**DIRC - The Particle Identification System for BaBar**

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**Outline:**

- DIRC Concept and Design
- Operational Issue Highlights
  - details in second DIRC talk, Sunday.
- Detector Performance
  - Detector Resolution
  - Photon Yield
- Physics Application Examples

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RICH2002, Nestor Institute, Pylos, June 2002
Novel RICH detector used for the first time in BABAR

DIRC combines with dE/dx from drift chamber and vertex detector (mostly in the $1/\beta^2$ region) as hadronic particle identification system for BABAR.

The BABAR-DIRC Collaboration


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b CEA-Saclay,
c LPNHE des Universités Paris 6 et Paris 7
d LAL, Université Paris Sud
e Ecole Polytechnique, LPNHE
f Laboratoire d'Annecy-le-Vieux, CNRS/CEA/Grenoble
g Lawrence Berkeley National Laboratory
h University of California, Santa Barbara
i Colorado State University
j University of Cincinnati
Covering all B Decays at BABAR requires Particle Identification (PID) up to 4.2 GeV/c momentum.

- $1.7 < |p| \leq 4.2$ GeV/c
  Pion/Kaon separation in rare charmless decays, e.g., $B \rightarrow \pi^+\pi^- / B \rightarrow \pi^\pm K^\mp$
  time dependent decay asymmetry measures $\sin(2\alpha)$

- $|p| < 2$ GeV/c
  B/$\bar{B}$ flavor tagging with Kaons via $b \rightarrow c \rightarrow s$ cascade
  PID using $dE/dx$ of the BABAR Vertex Detector and Drift Chamber is only effective for $|p| < 0.7$ GeV/c

**Design Constraints:**

- CsI Calorimeter needs to detect photons down to 20 MeV, thus small radiation length (<20%) and small radial size required.
- Radiation robustness (expect 10 krad within 10 year lifetime).
- $\pi/K$ separation at 4 GeV/c: 6.5 mrad
  $\rightarrow 3\sigma$ separation requires 2.2 mrad resolution
A charged particle traversing a radiator with refractive index $n$ with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos \theta_c = 1/n\beta$.

If $n > \sqrt{2}$ some photons are always totally internally reflected for $\beta \approx 1$ tracks.

**Radiator and light guide:** Long, rectangular Synthetic Fused Silica ("Quartz") bars

(Spectrosil: average $\langle n(\lambda) \rangle \approx 1.473$, radiation hard, homogenous, low chromatic dispersion;

144 bars: $490 \times 1.7 \times 3.5$ cm$^3$, polished to surface roughness $< 5\text{Å (rms)}$; square to better than 0.3 mrad.)

Square radiator bar $\rightarrow$ magnitude of $\theta_c$ preserved during internal reflections.
Typical DIRC photon:

$\lambda \approx 400$ nm,

~ 200 bounces,

~ 10-60 ns propagation time,

~ 5 m path in quartz.
• Only one end of bar instrumented; mirror attached to other (forward) end.

• Spectrosil wedge glued to readout end reduces required number of PMTs by ~ factor 2 and improves exit angle efficiency for large angle photons.

• Photons exit from wedge into expansion region (filled with 6m³ pure, de-ionized water).
  \( <n_{\text{water}}(\lambda)> \approx 1.346, \text{ Standoff distance} \approx 120 \text{ cm, outside main magnetic field; shielding: } B \leq 1 \text{ Gauss} \)

• Pinhole imaging on PMT array (bar dimension small compared to standoff distance).
  (10,752 traditional PMTs ETL 9125, immersed in water, surrounded by hexagonal “light-catcher”, transit time spread ~1.5nsec)

• DIRC is a 3-D device, measuring: x, y and time of Cherenkov photons.

• PMT / radiator bar combination plus track direction and location from tracking define \( \theta_c, \phi_c, t_{\text{propagation}} \) of photon.
3.1 GeV positrons on 9.0 GeV electrons

center of mass energy
\[ \approx \mathcal{M}_{\Upsilon(4S)} = 10.58 \text{ GeV/c}^2 \]
\[ \beta \gamma = 0.56 \]
THE BABAR DETECTOR

Instrumented Flux Return
19 layers of RPCs

Cherenkov Detector (DIRC)
144 synthetic fused silica bars
10,752 PMTs

1.5 T Solenoid

Drift Chamber
40 layers (24 stereo)

$e^+$ (3.1 GeV)

$e^-$ (9.0 GeV)

Electromagnetic Calorimeter
6,580 CsI crystals

Silicon Vertex Detector
5 layers of double sided silicon strips
THE DIRC IN BABAR

DIRC thickness:
- 8 cm radial incl. supports
- 19% radiation length
  at normal incidence

DIRC radiators cover:
- 94% azimuth, 83% c.m. polar angle

BABAR-DIRC Timeline:
- November 1998: installed SOB and one bar box, PMTs in water;
- April 1999: BABAR moves into beamline, added 4 more bar boxes;
- November 1999: all 12 bar boxes installed, start of first physics run.
DIRC OPERATIONAL EXPERIENCE: ISSUES

DIRC is Stable and Robust

• Calibration constants stable to typically rms < 0.1ns per year.

• No problems with water or gas systems.

The two most significant operational issues that have emerged during three+ years of running:

• Sensitivity of the DIRC to machine background interacting in the SOB (primarily DAQ issue)

• Concerns about PMT longevity due to PMT window degradation.

For more details on DIRC operations, see talk in Sunday session.
Concern: stability of photon yield

- PMT directly immersed in purified water since 1998;
- observed front glass corrosion in October 1999;
- no direct experience with maintaining high (>0.999) radiator reflection coefficient for 10 years.

Detailed study of photon yield using:

- LED pulser calibration,
- PMT aging tests,
- comparison of photon yield in real Bhabha and di-muon events separately for every radiator bar (box).

Consistent result:
1-2% photon yield loss per year.

→ very minor impact on PID performance over 10 year lifetime of DIRC.

Thanks to lead shielding, PMT rates acceptable even above design lumi.

PMT Rate vs. Luminosity shows that lead shielding essential in protecting DIRC from few MeV photon accelerator induced background (radiative Bhabhas etc).

Current shielding configuration “background safe” through 2002.

New TDC chips to be installed during shutdown Fall 2002: <5% deadtime at 2.5MHz rate.
DIRC “Ring” images:

- limited acceptance for total internal reflection,
- reflection ambiguities (initial reflection up/down, left/right, reflection off mirror, wedge → up to 16 \( (\theta_c, \phi_c) \) ambiguities per PMT hit),
- toroidal detection surface,

→ Cherenkov ring images are distorted:

complex, disjoint images

Low energy photons from accelerator hit Standoff Box.
At current luminosity that causes rates of 80-200 kHz/tube.

80-200 kHz \( \otimes \) 10,752 PMTs \( \otimes \) ± 300 nsec trigger window
→ 500-1300 background hits (~10% occupancy)
compared to
50-300 Cherenkov photons
Time information provides powerful tool to reject accelerator and event related background.

Calculate expected arrival time of Cherenkov photon based on

- track TOF
- photon propagation in radiator bar and in water

\[ \Delta t: \text{difference between measured and expected arrival time} \]

\[ \pm 300 \text{ nsec trigger window} \]
\[ (~500-1300 \text{ background hits/event}) \] → \[ \pm 8 \text{ nsec } \Delta t \text{ window} \]
\[ (1-2 \text{ background hits/sector/event}) \]
Calculate unbiased likelihood
for observed PMT signals to originate from e/μ/π/K/p track or from background.

(Likelihood: $\text{Pdf}(\theta_c) \otimes \text{Pdf}(\Delta t) \otimes \text{Pdf}(N_p)$)

Two complementary reconstruction algorithms:

• iterative process to maximize event likelihood, full correlation of all tracks;
• individual track fit provides $\theta_c$, $\sigma(\theta_c)$, number of signal/background photons.

Reflection ambiguities: $\Delta t$ cut reduces these from up to 16 to typically 2-3

Particle ID is based on log likelihood differences of the five hypotheses.

Example: Comparison of real event to simulated response of DIRC to e/π/K/p.
Single Photon Cherenkov angle resolution:

\[ \Delta \theta_{c,\gamma}: \text{difference measured } \theta_{c,\gamma} \text{ per photon solution and expected track } \theta_c \text{ (di-muons)} \]

\[ \sigma(\Delta \theta_{c,\gamma}) = 9.6 \text{ mrad} \]

Expectation: \(~9.5 \text{ mrad} \]

dominated by:

7 mrad from PMT/bar size,
5.4 mrad from chromatic term,
2-3 mrad from bar imperfections.

\(~10\% \text{ Background under } \Delta \theta_{c,\gamma} \text{ peak:}

combinatoric background, track overlap, accelerator background,
\delta \text{ electrons in radiator bar, reflections at fused silica/glue interface, ...} \]
Number of Cherenkov photons per track (di-muons) vs. polar angle:

Resolution of Cherenkov angle fit per track (di-muons):

Between 20 and 60 signal photons per track.

Very useful feature in BABAR environment:
higher momentum correlated with larger polar angle values
→ more signal photons,
better resolution ($\sim 1/\sqrt{N}$)

$\sigma(\Delta \theta_c) = 2.4$ mrad

Track Cherenkov angle resolution is within ~10% of design.
Should improve with advances in track- and DIRC-internal alignment.
• Select $D^0$ candidate control sample with mass cut ($\pm 0.5$ MeV/c$^2$)
• $\pi$ and $K$ are kinematically identified
• calculate selection efficiency and mis-id
• Correct for combinatorial background (avg. 6%) with sideband method.

$D^* \rightarrow D^0 \pi^- K^- \pi^+$

$\theta_C$ (rad)

Momentum (GeV/c)

M$_{K\pi\pi} - $ M$_{K\pi}$ (GeV/c$^2$)

Events

Example:

2.5<$|p|$<3 GeV/c
Kaon selection efficiency above 95% with mis-ID of 2-10% between 0.8-3GeV/c.

K selection efficiency for \( \mathcal{L}^K > \mathcal{L}^\pi \)
π/K separation power:

Measure Cherenkov angle resolution as function of track momentum for pions and kaons, kinematically identified in D* decays.

→ about 4.3σ separation at 3GeV/c, close to 3σ separation at 4GeV/c
Kaon Tagging for $\sin(2\beta)$ measurement:
- highest efficiency $\varepsilon$
- low mis-tag fraction $w$
- dominant contribution to measurement

\[
\sigma(\sin2\beta) \propto 1/\sqrt{Q.N_{CP}}
\]

<table>
<thead>
<tr>
<th>Flavor tag</th>
<th>Efficiency</th>
<th>$w$</th>
<th>$Q=\varepsilon(1-2w)^2$</th>
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<tbody>
<tr>
<td>Lepton</td>
<td>10.9 ± 0.3 %</td>
<td>8.9 ± 1.3 %</td>
<td>7.4 ± 0.5 %</td>
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<tr>
<td>Kaon</td>
<td>35.8 ± 0.5 %</td>
<td>17.6 ± 1.0 %</td>
<td>15.0 ± 0.9 %</td>
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<tr>
<td>NT1</td>
<td>7.8 ± 0.3 %</td>
<td>22.0 ± 2.1 %</td>
<td>2.5 ± 0.4 %</td>
</tr>
<tr>
<td>NT2</td>
<td>13.8 ± 0.3 %</td>
<td>35.1 ± 1.9 %</td>
<td>1.2 ± 0.3 %</td>
</tr>
<tr>
<td>Total</td>
<td>68.4 ± 0.7 %</td>
<td>35.1 ± 1.9 %</td>
<td>26.1 ± 1.2 %</td>
</tr>
</tbody>
</table>
Example for combination of DIRC likelihoods with drift chamber and vertex detector likelihoods

- Charged Hadron Spectra ($\pi^\pm$, $K^\pm$, $p/\bar{p}$) analysis.
- Cuts optimized to keep Mis-ID < 1-2% everywhere.
- In return, must accept somewhat lower ID efficiency especially at high momenta.
• The DIRC is a novel type of particle identification system, well matched to asymmetric B-factory environment, capable of $\pi$-K separation for momenta up to $\sim 4$ GeV/c.

• Three years of experience in PEP-II/BABAR B-factory mode: DIRC very reliable, robust, easy to operate, 99.2% of channels fully functional.

• Machine backgrounds up to 200 kHz/PMT at $4 \cdot 10^{33}/\text{cm}^2 \cdot \text{s}$ no problem for reconstruction; will install new TDC chips during Fall 2002 shutdown (for $10^{34}/\text{cm}^2 \cdot \text{s}$ luminosity).

• Single photon time and Cherenkov angle resolution and photon yield close to nominal.

• Track Cherenkov angle resolution within 10% of design.

• DIRC plays significant role in almost all BABAR physics analyses published to date.

• R&D program under way to prepare DIRC for $10^{34}/\text{cm}^2 \cdot \text{s}$ and beyond.