New Results on Focusing DIRC

Outline:

• DIRC Concept
• BABAR-DIRC Performance
• R&D for Focusing DIRC
  – Prototype Design
  – Photodetector Selection
  – Performance in Beam Test

from the conference poster

Poster shows compilation of results of PMT R&D for Focusing DIRC

Jochen Schwiening
for the Focusing DIRC group at SLAC
Detection of Internally Reflected Cherenkov Light

Novel Ring Imaging CHerenkov detector based on total internal reflection of Cherenkov light used for the first time in BABAR for hadronic particle identification.

Recent improvements in photon detectors have motivated R&D efforts to improve the successful BABAR-DIRC and make DIRCs interesting for future experiments (Super B-Factory, Panda, GlueX, ILC)

Focusing DIRC R&D group at SLAC:
- Ivan Bědajánek
- Jonathon Coleman
- Gholam Mazaheri
- Jochen Schwiening
- Jaroslav Va’vra
- Jose Benitez
- David W.G.S. Leith
- Blair N. Ratcliff
- Josef Uher

Acknowledgements:
- M. McCulloch and B. Reif (prototype construction)
- M. Barnyakov, M. Ji, S. Kononov, and K. Suzuki (beam test)
**DIRC Designs**

**BABAR-DIRC**  
*operating since 1999*

**3D imaging**
- a) x-coordinate
- b) y-coordinate
- c) time ($\sigma \approx 1.7$ns)

PID primarily from x&y coordinates

**TOP counter (Nagoya)**  
*proposed for BELLE*

**2D imaging**
- a) x-coordinate
- b) time ($\sigma < 100$ps)

PID from x&time coordinates

**Focusing DIRC prototype (SLAC):**

**3D imaging**
- a) x-coordinate
- b) y-coordinate
- c) time ($\sigma < 130$ps)

PID from all three coordinates
Work with manufacturers to develop and characterize one or more fast, pixelated photon detectors including:

- basic issues such as cross talk, tube lifetime, and absolute efficiency
- operation in 15 kG field

Measure timing resolution, uniformity, and cross talk in lab using fast laser system

Measure single photon Cherenkov angular resolution in a test beam

- use a prototype with a small expansion region and mirror focusing, instrumented with a number of candidate pixelated photon detectors and fast (25 ps) timing electronics.
- use 3D imaging (x&y coordinate and time)
  over-constraint very useful to deal with backgrounds and to develop corrections

- demonstrate performance parameters
- demonstrate correction of chromatic production term via precise timing
- measure $N_0$ and timing performance of candidate detectors.

See also poster #222
“Progress on the Focusing DIRC R&D”
J. Benitez et al.
• Charged particle traversing a radiator with refractive index \( n \) with \( \beta = v/c > 1/n \) emits Cherenkov photons on cone with half opening angle \( \cos \theta_c = 1/\beta n(\lambda) \).

• 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)

• Photons exit via wedge into expansion region (filled with 6m\(^3\) pure, de-ionized water).

• 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, ~30mm diameter)

• BABAR-DIRC is a 3-D device, measuring: \( x, y \) and time of Cherenkov photons, defining \( \theta_c, \phi_c, t_{\text{propagation}} \) of photon.
  (time measurement used primarily for rejecting accelerator background and resolving ambiguities)
BABAR-DIRC Operational Experience

Over six years of experience in PEP-II/BABAR B-factory mode §:

**DIRC is reliable, robust, easy to operate**

- DIRC reached performance close to design within first year of running.
- DIRC plays significant role in almost all BABAR physics analyses.
- Calibration constants stable to typically $rms < 0.1\text{ns}$ per year.
- 98% of channels fully functional after 7+ years immersed in ultra-pure water.
- No problems with water or gas systems.

Most significant operational issue: sensitivity to accelerator induced background interacting in the water of the Standoff Box (primarily a DAQ issue)

→ Added additional shielding; upgraded TDCs in 2002.
→ Time measurement essential in dealing with backgrounds.

Single Photon resolution

$\sigma(\Delta \theta_{c,\gamma}) = 9.6$ mrad

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

$\sigma(\Delta t_{\gamma}) = 1.7$ nsec

$\Delta t_{\gamma}$: difference between measured and expected photon arrival time

π/K separation power:

Measure Cherenkov angle resolution as function of track momentum for pions and kaons, kinematically identified in $D^*$ decays ($D^{*-} \rightarrow D^0 \pi^-$, $D^0 \rightarrow K^- \pi^+$).

→ about $4.3\sigma$ separation at $3\text{GeV/c}$, close to $3\sigma$ separation at $4\text{GeV/c}$
### BABAR-DIRC Performance

- **Typical PMT hit rates:** 200kHz/PMT  
  (few-MeV photons from accelerator interacting in water)
- **Timing resolution:** 1.7ns per photon  
  (dominated by transit time spread of ETL 9125 PMT)
- **Photon yield:** 18-60 photoelectrons per track  
  (depending on track polar angle)
- **Cherenkov angle resolution:** 9.6mrad per photon  →  2.4mrad per track

### Limited by

<table>
<thead>
<tr>
<th>BABAR-DIRC</th>
<th>Improvement strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of bar image</td>
<td>~ 4.1mrad</td>
</tr>
<tr>
<td>Size of PMT pixel</td>
<td>~ 5.5mrad</td>
</tr>
<tr>
<td>Chromaticity (n=n(λ))</td>
<td>~ 5.4mrad</td>
</tr>
</tbody>
</table>

### Focusing DIRC

- Improve single photon timing and angular resolution, decrease size of Cherenkov ring expansion region

![Chart showing Δθ_c (mrad) vs momentum (GeV)](chart)

**4mrad @ 5GeV/c**
Chromatic Effects in DIRC

**DIRC detector bandwidth**

Defined by choice of photodetector, glue, medium in expansion region, and loss during photon propagation.

Optimization: smaller bandwidth → fewer signal photons, smaller chromatic error

Typical DIRC bandwidth: $\lambda=300…650\text{nm}$, $<\lambda>=410\text{nm}$

**Chromatic effect at Cherenkov photon production**

Cherenkov photons produced according to $\cos \theta_c(\lambda) = 1/\beta n(\lambda)$

$n(\lambda)$: refractive (phase) index $n(\lambda)=1.49…1.46$

$\theta_c(\lambda)$: opening angle of Cherenkov cone $\theta_c(\lambda, \beta=1)=835…815\text{mrad}$

**Chromatic time dispersion during photon propagation**

Photons propagate in dispersive medium with group index $n_g(\lambda)$

\[ \text{time-of-propagation} = \text{path-in-bar} \cdot n_g(\lambda)/c_0 \]

$n_g(\lambda)$: group index $n_g(\lambda)=1.57…1.47$

Red photons propagate faster than blue photons
Photodetector Selection

Main criteria for selection

- **Timing resolution**
  - timing resolution $\sigma_t < 200\text{ps}$ required for chromatic correction
- **Pixel size**
  - small pixels allow reduction of size of expansion region without compromising angular resolution
- **Single photon efficiency**
  - need quantum efficiency $\sim 20\text{-}30\%$ and $>70\%$ packing efficiency to match BABAR-DIRC photon yield

Main candidates

- Burle 85011-501 MCP-PMT
- Burle 85011-430 MCP-PMT
- Burle 85021-600 MCP-PMT
- Hamamatsu H-8500 Multianode PMT
- Hamamatsu H-9500 Multianode PMT

Measure timing resolution, uniformity, and cross talk

- PiLas laser diodes (35ps FWHM, $\lambda = 407 / 635\text{ nm}$)
- Scan PiLas across PMT face using motion-controlled x&y stage (typical step size 200-500$\mu$m)
Burle 85011-501 MCP-PMT

- 64 pixels (8×8), 6.5mm pitch
- bialkali photocathode
- 25µm pore MCP, 6mm MCP-cathode distance
- gain ~5×10^5
- timing resolution ~70ps, distribution has tail
- good uniformity
Hamamatsu H-8500 Flat Panel Multianode PMT

- 64 pixels (8×8), 6.1mm pitch
- bialkali photocathode
- 12 stage metal channel dynode
- gain ~$10^6$
- timing resolution ~140ps

Efficiency relative to Photonis PMT
Detector Optics

Radiator
- use 3.7m-long bar made from three spare high-quality BABAR-DIRC bars
- use same glue as BABAR-DIRC (Epotek 301-2), wavelength cut-off at 300nm

Expansion region
- use smaller stand-off distance (25% of BABAR-DIRC)
- coupled to radiator bar with small fused silica block (RTV SES-403)
- filled with mineral oil (KamLand experiment) to match fused silica refractive index
- include optical fiber for electronics calibration
- would ultimately like to used solid fused silica block

Focusing optics
- spherical mirror from SLD-CRID detector (focal length 49.2cm)

Photon detector
- use array of flat panel PMTs focal plane
- readout to CAMAC/VME electronics
Prototype Readout

For 2005 beam tests read out two Hamamatsu H-8500 MaPMTs and three Burle 85011-501 MCP-PMTs (total of 320 pixels)

- Elantec 2075EL amplifier (130x) on detector backplane
- SLAC-built constant fraction discriminator
- Ten Phillips 7186 TDCs (25ps/count) for 160 channels
- Four SLAC-built TDC boards: TAC & 12 bit ADC (~31ps/count) for 128 channels
- Read out only pixels close to expected hit pattern of Cherenkov photons (155 pixels used in analysis shown today)
- Calibration with PiLas laser diode (~35ps FWHM) to determine and monitor TDC channel delays and ps/count calibration

Reconstruction:
	nice aspect of DIRC: geometry plus simple optics defines many photon properties
	→ Pixel with hit \((x_{\text{det}}, y_{\text{det}}, t_{\text{hit}})\) defines 3D photon propagation vector in bar and Cherenkov photon properties \((\text{assuming } 90^\circ \text{ track, } \beta=1, \langle \lambda \rangle = 410\text{nm})\)
	\(\alpha_x, \alpha_y, \cos \alpha, \cos \beta, \cos \gamma, L_{\text{path}}, n_{\text{bounces}}, \theta_c, \phi_c, t_{\text{propagation}}\)
Beam Test Setup

- Prototype located in beam line in End Station A at SLAC
- Accelerator delivers 10 GeV/c electron beam (e⁻)
- Beam enters bar at 90° angle.
- 10 Hz pulse rate, approx. 0.1 particle per pulse
- Bar contained in aluminum support structure
- Beam enters through thin aluminum foil windows
- Bar can be moved along long bar axis to measure photon propagation time for various track positions
- Trigger signal provided by accelerator
- Fiber hodoscope (16+16 channels, 2mm pitch) measures 2D beam position and track multiplicity
- Cherenkov counter and scintillator measure event time
- Lead glass calorimeter selects single electrons
- All beam detectors read out via CAMAC (LeCroy ADCs and TDCs, Phillips TDC, 57 channels in total)
Beam Test Data

• In July, August, and November 2005 we took beam data during five periods, lasting from few hours to several days.

• Total of 4.1M triggers recorded, 10 GeV/c e^-

• Reconstructed ~200k good single-track events

• Beam entered the radiator bar in 7 different locations.

• Recorded between 100k and 700k triggers in each beam location.

• Photon path length range: 0.75m – 11m.

• Simulated full detector with all efficiencies in Geant4.
Event selection:
- require single track signal in hodoscope
- require charge in lead glass to be consistent with single electron
- require start counter TDC signal in expected time window

Data corrections:
- use hodoscope beam spot to correct the path of photons in bar
- use ADC measurement in start counters to correct TDC value for time walk → resulting start counter resolution ~35ps
- use PiLas laser diode to calibrate prototype TDCs and cable delays → all pixels aligned in time
Cherenkov angle for all pixels with signal

- Have to assign angles to pads assuming that photons hit center of pad (single photons, no center-of-gravity interpolation possible)

- Clear pixelization effect visible,
  \( \theta_c \) resolution \( \approx 14-16 \text{ mrad} \)
  (total pixel size \( \approx 21 \text{ mrad} \) in \( \theta_c \) space)

- \( \theta_c \) resolution from pixels worse than expected, should improve with better alignment (plus systematic checks of hardware, calibration, and software)
Precise timing at 50ps level requires

- careful calibration of TDC conversion factor
  - Phillips 7186: nominal 25ps/count, varies across measurement range
- monitoring of electronics delays
  - to correctly align pixels in time space
  - temperature variations in hall matter
- use accelerator trigger signal as event time
  - and monitor event time using start counter (35ps resolution)
- correction for charge-sharing and cross talk

Challenging task, PiLas calibration system
  very important

Results shown today do not have
final calibrations and delays yet
Example for one selected detector pixel in position 1

- First peak \( \sim 81 \text{cm} \) photon path length
- Second peak \( \sim 930 \text{cm} \) photon path length
- Measure time of propagation (TOP)
- Calculate expected TOP assuming average \( <\lambda> \approx 410 \text{nm} \)
- Plot \( \Delta \text{TOP} \): measured minus expected time of propagation
- Fit to double-Gaussian
- Observe clear broadening of timing peak for mirror-reflected photons
Cherenkov angle from time of propagation (TOP)

- Use measured TOP for each pixel
- Combine with calculated photon path in radiator bar
- Calculate group index \( n_g(\lambda) \) from
  \[
  n_g(\lambda) = c_0 \cdot \text{TOP} / \text{path}
  \]
- Calculate refractive (phase) index \( n(\lambda) \) from group index
- Calculate photon Cherenkov angle \( \theta_c \) for \( \beta=1 \)
  \[
  \theta_c(\lambda) = \cos^{-1}(1/n(\lambda))
  \]
- Resolution of \( \theta_c \) from TOP is 6-7mrad
  for photon path length above \( \sim 4 \text{m} \).
- Expected to improve with better calibration.
Summary of preliminary results

- $\theta_c$ resolution from pixels is 14-16mrad for entire range.

- $\theta_c$ resolution from time of propagation improves rapidly with path length, reaches plateau at 6-7mrad after approx. 4m photon path in bar.

- Next steps: complete calibration and systematic checks, attempt correction of chromatic production term.
Plan for Future Prototype Tests

Next beam test of prototype is planned for summer 2006

- plan to add new photon detectors:
  - new 1024 pixel Burle MCP-PMT
  - new 256 pixel Hamamatsu Multianode PMT
  - new small cathode-to-MCP gap 64 pixel Burle MCP-PMT

- 256/1024 pixel PMTs will have modified readout
  combining pixels into $4 \times 16$ pseudo-pixels, 64 channels
  $\rightarrow$ provide finer segmentation in vertical direction
  $\rightarrow$ minimize pixelization effects, provide better
  $\theta_c$ resolution from pixels for chromatic correction.

- possibly add a second fiber hodoscope behind prototype
  to reject tracks with large scattering angle in bar
Burle 85011-430 MCP-PMT

- 64 pixels (8×8), 6.5mm pitch
- bialkali photocathode
- 25µm pore MCP, small 0.75mm MCP-cathode distance
- gain ~5×10^5
- timing resolution ~90ps, much smaller tail
- OK uniformity
Hamamatsu H-9500 Flat Panel Multianode PMT

- bialkali photocathode
- 12 stage metal channel dynode
- gain $\sim 10^6$
- typical timing resolution $\sim 220$ps
- 256 pixels (16×16), 3 mm pitch
- custom readout board – read out as 4×16 channels

Efficiency relative to Photonis PMT

$\sigma_{\text{narrow}} \approx 220$ps
Six years of experience in PEP-II/BABAR B-factory mode: DIRC successful, very reliable, robust, easy to operate, plays significant role in almost all BABAR physics analyses.

Focusing DIRC R&D has identified several PMT candidates capable of delivering timing resolution of <140ps with good uniformity and efficiency. Remaining questions include: behavior in magnetic fields, aging, rate capability.

Focusing DIRC prototype is a challenging detector, requiring new approaches to calibration, monitoring, software design, etc.

3D readout makes system more complex but also more robust, helps with backgrounds and calibrations. Redundancy makes correction of chromatic production error possible.

Test beam data for prototype show interesting initial results.

- Timing resolution sufficiently good to determine $\theta_c$ with precision better than BABAR-DIRC resolution.
- $\sigma(\theta_c) \approx 6 - 7$ mrad for photon path > 4m

We are looking forward to the next beam test run with an improved prototype this summer.

---

**Summary**

**θ_c from time (mrad)**

Preliminary $\sigma_{narrow} = 6.6 \pm 1.0$ mrad

$\langle \text{path} \rangle \approx 9.7$ m
Beam Test Setup

Setup in End Station A: movable bar support and hodoscope

Photodetector backplane

Radiator bar
Mirror

Oil-filled detector box:

Start counters, lead glass

SNIC 2006, SLAC, April 5, 2006
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

\( \pm 300 \text{ nsec trigger window} \) \( \rightarrow \) \( \pm 8 \text{ nsec } \Delta t \text{ window} \)

\(~500-1300 \text{ background hits/event}~\)

\(1-2 \text{ background hits/sector/event}~\)

\( \sigma(\Delta t) = 1.7 \text{ nsec} \)

Thanks to the BABAR-DIRC group for the plots.
Light source

- PiLas pico-second laser
- $\lambda = 407$ nm or $\lambda = 635$ nm
- FWHM pulse < 35 ps
- Operated in single photon mode

Motion Controller

- GPIB bus, positioning repeatability <7 $\mu$m

Laser Intensity Monitoring

- Two conventional PMTs for monitoring
- Photonis XP2262B, ETL 9125FLB17

Amplifiers

- Elantec 130× voltage gain, 2 GHz bandwidth

Readout

- SLAC-built constant fraction discriminator
- Phillips 7186, 25 ps per count TDC
- CAMAC based readout, linux PC

→ IEEE NSS 2003
Precisely measured detector pixel coordinates and beam/track parameters

→ Pixel with hit \((x_{\text{det}}, y_{\text{det}}, t_{\text{hit}})\) defines 3D photon propagation vector in bar and Cherenkov photon properties (assuming average wavelength)

\[
\alpha_x, \alpha_y, \cos \alpha, \cos \beta, \cos \gamma, L_{\text{path}}, n_{\text{bounces}}, \theta_c, \phi_c, t_{\text{propagation}}
\]

Use GEANT4 simulation and stand-alone ray-tracing software to obtain propagation vector for each pixel.

→ IEEE NSS 2005
Charge can be shared between anode pads if the photon hits close to the boundary between pixels.

If signals are detected simultaneously on two or more neighboring pads this signature can be used to constrain the photon hit position more precisely and improve thetaC resolution.
Various Efficiencies in the Focusing DIRC

Spreadsheet calculation:

- Assume: “Focusing DIRC prototype-like” DIRC is in the present BaBar.
- Burle QE peaks at higher wavelength than the Hamamatsu MaPMT or ETL PMT.

→ RICH 2004
Chromatic Effects

Compare measured resolution from time of propagation to expected resolution
model assumes 90° track angle and Focusing DIRC bandwidth

Short path length:
$\theta_c$ resolution dominated by timing resolution

Long path length:
$\theta_c$ resolution dominated by chromatic dispersion of group index $n_g(\lambda)$
\( \theta_c(\text{TOP}) \) measurement is equivalent to determination of photon wavelength

Graph shows measured photon wavelength compared to the expected wavelength spectrum for a device with perfect timing resolution.
Towards a Correction of the Chromatic Error

Simple first approach:

- use $\theta_c$(TOP) as measurement of required correction
- assume full correlation between pixel and TOP measurement
- correction: difference between measured $\theta_c$(TOP) and expected average $\theta_c(\lambda=410\text{nm})$
  $$\Delta \theta_c = \theta_c(\text{TOP}) - 822.1\text{mrad}$$
- $\theta_c$(corrected) $= \theta_c$(pixel) $- \Delta \theta_c$
- clearly does not combine measurements in optimum way
- this approach slightly improves resolution

Ultimately will want to use full likelihood analysis using all observables.