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Design and performance of the focusing DIRC detector

B. Dey [a,1], M. Borsato [b], N. Arnaud [b], D.W.G.S. Leith [c], K. Nishimura [c], D.A. Roberts [d], B.N. Ratcliff [c], G. Varner [e], J. Va'vra [c,*]

[a] University of California, Riverside, CA 92521, USA
[b] Laboratoire de l'Accélérateur Linéaire, Centre Scientifique d'Orsay, F-91898 Orsay Cedex, France
[c] SLAC National Accelerator Laboratory, Stanford, CA 94309, USA
[d] University of Maryland, College Park, MD 20742, USA.
[e] University of Hawaii, Honolulu, HI 96822, USA.

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ABSTRACT

We present the final results from a novel Cherenkov imaging detector called the Focusing DIRC (FDIRC). This detector was designed as a full-scale prototype of the particle identification system for the *SuperB* experiment [1], and comprises 1/12 of the *SuperB* barrel azimuthal coverage, with partial photodetector and electronics implementation. The prototype was tested in the SLAC Cosmic Ray Telescope which provided 3D tracking of cosmic muons with an angular resolution of ~1.5 mrad, a position resolution of 4–5 mm, a start time resolution of 70 ps, and muon tracks above ~2 GeV tagged using an iron range stack. The fused silica focusing photon camera was coupled to a full-size BaBar DIRC bar box and was read out, over part of the full coverage, by 12 Hamamatsu H8500 multi-anode photomultipliers (MaPMTs) providing 768 pixels. We used waveform digitizing electronics to read out the MaPMTs. We give a detailed description of our data analysis methods and point out limitations on the present performance. We present results that demonstrate some basic performance characteristics of this design, including (a) single photon Cherenkov angle resolutions with and without chromatic corrections, (b) signal-to-noise (S/N) ratio between the Cherenkov peak and background, which primarily consists of ambiguities of the possible photon paths from emission along the track to a given pixel, (c) $dTOP = TOP_{measured} - TOP_{expected}$ resolutions (with TOP being the photon Time-of-Propagation in fused silica), and (d) performance of the detector in the presence of high-rate backgrounds.

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1. Introduction

The DIRC [2] detector at the BaBar experiment provided excellent π/K particle identification performance [3]. Based on this success, we have been pursuing an R&D program to develop a compact and fast detector for future particle identification systems, especially those that operate at very high rates [4,5]. One such concept, the Focusing DIRC (FDIRC) [6–8], is a 3D device capable of measuring not only 2D coordinates of each Cherenkov photon with an angular resolution similar to the BaBar DIRC, but of also measuring each photon's Time-of-Propagation (TOP) along the fused silica bar with 100–200 ps single-photoelectron timing resolution. Though this is substantially better timing resolution than BaBar DIRC (with a timing resolution of ~1.6 ns/photon), it is less stringent than that of the TOP counter [9] in Belle-II (with a resolution of ~100 ps/photon) or the TORCH counter [10] at LHCb (which is planning a resolution of ~50 ps/photon). The FDIRC utilizes a full 3D readout, with resolutions in each dimension that enhance the PID performance. It can determine the Cherenkov angle with very good precision independent of the achieved timing performance, which improves the robustness of the design in practical experimental environments. This requirement determines the size of the focusing optics and the number and sizes of the pixels required. The improved timing resolution and large number of pixels compared with BaBar DIRC also provides better background rejection, an important feature for next generation detectors operating in high-intensity environments, for example at a *Super B-Factory*, while the improved timing could also modestly enhance the particle separation in some regions of phase space through particle time-of-flight (TOF). Precise timing would also allow one to correct for the chromatic dispersion contribution to the Cherenkov angle resolution and thus improve the single-photon angle measurement substantially by 1–2 mrad compared to uncorrected distributions ($\sigma_{Chromatic}$ ~4–4.5 mrad – see Section 7.4). By using photon detectors with 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 a similar spatial

* Corresponding author. Tel.: +1 650 926 2658; fax: +1 650 926 4178.
E-mail address: jjv@slac.stanford.edu (J. Va'vra).
[1] Currently at Physik Institut, University of Zurich.

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resolution (for comparison, the BaBar DIRC used a very large expansion volume of ~6000 l because the size of each detector element was ~2.5 cm). The smaller geometric size together with better timing resolution would improve background suppression by nearly two orders of magnitude.

The first FDIRC prototype, employing a single DIRC fused silica bar and a cylindrical mirror placed in a mineral oil expansion volume, was constructed and operated in a test beam in 2005, 2006, and 2007 [6–8], and later tested in the SLAC cosmic ray telescope (CRT) [11] using 3D tracks [12]. It was the first RICH detector to successfully correct for the chromatic error using timing. In this article, we describe final tests of a new FDIRC design [13,14], employing fused silica optics and a full size BaBar DIRC bar box. This prototype was designed as the final demonstration test for the barrel DIRC detector of the *SuperB* experiment [1] that was to be built in Frascati.

The new design had to utilize unmodified BaBar DIRC bar boxes [3] due to resource and cost constraints. This imposed a number of restrictions on possible focusing optics designs, which prevented achieving the best possible Cherenkov angle resolution. Nevertheless, the optics and photon detector choices of the present FDIRC prototype deliver similar Cherenkov angle resolutions as the BaBar DIRC in a significantly reduced camera volume. Performance could be further improved if the pixel size were reduced to 3×12 mm^2.

Other experimental applications that might benefit from this work are the GLUEX DIRC [15] and the LHCb TORCH [10] detectors, as they both intend to re-use the BaBar DIRC bar boxes. GLUEX plans to use very similar optics to the FDIRC design, presented in this paper, to measure both the photon Cherenkov angle and time. The TORCH detector will use new optics and concentrate on measuring particle TOF very precisely (~10 ps/track), but achieving this timing resolution will require an appropriately accurate measurement of the Cherenkov angle in order to correct for chromatic effects. We believe that this work may also be useful to the PANDA barrel DIRC [16], and the future barrel DIRC planned for the electron-ion collider (EIC) [17].

2. Description of the FDIRC prototype

The particle identification system for the *SuperB* experiment, like other high-intensity Super Flavor Factory experiments, needed to cope with much higher luminosity-related background rates, by about two orders of magnitude, compared to previous generation experiments such as BaBar, while maintaining similar physics performance. The basic design strategy for dealing with these increased rates was to make the photon camera smaller and faster, as shown in Fig. 1a–e. The design decision was to use a new photon camera-imaging concept based on cylindrical mirror focusing optics [13]. The focusing element was machined from radiation-hard Corning 7980 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 the water-filled expansion volume used in the BaBar DIRC. 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 onto the photodetector plane, we can remove the pinhole-size (i.e. bar thickness) component of the angular resolution in one dimension of the fused silica bar that was one of the limiting factors in the BaBar DIRC design.

The FDIRC prototype was constructed utilizing a spare bar box from the BaBar DIRC [3]. This is a complete bar box consisting of 12 fused silica bar radiators surrounded by a light and gas tight enclosure and support structure. The individual fused silica bars have nominal dimensions of 35 mm width $\times$ 17.25 mm height $\times$ 4900 mm length, as shown in Fig. 1f and g. They each are attached to an individual wedge of approximately the same width as the bar, and all 12 bar assemblies are coupled to the bar box window. Fig. 1d and e shows the new optical components: a new wedge and a large focusing block (FBLOCK) [14]. The dimensions of the FBLOCK were nominally 560 mm height $\times$ 217 mm length $\times$ 422 mm width. The new wedge was coupled to the bar box window with optical epoxy (50~75 μm thick Epotek 301-2). The FBLOCK was then coupled to the new wedge with RTV (1 mm thick Shin-Etsu 403). The entire assembly was housed in a light-tight mechanical support structure that is connected to the bar box, as shown in Fig. 1c.

3. Photon detectors and electronics

The focal plane of the FBLOCK was populated with 12 of the Hamamatsu H-8500 multi-anode photomultiplier tubes (MaPMT) shown in Fig. 2a; this only partially covers the focal plane of the FBLOCK – complete coverage would require 48 such photomultipliers (PMTs). The location of the 12 MaPMTs was chosen to optimize coverage for the expected photon hit locations from "roughly" vertical cosmic ray muons hitting the bars in the SLAC CRT. Each MaPMT provides 64 pixels, each approximately 6×6 mm^2. H-8500 PMTs are moderately fast: Fig. 2b shows their rise time of ~0.7 ns, and pulse width of ~1.3 ns. To utilize the speed of the tube, we decided to employ a slower amplifier with a modest gain of 40 [4–6]. Fig. 2c shows its circuit. The same amplifier concept was used successfully on the first FDIRC prototype [4–6]. Using this amplifier and constant fraction discriminator (CFD) electronics, we measured a single photo-electron Transit Time Spread ($\boldsymbol{\sigma}_{TTS}$) of ~140 ps [4,5], as shown in Fig. 2d. The H-8500 tube does not have very uniform response; Fig. 2e shows a 2D scan of the single photo-electron response across all 64 pixels using the first FDIRC prototype electronics [4,5]. Fig. 2f shows scans for all 12 tubes used in this prototype using the central position of each pixel. These measured parameters are incorporated into our Monte Carlo simulation and data analysis.

The SLAC amplifier's PC-board had to be modified to accommodate the IRS2 electronics,[2] as shown in Fig. 3a and b. Fig. 3c shows the electronics mounted on the FDIRC prototype. A more detailed description of the IRS2 electronics is provided in the next section.

The proposed *SuperB* design, shown in Fig. 3d, utilized CFD-on-a-chip electronics [18]. However, as it was not available before the end of the data taking, the IRS2 was used instead to readout the FDIRC prototype as discussed below.

4. IRS2 electronics

After passing through a SLAC amplifier, the PMT signals are coupled into the IRS2 application-specific integrated circuit (ASIC). The basic architecture of the IRS2 is shown in Fig. 4a.

Each of the 8 input channels couples into a 128-cell switched capacitor array. A pair of externally supplied sampling strobes propagates down a delay line and controls the opening and closing of the switches to the capacitor array. This results in an effective sampling rate 128 times that of the frequency of the sampling strobe. The IRS2 is designed to operate at sampling rates from 1 to 4 gigasamples-per-second (GSa/s). For the FDIRC, the IRS2 is

[2] The Ice Radio Sampler (IRS) is an offshoot of the Buffered LABRADOR (BLAB) series of ASICs [19,20], originally designed for performing radio searches for ultra-high energy neutrinos in antennas embedded in Antarctic ice.

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