The Future of RICH Detectors through the Evolution of the LHCb RICHes
(Carmelo D’Ambrosio on behalf of the LHCb RICH collaboration)

The LHCb-RICH system was born in the 20th century, what will it be in 2035?

Drive for upgrades in LHC: more physics and physics reach.
How? By increasing Luminosity ... and detectors must follow.
Drag: Resources, Space (the sub-det envelopes are defined).

In the LHCb framework*:

Upg1  2021 will see the first upgrade of the RICHes and LHCb (x10 present Lumi);
Upg2a  2025 may see a small upgrade in preparation for
Upg2b  203x, a major possible upgrade (HL-LHC, x50 present Lumi).

* Disclaimer: apart from the 2021 upgrade, there are no official requests for the successive upgrades. But LHC is like a train, either you are on it or you are left behind...
RICH1 and RICH2

Magnetic Shield
Aerogel
C$_{4}$F$_{10}$
Beam pipe
Photon Detectors
250 mrad
Spherical Mirror
Track
Carbon Fiber Exit Window
VELO exit window
Plane Mirror
Spherical & Flat Mirrors
Present, Run II, 25 ns, $\sim 2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

**RICH 1**
Wide acceptance (300 mrad), tight space
Low-medium mom. range ($\sim$10 to $\sim$ 60 GeV/c)
High photon yields
and medium resolutions (1.60 mrad per hit).

**RICH 2**
Small acceptance (120 mrad), wide space
Medium-high mom. range ($\sim$50 to $\sim$100 GeV/c)
Lower photon yields
and high resolutions (0.67 mrad per hit).

Improved PID and online cal. and mon.;
RICH system fully included in HLT.
Contents

• Detector limitations and improvements with increasing luminosity

• The case for RICH 1

• Critical issues and associated R&D

• Photodetectors still own the game!

• Conclusions
With Luminosities increasing:

1. Occupancies jump up: improve granularity;
With Luminosities increasing and Physics Reach extending

1. Occupancies jump up: improve granularity;

\[ \frac{A_p}{A_i} \propto \frac{A_p}{f^2} \]

\( A_p \) is the pixel area
\( A_i \) is the image area
\( f \) is the mirror focal length

Example:

In the Upg1 RICH1, we are increasing the mirror focal length (x 2 Occupancy decrease).
Lightweight CF spher. mirrors
The RICH1 Magnetic Shield defines the available volume (unless it is not needed ...)

VeLo detector on this side

UT on this side
With Luminosities increasing

1. Occupancies jump up: improve granularity;

\[
\frac{A_p}{A_i} \propto \frac{A_p}{f^2}
\]

\(A_p\) is the pixel area
\(A_i\) is the image area
\(f\) is the mirror focal length

In the Upg2 and in RICH1, we can decrease the pixel area (from \(~7\text{mm}^2\) to \(1\text{mm}^2\)).

Worth noting, in some cases* a 2-bits readout can be equivalent to \(/4\) in pixel surface.

*This is strictly true for HPDs and SiPMs, where the \(1^{\text{st}}\) and \(2^{\text{nd}}\) photoelectron peaks are well separated.
Going to $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ increases occupancies on both RICH 1 and 2.

At $\nu = 38^*$, peak occupancies are in excess of 100% in RICH 1. However the region of extreme occupancies is limited.

From experience, we try to keep Occupancies always below $\sim30\%$.

- **Present**: $30\%$  \quad $A_p=6.3\text{mm}^2$, $f=1.35\text{ m}$
- **Upg1**: $\frac{1}{2} \times 30\%$  \quad $A_p=6.8\text{ mm}^2$, $f=1.9\text{ m}$
- **Upg2**: $\frac{1}{7.5} \times 30\%$  \quad $A_p=1\text{ mm}^2$, $f=2\text{ m}$

* $\nu = 38$ is the number of primary vertices per collision at $10^{34}\text{ cm}^{-2}\text{s}^{-1} (\text{upg2})$.  

5-9 September 2016, Carmelo, RICH 2016
With Luminosities increasing

2. Pattern recognition a challenge:

Granularity is a necessary but not sufficient condition to ensure pattern recognition: improve the single photon Cherenkov angle resolution.

\[ (\sigma_\theta \cdot f) \lesssim \sqrt{A_p} \]

Essentially keep this smaller than the pixel size!!

For Upg2*, \( \sigma_\theta \lesssim 0.5\text{mrad} \) (present 1.6 mrad)

\( \sigma_\theta \) is the Cherenkov angle resolution
\( f \sim 2m \) is the mirror focal length
\( A_p \) is the pixel area

*and for RICH1 regions with high occupancies
Improve Cherenkov angle resolution...

$\sigma_\theta$ depends on a sum (in quadrature) of uncertainties:

Pixel size, $\sim \sqrt{\frac{A_p}{12}}$

Emission Point, optical system aberrations

Chromatic dispersion, $\cos \vartheta_c(\lambda) = \frac{c}{n(\lambda)v}$

of course ultimately we want $\frac{\sigma_\theta}{\sqrt{N}}$

$\vartheta_c$ is the Cherenkov angle
$\sigma_\theta$ is the Cherenkov angle resolution
$N$ is the number of detected photons
$A_p$ is the pixel area
A few slides to show a possible way to improve the LHCb RICH System*

*For the sake of simplicity, let us suppose to be able to use SiPM detectors.
Optical Performance and Photon Yields

Lumi = 2 x 10^{32} \text{ cm}^{-2} \text{ s}^{-1}; \text{ Occupancy < 30%}

<table>
<thead>
<tr>
<th>Detector Version</th>
<th>RICH-1 Current (HPD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avr. Phel. Yield</td>
<td>30</td>
</tr>
</tbody>
</table>

### Single Photon Errors [mrad]

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromatic</td>
<td>0.84</td>
</tr>
<tr>
<td>Pixel</td>
<td>0.9</td>
</tr>
<tr>
<td>Emission Point</td>
<td>0.8</td>
</tr>
<tr>
<td>Track resolution</td>
<td>0.4</td>
</tr>
<tr>
<td>Overall</td>
<td>1.52</td>
</tr>
</tbody>
</table>

depends on spherical mirror tilt and focal length

Chromatic depends on the overlap between dispersion and photodet. QE
Optical Performance and Photon Yields

Lumi \(\leq 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \); Occupancy < 30%

<table>
<thead>
<tr>
<th>Detector Version</th>
<th>RICH-1 Upg1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avr. Phel. Yield</td>
<td>40</td>
</tr>
<tr>
<td>Single Photon Errors [mrad]</td>
<td></td>
</tr>
<tr>
<td>Chromatic</td>
<td>0.58</td>
</tr>
<tr>
<td>Pixel</td>
<td>0.44</td>
</tr>
<tr>
<td>Emission Point</td>
<td>0.37</td>
</tr>
<tr>
<td>Track resolution</td>
<td>0.4</td>
</tr>
<tr>
<td>Overall</td>
<td>0.9</td>
</tr>
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depends on spherical mirror tilt and focal length

Chromatic depends on the overlap between dispersion and photodet. QE
## Optical Performance and Photon Yields

Lumi = $10^{34}$ cm$^{-2}$ s$^{-1}$; Occupancy > 100%

<table>
<thead>
<tr>
<th>Detector Version</th>
<th>RICH-1 Upg2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avr. Phel. Yield</td>
<td></td>
</tr>
<tr>
<td>Single Photon Errors [mrad]</td>
<td></td>
</tr>
<tr>
<td>Chromatic</td>
<td>0.58</td>
</tr>
<tr>
<td>Pixel</td>
<td>0.44</td>
</tr>
<tr>
<td>Emission Point</td>
<td>0.1</td>
</tr>
<tr>
<td>Track resolution</td>
<td>?</td>
</tr>
<tr>
<td>Overall</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Use lightweight flat mirror in the acceptance (reduce aberrations)

Chromatic depends on the overlap between dispersion and photodet. QE
Optical Performance and Photon Yields

Lumi = $10^{34}$ cm$^{-2}$ s$^{-1}$; Occupancy < 30%

<table>
<thead>
<tr>
<th>Detector Version</th>
<th>RICH-1 Upg2</th>
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<tbody>
<tr>
<td>Avr. Phel. Yield</td>
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<td>Pixel</td>
<td>0.15</td>
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<td>0.1</td>
</tr>
<tr>
<td>Track resolution</td>
<td>?</td>
</tr>
<tr>
<td>Overall</td>
<td>0.6</td>
</tr>
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Reduce pixel size to ~1mm

Chromatic depends on the overlap between dispersion and photodet. QE

5-9 September 2016, Carmelo, RICH 2016
**Optical Performance and Photon Yields**

Lumi = $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$; Occupancy < 30%

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<thead>
<tr>
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<th>RICH-1 Upg2</th>
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<tbody>
<tr>
<td>Avr. Phel. Yield</td>
<td>60 - 40</td>
</tr>
<tr>
<td>Single Photon Errors [mrad]</td>
<td></td>
</tr>
<tr>
<td>Chromatic</td>
<td>0.24</td>
</tr>
<tr>
<td>Pixel</td>
<td>0.15</td>
</tr>
<tr>
<td>Emission Point</td>
<td>0.1</td>
</tr>
<tr>
<td>Track resolution</td>
<td>?</td>
</tr>
<tr>
<td>Overall</td>
<td>0.3</td>
</tr>
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Reduce chromatic by choosing a photodetector with a “green-shifted” QE curve (and filter the shorter wavelengths)

Chromatic depends on the overlap between dispersion and photodet. QE
### Optical Performance and Photon Yields

Lumi = $10^{34}$ cm$^{-2}$ s$^{-1}$; Occupancy < 30%

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![Diagram showingchromatic effect and photodetector QE curves](image)

Reduce chromatic by choosing a photodetector with a “green-shifted” QE curve (and filter the shorter wavelengths)

Chromatic depends on the overlap between dispersion and photodetector QE
### Simulated Optical Performance and Photon Yields

<table>
<thead>
<tr>
<th>Radiator</th>
<th>( \text{C}<em>4\text{F}</em>{10} )</th>
<th>( \text{CF}_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detector Version</strong></td>
<td><strong>Current (HPD)</strong></td>
<td><strong>Upg1</strong></td>
</tr>
<tr>
<td>RICH-1</td>
<td>25 (30)*</td>
<td>40 (rms=8)</td>
</tr>
<tr>
<td>RICH-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Avr. Ph.Electron Yield</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Single Photon Errors [mrad]</strong></td>
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<td>0.37</td>
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<tr>
<td>Track resolution</td>
<td>0.4</td>
<td>?0.4?</td>
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<td><strong>Overall</strong></td>
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*Value from data (expected)
RICH1 using SiPM and improved geometry (version7, upg2)

Compared to upg1: spherical mirror tilt reduced; flat mirror extends to the charge particle acceptance.

Sph Mirror RoC=3800 mm

The detector plane with SiPM SiPM pixel size = 1mm X 1 mm
RICH1 resolutions: SiPM with low WL cut-off, new geometry, upg2

Resolution is improved compared to current upgrade geometry

5-9 September 2016, Carmelo, RICH 2016
With Luminosities increasing

**Time resolution** (time granularity) will also help disentangle busy events, while delivering more information:

Provide the system with **time resolution**
- \(\sim 0.2 \text{ to } 1 \text{ ns} \) (time resolution on single photon)
- and \(\sim 50 \text{ to } 150 \text{ ps} \) (time resolution with \(\sim 40 \) detected photons).

Provide a time-over-threshold information (similar to **2-bits readout**).

Already our **existing electronics** could provide figures close to the aforementioned.
Timing performance of the CLARO8 chip

Excellent timing performance at 0.7 mW/channel:
- Time walk < 3 ns
- Leading edge jitter from 110 ps RMS (just above threshold) to 11 ps RMS (large signals)

Even better performance could be achieved by doubling the power to 1.5 mW/channel.

C. Gotti - TIPP 2014
Upg2, Run XX, 25 ns, up to $10^{34}$ cm$^{-2}$ s$^{-1}$, 202x onwards

The recipe 😊

Increase granularity, or/and provide a 2-bits readout electronics

Improve optical error,
  by moving light-weight flat mirrors into the acceptance,
  by further reducing mirror tilts

Further reduce chromatic error
  by tuning the gas
  by further moving the photodetector sensitive region towards the green
  by increasing photodetector QE

Provide the system with time resolution

Work on new and specific pattern recognition algorithms

Perhaps get rid of the magnetic shielding by using B-insensitive photodetectors
Upg2, Run XX, 25 ns, up to $10^{34}$ cm$^{-2}$ s$^{-1}$, 202x onwards

The shopping list 😞

Light-weight flat mirrors and supports:
CF spherical mirrors and supports already in RICH1;
First CF flat mirror prototype for RICH1 produced;
Good resistance to radiation.

Photodetectors:
Vacuum devices: MaPMTs, HPDs and MCP-PMTs with green-enhanced QE response;
Solid State: -50°C cooled SiPMs (see LHCb SciFi detector);

On-detector electronics with space and time resolution:
CLARO8 already features some of the needed functionalities;
The PDM Digi Board can be developed accordingly.

DAQ is a challenge; compress/reduce data on detector.
Work on new and specific pattern recognition algorithms.

All marked in red needs R&D!!
... If we want to be ready for LS3!! ... (2025, upg2a)

Perhaps only in the central regions of RICH 1
Improvement in PID in the 20-100 GeV/c region, when using SiPM.
Conclusions

“The politics of small steps may nicely reward the patient ones”, (from an old saying) … especially if there is no other choice!

Through further improvements and staying in the present envelope, the LHCb RICHes could continue to perform PID efficiently at luminosities up to $10^{34}$ cm$^{-2}$ s$^{-1}$.

The single-photon cherenkov angle resolution could be squeezed from 1.6/0.7 mrad (present system) to 0.2/0.1 mrad for RICH 1 and 2 respectively.

A critical point will be the development of green-enhanced photodetectors with high space and good time resolution.

We see the future of LHCb RICHes as high-precision, green-enhanced, compact machines.