Particle ID with the LHCb RICH System

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On behalf of the LHCb RICH Group

TRD 2005 Workshop

8th September 2005
Overview

- General introduction
  - LHCb experiment
  - Particle ID requirements of LHCb
- The LHCb RICH Detectors
  - RICH1
  - RICH2
  - Photon detection using HPDs
  - RICH Readout system
  - System test results
  - Magnetic corrections
- Particle ID performance
- Summary and outlook
The LHCb experiment

- LHCb: A single-arm spectrometer for precision measurements of CP violation and rare decays in B-meson system at the LHC
- Search for signals of New Physics beyond Standard Model
The need for particle ID

Example:
measurement of the angles \( \alpha \) and \( \gamma \):

Separation of 
\( B \rightarrow \pi \pi \) events from other 2-body decays of similar topology
Coverage of B decay phase space

Need for 2 RICHes, 3 radiators

\[ \cos(\theta_c) = \frac{1}{\beta \cdot n} \]

Momentum vs polar angle for all tracks from B\( \rightarrow \pi \pi \)

\( \theta_c \) vs p for Aerogel, \( C_4F_{10} \) & \( CF_4 \)
RICH1

- RICH1 parameters
- Spherical mirrors
- Aerogel performance
The RICH1 detector

RICH1 is undergoing phased programme of design and construction

HPD plane: 7 columns, 14 tubes each

Magnetic shield box

Vertical X-section

Photon Detectors

Aerogel

C₄F₁₀

Spherical Mirror

Beam pipe

Right-angled section

Track

VELO exit window

Plane Mirror
RICH1 parameters

- **Aerogel**
  - $L = 5 \text{ cm}$
  - $p : 2 \rightarrow 10 \text{ GeV/c}$
  - $n = 1.03 \text{ (at 540 nm)}$
  - $\langle N_{\text{photoelectrons}} \rangle \sim 7 \text{ (} \beta \approx 1 \text{ track)}$
  - $\text{Sigma} \left( \theta_C \right) \sim 2.5 \text{ mrad (per photoelectron)}$

- **$C_4F_{10}$**
  - $L = 85 \text{ cm}$
  - $p \text{ up to } \approx 70 \text{ GeV/c}$
  - $n = 1.0014 \text{ (at 400 nm)}$
  - $\langle N_{\text{photoelectrons}} \rangle \sim 31 \text{ (} \beta \approx 1 \text{ track)}$
  - $\text{Sigma} \left( \theta_C \right) \sim 1.6 \text{ mrad (per photoelectron)}$

- **Acceptance:**
  - $25 \rightarrow 250 \text{ mrad (vertical)}$
  - $25 \rightarrow 300 \text{ mrad (horizontal)}$
RICH1 spherical mirrors

- Need to minimize material thickness → use beryllium mirrors
- 8 Be-mirrors machined at Kompozit in Moscow-Russia
- Radius curvature: 2700 mm, 1%
- < 4 mm thick Be, aluminized, + 0.3 mm glass surface (0.8% $X_0$)

First mirror characterization:
- R: 2690 mm
- $D_0$: 3.3 mm
- 16-bit camera
- Laser
- Optical bench
- Be mirror
- Mirror mount
RICH1 Aerogel

- SiO$_2$ - based radiator
- Density = 0.15 g/cm$^3$
- Produced for LHCb by the Boreskov Institute for Catalysis in Novosibirsk
- Transparent over a wide range: optical properties dominated by Rayleigh scattering

$$T = Ae^{-\frac{Ct}{\lambda^4}}$$

Transmittance $T$, clarity factor $C$, surface scattering factor $A$, thickness $t$, wavelength $\lambda$

LHCb parameters: $t = 5$ cm (world best)
- $n = 1.030 \pm 0.001$
- $C=0.006$ $\mu$m$^4$/cm
Aerogel testbeam

with 3 pixel-HPD

Aerogel

Mirror

10 GeV/c \( \pi^- \)

Assumes full HPD detector coverage

Studies ongoing

<table>
<thead>
<tr>
<th>Aerogel Thickness</th>
<th>Light yield Per Event (( N_{\text{photons}} ))</th>
<th>Cherenkov Angle in mrad. ( \theta_c )</th>
<th>( \sigma_{\theta} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 cm DATA</td>
<td>( 9.7 \pm 1.0 )</td>
<td>250.0</td>
<td>5.4</td>
</tr>
<tr>
<td>4 cm MC</td>
<td>( 11.5 \pm 1.2 )</td>
<td>248.7</td>
<td>4.0</td>
</tr>
<tr>
<td>8 cm DATA</td>
<td>( 12.2 \pm 1.3 )</td>
<td>246.8</td>
<td>5.8</td>
</tr>
<tr>
<td>8 cm MC</td>
<td>( 14.7 \pm 1.6 )</td>
<td>245.0</td>
<td>3.9</td>
</tr>
</tbody>
</table>

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RICH2

- RICH2 parameters
- Mirror alignment
The RICH2 detector

RICH2 Optics Top View

- Beam Axis
- Support Structure
- Spherical Mirror
- Mirror Support Panel
- Photon funnel + Shielding
- Central Tube
- Flat Mirror

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RICH2 parameters

- $\text{CF}_4$
  - $L = 196\ \text{cm}$
  - $p$ up to $\approx 100\ \text{GeV/c}$
  - $n = 1.0005$ (at 400 nm)
  - $\langle N_{\text{photoelectrons}} \rangle \sim 23$ ($\beta \approx 1\ \text{track}$)
  - $\sigma(\theta_C) \sim 0.7\ \text{mrad}$ (per photoelectron)

- **Acceptance:** $15 \rightarrow 100\ \text{mrad}$ (vertical)
  - $15 \rightarrow 120\ \text{mrad}$ (horizontal)

- **Gas vessel:** $100\ \text{m}^3$
RICH2 under construction

- All 56 spherical mirrors in place and aligned.
- All 40 flat mirrors installed and aligned.
- Final leak test completed
- Transport to the LHCb pit in ~4 weeks
RICH2 mirror alignment

- Laser shines from mirror centre of curvature, reflected back to same common point.
- Spot measured with CCD
- Each spherical mirror surveyed and adjusted in turn

Alignment and stability set a 50 μrad contribution to the overall uncertainty in the single photon Cherenkov angle reconstruction
Photon Detector

- The Hybrid Photon Detector (HPD)
- Fabrication
- Performance studies
- Integration and readout
The Pixel Hybrid Photo-Detector (HPD)

- The pixel HPD has been developed by LHCb in collaboration with industry
- 196 + 288 HPDs to be equipped in RICH1 + RICH2

83mm photocathode window
Electron Optics:
  - 20 kV
  - Factor 5 demagnification
Requirements of photodetector

- In total ~ 2.6 m$^2$ area to be equipped with photodetectors:
- The Pixel HPD satisfies the PID performance of LHCb
  - Good single Photon Sensitivity (wavelength range: 200nm - 600nm)
  - 2.5 x 2.5 mm$^2$ granularity (500µm x 500µm silicon pixel)
  - LHC speed electronics (25ns peaking time, 40MHz readout)
  - High active-area fraction ~ 70%
  - ~500,000 channels at affordable cost (1024 ch/HPD)
  - Operation in radiation environment (3kRad/year)
  - Operation in a fringe magnetic field (2.5 mT)
Stages of HPD production (1)

- Silicon sensor
- Readout chip
- Ceramic carrier
- Bump-bonding
- Brazing and gold-plating
- Packaging
- HPD encapsulation
Stages of HPD production (2)

Tube body assembly

Photo-cathode deposition and vacuum sealing

83 mm

124 mm
### HPD pre-series: performance results

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel response</td>
<td>&gt;95%</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>Min. threshold Noise</td>
<td>&lt;2000e-</td>
<td>Typ. 1200e-</td>
</tr>
<tr>
<td></td>
<td>&lt;250e-</td>
<td>Typ. 160e-</td>
</tr>
<tr>
<td>Leakage current</td>
<td>Typ. 1uA @ 80V bias</td>
<td>&lt; 1uA</td>
</tr>
<tr>
<td>Dark count rate</td>
<td>Max. 5kHz/cm²</td>
<td>0.03–3kHz/cm²</td>
</tr>
<tr>
<td>Ion feedback rate</td>
<td>Max. 10^{-2} rel. to signal</td>
<td>&lt;10^{-3}</td>
</tr>
<tr>
<td>P.e. detection efficiency</td>
<td>Typ. 85%</td>
<td>Mean ~85%</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>See next picture</td>
<td>Generally well above specs</td>
</tr>
</tbody>
</table>

Statistics based on 9 pre-series tubes
HPD pre-series: QE curves

Quantum Efficiency (%)

Wave Length (nm)

dark counts 3.03 kHz / cm²

dark counts 0.03 kHz / cm²

by CERN
by DEP

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Long-term performance tests of HPDs

- Intense LED photocathode illumination of a pixel HPD
  - 40% occupancy at 50°C for 1 month (Normal occupancy: ~1%)
  - equivalent to 10 years of LHCb running

- Measurements made of:
  - Dark counts
  - Ion feedback (indicator of vacuum quality)
  - Light response
  - Photocathode quantum efficiency
Ageing tests (2)

- No degradation observed of:
  - QE
  - Dark current
  - Ion feedback
  - Light yield

- Dark counts: slight decrease with time

- Ion feedback - increases from 1 to 3% but recovers.

Photocathode efficiency

Aged HPD3 QE 10V without diaphragm 25.06.2003

<table>
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<tr>
<th>Wavelength [nm]</th>
<th>Before</th>
<th>After</th>
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<tr>
<td>200 nm</td>
<td></td>
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<tr>
<td>700 nm</td>
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Dark count rate

Ion feedback rate

Light yield

Aged HPD3 QE 500V with Diaphragm 11.04.03

<table>
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<th>Center</th>
<th>Midway</th>
<th>Edge</th>
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No degradation observed of:

- QE
- Dark current
- Ion feedback
- Light yield

Photocathode efficiency

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Light yield

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HPD integration

- Two arrays of photon detectors to measure Cherenkov light in each of RICH1 & RICH2
- HPDs mounted on columns together with readout electronics, power distribution & active cooling

RICH2 array
On-detector

Off-detector

RICH2 column

data fibres

TTC fibres

power cables

data fibres

TTC fibres

power cables

control system

DAQ link

L1

LV supplies

Bias supplies

HV supplies

System tests
System tests (1)

- CERN PS beam: 10 GeV/c $\pi^-$, $e^-$
- 6 pre-series HPDs (all operating at 40MHz)
- Radiators: $N_2$ and $C_4F_{10}$
- Full prototype readout chain
System tests (3)

$N_2$ run, one HPD accumulated rings

$C_4F_{10}$ run, ring on four HPDs.

Reconstructed Cherenkov angle ($N_2$ run)

Width of the peaks ($\sigma = 0.5$ mrad) due to:

- Chromatic effect
- Emission point error
- Beam divergence
- Pixelisation
Photon yields - Nitrogen

<table>
<thead>
<tr>
<th>HPD</th>
<th>( \mu ) (measured)</th>
<th>( \mu ) (Monte Carlo)</th>
<th>Ratio</th>
</tr>
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<tbody>
<tr>
<td>L1</td>
<td>10.2</td>
<td>10.0</td>
<td>1.03</td>
</tr>
<tr>
<td>C1</td>
<td>11.5</td>
<td>11.2</td>
<td>1.03</td>
</tr>
<tr>
<td>R0</td>
<td>8.8</td>
<td>8.9</td>
<td>0.99</td>
</tr>
<tr>
<td>R1</td>
<td>9.7</td>
<td>10.7</td>
<td>0.90</td>
</tr>
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Typical Poisson fit

Good overall performance meets LHCb requirements
HPD Magnetic Field Sensitivity
Magnetic distortions (1)

- HPDs have to operate in the fringe field of the LHCb magnet.
- RICH1 shielding gives maximum field of \(~2.5\) mT (25 Gauss)
- RICH2 HPDs only experience field of \(~0.8\) mT → consider only RICH1

Measurements taken in a 10cm grid in the HPD plane
Local shielding of HPD’s reduce B field below 1 mT (10G) inside HPD volume

Mu-metal shield grounded and insulated with ~200um-thick Polyester
Magnetic distortions (2)

Response to LED cross-pattern at the HPD entrance window

Movement in pattern in \( r \) and \( \phi \)

Longitudinal

Transverse

B\( \parallel \) 3 mT

B\( \perp \) 5 mT
**B corrections: longitudinal field**

- Shielded HPD in 3 mT: no loss of active area
- Shielded HPD in 5 mT: 4.8% loss

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**Parameterisation understood for both axial and transverse field distortions**
RICH PID performance

- Simulation
- Pattern recognition
- $\pi/K$ separation performance
RICH simulation

- Hit pixels shown on HPD planes, for typical events in RICH1 & RICH2
- Simulation includes effects of all expected backgrounds, relies on tracks actually reconstructed
Global Pattern Recognition

- For a given set of track ID hypotheses, determine probability distribution for finding photons in each pixel of the detector plan.

  Single track

  Many tracks

- Use this to form likelihood from comparison with observed hit distribution.

- Adjust set of particle ID hypotheses to maximize the likelihood.
RICH performance

- FULL MC simulation
- Efficiency (in %) of pion and kaon identification
- Probability (in %) of misidentifying pion and kaon

\[ \pi \rightarrow e, \mu \text{ or } \pi \]

\[ K \rightarrow K \text{ or } p \]

\[ K \rightarrow e, \mu, \text{ or } \pi \]

\[ \pi \rightarrow K \text{ or } p \]
B→ ππ with RICH ID

No RICH

Events / 20 MeV/c²

Invariant mass [ GeV/c² ]

With RICH

Events / 20 MeV/c²

Invariant mass [ GeV/c² ]
Summary and outlook

- RICH1 - phased programme of design and construction
- RICH2 constructed - installation in the LHCb pit in ~4 weeks
- HPD performance well characterized. HPDs out for production, ~30 delivered each month until February 2007
- Successful lab and beam tests. Cherenkov light yield and resolution agree with expectations.

The RICH system will be ready for first LHC collisions in 2007