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# Status of the Fast Focusing DIRC (fDIRC)[§]

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**Abstract - We have built and successfully tested a novel particle identification detector concept, the Fast Focusing DIRC (fDIRC). The prototype's concept is based on the BaBar DIRC with several important improvements: (a) much faster pixelated photon detectors based on Burle MCP-PMTs and Hamamatsu MaPMTs, (b) a focusing mirror allowing a smaller photon detector, reducing the sensitivity to backgrounds in future applications, (c) electronics capable of measuring the single photon resolution to better than σ ≈100-200ps. The fDIRC is the first RICH detector to successfully correct the chromatic error by timing.**

Keywords: Photodetectors, Cherenkov detectors, RICH, B Factory, Super Flavor Factory

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## 1. Introduction

The DIRC detector at the BaBar experiment provides excellent particle identification (PID) performance [1]. Based on this success, our group has been following an R&D program to develop a RICH system for PID at future experiments. One such idea, a Fast Focusing DIRC (fDIRC) [2-4], 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) 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. Better timing will therefore allow the correction of the chromatic error and thus improve the angle measurement substantially. A smaller pixel size would allow the design of a photon detector expansion volume up to a factor of 10 smaller than the existing BaBar DIRC[1]. This smaller geometrical size together with better timing will allow the suppression of the background by one to two orders of magnitude. 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 flavor factory, such as SuperB [5], 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 an fDIRC and had three successful test beam runs in 2005, 2006, and 2007. 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 Geant4 [6] Monte Carlo simulation of the prototype. This paper describes the prototype as used in the beam tests in 2006 and 2007. All experimental results presented are based on the 2006 beam test data.

## 2. Description of the fDIRC prototype

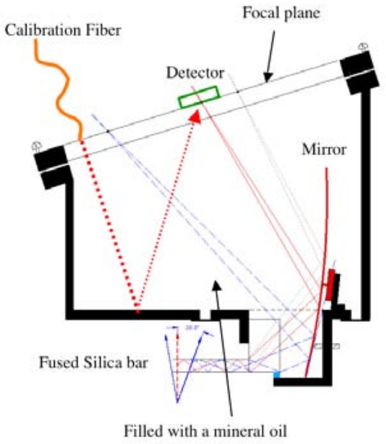

**Fig. 1.** Schematic of the f DIRC prototype.

Figure 1 shows the concept and practical realization of the fDIRC 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 seven 64-pixel photon detectors, which include five Burle MCP-PMTs and two Hamamatsu Flat-panel MaPMTs. These photon detectors are described in detail in our three previous publications [2-4]. The system is instrumented with ~300 channels of electronics. For readout of six of the PMTs we have developed fast amplifiers based on a pair of two

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[1] Neutral particles ($\gamma$,n) interacting in the large water-filled expansion region are the dominant source of background in the BaBar DIRC system, causing typical counting rates of 200 kHz per PMT [1].

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

Elantek 2075 chips producing a voltage gain of 130x with a ~1.5 ns rise time. The amplifiers are connected to constant-fraction discriminators (CFD) which are coupled to Philips 7186 TDCs, providing 25 ps/count. For the 2007 test beam one of the PMTs was read out using the compact buffered version [7] (BLAB1) of the LABRADOR ASIC [8] which provides high speed waveform sampling at ~5.8 GSa/s. The prototype was designed to study the chromatic effects in a test beam environment, and no effort was made to optimize it for an application as a particle identification device in a physics experiment.

## 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 typically 0.1–0.2 particles per pulse with a repetition rate of 10-30Hz. The beam spot size is a few mm and the beam divergence is less than ~0.2 mrad. The beam spot was monitored in front of the bar with a fiber hodoscope made of 2x2 $mm^2$ scintillation square fibers, which were read out by two 4x4 Hamamatsu R5900-L16 MaPMTs coupled to LeCroy ADC 2249A. A second fiber hodoscope, located behind the bar, was added to the setup for the 2007 beam test. The system START time, which was used to start all TDCs in the system, was derived from the Linac RF pulse. We used a lead glass block read out by the LeCroy ADC 2249 to reject a slight $\pi^-$ contamination or multiple electrons in the beam. The "good event" tag 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 six positions[3] along its 3.7 m length. The total weight of the prototype was ~280 kg, the total weight of the support structure was ~700 kg, i.e., a non-trivial mechanical challenge. The bar was laser-aligned to be perpendicular to the beam within less than ~1 mrad for all positions along the bar. The bar position along its length relative to the beam was known to ~1 mm.

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, as shown in Fig. 2. Based on the photon spectrum and detector bandwidth we expect the chromatic smearing to be 3-4 mrad, with a most probable wavelength of $\lambda \approx 410$ nm. 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 length is sufficiently long. The Fast 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 the TOP/Lpath variable[4] because of its direct relationship to the quantity which is actually measured: time.

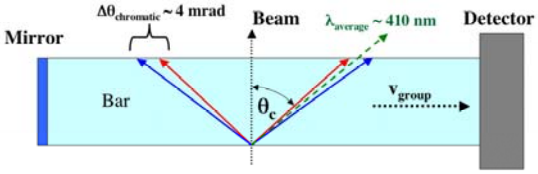

**Fig. 2.** Schematic diagram of the Cherenkov angle production for various wavelengths.

Fig. 3a shows the chromatic behavior of the Fast Focusing DIRC prototype in terms of the change in the Cherenkov angle as a function of the 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

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[3] The positions are approximately 50 cm apart with position 1 being the closest to the photon detectors at 0.59 m from the end of the bar and position 6 the furthest at 3.12 m. The corresponding path lengths of photons detected range from 1.3 m to 10.5 m.

[4] Definition: $TOP(\Phi, \theta c, \lambda) = [L/vg(\lambda)]\, qz(\Phi,\theta c)$, θc - Cherenkov angle, L – photon path length, vg(λ) - group velocity of light, λ - photon wavelength, and qz(Φ,θc) – z-component of the unit velocity vector.

the fDIRC prototype efficiency. The shape of the curve in Fig. 3a is driven by the refraction index dependence on the wavelength and is evaluated for $\beta = 1$, 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 mrad. Fig. 3b shows the same correlation in our data for the longest photon paths observed in our prototype, Lpath ≈10 m.

The chromatic correction dθ of the observed Cherenkov angle $\theta_c$ is calculated from the measured dTOP/Lpath using the expected correlation function shown in Fig. 3a.

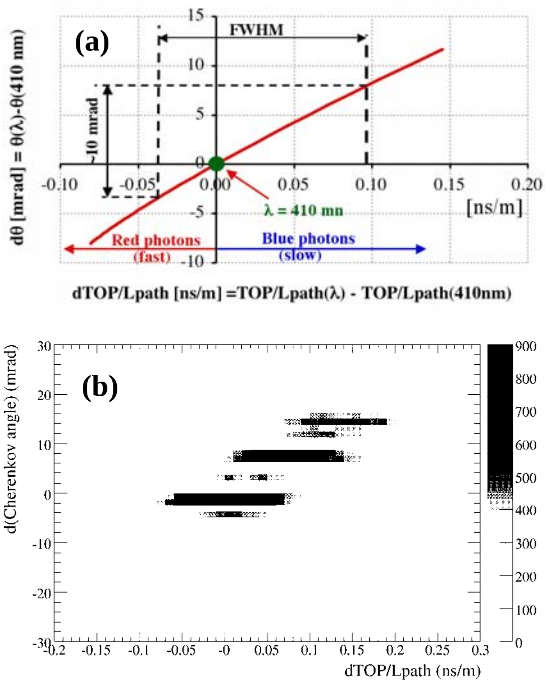

**Fig. 3.** Expected (a) and observed (b) correlation between the change in the Cherenkov angle and the change in TOP/Lpath, where the change is taken relative to their respective values evaluated at the most probable wavelength of 410 nm.

Figures 4a,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 mrad and starts working for Lpath ≥2-3 meters. For shorter path lengths we would need better time resolution and an improved likelihood analysis[5] to obtain dθ.

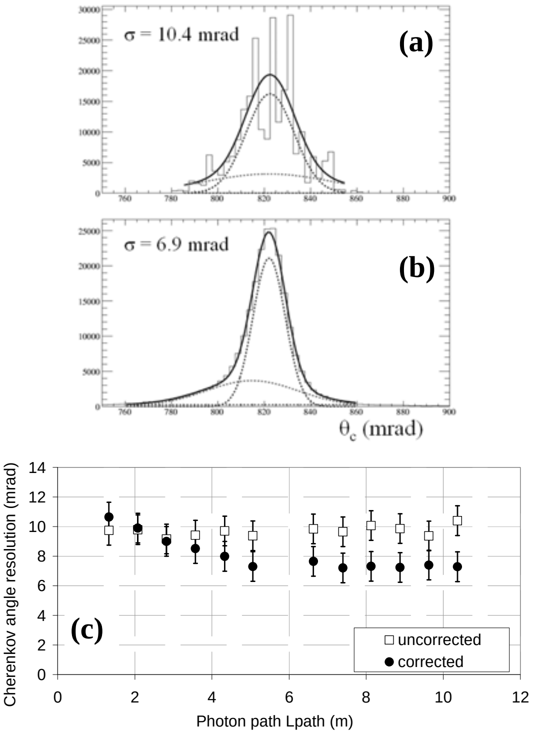

**Fig. 4.** Measured Cherenkov angle resolution using all pixels for position 1 and for the indirect photons: (a) without the chromatic correction, (b) the same but corrected for the chromatic error by timing, and (c) both as a function of photon path (Lpath).

The observed improvement of ~1-2 mrad in the total Cherenkov angular resolution is more than we expect based on our estimate of the chromatic error contribution alone, which is 3-4 mrad. This is likely caused by a special condition in our beam tests. The small beam divergence creates a non-uniform illumination of the pixels by Cherenkov photons, which causes an additional discrete pixelization

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[5] The current analysis does not use the $\theta_c$ value derived from the pixel information as a constraint (known prior) on the value of the correction dθ, causing the corrected resolution at short path lengths to deteriorate.

effect; this would not be present in a real experiment where there is sufficient smearing of incident angles.

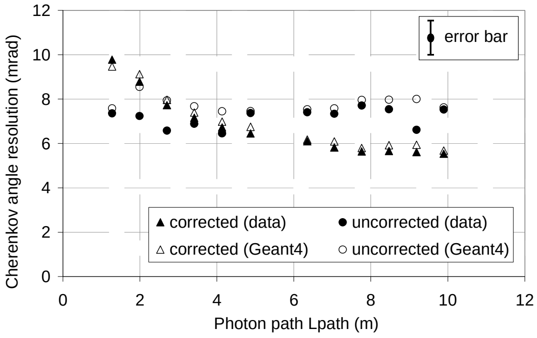

**Fig. 5.** Measured and simulated Cherenkov angle resolution as a function of photon path (Lpath) using only the 3x12 mm$^2$ pixels.

Figures 5 shows the Cherenkov angle resolution as a function of the photon path only for 3x12 mm$^2$ pixels. We clearly obtain much better resolution with smaller pixel sizes. The observed Cherenkov angle resolution is well described by our Geant4 simulation. The main contributions to the Cherenkov angle resolution are (a) chromatic dispersion (3-4 mrad), (b) pixel size (5.5 mrad for 6 mm pixels), and (c) optical aberration due to the spherical mirror in the present design, which increases from 0mrad near the ring center to 9 mrad in the outer region [4].[6] In addition, we see a discrete pixelization effect (see earlier discussion).

We determined the Cherenkov figure of merit, $N_0$, using the same bar geometry as in the BaBar DIRC, but with new detectors, based on our estimates of all efficiencies involved. To check this method, we have verified that the measured and calculated numbers of photoelectrons in a single PMT are consistent; we then extrapolate the expected performance to a possible final SuperB RICH design assuming the measured Cherenkov angle resolution. Fig. 6 shows the expected $\pi$/K PID performance of the fDIRC if we use ~3x3 mm$^2$ pixels, which is our preferred choice; one can see that it would exceed the BaBar DIRC performance[7]. We expect $N_0 \approx 31$ cm$^{-1}$ and $N_{pe} \approx 28$ for 1.7cm thick quartz bar radiator for a Hamamatsu H-9500 MaPMT, and $N_0 \approx 20$ cm$^{-1}$ and $N_{pe} \approx 20$ for Burle/Photonis MCP-PMT. This is to be compared to the present BaBar DIRC performance of $N_0 \approx 30$ cm$^{-1}$ and $N_{pe} \approx 27$.

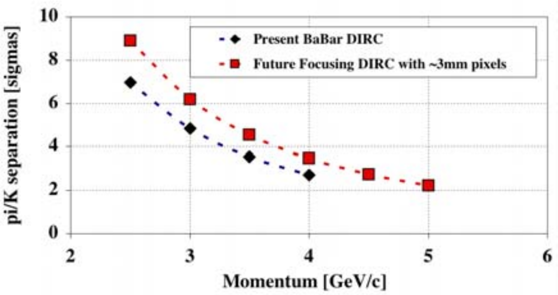

**Fig. 6.** Expected $\pi$/K separation as a function of momentum for an fDIRC detector comprising H-9500 MaPMTs with 3x3 mm$^2$ pixels, compared to the BaBar DIRC performance [1].

## Acknowledgments

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[6] We hope to reduce these effect in future optical designs.

[7] The $\pi$/K separation is calculated from the measured single photon $\theta_c$ resolution and $N_{pe}$, assuming the same tracking resolution of 1.5 mrad, for both the BaBar DIRC and the fDIRC.

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