Timing characteristics of a micro-channel plate and fine mesh photomultiplier tubes in a 1 T field

Hiromichi Kichimi, Hiroyuki Sagawa and Yoshio Yoshimura
KEK, National Laboratory for High Energy Physics, 1-1 Oho, Tsukuba, Ibaraki, 305 Japan

Takashi Kishida
Physics Department, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, 113 Japan

Norio Tamura
Physics Department, Okayama University, 3-1-1 Tsushima-Naka, Okayama, 700 Japan

Hiroyuki Suzuki and Takeshi Taguchi
Hamamatsu Photonics K.K., Electron Tube Center 314-5 Shomokanzo, Toyooka, Iwata, Shizuoka, 438 Japan

Received 20 July 1992 and in revised form 27 July 1992

Timing characteristics of a micro-channel plate (MCP) and a fine mesh (FM) photomultiplier tubes were investigated in magnetic fields up to 1.5 T as functions of the field strength and direction. The r.m.s. values of transit time spread of the MCP and the FM tubes in 1 T field were found to be 40 ps and 140 ps, respectively. For a simulated scintillation light equivalent to 160 photoelectrons, the FM tube gave a time resolution better than 100 ps even in a 1 T field in spite of a large gain reduction to less than a 10%.

1. Introduction

The time resolution of scintillation counters is basically limited by the number of photons and the time distribution of the photons arriving at the readout phototube [1,2]. The arrival time distribution is primarily a result of the timing properties of scintillation (rise time and width), and also of the path length difference of photons propagating inside the counter. The time dispersion from the latter effect is approximately proportional to the square root of the propagation distance [1]. Therefore, an efficient way to improve the time resolution is to mount a phototube directly on the end of the scintillator thus minimizing the time dispersion, and to cover a larger area maximizing the photon collection efficiency. Such a compact readout for a time-of-flight (TOF) counter is also desirable to minimize interference with other detector components in a detector complex, in particular for collider experiments. For this application, it is essential to develop a magnetic field resistant photomultiplier tube which can work even in a 1 T field with good time resolution and a gain greater than $10^5$. Recently, several R&D results have been reported on these kinds of photomultiplier tubes [3–6].

There are two candidates, a micro-channel plate (MCP) photomultiplier tube and a fine mesh dynode (FM) photomultiplier tube. We tested Hamamatsu R2809U (MCP) and R2490-5 (FM) tubes shown in fig. 1. Their characteristics are listed in table 1. A MCP tube is mostly used in bio-chemical or bio-physics research for single photon counting with an accuracy of 50 ps in FWHM. The R2809U (MCP) tube consists of 2 stages of 6 µm diameter micro-channel plates. Its sensitive photocathode area is 18 mm in diameter. The micro-channel axes are tilted by 13° with respect to the normal of each plate, and their axes in the two plates are aligned in a vertical plane. The R2490-05 (FM) is a 2 in. diameter tube with 16 stages of fine mesh dynodes. The sensitive photocathode area is 36 mm in diameter. R2490-01 tube, an old version of the R2490-05 tube, has been successfully used for the endcap TOF counters of the CLEO II detector in a 1.5 T field and a TOF time resolution of 220 ps is reported for single phototube readout [7]. The distance between the photocathode and the first dynode was 20 mm and the...
Fig. 1. Pictures of the micro-channel plate photomultiplier tube R2809U and the fine mesh dynode photomultiplier tube R2490-05.

Table 1
Photomultiplier tube characteristics.

<table>
<thead>
<tr>
<th>Tube</th>
<th>$\tau_{\text{rec}}$ [ns]</th>
<th>$\Delta T$ [ns]</th>
<th>$\Delta_{\text{TTS}}$ [ps]</th>
<th>Curr. amp. gain</th>
<th>e.p.c. mm$\phi$</th>
<th>HV [V]</th>
<th>Cathode type</th>
<th>stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2083</td>
<td>0.7</td>
<td>16</td>
<td>160</td>
<td>$2.5 \times 10^6$</td>
<td>46</td>
<td>3000</td>
<td>bialkali</td>
<td>8</td>
</tr>
<tr>
<td>R2809U (MCP)</td>
<td>0.15</td>
<td>0.4</td>
<td>25</td>
<td>$5 \times 10^5$</td>
<td>18</td>
<td>3000</td>
<td>bialkali</td>
<td>2 mcp</td>
</tr>
<tr>
<td>R2490-05 (FM)</td>
<td>2.7</td>
<td>14</td>
<td>150</td>
<td>$3 \times 10^6$</td>
<td>36</td>
<td>2500</td>
<td>bialkali</td>
<td>16</td>
</tr>
</tbody>
</table>

Fig. 2. Test setup in single photon mode. A 2 T dipole magnet of 15 cm gap was used for the test. A fast light pulser Hamamatsu PLP-01 was used for TTS measurement with constant fraction discriminator scheme.
adjacent dynode planes were mutually separated by a few mm. Those distances are made smaller in the latest version, the R2490-05 tube, in order to improve the time resolution and the gain stability in magnetic field.

As an R&D project on a high resolution TOF counter for a B factory detector at KEK [8], we investigated timing characteristics of these photomultiplier tubes in magnetic fields up to 1.5 T as functions of the field strength and direction.

The time resolution of a photomultiplier tube is usually evaluated by the transit time spread (TTS), the timing response to a single photon. A more practical test as a readout device for TOF counters requires a well defined scintillation light. Therefore, we used two kinds of pulsed lights. One is a very fast pulse with a width of 40 ps in FWHM and a time jitter less than ±10 ps, provided by Hamamatsu PLP-01 (410 nm). It was used to measure TTS in single-photon mode. The other is a rather slow pulse provided by Laser Science Inc. VSL Laser. It is a N₂ dye (Stilbene 420 nm) laser, for which we obtained a 90% rise time of 0.9 ns and a pulse width of 2.8 ns in FWHM. It provides a simulated scintillation light with an adjustable number of photons and with the well defined timing properties.

This is the first report on the timing characteristics of these photomultiplier tubes in magnetic fields up to 1.5 T. We will describe the setup and results of single-photon mode in section 2 and those of multi-photon mode in section 3, the test results for time resolution vs photon statistics in section 4.

2. Timing characteristics in single-photon mode

Fig. 2 shows the setup used to study single photon response. The test tube was set in a dipole magnet with a 15 cm gap providing a field up to 2 T in a 40 cm × 100 cm area. The fast light pulser, PLP-01 (410 nm), was used as a light source, which produced a few hundred photons per pulse. The light pulse was led to a prism on top of a small lightguide, through a 1 m long graded index optical fiber (50 µm in diameter). Due to its small optical aperture, only a small fraction of the photons could enter into the fiber. The photons were reflected by the prism and diffused into the light guide to illuminate uniformly the central area of the photocathode. The number of photons per pulse was reduced to much less than one. The time jitter of the
phototube output relative to the trigger signal (TDC start) was recorded by a system of a constant fraction discriminator and a multi-channel analyser (CFD scheme). The jitter in the readout electronics is expected to be less than 10 ps. The gain was also measured separately.

The results of the R2809U (MCP) tube for single photon mode are shown in fig. 3 as functions of the field strength and the direction. The supply voltage was -3300 V. The direction of the test tube was varied between -60° and +60° by 30° steps in the field up to 1.5 T. The relative gain shown in fig. 3a slowly increases with field strength and shows a broad bump depending on the field direction. Fig. 3b shows the r.m.s. TTS value, $\sigma_{\text{TTS}}$, which includes the intrinsic time jitter in the readout system. It exhibits a weak dependence on the field strength and the direction, and stays between 20 and 35 ps. The results show asymmetries both in gain and TTS with respect to the symmetry axis of 0°, which may have been caused by the tilt angles of the micro-channels in the plates.

The results for R2490-05 (H2611) (FM) tube are shown as dashed lines in fig. 4. The supply voltage was -2500 V. Fig. 4a shows the relative gains and fig. 4b shows $\sigma_{\text{TTS}}$ at the angles 0° and 30°. The data at 60° is not shown, because the signal was too small. On the

![Fig. 5. Test setup in multi-photon mode. VSL laser, N₂ dye (Stilbene 420 nm) laser was used. The time resolution, $\sigma_{\text{FWC}}$, was obtained after correction for time walk.](image)

![Fig. 6. Single photoelectron signal of the N₂ dye laser measured by Hamamatsu R2083. (a) Pulse height distribution and (b) time distribution of single photoelectron signal.](image)
other hand, the timing characteristics are found to be rather stable in spite of such a large reduction in gain; $\sigma_{TTS}$ is 100 ps to 140 ps with a weak dependence on field strength and direction.

3. Timing characteristics in multi-photon mode

Fig. 5 shows the test setup in multi-photon mode. The $N_2$ dye (Stilbene 420 nm) laser was used to simulate typical scintillation light. The light intensity was adjusted by changing the diffuser thickness in front of the inlet of a 25 m long optical fiber, whose outlet was connected to the 1 m long optical fiber described in the previous section. The light reflected by a half mirror was detected by a biplanar phototube, Hamamatsu R1328U-02, to monitor the light intensity and to pick up the start timing. The signal from the test tube was fed to an ADC (0.25 pC/channel) and also to a TDC (25 ps/channel) through a leading edge discriminator. The raw timing data was corrected for a time walk in linear proportion to $1/(\text{pulse height})^{1/2}$ to obtain the time resolution $\sigma_{TW_c}$ (LED scheme). The time jitter in this scheme is estimated to be 15 ps.

We separately tested the timing properties of the $N_2$ dye laser by a photomultiplier tube, Hamamatsu R2083 (H2431) using the same test bench with no magnetic field. The light intensity was adjusted to produce at most one photoelectron on the photocathode. Fig. 6a shows the pulse height distribution for the triggered events. The two clear peaks around 50 and 100 ADC counts are visible, corresponding to one and two photoelectron signals. The fraction of the single photoelectron events is estimated to be about 80%.

Fig. 6b shows the measured timing distribution of the single photons from the dye laser. A rise time $\tau_{pe} = 0.9$ ns (90%) and a pulse width of 2.8 ns in FWHM are obtained. In this measurement, the contribution from the time jitter (160 ps) of the R2083 tube is negligibly small. The other contribution due to time walk is expected to be the same order. The rise time and the pulse width are fairly close to those of the scintillators used for TOF counters [9]. The dye laser, therefore, provides a scintillation light with an adjustable number of photons, which is suitable for a practical test of photomultiplier tubes.

In a real size counter, a 4 cm thick and 6–10 cm wide counter, the number of photoelectrons produced on the photocathode of readout phototube is expected to be a few hundreds for a scintillation pulse created at a distance of 2–3 m. The dispersion effect in photon propagation inside the counter degrades both the pulse width and the rise time as a function of the distance. Instead of simulating this complex effect, we chose as a typical signal the laser intensity producing 160 photoelectrons in the following test of R2490-05 (H2611) (FM) tube. The supply voltage was $-2500$ V. The results are shown as solid lines in fig. 4, where (a) and (b) are relative gain and $\sigma_{TW_c}$, respectively. The $\sigma_{TW_c}$ value stays around 80 ps below 0.7 T, and it increases only slowly with decreasing gain at higher fields. Consequently, as far as the timing properties are concerned, the performance of the FM tube is little affected at high magnetic fields where the gain is considerably reduced.

4. Time resolution vs photon statistics

In this section, we compare the FM tube with the MCP tube from a viewpoint of practical readout device for scintillation TOF counter. $\sigma_{TTS}$ of the MCP tube was also measured by the LED scheme for single photons from the PLP-01 pulser. The measured $\sigma_{TTS}$ of 30 ps was consistent with that of 20 ps by the CFD scheme within error, which are shown in fig. 7.

The time resolutions of the FM and the MCP tubes were investigated in terms of the number of photoelectrons $N_{pe}$ produced on the photocathode. This study was carried out by using the simulated scintillation pulse from the $N_2$ dye laser under no field. The same setup described in the previous section was used. The results are shown in fig. 7. The observed $\sigma_{TW_c}$ value of the FM tube improves in proportion to $1/\sqrt{N_{pe}}$. On the other hand, that of the MCP tube does not improve with $N_{pe}$ and it is comparable with or worse than those of the FM tube. The $\sigma_{TW_c}$ values for 20 pe obtained by LED and CFD schemes were 180 ps and 200–220 ps, respectively, and that for 160 pe obtained by the LED scheme was 190 ps. These values were not good as expected from its small TTS value of 20–30 ps.
A similar phenomenon was also reported in the test of a micro-channel plate photomultiplier tube R1564U-01 [7].

The output signals were investigated by a 500 MHz digital oscilloscope. Fig. 8a shows the output of the MCP tube (HV = -3400 V), and fig. 8b shows that of the FM tube (HV = -2700 V) for the simulated scintillation light (160 pe). The signal from the biplanar tube was used as a trigger. The MCP signal was narrower than the FM, but the jitter in rising edge of the MCP tube was much larger. Owing to its very fast rise time (0.15 ns), the MCP output signal is expected to be very sensitive to the pulse shape of the scintillation, namely to a statistical fluctuation of the number of photons in the rising edge (0.9 ns). As a result, $\sigma_{\text{TTS}}$ of the MCP tube is not good as that expected from its small TTS value for the simulated scintillation pulse with a slow rising edge.

The effective area of the photocathode of the available MCP tube is one half of the FM tube in diameter, and it has a problem of long term stability and lifetime [4]. In addition, the MCP tube is a few times more expensive than the FM tube. The test results and the above argument conclude that the R2809U (MCP) tube does not have a great advantage over the R2490-05 (FM) tube as a readout device for a scintillation TOF counter.

5. Conclusion

The timing characteristics of two types of the photomultiplier tubes, a microchannel plate R2809U (MCP) tube and a fine mesh dynode R2490-05 (FM) tube, were investigated in magnetic fields up to 1.5 T. The test results indicate that the transit time spreads (TTS) of those tubes are rather stable against the field strength and direction. The measured r.m.s. TTS values are 30 ps and 140 ps in a 1 T field for the MCP and the FM tubes, respectively. The MCP tube shows excellent results in both gain and timing properties in the single photon mode. On the other hand, for a simulated scintillation light from a N$_2$ dye (Stilbene 420 nm) laser, it gave a time resolution comparable with that of the FM tube, in spite of the superior TTS value. The FM tube shows a time resolution of better than 100 ps for the simulated scintillation signal with 160 photoelectrons even in a magnetic field of 1 T. The FM tube can be used as a compact read out phototube, being mounted directly on a TOF counter in a high magnetic field. For practical use, further R&D study is required to develop a tube with a larger photocathode area and a gain higher than $10^6$ at 0° in a 1 T field.

Acknowledgement

We would like to express our thanks to Mr. T. Hakamada and Mr. S. Suzuki of Hamamatsu Photonics for valuable information and to Dr. K. Tanaka at KEK for his support, and to Prof. F. Takasaki and Prof. S. Iwata for their encouragement.

References