More than 80 experts reviewed the experimental aspects related to Cherenkov Light Imaging and discussed on newly emerging techniques.

Talk slide’s repository: www.nestor.org.gr/rich2002
TRENDS IN THE DEVELOPMENT OF LARGE AREA PHOTODETECTORS FOR CHERENKOV LIGHT IMAGING APPLICATIONS

Outline:

- Cherenkov Light Imaging detectors:
  - RICH & DIRC basic principles and properties

- Gaseous photodetectors
  - CsI

- Vacuum based photodetectors
  - Multianode photomultipliers
  - HPDs

- Novel photon detectors
Cherenkov Light Imaging

Detection of Internally Reflected Cherenkov light

new direction: correct the chromatic error out

© 2002 New Developments in Photodetection

Eugenio Nappi
INFN-Bari

Measure (in a field of a few Gauss):
- a) a time to $\sigma \sim 100\text{ps}$, and
- b) photon position in both $x$ & $y$. 
Fundamentals

\[ \theta_c = \arccos \left( \frac{1}{n(\lambda) \beta} \right) \]

\[ \theta_c = \theta_c(\beta) \]

intrinsic "chromaticity"
dispersion limit

Particle Identification:
Cherenkov angle $\rightarrow$ particle velocity + momentum known

\[ m = p \sqrt{n^2 \cos^2 \theta_c - 1} \]

Separation power:

\[ \cos \theta = \frac{1}{n\beta} \Rightarrow \left( \frac{\sigma_\beta}{\beta} \right)^2 = (\tan \theta \sigma_\theta)^2 + \left( \frac{\Delta n}{n} \right)^2 \]

\[ \sigma_\theta^2 = \sum_i \Delta \theta_i^2 \Rightarrow \sigma_{\theta} = \frac{\sigma_\theta}{\sqrt{N_{\text{p.e.}}}} \]

Cherenkov Light Imaging counters: detect the maximum number of photons with the best angular resolution
Photon Yield

N = \frac{2\pi L Z^2}{\beta_n} \alpha \int_{\beta_n} \left(1 - \left(\frac{\beta_n(\lambda)}{\beta}\right)^2\right) d\lambda \left(1 - \frac{1}{n^2}\right)

N(cm^{-1} eV^{-1}) = 370 Z^2 \left(1 - \frac{1}{n^2}\right)

e = single photoelectron detection efficiency
Q = photoconverter Quantum Efficiency
T = transmission of radiator, gas and windows
R = mirror reflectivity

N_0 = figure of merit = \frac{2\pi \alpha}{\hbar} \int \epsilon \cdot Q \cdot T \cdot R \cdot dE

N_{pe} = mean number of detected photoelectrons = N_0 L \sin^2 \theta

sin^2 \theta_{\text{max}} = \frac{1}{\gamma_i^2} \Rightarrow N_{pe\text{-max}} = \frac{N_0 L}{\gamma_i^2}

too few Cherenkov photons

The number of photo-electrons N_{pe} is even smaller!

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive index</th>
<th>\gamma</th>
<th>\theta_{\text{max}}(\degree)</th>
<th>N\gamma(cm eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>plexiglass</td>
<td>1.48</td>
<td>1.36</td>
<td>44</td>
<td>220</td>
</tr>
<tr>
<td>water</td>
<td>1.33</td>
<td>1.56</td>
<td>41.2</td>
<td>160</td>
</tr>
<tr>
<td>aerogel</td>
<td>1.01-1.07</td>
<td>27-4.5</td>
<td>11-25</td>
<td>20-80</td>
</tr>
<tr>
<td>argon</td>
<td>1.00059</td>
<td>31</td>
<td>1.8</td>
<td>0.46</td>
</tr>
<tr>
<td>helium</td>
<td>1.000033</td>
<td>120</td>
<td>0.47</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Number of detected photoelectrons $N_{p.e.}$

$$N_{p.e.} = L \sin^2 \theta \frac{\alpha}{\hbar c} \int_{E_i}^{E_2} \epsilon_Q(E) \prod_i \epsilon_i(E) dE \Rightarrow N_{p.e.} \propto \Delta E = E_2 - E_1 \text{ (detector bandwidth)}$$

Unfortunately: $\langle \sigma_{\theta_i} \text{ (Chromaticity)} \rangle \propto \Delta E$

For any combination of radiator and detection bandwidth there is an intrinsic (chromaticity) performance limit:

sub-millimetric pixels useless

Refractive index $(n-1)$ and dispersion $dn/dE$ increase with the photon energy
Photon Detector Requirements

- Large area coverage with single photon sensitivity
- High “effective” efficiency
  - Active-area fraction > 70%
- High granularity
- Rate capability
- Reliability and long term ageing resistance
- Timing resolution ($\sigma \sim 100$ ps)
- Affordable procurement and operating costs

In red, requirements very peculiar to Cherenkov light Imaging applications
Large Surface Sensitive to Single Photons

Examples:

HADES-GSI
Photon Detector:
- CH$_4$ MWPC – CaF$_2$ windows
- CsI photo-cathode
- 28,600 pads

Super-Kamiokande
- 50,000 ton water
- ~11,000 PMTs, 50cm ∅
High photon and charged particle flux

Examples:

- Challenge: occupancy exceeds 10% in hottest regions, significant ring overlap

10-20 MHz interaction rates
Photon fluxes: ~ MHz/cm²

HADES simulation: Au + Au, E = 1 AGeV
Low energy photons from accelerator hit Standoff Box
Luminosity \(>10^{33}/\text{cm}^2\text{s}\) \(\rightarrow\) bgk rates of 80-200 kHz/tube

80-200 kHz \(\otimes\) 10,752 PMTs \(\otimes\) \(\pm 300\) nsec trigger window
\(\rightarrow\) 500-1300 background hits (\(~10\%\) occupancy)

compared to
50-300 Cherenkov photons

\(\pm 300\) nsec trigger window \(\rightarrow\) \(\pm 8\) nsec \(\Delta t\) window
\(~500-1300\) background hits/event (1-2 background hits/sector/event)
Reliability and long term ageing resistance

Strongly corroded (*frosty*) tubes
bad batch of PMT glass (no zinc)

Milky window
sodium depletion in near surface
(window thickness = 1mm)

Front glass corrosion of some **DIRC PMTs** in ultra-pure water discovered after ~ 1 year immersion (Oct.99)

⇒ Photon yield shows small loss at rate of 1-2%/year, no problem for PID performance

⇒ Might loose vacuum in some of the ~ 50 *frosty* tubes on 10 year time scale
Gaseous photon detector

PHOTOELECTRIC ABSORPTION

gas photoionization

gas volume: photosensor (TMAE or TEA) + carrier (CH₄ or C₂H₆)

photoelectric effect

gas volume: CH₄

Cathode pad read-out with fully integrated electronics over the back side ➔ reduced cabling, less dead space
**Photoconverter properties**

<table>
<thead>
<tr>
<th>Photosensor</th>
<th>$E_{th}(eV)$</th>
<th>Vapour Pressure (torr)</th>
<th>$l_{abs}(mm)$</th>
<th>Operational Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMAE</td>
<td>5.6</td>
<td>0.3</td>
<td>30</td>
<td>Hazardous material, strong anode wire ageing</td>
</tr>
<tr>
<td>TEA</td>
<td>7.2</td>
<td>52</td>
<td>0.6</td>
<td>Operation in the far UV: CaF$_2$+ultrapure gas mixture, high chromat.</td>
</tr>
<tr>
<td>CsI</td>
<td>5.6</td>
<td>-</td>
<td>$2 \times 10^{-5}$ (*)</td>
<td>Moisture sensitive, long term ageing (?)</td>
</tr>
</tbody>
</table>

(*) electron escape length $\sim O(10\ \text{nm})$
Gaseous photodetectors: intrinsic time resolution

Photosensitive vapours
Jitter created by drift time for different primary electrons:
\[ \Delta t \approx 3\sigma_t = 3l_{ph}/v_d \]

\( l_{ph} \) = photoabsorption length; \( v_d = \) electron drift velocity (O(100 \( \mu \)m/ns))
\[ \Delta t = 10 \text{ ns} \rightarrow l_{ph} \sim 0.3 \text{ mm} \] (TEA at room temperature or TMAE at 100 \( ^0 \)C)

CsI
Photoelectrons are extracted isochronously → “FAST RICH DETECTORS”

Beginning of 1990s: design of RICH counters for high luminosity B-factories operating at several MHz → digital measurement with fast (\( \Delta f = 50 \text{ MHz} \)) low noise current amplifier → small charge induced on the cathode pads → small MWPC gap (~ 0.5 mm) & high gain \( 4 \times 10^5 \)
Very high cathode gradient (8-10 KV/cm) → Unstable detector operation

Breakthrough
RD26 (F. Piuz et al., R&D for the development of large area CsI photocathodes, 1992): read-out electronics with long integration time (1.2 \( \mu \)s) → low gas gain (6-8 \( 10^4 \))
Full detection efficiency & very stable detector operation attained
Low photon feedback → “open” geometry no blind electrodes
CsI Photocathodes

Photocathode PCBs split into two multilayer circuits (SMD connectors for FEE cards)

gold front surface (0.4 µm)

nickel barrier layer (7 µm)

multilayer pcb with metalized holes

GROUND PLANE

Beaune 2002
New Developments in Photodetection

Eugenio Nappi
INFN-Bari
Beaune 2002
New Developments in Photodetection

**CsI deposition plant at CERN**

- **Slow deposition rate** (~1 nm/s)
- **min. CsI dissociation**
- **little or no reaction with residual gases**

- **Thermal treatment during and after CsI deposition** (~8 hrs at 60°C)
- **In situ encapsulation under dry Argon before the implementation in the MWPC**

in situ QE evaluation under vacuum
CsI Quantum Efficiency
# Experiments employing gaseous photon detector

<table>
<thead>
<tr>
<th>Experiment</th>
<th>πK separation momentum range (GeV/c)</th>
<th>Max interaction rate (Hz)</th>
<th>Radiator (length)</th>
<th>Photon detector/surface (m²)</th>
<th>Photocathode</th>
<th>Magnetic Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO III</td>
<td>0.1–2.8</td>
<td>10⁵</td>
<td>LiF (10 mm)</td>
<td>MWPC (CH₄) / 14</td>
<td>TEA</td>
<td>1.5 T</td>
</tr>
<tr>
<td>HADES-GSI</td>
<td>0.1–1.5 (hadron blind)</td>
<td>10⁶</td>
<td>C₆F₁₀ (0.5 m)</td>
<td>MWPC (CH₄) / 1.4</td>
<td>CsI</td>
<td>NO</td>
</tr>
<tr>
<td>ALICE-LHC</td>
<td>0.8 – 3</td>
<td>10⁴</td>
<td>C₆F₁₄ (10 mm)</td>
<td>MWPC (CH₄) / 12</td>
<td>CsI</td>
<td>0.5 T</td>
</tr>
<tr>
<td>TJNAF - Hall A</td>
<td>0.8 - 3</td>
<td>10⁶</td>
<td>C₆F₁₄ (10 mm)</td>
<td>MWPC (CH₄) / 2</td>
<td>CsI</td>
<td>NO</td>
</tr>
<tr>
<td>COMPASS-SPS</td>
<td>3 - 120</td>
<td>10⁶</td>
<td>C₄F₁₀(3 m) / N₂+C₂F₆ (8 m)</td>
<td>MWPC (CH₄) / 8 (RICH-1)</td>
<td>CsI (RICH-1)</td>
<td>NO</td>
</tr>
</tbody>
</table>

**Note:**
- large area coverage (up to several m²)
- operation in magnetic field
CsI Photodetectors

- Reflective CsI layer
- Electron extraction in CH$_4$ at 1 atm

MWPC configuration

- Analogue read-out:
  Noise $\leq 1000$ e$^-$
  Single electron eff. $\varepsilon_{\text{S.e.}} \geq 95$

CsI substrate

G10 + Ni/Au precoated with RSG = Resin Stab. Graphite

HADES

ALICE-TJNAF-COMPASS

CsI Photodetectors

HADES

CsI Photodetectors

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HADES

ALICE-TJNAF-COMPASS

CsI Photodetectors
Gaseous photodetectors: photon feedback & ageing

RICH2002 Workshop: F. Piuz (CERN)

“RING IMAGING CHERENKOV SYSTEMS BASED ON GASEOUS PHOTO-DETECTOR: TRENDS AND LIMITS”

Gas gain

\[ P(q) = \frac{e^{-q/\eta}}{q} \Rightarrow \varepsilon = \int_{0}^{\infty} P(q) dq = e^{-\eta/\bar{q}} \]

\[ P(q) = \left( \frac{q(1+\theta)}{\bar{q}} \right)^{\theta} \exp \left( \frac{-q(1+\theta)}{q} \right) \]

\[ N_{\text{feed.photo}} = K \times \text{Gain} \]

K=\text{gas dependent}

optimize FEE sensitivity and chamber gain

Radiation ageing:

MAX DOSE: 5 mC/cm² (50µC/mm²)
(equivalent to draw 10 nA along a wire of 1 m during 230 days)

IT INDUCES A QE DROP OF 20%
Recent trend in RICH technique: shift the detector design from UV to visible

Driven by:
- Ever increasing acquisition rate of future experiments
- Availability of multianode PMTs and hybrid devices
- Exploitation of aerogel as radiator medium

Multi-anode Photomultipliers MaPMTs (HERA-B, AMS)

Quantacon-like PMTs (DIRC, SELEX, HERMES)

Hybrid Photo Diodes HBDs (LHCb, BTeV)
**Imaging of Cherenkov light from aerogel**

<table>
<thead>
<tr>
<th>Radiator</th>
<th>Refractive index (7 eV)</th>
<th>$\pi$ threshold momentum (GeV/c)</th>
<th>$K$ threshold momentum (GeV/c)</th>
<th>$p$ threshold momentum (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_6F_{14}$</td>
<td>1.28</td>
<td>0.18</td>
<td>0.62</td>
<td>1.18</td>
</tr>
<tr>
<td>Aerogel</td>
<td>1.03</td>
<td>0.6</td>
<td>2</td>
<td>3.8</td>
</tr>
<tr>
<td>$C_4F_{10}$</td>
<td>1.0015</td>
<td>2.5</td>
<td>8.9</td>
<td>17</td>
</tr>
</tbody>
</table>

most of the photons experience Rayleigh scattering

production of hydrofobic aerogel of outstanding quality driven by BELLE

visible light detection
Aerogel & Conventional PMTs: HERMES

3870 PMTs, Philips XP1911/UV, Ø 3/4” + light funnels

Online Event Display

\(<N_{p.e. \text{ (aerogel)}}> = 8
\<N_{p.e. \text{ (C}_4\text{F}_{10})}> = 12
Advantages

⇒ improved performance (large $N_0$, small chromatic aberration, rate capability)
⇒ wider range of materials for detector construction
⇒ easy to operate

Disadvantages:

⇒ small filling factor (packing density)
⇒ do not work in magnetic field
⇒ high cost per channel (limited coverage applications)
~ 3 m² area have to be equipped with photodetectors providing:
- Single Photon Sensitivity (200 - 600 nm)
- 2.5 x 2.5 mm² granularity
- Fast readout (40 MHz)
- Active-area fraction > 70%

Baseline: Hybrid Photo Diodes (HPD)

168 HPDs RICH1 340 K channels
262 HPDs RICH2

Backup: ~4000 Multianode Photomultipliers (MaPMT)
Pixel-HPD

61 pixel HPD prototype

83 mm diameter
75 mm photocathode diameter

- Quartz window
- S20 photo cathode $\int QE \, dE = 0.77 \, eV$
- 1024 (320 x 32) Si pixel array: 500 $\mu m \times$ 50 $\mu m$
- Cross-focusing optics
  - demagnification $\sim 5$ (pixel size at photocathode $2.5 \times 2.5 \, mm^2$)
  - 50 $\mu m$ point-spread function
  - 20 kV operating voltage 5000 $e$ signal at Si anode
- Encapsulated binary electronics
- Tube, encapsulation: DEP (NL)
- Silicon Pixel sensor bump bonded to readout chip

82% active area
Multi Anode PMT*

Hamamatsu R5900 series. M64 (64 anodes – metal dynode chains)

8x8 channels, pixel 2x2 mm².
Size: 26x26 mm². UV glass window.
Bialkali PC: Q.E. ~ 22% at $\lambda_{\text{max}} = 400$ nm.
Gain $\approx 3 \times 10^5$ at 800 V.

- **MAPMT active area fraction**: 38% (includes pixel gap)
- Increase with quartz lens with one flat one curved surface to 85%

*RICH2002 Workshop: Franz Muheim (University of Edinburgh)*
Measured sensitivity of MaPMT to magnetic fields

- longitudinal up to 100 G with 0.9 mm $\mu$-metal shield
- insensitive to transverse fields up to 250 G
• Simple **Gaussian** Signal fit
• Mean signal \( s / \text{pedestal} \sigma = 40:1 \)
• Signal loss below 5 \( \sigma \) cut: 11.5 %
Comparison Pixel HPD and MaPMT

DEP 61 pixel HPD

Hamamatsu R5900-M64

Multiphoton counting feature

A. Duane et al. LHCb 98-039
and N. Smale, Oxford Univ.,
private communication

Collection efficiency
of R5900-64 is not
very uniform.
Deep valleys
between pixels.

Channel-channel gain
variations ~factor 2-3.
Quantum efficiency
- QE = 25 - 27% at 360 nm
- 3-5 % higher with respect to 3x3 cluster
14-23 % more photons

Better Focusing
- additional focusing wires
- larger acceptance at edge
- reduced distance between focusing grid and entry slits
RICH2002 Workshop: J. Va’vra (SLAC):
“Novel Photon Detectors for RICH applications”

Many interesting developments:

- 5” and 10” Pad-HPDs (see C. Joram’s talk at Beaune 2002)
- HAPDs
- Flat-panel PMTs
- Silicon-PMTs (see B. Dolgoshein’s talk at Beaune 2002)
- Multiple-GEMs + pads
- MICROMEGAS + single-GEM + pads
**Flat panel PMT: still a dream....**

PMT Type Number: R8400-M64
Hybrid Assembly: H8500

**HERA-B PMT vs. Flat Panel PMT:**

- HERA-B PMT: Effective area 69%
- Flat Panel PMT: Effective area 97%
### Flat panel PMT: main characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description or Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Response</td>
<td>300 to 650</td>
<td>nm</td>
</tr>
<tr>
<td>Photocathode Material</td>
<td>Bialkali</td>
<td>-</td>
</tr>
<tr>
<td>Window</td>
<td>Material: Borosilicate glass</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Thickness: 2.0 mm</td>
<td></td>
</tr>
<tr>
<td>Dyname</td>
<td>Structure: Metal channel Dynode</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Number of Stage: 12</td>
<td></td>
</tr>
<tr>
<td>Number of Anode Pixels</td>
<td>64 (8 x 8 matrix)</td>
<td></td>
</tr>
<tr>
<td>Pixel Size / Pitch</td>
<td>5.6 x 5.6 / 6.0 mm</td>
<td></td>
</tr>
<tr>
<td>Effective Area</td>
<td>49 x 49 mm</td>
<td></td>
</tr>
<tr>
<td>Dimensional Outline</td>
<td>52 x 52 x 28 mm</td>
<td></td>
</tr>
<tr>
<td>Packing Density (effective area/external size)</td>
<td>89 %</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>135 g</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode Luminous Sensitivity</td>
<td>40 uA/Lm</td>
<td>55 uA/Lm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue Sensitivity Index (CS 5-58)</td>
<td>5.5 -</td>
<td>7.0 -</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>QE at 420 nm</td>
<td>17.5 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode Luminous Sensitivity</td>
<td>55 A/Lm</td>
<td>0.5 nA</td>
<td>32 100 nA</td>
<td></td>
</tr>
<tr>
<td>Gain</td>
<td>1x10^5</td>
<td>1x10^6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode Dark Current per channel</td>
<td>0.5 nA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode Dark Current with all channels</td>
<td>32 nA</td>
<td>100 nA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rise Time</td>
<td>0.7 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit Time</td>
<td>8.5 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transit Time Spread (FWHM)</td>
<td>0.3 ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Linearity per channel (+/- 2 % dev.)</td>
<td>1 mA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-talk (DC light with Mask of 5 x 5 mm)</td>
<td>3 %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniformity (DC light and Full illumination)</td>
<td>1 : 3</td>
<td>1 : 6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Flat panel PMT: light response

Single electron PH spectrum (Hamamatsu data)

RICH2002 Workshop: J. Va’vra (SLAC)
Timing resolution per single photon $\sigma \sim 125$ps
It is necessary to correct the timing for the pulse height variation.
This means an additional considerable cost increase !!!
RICH2002 Workshop: R. Chechik (Weizmann Institute)

**Semitransparent PC**
- fast signals [1-10 ns]
- high gain [>10^6]
- sensitivity to single photoelectrons
- operation in noble gases (mixtures)
- high 2D precision
- largely reduced photon feedback compared to “open” geometry

**Reflective PC**
- no photon feedback
- easier production of thick pc.
Triple GEM + pads: lab results

Gain with 3 GEMs

- $e^-$ backscattering in the gas $\Rightarrow$ QE(gas) < QE(vacuum)
- depends on $\sigma$(elastic) / $\sigma$(inelastic)
- worst in noble gases (particularly He), best in CH$_4$ & CF$_4$
  - $\varepsilon$(CH$_4$) $\sim$ 90-95%;
  - $\varepsilon$(CF$_4$) $\sim$ 95%;
  - $\varepsilon$(Ar/CH$_4$) < 70%

ion feedback not fully suppressed $\Rightarrow$ under study (gating)
Development of Cherenkov Light Imaging Techniques is a lively and fertile field of research with beneficial feedbacks in many other scientific sectors. It would not have advanced to the present state without Tom Ypsilantis’s ideas, enthusiasm, constructive arguments and outstanding achievements.
$\tau_{\text{peak}} \sim 25 \text{ ns}, \text{ Noise } \sim 250 \text{ e.}

Other variables:
- Discriminator threshold: 2000e
- Chip power consumption: $\sim 0.5 \text{ W}$
- Radiation dose over 10 years: 30 kRad
- Level-0 trigger: 1 MHz, 4 $\mu$s latency
- Process: 0.25 $\mu$m CMOS

**IBM 0.25$\mu$m process**

- Pixel size 50 $\mu$m x 425 $\mu$m
- 40 MHz read-out clock
- **Bump bonded** to Si-sensor