Nucl. Instr. &
Methods

The Focusing DIRC – the first RICH detector to correct the chromatic error by timing, and the development of a new TOF detector concept

J. Va'vra*, J. Benitez, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, and K. Suzuki

*SLAC, Stanford University, CA 94309, U.S.A.***

We have built and successfully tested a novel particle identification detector called Focusing DIRC. The prototype's concept is based on the BaBar DIRC with several important improvements: (a) much faster pixilated photon detectors based on Burle MCP-PMT and Hamamatsu MaPMT, (b) mirror allowing to make the photon detector smaller and less sensitive to background in future applications, (c) electronics allowing to measure the single photon resolution to better than σ ≈100-200ps, which allows a correction of the chromatic error. While testing the timing resolution limits of a 64-pixel MCP-PMT with 10 μm MCP holes, we have achieved a timing resolution of σ ≈30ps with single photoelectrons. In this paper we further investigate limits of the timing resolution with this particular detector.

Keywors: Photodetectors, Cherenkov detectors, RICH, TOF

* Corresponding author. Tel.: 650-926-2658; fax: 650-926-4178; e-mail: jjv@slac.stanford.edu.
** Work supported by the Department of Energy, contract DEAC02-76SF00515.

1. Introduction

The DIRC detector at the BaBar experiment provides excellent particle identification performance [1,2]. Based on this success, our group has been following an R&D program to develop an appropriate photon detector for future particle identification systems. One such idea, a focusing DIRC [3-5], would be capable not only of measuring an (x,y) coordinate for each photon with an angular resolution similar to the present BaBar DIRC, but, in addition, measuring each photon's time-of-propagation (TOP[1]) along the Fused Silica bar with ~100-200 ps single-photoelectron timing resolution or better (the present BaBar DIRC has a timing resolution of only $\sigma \approx 1.6$ ns). This precise timing allows a measurement of the Cherenkov angle, with a precision similar to that provided by the direct angular measurement. Small pixel size would allow a design of a photon detector expansion volume up a factor 10 smaller than the existing BaBar DIRC. Smaller geometrical size together with better timing will allow the suppression of the background by more than one order of magnitude; in addition, better timing will allow a correction of the chromatic error and thus improve the angle measurement substantially. The focusing element also removes the bar thickness as a term that contributes to resolution smearing. Such a device could be important for a future Super B-factory, and could also be useful in an ILC detector, especially one like SiD without a gaseous tracking detector allowing PID capability.

We have built the first prototype of a focusing DIRC and had two successful test beam runs with it. In these runs, we established that (a) the new photon detectors work as expected, based on our bench tests; (b) we can achieve similar Cherenkov angle resolution as the BaBar DIRC with much more compact and faster detectors; (c) we can achieve single-photon timing resolution at a level of 100-200 ps; (d) we can clearly observe the expected chromatic dispersion on a photon by photon basis; and finally, (e), we can correct the chromatic error through this timing measurement. In addition we have developed software analysis packages and a Geant 4 Monte Carlo simulation of the prototype.

We have also investigated a timing resolution limit of the large size Burle/Photonis MCP-PMT with 10 μm holes. Reference [6] shows our single-photoelectron measurement of $\sigma \approx 32 \pm 0.6$ ps. One should point out that this number includes a resolution contribution of the lased diode ($\sigma \approx 15$ ps for $N_{pe}=1$), and of the electronics used at that time ($\sigma \approx 11$ ps), which means that the MCP-PMT transit-time-spread σ_{TTS} is actually approaching a likely limit of $\sigma \approx 25$ ps. A TOF detector with a 1cm Fused silica radiator is expected to have ~50 photoelectrons with Burle/Photonis Bialkali photocathode. One would then expect that one could reach a TOF resolution of $\sigma \approx$ 4-5 ps if one would further improve the electronics resolution, at least in principle. However, until now, we have reached a limit of about $\sigma \approx 12$ ps for $N_{pe} \approx 50$, i.e., still higher than the expected ultimate limit. We discuss various limiting factors.

2. Description of the Focusing DIRC prototype

Figure 1 shows the concept and practical realization of the Focusing DIRC prototype. This prototype has a single DIRC bar of ~3.6 meters length (1.7 cm thick and 3.5 cm wide), a focusing element made of a 50 cm focal length spherical mirror placed in a small optical box filled with a mineral oil[2], which is the coupling medium between the bar and six 64-pixel photon detectors, which include four Burle MCP-PMTs and two Hamamatsu Flat-panel MaPMTs. The detailed studies of these photon detectors are described in detail in our three previous publications [3-5]. The system is instrumented with ~300 channels of electronics. We have developed fast amplifiers based on a pair of two Elantek 2075 chips producing a voltage gain of 130x with a ~1.5 ns rise time. The constant-fraction discriminators (CFD) are coupled to Philips TDC 7186, providing 25 ps/count. Fig. 1a shows how the prototype's spherical mirror is designed to remove

[1] Definition: TOP(Φ, θ_c, □) = $[L/v_g(\lambda)]\, q_z(\Phi,\theta_c)$, θ_c - Cherenkov angle, L - distance of light travels in the bar, $v_g(\lambda)$ - group velocity of light, λ - photon wavelength, and $q_z(\Phi,\theta_c)$ – z-component of the unit velocity vector.

[2] KamLand experiment mineral oil: BC-599-14, made by BICRON.

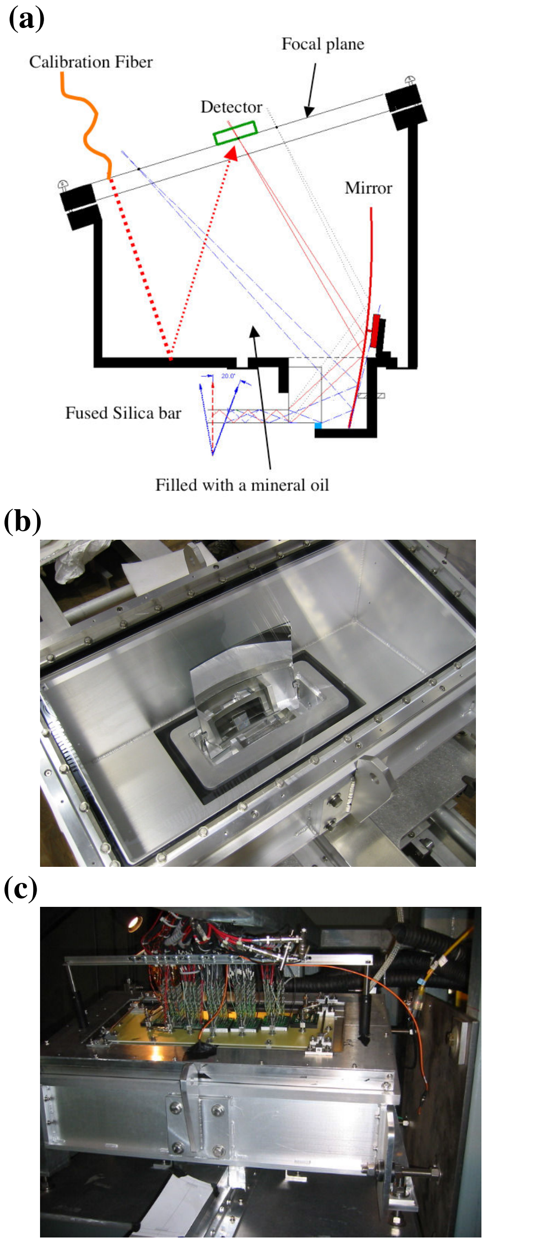


Fig. 1. (a) Principle of the Focusing DIRC prototype. (b) Optical box, filled with mineral oil, shows a spherical mirror, and a 3.6 m-long bar atteched to it. (c) Electronics and photon detectors located on the focal plane.

the effect of bar thickness on the resolution. One should add that the prototype was designed to study the chromatic effects in the beam, and no effort was made to optimize it for any real application as a particle identification device. Fig. 1a also shows schematically a calibration system for the detectors using PiLas laser diode[3].

3. Experimental results in the test beam

We used a 10 GeV/c secondary electron beam at the SLAC ESA test beam facility. The beam flux was less than 0.1-0.2 particles per pulse with a repetition rate of 10Hz typically. The beam spot is a few mm and the beam divergence is less than ~0.2mrad. The beam spot was monitored in front of the bar with a fiber hodoscope made of 2x2mm^2 scintillation square fibers, which were read out by two 4x4 Hamamatsu R5900-L16 MaPMTs coupled to LeCroy ADC 2249A. The system START time, which was used to start all TDCs in the system, was derived from the Linac RF pulse, which is the best possible method; in addition, we had two local start counters available for possible corrections of the thermal effects. The local start counters were either a fused silica double radiator (each 1.7cm thick, and rotated by ~47^o relative to the beam direction), or a 10cm thick BC-408 scintillator, both coupled to the Burle four-pad MCP-PMT, each pad coupled to the leading edge discriminator Phillips 706 with a 10mV threshold, Phillips TDC 7186 and LeCroy ADC 2249 to correct time for the pulse height variation. The timing resolution of the local start time was about $\sigma \approx$35ps when averaged over all participating pads and two start counters. We used the lead glass block read out by the LeCroy ADC 2249 to reject a slight π^- contamination or the multiple electrons in the beam. The "good event" required a single electron hit in the lead glass and the fiber hodoscope.

The prototype was placed on a traversing table allowing easy movement of the bar to seven positions along its 3.6 m length. The total weight of the prototype was ~600 lb, the total weight of the support structure was ~1500 lb, i.e., a non-trivial mechanical challenge. The bar was aligned with a help of a laser to be perpendicular to the beam within less than ~1 mrad for all positions along the bar. The position of

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

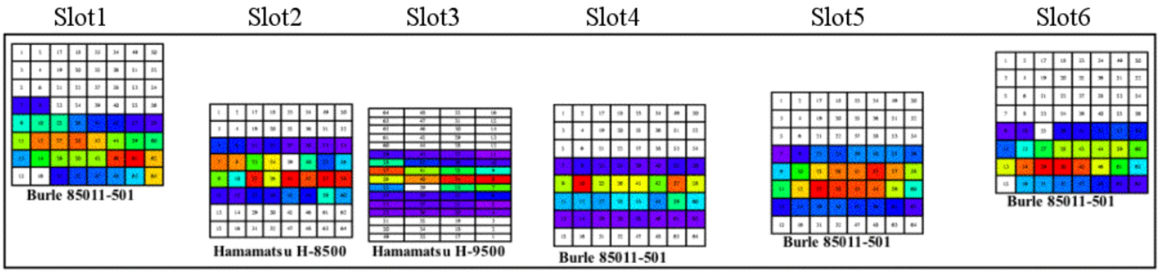


Fig. 2. Cherenkov ring measured in pixel domain. Slot 3 has the Hamamatsu MaPMT H-9500 where small pixels were interconnected into larger pads of 2.8x11.2mm^2 in size to provide finer sampling of the Cherenkov angle.

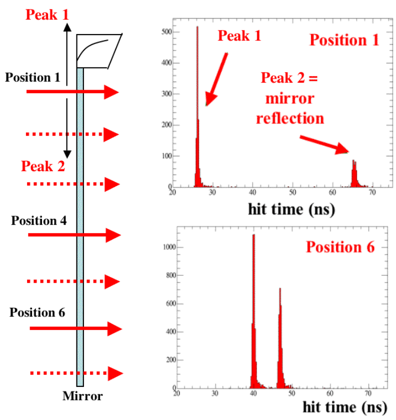
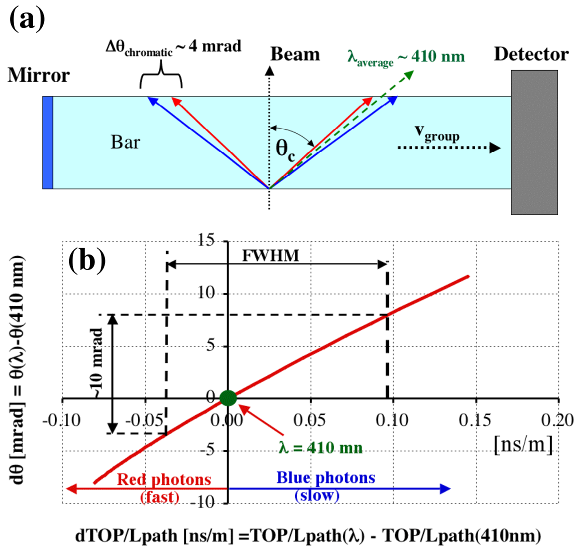


Fig. 3. Cherenkov ring measured in the time domain for different positions along the bar. The bar has a mirror at the far end to reflect indirect photons. The beam enters the bar perpendicularly.

the bar along its length relative to the beam, and its repeatability, was known to ~1 mm.

The Cherenkov angle can be displayed either in the pixel domain (Fig.2), or in the time domain (Fig.3).



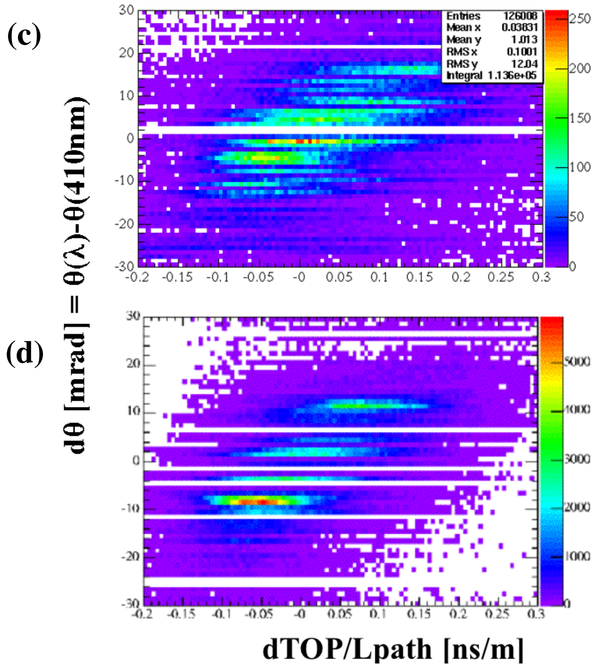


Fig. 4. (a) A schematic diagram of the Cherenkov angle production for warious wavelengths. (b) A correlation between a change in the Cherenkov angle as a function of a change in TOP/Lpath, where the change is taken relative to their respective values evaluated at the most probable wavelength of 410 nm determined by the Focusing DIRC prototype efficiency. (c) The same correlation as in (b) shown for the data from the prototype. (d) The Geant 4 MC simulation.

The radiator refraction index is a function of wavelength. This leads to dispersion in the Cherenkov angle, the red photons corresponding to smaller angles compared to blue photons - Fig. 4a. Based on our efficiencies, we expect the chromatic smearing to be 3-4mrad, with a most probable wavelength of $\lambda \approx$410nm. While the red photons have a small path handicap from the production point to the detector, their group velocity is larger ($v_{group}(\lambda) = c_0 / n_{group} = c_0 / [n_{phase} - \lambda * dn_{phase}/d\lambda]$), so they arrive at the detector before the blue photons, resulting in an easily measured time dispersion of up to a few ns over the full range of Lpath. The final time difference can be well measured already after photon path lengths of a few meters, and therefore the color dispersion at the Cherenkov angle production point can be corrected by time once the path lengths is sufficiently long. The Focusing DIRC prototype is the first RICH detector ever achieving this capability, thanks to its excellent time resolution of the photon detectors. There are various ways to parameterize the chromatic effect. We choose a parameterization as a function of TOP/Lpath variable because of its direct relationship to a quantity which is actually measured: time.

Fig.4b shows the chromatic behavior of the Focusing DIRC prototype in terms of a correlation between a change in the Cherenkov angle as a function of a change in TOP/Lpath = $1/v_{group}(\lambda)$, where the change is taken relative to their respective values evaluated at the most probable wavelength of 410 nm determined by the Focusing DIRC prototype efficiency; in other words, if a photon has an average wavelength of 410 nm, there is no chromatic correction. The shape of the curve in Fig. 4b is driven by the refraction index dependence on the wavelength and is evaluated for β =1, which is the case for our test beam. There is a family of similar curves for different β. Our calculated probability distribution as a function of dTOP/Lpath variable indicates a FWHM range of ~140 ps/m. From here we conclude that the expected FWHM range of the Cherenkov angle correction is about ~10 mrads (Fig. 4b). Fig. 4c shows the same correlation in our data for a bar position 1 and using the indirect photons, which in this particular case travel over a long average distance of Lpath ≈10 m. Fig. 4d shows a full Geant 4 MC simulation.

We were analyzed several methods how to apply the chromatic correction: (a) an analytical chromatic correction – see Fig. 4b, (b) an empirical method relying on the data – see Fig. 4c, (c) the Geant 4 Monte Carlo method with a pixelization – see Fig. 4d, and (d) maximum likelihood method. For a real PID in a real detector, we will have to use a likelihood-based method to handle the corrections properly; in this paper we will show results of this method, because it performed best in the region Lpath < 3m; above this photon path length limit all other methods gave identical results.

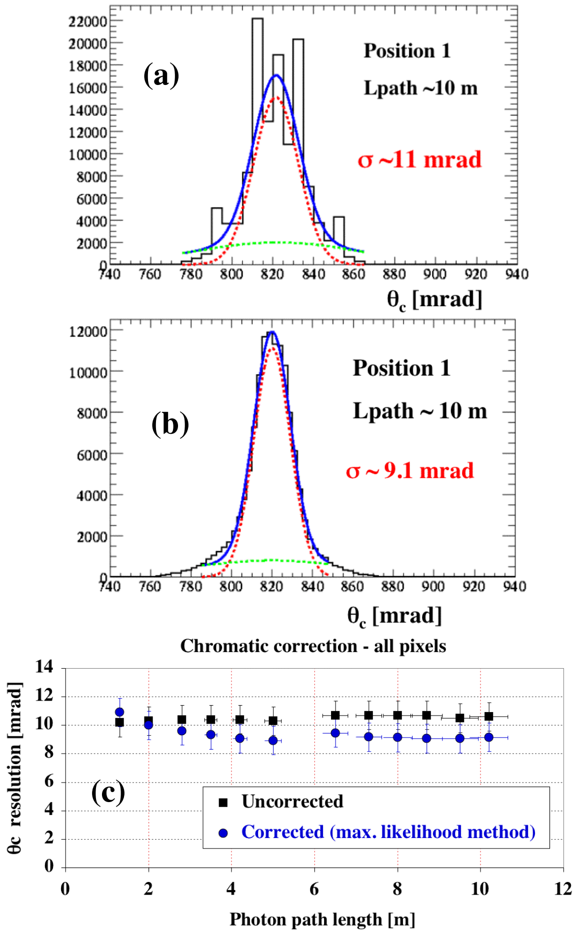


Fig. 5. Measured Cherenkov angle resolution using all pixels for position 1 and for the indirect photons: (a) without the chromatic correction, (b) the same but corrected for the chromatic error by timing, and (c) both as a function of photon path (Lpath).

Figures 5a,b,c show the measured Cherenkov angle resolution using all pixels in the prototype, with and without the chromatic error correction by timing. One can see that the time-based chromatic correction seems to improve the resolution by 1-2 mrads and starts working for Lpath ≥2-3 meters. For shorter path lengths we would need better time resolution. The observed improvement of ~1-2 mrads in the total Cherenkov angular error of over 10 mrad is more than we expect based our estimate of the chromatic error contribution alone, which is 3-4 mrad. We have a special condition in this particular beam test due the beam divergence being small, which creates a non-uniform illumination of the pixels by Cherenkov photons, which creates an additional discrete pixilization effect; this would not be present in real experiment where there is sufficient smearing of incident angles. Figures 6a,b,c show the same for the small pixels only for 2.8mmx12mm pixels in the slot 3. We obtain clearly much better resolution with smaller pixel sizes. Again, for the correction to work at shorter path lengths we would need better timing resolution. Both data and the MC simulation points show a preliminary systematic error of ~1 mrad.

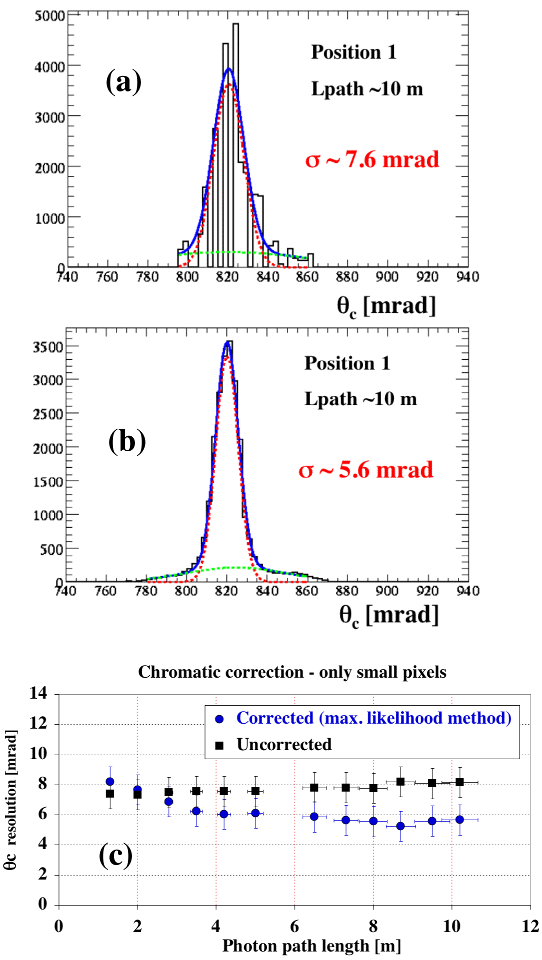


Fig. 6. Measured Cherenkov angle resolution using 3 mm pixels only for position 1 and for the indirect photons: (a) without the chromatic correction, (b) the same but corrected for the chromatic error by timing, and (c) both as a function of photon path (Lpath).

Fig. 7 shows a comparison of measured and GEANT 4 simulated Cherenkov angle resolution using pixels without the chromatic correction as a function of photon path Lpath. Main contribution to the Cherenkov angle resolution is (a) chromatic smearion (3-4mrad), (b) pixel size (5.5 mrad for 6 mm pixels), and (c) an optical abberation of the present design with the spherical mirror, which extends from 0 mrad near the ring center to 9 mrad near outer wings [5].[4] In addition we observe a discrete pixilization effect (see earlier discussion).

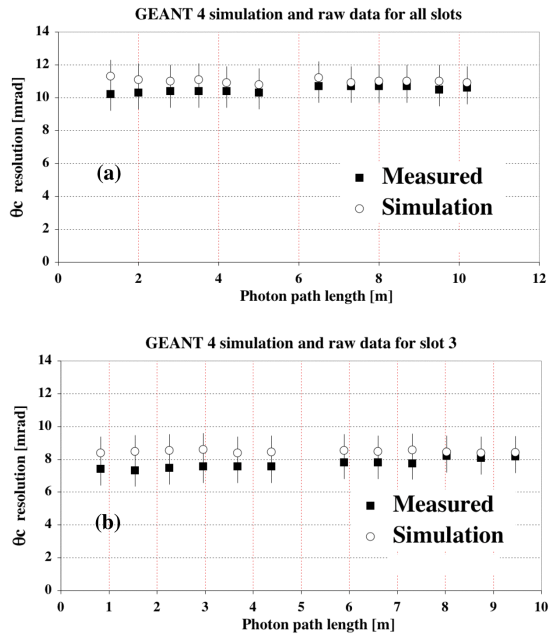


Fig. 7. Comparison of measured and GEANT 4 simulated Cherenkov angle resolution using pixels without the chromatic correction as a function of photon path (Lpath) using (a) all pixels, (b) 3mm pixels only.

We determined the figure of merit of RICH detectors, N_o, using a bar geometry as used in BaBar DIRC, but with new detectors, based on our knowledge of all efficiencies involved. To check this method, we have verified a consistency between measured and calculated number of photoelectrons in slot 4; we then extrapolate the expected performance to a possible final Super B RICH design. Fig. 8 shows expected π/K PID performance of the Focusing DIRC if we use ~3x3mm^2 pixels, which is our prefered choice; one can see that it would exceed

[4] We hope to reduce this effect in future optical designs.

the BaBar DIRC performance. We expect $N_o \approx 31\text{cm}^{-1}$ and $N_{pe} \approx 28$ for 1.7cm thick quartz bar radiator for a Hamamatsu H-9500 MaPMT, and $N_o \approx 20\text{cm}^{-1}$ and $N_{pe} \approx 20$ for Burle/Photonis MCP-PMT. This is to be compared to the present BaBar DIRC performance of $N_o \approx 30\text{cm}^{-1}$ and $N_{pe} \approx 27$.

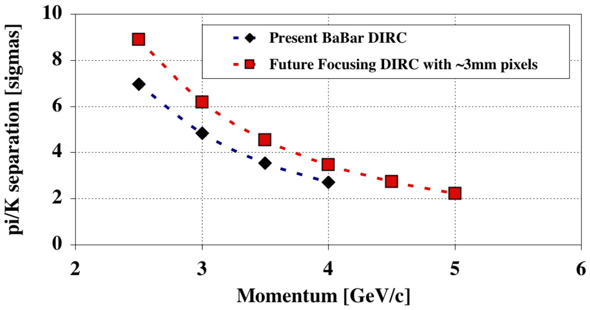


Fig. 8. Expected performance of the Focusing DIRC with 2.8mmx2.8mm pixels of H-9500 MaPMT, compared to BaBar DIRC performance.

4. Timing resolution limit of Burle MCP-PMT

In our previous work, we have measured single photoelectron timing resolution of $\sigma \approx 32 \pm 0.6$ps with the 64-pixel MCP-PMT 85012-501 [6]. One should point out that this number includes a resolution contribution of the laser diode ($\sigma \approx 15$ps for $N_{pe}=1$), and of the electronics used at that time ($\sigma \approx 11$ps), which means that the MCP-PMT transit-time-spread σ_{TTS} is actually approaching a likely limit of $\sigma \approx 25$ps. The tube had 10μm holes, ~6mmx6mm pixel size. The timing resolution study was done on a single pad, illuminated at its center, and connected coaxially to a fast amplifier ~1ns away, while all other pads were grounded; this represents an ideal case. To do this measurement, we used the PiLas 635nm laser diode.

In this paper we describe new measurements with a better electronics,[5] and discuss limits of various timing strategies and MCP-PMT detector in more detail. An example of the experimental setup is shown schematically in Fig. 9.

[5] We have added an Amplifier/CFD 9327 and TAC 566 & 14 bit ADC AD114 made by Ortec Co, Tenn., USA.

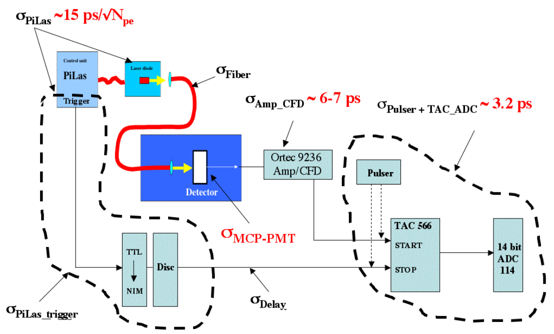


Fig. 9. An example of the timing setup to measure the timing resolution of the Burle/Photonis MCP-PMT.

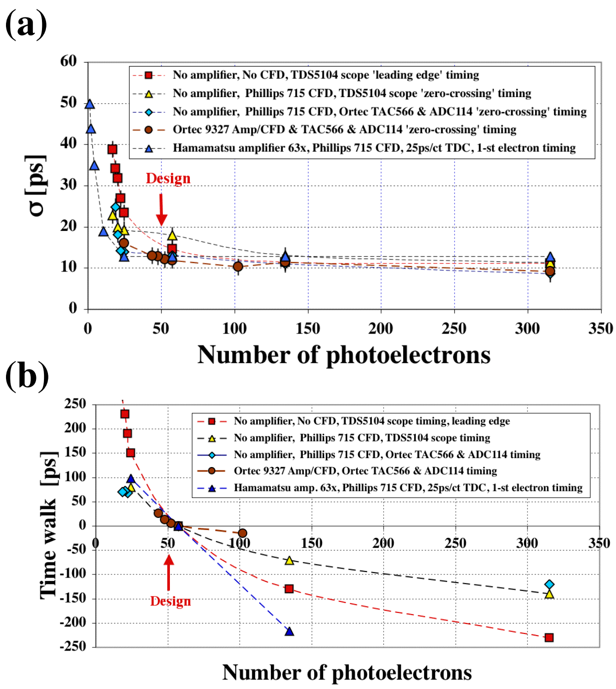


Fig. 10. (a) Timing resolution as a function of number of photoelectrons (N_{pe}) using various methods for Burle MCP-PMT 85001-501 P01 with 10 μm hole diameter. (b) Time walk as a function of N_{pe}.

Figure 10 shows the measured timing resolution as a function of number of photoelectrons N_{pe}. There are several conclusions one could make. First, in the region of interest, i.e., for $N_{pe} \approx 50$ photoelectrons expected from a 1cm quartz radiator, we were not able to achieve a better resolution than $\sigma \approx 12$ps so far, i.e. a factor 3-4 worse than what one would expect from a value based on $\sigma_{TTS}/\sqrt{N_{pe}}$.

We tried several timing strategies: (a) the first single electron timing using a Hamamatsu amplifier C5594-44 and Phillips CFD 715 (tube at 2.8kV), (b) no amplifier, Phillips CFD 715 zero-crossing output to the scope [7] (tube at 2.8kV), (c) no amplifier, Phillips CFD 715 and Ortec TAC588/ADC114 timing (tube at 2.8kV), and (d) Ortec amplifier/CFD 9327 and TAC588/ADC114 method (tube at 2.33kV). One can see that the first electron timing yields a good resolution all the way down to $N_{pe} \approx 20$, however, its has the worst timing-walk compared to other methods using the Ortec 9327 CFD. There is always some time-walk for any timing method, and this effect has to be corrected off-line to achieve the best possible timing resolution. The number of photoelectrons may vary substantially, if for no other reason but the non-uniformity of the photocathode QE, which can be easily 2:1. To do the amplitude correction is not entirely easy as the MCP pulses are too fast for the conventional electronics.

It is useful to investigate what is the timing contribution of the MCP-PMT itself. In the example of Fig.9, the measured resolution is $\sigma \approx \sqrt{\{\sigma^2_{MCP\text{-}PMT} + \sigma^2_{Fiber} + \sigma^2_{Amp\_CFD} + \sigma^2_{Delay} + \sigma^2_{PiLas} + \sigma^2_{Pulser+TAC\_ADC} + \sigma^2_{PiLas\_trigger}\}}$, where $\sigma_{PiLas} \approx 15ps/\sqrt{N_{pe}}$,[6] $\sigma_{Amp\_CFD} \approx$ 6-7ps,[7] and $\sigma_{Pulser+TAC\_ADC} \approx 3.2ps$.[8] To estimate the MCP-PMT limit we set the PiLas laser intensity to $N_{pe} \approx 300$, which minimizes a contribution from $\sigma_{PiLas} \approx 15ps/\sqrt{N_{pe}}$; with that condition, we measured $\sigma \approx 9.2ps$. From here we can estimate $\sigma_{MCP\text{-}PMT} < \sqrt{\{\ \sigma^2 - \sigma^2_{PiLas}\ (N_{pe}) - \sigma^2_{Amp\_CFD} - [\sigma^2_{Pulser+TAC\_ADC} - \sigma^2_{Pulser}\ ]\}} \approx 5.8$ ps.

The MCP-PMT we used in the tests so far has still several imperfections which will influence the timing limit: (a) the MCP-to-Anode gap is ~5mm, which is too large as it contributes to a very large charge spread of 6-7mm (FWHM)[9], which in turn also affects the timing limit substantially ($\sigma \approx$5-6 ps for a fully illuminated 6mm pixel); (b) the AC ground return for each pad is too long. A large size MCP flatness and the photoelectron reflections at the anode may also play a role in future applications. Burle/Photonis is aware of these points and plan to improve them in future versions; therefore our results are just starting points.

[6] σ ~ 15 ps is manufactur's quote, Npe is determined by our test.
[7] σ ~ 6-7 ps is manufactur's quote for Ortec Amp/CFD 7327.
[8] σ ~ 3.2ps is our test result with a pulser, which contributes to Start-Stop timing with σ_{Pulser} =1-2ps [8].
[9] T scanning [4]

Acknowledgments

We would like to thank M. McCulloch for help to prepare various setups. We also appreciate comments of Jeff Peck.[10]

References

[1] I. Adam et al., "Particle Identification System for the BaBar experiment," Nucl. Instr.&Meth., A538(2005)281-357.
[2] B.N. Ratcliff, Nucl. Instr.&Meth., A502(2003)211.
[3] C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher and J. Va'vra, "Development of photon detectors for a fast focusing DIRC," Nucl. Instr.&Meth., A553(2005)96-106.
[4] C. Field, T. Hadig, M. Jain, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, and J. Va'vra, "Novel photon detectors for focusing DIRC prototype," Nucl. Instr.&Meth., A518(2004)565-568.
[5] J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. K. Suzuki, J. Schwiening, J. Uher and J. Va'vra, "Development of a Focusing DIRC," IEEE Nucl.Sci, Conference records, October 29, 2006, and SLAC-PUB-12236, 2006.
[6] J. Va'vra, J.F. Benitez, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff and J. Schwiening, "A 30 ps timing resolution for single photons with multi-pixel Burle MCP-PMT," Nucl. Instr.&Meth., A572(2007)459-462.
[7] 1GHz BW digital oscilloscope Tektronix TDS-5104 with a software option 2A, providing a histogram with a 0.5ps/bin.
[8] 200MHz pulser made by Impeccable instruments, LLC, www.ImpeccableInstruments.com, Knoxville, Tn., USA.

[10] A former Ortec engineer who designed 9327 Amp/CFD unit when with Ortec.