The LHCb RICH Upgrade for the LHC Run 3

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On behalf of the LHCb RICH Collaboration
The (current) LHCb Upgrade

- Increase luminosity to $2 \times 10^{33} \text{s}^{-1} \text{cm}^{-2} \times 5$
- Remove hardware trigger and readout the full 40MHz LHC bunch crossing
- More complex events
- More radiation damage
- New electronics
- Almost a completely new detector

**Goal:** 50 fb$^{-1}$

<table>
<thead>
<tr>
<th>Run 1</th>
<th>LS1</th>
<th>Run 2</th>
<th>LS2</th>
<th>Run 3</th>
<th>LS3</th>
<th>Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 - 2012</td>
<td></td>
<td>2015-2018</td>
<td></td>
<td>2021-2024</td>
<td></td>
<td>2027-</td>
</tr>
</tbody>
</table>
The RICH System

RICH1 (25-300 mrad)
4 m$^3$ C$_4$F$_{10}$ \(n = 1.0014\), up to 60 GeV

RICH2 (15-120 mrad)
100 m$^3$ CF$_4$ \(n = 1.0005\), up to \(\approx 100\) GeV
The RICH Upgrade (i)

More complex events

- Completely new RICH1
- New mirrors with longer focus
- New position for the photon detectors
- New gas enclosure, exit window, cooling and support structures
The RICH Upgrade (ii)

Continuous 40 MHz readout

- MaPMTs from Hamamatsu
- New radiation hard ASIC (CLARO) for MaPMT readout
  DOI: 10.1088/1748-0221/10/01/C01013
- FPGA based digital board
- GBT for data transmission

Single photon spectrum
The Elementary Cell

Early Prototype Version

CLARO FEBs
8 CLARO ASICs per FEB

Digital boards
Manage digital signals processing and data transmission

Back-Board
Adapter to the digital board

Mechanics and cooling

2×2 PMTs

Base-Board

Cherenkov photons

PMT

FE ASIC

FPGA

Data link

Off detector
## Contributions to resolution (in mrad)

<table>
<thead>
<tr>
<th>Contributions to resolution (in mrad)</th>
<th>RICH1-2015 HPD</th>
<th>RICH1-Upgrade MaPMT</th>
<th>RICH2-2015 HPD</th>
<th>RICH2-Upgrade MaPMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromatic</td>
<td>0.84</td>
<td>0.58</td>
<td>0.48</td>
<td>0.31</td>
</tr>
<tr>
<td>Pixel</td>
<td>0.60, PSF=0.86</td>
<td>0.44</td>
<td>0.19, PSF=0.29</td>
<td>0.19, 0.41 (large)</td>
</tr>
<tr>
<td>Emission Point</td>
<td>0.76</td>
<td>0.37</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td><strong>1.60</strong></td>
<td><strong>0.78</strong></td>
<td><strong>0.65</strong></td>
<td><strong>0.45</strong></td>
</tr>
</tbody>
</table>

Improvements due to:
- Chromatic error; MaPMTs QE peaks at higher wavelength
- No Point Spread Function for MaPMTs
- Better emission point error with new RICH1 geometry
MaPMT production/QA

Correlation between the MaPMT gain measured by Hamamatsu and the RICH test centres:
- Two different techniques: current vs single photon spectrum

450 2” tubes

3100 1” tubes

https://doi.org/10.1016/j.nima.2019.05.046
Two locations: Ferrara and Edinburgh
Two stations at each location

Test protocol:
- Threshold scans
- S-curve fitting
- Dark counts
## EC QA so far

<table>
<thead>
<tr>
<th></th>
<th>ECs Including Spares</th>
<th>ECs Excluding Spares</th>
<th>Sent ECs (Ferrara)</th>
<th>Sent ECs (Edinburgh)</th>
<th>Sent ECs (Total)</th>
<th>Sent ECs to ECs Excluding Spares</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC-R</td>
<td>810</td>
<td>672</td>
<td>249</td>
<td>80</td>
<td>329</td>
<td>&gt;48%</td>
</tr>
<tr>
<td>EC-H</td>
<td>460</td>
<td>384</td>
<td>167</td>
<td>71</td>
<td>238</td>
<td>&gt;61%</td>
</tr>
<tr>
<td>EC-R + EC-H</td>
<td>1270</td>
<td>1056</td>
<td>416</td>
<td>151</td>
<td>567</td>
<td>&gt;53%</td>
</tr>
</tbody>
</table>

- Batches of 40 / 80 ECs,
- Encapsulated in Korvu plastic jars.
Digital board production

<table>
<thead>
<tr>
<th>Assembled</th>
<th>Pre-tested (CB)</th>
<th>Under test (OX)</th>
<th>Tested (OX)</th>
<th>Shipped</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDMDB-H</td>
<td>105</td>
<td>105</td>
<td>0</td>
<td>98</td>
</tr>
<tr>
<td>PDMDB-R</td>
<td>378</td>
<td>378</td>
<td>0</td>
<td>195</td>
</tr>
</tbody>
</table>

Modular design:
- GBT modules separate from FPGA board; allows for unexpected radiation damage

Minor production problems:
- Missing DCDC connector
- Missing resistor

Issues with faulty connectors:
- Open contacts or shorted pins
- Established procedure to safely repair the boards
modularity: RICH organised in columns

columns form planes

first column assembled at CERN

RICH 2 mechanics + readout + services assembled
The mechanics of the RICH1 columns are being worked out.
A nanosecond time gate in the Run 3 front-end electronics

- The prompt Cherenkov radiation and focusing mirrors result in an excellent time resolution of the RICH detectors of less than 10 ps (DOI:10.17863/CAM.45822).
- The RICH photon detector hit time distribution has a signal (S) peak with a width of ~ 0.5 ns (FWHM) dominated by the primary vertex spread.
- A nanosecond time gate can be applied around the signal peak. This helps to eliminate background photons (B and R) as well as sensor noise.
- The reduction in hit occupancy benefits the performance of the particle identification algorithm.

Studies in the CERN PS/SPS charged particle beam have confirmed the reduction in uncorrelated background using a time gate at the front-end readout electronics.
Timing gate implementation

- FPGAs capture the digital signals from the FE, format the data and transmit it using GBTX transceiver ASICs.
- The programmable FPGA logic can sample the CLARO signals at 320 Mbit/s using the de-serialiser embedded in every input-output logic block.
- The byte from the de-serialiser is used to address a lookup table. The value of the bit at this memory location is presented at the output of the lookup table on each 40 MHz clock edge.
- The lookup table can therefore be programmed to detect specific signal patterns arriving from the CLARO channel and for example, to apply a time gate of 3.125 ns or 6.25 ns at the front end.
<table>
<thead>
<tr>
<th>Gas</th>
<th>Formula</th>
<th>100-year GWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfluoromethane</td>
<td>CF₄</td>
<td>7,390</td>
</tr>
<tr>
<td>Perfluoropropane</td>
<td>C₃F₈</td>
<td>8,830</td>
</tr>
<tr>
<td>Perfluorobutane</td>
<td>C₄F₁₀</td>
<td>8,860</td>
</tr>
<tr>
<td>Perfluoropentane</td>
<td>C₅F₁₂</td>
<td>13,300</td>
</tr>
<tr>
<td>Perfluorohexane</td>
<td>C₆F₁₄</td>
<td>9,300</td>
</tr>
</tbody>
</table>

https://climatechangeconnection.org/emissions/co2-equivalents/

C₆F₁₄ replaced with Novec® with GWP=1

We are starting an R&D programme to develop a leak-less gas enclosure for C₄F₁₀ (< 0.1 l/day) with the potential to install it in LS3 (2025)
Summary and Outlook

- The LHCb Upgrade is progressing well delivering a much improved detector cable of collecting 5 times more data.
- The LHCb RICH plans for a PID detector capable of the same or better performance at 5 times the luminosity are also being realised without delays.
- All of the required components for the new photon-detectors have been produced or being ordered for assembly at CERN.
- We have developed the capability for a 3 or 6 ns timing gate at the front end in order to reduce backgrounds.
- The first photo-detector columns are expected to be installed in March 2020.