The Focusing DIRC – the first RICH detector to correct the chromatic error by timing, and the development of a new TOF detector concept

(High resolution timing in the photon detection - a new frontier in physics ?)

J. Va’vra, SLAC

Representing:

Collaboration to develop the Focusing DIRC:
Content

• **Focusing DIRC prototype**
  - The very 1-st first RICH detector, which tags the photon color by timing to correct the chromatic error

• **TOF detector**
  - Progress on a road to reach $\sigma \sim 10-15$ps per track.

• **Both developments are for possible for Super-B**
**BaBar DIRC RICH** = Detection of Internally Reflected Cherenkov light

Nucl.Inst.&Meth., A 538 (2005) 281

- **Very successful** in hadronic particle identification, with ~ $3\sigma$ π-K separation at 4 GeV/c.
- **3D imaging of photons**: $\theta_c$, $\phi_c$ & time

Principle of BaBar DIRC RICH:

- ~11,000 PMTs
- ~5 m long bars
- Single photon $\sigma_{\text{single photon}} \approx 1.7$ ns
- Single photon $\sigma_{\text{single photon}} = 9.6$ mrad

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Motivation to develop a new DIRC at Super-B

**Goal:**
- **Super-B** will have 100x higher luminosity
- Backgrounds are not yet understood, but they would scale with the luminosity if they are driven by the radiative Bhabhas

⇒ **DIRC needs to be smaller and faster:**
- Focusing and smaller pixels can reduce the expansion volume by a factor of 7-10!
- Faster PMTs reduce a sensitivity to background.

**Additional benefit of the faster photon detectors:**
- Timing resolution improvement: \( \sigma \sim 1.7\text{ns (BaBar DIRC)} \rightarrow \sigma \leq 150\text{ps (\sim10x better)} \) which allows a measurement of a **photon color** to correct the chromatic error of \( \theta_c \).

**Focusing mirror effect:**
- Focusing eliminates effect of the bar thickness (contributes \( \sigma \sim 4\text{ mrad in BaBar DIRC} \))
- However, the spherical mirror introduces an aberration, so its benefit is smaller.
Focusing DIRC prototype optics

- **Radiator:**
  - 1.7 cm thick, 3.5 cm wide, 3.7 m long fused silica bar (the same as for BaBar DIRC).

- **Optical expansion region:**
  - filled with a mineral oil to match the fused silica refraction index (KamLand oil).
  - include optical fiber for the electronics calibration.

- **Focusing optics:**
  - a spherical mirror with 49cm focal length focuses photons onto a detector plane.
Focusing DIRC prototype photon detectors
Nucl.Inst.&Meth., A 553 (2005) 96

1) Burle 85011-501 MCP-PMT (64 pixels, 6x6mm pad, $\sigma_{TTS} \sim 50-70$ps)

- Timing resolutions were obtained using a fast laser diode in bench tests with single photons on pad center.

2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, $\sigma_{TTS} \sim 140$ps)

3) Hamamatsu H-9500 Flat Panel MaPMT (256 pixels, 3x12mm pad, $\sigma_{TTS} \sim 220$ps)
Amplifier, based on two Elantek 2075EL chips, has a voltage gain of \sim 130\times, and a rise time of \sim 1.5\text{ns}.

- **Constant-fraction-discriminator** (32 channels/board).
- **Phillips TDC** with 25ps/count.
Beam Test Setup

- SLAC 10 GeV/c electron beam
- Beam enters bar at 90° angle.
- Prototype is movable to 7 beam positions along bar.
- Time start from the LINAC RF signal, but correctable with a local START counter

Beam spot: $\sigma < 1 \text{mm}$

Hodoscope (scint. fibers)

10 GeV electrons

Beam Pipe

Prototype photon detectors

Scintillator counter (MCP-PMT)

Quartz counter (MCP-PMT)

Quantacon PMT

Lead Glass

Lead glass:

Local START time:

$\sigma \sim 36 \text{ps}$
Cherenkov Photons in **Time** and **Pixel** domains

- 10 GeV/c electron beam data.
- ~ 200 pixels instrumented.
- Ring image is most narrow in the 3 x 12 mm pixel detector.

![Graph showing Cherenkov photons in time domain](image)

**Cherenkov ring in pixel domain:**

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Focusing DIRC prototype reconstruction

Prototype coordinate systems:

Geant 4 simulation of the prototype:

- Each detector pixel determines these photon parameters for average $\lambda$:
  $\theta_c$, $\cos \alpha$, $\cos \beta$, $\cos \gamma$, Photon path length, time-of-propagation, number of photon bounces.

- We use GEANT4 simulation to obtain the photon track parameters for each pixel.
  (it is checked by a ray-tracing software)
Color tagging by measurement of photon propagation time

\[ \frac{d\lambda}{\lambda} = \frac{d\text{TOP}}{L} \approx 40\text{ps/meter}. \]

**Dispersive medium**

\[ v_{\text{group}} = \frac{c_0}{n_{\text{group}}} = \frac{c_0}{[n_{\text{phase}} - \frac{\lambda}{\lambda_{\text{phase}}}]} \]

\[ t = \frac{\text{TOP}}{L} = \frac{L}{v_{\text{group}}} = \frac{L}{[n_{\text{phase}} - \frac{\lambda}{\lambda_{\text{phase}}}]} \]

\[ \frac{d\tau}{L} = \frac{d\text{TOP}}{L} = \lambda \frac{d\lambda}{\lambda} \approx \frac{d^2 n/d\lambda^2}{c_0} \]

\( d\tau \) is pulse dispersion in time, length \( L \), wavelength bandwidth \( d\lambda \), refraction index \( n(\lambda) \)

- We have determined in Fused Silica: \( \frac{d\tau}{L} = \frac{d\text{TOP}}{L} \approx 40\text{ps/meter} \).
- **Our goal is to measure the color of the Cherenkov photon by timing!**

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Cherenkov light: tagging color of photon by time

Principle of chromatic correction by timing:

- Cherenkov angle production controlled by $n_{\text{phase}}$ ($\cos \theta_c = 1/(n_{\text{phase}} \beta)$): $\theta_c (\text{red}) < \theta_c (\text{blue})$
- Propagation of photons is controlled by $n_{\text{group}}$ ($v_{\text{group}} = c_0/n_{\text{group}} = c_0/(n_{\text{phase}} - \lambda_{\text{phase}} \lambda)$): $v_{\text{group}} (\text{red}) > v_{\text{group}} (\text{blue})$

$\Delta \theta_{\text{chromatic}} \approx 4 \text{ mrad}$

$\lambda_{\text{average}} \approx 410 \text{ nm}$

$\text{TOP} = \text{time of propagation of photon in the bar}$

$\text{TOP/Lpath} = 1/v_{\text{group}}(\lambda)$

$\text{FWHM}$

$d\text{TOP/Lpath} = \text{TOP/Lpath}(\lambda) - \text{TOP/Lpath}(410\text{ nm})$
The chromatic correction starts working for $L_{\text{path}} > 2-3$ meters due to a limited timing resolution of the present photon detectors. The maximum likelihood technique does better for short $L_{\text{path}}$ than other methods.

Holes in the uncorrected distributions are caused by the coarse pixilization, which also tends to worsen the resolution. In the corrected distributions this effect is removed because of the time correction.

Smaller pixel size (3mm) helps to improve the Cherenkov angle resolution; it is our preferred choice.
$\theta_c$ resolution and Geant 4 MC simulation

$\theta_c$ resolution - all pixels:

- chromatic smearing: $\sim 3$-4 mrad
- 6mm pixel size: $\sim 5.5$ mrad
- optical aberrations of this particular design:
  grows from 0 mrad at ring center to 9 mrad in outer wings of Cherenkov ring
  (this effect is caused by the spherical focusing mirror in the present design)

$\theta_c$ resolution - 3mm pixels only:

- Measured
- Simulation

(3.5 mrad/bin)

(2.5 mrad/bin)
Expected final performance at incidence angle of $90^\circ$

Focusing DIRC prototype bandwidth:

- Prototype’s $N_{pe\_measured}$ and $N_{pe\_expected}$ are consistent within ~20%.

- **Hamamatsu H-9500 MaPMTs:**
  We expect $N_0 \sim 31 \text{ cm}^{-1}$, which in turn gives $N_{pe} \sim 28$ for 1.7 cm fused silica bar thickness, and somewhat better performance in $\pi/K$ separation than the present BaBar DIRC.

- **Burle-Photonis MCP-PMT:**
  We expect $N_0 \sim 22 \text{ cm}^{-1}$ and $N_{pe} \sim 20$ for $B = 0kG$.

- **BaBar DIRC design:**
  $N_0 \sim 30 \text{ cm}^{-1}$, and $N_{pe} \sim 27$.

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New trends in timing

- Goal: to reach a timing resolution of ~15 ps
New laser-based testing methods

J.Va’vra, log book

PiLas laser head:

Control unit 

PiLas

Laser diode

Lens + collimator

1.5-meter long cable

x & y stage + rotation

Start

5-m long fiber

Lens + collimator

Detector

Calibration of a fast detector:

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>SLAC tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser diode source</td>
<td>PiLAs</td>
</tr>
<tr>
<td>Wavelength</td>
<td>635 nm</td>
</tr>
<tr>
<td>TTS light spread (FWHM)</td>
<td>~ 35 ps</td>
</tr>
<tr>
<td>Fiber size</td>
<td>62.5 µm</td>
</tr>
</tbody>
</table>
Limit of the Single-photon timing resolution - $\sigma_{TTS}$

Timing measurement setup in trailer 233 at SLAC

Burle/Photonis MCP-PMT 85012-501 (ground all pads except one)

- 10 $\mu$m MCP hole diameter
- $B = 0$ kG
- 64 pixel devices, pad size: 6 mm x 6 mm.
- Phillips CFD
- PiLas red laser diode operating in the single photoelectron mode (635 nm).
- $\sigma_{TTS} < \sqrt{(32^2 - 15^2 - 11^2)} = 26$ ps ($N_{pe} = 1$)

Hamamatsu C5594-44 amplifier
1.5 GHz BW, 63x gain

Ortec VT120A amplifier
~0.4 GHz BW, 200x gain + 6dB

$\sigma_{narrow} = (32.4 \pm 0.4)$ ps
$\sigma_{wide} = (135.6 \pm 3.3)$ ps

Fit: $g + g$

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Timing resolution with TAC & ADC

Timing measurement setup in trailer 233 at SLAC

\[ \sigma = \sqrt{\sigma_{\text{MCP-PMT}}^2 + \sigma_{\text{Fiber}}^2 + \sigma_{\text{Amp_CFD}}^2 + \sigma_{\text{Delay}}^2 + \sigma_{\text{PiLas}}^2 + \sigma_{\text{Pulser+TAC_ADC}}^2 + \sigma_{\text{PiLas_trigger}}^2}\]

+ Systematic effects: laser & temperature drifts, ground loops, etc.

\[ \sigma_{\text{PiLas}} \sim 15 \text{ ps}/\sqrt{N_{\text{pe}}} \]

\[ \sigma_{\text{Fiber}} \sim ? \]

\[ \sigma_{\text{Amp_CFD}} \sim 6 - 7 \text{ ps} \]

\( \sigma_{\text{Pulser+TAC_ADC}} \sim 3.2 \text{ ps} \) (My measurement)

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Timing resolution $\sigma = f(N_{pe})$

- $N_{pe} = 50-60$ for 1cm-thick Quartz radiator + window & with Burle Bialkali QE.
- A goal to reach $\sigma < 15$ ps seems possible.
- The Ortec 9327-like performance is good.
Time-walk = f(Npe)

- Time-walk needs to be corrected for any variation of Npe, for all methods!
- Ortec 9327 time-walk is smallest, but still significant.
Determine upper limit on $\sigma_{MCP-PMT}$

- MCP-PMT with 10 $\mu$m holes, 64 pads, ground all pads except one being used
- 2.33 kV with Ortec 9327 Amp/CFD (max. allowed voltage is 2.8 kV => plenty of margin available for a future magnetic field operation.

**Calibrate $\sigma_{Pulser + TAC\_ADC}$**:

- $\sigma_{Pulser\_TAC\_ADC} \sim 3.2$ ps

**Determine $\sigma$ for $N_{pe} \sim 300$**:

- $\sigma \sim 9.6$ ps

(Note: $\sigma \sim 8.6$ ps with Phillips CFD 715)

Upper limit on MCP-PMT contribution to the resolution:

$$\sigma_{MCP-PMT} < \sqrt{\sigma^2 - \sigma^2_{Pilas\ (N_{pe})} - \sigma^2_{Amp\_CFD} - [\sigma^2_{Pulser+TAC\_ADC} - \sigma^2_{Pulser}]} < 6.5$ ps

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Conclusions

- **We have demonstrated that we can correct the chromatic error of $\theta_C$.** This is the first RICH detector which has been able to do this.
- **Expected $N_o$ and $Npe$ is comparable to BaBar DIRC for MaPMT H-9500.**
- **Expected improvement of the PID performance with 3x3mm pixels: ~20-30% compared to BaBar DIRC for pi/K separation, if we use H-9500 MaPMT.**
- The main defense against the background at Super-B is to make (a) the expansion volume much smaller, which is possible only with highly pixilated photon detectors, and (b) use of faster detectors.

- **Our present best results with the laser diode:**
  - $\sigma \sim 12$ ps for $Npe = 50-60$ (expected from 1cm thick Cherenkov radiator).
  - $\sigma_{TTS} < 26$ ps for $Npe \sim 1$.
  - Upper limit on the MCP-PMT contribution: $\sigma_{MCP-PMT} < 6.5$ ps.
  - TAC/ADC contribution to timing: $\sigma_{TAC\_ADC} < 3.2$ ps.
  - **Total electronics contribution at present:** $\sigma_{Total\_electronics} \sim 7.2$ ps.
    (One has to be aware that the time-walk, due to variation of $Npe$, has to be corrected).

- **Next test beam run:** Add (a) ADC-based pixel interpolation, (b) 2-nd hodoscope after a bar, (c) ASIC-based readout on one MCP-PMT allowing a measurement of time and pulse height, (d) test of the TOF detector.
Backup slides
BaBar detector at SLAC

- **1.5T solenoid**
- **DIRC (PID)**
  - 144 quartz bars
  - 11000 PMs
- **EMC**
  - 6580 CsI(Tl) crystals
- **Detected Electron**
  - e^+ (3.1 GeV)
  - e^- (9 GeV)
- **Drift Chamber**
  - 40 layers
- **Silicon Vertex Tracker**
  - 5 layers, double sided strips
- **Instrumented Flux Return**
  - Iron / Resistive Plate Chambers or Limited Streamer Tubes (muon / neutral hadrons)
- **Detector commissioned in 1999**
BaBar DIRC photon detector

- 10752 ETL 9125 PMTs, 1 inch dia.
- TDC: 0.5 ns/count
- No dead time up to rate of ~500 kHz/PMT
- Serial data link: 1.2 Gbits optical fibers
Comparison of various methods to determine the chromatic correction
Cherenkov light: tagging color by time

Analytical calculation:

\[ \text{Chromatic growth rate: } \sigma \sim 40 \text{ps/m} \]

\[ \text{dTOP/Lpath [ns/m] = TOP/Lpath(}\lambda\text{) - TOP/Lpath (410nm)} \]

Cherenkov angle production controlled by \( n_{\text{phase}} \):

\[ \cos \theta_c = 1/(n_{\text{phase}} \beta), \quad n_{\text{phase}}(\text{red}) < n_{\text{phase}}(\text{blue}) \Rightarrow \theta_c < \theta_c \]

Propagation of photons is controlled by \( n_{\text{group}} \) (\( \neq n_{\text{phase}} \)):

\[ v_{\text{group}} = c_0 / n_{\text{group}} = c_0 / [n_{\text{phase}} - \lambda / \lambda_{\text{phase}}] \]

\[ v_{\text{group}}(\text{red}) > v_{\text{group}}(\text{blue}) \]

Geant 4 - without and with pixilization:

Data from the prototype:
• There is a good agreement among various methods for $L_{\text{path}} > 4$ meters. For smaller $L_{\text{path}}$ values the max. likelihood has a best performance.
There is a good agreement among various methods for $L_{\text{path}} > 5-6$ meters. For smaller $L_{\text{path}}$ values the max. likelihood performs best.
TOF detector
Timing at a level of $\sigma < 15\text{ps}$ can start competing with the RICH techniques.

Recent progress in the TOF technique is driven by these advances:

(a) a fast Cherenkov light rather than a scintillation, (b) new detectors with small transit time spread $\sigma_{\text{TTS}}$, (c) fast electronics, and (d) new fast laser diodes for testing.

Example of various Super-B factory PID designs:

Calculation done for Flight Path Length = 2m
Super-B detector options

- Forward TOF detector with $\sigma \sim 15$ps is one option