A 30 ps timing resolution for single photons with multi-pixel Burle MCP-PMT


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Abstract

We have achieved ~30 ps single-photoelectron and ~9.1 ps for multi-photoelectron timing resolution with a new 64-pixel Burle MCP-PMT with 10 μm microchannel holes. We have also demonstrated that this detector works in a magnetic field of 15 kG, and achieved a single-photoelectron timing resolution of better than 60 ps. The study is relevant for a new focusing DIRC RICH detector for particle identification at future colliders such as the super B-factory or ILC, and for future TOF techniques. This study shows that a highly pixilated MCP-PMT can deliver excellent timing resolution.

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1. Introduction

The DIRC detector for the BaBar experiment provides excellent particle identification performance [1,2]. We are developing a next generation DIRC, which is capable not only measuring an x and y coordinate of each photon with similar angular resolution to the present BaBar DIRC, but, in addition, each photon’s time-of-propagation (TOP [3]) through the fused silica bar with ≤150 ps timing resolution (the present BaBar DIRC has a timing resolution of only σ ≈ 1.6 ns). Here we present studies of the limit of the timing resolution of a new 64-pixel Burle/Photonis MCP-PMT with 10 μm holes. This tube has been shown to perform well in the magnetic field of 15 kG. One expects to achieve better timing resolution because the tube is faster than the MCP-PMT tubes with 25 μm holes used in the present focusing DIRC prototype. With such tube one could achieve better DIRC performance at shorter photon path lengths.

In addition to RICH applications, there is a new interest to push the TOF performance to new limits approaching σ ≈ 5–20 ps with new MCP-PMT type of detectors [6–8].

2. Photon detector and experimental setup

Fig. 1 shows the 64-pixel MCP-PMT 85012-501 used in this study. The tube has 10 μm holes, 6 × 6 mm² pixel size, and the cathode-to-MCP distance of 6–7 mm, which means that the recoiling electrons can land up to ~12 mm away from the cathode.
from the original point of impact, and this in turn causes a long timing tail. The tail can be eliminated if the gap is reduced to ~0.75 mm [4].

The timing resolution study was done on a single pad, illuminated at its center, and connected coaxially to a fast amplifier ~1 ns away, while all other pads were grounded; this represents an ideal case. This arrangement was fixed while varying amplifiers of various noise and bandwidth (BW) performance, coupled to two types of constant fraction discriminators (CFD), and LeCroy TDC with 24 ps/count—see Table 1.

To do this measurement, we use the PiLas 635 nm laser diode, for which the manufacturer quotes a timing resolution of ~35 ps FWHM for timing between an internal electrical trigger and a light pulse. The light was attenuated with optical filters and brought to a detector via a multi-mode 62.5 μm dia. fiber, equipped with lenses at both ends to make a small sub-mm spot on the photocathode. For some measurements we tried to improve the timing resolution by triggering on light, which was achieved by an optical splitter and feeding one branch to a 2 GHz bandwidth Si diode. No improvement was achieved compared to the PiLas electronic trigger.

3. Single photoelectron timing resolution

Fig. 2 shows the best single photoelectron timing resolution results: σ ≈ 32 ± 0.6 ps with both Hamamatsu 1.5 GHz BW and Ortec VT120A ~0.4 GHz BW amplifiers.

The resolution was evaluated with a double-Gaussian fit function. Table 1 summarizes all results with other amplifier choices. As we pointed out in footnote 1, the best ever single photoelectron timing resolution obtained with the MCP-PMT with 25 μm holes was σ ≈ 54 ± 4 ps [4,5].

The overall conclusion is that in the “single-photoelectron domain,” it is sufficient to have a relatively slow amplifier (~0.4 GHz BW) to achieve a timing resolution of σ ≈ 32 ps, provided that its noise performance is good, and the amplifier is fast enough to follow fast pulses from the MCP-PMT. For example, a combination of two Elantek chips with an overall voltage gain of 130 × with a rise time of ~1.5 ns is too slow for this type of tube, although such speed is sufficient for MCP-PMT with 25 μm hole diameter—see Table 1 for various examples.

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Table 1: Single photoelectron timing resolution = f (amplifier bandwidth) for 64-pixel MCP-PMT with 10 μm holes, at 2.80 kV, and B = 0 kG

<table>
<thead>
<tr>
<th>Amplifier type</th>
<th>Bandwidth (GHz)</th>
<th>Total voltage gain</th>
<th>Vp noise/signal (mV)</th>
<th>CFD type</th>
<th>Resolution σnarrow (ps)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ortec VT120A + 6 dB att.</td>
<td>~0.4</td>
<td>100 ×</td>
<td>~1/450</td>
<td>Phillips 715</td>
<td>32, 100</td>
<td>The best result</td>
</tr>
<tr>
<td>Hamamatsu C5594-44</td>
<td>1.5</td>
<td>63 ×</td>
<td>1–2/450</td>
<td>Phillips 715</td>
<td>32, 135</td>
<td>Very good</td>
</tr>
<tr>
<td>Ortec 9306</td>
<td>1.0</td>
<td>100 ×</td>
<td>~8/400</td>
<td>Ortec 9307</td>
<td>43, 134</td>
<td></td>
</tr>
<tr>
<td>Tandem of 2 THS-4303</td>
<td>~0.5</td>
<td>30–40 ×</td>
<td>~8/200</td>
<td>Phillips 715</td>
<td>47, 120</td>
<td>Fast, but bad S/N</td>
</tr>
<tr>
<td>Tandem of 2 Elantek-2075</td>
<td>~0.2</td>
<td>130 ×</td>
<td>~10/50</td>
<td>Phillips 715</td>
<td>—</td>
<td>Slow, bad S/N</td>
</tr>
</tbody>
</table>

*THS-4303 and Elantek-2075 chips have a bandwidth of 1.5 GHz for a gain of 10 ×.
For comparison, it is interesting to point out that the best result we have achieved in the same setup with a Geiger mode APD (G-APD or SiPMT) was \( \sigma_{\text{narrow}} \approx 38 \, \text{ps} \) and \( \sigma_{\text{wide}} \approx 111 \, \text{ps} \) [4]. This indicates that the new vacuum Burle MCP-PMT competes well with a G-APD performance.

4. Single photoelectron timing resolution at 15 kG

This particular measurement was performed with Burle 4-pixel MCP-PMT 85001-501 P01 with 10\( \mu \)m hole diameter (a different tube than the tube used for the rest of the measurement in this paper). The MCP-PMT was placed in a dipole capable of reaching \( \sim 15 \, \text{kG} \). The magnetic field direction was nominally perpendicular to MCP face, however, this angle could be changed in small steps up to an angle of 15\( ^\circ \). We have achieved the timing resolutions close to \( \sigma \approx 50 \, \text{ps} \) at 2.7 kV (\( \sim 150 \, \text{V} \) lower than allowed maximum voltage, which means we have not reached the best possible resolution limit)—see Fig. 3. The measurement was made using the Ortec VT120A amplifier with a voltage gain of 200 \( \times \) (in this case we did not use a 6 dB att.). Larger amplifier gain was necessary in this case as there is a large MCP gain drop at higher magnetic field (more than a factor of five as one goes from \( B = 0 \) to 15 kG).

We also found that the MCP can be tilted by 3–5\( ^\circ \) (angle between a normal to the MCP face relative to the field axis) with no effect on the pulse height. At 10\( ^\circ \), one observes a factor of two in reduction of the pulse height, i.e., the tube can still be used. However, above 15\( ^\circ \) angle, the pulse height is reduced by a factor of 10.

5. Multi-photoelectron timing resolution

The aim of this measurement was (a) to determine the electronics contribution to the measurements shown in Fig. 2 and (b) to investigate the limit of the MCP-PMT resolution for a larger number of photoelectrons, a region relevant to the TOF counters.

Figs. 4 and 5 show that the limiting resolution is reached for \( N_{\text{pc}} \geq 20 \) photoelectrons, and is \( \sigma \approx 13 \, \text{ps} \) for the Hamamatsu 1.5 GHz BW, and \( \sigma \approx 24 \, \text{ps} \) for the Ortec VT120A \( \sim 0.4 \, \text{GHz BW} \) amplifiers. These results were obtained with a CFD and LeCroy TDC with 25 ps/count. However, our overall best result was without an amplifier and with no CFD, where a pulse from the MCP-PMT went directly to the scope: \( \sigma \approx 9.1 \, \text{ps} \)—see a single point in Fig. 5. This particular result was obtained using a “histogram option” on the digital oscilloscope [9], and after subtracting a scope jitter contribution, determined in a separate run with a pulser [10]. In the “multi-photoelectron domain” the...
speed of the amplifier is clearly crucial. One is tempted to follow a simple explanation: the expected timing resolution with a CFD discriminator is \( \sigma_t \approx \sigma_A/(d\sigma_0/dt)_{t=0} \), where \( \sigma_A \) and \( (d\sigma_0/dt)_{t=0} \) are the noise and the slope measured at the zero-crossing point. Using these formulas we would expect to obtain \( \sigma_t \approx 12\text{ps} \) for the Hamamatsu amplifier, and \( \sigma_t \approx 17\text{ps} \) for the Ortec VT120A amplifier. Because we did not have a fast enough scope to measure the MCP-PMT rise-time directly we cannot estimate the expected resolution for the “no amplifier” case (expected MCP-PMT rise time is \( \approx 200\text{ps} \)). Although the formula seems to work at some level, the reality in the “sub-10\text{ps} resolution domain” is clearly more complicated as resolution is a fine tune of signal-to-noise ratio, detector response, amplifier and CFD bandwidths, amplifier pulse shape uniformity (partial saturation), CFD delay, CFD threshold, amplifier-to-CFD delay, TDC resolution, TDC diff. linearity, wiring impedance, thermal drifts, ground loops, etc.

Although the resolution in Fig. 5 is constant for \( N_{\text{pe}} > 20 \), there is a walk of the mean value even with the CFD discriminator, indicating that the saturated pulse is changing shape with larger input charge; therefore, it would be necessary to either measure a pulse height (ADC), or use a double threshold timing. Further tests will determine the right timing strategy.

Acknowledgment

We would like to thank M. McCulloch for help to prepare various setups.

References

[3] Definition: \( \text{TOP}(\Phi, \theta_c, \lambda) = [L/\psi(\lambda)] k_z(\Phi, \theta_c) \), \( \theta_c \)-Cherenkov angle, \( L \)-distance of light travels in the bar, \( \psi(\lambda) \)-group velocity of light, \( \lambda \)-photon wavelength, and \( k_z(\Phi, \theta_c) \)-2-component of the unit velocity vector.
[9] 1 GHz BW digital oscilloscope Tektronix TDS-5104 with a software option 2A, providing a histogram with a 0.5 ps/bin.