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FDIRC design for SuperB

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***Abstract* – We describe a new design of a focusing DIRC (FDIRC) for the barrel PID at SuperB.[1] The new FDIRC will use a new detector camera attached to the existing BaBar DIRC bar boxes. The camera's double-folded optics, made of solid fused silica, uses two mirrors, one cylindrical, and one flat. The camera's volume is 25-times smaller than the BaBar DIRC stand-off box, and its photon detectors will be 10-times faster than the BaBar DIRC PMTs, ensuring a good protection against backgrounds at SuperB, which is designed to operate at ~100-times higher luminosity than BaBar. The detector plane consists of a matrix of H-8500 MaPMTs.**

INTRODUCTION

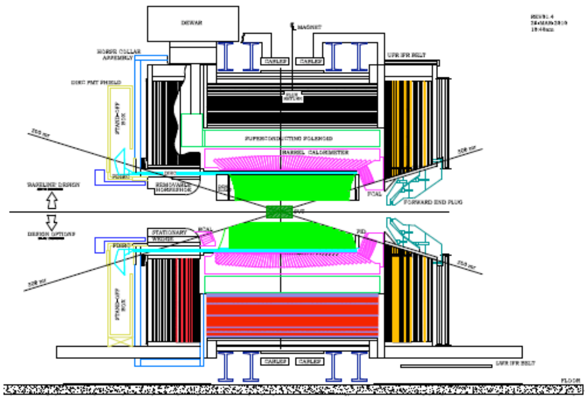

Fig. 1 Preliminary layout of the SuperB detector with the barrel FDIRC [1]. The top part of the schematic represents the nominal design, the bottom part depicts various possible options: (a) a different shape of drift chamber with a possibility for cluster counting instead of standard dE/dx, (b) forward endcap PID instrumented with either a TOF or ARICH detectors, and (c) a backward veto electromagnetic calorimeter.

Figure 1 shows the present concept of the SuperB detector [1]. The new FDIRC barrel PID detector will re-use the BaBar bar boxes with minimum changes. However it will have a new photon detector camera, about 25-times smaller than the BaBar stand-off box, with photodetectors about 10-times faster than BaBar PMTs. The entire Cherenkov radiator has 144 fused silica bars, each ~1.7cm thick, ~3.5cm wide and ~4.9 m-long, all located in 12 bar boxes. Thanks to an internal reflection coefficient of ~0.9997, good quartz transmission and orthogonal bar faces, Cherenkov photons are transported to the detector end with the magnitude of their angles conserved and only a modest loss of photons.

In the BaBar DIRC [2,3], the Cherenkov light angular information, produced in ultra-pure synthetic fused silica bars, is preserved while propagating along the bar via internal reflections to the camera where an image is produced and detected. The principle is shown in Fig.2a. The BaBar bar boxes couple to the water filled stand-off box with ~11,000 PMTs in water serving as the photodetection surface. Its main performance parameters are the following: (a) a measured time resolution per photon of ~1.7 ns, close to the PMT transit time spread of 1.5ns, (b) a single photon Cherenkov angle resolution of 9.6 mrad for tracks from di-muon events, (c) a Cherenkov angle resolution per track of 2.5mrad in di-muon events, and (d) π-K separation greater than 2.5 'σ' over the entire track momentum range from the pion Cherenkov threshold up to 4.2 GeV/c. The DIRC proved to be a very reliable detector over the lifespan of BaBar.

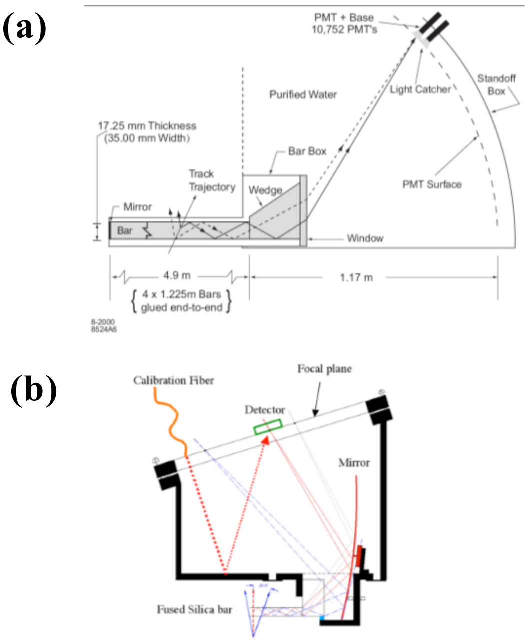

Fig. 2 (a) A schematic of the BaBar DIRC showing the water coupling between the bar box end and the PMTs [3]. (b) FDIRC prototype showing bar end, and camera with its spherical mirror and pixelized photon detectors (MaPMTs or MCP-PMT [4]). The coupling medium was mineral oil from the Kamland experiment [4-7].

As an intermediate step towards an upgrade of DIRC for the SuperB detector, we have built and tested an FDIRC prototype (see Fig.2b), in order to learn how to design a smaller FDIRC with new highly pixelated fast detectors [4].

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[1] Paper was presented at the RICH 2010 workshop by J. Vavra, corresponding author, e-mail: jjv@slac.stanford.edu.

This prototype demonstrated for the first time that the chromatic correction could be done with timing [4-7]. The principle is displayed in Fig.3a, which shows the analytical correlation between the Cherenkov angle (as determined from the space position of the pixel) and the time-of-propagation (TOP) as measured by that pixel arising from the wavelength of the particular photon being measured. Figure 3b shows a final result of this correction in the beam test data. One can see that the chromatic correction improves the Cherenkov angle resolution by 0.5-1mrads depending on photon propagation path length. To achieve this, a single photoelectron timing resolution of ~200ps is required. We have also learned from this prototype that the Cherenkov ring has worse resolution on its wings than its center – due to the optical aberration caused by the bar, which is amplified by a mirror. This error contribution goes from 0 mrad (at ring center) to ~9 mrad (near the ring's wings) – see Fig.3c [5,8].

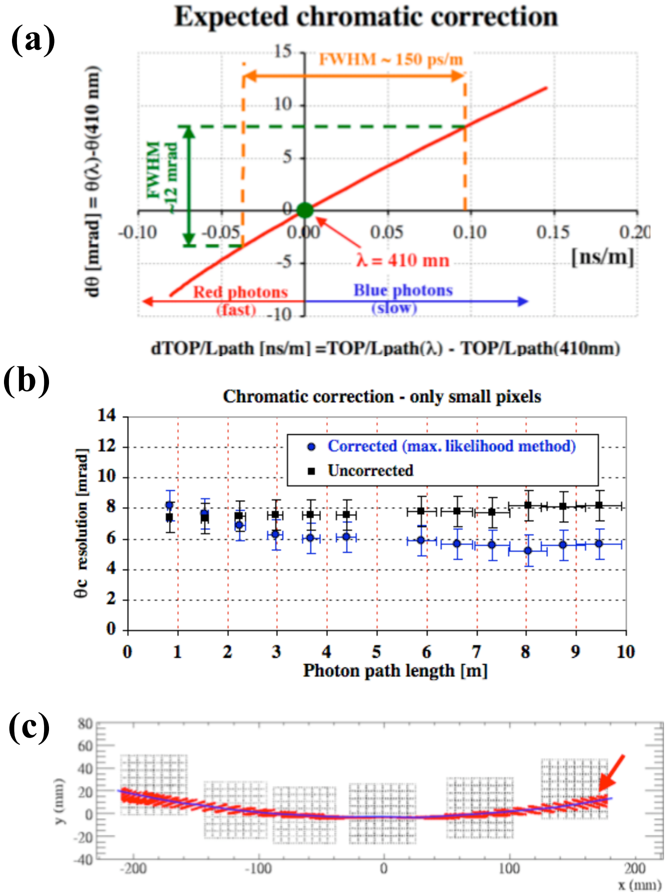

Fig. 3 (a) Analytical correlation between the change of the Cherenkov angle and the change in TOP, relative to the mean wavelength of 410nm. (b) Beam test data showing the effect of the chromatic correction for 3mm x 12mm pixels obtained with H-9500 MaPMT in the FDIRC prototype. Note that the SuperB active region starts 1-2 meters from the detector camera end. (c) Optical aberration near the ring wings [5,8].

The new PID system in SuperB must cope with much higher luminosity related background rates than in BaBar; current estimates are on the order of 100-times higher. The basic strategy is to make the camera much smaller and faster. A new photon camera-imaging concept, based on focusing optics, is therefore envisioned. The focusing blocks (FBLOCK), responsible for imaging the Cherenkov photons onto the PMT cathode surfaces would be machined from radiation hard pieces of fused silica – see Fig.4.

NEW OPTICAL DESIGN

A. Design goal

The major design constraints for the new camera are the following: (a) it must be consistent with the existing BaBar bar box design, as these elements will be reused in SuperB; (b) it must coexist with the BaBar mechanical support and magnetic field constraints; (c) it requires very fine photon detector pixelation and fast photon detectors. The very fast timing of the new PMT's is expected to provide many additional advantages: (a) an improvement of the Cherenkov resolution; (b) a measurement of the chromatic dispersion term in the radiator [5-7]; (c) separation of ambiguous solutions in the folded optical system; and (d) another order of magnitude improvement in background rejection.

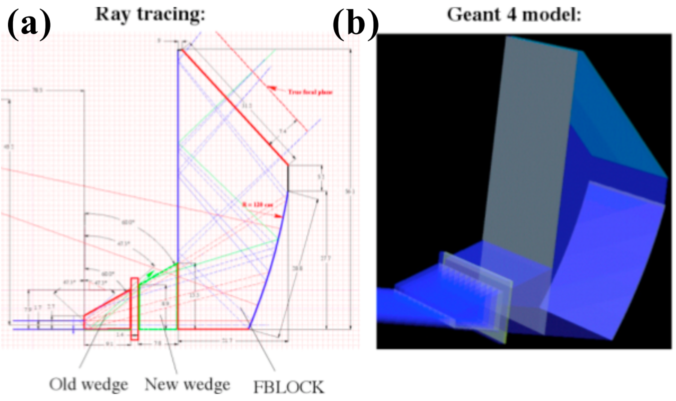

Fig. 4 (a) A new FDIRC design obtained using the ray tracing technique [8]. The bar box window, the new wedge and FBLOCK are coupled by RTV[2]. (b) the FDIRC model in the GEANT 4 Monte Carlo program [9].

There are several important advantages gained in moving from the BABAR pinhole focused design with water coupling to a focused optical design made of solid fused silica: (a) the design is modular; (b) sensitivity to background, especially to neutrons, is significantly reduced; (c) the pinhole-size component of the angular resolution in the focusing plane can be removed, and timing can be used to measure the chromatic dispersion, thus improving performance; (d) the total number of multi-anode photomultipliers (MaPMT) is reduced by about one half compared to a non-focusing design with equivalent performance; (e) there is no risk of water leaks into the SuperB detector, and no time-consuming maintenance of a water system, as was required to operate BaBar safely. Photons that enter the FBLOCK at large x-angles reflect from the parallel sides, leading to an additional ambiguity. However, the folded design makes the optical piece small, and places the photon detectors in an accessible location, improving both the mechanics and the background sensitivity. Since the optical mapping is 1-to-1 in the y-direction, this "folding" reflection does not create an additional ambiguity. Since a given photon bounces inside the FBLOCK only 2-4 times, the requirements on surface quality and polishing for the optical pieces are much less stringent than those required

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[2] We plan to use a Shin-Etsu 403 RTV (Silicone-based transparent glue).

for the DIRC bar box radiator bars. This significantly reduces the cost of optical fabrication.

In summary, the FDIRC camera design is 25-times smaller in volume than the BaBar SOB, and photodetectors that are 10-times faster than the BaBar PMTs.

B. *Ray tracing*

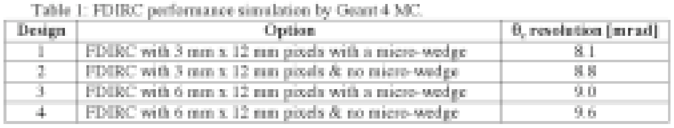
We have used manual ray tracing to make an initial design. This is a simple method, allowing easy tweaks and judgment to ensure that a chosen path is a good one. We have two problems to overcome. First, each of 12 bars in a bar box is coupled to the exit window through an "old" wedge that has a 6mrad inclined angle at the bottom. This wedge was intended to do simple focusing pinhole optical system of BaBar DIRC, but it actually worsens the resolution somewhat in the mirror focuses new design by creating a double image. Second, in the new folded geometry, the "old" wedge is too short, allowing some rays to emerge at angles well above 45 degrees. Since such rays do not hit the cylindrical mirror, they would not be focused. Therefore, it is necessary to add a new wedge outside of the box to rotate all rays that emerge from the bar with large y angles so that they hit the cylindrical mirror. The result of the ray tracing method is shown on Fig.4a. The design has a double-folded mirror optical arrangement, allowing good access to photon detectors and electronics. The cylindrical mirror radius is 120 cm. The focusing is in y only implying the use of small pixels in y, and larger pixels in the pin-hole focused x-direction. The size of the camera is such that the Cherenkov angle resolution in pixel space is similar to that of BaBar DIRC.[3]

The initial design was then verified using ray tracing generated within the framework of Mathematica [8]. The program ray-traced each photon through the entire optical system. In using this program, it was realized that the old bar box wedge is too short, and we therefore had to add a new external wedge.

C. *GEANT 4 MC simulation*

Following this initial design phase, the base design and a number of variants were studied more completely in a full GENT4 Monle Carlo simulation. Table 1 shows the options considered and the single photon resolution obtained. Two of the options (#1 & #3) assume that we would glue micro-wedges to the "old" wedges in order to correct the 6 mrad angles. However, this is quite a difficult and delicate operation, so the other two options are preferred if their performance is adequate. Option #4 is our likely choice because it is the most conservative. It would produce about the same resolution from the space measurement as did the BaBar DIRC, however, as the new design can also correct the chromatic errors, it leads to reduction in the resolution by 0.5-1 mrad.

Table 1: FDIRC performance simulation by Geant 4 MC



Design	Option	θ_c resolution [mrad]
1	FDIRC with 3 mm x 12 mm pixels with a micro-wedge	8.1
2	FDIRC with 3 mm x 12 mm pixels & no micro-wedge	8.8
3	FDIRC with 6 mm x 12 mm pixels with a micro-wedge	9.0
4	FDIRC with 6 mm x 12 mm pixels & no micro-wedge	9.6

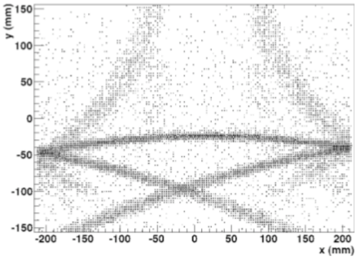


Fig. 5 Cherenkov ring image from GEANT 4 for tracks with θ_{dip} = 90° in the central bar. The image was obtained assuming no magnetic field and 3mm x 3mm pixels at 4GeV/c [9]. Generally, images in FDIRC are complicated due to reflections from the sides of the FBLOCK, and are different for each bar. The image is actually three dimensional and can be simplified if one uses TOP as a way to slice it.

Figure 5 shows a Cherenkov ring image for one of the central bars in the new FDIRC. It is more complicated than those from BaBar DIRC. The ring radius is not used in the analysis. Instead, we use a dictionary of MC assignments for each pixel: $\mathbf{k}_{pixel} \equiv \{k_x, k_y, k_z\}$, and time-of-propagation for direct and indirect photons TOP_{direct} & $TOP_{indirect}$ for tracks with $\theta_{dip} = 90^o$ & $z = z_{middle}$ for each bar. For any other track direction one can then calculate the Cherenkov angle simply as a dot product of two vectors: $\cos\theta_c = \mathbf{k}_{track}.\mathbf{k}_{pixel}$. This procedure has been used successfully with the FDIRC prototype in the cosmic ray telescope with 3D tracking.

Figure 6 shows a MC simulation of the chromatic correction for a nominal choice of 6mm x 12mm pixels. For an assumed final single photoelectron time resolution, σ_{final} ~170ps, one can improve the Cherenkov angle resolution by ~0.7 mrad if one does the chromatic correction. This is consistent with the FDIRC prototype beam test results [5-7].

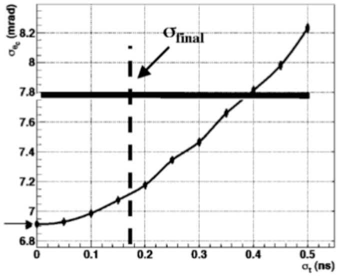


Fig. 6 MC prediction of chromatic error reduction as a function of timing resolution [9]. For σ_{final} ~ 170ps one can reduce the Cherenkov angle resolution by ~0.7 mrad by applying the chromatic correction by timing.

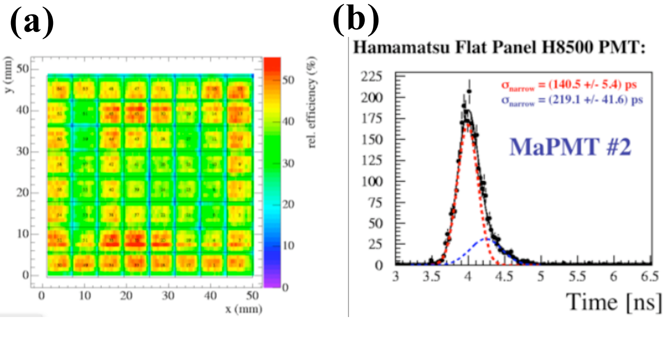


Fig. 7 (a) Scan of H-8500 with single photoelectrons normalized to Photonis XP2262/B PMT [4], (b) Single photoelectron transit time resolution of of H-8500, obtained in a special laser test, is σ_{TTS} ~ 140ps [4].

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[3] BaBar DIRC obtains a single photon resolution of ~9.6 mrads for tracks from di-muons events.

PHOTON DETECTORS

A beauty of the BaBar DIRC implementation is that it has photon detectors outside of magnetic field as the bars penetrate the magnet iron. This simplifies the detector choice considerably. We are deciding between two MaPMTs by Hamamatsu, the H-8500 and the H-9500. The H-8500, which is the tube preferred by the medical community, has much smaller price than the H-9500 MaPMT, it has a smaller TTS spread (~140ps – see Fig.7b), it is available with somewhat "enhanced" QE (~24%), and Hamamatsu "strongly" recommends this tube to keep a reasonable delivery schedule of large quantities. On the other hand, the H-9500: MaPMT can provide finer sampling in y-direction and thus provides better Cherenkov angle resolution. In both cases we would short some pixels in the x-direction as there is only pinhole focusing available, and thus create either 6mm x 12mm pixels (H-8500) or 3mm x 12mm pixels (H-9500). Figure 7a shows a scan of an H-8500 MaPMT with single photoelectrons, normalized to the efficiency of the Photonis XP2262/B PMT. Figure 7b shows its TTS timing resolution. Figure 8 shows the detector matrix of one camera with 48 H-8500 PMTs. The entire FDIRC system needs 576 tubes and 18,432 pixels. Figure 9 shows the wavelength response. For a peak QE of 24%, one obtains ~20 photoelectrons for tracks with θ_{dip} = 90^{o}. This assumes that the PMT coupling to FBLOCK is done with RTV and that the tubes are closely packed to that the loss due to gaps between the tubes is as small as possible. We expect a rate of ~50-100kHz/single pixel at SuperB, well within a maximum rate capability of these MaPMT tubes.

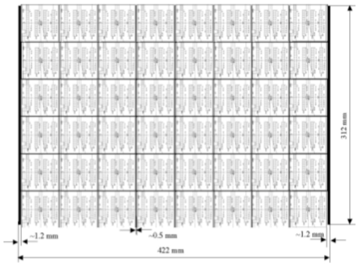

Fig. 8 Detector matrix on one FDIRC detector camera with 48 H-8500 MaPMTs.

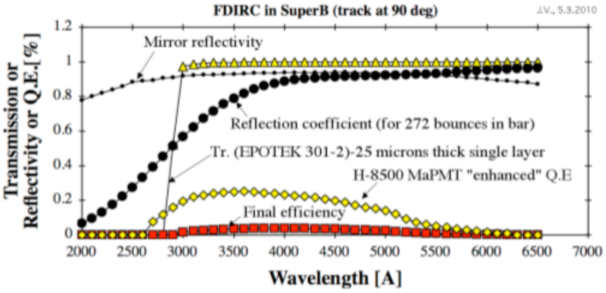

Fig. 9 FDIRC wavelength response is limited on low wavelength side by EPOTEK 301-2 glue used to glue bars together.

MECHANICAL DESIGN

Figure 10 shows the present mechanical concept [10]. The optical coupling between the bar box window, new wedge and FBLOCK will be done with RTV. There is easy access to detectors thanks to double-folded optics. H-8500 tubes can tolerate 10-20 times higher magnetic field compared to DIRC PMTs, an therefore the magnetic shield does not have to be as massive as was required for BaBar DIRC.

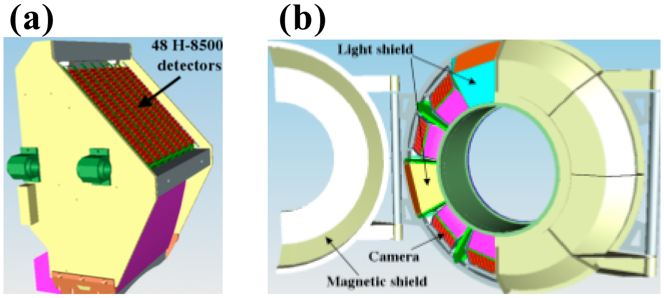

Fig. 10 Mechanical concept of FDIRC: (a) Detector camera housing the new wedge and FBLOCK with double-folded optics and 48 H-8500 MaPMTs. (b) A possible arrangement of a magnetic shield.

ELECTRONICS

Figure 11 shows the probable concept for the electronics [11]. It is a conservative design, employing a leading edge discriminator with a 100 ps/count TDC, together with an ADC to provide the pulse height corrections that are needed to improve timing resolution using the TDC/ADC method. The front end chip will be taking care of one 16-channesl MaPMT connector. The overall aim is to achieve the electronics resolution of about $\sigma_{Electronics}$ ~100ps. The electronics is split into two components: (a) the first one is mounted on MaPMTs, amplifies signals and processes them with TDCs/ADCs. The second one, located some distance away, packages all channels and sends the data to the DAQ. The aim is to have a maximum rate capability of ~2.5MHz/pixel, with a double hit resolving time of ~50ns. The electronics resolution of $\sigma_{Electronics}$ ~100ps will allow us to obtain σ_{Final} = 170-200ps with the H-8500 MaPMT, which satisfies our goal to improve the timing resolution by a factor of ~10 compared to BaBar DIRC.

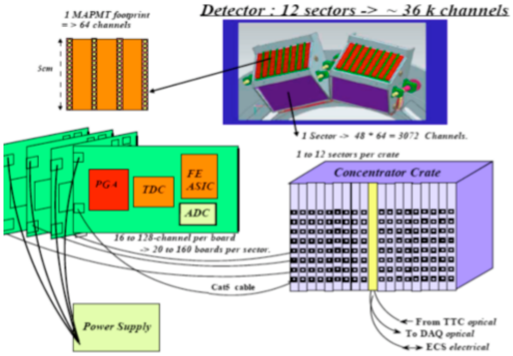

Fig. 11 Possible electronics concept of FDIRC.

CONCLUSION

We have designed a new FDIRC for operation at SuperB. The new detector will have 25-times less camera volume and will be 10-times faster than the camera in BaBar DIRC, which should provide the improved performance and background rejection capability needed at the 100 times higher luminosity of SuperB.

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