Rethinking Particle Identification For BaBar: The DIRC Imaging Cherenkov Detector

Outline:
• “The Past is never dead. It’s not even Past.” (Faulkner)
• The BaBar DIRC
• Future directions for DIRC

Blair Ratcliff

"Physics and Friendships" - Leith
1. B Tagging requires efficient PID for hadrons and leptons with low Mis-ID:

- Effective Tagging Efficiency = $\epsilon(1-2w)^2$ where $\epsilon$ is fraction of events tagged and $w$ is the fraction of wrong sign tags
- Need to cover as much solid angle as possible with all detectors
- Hadronic momenta fairly soft (kaons up to about 2 GeV/c) and correlated with angle. $dE/dX(1/\beta^2)$ alone is not nearly enough.

![Average Momenta and Angular Distribution](image)

- 9 on 3.1 GeV/c
- From SLAC-R373 (1991) Workshop on Physics and Detector Issues for a High Luminosity Asymmetric B Factory at SLAC
2. Final state reconstruction requires efficient PID up to around 4GeV/c

- $dE/dX$ PID separation in the low momentum region “~ for free”, but covers little of the momentum range.
- Hadronic momenta can be hard for low multiplicity decays (kaons up to about 4 GeV/c)
- Strong angle versus momenta correlation.

Momentum Distribution

\[ B^0 \rightarrow \pi^+ \pi^- \]

Mean Momentum Versus

\[ \text{Cos } \theta \text{ for } B^0 \rightarrow \pi^+ \pi^- \]

- 9 on 3.1 GeV/c
- From SLAC-R373 (1991) Workshop on Physics and Detector Issues for a High Luminosity Asymmetric B Factory at SLAC
“It is generally agreed that high quality hadronic particle identification is fundamental to the central mission of understanding CP violation at the B Factory, but there is as yet no clear or “consensus” technical solution for such a detector.”

“Everyone” wants high quality calorimetry (such as can be provided by CsI crystals), but such devices cost a great deal per unit volume, and the cost scales roughly like the inner radius squared. Moreover, no one wants to see the high quality (expensive) calorimetry compromised by excessive mass in front. Thus, the essence of the particle identification problem is that there is no approximately massless, thin particle identification device known with adequate performance.

Ideal PID Device needs to be:
1. Thin
2. Low (uniform) mass
3. ~ Complete solid angle coverage
4. Cover ~ 0.5 to 4 GeV/c momentum range with best performance needed forward
5. Fast (to perform in high lumi/high background environment)
6. Positive ID for both wanted and unwanted particles (to reduce mis-ID)
7. Robust operationally in a Factory environment
8. And inexpensive is better!
Broad based BaBar R&D and workshops (see e.g., SLAC R-373 (1991) ... and BaBar PID workshop notes)

Techniques being considered by various BaBar groups included fast TOFs, dE/dX in tracking chambers, and, especially, new kinds of Cherenkov counters, both imaging and threshold (aerogel and pressurized gas) types.

The performance potential for extremely high quality, positive-ID ring imaging Cherenkov devices (and our history with Cherenkov detectors and Ring Imagers such as CRID) suggested Group B’s direction, with a variety of potential ring imaging techniques being seriously explored.
Large Aperture Pressurized Gas Cherenkov Hodoscope
( H. H. Williams, A. Kilert, and D.W.G.S Leith, NIM 105 (1972) 483-491. )

Used in E-41, E-67, E-75, E-85, LASS
38 cell C1 hodoscope with Freon 114 fill + TOF

CRID Detector at SLD

• Taught us about the merits of “positive” ID for both wanted and unwanted particles.
• As a seemingly peripheral issue: CRID teaches us that some Cherenkov light from particles near $\beta=1$ is always captured in a radiator when $n$ exceeds $\sqrt{2}$. The collection ratio is rather high for most angles and particle velocities.
Circa 1990-The recognition of the “DIRC Principle”.

DIRC PRINCIPLE ➔ A long bar(plate) with rectangular bar cross sections retains all information about the magnitudes of the angles in its coordinate system during photon transport to the end.

- Requirements on figure and parallelism are “modest” even for a large number of bounces.
- Radiator is simultaneously a Cherenkov light radiator and a light guide.
- Imaging can occur in a camera outside the path of the particles, where angles measured can be transformed back into Cherenkov angles (up to discrete ambiguities), and precise timing of each photon can be measured (limited almost entirely by the Photo-detector speed, and chromaticity).
- ~1990 I recall describing this “epiphany” to David (over lunch?). Amusing idea, but at the time I was thinking about using wire chamber photo-cathodes which worked in the UV, but with the limited speed of such detectors, and chromatic dispersion, Rayleigh and surface scattering, and absorption, etc. in the radiators, it didn’t pan out as a workable device.
- Finally (in 1992) I tried a design using visible-light sensitive PMT’S which required taking the Cherenkov light out of magnetic field….and everything clicked!
From “The DIRC Counter: A Particle Identification Device for the B Factory” BaBar Note 92 (1992), B. Ratcliff
• 3 measurements ($\alpha_x$, $\alpha_y$, $t_p$) available to measure the 2 Cherenkov angles ($\theta_c$, $\varphi_c$) with respect to a known track $\Rightarrow$ nominal over-constraint at the single p.e. level.

• Depending on the resolutions achieved, single photon timing can provide:
  - Spatial separation of events along the bar.
  - A reliable tag of beam crossings (~ 4 ns at BaBar)
  - Separation of signal hits from backgrounds
  - Separation of some of the ambiguities
  - A measurement of Cherenkov polar angle and the TOF resolution on each track that both improve like $\sqrt{N_{PE}}$. Many modern counters (see below) exploit this approach using very fast modern parallel multiplication PMTs or MCP-PMTs.

**Issues above the line were understood by BaBar Note 92 (1992).**

• Can also measure the wavelength photon by photon and correct for chromatic dispersion. This possibility wasn’t understood until we saw DIRC data. It has now been demonstrated in the FDIRC prototypes (see below).
Set up a 'quickie' to look @ end injected ring piece

Emission thru 3 - 30 cm bars. Results below.

Setup 1

[Diagram showing laser setup]
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>RICH →</td>
<td><strong>Ring Imaging CHerenkov Counter</strong> (renamed from the earlier name <strong>CRID</strong> by the Ypsilantis, Seguinot et al. Cherenkov Imaging R&amp;D group, at CERN, at least in part, because they had no money)</td>
</tr>
<tr>
<td>CRID →</td>
<td><strong>Cherenkov Ring Imaging Detector.</strong> Name retained at SLD for PID system</td>
</tr>
<tr>
<td>DIRC →</td>
<td><strong>Detection of Internally Reflected Cherenkov</strong> (light)</td>
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</tbody>
</table>
DIRC combines with dE/dx from CDC and SVT (mostly in the 1/β² region) as hadronic particle identification system for BABAR.
• A charged particle traversing a radiator with refractive index $n$ with $\beta = \frac{v}{c} > \frac{1}{n}$ emits Cherenkov photons on cone with half opening angle $\cos \theta_c = \frac{1}{n\beta}$.

• 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 (average $\langle n(\lambda) \rangle \approx 1.473$, radiation hard, homogenous, low chromatic dispersion; 144 long bars, $490 \times 1.7 \times 3.5$ cm$^3$, polished to surface roughness $<5$ Å ($rms$); square to better than 0.3 mrad.)

• Rectangular radiator bar $\rightarrow$ magnitude of angles 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.
• 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).

\[ \langle n_{\text{water}}(\lambda) \rangle \approx 1.346 \text{, Standoff distance } \approx 120 \text{ cm, outside main magnetic field; shielding: } B < \sim 1 \text{ Gauss} \]

• Pinhole imaging on PMT array (bar dimension small compared to standoff distance).

\(10,752\) traditional dynode 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.
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 Radiators
Drift Chamber
Silicon Vertex Detector
Electromagnetic Calorimeter

e^- (9.0 GeV)
e^+ (3.1 GeV)

DIRC Standoff Box and Magnetic Shielding

1.5 T Solenoid

Drift Chamber

Central Support Tube
Support Gusset
Bar Box
Bucking Coil
Strong Support Tube
Standoff Box

Quartz Bar
Quartz Wedge
Quartz Window

M Mirrors
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) $\rightarrow$ $\pm 8$ nsec $\Delta t$ window ($1$-$2$ 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: ~9.5 mrad

dominated by:

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

~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, ...
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

"Physics and Friendships" - Leith

Blair Ratcliff, SLAC
• 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.

example: $2.5 < |p| \leq 3$ GeV/c
Four different Likelihood Ratio selectors

Four different ECOC (error correcting output code) selectors based on decision trees
• Modern DIRC designs typically utilize much faster PMTs with more (and smaller) pixels. (MCP-PMTs can even operate inside a magnet)

• New designs typically emphasize one or more time sensitive elements including
  1. Time imaging of Cherenkov angles,
  2. Chromatic correction photon by photon
  3. TOF of particle.
iTOP Counter at BELLE-II

- Quartz radiator
  - With mirror and expansion block
- Mechanics, Quartz Bar Box (QBB)
- MCP-PMT + Readout electronics
  - 32 PMTs x 16ch = 512ch

Challenging Reconstruction - many ambiguities and multivariate PID separation

From K. Inami et. al., speaking on behalf of the Belle-II PID Group at RICH 2013.

"Physics and Friendships" - Leith

Blair Ratcliff, SLAC
FDIRC Prototype (for SuperB)

- 3-D readout device using BaBar Barboxes & new camera
- Much more compact camera than Babar (but larger than iTOP at Belle-II)
- More ambiguities than BaBar but many fewer than iTOP at Belle-II.
- Timing used to correct chromaticity, resolve ambiguities, separate signal from background, and provide modest separation performance improvement.
- See arXiv:1410.0075 (TBP in NIMA); Dey, Borsato, Arnaud, Leith, Nishimura, Roberts, Ratcliff, Varner, Va’Vra

Correcting chromaticity

- All track angles
  - Backward photons
  - $n_x < 10$
  - $|d\text{TOP}_{\text{back}}| < 2.5$ ns

No chromatic correction

- $\sigma \sim 9.34$ mrad

With chromatic correction

- $\sigma \sim 8.16$ mrad
Reusing DIRC Bar Boxes-TORCH(for LHCB)

- Particle ID is achieved in TORCH through 3-D measurement emphasizing time of flight (TOF) of charged particles. Need Cherenkov angles to determine photon TOP

- Goal
  - To provide $3\sigma$ K-π separation for a momentum range 2-10 GeV/c (up to kaon threshold of RICH1)

- Requirement
  - TOF difference between K-π is 37.5ps at 10 GeV/c at 9.5m
  - Required per-track time resolution set at 10-15ps

- Prototype being built soon using a BaBar Barbox
Reusing Bar Boxes - GLUEX at JLAB

Particle ID achieved with DIRC barboxes and FDIRC-like readout, doing TOF for each photon.

Final design uses 4 BaBar Barboxes, which have been allocated, and will be transported very soon to JLAB.
- DIRC based devices have become the “Gold Standard” for PID in the low momentum regime.

- Fast timing can enhance the performance and decrease background sensitivity
  - At high luminosity, fast timing becomes crucial.

- There are many new DIRC-like devices now being built or in the R&D phase which will reframe the technology.

- After nearly 15 years, life goes on for BaBar DIRC’s Barboxes.
Group B represents an older organizational style for doing science, emphasizing a long term collaborative “family” of colleagues, strong technical capabilities within the group, continuous detector R &D and fabrication of large scale detectors, leading to continuous front line physics output.

It was a poster child for “Pief’s Way”, which was a “sociology” for doing outstanding science created by Pief and other SLAC colleagues of the early generations. A similar spirit existed across much of HEP, but at SLAC and within Group B, under David’s leadership, it worked wonderfully well.

BaBar succeeded in extrapolating much of this sensibility into a large modern international collaboration, which is very successful technically, scientifically, socially, and was the most joyful of the large collaborations that I know.

Many thanks to David for his outsized contributions to making all of this a reality during his long and outstanding career!

I am very lucky and grateful to have been along for the ride.