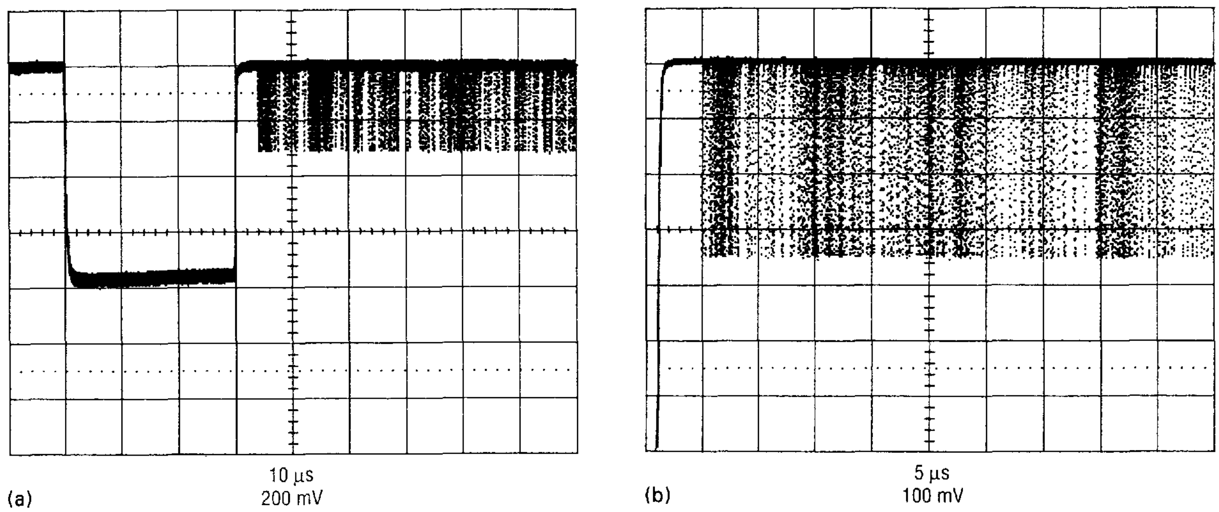

Fig. 6. (a) The PMT (R3256-02, 2 inch diameter, with multi-alkali photocathode) output when illuminated with 10^9 photons in a 30 μs time period and − 1000 V at the base. The test signal height is not affected by the light flash. The time and voltage scales are 10 μs and 200 mV per division respectively. (b) The same output as Fig. 6(a) in different horizontal and vertical scales (5 μs and 100 mV per division respectively).

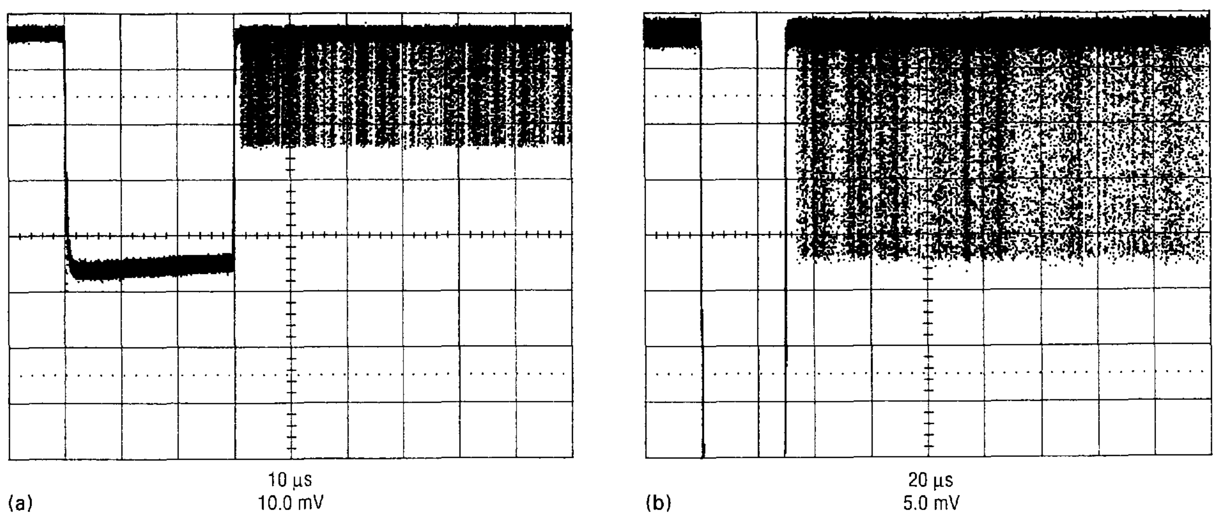

Fig. 7. (a) The PMT (R1355 W/S-20, 1 inch diameter, with multi-alkali photocathode) output when illuminated with 10^9 photons in a 30 μs time period and − 500 V at the base. The test signal height is not affected by the light flash. The time and voltage scales are 10 μs and 10 mV per division respectively. (b) The same output as Fig. 7(a) in different horizontal and vertical scales (20 μs and 5 mV per division respectively).

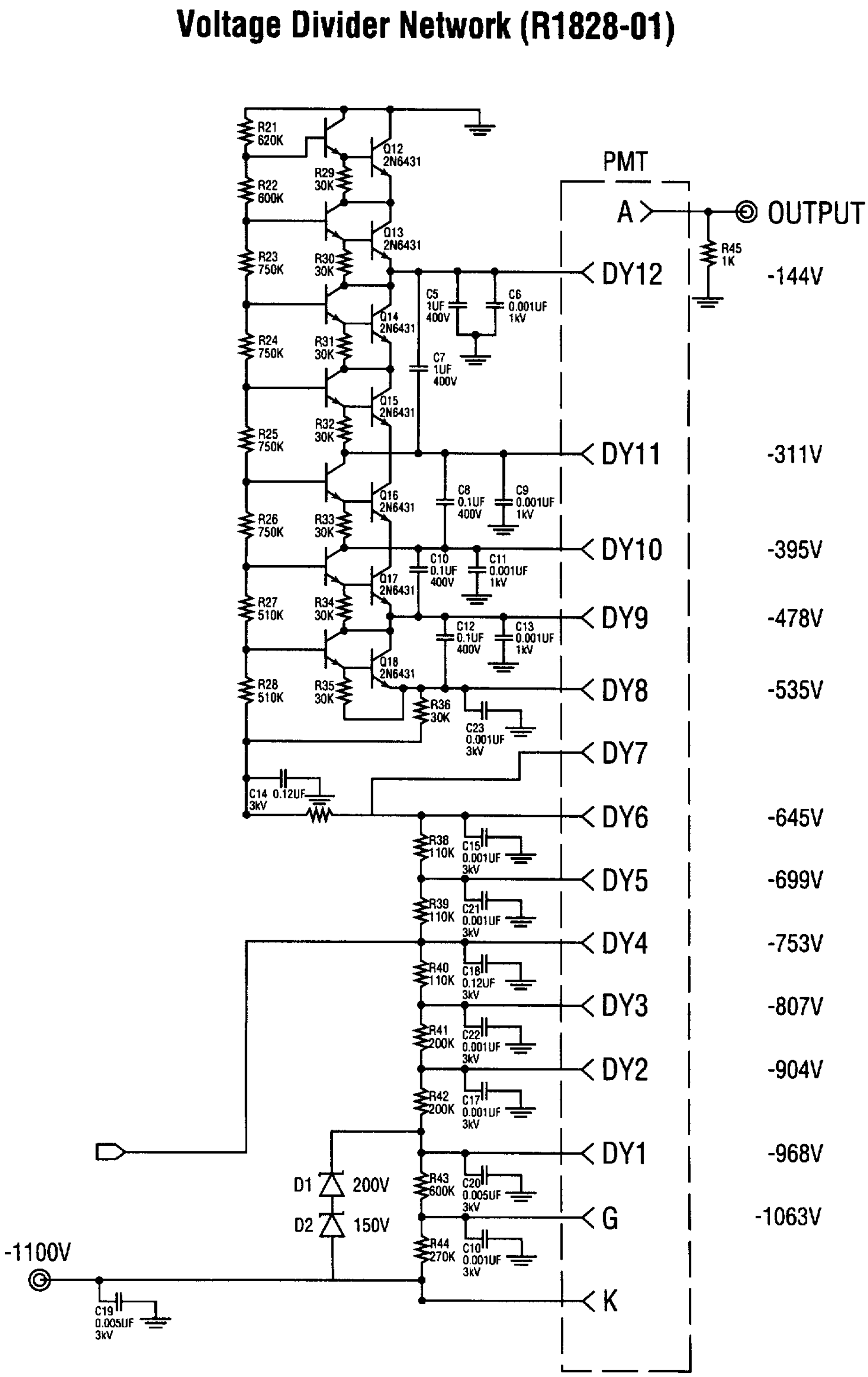

Fig. 8. The R1801-01 photomultiplier base diagram used during the tests (from Ref. [6]).

Similar tests were carried out with the 10-stage multi-alkali PMT types R3256-02 (2 inch) and R1355 W/S-20 (1 inch) from Hamamatsu. Figs. 6(a) and (b) show the result for the 2 inch tube, while Figs. 7(a) and (b) are for the 1 inch tube. For these tests the light flash was set to 10^9 photons in 30 μs (1.5 as intense as for the bi-alkali tests reported above). In both cases there was no appreciable change of gain after the simulated flash. This is consistent with the known much smaller photocathode resistance in the multi-alkali tubes. The small droop of the primary square pulse was ascribed to sagging of some base capacitors and this was verified by running at even lower PMT voltage (lower anode current). As a result of this investigation the $(g-2)$ detector group has decided to use the R3489 PMT for the calorimeter readout which is similar to R1828-01 but with the bi-alkali photocathodes replaced by multi-alkali under special purchase from Hamamatsu. Preliminary tests show no paralysis, consistent with the multi-alkali results given above. In Fig. 8 we show the base diagram of the R1828-01 PMT used in the tests.

3. Time delays

In the Hamamatsu R1828-01 photomultiplier the distance between photocathode and D1 is 6 cm. We checked by modeling the electrode configuration between the photocathode and D1 with Opera-2d [8] that the electric field in this region is practically uniform. Using this approximation the transit time between photocathode and D1 comes to 13.7 ns, with a potential difference of 216 V for − 1800 V applied to the tube. Any small change in the photocathode potential will affect the mean electron velocity and change this delay. For example with 5×10^8 photons incident in a short time the change of potential is 24 V and this will increase the transit time by 0.83 ns immediately after and 0.26 ns after 20 μs from the flash. This will be important for coincidence or time of flight measurements following an intense flash.

In contrast, the multi-alkali phototube, because of its low photocathode resistance, will be free of all such effects.

4. Conclusion

Care is needed with bi-alkali photomultiplier tubes if pulse height and timing is to be measured following an intense burst of radiation. In these situations multi-alkali photocathodes are strongly to be preferred.

Acknowledgements

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References

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[2] Phillips Handbook "Photomultiplier Tubes, Principles and Applications" by Phillips Photonics, International Marketing, BP 520, F-19106 Brive, France.

[3] BNL E821 Design Report, 3rd ed., p. 46, March 1995; J. Bailey et al., Nucl. Phys. B 150 (1979) 1.

[4] It should be noted that the average quantum efficiency does not change during the illumination of the photocathode due to the minute fraction of the available electrons released.

[5] The time constant does not depend on the high voltage values used up to − 1100 V, above which the charge depletion of the base capacitors start to influence the results. Also, at much higher photon fluxes, the photocathode resistivity changes due to the creation of a large number of free electron carriers, an effect which is beyond the scope of this article.

[6] J. Ouyang and W.E. Earle, internal g-2 note 202, E821 at BNL, July 1994.

[7] We have assumed a time constant of 50 μs for the gain recovery since at − 1800 V the gain has mainly linear dependence on the photocathode voltage drop.

[8] OPERA-2d, Vector Fields Limited, 24 Bankside, Kidlington, Oxford OX5 1JE, England.