Performance of fine mesh photomultiplier tubes in magnetic fields up to 0.3 T

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Abstract

We have studied the performance of fine mesh photomultiplier tubes (R2490-05, R2021, H5756, R3423-01) in magnetic fields up to 0.3 T. The tube gain and the average number of photoelectrons have been measured as a function of the magnetic field, of the angle between the field direction and the phototube axis, and of the rotation of the phototube around its axis. The reduction of the photocathode effective area in a magnetic field has also been measured.

1. Introduction

The recently developed fine mesh phototmultipliers, PM, by Hamamatsu [1,5] are designed to operate also in relatively high magnetic fields. In these tubes the electron multiplication takes place between dynodes made of a fine mesh, very close to each other (1 mm typical distance) in order to reduce the path length of the electrons. The gain and the average number of photoelectrons emitted from the photocathode which are collected, are however affected by the magnetic field magnitude. The former is due to the reduced transparency of the dynode structure and the latter to a reduction of the photocathode area imaged on the first dynode. We report in the following on measurements done on fine mesh PMs intended for the KLOE experiment. The main aim of KLOE is to do high precision CP violation studies in K^0 decays at the Frascati Φ-factory DAFNE [6,7].

The KLOE apparatus is located inside a 0.6 T magnetic field. Its electromagnetic calorimeter is constructed of alternate layers of lead and scintillating fibers. The calorimeter is designed to measure energy and time with high resolution [8]. A magnetic field of 0.1-0.2 T is present where the calorimeter read-out PMs are located. The magnetic field is inclined with respect to the PM axis by no more than 25° [9].

A systematic study of the performance of the R2490-05 2 in. (16 dynodes) PM has been carried out. We have also performed some measurements on several smaller size fine mesh PMs: R2021 1.5 in (16 dynodes), H5756 $1\frac{1}{8}$ in. (16 dynodes), and R3423-01 1 in. (15 dynodes). A description of the set-ups is given in Section 2. Measurements and results are discussed in Section 3.

2. Experimental set-up

Two set-ups, 1 and 2, were used.
(1) The photomultiplier tube is placed in the fringing

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field outside a superconducting solenoid. The PM can be rotated in such a way as to change the angle θ, between the field direction and the PM axis, from 0° to 90°. The maximum field magnitude is $B = 0.2$ T. The fringing field has been mapped and found to be uniform, inside the PM volume, within 15%.

(2) The PM is placed inside a solenoidal magnetic field of magnitude up to 0.28 T, as sketched in Fig. 1. The magnetic field has been mapped at various current values, in order to check its uniformity and linearity as a function of the supply current. The angle θ ranges from 0° to 36°, being limited by the solenoid's internal radius.

In both experimental set-ups 1 and 2, the PM can be rotated around its symmetry axis by 360°. Both θ and the rotation ϕ are defined to ±3°. We use green light emitting diodes (LEDs) as light sources. The light can be either uniformly diffused over the whole PM photocathode or collimated in a small spot of 1 mm diameter. The PM output signal is sent to a charge sensitive ADC. The measured charge (Q) spectrum is approximately Gaussian, thus the average number of photoelectrons N collected by the multiplier structure, about 10^2, is obtained from the ration $\sigma(Q)/\langle Q \rangle$ according to $\sigma(Q)/\langle Q \rangle = 1/\sqrt{N}$ and assuming that the main fluctuation is due to photoelectron statistics. The PM gain G is obtained from the ratio of the anode collected charge to the cathode charge. By repeated measurements under the same conditions, we estimate that both n and G have a systematic uncertainty of 3–5%,
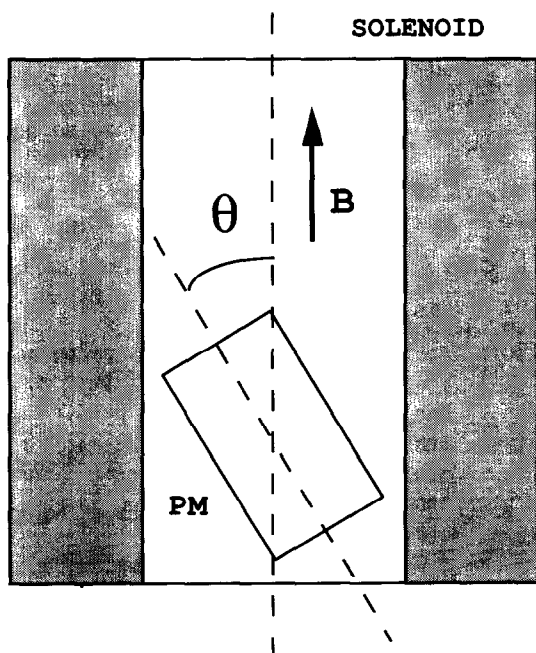
coming mainly from LED instabilities and reproducibilities of position and angle.

All tubes were run with Hamamatsu grounded anode high voltage dividers. Voltage drops between all electrodes are the same, except for that between the cathodes–first dynode which is twice the amount. During the test the PMs were run at from 2.0 to 2.5 kV.

3. Results

3.1. Gain and photoelectron collected dependence on magnitude and direction of magnetic field

Measurements on the R2490-05 PM were done with set-up 1, see Section 2, allowing us to explore the full θ range. Fig. 2a shows the mean value of the signal vs. θ when illuminating uniformly the photocathode for $B = 0.2$ T. The signal rises between 0° and 50° and sharply decreases between 50° and 70°. For θ greater than 70° the signal disappears. The rise of the signal is due to an increase of the PM gain with θ, as shown in Fig. 2b. The sharp decrease for angles greater than 50° (see Fig. 2c) is due to a loss in photoelectrons collected by the dynodes, as shown in Fig. 2c.
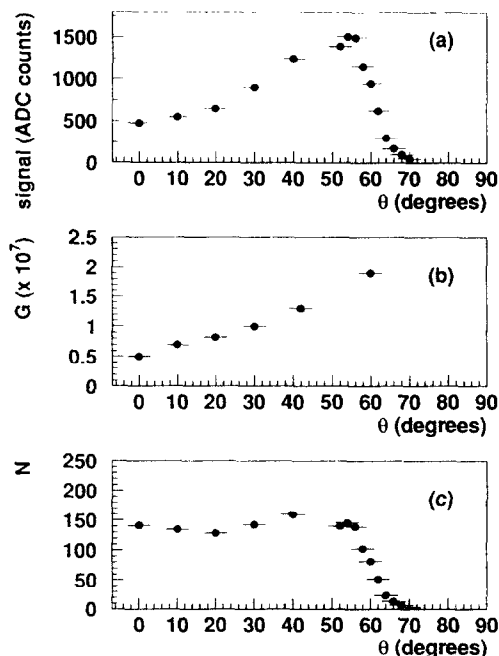

Fig. 1. Sketch of the measurement set-up 2. Magnetic field direction and PM position are shown.

Fig. 2. (a) Signal mean value (in ADC counts) for a R2490-05 2 in. PM as a function of the angle θ between tube axis and magnetic field; $B = 0.2$ T. (b) The PM gain as a function of the angle θ. (c) The average number of photoelectrons N as a function of the angle θ.

We define the critical angle θ_c as the value of θ above which N sharply decreases, as shown in Fig. 2c. θ_c is plotted in Fig. 3 vs. B. The PM works without signal loss in the (B, θ) region below the line.

As expected the response of the PM depends both on the magnitude of B, and on the angle θ [10].

The response of the R3423-01 tube with a diameter of 1 in. in shown in Fig. 4. The measurements were performed with set-up 1.

3.2. Response dependence on the rotation around PM axis

We found a dependence of the fine mesh PM response on the rotation around its symmetry axis in a magnetic field, when the photocathode is uniformly illuminated. Two phototubes, with 2 in. and 1 in. diameter, were tested with set-up 1. For a given B and θ, a ϕ-angle scan of 360° around the PM axis (referred to the position of the first dynode pin as $\phi = 0°$) is performed in 11 steps. For each ϕ the pulse height spectrum is measured, and the average number of photoelectrons and the gain are obtained.

In Fig. 5 the relative variation of the gain G with respect to its mean value and of the average number of photoelectrons N with respect to its mean value, are shown as a function of ϕ at $\theta = 0°$ and $\theta = 40°$, and at $B = 0.13$ T for the R2490-05 PM. Results for the R3423-01 1 in. PM are shown in Fig. 6 at the same B and θ values as in Fig. 5.

We observed a quasi-sinusoidal dependence of G and N on ϕ for both PMs. This effect increases with θ and is larger for the 1 in. tube. Note however, that the G peaks are displaced by 180° with respect to the N peaks.

By looking at the 2 in. PM we observed that the photocathode and the first dynode are not perfectly parallel or, in other words, the multiplier's axis is not exactly orthogonal to the photocathode plane. By measuring the distance between the photocathode and the first dynode along the first mesh ring, we have found a distance variation larger than 1 mm, i.e. the multiplier axis is inclined by more than 1.5° with respect to the PM tube axis. Hence the magnetic force on the electrons causes a sideway shift of the cathode image on the first dynode which depends on the angle ϕ with a 360° periodicity. A rough geometrical calculation reproduces the observed quasi-sinusoidal dependence on ϕ, both for N and G.

Finally, we have verified that the dependence of N and G on θ presented in the previous section (see Figs. 2 and 4) does not change in shape if studied at different ϕ values. In other words, θ_c depends only weakly on ϕ. In conclusion, the PM's response depends both on θ and on ϕ, but the θ dependence is the dominant one.

3.3. Photocathode uniformity and effective area

In order to study the effect of the magnetic field on photocathode uniformity and effective area, a 2 mm step
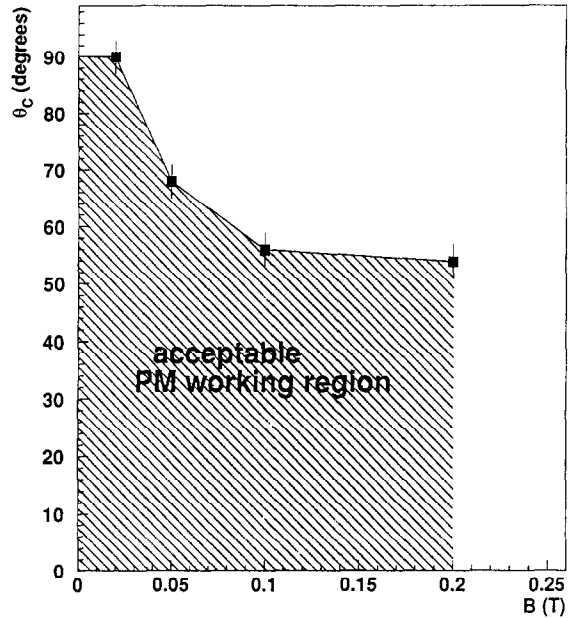

Fig. 3. Critical angle θ_c as a function of the magnetic field. θ_c is the angle between tube axis and magnetic field beyond which the photoelectrons collected by the multiplier starts to decrease sharply, as shown in Fig. 2c. the line is drawn to guide the eye.
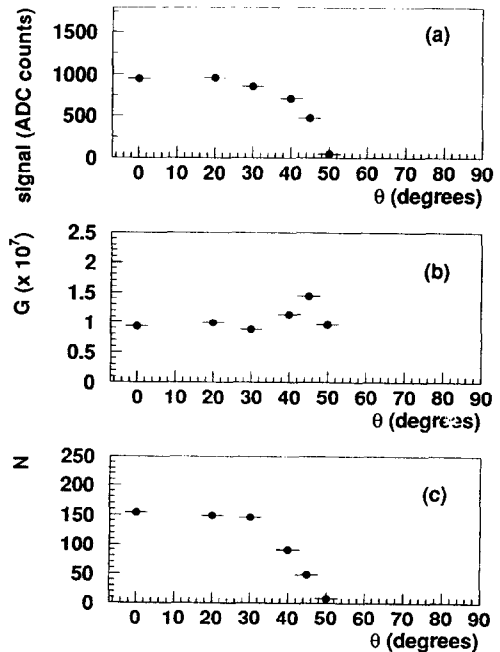

Fig. 4. (a) Signal mean value (in ADC counts) for a R3423-01 1 in. PM as a function of the angle θ (degrees) between tube axis and magnetic field; $B = 0.2$ T. (b) PM gain as a function of θ. (c) The average number of photoelectrons N as a function of θ.
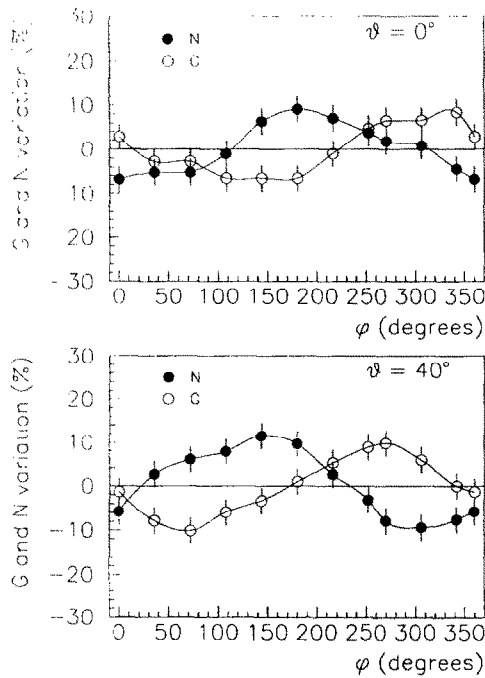
Fig. 5. Relative variation of the PM gain G with respect to the mean G value, and of the average number of photoelectrons N with respect to the N mean value, as a function of angle ϕ at $B = 0.13$ T, $\theta = 0°$ and $\theta = 40°$, for a R2490-05 tube. The lines are drawn to guide the eye.
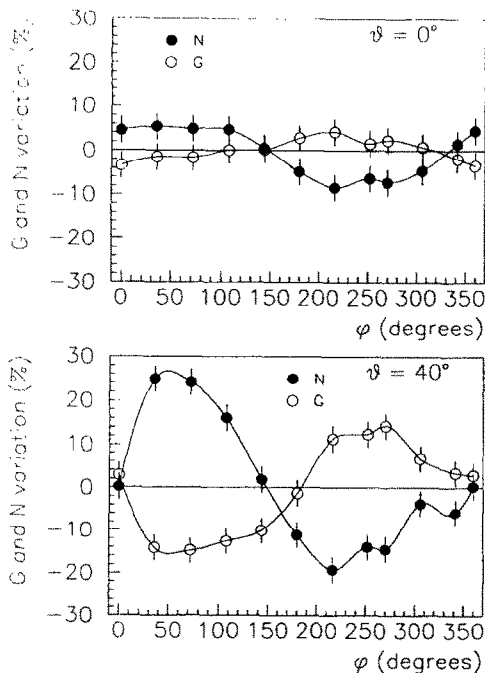

Fig. 6. Same plots as in Fig. 5 for a 1 in. R3423-01 tube.

scan has been performed along several photocathode diameters, using a light spot of 1 mm diameter. Measurements have been performed with set-up 2, both at zero field an in several magnetic field configurations, on the R2490-05, R2021, and H5756 tubes.

3.3.1. Response at zero magnetic field

The results of a photocathode diameter scan for a R2490-05 tube at $B = 0$ are shown in Fig. 7. The three plots show the pulse height mean value, the average number of photoelectrons, and the PM gain as a function of the light spot position along the diameter (x-coordinate) on the PM cathode. The useful photocathode diameter is the FWHM of the signal mean value distribution and is (37 ± 1) mm (in agreement with the Hamamatsu specification of photocathode minimum diameter being 36 mm [1]). This result does not depend on the diameter chosen, and is confirmed by measurements performed on another R2490-05 tube. (The lines in Fig. 7, as well as in the following Figs. 8, 9, 10, 11 and 12, are drawn to guide the eye.)

In Figs. 8 and 9 the signal mean value, the number of photoelectrons and the PM gain are plotted as functions of x-coordinate for a diameter scan at $B = 0$ of a R2021, and H5756 tube. The effective photocathode diameters are (27 ± 1) mm, and (19 ± 1) mm respectively, both in agreement with the Hamamatsu specifications [1] (tests on another H5756 tube give quite similar results).
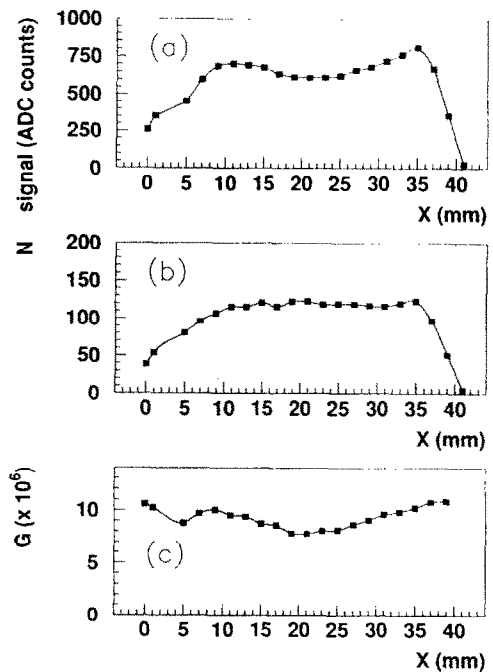

Fig. 7. Response of a 2 in. R2490-05 tube as a function of the light spot position along a diameter at zero magnetic field. (a) Signal mean value; (b) average number of photoelectrons N; (c) PM gain G.
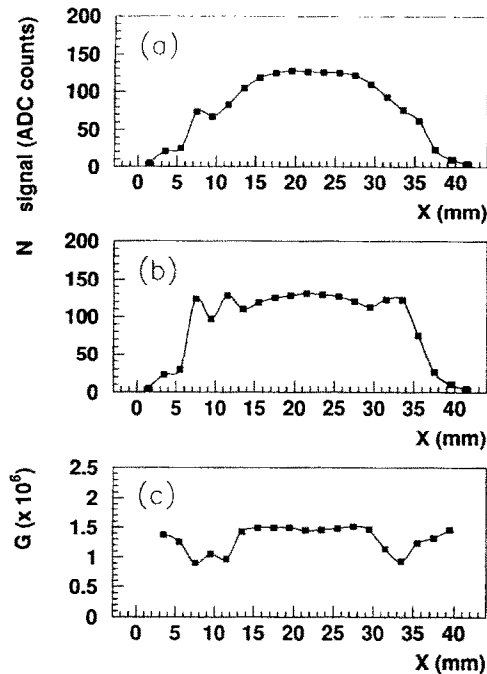
Fig. 8. Response of a 1.5 in. R2021 tube in the same experimental conditions as in Fig. 7.
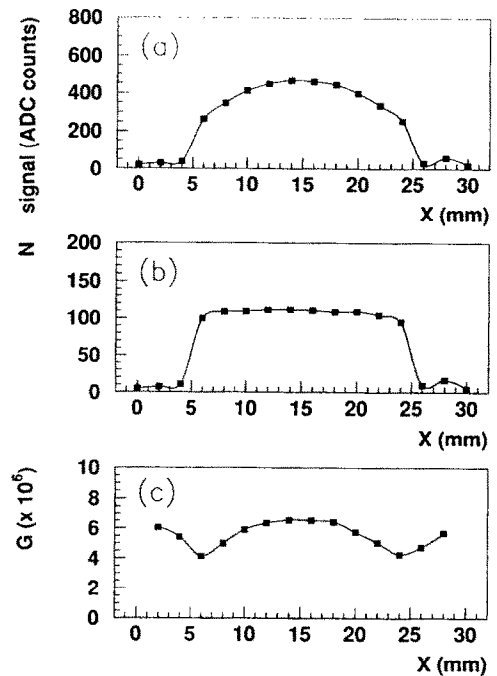

Fig. 9. Response of a $1\frac{1}{8}$ in. H5756 tube in the same experimental conditions as in Fig. 7.

3.3.2. Results in magnetic field

In order to investigate the effective photocathode area, the same measurement of Section 3.3.1 has been done along the diameter lying in the plane defined by the PM axis and the field direction.

The signal mean value, the average number of photoelectrons, and the PM gain as functions of x-coordinate at $B = 0.28$ T and $\theta = 0°$, $20°$, $25°$, $35°$ are shown in Fig. 10 for a R2490-05 PM. The result of the same measurement for a R2021 PM at $B = 0.1$ T and $\theta = 0°$, $9°$, $18°$, $27°$, $36°$ is shown in Fig. 11. A few measurements were done with a H5756 tube, namely $\theta = 0°$, $25°$ at $B = 0.1$, they are shown in Fig. 12.

The field causes a sideway shift of the cathode image on the dynodes, thus it reduces the effective area, and increases the photocathode nonuniformity both in gain and in photoelectron number. The tube's response is partially compensated by an increased photoelectron number, as well as by an increase in gain (see Figs. 10, 11 and 12). Some scans along a diameter were performed on 2 in. and $1\frac{1}{8}$ in. tubes at several B magnitudes, and at $\theta = 10°$ and $25°$. In Fig. 13 the effective diameter as a function of B is shown. A diameter reduction of 20% (10%) for $\theta = 25°$ ($\theta = 10°$) is found at $B > 0.1$ T. In the range $B = 0.1$–0.3 T the effective diameter does not depend on the field magnitude, and the dominant parameter is the angle θ. In Fig. 13 a measurement at $\theta = 25°$ is also reported for a H5756 PM, showing a similar behaviour and a 25% reduction at $B > 0.1$ T.
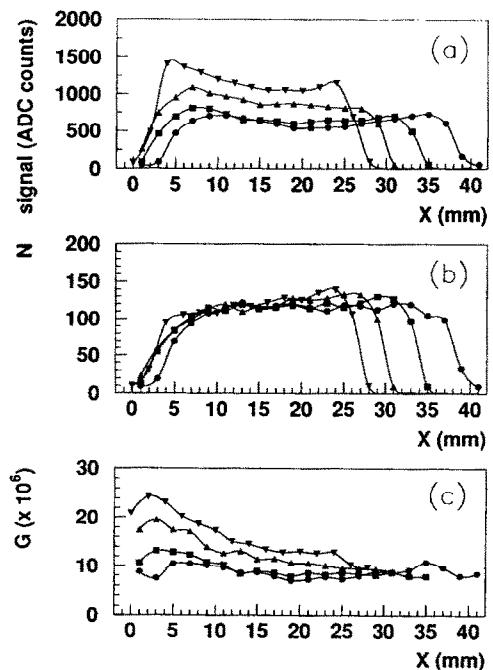

Fig. 10. Response of a 2 in. R2490-05 tube as a function of the light spot position along a diameter at $B = 0.28$ T and $\theta = 0°$, $20°$, $25°$, $35°$ (circles, squares, upwards and downwards triangles, respectively). (a) Signal spectrum mean value; (b) average number of photoelectrons N; (c) PM gain G.
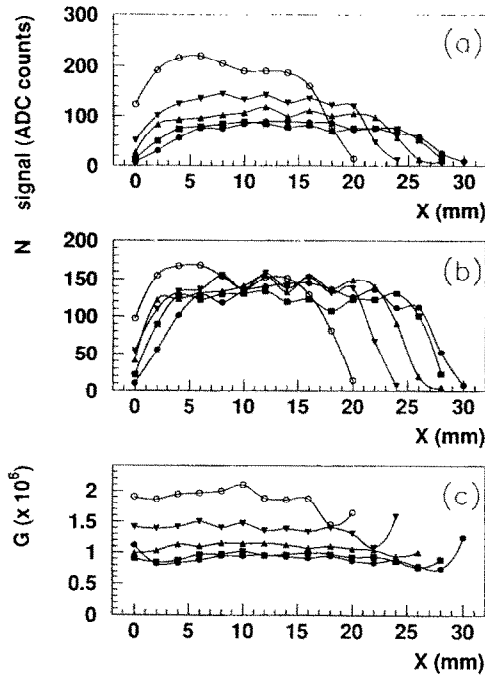
Fig. 11. Response of a 1.5 in. R2021 tube as a function of the light spot position along a diameter at $B = 0.1$ T and $\theta = 0°$, 9°, 18°, 27°, 36° (full circles, squares, upwards triangles, downwards triangles, open circles, respectively). Plots (a), (b) and (c) as in Fig. 10.
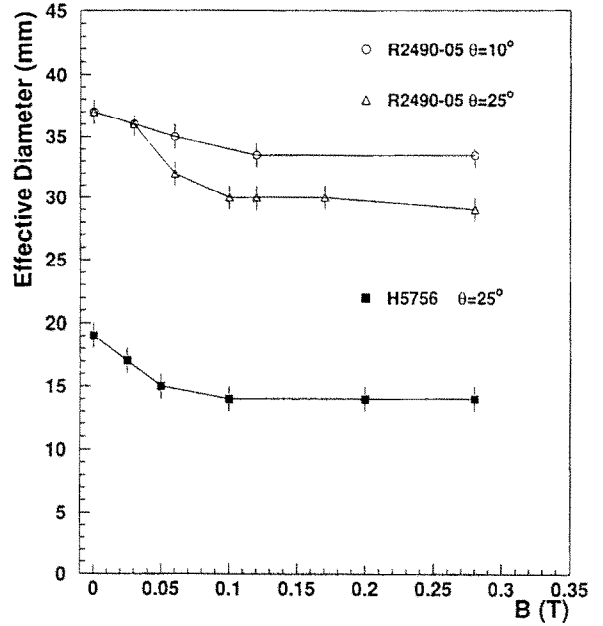

Fig. 13. Effective photocathode diameter (FWHM) for a 2 in. R2490-05 tube and a $1\frac{1}{8}$ in. H5756 tube, as a function of the magnetic field B. The angles are $\theta = 25°$ and $\theta = 10°$.
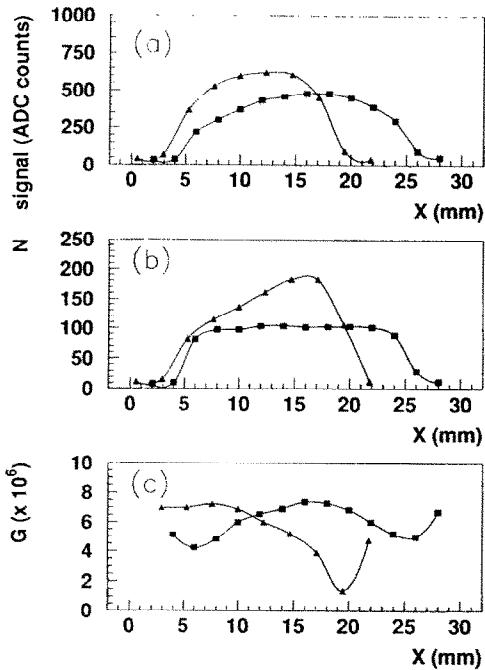

Fig. 12. Response of a $1\frac{1}{8}$ in. H5756 tube as a function of the light spot position along a diameter at $B = 0.1$ T and $\theta = 0°$, 25° (squares, and triangles respectively). Plots (a), (b) and (c) as in Fig. 10.
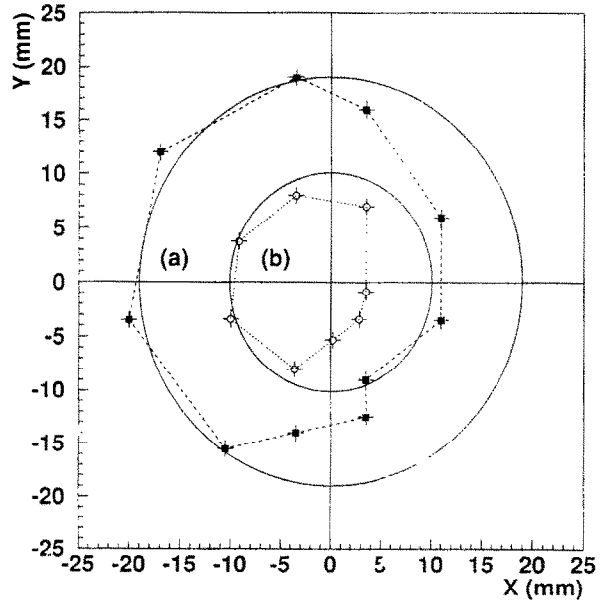

Fig. 14. (a) Mapping the effective area of a 2 in. R2490-05 tube at $B = 0.1$ T. $\theta = 25°$. the polygonal (dashed line) joins the ends of 5 measured diameters; the internal area approximates the photocathode effective area. The circle encloses the effective area at $B = 0$. (b) Same map for a $1\frac{1}{8}$ in. H5756 tube, with 4 measured diameters (dotted polygonal).

In order to get a map of the photocathode effective area, a scan along several diameters has been done on the 2 in. and $1\frac{1}{8}$ in. phototubes, at $B = 0.1\ T$ and $\theta = 25°$. In Fig. 14a the shrinking of effective area is shown for a R2490-05 PM. The circle gives the photocathode area at $B = 0$. The polygonal joining the ends of each measured effective diameter approximates the effective area perimeter. The reduction of the photocathode effective area is estimated to be roughly 25%. The number of collected photoelectrons is only reduced by about 10%, due to the compensation mentioned above.

The result for a $1\frac{1}{8}$ in. tube is also shown in Fig. 14b. The effective arcs shrinks by roughly 45%, more than for a 2 in. tube. Due to the quoted compensation, larger than for 2 in. PM, the photoelectron reduction is about 10%.

4. Conclusions

Fine mesh photomultiplier tubes have been tested in a magnetic field. The results can be summarized as follows.

1) The PM response depends on both the field magnitude and the angle θ between the field and the tube axis, in such a way that a (B, θ) region of response loss can be defined for each type of tube.

2) The effective photocathode area is reduced by the presence of a magnetic field. The area loss does not depend on the B magnitude in the B range 0.1–0.3 T, but it depends on the angle θ. Moreover the smaller the tube diameter, the larger is the relative loss in the effective area.

3) In addition, a dependence on the rotation around the tube axis is found, both for the gain and the number of photoelectrons. This is however reasonably correlated with the PM's multiplier orientation, therefore each single tube can be oriented to obtain an optimum response.

Acknowledgements

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