**Outline:**

- DIRC Concept and Design
- Operational Experience
  - Performance Highlights
  - Backgrounds and Longevity
- R&D Towards the Future
• DIRC grows out of our experience with the ring imaging Cherenkov detector in the SLD experiment, that was founded on a long partnership with Tom Ypsilantis—and called the CRID device.

• Blair Ratcliff had the brilliant idea of using the totally internally reflected light transported out to the end of the quartz bar radiators, to be his newly invented PID instrument.

\[
\text{DIRC = CRID Backwards}
\]

• The DIRC was the creation of a large international collaboration of US and French groups (see names).

• It has turned out to be a very robust detector

• And, is working very well in BaBar.
DIRC combines with dE/dx from CDC and SVT (mostly in the 1/β^2 region), to provide the hadronic particle identification system for BABAR.

The BABAR-DIRC Collaboration

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BaBar requires Particle Identification (PID) up to 4.2 GeV/c momentum.

There are two distinct momentum regions and task to be done:

- $1.7 \leq p \leq 4.2$ GeV/c
- $p < 2$ GeV/c

The Particle Identification is achieved using $dE/dx$ information from the Drift Chamber and the silicon vertex detector together with DIRC.

[$dE/dx$ is 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).**
- **π/K separation at 4 GeV/c; this requires 2.2 mrad angular resolution, to provide a 3σ separation.**
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
DIRC PRINCIPLE, PART I

- 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 $<n(\lambda)> \approx 1.473$, radiation hard, homogenous, low chromatic dispersion; 144 bars: $490 \times 1.7 \times 3.5$ cm$^3$, polished to surface roughness $<5\AA$ (rms); square to better than 0.3 mrad.)

- Square radiator bar → magnitude of $\theta_c$ preserved during internal reflections.

Typical DIRC photon:
- $\lambda \approx 400$ nm,
- $\sim 200$ bounces,
- $\sim 10$-60 ns propagation time
- $\sim 5$ m average path in bars.

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• 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 6m$^3$ pure, de-ionized water).

  ($<n_{\text{water}}(\lambda)> \approx 1.346$, Standoff distance $\approx 120$ cm, outside main magnetic field; shielding: $B < \sim 1$ 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 $\sim$1.5 nsec)

• **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.
**DIRC MEASUREMENTS**

- **DIRC measures photon arrival time at PMT position**

- **expected uncertainties**

\[
\Delta t = t_{arrival} - t_{propagation}
\]

\[
\chi_{PMT}, y_{PMT}, t_{arrival} \rightarrow \left\{ \begin{array}{l}
\theta_c, \\
\phi_c
\end{array} \right. 
\]

- per photon:
  \[
  \Delta \theta_c = \Delta \theta_{C, \text{track}} + \Delta \theta_{C, \text{dispersion}} + \Delta \theta_{C, \text{transport}} + \Delta \theta_{C, \text{imaging}} \\
  \sim 1-2 \text{ mrad}
  \sim 5.4 \text{ mrad}
  \sim 1-4 \text{ mrad}
  \sim 7.0 \text{ mrad}
\]

- per track:
  \[
  \Delta t^2 \sim \Delta t^2_{\text{PMT}} \sim (1.7 \text{ ns})^2
  \]

\[
\Delta \theta_{\text{track}}_c \sim \Delta \theta_{\text{photon}}^c \frac{1}{\sqrt{N_{\text{photons-per-track}}}} \oplus \Delta \theta_{C, \text{track}}^2
\]
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

$\Delta t$: difference between measured and expected arrival time

$\pm 300$ nsec trigger window

($\sim 500$-$1300$ background hits/event)

$\Delta t$ window

$\pm 8$ nsec

$\pm (1$-$2$ background hits/sector/event)
Single Photon Cherenkov angle resolution:

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

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

Expectation: \( \sim 9.5 \text{ mrad} \)

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

\( \sim 10\% \) Background under \( \Delta \theta_{c,\gamma} \) peak:
- combinatoric background, track overlap, accelerator background,
- \( \delta \) electrons in radiator bar, reflections at fused silica/glue interface, ...
**DIRC PERFORMANCE**

Number of Cherenkov photons per track (di-muons) vs. polar angle:

![Graph showing number of Cherenkov photons per track (di-muons) vs. polar angle.](image)

- Data (di-muon tracks)
- Monte Carlo Simulation

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

![Graph showing resolution of Cherenkov angle fit per track (di-muons).](image)

- $\sigma(\Delta \theta_C) = 2.4$ mrad

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 ($\sim 1/\sqrt{N}$)

Track Cherenkov angle resolution is within $\sim 10\%$ of design.

Should improve with advances in track- and DIRC-internal alignment.

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Concern: stability of photon yield

- Observed PMT front glass corrosion;
- 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.
PEP-II Luminosity and currents are rapidly increasing
- $4 \times 10^{33} \text{ cm}^{-2} \cdot \text{s}$ now,
- expect $>5 \times 10^{33} \text{ cm}^{-2} \cdot \text{s}$ at the end of the 2001/2002 run,
- 1-2 $\times 10^{34} \text{ cm}^{-2} \cdot \text{s}$ in 2004/5;
- $10^{35} - 10^{36} \text{ cm}^{-2} \cdot \text{s}$ discussed (“SuperBABAR”).

$\Delta t$ cut very effective in removing accelerator induced background from reconstruction.

But high counting rates cause inefficiency of present DIRC DAQ:

~5% inefficiency at 250 kHz
In January 2001, installed new, more homogenous lead shielding (5-7cm of lead in upper 2/3, 2-3cm in lower 1/3 of shield).

Scaler rates acceptable even above design luminosity.

Current shielding configuration “background safe” through 2002.

New TDC chips to be installed during shutdown Fall 2002: <5% deadtime at 2.5MHz rate.
**DIRC PARTICLE ID PERFORMANCE**

\[ \text{Select } D^0 \text{ candidate control sample with mass cut (±0.5 MeV/c}^2) \]

- $\pi$ and K are kinematically identified
- Calculate selection efficiency and mis-id
- Correct for combinatorial background (avg. 6%) with sideband method.

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**Example:**

\[ 2.5 < |p| \leq 3 \text{GeV/c} \]

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~200,000 D⁰ reconstructed from 9 fb⁻¹ of data.
average K selection efficiency: 88%
average π mis-id: 2%
average rejection factor: 44
- MC from Charged Hadron Spectra analysis.
- Cuts different than the “standard”...designed to keep mis-ID <1-2% everywhere.
- In return, must accept somewhat lower ID efficiency especially a high momenta
- Note that mis-ID ≥ p̅ mis-ID due to different interaction probability.
• The lab’s goals for the luminosity for PEP-II/BaBar, in the midterm, is to integrate ~ ½ atobarn;

• Long-term, there is discussion of a possible $30^{36}$ cm$^{-2}$sec$^{-1}$ machine delivering 10 atobarn physics sample.

• Can we remove the 6 tons of water in DIRC and improve the particle ID performance for this era?
LONG-TERM LUMINOSITY

Luminosity Profile "Adiabatic Scenario"

From J. Seeman 10/26/2001

Realistic

LhcB, Btev?

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THE R&D PROGRAM

• Cosmic ray telescope test bed;

• Evaluate new multianode photodetectors;

• On the basis of measured performance, work on optimal focusing arrangement.
COSMIC RAY TELESCOPE

- Four layers of 13” thick steel absorber to harden muon spectrum (400 MeV to 2.5 GeV in 400 MeV steps).
- Trigger counters 1” thick and 60” x 90”
- Scintillation hodoscope for tracking
  - ~1 mrad angular accuracy
  - ~3 mm spatial accuracy
COSMIC RAY SETUP

Side view

Sims
a) $T_1$: $1^\circ \times 24^\circ \times 6$
$T_2$: $1^\circ \times 24^\circ \times 6$
$T_3$: $1^\circ \times 1^\circ \times 6$
$b) \text{ Iron: } 3\times 11.7^\circ \times 6^\circ \times 9.9^\circ$
$1\times 13^\circ \times 4^\circ \times 9^\circ \times 9.1^\circ$
c) Hodoscopes: $x, y, \theta$
$2a, b_x, y$

Hodoscope_2 ($10^\circ \times 28^\circ \times 1/2^\circ$, ~3 mm resolution)

Tr(1) Movable

Mirror

Pixel Detector

DIRC Movable

Hodoscope_1 ($10^\circ \times 28^\circ \times 3/13^\circ$, ~5 mm resolution)

Py (11.7$^\circ \times 9^\circ \times 61.1^\circ$)

Fe (11.7$^\circ \times 9^\circ \times 61.1^\circ$)

Fe (11.7$^\circ \times 9^\circ \times 61.1^\circ$)

Fe (11.7$^\circ \times 9^\circ \times 61.1^\circ$)

Floor Tr(6)

13$^\circ$

3$^\circ$

11.7$^\circ$

62$^\circ$

2$^\circ$

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Requirement:

- compact devices;
- good quantum efficiency (20-30%);
- good spatial resolution (~ mm);
- good time capability (~ 150 psec);

→ embarking on a program to evaluate performance of the new devices.
1) Hamamatsu flat panel 64-channel PMT [H8500].

Specifications:
- 8x8 array of 6 mm x 6 mm pads.
- gain ~ a few $10^6$
- rise time < 1 nsec., with $\pm 150$ psec spread
- cross talk ~ few %
- gain variation across 64 anodes ~ x 2
- active area 49.7 mm x 49.7 mm
- total package size 50.5 mm x 50.5 mm
- bi-alkali cathode
- 800-1100 volts HV
NEW PHOTODETECTORS

2. DEP HPD (hybrid photodiodes)

a) Electrostatically focusing device
[HPD PP0380 AU]
with 61 channels of 2x2 mm pads.

b) Proximity focusing device
[HPD 0380 AJ]
with 73 channels with 2x2 mm pads.

Both HDP’s come with direct connection from the pad to the outside world.
Hamamatsu 64-Channel Multi-Anode PMT

Timing study with a single threshold, with an amplifier:
(preliminary)

Counts

$\sigma \sim 189 \text{ ps}$

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DEP HPD [61 pixel of (2x2) mm]
DEP HPD [PPO380AU]

S20 photocathode: 72 mm Ø active

- Vacuum
- Photocathode (-300V)
- Photoelectron
- Electrode
- Optical input window
- Si pixel array (61 elements)
- Ceramic carrier
- Solder bump bonds
- Binary electronics chip

Pixel size 2x2 mm square

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DEP 73-Channel Proximity Focusing HPD (0380AJ)
• **Barrel**

  – Use magnetic shielding volume of existing SOB, conceptional geometry

• **End Cap**

  – With improved performance, $\pi/K$ separation in the forward region could be increased.
R&D PROGRAM SUMMARY

- Cosmic ray telescope now beginning operation,
- New multianode, single-photon detectors are now in hand,
- First results look promising,
CONCLUSIONS

- Brilliant idea for a $\pi/K$ detector in B factory energy regime!

- Robust device delivering close to promised performance.

- Particle Identification is important in almost all BaBar physics analyses.

- With the current upgrade of DAQ electronics should be OK up to luminosities x10 design ($10^{34}$ cm$^{-2}$ sec$^{-1}$).

- R&D for improved PID performance, and to survive in a high-luminosity environment, is under way—expect results in Fall of 2002.
Please join me in thanking our hosts for their hospitality and this stimulating conference—continuing a long line of such meetings, since 1977.

I have the privilege in welcoming you all to the next meeting of the Instrumentation for Colliding Beams in 2005, to Stanford—hosted by SLAC and Stanford University.

I wish you all safe travels home!