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A high-resolution TOF detector – a possible way to compete with a RICH detector.*

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Abstract – Using two identical 64-pixel Burle/Photonis MCP-PMTs to provide start and stop signals, we have achieved a timing resolution of $\sigma_{\text{Single_detector}} \sim 7.2$ ps for $N_{\text{pe}} \sim 100$ photoelectrons (N_{pe}) with a laser diode providing a 1 mm spot on the MCP window. The limiting resolution achieved was $\sigma_{\text{Single_detector}} \sim 5.0$ ps for $N_{\text{pe}} \sim 250$, for which we estimate the MCP-PMT contribution of $\sigma_{\text{MCP-PMT}} \sim 4.5$ ps. The electronics contribution is estimated as $\sigma_{\text{Electronics}} = 3.42$ ps. These results suggest that an ultra-high resolution TOF detector may become a reality at future experiments one day.

Keywords: Photodetectors, Cherenkov detectors, RICH, TOF

1. Introduction

We present new timing measurements with Burle/Photonis MCP-PMT (micro-channel plate PMT) with 10 μm holes. Our measurements use two identical MCP-PMT and electronics setups, driven from a fiber splitter and operated in a relative start-stop mode (which eliminates drifts in an external laser diode start signal). A similar arrangement was used in the test beam. We have operated both MCP-PMTs at a lower gain ($<10^5$), where the detection is not sensitive to single photoelectrons, but where it has a linear response in the range of $N_{\text{pe}} \sim 30$ -50 photoelectrons. This is a departure from the previous methodology [1], where we operated in single photoelectron mode. This provided good timing resolution already at $N_{\text{pe}} \sim 20$, however, at the expense of worse linearity, aging, rate handling capability, and pulse recovery.

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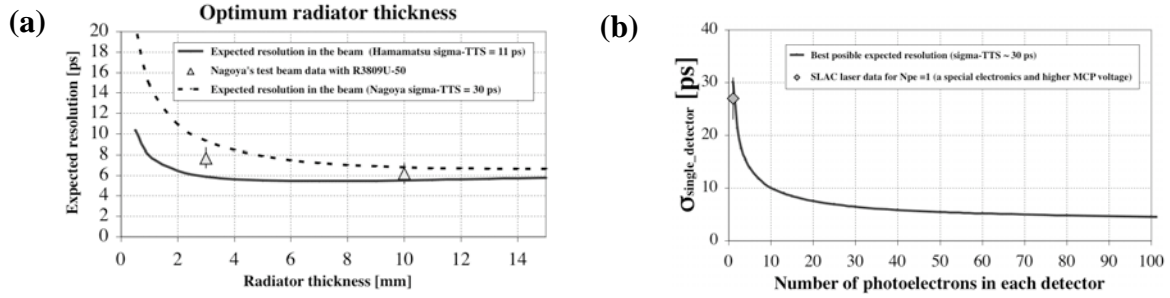


Fig. 1. Expected resolution with a simple model (a) in a beam¹ as a function of radiator thickness, and (b) with a laser² as a function of number of photoelectrons. The calculation assumes measured numbers of $\sigma_{TTS} \sim 27$ ps for our laser test [1], and $\sigma_{TTS} \sim 11$ ps³ or $\sigma_{TTS} \sim 30$ ps⁴ for Nagoya beam test [2].

Fig. 1 shows the expected resolution in the beam and with a laser. These are simple estimates, which neglect intricacies of pulse shaping, constant-fraction (CFD) timing, photoelectron creation and transport, MCP multiplication, etc.

The presented TOF detector is being considered as one possible option for a Super-B PID detector [3] in the forward/backward regions. For that application, all 64 pads need to be instrumented, the detector must work at 16 kG, its radiator would be a 7-10 mm thick MCP-PMT's window, and its electronics would be based either on a similar concept as presented, or a waveform digitization.

Generally, a TOF-based PID is competitive with a RICH PID, if one can obtain $\sigma_{TOF} \sim 5-10$ ps (for an Aerogel RICH with $n \sim 1.03$), or $\sigma_{TOF} \sim 15-20$ ps (for a DIRC-like RICH with $n \sim 1.47$), and one has at least 2 m of TOF path [3]. There is no practical way to compete with a gaseous RICH at higher momenta [4].

1. Experimental setup.

Fig. 2 shows the MCP-PMT enclosure with a Fused silica radiator (10 mm dia., 10 mm long) and the fiber optics. MCP-PMT has 64 pads; four pads under the radiator were shorted together and connected to an amplifier. The rest of the pads were shorted to ground. The laser diode optics produced a 1 mm spot on the MCP face, while the ESA test beam had a spot size of $\sigma \sim 1-2$ mm. Two identical MCP-PMT detectors were prepared, both having 10 μm dia. holes⁵. Electronics⁶ of this test and its pulser⁷ calibration are shown on Fig. 3. The laser light was split in a fiber splitter.

¹ **Beam:** $\sigma \sim \sqrt{[\sigma_{MCP-PMT}^2 + \sigma_{Radiator}^2 + \sigma_{Pad}^2 + \sigma_{Electronics}^2] \sim \sqrt{[(\sigma_{TTS}/\sqrt{N_{pe}})^2 + ((L/\cos\Theta_c)/(300\text{mm/ps})/n_{group})/\sqrt{(12N_{pe})^2} + (L_{pad}/300\text{mm/ps})/\sqrt{(12N_{pe})^2} + (3.42 \text{ ps})^2]}$, where L is a radiator length, L_{pad} is a pixel size, N_{pe} is a number of photoelectrons, and n_{group} is a group refraction index.

² **Laser:** $\sigma \sim \sqrt{[\sigma_{MCP-PMT}^2 + \sigma_{Laser}^2 + \sigma_{Electronics}^2] \sim \sqrt{[\sigma_{TTS}/\sqrt{N_{pe}}]^2 + \sqrt{((FWHM/2.35)/\sqrt{N_{pe}})^2 + (3.42 \text{ ps})^2}] \sim \sqrt{[3.8^2 + 1.8^2 + 3.42^2]} \sim 5.4$ ps for $N_{pe} = 50$ photoelectrons;

PiLas laser diode is made by Advanced Laser Diode Systems, D-12489 Berlin, Germany.

³ Hamamatsu data sheet info for R3809U-50 tube: $\sigma_{TTS} \sim 11$ ps

⁴ Nagoya people measured for R3809U-50 tube: $\sigma_{TTS} \sim 30$ ps.

⁵ Two Burle/Photonis MCP-PMTs, S/N: 11180401 & 7300714.

⁶ Electronics: Ortec TAC 588, CFD 9327, 14 bit ADC 114.

⁷ 200MHz pulser with one start & multiple equally spaced random stops, made by Impeccable instruments, LLC, Knoxville, Tn., USA, www.ImpeccableInstruments.com.

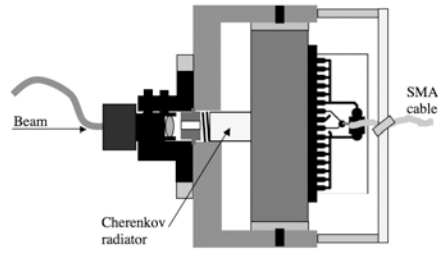


Fig. 2. Two identical detector setups were built to allow a relative start-stop measurement using either a laser or a beam (in the beam we remove the fiber to reduce the mass).

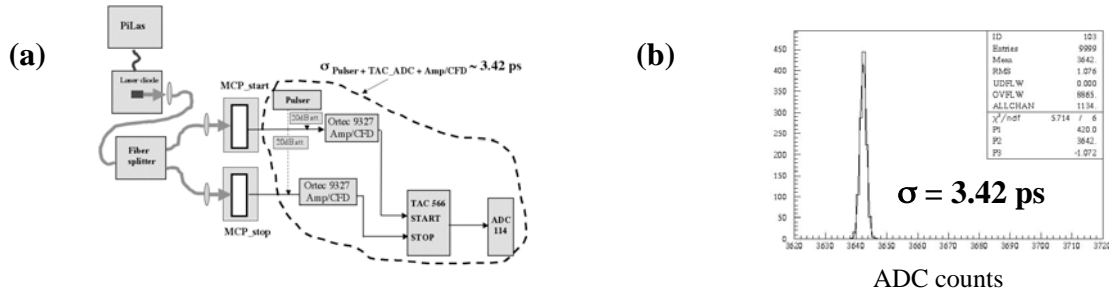


Fig. 3. (a) Electronics⁶ that was used for laser or beam tests, and its calibration scheme (b) Calibration results: $\sigma_{\text{Electronics}} = 3.42$ ps, to which the pulser⁷ contributed $\sigma_{\text{Pulser}} < 2$ ps (3.19 ps/count).

1. Experimental results with a laser diode

Fig. 4 shows the time resolution obtained with a laser diode⁸ with a fiber splitter and a tandem of two identical detectors, and each having a signal of $N_{pe} \sim 100$ photoelectrons, providing start & stop TAC signals (the circuit is shown in Fig. 3a). The single detector resolution is obtained by dividing the measured resolution by $\sqrt{2}$, resulting in $\sigma_{\text{Single_detector}} = \sigma/\sqrt{2} \sim 7.2$ ps. Fig. 5 shows this resolution as a function of number of photoelectrons N_{pe} for the CFD arming thresholds of -10 mV, the CFD walk (zero-crossing) threshold of $+5$ mV and MCP-PMT voltages of 2.28 & 2.0 kV respectively, and compares it with a prediction.² This prediction² agrees well with the data if we assume $\sigma_{\text{TTS}} \sim 110$ ps, which is close to our measured number of $\sigma \sim 106$ ps for $N_{pe} \sim 2-3$. Such a large value of σ_{TTS} is consistent with our choice of being linear for signals of $N_{pe} \sim 30-50$, for which we measure $\sigma \sim 19$ ps, according to Fig. 5.

The limiting resolution at large $N_{pe} \sim 250$ (a large number for most of the applications) is found to be $\sigma_{\text{Single_detector}} \sim 5.0$ ps. We estimate the MCP-PMT contribution to this result is $\sigma_{\text{MCP-PMT}} < 4.5$ ps.⁹

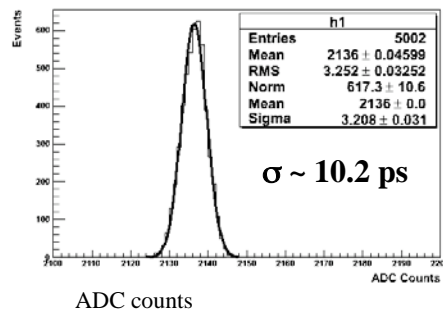


Fig. 4 Time resolution ($T_{\text{start}} - T_{\text{stop}}$) obtained with a laser diode for $N_{pe} \sim 100$ (3.19 ps/count and $\sigma_{\text{single_detector}} \sim \sigma/\sqrt{2} \sim 7.2$ ps).

⁸ PiLas laser diode, 635 nm, FWHM light spread ~ 30 ps.

⁹ MCP-PMT contribution to resolution: $\sigma_{\text{MCP-PMT}} < \sqrt{1/2 \{ \sigma^2 - [\sigma_{\text{Electronics}}^2 - \sigma_{\text{Pulser}}^2] \}} < 4.5$ ps, where $\sigma \sim 7.0$ ps, $\sigma_{\text{Pulser}} \sim 2$ ps, and $\sigma_{\text{Electronics}} = 3.42$ ps, $\sigma_{\text{Single_detector}} = 7.0$ ps/ $\sqrt{2} = 5.0$ ps.

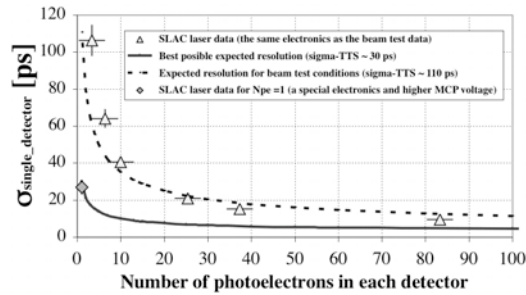


Fig. 5 Measured timing resolution as a function of number of photoelectrons (N_{pe}) for (a) the electronics intended for the beam test⁶ (not sensitive to single $N_{pe} = 1$, but linear for $N_{pe} = 30-50$), and (b) the electronics sensitive to single pe [1]. Dashed curve assumes¹ $\sigma_{TTS} \sim 110$, solid curve assumes² $\sigma_{TTS} = 27ps$.

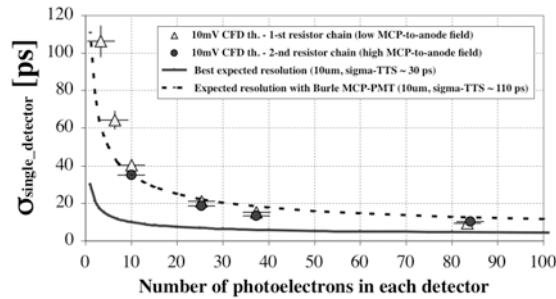


Fig. 6 Timing resolution as a function of number of photoelectrons (N_{pe}) for two resistor chains, providing two MCP-to-anode electric fields: $\sim 400V/cm$ and $\sim 940V/cm$. The theoretical curves are the same as in Fig.5.

We tried to improve the resolution by reducing the MCP rise time. This can be done, for example, by doubling the MCP-to-anode electric field [5] by modifying the MCP resistor chain.¹⁰ Fig. 6 shows that the results are slightly better at higher electric field.

For a red laser and Bialkali photocathode, the emitted photoelectrons are practically at rest and the MCP rise time does not change as a function of the cathode-to-MCP electric field [5]; therefore we did not vary this field.

For any timing method there is some time-walk when one varies the number of photoelectrons (N_{pe}) [6], and this effect has to be corrected off-line to achieve the best possible timing resolution. The amplitude correction is not entirely easy, as the MCP pulses are very fast. Fig. 7 shows the time-walk for the measurements shown in Fig. 6 using Ortec 9327 CFD; it is small for $20 \leq N_{pe} \leq 50$, and it is also smaller for the 2nd resistor chain, which means the time-walk is smaller for smaller MCP rise time.

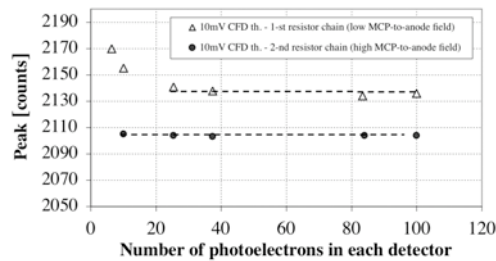


Fig. 7 CFD time-walk as one varies the number of photoelectrons in the measurements in Fig. 6 (3.19 ps/count).

¹⁰ Another example: smaller MCP hole dia., smaller rise time [6].

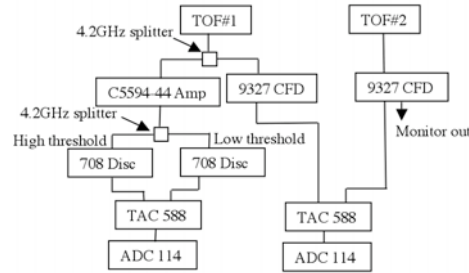


Fig. 8 Schematic of the circuit added to the TOF1 counter, based on Ortec electronics,⁶ which is capable of correcting the pulse height variation.

To see if we can improve the above results further by additional pulse height correction, especially for small N_{pe} values, we have added double-threshold timing into the circuit - see Fig. 8. Although one can nicely correct the pulse height variation using this method, in the final analysis, the results are not better compared to the method using the circuit on Fig.3, which indicates that the CFD timing handles a small level of pulse height variation rather well.

1. Lessons from the test beam

We have tested the tandem of two detectors in a 10 GeV/c electron test beam at SLAC. The best expected N_{pe} is $\sim 30-40$ from a 10 mm-long quartz radiator and the Burle Bialkali photocathode data for our two tubes. In addition, the aluminium coating of the quartz rods was as not uniform. As can be seen in Fig. 7, time-walk correction is necessary for $N_{pe} < 20$. There was no external pulse height measurement implemented in this particular beam test to correct the time-walk. During the test we used the 1st resistor chain (triangles in Fig. 7). If we had used the 2nd resistor chain the time-walk would be smaller. In addition to the time-walk contribution, the expected resolution is worse for smaller N_{pe} - see Figs. 5 and 6. As a result of these contributions, our initial test beam result resulted only in $\sigma_{\text{Single_detector}} \sim 23$ ps.¹¹

Possible ways to improve the result in future are: (a) implement a pulse height measurement on fast MCP-PMT pulses, (b) ensure that $N_{pe} > 25$, (c) run with highest possible MCP-to-cathode and anode-to-MCP electric fields, (d) small MCP-to-cathode and anode-to-MCP gaps, and (e) have smallest possible MCP holes, or (f) for some low rate applications use timing method described in Ref.1.

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¹¹ We plan to provide a full account of our beam tests in future publication.

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