The LHCb RICH system: current detector performance and status of the upgrade program

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on behalf of the LHCb RICH Collaboration

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The LHCb Experiment

- **pp collision**
- **Tracking detectors**
- **Muon System**
- **Calorimeters**
- **Ring Imaging Cherenkov**

Acceptance:
- 10 mrad
- 250/300 mrad

(side view)
RICH Detectors

RICH-1 (25-300 mrad)
4 m³ C₄F₁₀  n = 1.0014,  up to 60 GeV

RICH-2 (15-120 mrad)
100 m³ CF₄  n = 1.0005,  up to ~100 GeV
Pixel HPD developed in collaboration with industry
- Vacuum technology and silicon pixel read-out
- 484 HPDs for a total area of 3.3 m²
- $32 \times 32 = 1024$ pixels, $0.5 \times 0.5$ mm²
- Very good QE (~27% @270nm)
- Silicon sensor bump-bonded to binary read-out chip (1.1 MHz)
- Very low noise
  - 145 e⁻ (signal 5000 e⁻ typ.)

References: NIMA 595 (2008) 142
EPJ C 73 (2013) 2431
Detector occupancy

RICH-1  
RICH-2
Online calibrations (1)

- Performed online since the beginning of Run 2
- Refractive index
  - May change due to temperature, pressure and gas mixture variation
  - Fit the Cherenkov angle distribution for $\beta=1$ tracks

Talk on LHCb real-time calibration/alignment by R. Aaij
Online calibrations (2)

- HPD image
  - Position of the photocathode image on the anode can change due to charging effects
  - Anode images are cleaned and a Sobel filter used to detect the edge
  - Automatic update of the photo-cathode center position
$\theta_C$ versus Momentum

Using isolated tracks for RICH-1


Talk on LHCb PID performance by M. Fontana
LHCb Upgrade Plans

- During Run 1 operated at tunable leveled luminosities up to $\sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, 2 $\times$ higher than design value
- In Run 2 we should collect $\sim 5 \text{ fb}^{-1}$ more
  - Main limitation: 1 MHz L0 trigger rate

<table>
<thead>
<tr>
<th>LHC era</th>
<th>HL-LHC era</th>
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<tbody>
<tr>
<td>Run 1 (2010-12)</td>
<td>Run 3 (2021-23)</td>
</tr>
<tr>
<td>3 fb$^{-1}$</td>
<td>$\sim 25 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>Run 2 (2015-18)</td>
<td>Run 4 (2027-29)</td>
</tr>
<tr>
<td>8 fb$^{-1}$</td>
<td>$\sim 50 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td></td>
<td>Run 5+ (2031+)</td>
</tr>
<tr>
<td></td>
<td>$\sim 100 \text{ fb}^{-1}$</td>
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</table>

- LHCb Upgrade
  - Operate detector at luminosities of $\sim 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
  - Upgrade detectors to be able to readout at 40 MHz
  - Install upgraded LHCb during long shutdown 2 (2019-20)
RICH Upgrade

- Adapt to higher luminosity
  - RICH-1 spherical mirrors focal length increased to reduce occupancy (optical system redesigned)
  - Support mechanics and cooling

- 40 MHz readout → replace HPDs with commercial Multi-Anode Photo-Multiplier Tubes (Ma-PMTs) and new front-end electronics
  - 64 ch. Ma-PMTs
  - 40 MHz Front-End: CLARO8 chip plus FPGA-based digital board and GBT chip for data transmission
Photo-multiplier tubes

- Hamamatsu R11265 (1'', 64 pixels) for RICH-1 and RICH-2
- Hamamatsu R12699 (2'', 64 pixels) for RICH-2 only
  - Outer (low occupancy) regions of RICH-2
The Elementary Cell (EC)

- Two versions for small (and large) Ma-PMTs
  - 4 (1) Ma-PMTs
  - 1 Base-board, 1 Back-board
  - 4 (2) Front-end boards (FEB)
  - Magnetic shield
  - Mechanics
Electronics requirements

- Hamamatsu Ma-PMTs main characteristics
  - Typical gain at 1000 V for R11265 is $\sim 1 \times 10^6$
  - 1:3 pixel gain spread in PMT, 1:3 spread in different PMTs

- Requirements coming from the LHCb environment:
  - Single photon counting at 40 MHz with Ma-PMTs (no dead time at 25 ns)
  - Radiation hardness for 50 fb$^{-1}$ total integrated luminosity (200 krad, $3 \times 10^{12}$ 1 MeV $n_{eq}$/cm$^2$, $1.2 \times 10^{12}$ HEH/cm$^2$)
The CLARO8 chip

- The CLARO8 is a 8-channel amplifier/discriminator ASIC designed for single-photon counting with Ma-PMTs

- Main features:
  - 0.35 µm CMOS technology from AMS (→ low cost, high yield)
  - Allows 40 MHz operation (recovery < 25 ns)
  - Power consumption ~1 mW/ch.
  - Adjustable threshold (6 bits)
  - Adjustable gain (2 bits)
  - Binary read-out
  - 128 bit register TMR protected
  - Radiation-hard by design cells

- Block diagram:
Test beam activities

- A compact detector based on solid radiator was proposed and tested in 2014 – 2016 to measure the performance of close-to-final opto-electronics chain

- Operation of a complete setup in a realistic environment
  - Calibrations, noise, thermal test, Cherenkov ring fitting
  - Validation of both EC types
Conclusions

- The LHCb RICH detectors have been operating with high efficiency in a high multiplicity environment and form an essential part of the experiment
  - Online calibrations and alignment in Run 2
- The LHCb RICH upgrade program, proposed to cope with $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ luminosity, is progressing well
  - New photo-detectors and electronics chain for full detector read-out at 40 MHz
  - Modified RICH optics and mechanics
  - Very successful test-beams validated the close-to-final opto-electronics chain in realistic conditions
  - We recently had the first production readiness review
  - On schedule for installation during 2019-20
SPARES
Photon detector plane: 14×7 HPDs

VELO Exit Window
2 mm aluminum
Sealed to gas enclosure
No RICH-1 entrance window

Spherical Mirrors Lightweight carbon fiber mirrors
1.5% radiation length
(4 segments)

Flat Mirrors (16 segments)

RICH-1 Exit Window
Carbon fiber and foam
Sealed direct to the beam pipe
Spherical Mirrors (56 segments)

RICH-2 entrance/exit windows carbon fiber and foam sandwich

Gas Enclosure contains CF$_4$ gas radiator and the optical system

Flat Mirrors each made from 40 square glass segments

Magnetic Shields protect the HPD planes

Photon detector plane: 9×16 HPDs
Radiators and material budget

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$C_4F_{10}$</th>
<th>$CF_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ [cm]</td>
<td>$\sim 110$</td>
<td>167</td>
</tr>
<tr>
<td>$n$</td>
<td>1.0014</td>
<td>1.0005</td>
</tr>
<tr>
<td>$\theta_c^{\text{max}}$ [mrad]</td>
<td>53</td>
<td>32</td>
</tr>
<tr>
<td>$p_{\text{thresh}}(\pi)$ [GeV/c]</td>
<td>2.6</td>
<td>4.4</td>
</tr>
<tr>
<td>$p_{\text{thresh}}(K)$ [GeV/c]</td>
<td>9.3</td>
<td>15.6</td>
</tr>
<tr>
<td>$p_{\text{thresh}}(p)$ [GeV/c]</td>
<td>17.7</td>
<td>29.7</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>RICH 1</th>
<th>RICH 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance window</td>
<td>0.001</td>
<td>0.014</td>
</tr>
<tr>
<td>Gas radiator</td>
<td>0.026</td>
<td>0.017</td>
</tr>
<tr>
<td>Mirror</td>
<td>0.015</td>
<td>0.079</td>
</tr>
<tr>
<td>Exit window</td>
<td>0.006</td>
<td>0.014</td>
</tr>
<tr>
<td>Total ($X_0$)</td>
<td>0.048</td>
<td>0.124</td>
</tr>
</tbody>
</table>
Magnetic field corrections

- HPD image distortion due to magnetic field
- Projection of test pattern with and without magnetic field to extract correction parameters

RICH-1
σ=0.5mm

RICH-2
σ=0.47mm
Alignment

- Many components aligned with an accuracy of 0.1 mrad
  - Whole detector, detector halves, mirror segment and HPD

- Then use reconstructed Cherenkov angle for $\beta=1$ tracks
  - Misalignment observed as shift of track projection point w.r.t. the center of the corresponding Cherenkov ring
Cherenkov angle resolution

- Single photon resolution
  - Distributions for saturated ($\beta=1$) tracks

\[\sigma_{\Delta \theta} = 1.618 \pm 0.002 \text{ mrad} \]
\[\sigma = 1.52 \pm 0.02 \text{ (MC)} \]

\[\sigma_{\Delta \theta} = 0.68 \pm 0.02 \text{ mrad} \]
\[\sigma = 0.68 \pm 0.01 \text{ (MC)} \]
**PID algorithm**

- Consider all photons and all tracks and all radiators at once and maximize likelihood function:
  \[ L = L(n_{\text{pixel}}, \sum_{\text{track}} e_{\text{pixel,track}}, b_{\text{pixel}}) \]

- Take all PIDs to be pions
  - Estimate background parameter \( b_{\text{pixel}} \) per HPD

- Calculate likelihood of given pixel distribution

- Iterate
  - Change PID hypothesis one track at a time
  - Recalculate likelihood
  - Choose change that had biggest impact
  - Assign new PID to that track

- Until no significant improvement is found
  - As signal photons are now identified better, update background estimate and start a 2nd (and usually final) iteration
PID Performance (1)

- PID performance evaluated from data for Run1
  - Genuine $\pi/K/p$ samples identified from kinematics only
PID Performance (2)

- Invariant mass distribution for $B \rightarrow h^+h^-$ decays
  - before (left) and after (right) using RICH PID information

- Signal: $B^0 \rightarrow \pi^+\pi^-$ (turquoise dotted line)

- Other contributions are eliminated ($B^0 \rightarrow K\pi$, $B^0 \rightarrow 3$–body, $B_s \rightarrow KK$, $B_s \rightarrow K\pi$, $\Lambda_b \rightarrow pK$, $\Lambda_b \rightarrow p\pi$)

for Run1
Ion Feedback (IFB) occurs when a photoelectron ionises a residual gas atom

- The ion drifts to the photocathode and produces on impact a cluster of secondary electrons
- The cluster of electrons arrives at the sensor with a characteristic delay of typically 200-300 ns due to the drift time of the ion
Occupancy for upgrade phase
Ma-PMT Vs HPD QE

![Graph showing the quantum efficiency (QE) of Ma-PMT and HPD S20 vs wavelength. The graph includes data points for SBA Borosilicate and HPD S20.](image-url)
## Angular resolutions

<table>
<thead>
<tr>
<th>Resolutions</th>
<th>Current RICH 1 (HPDs)</th>
<th>Upgraded RICH 1</th>
<th>Upgraded RICH 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission point</td>
<td>0.61</td>
<td>0.37</td>
<td>0.27</td>
</tr>
<tr>
<td>Chromatic</td>
<td>0.84</td>
<td>0.58</td>
<td>0.31</td>
</tr>
<tr>
<td>Pixel</td>
<td>0.99</td>
<td>0.44</td>
<td>0.20</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Total resolution</td>
<td>1.50</td>
<td>0.88</td>
<td>0.60</td>
</tr>
</tbody>
</table>
PID performance

- $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$ current geometry
- $10 \times 10^{32}$ cm$^{-2}$s$^{-1}$ current geometry
- $20 \times 10^{32}$ cm$^{-2}$s$^{-1}$ current geometry
- $20 \times 10^{32}$ cm$^{-2}$s$^{-1}$ upgraded geometry
CLARO timeline

(2011) - Design of the 4 ch. CLARO prototype
- Deep characterization on the test bench

(2012) - First tests with R11265 Ma-PMTs and Silicon Photomultipliers

(2013) - Radiation hardness tests
- More tests with the R11265 Ma-PMTs
- Chosen as the baseline front-end ASIC for the LHCb RICH Upgrade

(2014) - CLARO8 designed and produced (v0, v1)
- CLARO8 bench, beam and radiation hardness tests

(2015) - CLARO8 v2 designed and produced
- CLARO8 v2 bench and beam test

(2016) - CLARO8 v3 designed, produced and tested
- CLARO8 Production Readiness Review (PRR)
CLARO8 signals

- The amplifier and DAC of any channel are buffered to output pins through a multiplexer controlled by global bits in the configuration register.

- LHCb RICH binary read-out: hit or no-hit information for each bunch crossing at 40 MHz
  - Hits are “collected” by FPGA and sent off-detector.
Magnetic shield design

- Design almost finalized

Central pixel

Edge pixel
Digital board

- Motherboard with FPGAs and power distribution (DC-DC)
- Plugins for control and data link
- Thermally coupled to cold bar
RICH columns

- Ultimate mechanical support for (MaPMTs $\rightarrow$ Elementary Cells) + PDMDB + harness + cooling + …
- Photo Detector Assembly (PDA)