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

## 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 by 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 $N_{\mathrm{pe}}{\sim}30$–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 $N_{\mathrm{pe}}{\sim}20$, however, at the expense of worse linearity, aging, rate handling capability, and pulse recovery.

Fig. 1 shows the expected resolution in the beam[2] and with a laser[3]. These are simple estimates, which neglect intricacies of pulse shaping, constant-fraction (CFD) timing, photoelectron creation and transport, MCP multiplication, etc.[4,5]

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 $\sigma_{\mathrm{TOF}}{\sim}5$–10 ps (for an Aerogel RICH with $n{\sim}1.03$), or $\sigma_{\mathrm{TOF}}{\sim}15$–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].

## 2. Experimental setup

Fig. 2 shows the MCP-PMT enclosure with a fused silica radiator (10 mm diameter, 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 diameter holes[6]. Electronics[7] of this test and its pulser[8] calibration are shown in Fig. 3. The laser light was split in a fiber splitter.

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

[3] Laser: $\sigma{\sim}\surd[\sigma^2_{\mathrm{MCP\text{-}PMT}}+\sigma^2_{\mathrm{Laser}}+\sigma^2_{\mathrm{Electronics}}]{\sim}\surd[(\sigma_{\mathrm{TTS}}/\surd N_{\mathrm{pe}})^2+\surd((\mathrm{FWHM}/2.35)/\surd N_{\mathrm{pe}})^2+(3.42\,\mathrm{ps})^2]{\sim}\surd[3.8^2+1.8^2+3.42^2]{\sim}5.4$ ps for $N_{\mathrm{pe}} = 50$ photoelectrons; PiLas laser diode is made by Advanced Laser Diode Systems, D-12489 Berlin, Germany.

[4] Hamamatsu data sheet info for R3809U-50 tube: $\sigma_{\mathrm{TTS}}{\sim}11$ ps.

[5] Nagoya people measured for R3809U-50 tube: $\sigma\mathrm{TTS}{\sim}30$ ps.

[6] Two Burle/Photonis MCP-PMTs, S/N: 11180401 and 7300714.

[7] Electronics: Ortec TAC 588, CFD 9327, 14 bit ADC 114.

[8] 200 MHz pulser with one start and multiple equally spaced random stops, made by Impeccable instruments, LLC, Knoxville, TN, USA, www.ImpeccableInstruments.com.

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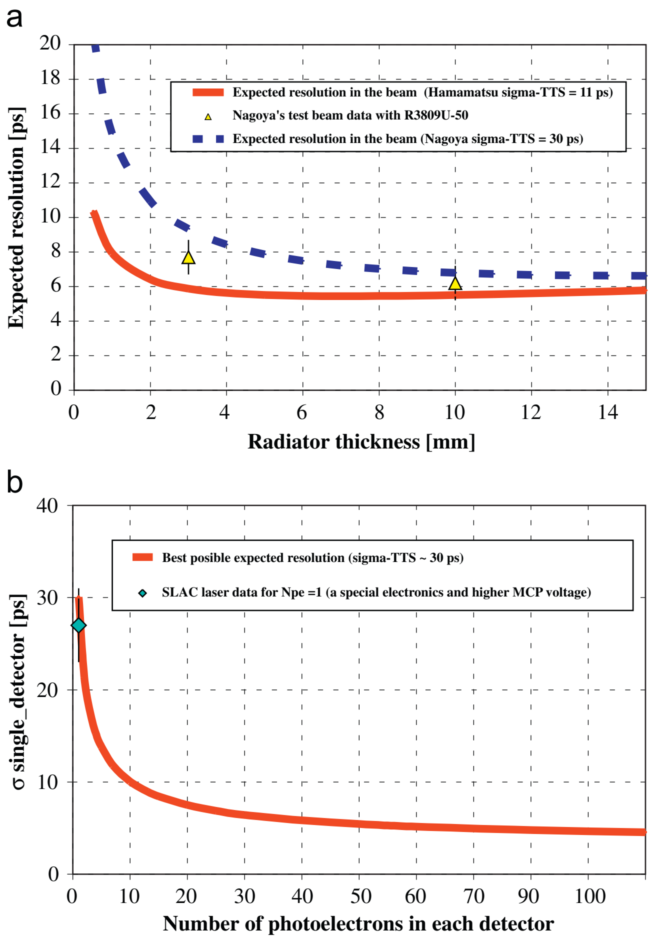

**Fig. 1.** Expected resolution with a simple model (a) in a beam as a function of radiator thickness, and (b) with a laser as a function of number of photoelectrons. The calculation assumes measured numbers of $\sigma_{\text{TTS}}$~27 ps for our laser test [1], and $\sigma_{\text{TTS}}$~11 ps or $\sigma_{\text{TTS}}$~30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

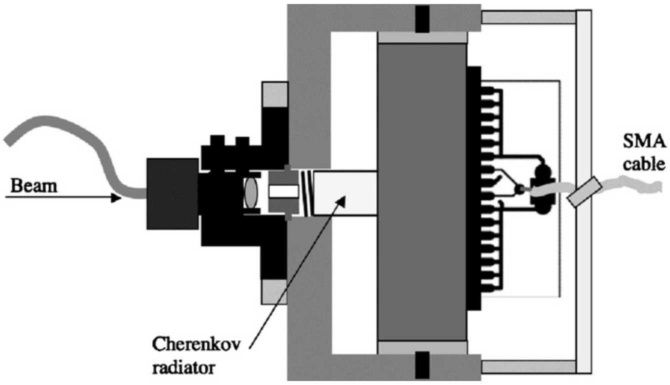

**Fig. 2.** Two identical detector setups were built to allow a relative start–stop measurement using either a laser or a beam (in the beam we remove the fiber to reduce the mass).

## 3. Experimental results with a laser diode

Fig. 4 shows the time resolution obtained with a laser diode[9] with a fiber splitter and a tandem of two identical detectors, and each having a signal of $N_{\text{pe}}$~100 photoelectrons, providing start and 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 $N_{\text{pe}}$ for the CFD arming thresholds of −10 mV, the CFD walk (zero-crossing) threshold of +5 mV and MCP-PMT voltages of 2.28 and 2.0 kV, respectively, and compares it with a prediction. (see foot note 3) This prediction (see foot note 3) agrees well with the data if we assume $\sigma_{\text{TTS}}$~110 ps, which is close to our measured number of $\sigma$~106 ps for $N_{\text{pe}}$~2–3. Such a large value of $\sigma_{\text{TTS}}$ is consistent with our choice of being linear for signals of $N_{\text{pe}}$~30–50, for which we measure $\sigma$~19 ps, according to Fig. 5.

The limiting resolution at large $N_{\text{pe}}$~250 (a large number for most of the applications) is found to be $\sigma_{\text{Single\_detector}}$~5.0 ps. We estimate the MCP-PMT contribution to this result as $\sigma_{\text{MCP-PMT}} < 4.5$ ps.[10]

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.[11] 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 ($N_{\text{pe}}$) [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 $20 \leqslant N_{\text{pe}} \leqslant 50$, and it is also smaller for the second resistor chain, which means the time-walk is smaller for smaller MCP rise time.

To see if we can improve the above results further by additional pulse-height correction, especially for small $N_{\text{pe}}$ 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.

## 4. 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 $N_{\text{pe}}$ is ~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 not uniform. As can be seen in Fig. 7, time-walk correction is necessary for $N_{\text{pe}} < 20$. 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 $N_{\text{pe}}$—see Figs. 5 and 6. As a result of these contributions, our initial test beam result resulted only in $\sigma_{\text{Single\_detector}}$~23 ps.[12]

Possible ways to improve the result in future are: (a) implement a pulse-height measurement on fast MCP-PMT pulses, (b) ensure that $N_{\text{pe}} > 25$, (c) run with highest possible MCP-to-cathode and anode-to-MCP electric fields, (d) small

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[9] PiLas laser diode, 635 nm, FWHM light spread ~30 ps.

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

[11] Another example: smaller MCP hole diameter, smaller rise time [6].

[12] We plan to provide a full account of our beam tests in future publication.