LAL 99-56
October 1999

Laboratoire de l'Accélérateur Linéaire

DIRC - A Particle Identification System for BaBar

A. Höcker

Laboratoire de l'Accélérateur Linéaire
IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex

Talk given at the "6th International Conference on B-Physics at Hadron Machines **BEAUTY 99**"
Bled, Slovenia, 21-25 June, 1999

U.E.R
de
l'Université Paris-Sud

Institut National
de Physique Nucléaire
et de Physique des Particules

 B.P. 34 ~ Bâtiment 200 ~ 91898 ORSAY CEDEX

LAL 99-56
October 1999

DIRC - A Particle Identification System for BaBar

Andreas Höcker
for the DIRC group [1]
E-mail: hoecker@slac.stanford.ed

Laboratoire de l'Accélérateur Linéaire,
IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex

Abstract

The DIRC (an acronym for Detection of Internally Reflected Cherenkov light) is a novel type of Cherenkov imaging device that has been developed, built and installed as part of the BaBar detector at the asymmetric B-factory PEP-II at SLAC. The DIRC is based on total internal reflection of Cherenkov photons produced and guided within thin, rectangular quartz bars covering the barrel region of BaBar. The photon detector is an array of photomultiplier tubes covering the photon phase space at the backward end of the bars. In its first few months of operation the DIRC performance has been found to achieve the design requirements. This note presents results from cosmic ray data and an analysis of the first beam collision runs.

1 Introduction

PEP-II [2] is an asymmetric e^+e^- B-factory accelerating electrons to 9 GeV and positrons to 3.1 GeV which produce $\Upsilon(4S)$ resonances in collision with a boost of $\beta\gamma \simeq 0.56$. The design luminosity is 3×10^{33} cm^{-2}s^{-1} corresponding to a $B\bar{B}$ production rate of 3 Hz. The primary physics challenge of PEP-II and its detector, BaBar [3], is to measure CP violation and to overconstrain the unitarity triangle in order to probe the Standard Model of particle interactions. To a large extent, the assembly of BaBar was finished by October 1998, followed by several months of systematic acquisition of cosmic ray data. Starting in 1997 and continuing in parallel, PEP-II was tuned and background studies were performed. In May 1999, BaBar moved onto the beam line and first $\Upsilon(4S)$ collision data were recorded. Till August 1999, a maximum peak luminosity of 8×10^{32} cm^{-2}s^{-1} has been achieved in production mode and about 0.5 fm^{-1} of data on the $\Upsilon(4S)$ resonance have been collected.

A particle identification (PID) system is an indispensable tool in order to accomplish the ambitious physics goals of BaBar. In particular, π/K separation up to 4 GeV/c track momentum is necessary to analyze the final states of $B(\bar{B})$ decays as well as flavor tagging of kaons up to 2 GeV/c for the recoil $\bar{B}(B)$. In addition, the identification of strange final states is of great importance for τ and charm physics.

The DIRC [4, 5, 6] provides π/K separation of better than 3.5 standard deviations over the entire momentum range from the transverse momentum cutoff up to 4 GeV/c. Particle identification using the specific ionization, dE/dx, in the drift chamber is effective for a π/K separation of at least 3σ up to approximately 0.7 GeV/c. The DIRC design is based on an integrated Cherenkov radiator and light pipe consisting of thin quartz bars [7] with a rectangular cross section and a photodetector surface mounted at the backward end of the detector outside the BaBar acceptance. Cherenkov light is transported *via* internal reflection through the bars, and then expands in a water volume onto the detection plane. As will be shown later, the DIRC is a 3-dimensional device, measuring the polar and azimuthal Cherenkov angles, θ_C, ϕ_C, and the time of the Cherenkov photons.

Preliminary PID results with the DIRC, using cosmic ray data recorded between November 1998 and May 1999, as well as beam collision data (recorded since May 1999) are presented in this note. Emphasis is put on general aspects of the performance, the number of Cherenkov photons observed and the resolution obtained.

2 The BaBar Detector

BaBar is similar to conventional e^+e^- detectors but with a shifted geometry to work with asymmetric beams (see Fig. 1). The forward boost of the center-of-mass is accounted for by a backward shift of the interaction point of -37 cm with respect to the geometrical center of the detector. At its inner radius, BaBar has a 5 layer double-sided silicon strip vertex detector followed by a 40 layer drift chamber with stereo and axial wires. The DIRC is mounted between the drift chamber and the electromagnetic crystal (CsI) calorimeter (EMC). The support structure of the DIRC quartz bars has a radial thickness of 8 cm, and a total radiation length of 19% (14% from the quartz bars) at normal incidence. The very small radial space and modest and uniform radiation length are important to maximize the performance of the calorimeter and to minimize its costs. The EMC is radially surrounded in the barrel by a 1.5 T solenoid which is followed by the instrumented flux return used primarily for muon identification.

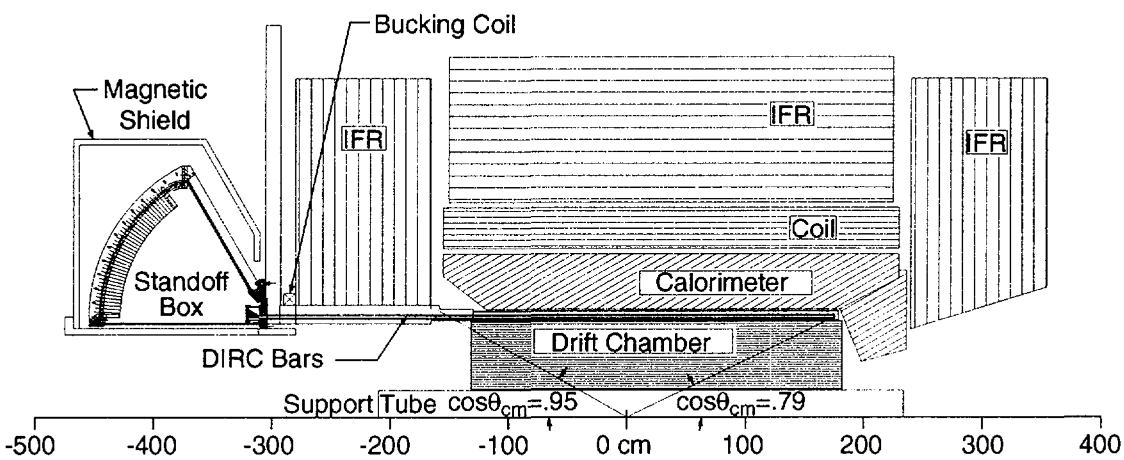

Figure 1: Upper half of the BaBar Detector with DIRC quartz bars between drift chamber and electromagnetic calorimeter.

The DIRC is a barrel device covering 94% of the azimuthal angle and 87% of the polar angle. In the backward region photons enter an expansion volume, the Stand-Off-Box (SOB) that is filled with 6 m^3 purified water, before reaching the PMT surface. Mirrors at the forward ends of the quartz bars reflect incoming photons back in the direction of the SOB. The toroidal inner surface of the SOB is covered by an array of 10752 PMT's each with a diameter of 2.9 cm. An iron enclosure around the SOB together with a bucking coil keeps the fringe field from the BaBar solenoid below 2 Gauss ensuring the relative PMT detection efficiency to be larger than 95% [8]. The production of the 576 high quality quartz bars has been slower than originally expected. As a consequence, BaBar is presently running with only 5/12 of the nominal azimuthal coverage. The remaining bars will be installed during a shutdown period in October 1999.

3 The DIRC principle

Charged tracks with a velocity of $\beta \approx 1$ penetrating a medium with refractive index $n(E_\gamma) > 1$, where E_γ is the photon energy, produce Cherenkov light emitted in a cone with opening angle

$$\cos\theta_C = \frac{1}{\beta n(E_\gamma)} \tag{1}$$

around the track. The quartz bars used as a radiator material in the DIRC have a mean $n \approx 1.47$. The average expected number of photoelectrons (photons that are reconstructed in the PMT's) is related to θ_C by

$$N_{PE} \simeq \epsilon_{coll} N_0 \frac{1}{\cos\theta_{dip}} \sin^2\theta_C \ . \tag{2}$$

Here $\epsilon_{coll} = \epsilon_{coll}(l_{bar}, E_\gamma)$ is the photon collection efficiency which is a function of the total photon path length, l_{bar}, in the bar and the photon energy. The angles θ_C and θ_{dip} are the polar Cherenkov angle in the track reference system and the dip angle of the track with respect to the normal to the quartz surface, respectively. The "Cherenkov quality factor" is measured to be $N_0 \approx 145\ cm^{-1}$ [9]. The Cherenkov angle, the photon hit time and the number of radiated photons depend on the particle mass so that the simultaneous measurement of these quantities together with the momentum yields the particle's identity.

The concept of the DIRC is sketched in Fig. 2. Cherenkov photons trapped in a quartz bar are reflected internally[1] preserving the absolute value of the angle at each reflection. The photons propagate either directly to the backward detection region or are reflected by the mirror mounted on the forward end of the bar and then travel to the SOB. Before entering the water, the photons penetrate a quartz wedge which reduces the number of necessary PMT's in the detection plane by more than a factor of two (see Fig. 2). A thin (0.9 cm) quartz window separates the radiator and light pipes from the water in the SOB. The photons enter the water ($n_{water} \simeq 1.33$) and are eventually detected at the PMT surface mounted at a distance of about 1.2 m from the quartz window. Hexagonal reflectors (the Light Catchers) with water resistant Rhodium surfaces surround the PMT cathodes, improving the detection efficiency by about 20%.

Due to the internal reflections within each bar and wedge, the measured Cherenkov photons have ambiguities in the reconstruction. Some of these, but not all, can be resolved by using the timing information.

[1] An excellent reflectivity is important since a typical photon, emitted in forward direction, bounces about 300 times before entering the SOB which, for the quartz bars used in the DIRC, corresponds to a photon loss of about 20%.

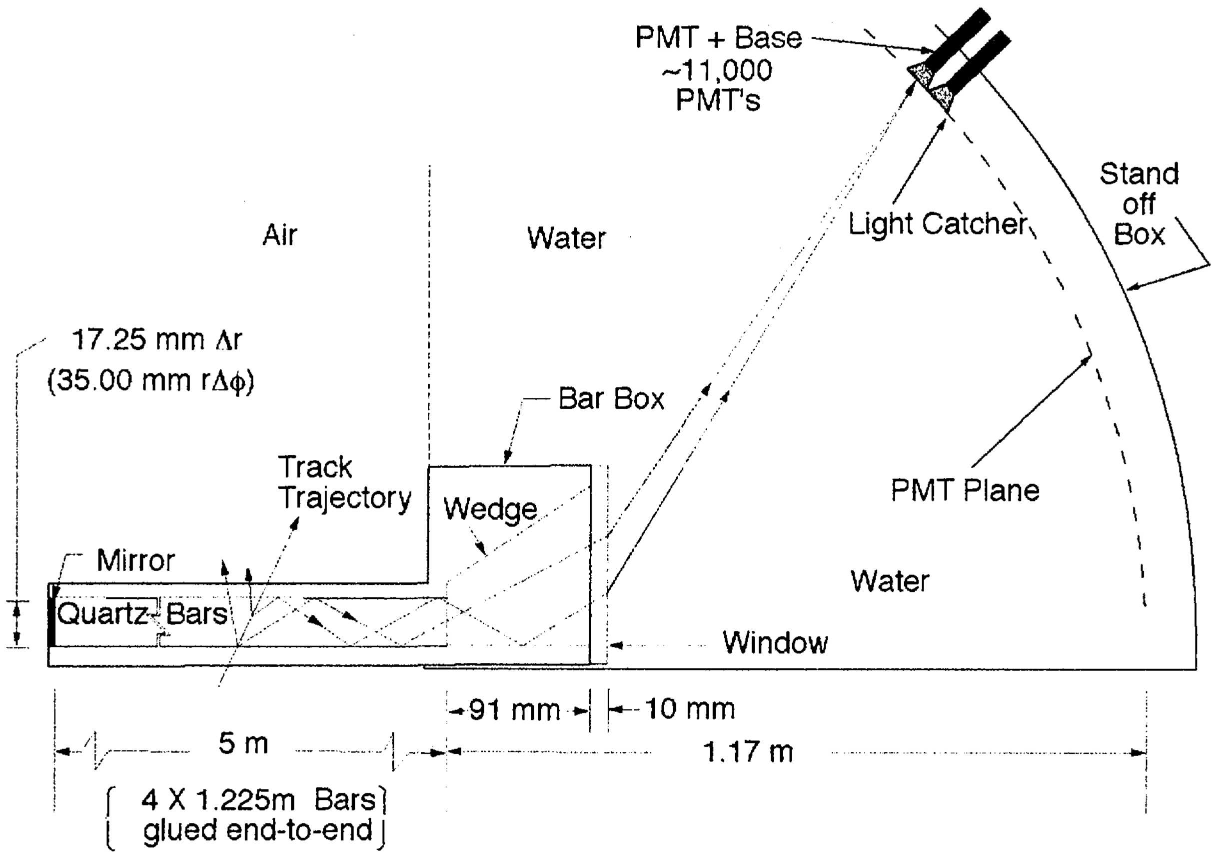

Figure 2: The DIRC principle.

The azimuthal structure of the DIRC is a 12-sided polygonal barrel, each side of which consists of a bar box with 12 bars of dimension $3.5_x \times 1.7_{y(r)} \times 490_z$ cm^3. The bars are made out of four horizontal pieces that are glued together. The wedges have a length of 9.1 cm and a top angle of 30°. The detection plane reflects the bar box structure incorporating 12 sectors each with 896 traditional Thorn EMI PMT's [10] ($\approx$ 30% detection efficiency), arranged in a toroidal, pointing geometry. Twelve independent read-out electronics crates are mounted on the support structure outside the SOB. Of great importance for the suppression of accelerator background and photons from other tracks is an excellent hit time resolution. A time sampling of 0.5 ns is provided by the TDC chip [11]. The DIRC overall time resolution is then determined by the 1.8 ns intrinsic PMT signal width. An LED light flasher system is used for a frequent and automated tube-to-tube time calibration. The DIRC electronics [12] provides both time and charge measurement, the latter used to control efficiency and quality of the PMT signals. The data are sent *via* 1.2 Gbit optical fibers to the acquisition farm where they are processed and built to become BaBar events.

The Cherenkov angle resolution per reconstructed photon can be written as the following quadratic sum [4]:

$$\begin{aligned}\Delta\theta^2_{\mathrm{C,\,tot}} &= \Delta\theta^2_{\mathrm{C,\,track}} + \Delta\theta^2_{\mathrm{C,\,production}} \\ &+ \Delta\theta^2_{\mathrm{C,\,transport}} + \Delta\theta^2_{\mathrm{C,\,imaging}} + \Delta\theta^2_{\mathrm{C,\,det}} \,. \end{aligned} \tag{3}$$

The track error, $\Delta\theta_{C,\text{track}}$, arises from the uncertainties in the track direction with respect to the bar axis as well as in the momentum and is presently smaller than 3 mrad. It also depends upon multiple scattering of the track within the bar ($\propto (\beta p)^{-1}$). The production uncertainty, $\Delta\theta_{C,\text{production}}$, is dominated by the chromatic dispersion of 5.4 mrad within the bars. Transport errors, $\Delta\theta_{C,\text{transport}}$ are caused by smearing down the bar and the wedge (non-parallel sides, non-planar surfaces and non-orthogonal sides and faces) as well as misalignment within the DIRC and between DIRC and the tracking system (measured to be smaller than 2 mrad). The detection uncertainty is obtained from the simple expression

$$\begin{aligned} \Delta\theta_{C,\text{det}} &\simeq \sqrt{((\text{radial bar size})^2 + (\text{PMT size})^2)/12} \\ &\approx 7 \text{ mrad} \end{aligned} \tag{4}$$

for the *pinhole* detection system adopted by the DIRC. In fact, for a particle with momentum p and $\beta = p/E \approx 1$ entering a radiator of refractive index n, the number of standard deviations of separation between particle species A and B with masses m_A and m_B is approximately given by the formula [13]

$$N_\sigma \simeq \frac{|m_A^2 - m_B^2|}{2p^2\sqrt{n^2-1}} \frac{1}{\Delta\theta_{C,\text{tot}}} . \tag{5}$$

The separation power depends on the inverse of the refractive index, limiting the DIRC PID capability to the relatively low momenta that are typical for B-factories.

4 Analysis of Cosmic Ray Data and First Beam Collision Runs

Compared to the relatively clear Cherenkov images in traditional RICH devices, DIRC projections may have a more complicated pattern due to the photon reflections which sometimes make it difficult to recognize rings in the hit pattern. Fig. 3 shows as an example, a typical multi-hadron event. The DIRC hits are represented by the small circles. Depicted in addition are the 12 curved sectors of the SOB. Some of the tracks enter sectors that are not yet equipped with quartz bars and thus do not produce Cherenkov light.

The current DIRC reconstruction algorithm follows a deconvolution principle: all PMT hits are propagated back through the water, the wedge and the quartz bar to all tracks, taking into account the top-bottom, left-right and forward-backward ambiguities created by the internal reflections. For each track/hit pairing there may exist several physical solutions for θ_C, some of which may be resolved using the timing information. In the following, the solutions are associated with tracks after applying loose cuts on physical θ_C angles and on the difference between expected propagation time and measured hit time. A fit algorithm determines for a given track the number of signal photons (in a peak of the θ_C distribution) for each of the five particle hypotheses, e, μ, π, K, p. The hypothesis with the largest number of signal photons is chosen. Many variations of this method, including global likelihood fits are under development within the BaBar Collaboration.

The residual $\theta_C^{\text{measured}} - \theta_C^{\text{muon}}$ resolution per tube for cosmic ray data (mostly muons) is plotted in Fig. 4. The double gaussian fit corresponds to signal and background contributions of which the signal peak has a resolution (per photon) of 9.3 mrad.

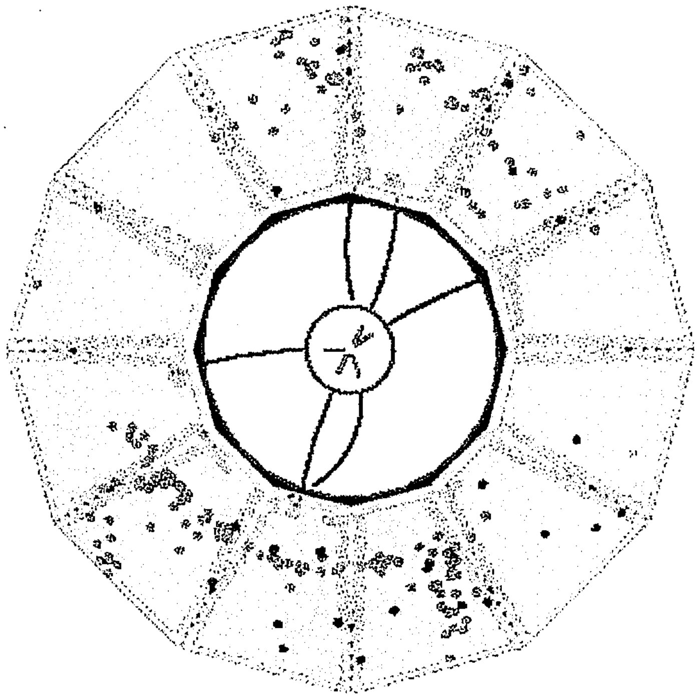

Figure 3: Event display of multi-hadron event. The small circles represent the hits in the DIRC Stand-Off-Box.

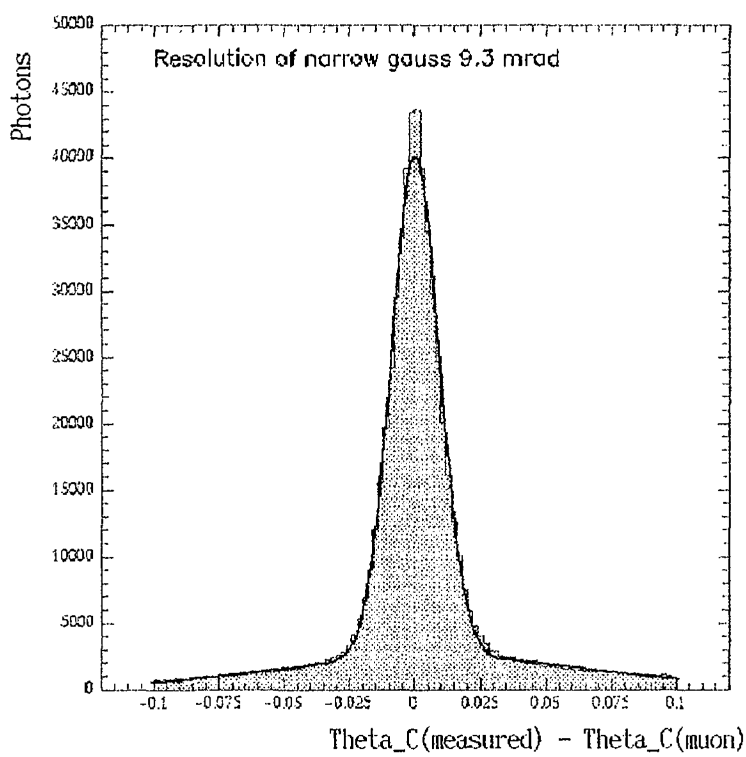

Figure 4: Resolution of the Cherenkov angle reconstruction per photon for cosmic ray data.

Figure 5 shows the measured Cherenkov angle resolution per track for Bhabha events from first collision data.

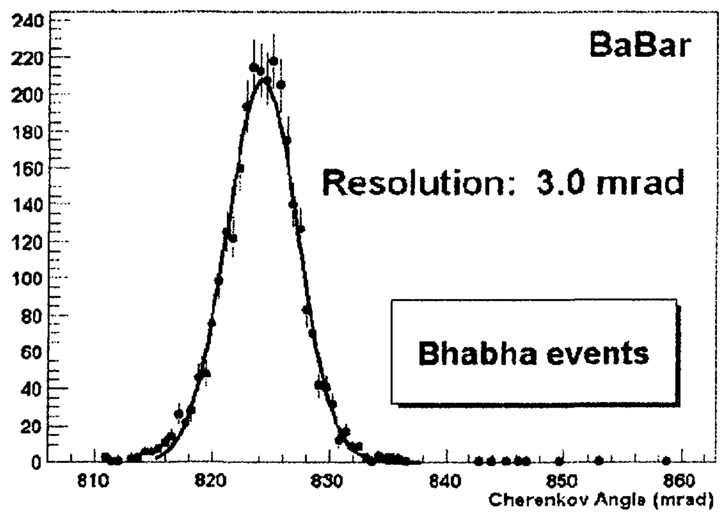

Figure 5: Resolution of the Cherenkov angle reconstruction per track for tracks from Bhabha events.

It is interesting to plot the number of reconstructed photons as a function of their effective bar transmission distance z (see Fig. 6), giving a measure of at least two important design parameters: the photon transmission in the bar, the slope (absorption of 5.2% of the photons per meter bar), and the reflectivity of the forward mirror (92%) obtained from the height of the discontinuity.

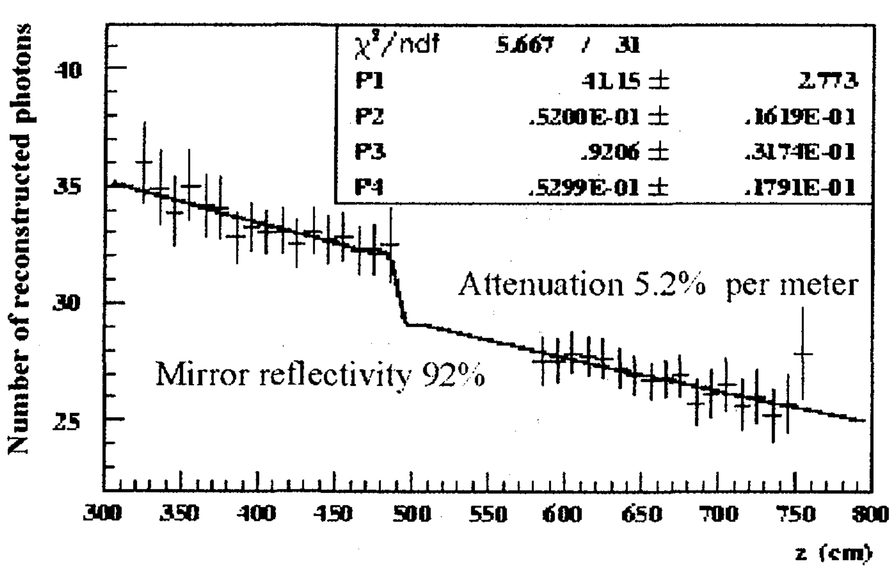

Figure 6: Number of reconstructed photons as a function of the bar transmission distance z. The slope is a measure of the bar absorption, while the discontinuity is a measure of the mirror reflectivity.

As a first example for a DIRC physics application, Fig. 7 shows the invariant mass spectrum of inclusive $K\pi$, originating from the decay $D^0 \to K^{\pm}\pi^{\mp}$ with and without use of the DIRC PID for the kaon. The DIRC selection corresponds to a background rejection factor of 14.

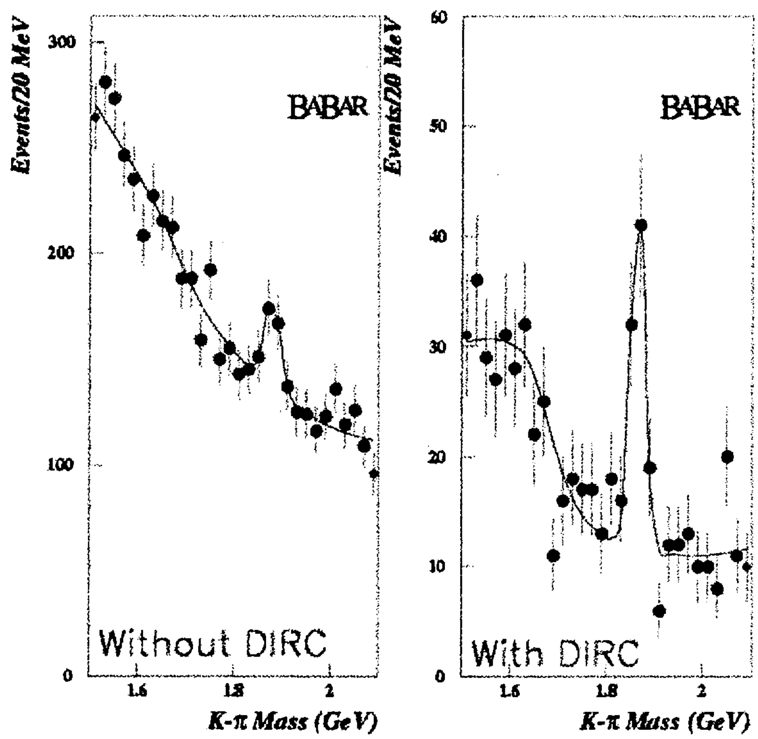

Figure 7: Invariant mass spectrum of the inclusive $K\pi$ spectrum without (left hand plot) and with (right hand plot) use of the DIRC PID for the kaon based on 50k hadronic events. The mass peak corresponds to the $D^0 \to K^{\pm}\pi^{\mp}$ resonance.

5 Background

There are four sources of background hits in the DIRC:

1. Event related background from other tracks; and delta rays, scintillation, etc., from the track itself.
2. Beam related background from PEP-II. Although the high energy, lower current (now 0.4 A, 0.7 A nominal) electron beam approaches the interaction point from the backward direction through the inner ring of the SOB magnetic shield, the main source of background photons are the low energy positrons entering with high current (currently about 1A, 2A nominal) from the forward side of BaBar.
3. Cosmic rays entering the SOB produce a large number of Cherenkov photons. However, these are rare and produce an average photon background of only 80-120 Hz per tube. Thus, cosmic rays are of negligible influence on the reconstruction.
4. Background from electronics noise is negligible.

The most powerful tool to suppress background makes use of the precise time resolution of the PMT signals. As an example, the current PEP-II background amounts to about 40 kHz per tube with variations of about ±20 kHz depending on the position of the PMT with respect to the beam pipe of the low energy ring. Only about 5 background photons are found within a window of 10 ns for the propagation time of reconstructed photons, while for an average number of 10 tracks per event, approximately 300 signal photons are expected.

At present, track related backgrounds are the dominant source. The quantitative contributions of the various components to the overall background are still under study.

6 Conclusions

The DIRC is a new type of particle identification device, suitable for $\pi - K$ separation for momenta up to 4 GeV/c. The analysis of cosmic ray data indicates that the DIRC capabilities meet the design requirements. The whole measurement and reconstruction chain has been tested successfully and first collision data have been analyzed. The average Cherenkov angle resolution per track presently obtained for Bhabha events is 3 mrad, corresponding to a $\pi - K$ separation of better than 3.5 standard deviations at 3 GeV/c. Due to the precise DIRC timing resolution, current machine background rates of about 40 kHz per photomultiplier tube do not significantly deteriorate the accuracy of the Cherenkov angle reconstruction. We are looking forward to the analysis of the first high luminosity runs in order to tune the PID reconstruction methods.

References

[1] The DIRC Detector at BaBar: I. Adam, R. Aleksan, D. Aston, P. Bailly, C. Beigbeder, M. Benayoun, M. Benkebil, G. Bonneaud, D. Breton, H. Briand, D. Brown, Ph. Bourgeois, J. Chauveau, R. Cizeron, J. Cohen-Tanugi, M. Convery, S. Dardin, P. David, G. de Domenico, C. de la Vaissiere, A. de Lesquen, M. Doser, S. Emery, G. Fouque, A. Gaidot, F. Gastaldi, J.-F. Genat, T. Geld, L. Gosset, D. Hale, G. Hamel de Monchenault, O. Hamon, A. Hoecker, D. Imbault, R.W. Kadel, J. Kadyk, M. Kalelkar, M. Karolak, H. Kawahara, H. Krueger, H. Lebbolo, F. Le Diberder, P.H. Leruste, G. London, M. Long, J. Lory, A. Lu, A.-M. Lutz, G. Lynch, G. Mancinelli, M. McCulloch, D. McShurley, R. Malchow, P. Matricon, B. Mayer, B. Meadows, P. Micout, D. Muller, J.-L. Narjoux, J.-M. Noppe, D. Oshatz, G. Oxoby, R. Plano, S. Plaszczynski, M. Pripstein, J. Rasson, B. Ratcliff, R. Reif, C. Renard, L. Roos, E. Roussot, A. Salnikov, M.-H. Schune, J. Schwiening, S. Sen, V. Shelkov, M. Sokoloff, H. Staengle, S. Spanier, P. Stiles, R. Stone, Ch. Thiebaux, K. Truong, W. Toki, A. Valassi, G. Vasileiadis, G. Vasseur, J. Va'vra, M. Verderi, S. Versille, D. Warner, T. Weber, T. F. Weber, W. Wenzel, R. Wilson, G. Wormser, Ch. Yèche, S. Yellin, B. Zhang, M. Zito

[2] J.T. Seeman, *"Status of the PEP-II B-Factory*, Talk given at 14th Advanced ICFA Beam Dynamics Workshop: Beam Dynamics Issues for e^+e^- Factories (ICFA 97), Frascati, Italy, 1997; E. Bloom *et al.*, *The PEP-II Asymmetric B-Factory: Design Details and R&D Results*, SLAC-PUB-6564 (1994); *PEP-II: An Asymmetric B-Factory. Conceptual Design Report*, SLAC-R-418 (1993)

[3] The BaBar Collaboration, *Technical Design Report*, SLAC-REP-950457 (1995)

[4] B. Ratcliff, *"The DIRC Counter: A new Type of Particle Identification Device for B-Factories"*, Talk given at International Workshop on B Factories: Accelerators and Experiments, Tsukuba, Japan, 1992, SLAC-PUB-6047 (1993);
P. Coyle *et al.*, *Nucl. Inst. Meth.* **A343** (1994) 292

[5] H. Staengle *et al.*, *Nucl. Inst. Meth.* **A397** (1997) 261

[6] C. Lu *et al.*, *"Detection of Internally Reflected Cerenkov Light: Results from the BELLE DIRC Prototype"*, Talk given at 2nd International Workshop on Ring Imaging Cerenkov Detectors (RICH 95), Uppsala, Sweden 1995; *Nucl. Inst. Meth.* **A371** (1996) 82

[7] I. Adam *et al.*, *"An Internally Reflecting Cerenkov Detector (DIRC): Properties of the Fused Silica Radiators"*, SLAC-PUB-7707 (1997); *IEEE Trans. Nucl. Sci.* 45 (1998) 450

[8] P. Bourgeois, M. Karolak and G. Vasseur, *"Performance of the Photomultiplier Tubes Used in the DIRC of BaBar: Effect of Magnetic Field and of Helium"*, Talk given at 2nd International Conference on New Developments in Photodetection (Beaune 99), Beaune, France 1999, DAPNIA-99-03 (1999)

[9] M. Benkebil, *"La mesure des performances du détecteur Cerenkov DIRC de BaBar: Prototype-II et détecteur final"*, *Thesis*, Université de Paris VII, LAL 99-15 (1999)

[10] Electron Tubes Limited (formerly: Thorn EMI Electron Tubes), Bury Street, Ruislip, Middlesex HA47TA, U.K.

[11] P. Bailly, *Nucl. Inst. Meth.* **A432** (1999) 157

[12] C. Beigbeder *et al.*, *"BaBar DIRC Electronics Front-End Chain*, LAL-RT-97-09 (1997)

[13] B. Ratcliff and S. Spanier, *"DIRC Dreams"*, Talk given at 3rd International Workshop on Ring Imaging Cerenkov Detector (RICH 98), Ein Gedi, Dead Sea, Israel 1998, SLAC-PUB-8064 (1999)