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DOE/ER/40664--T1

University of Iowa

PROGRESS REPORT

in

FY 1993

"Ultrafast Readout of Scintillating Fibers Using
Upgraded Position-Sensitive Photomultipliers"

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January 1994

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Abstract

Experimental results obtained with commercially available position-sensitive photomultipliers (PSPM) coupled with 0.5 mm diameter scintillating fiber arrays show some promising performances such as space resolution better than 200 μm and time resolution $\approx 1.5\text{ ns}$ with a detection efficiency higher than 90%.

Major progress has also been recently achieved with an upgrade of a PSPM based on new grid dynode structures. Two-track spatial resolution has been studied using the upgraded PSPM. Initial studies demonstrate that two tracks separated by a minimum distance of 3 mm are resolved.

1. Introduction

With the development of high quality small diameter scintillating fibers (SciFi) and of fast multichannel position-sensitive photomultipliers (PSPM) [1], the *scintillation counter* technique is continuing to find large applications in nuclear and particle physics [2]. In addition to its traditionally inherent merits like fast response, high gain, low noise, and simple and reliable operation, this development has led to the achievement of high-spatial resolution.

As an additional bonus, the upgraded dynode structures (mesh or fine grid) developed in view of obtaining localization properties in the PSPM provide an increased immunity to magnetic fields. Studies of the magnetic properties of these PSPMs are underway and will be the subject of a future publication.

We report on recent progress in the construction and operating experience of optimized prototypes of hodoscopes based on SciFi arrays coupled to a PSPM in order to measure with high accuracy the spatial position of charged particle trajectories, with fast-timing properties that make such detectors particularly suited to applications in the high-luminosity environment of future high-colliders.

These studies are the natural continuation of an earlier study using coarser prototypes with 1 mm diameter fibers.

2. Description of the Prototypes

2.1 Mechanical Structure

We have constructed a small hodoscope with 0.5 mm diameter scintillating fibers. As illustrated in Fig. 1, the SciFi hodoscope, 28 mm wide, consists of five single layers of fibers assembled by staggering each layer by 0.25 mm (Fig. 1a). On the readout edge, the SciFi array is split into four segments of 7 mm each. Each segment is stretched over 35 mm on the photocathode (Fig. 1b) so as to provide a magnification factor $\alpha = 5$, and a space resolution of $\sigma = 200 \mu\text{m}$.

measure the relative time difference between the PMT anode pulses emerging from the two ends of the delay line. The anode pulses are then amplified,* discriminated (constant fraction or leading edge) and then fed into a TDC, a monitoring circuit (not shown), and a Real Time Digitizer (RTD). Using the timing information from the x delay line, one can determine the segment which was hit. Similarly, from the y delay line, one gets the position within the segment.

3. Experimental Results

We have installed the apparatus in a test beam (5–10 GeV/c pions and protons) of the CERN Proton Synchrotron (Fig. 3). It consists of two beam-defining counters S1 and S2, two narrow finger counters S3 and S4 (0.5 mm wide across the beam) and three SciFi-PSPM hodoscopes. HA1 and HA2 are of identical construction, while HB is made of two parallel SciFi arrays movable with respect to each other, in order to simulate two track events. With this versatile setup we studied the space and time resolution of our hodoscopes, as well as the imaging and multi-track properties.

3.1 Space Resolution

The space resolution of the hodoscopes was first studied using a self-calibrating method by selecting track definition fibers of the SciFi array at a given interval and extending them to a second small PMT. Figure 4 shows the results obtained with 7 GeV/c positive beam particles. After unfolding the effect of the width of the definition fibers (0.5 mm diameter) the resolution is estimated to be $\approx 200 \mu\text{m}$, which is fairly close to the expected value based on the properties of the presently available PSPMs.

Similar results were obtained by using two 0.5 mm wide definition counters placed up and down stream of the hodoscope.

*A 100x amplification is presently needed because the gain of the PSPM is $10^5 - 10^6$.

Figure 2. Block diagram of the readout electronics showing the PMT anode-X connections (left) and the RTD circuit (right).

3.2 Linearity of the Reconstructed Position

The linearity of the reconstructed position was measured by scanning the full width of the SciFi array with a finger counter, 0.5 mm wide, by steps of 0.5 mm. The results are seen in Fig. 5.

The linearity within each of the four segments is quite good. Small nonlinearities are seen near the boundaries. This effect is most likely due to the edge of a segment being near the edge of the PSPMs active area. Note that the width

RD-17 Experimental Set-up

Figure 3. Typical setup.

of the segments (35 mm), is seen by 12 anodes each separated by 3.75 mm. This configuration provides only one *guard* anode beyond the SciFi array extremities.

3.3 SciFi/PSPM Detection Efficiency

The spatial detection efficiency has been studied by normalizing the number of events detected by the last dynode of the PSPM with respect to the incident flux as defined by the finger counter. This *raw* efficiency, not including any losses by the RTD, is plotted in Fig. 6 over the full width of the SciFi array. It is greater

Figure 4. Space resolution. before unfolding the width of the definition fibers ($0.5 \text{ mm } \phi$).

than 90% almost everywhere, except at the boundaries of the SciFi segments. This average efficiency is due mostly to the amount of light produced in the fibers and the attenuation length within the fiber.

Note that the areas of lower efficiencies correspond to a periphery of $d \approx 5.0 \text{ cm}$ on the photocathode of $\approx 6 \text{ cm}$ in the nominal diameter. Another local effect that was previously observed at each break between adjacent segments of the fiber array on the photocathode has been improved by arranging the segments on the photocathode in alternate directions. This guarantees that the fibers that are adjacent in the detector remain adjacent on the PMT face, even though they fall in different segments.

In order to maximize the efficiency, it proved useful to place a reflector on the opposite end of the fibers. Optical contact between SciFi and the photocathode was made with silicon grease. In this connection it is important to understand that the

Figure 5. Linearity of the reconstructed position.

quality of the scintillating fiber as well as the geometry of the array structure affect the efficiency. For example, the stacking of five single layers locally provides only two fibers traversed by incident particles. Assuming the thickness of the cladding is $\approx 3\%$ of the fiber diameter ($\approx 15 \mu\text{m}$ for 0.5 mm fibers) the portion of such a *weak* region presents $\approx 6\%$ of the array surface. A fine structure often seen in the local efficiency can be explained by this effect.

3.4 Time Characteristics

Another important issue concerns the time characteristics of the readout system based on the delay-line method. The time characteristics were studied by computing the mean time, $t_L + t_R$, with respect to a reference time t_0 , where t_L and t_R are the TDC contents corresponding to the arrival times of the left- and right-propagating signals coming out of the delay line, and t_0 is generated by either the last dynode of the PSPM or an external counter. Figure 7 shows the $(t_L + t_R)$

Figure 6. *Raw* detection efficiency measured with the last dynode signals of the PSPM using leading edge and constant fraction discriminators.

distribution with respect to t_0 as defined by the last dynode signal of the PSPM. The two peaks were obtained by adding a delay of 10 ns to t_0 in order to provide a calibration of the time scale.

The resolving time of $\sigma \approx 0.7$ ns can be interpreted mainly as an *internal* time spread of the last dynode signals with respect to the corresponding anode signals. Such a good time resolution will allow a fast strobe coincidence at the level of the RTD as is required for two-hit discrimination.

Figure 8 presents a similar result obtained with t_0 defined by an external counter. Assuming that the time resolution of the external counter is comparable with that of the PSPM the total resolving time of the hodoscope is estimated to be $\sigma \approx 1.5$ ns.

Figure 7. *Internal* time resolution. The two peaks were obtained by shifting the t_0 signal by 10 nanoseconds.

3.5 Two-Dimensional Imaging

The spatial resolution as achieved with this prototype allows us to obtain two-dimensional images; as an example, in Fig. 9, is shown the profile of a scintillator shaped as the letters “HC” placed in the beam just downstream of the hodoscopes. This profile is obtained in real time from two planes of SciFi hodoscopes gated by the shaped scintillator.

4. Two-Hit Resolution

The second hodoscope prototype (referred to as type B), shown in Fig. 10, is dedicated to the study of the two-track spatial resolution. Two track events can be simulated by a double array structure providing one of the array movable with respect to the other. Both arrays are seen by the same rows of pad anodes of a R3941-Mod. PSPM, custom manufactured by Hamamatsu.

Figure 8. Time sum ($t_L + t_R$) distribution obtained with the reference time t_0 defined by an external counter.

Figure 9. An example of two-dimensional images obtained in real time with two planes of hodoscopes.

Figure 10. "Type B" hodoscope showing the two movable layers.

Figure 11. The anode signals from the delay line.

As shown in Fig. 11, the anode signals from the delay line of the hodoscope are connected to the CFD discriminators. The pictures in Fig. 12 show typical examples of “simulated” two-track events produced by 10 GeV/c beam particles passing through the hodoscope, as a function of the relative displacement of the two fiber arrays. Changing the separation (d) between the two hits from 0 to 5 mm, the discriminator correctly triggers down to 3 mm.

5. General Discussion

Improving commercially available PSPMs, such as the R3941 produced by Hamamatsu Photonics, and creating new PSPMs by using finer grid dynodes is planned. The space resolution under an axial magnetic field of ≈ 500 G should provide an intrinsic resolution of ≈ 2 mm in FWHM against the present 8 mm resolution.

A PMT readout system based on a delay line has not been used for the real-time digitization until now. A delay line less than 50 ns long is well suited to the moderate intrinsic spatial resolution of the PSPM and the use of this purely passive element makes its readout simple, inexpensive, very fast, and reliable. In the near future the FAROS group will concentrate on the improvements of the time characteristics of the whole readout system. This is necessary not only for high-rate performance but also for good reconstruction of multi-hit events in real time.

Figure 12. Typical examples of "simulated" two-track events.

The number of photoelectrons emitted from the photocathode of the PSPM is inferred to be about four photoelectrons from the measurement of the spacial resolution. Some new SciFi ribbons developed by Nagoya University yielded ten photoelectrons for four layers of 0.5 mm fibers (SCSF38-KURARAY), yielding a clean pulse height spectrum, well separated from the background noise (Fig. 13).

6. Conclusion

It is clear from the present studies that the commercially available PSPM constitutes a promising step toward a novel *high-space and time-resolution* detector.

With a spatial accuracy better than 200 μm , a time resolution of 1.5 ns, a two-hit separation of 3 mm, good linearity and an efficiency better than 90%, this type of detector is already an attractive candidate for high rate topological triggering and

a) Anode signal through the delay line.

b) Last- dynode signal

Figure 13. Pulse shape of PSPM observed with Nagoya's SciFi array.

tracking applications in particle physics and accurate real-time imaging. Relatively simple construction techniques and moderate cost per anode channel, due to the delay-line readout system, are quite encouraging in view of the needs of future large scale systems.

In addition, there is ample room for improvements based on the present results and in view of forthcoming developments in the field of upgraded PSPMs. Future efforts will also be dedicated to improving the quality of the SciFi arrays as well as the time characteristics of the front-end electronics.

References

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A P P E N D I X

HOW TO USE FAROS SciFi Hodoscope

FAROS Collaboration

Brief description of the device

Fig. 1 Structure of the SciFi array.

The Faros Type A (for single hits) hodoscope consists of 6 layers of 0.5 mm ϕ scintillating fibres (SciFi) piled up in "straight stacking" as shown in Fig.1. The sensitive area, 60 mm wide, is split into 6 segments of 10 mm each. The readout edge of each segment is stretched by an "aspect ratio" $\alpha = 3.45$ so as to get a space resolution of $\sim 200 \mu\text{m}$ on the fiducial surface.

Fig. 2 shows the location of the 6 segments on the photocathode window of R2486 (Hamamatsu). The tube has crossed wire anodes, 16 in X and 16 in Y direction placed with interval of 3.75 mm.

All the anodes in each direction are connected to a delay line with interval of 3 ns. The position of hit fibres is reconstructed by a delay-line method by using time signals t_1 , t_2 , t_3 and t_4 coming out of the delay lines.

Fig. 2 Location of array segments on the photocathode window.

Reconstruction of hit position

Fig. 3 Two - dimensional event - distribution obtained with a flat beam.

Fig. 4 Projection of events on $(t_3 - t_4)$.

Fig. 5 Typical example of event - distribution as a function of $(t_1 - t_2)$, obtained with selected fibres distant by 1.74 mm.

Fig. 3 presents an example of a 2-dimensional event distribution, obtained with a flat beam, plotted as function of $t_1 - t_2$ (horizontal) and $t_3 - t_4$ (vertical).

The number of hit segment i ($i=1$ to 6) can be defined by looking at the projection of events onto $(t_3 - t_4)$ co-ordinate as indicated in Fig. 4.

The position inside a segment i is given by;

$$x_i = +(or-) c_i (t_1 - t_2) + d_i,$$

where c_i and d_i can be determined by a calibration run using some selected fibre columns. The sign in front of c_i refers the readout direction of the segment. A typical example of result obtained with selected fibres, regularly distant by 1.74 mm, is shown in Fig. 5.

The hit position in full range is thus obtained by

$$x = x_i + i \Delta S,$$

where $\Delta S = 10.07$ mm, the lateral width of the SciFi array segments.

Multihit events can be rejected by a simple criterion,

$$t_1 + t_2 = \text{constant, and}$$

$$t_3 + t_4 = \text{constant.}$$

Performances

One of such a type of hodoscope has been studied in details during a beam run in July 93. Some typical results are shown in Fig. 6-a, 6-b and 6-c.

Fig. 6 - a presents the local detection efficiency obtained with a finger counter defining the incident beam flux; the number of time signals (t_1 for example) in coincidence with the finger counter is normalised by the number of incident particles passing through this definition counter. Such a "raw" detection efficiency will eventually be affected by the reconstruction efficiency of hit position, which is estimated $> 95\%$ following our preceding results.

Fig. 6 - b presents a typical results of space resolution measurements obtained with selected fibres regularly placed with interval of 1.74 mm at the fiducial surface. The resolution varies slightly at different position of the photocathode due to a shadow effect of supports incorporated in the fine grid dynode structure. The average resolution is however better than 0.6 mm in FWHM.

The linearity of reconstructed position is shown in Fig. 6 - c. for the individual segments (open circles), as well as for the full range of SciFi array (closed circles). Note that the readout direction of fibres is inverted from segment to segment except for #4 to #5.

The linearity is good within a precision of $< 150\ \mu\text{m}$ over the full range.

Fig. 6 Typical performances of the hodoscope;
a) Local detection efficiency,
b) Space resolution,
c) Linearity.

Installation in the Experimental area

Fig. 7 Bloc diagram of the proposed electronics.

Two planes of the hodoscope have been installed on the muon test beam, and the front-end electronics are now ready to send the time signals from both horizontal and vertical planes. These signals are sent through ~ 200 ns BNC cables to TDC modules already installed in the CAMAC station # 23 of the spectrometer section.

The bloc diagram of the proposed electronics is shown in Fig. 7. A "local" trigger signal is defined by a triple coincidence between our beam counter, 10 cm ϕ , and the last dynode signals of both R2486 tubes. This signal is used as the common start of the TDCs located on slots #21 and #22, which receive the stop signals $t_1 - t_4$ from the horizontal and vertical hodoscopes.

TDC contents corresponding to a local trigger signal are maintained until arrival of the 'main' trigger coming through the station #24A. The maximum waiting time of, say 1 μ s, is fixed by the timers #1 and #2.

The timing of the local trigger with respect to the main trigger is registered by TDC on slot #20. During the conversion time of the TDCs (~100 μ s) local trigger signals are vetoed by the timer #3.

When the main trigger is absent a fast clear signal is produced by ADD #1, and sent to all the TDCs. The recovery time of TDC, ~ 1.4 ns is provided by the timer #4.

The present scheme is based on the assumption that the accidental rate of the local trigger is negligible within the maximum waiting time of $\sim 100 \mu\text{s}$. Otherwise it is necessary to synchronise all the time signals, through very long delays, with respect to the main trigger. The above assumption is valid under the present test beam intensity (< 1000 particles / burst), but a care should be taken for the calibration run using e^-/π^- beam.

Calibration of the hodoscope

Fig. 8 Light outlet disk; lower figure presents selected outlets for the calibration.

In order to provide the absolute co-ordinates it is necessary to calibrate our device by selecting some of the fibre columns. For example, 3 columns at the centre and the extremities will be selected by masking other light outlet of fibres as shown in Fig. 8.

The number of useful events for the calibration is therefore $\sim 10\%$ of the total beam flux hitting the fiducial area. Assuming a few thousands events needed for each reference point, this requires ~ 2000 bursts if the muon-beam intensity is $\sim 150/\text{burst}$.

The calibration needs also a high efficiency of the main trigger rate with respect to the local trigger.

A model calculation of the spatial resolution of the position-sensitive photomultiplier

In the development of position-sensitive photomultipliers (PSPM) and the study of the scintillating-fiber readout by using them, the spatial resolution is considered to be one of the most important characteristics of the device. A lot of effort in the past has been spent in order to determine experimentally the spatial resolution of a given PSPM. Yet, the mechanism determining this physical quantity has been rather overlooked so far.

We try to calculate the spatial resolution of a PSPM by using a simple model. A Monte Carlo technique has been used where an analytical study is difficult. We expect the result to be useful for the future design of a new PSPM.

1. Model

Although the spread of the secondary electrons in a PSPM is a three-dimensional phenomenon, we treat this problem as a two-dimensional one. We assume that N photoelectrons are emitted from the photocathode at $x=0$, the hit point of the light. Later, we will take into account the statistical variation of N , but at this state, we assume this to be a fixed number. The photoelectrons hit the first dynode at different positions in x , denoted by x_0^i . We assume that the distribution of x_0^i follows a Gaussian distribution centered at $x=0$ with the standard deviation σ_0 .

We further assume that m secondary electrons are emitted from the first dynode at $x=x_0^i$. The hit points of those secondary electrons of the second dynode, denoted by x_1^i , distribute according to a Gaussian distribution centered at x_0^i and with the standard deviation σ . The way this happens is schematically shown in Fig. 1. As the structure of all k dynodes is the same, we can well assume that all the secondary electrons emitted from these dynodes follow the same Gaussian distribution, always with the standard deviation σ .

The last stages would however need a special consideration. The gap between the k -th dynode and the anodes, in the case of pad anodes, and the gaps between $(k-1)$ -th and k -th dynodes and the anodes, in the case of wire anodes are eventually different from the gaps between former stages. We however choose to treat these stages the same way as the former stages. The physical quantities which we can measure experimentally are quite limited, and the introduction of too many parameters in the calculation will render the analysis difficult. Also we can well assume that for those last stages, a small deviation from the model will not change drastically the results. Also if a space charge effect exists in the last

stages, the distribution must be affected. But as we are dealing with cases where very few photoelectrons are amplified in the tube, we neglect this effect too.

It is obvious that m , the number of secondary electrons, fluctuates also. If we know the statistical distribution which m follows, it is not so difficult to introduce in the simulation. But for the time being, we assume that it is a fixed number for all the stages for a given high voltage applied to the tube.

2. Positional uncertainty

The mean of the first dynode position X_0 hit by the photoelectrons is expressed as

$$\bar{X}_0 = \frac{1}{N} \sum_i^N x_0^i. \quad (1)$$

As we assume a Gaussian distribution, the uncertainty involved in the mean of X_0 is expressed as

$$\sigma_{\bar{X}_0} = \frac{\sigma_0}{\sqrt{N}}. \quad (2)$$

In total Nm secondary electrons are emitted from the impact points, their hit points of the second dynode X_1 is expressed as

$$\begin{aligned} \bar{X}_1 &= \frac{1}{Nm} \sum_i^{Nm} (x_0^i + x_1^i) \\ &= \frac{1}{N} \sum_i^N x_0^i + \frac{1}{Nm} \sum_i^{Nm} x_1^i. \end{aligned} \quad (3)$$

Thus its uncertainty is

$$\begin{aligned} \sigma_{\bar{X}_1} &= \sqrt{\left(\frac{\sigma_0}{\sqrt{N}}\right)^2 + \left(\frac{\sigma}{\sqrt{Nm}}\right)^2} \\ &= \frac{1}{\sqrt{N}} \sqrt{\sigma_0^2 + \frac{\sigma^2}{m}}. \end{aligned} \quad (4)$$

So, after an amplification of k -stages, the mean of the anode position X_a hit by the electrons is expressed as

$$\begin{aligned} \bar{X}_a &= \frac{1}{Nm} \sum_i^{Nm} (x_0^i + x_1^i + \dots + x_k^i) \\ &= \frac{1}{N} \sum_i^N x_0^i + \frac{1}{Nm} \sum_i^{Nm} x_1^i + \dots + \frac{1}{Nm^k} \sum_i^{Nm^k} x_k^i. \end{aligned} \quad (5)$$

And its uncertainty is

$$\begin{aligned}
\sigma_{X_a} &= \sqrt{\left(\frac{\sigma_0}{\sqrt{N}}\right)^2 + \left(\frac{\sigma}{\sqrt{Nm}}\right)^2 + \left(\frac{\sigma}{\sqrt{Nm^2}}\right)^2 + \dots + \left(\frac{\sigma}{\sqrt{Nm^k}}\right)^2} \\
&= \frac{\sigma}{\sqrt{N}} \sqrt{\frac{\sigma_0^2}{\sigma^2} + \frac{1}{m} + \frac{1}{m^2} + \dots + \frac{1}{m^k}} \\
&= \frac{\sigma}{\sqrt{N}} \sqrt{\frac{\sigma_0^2}{\sigma^2} + \frac{1}{m-1}} \quad (k \gg 1). \tag{6}
\end{aligned}$$

3. Electron spread

We define the electron spread S_j at stage j to be the root mean square of X_j ;

$$S_j^2 = \frac{1}{Nm^{j+1}} \sum_i X_j^2 \tag{7}$$

Thus the spread at the anode after j stages of amplification can be expressed as

$$\begin{aligned}
S_j^2 &= \frac{1}{Nm^{j+1}} \sum_i (x_0 + x_1 + \dots + x_j)^2 \\
&= \frac{1}{Nm^{j+1}} \left[\sum_i (x_0^2 + x_1^2 + \dots + x_j^2) \right. \\
&\quad \left. + \sum_i (x_0 x_1 + x_0 x_2 + \dots) \right] \tag{8}
\end{aligned}$$

If there is no correlation between x of different stages, the sum over the cross terms drops and,

$$\begin{aligned}
S_j^2 &= \frac{1}{N} \sum_i x_0^2 + \frac{1}{Nm} \sum_i x_1^2 + \dots + \frac{1}{Nm^{j+1}} \sum_i x_j^2 \\
&= \sigma_0^2 + \sigma^2 + \dots + \sigma^2. \tag{9}
\end{aligned}$$

So, the electron spread is given by

$$S_j = \sigma \sqrt{\frac{\sigma_0^2}{\sigma^2} + j - 1} \tag{10}$$

which is independent of N and m .

4. Simulation

The gain of a commercially available PSPM, Hamamatsu R2486 for example with 12-stage dynodes, is typically several times 10^6 . So the electron multiplication at each dynode m is about 3. We did a Monte Carlo calculation for

the case of $m=3$. Fig. 2 shows the electron spread (rms) and the uncertainty involved in the mean of X_j which is usually interpreted as the spatial resolution, at each stage of amplification in the PSPM. The result is shown for the case of $N = 5$. The resolution and the electron spread are both expressed in terms of σ . The curves are shown for the cases of $\sigma_0 = \sigma$, and $\sigma_0 = 2\sigma$. They are shown to follow quite well the equations 6 and 10. We can see that the increase of the number of stages adds to the electron spread, but the resolution stays more or less constant.

Fig. 3 shows the electron spread at the anode level (S_a) in a 1-stage tube as a function of the number of photoelectrons (N). The curves are shown for the cases of $\sigma_0 = \sigma$, and $\sigma_0 = 2\sigma$. One thousand events are generated in the Monte Carlo study. One can see that the spreads are almost independent of N and follow well the equation 10.

Fig. 4 shows the N dependence of the resolution. The curves are calculated for the cases of $\sigma_0 = \sigma$, and $\sigma_0 = 2\sigma$. One can clearly see the $1/\sqrt{N}$ dependence of the resolution.

When N is small, the resolution varies a lot with N . Therefore it is necessary to take into account explicitly the statistical variation of N . We can assume that when the average number of photoelectrons is N , it varies according to a Poisson's distribution with the mean N . The spatial resolution is therefore calculated for each average N with statistical variation folded in. The results are shown in fig. 5 for the cases of $\sigma_0 = \sigma$, and $\sigma_0 = 2\sigma$. The resolution becomes worse. Compared with the non-folded case, the resolution with a Poisson's distribution folded in at average N is almost identical to that at $N+1$ at fixed N , except for very small N , where the resolution is improved at the sacrifice of the efficiency.

5. Discussion and conclusion

What is of the central interest when a PSPM is given is how to know the best resolution one can obtain with that tube. The only quantity one can measure in the given PSPM is the electron spread at the anodes. As it hardly varies with N , the number of photoelectrons, according to the model analysis confirmed with the Monte Carlo method, one cannot expect to obtain more information experimentally by varying N . So, to relate the resolution to the electron spread, one has to estimate the ratio σ_0/σ from the geometry of the PSPM. One can expect that σ increases roughly with the square root of the distance.

In the case of R2486, the distance between the photocathode and the first dynode is 8.6 mm whereas the inter-dynode distances are 1.45 mm. Thus the former is about 5.9 times larger than the inter-dynode distances. So we can assume σ_0 to be 2.4 times σ . In the case of R2486-MOD-A which was fabricated and measured recently in the framework of RD-17 the former is 4.0 mm while the latter is 3.44 mm, thus the ratio is 1.16, and σ_0 is expected to be 1.08 times larger than σ . Fig. 6 shows the resolution and electron spread at the anodes for R2486 where the ratio σ_0/σ equals 2.4.

The electron spread was measured to be 8mm FWHM which means 3.4 mm rms for both PSPMs. This corresponds to 4.2σ in the case of R2486 according to fig. 6, and 3.6σ in the case of R2486-MOD-A according to fig. 3. If we choose the number of fibers such a way that we obtain some 25 photons from minimum ionizing particles, and we assume the quantum efficiency to be 20%, the average N must be about 5. Then the resolution is 0.8σ namely 0.65mm according to fig. 6 for R2486. So, 200mm which was obtained as an experimental spatial resolution with the mapping density ratio equal 5 with R2486, is 1.5 times the best we can expect. It should still be possible to improve the experimental result.

Whereas in the case of R2486-MOD-A which has smaller photocathode-first dynode distance, but larger inter-dynode gap, as mentioned above, the spatial resolution is unfortunately not yet known. However we can expect to measure the resolution to be 1.2σ , namely 1.13mm at the photocathode. With a mapping density ratio of 5, the best spatial resolution we can expect is about 230 μ m. Despite a larger distance between the photocathode and the first dynode, the smaller inter-dynode gap in R2486 seems to play an important role in giving us a better spatial resolution. This is an important consideration when we design improved PSPMs in the future. Also it is advantageous to apply a higher HV. It will reduce σ_0 as well as σ , and at the same time will increase m which again will act to improve the resolution according to eq. 6.

This study shows the dependence of the spatial resolution of a PSPM on the number of photoelectrons, secondary-electron multiplication, number of stages, and σ_0 and σ , the standard deviation of the spread of the photoelectrons and the secondary electrons by using a model. It shows also a way to relate the resolution to the electron spread at the anodes. These relations could be useful in the further development of the PSPMs and the study of the scintillating-fiber readout by using them.

The result shows that it has a vital importance to reduce the distance between the photocathode and the first dynode, and the inter-dynode gap. It shows also that to increase the electric field is effective not only to reduce σ and σ_0 , but also to increase m to improve the spatial resolution.

Fig. 1 Schematical view of the electron amplification mechanism

Fig. 2 Spatial resolution and electron spread (N=5)

Fig. 3 Electron spread as a function of N

Fig. 4 Spatial resolution as a function of N

Fig. 5 Spatial resolution with a statistical fluctuation of N taken into account

Fig. 6 Spatial resolution and electron spread in R2486

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