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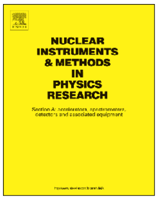

Results from the FDIRC prototype

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ABSTRACT

We present results from a novel Cherenkov imaging detector called the Focusing DIRC (FDIRC). This detector was designed as a prototype of the particle identification system for the SuperB experiment, and comprises 1/12 of the SuperB barrel azimuthal coverage with partial electronics implementation. The prototype was tested in the SLAC Cosmic Ray Telescope (CRT) which provides 3-D muon tracking with an angular resolution of ~1.5 mrad, track position resolution of 5–6 mm, start time resolution of 70 ps, and a muon low-energy cutoff of ~2 GeV provided by an iron range stack. The quartz focusing photon camera couples to a full-size BaBar DIRC bar box and is read out by 12 Hamamatsu H8500 MaPMTs providing 768 pixels. We used IRS2 waveform digitizing electronics to read out the MaPMTs. We present several results from our on-going development activities that demonstrate that the new optics design works very well, including: (a) single photon Cherenkov angle resolutions with and without chromatic corrections, (b) S/N ratio between the Cherenkov peak and background, which consists primarily of ambiguities in possible photon paths to a given pixel, (c) $dTOP = TOP_{measured} - TOP_{expected}$ resolutions, and (d) performance of the detector in the presence of high-rate backgrounds. We also describe data analysis methods and point out limits of the present performance.

1. Introduction

The DIRC detector at the BaBar experiment provided excellent particle identification performance [1]. Based on this success, we have been pursuing an R&D program to develop a compact and fast detector for future particle identification systems. One such idea, a Focusing DIRC (FDIRC) [2], would be capable not only of measuring the (x,y) coordinate of each photon with an angular resolution similar to the BaBar DIRC, but would also measure each photon's time-of-propagation (TOP) along the fused silica bar with ~100–200 ps single-photoelectron timing resolution (the BaBar DIRC had a timing resolution of σ ~1.6 ns).

The precise timing would allow one to correct for the chromatic dispersion contribution to the Cherenkov angle resolution and thus improve the angle measurement substantially (~1 mrad). The improved timing resolution would also provide better background rejection, an important feature for detectors operating in the high-intensity environment of a Super Flavor Factory for example, and could also provide modest improvement to the particle separation in some regions of phase space through the particle time of flight. By using photon detectors with a small pixel size one can reduce the size of the expansion volume by up to a factor of 10 relative to the BaBar DIRC while maintaining similar spatial resolution. The smaller geometric size together with better timing resolution would improve background suppression by nearly two orders of magnitude.

The first prototype of the FDIRC concept was constructed and operated in a test beam in 2005, 2006, and 2007 [3,4]. This prototype utilized a single DIRC quartz bar and a cylindrical mirror placed in a mineral oil expansion volume. It was the first RICH detector to successfully correct the chromatic error using timing. Here, we describe a FDIRC design developed for the SuperB experiment that was to be built in Fascati [5,6]. Fig. 1 shows a GEANT4 realized image of the FDIRC, indicating key components.

2. Description of the FDIRC prototype

The particle identification system for the SuperB experiment, or any other high-intensity Super Flavor Factory experiment, must

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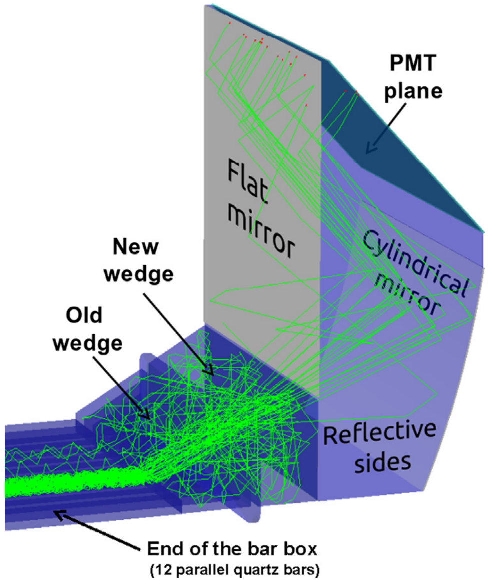

Fig. 1. The FDIRC optics as simulated in GEANT4.

cope with much higher luminosity related background rates than in the previous generation's experiments such as BaBar while maintaining similar physics performance. The estimated increase in background rates is on the order of 100-times higher. The basic design strategy for dealing with these increased rates was to make the camera much smaller and much faster. The design decision was to use a new photon camera-imaging concept based on focusing optics. The focusing element and expansion volume responsible for imaging the Cherenkov photons on to the PMT cathode surfaces were machined from radiation hard pieces of fused silica. In addition to the reduced background sensitivity gained from the geometric reduction in size, the use of fused silica also reduces background sensitivity, especially to neutrons, compared to a water-filled expansion volume. The improved timing not only helps with background suppression, but can also be used to measure and correct for the chromatic dispersion, thus improving performance. By including a cylindrical mirror that focuses light on to the photodetector plane we can remove the pinhole-size (i.e. bar thickness) component of the angular resolution in one dimension of the quartz bar.

The prototype was constructed utilizing a spare bar box from the BaBar DIRC. This is a complete bar box with 12 quartz bar radiators. The individual quartz bars had nominal dimensions of 35 mm wide × 17.25 mm high × 4900 mm long. The new optical components are a new wedge and a large focusing block (FBLOCK), both manufactured from solid fused silica [6]. The dimensions of the FBLOCK were nominally 560 mm high × 217 mm long × 422 mm wide. The new wedge was coupled to the bar box window with 50–75 mm thick epoxy. The FBLOCK was then coupled to the new wedge with 1 mm thick RTV. The entire assembly was housed in a light-tight mechanical support structure that connects to the bar box.

The focal plane of the FBLOCK was populated with 12 Hamamatsu H8500 multi-anode photomultiplier tubes (MaPMT). This only partially covers the focal plane of the FBLOCK; complete coverage would require 48 MaPMTs. The location of the 12 MaPMTs was chosen to optimize the coverage for the expected hit locations from cosmic ray muons. Each MaPMT provides 64 pixels, with each pixel being approximately 6 × 6 mm^2.

The MaPMTs were read out with IRS2 [7] waveform digitizing electronics, preceded by a ×40 preamplifier. The IRS2 was operated at a sampling rate of 2.7 GHz, and was configured to utilize 1.5 μs of its 12 μs analog storage buffer. The digitized waveforms were analyzed off-line.

The entire assembly was placed in the SLAC Cosmic Ray Telescope (CRT) [8]. The telescope features include: two planes of scintillator hodoscopes that provide 3-D tracking of cosmic ray muons with an angular resolution of ~1.5 mrad and track position resolution of 5–6 mm; a quartz start counter providing start time resolution better than 70 ps; and an instrumented iron range stack used to select muons with energy greater than ~2 GeV. The scintillator hodoscopes had active areas of 51 cm × 107 cm and provided an angular tracking acceptance of $\pm 17^\circ \times \pm 27^\circ$ in two respective directions. The bar box was located within the CRT such that the cosmic muons were incident near the midpoint along the length of the quartz radiators. The results to follow are based upon over 600,000 cosmic ray triggers in the CRT.

3. Experimental results

To reconstruct the Cherenkov angle in a given event, we used a Monte Carlo generated dictionary that maps MaPMT pixel to photon direction inside the quartz bar, $\mathbf{k}_{pixel}$, as well as the time of propagation of the photon inside the FBLOCK. The dictionary was generated by simulating single photons in the quartz, drawn from an isotropic initial angular distribution. There may be more than one photon path that will lead from the quartz bar to a given pixel, giving rise to multiple solutions of $\mathbf{k}_{pixel}$ for a given MaPMT hit. The dictionary is therefore multi-valued. Many of these ambiguous solutions can be eliminated either via timing information or because they give rise to unphysical values of the Cherenkov angle. The cosine of the Cherenkov angle was then calculated as the dot product of the track direction and the photon direction: $\cos\theta_C = \mathbf{k}_{track} \cdot \mathbf{k}_{pixel}$ [9].

The expected time-of-propagation (*TOP*) of a photon can be calculated from the track's entry location in the quartz bar as measured by the CRT, the photon direction $\mathbf{k}_{pixel}$, and the time-of-propagation inside the FBLOCK taken from the Monte Carlo dictionary. This was then compared to the measured *TOP*, $dTOP = TOP_{measured} - TOP_{expected}$. This variable, *dTOP*, provides the primary background rejection and ambiguity resolving power. Fig. 2 shows the measured *dTOP* for forward traveling (direct) and backward traveling (indirect) photons. The difference in *dTOP* resolution between forward and backward photons is primarily explained by chromatic dispersion and is well modeled by the Monte Carlo simulation.

Fig. 3 shows the Cherenkov angle distribution for all photons after a cut on *dTOP* of $|dTOP| < 2$ ns for forward photons and $|dTOP| < 2.5$ ns for backward photons has been applied. The measured resolution of 10.4 mrad is somewhat worse than our present Monte Carlo simulation's prediction of 9.1 mrad. The background under the peak comes primarily from ambiguous solutions to the photon direction.

The refractive index of the radiator is a function of wavelength. This produces dispersion in the Cherenkov angle, with the red photons corresponding to smaller angles compared to blue photons. However, the red photons have a larger group velocity and therefore arrive at the detector before the blue photons. By measuring $dTOP/L_{path}$, where L_{path} is the total path length of the photon in the detector, one can infer the color of the photon and apply a correction to the measured Cherenkov angle. For forward photons, L_{path} is typically ~275 cm, while for backward photons L_{path} ranges from 900 cm to 1400 cm. In Fig. 4 we show the measured Cherenkov angle relative to the expected angle vs. $dTOP/L_{path}$ for both forward and backward photons. As the forward photons travel a shorter distance, the correction is less effective than for backward photons. After applying this correction we see

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