42ND INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

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Prague, Czech Republic

The LHCb RICH Upgrade II

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on behalf of the LHCb RICH collaboration

THE UNIVERSITY of EDINBURGH

EDINBURGH PARTICLE PHYSICS EXPERIMENTS

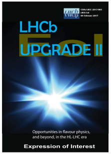
I RICH

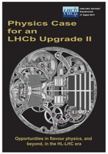
LHCb

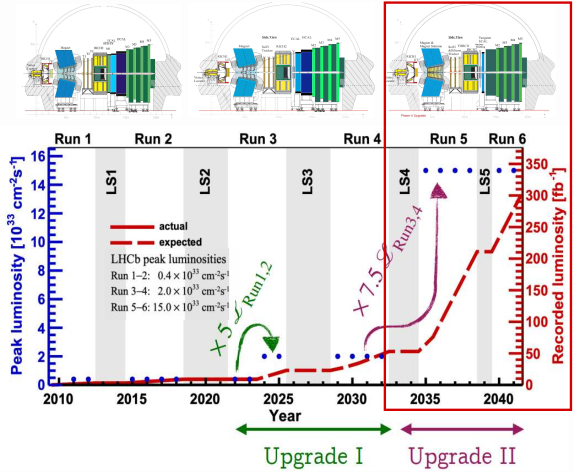
The LHCb Upgrade II

- LHCb experiment[2010-2018] collected 9 fb^{-1}
  see Yasmine's talk
- LHCb Upgrade I[2022-] expected to collect $\sim$ 50 fb^{-}1
  see Giulia's talk
- LHCb Upgrade II[2034-] to collect $\sim$ 300 fb^{-1}
  see Renato's talk

[CERN-LHCC-2017-003]
[CERN-LHCC-2018-027]
[CERN-LHCC-2021-012]







LHCb Upgrade II: programme to fully realise the flavour-physics potential of the HL-LHC

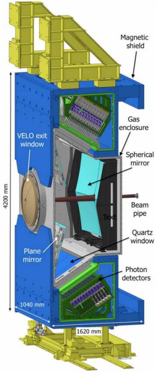
The challenge for the RICH system

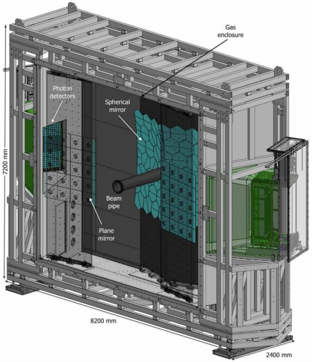
- RICH 1 (C_4F_{10}): upstream, 2 GeV/c - 40 GeV/c over 25 mrad - 300 mrad
- RICH 2 (CF_4): downstream, 15 GeV/c - 100 GeV/c over 15 mrad - 120 mrad
- system installed and operated in Run1&2

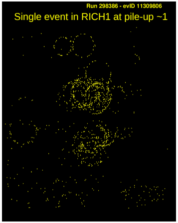
  [Eur. Phys. J. C 73 (2013) 2431

  [JINST 17 P07013 (2022)]
- system Upgraded during LS2 and operating since 2022 (see Giovanni's talk)

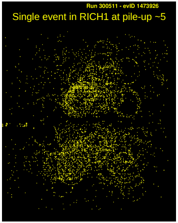
Improve or at least maintain the same PID performance of Run3 but in much harsher conditions and a well constrained envelope



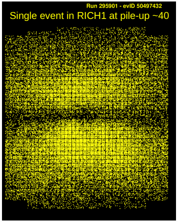



Run 298386 - evID 11309806

Single event in RICH1 at pile-up ~1


Run 300511 - evID 1473926

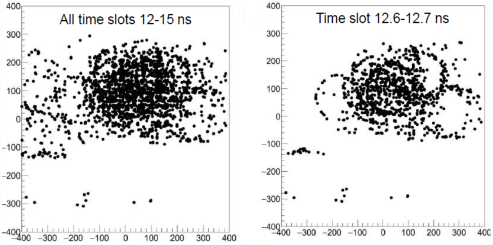
Single event in RICH1 at pile-up ~5

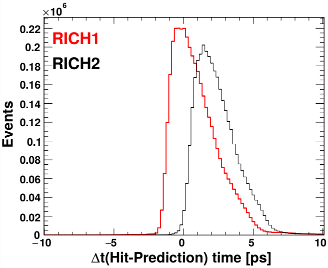

Run 295901 - evID 50497432

Single event in RICH1 at pile-up ~40

The power of timing

Prompt nature of Cherenkov light: time of arrival of Cherenkov photons for a given track can be predicted to better than 10 ps





timing implementation on RICH detectors helps in reducing the peak occupancy and recover PID performance [https://doi.org/10.17863/CAM.78867]

⇒ need for fast Photon Detector and fast electronics

Possible candidates: SiPM

SiPMs have several advantages:

- extremely fine granularity
- resilience to magnetic fields
- high photon detection efficiency
- good time resolution ($\sim 100\,\text{ps}$)

But important drawbacks:

- dark count rates after irradiation

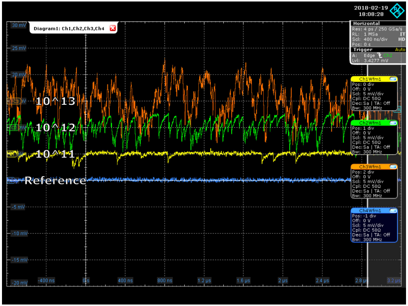
⇒ R&D on cryogenic operations

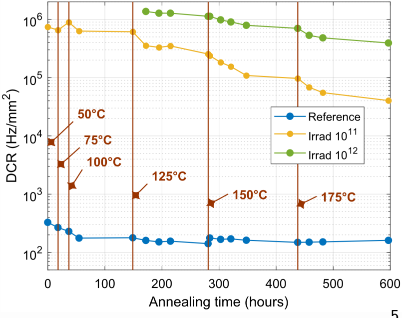
⇒ R&D on local cooling of SiPM with design of dedicated housing

⇒ R&D on implementing annealing to compensate for irradiation effects

[NIM A 922, 243-249 (2019)]

measurements performed at -30°

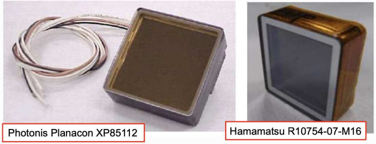




Possible candidates: MCP

Extremely good time resolution < 40 ps, custom pixelisation tailored for individual applications, but important drawbacks related to lifetime and rate capability: R&D ongoing

Conventional MCPs

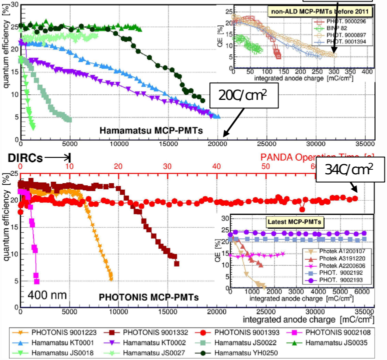


Status in 2023

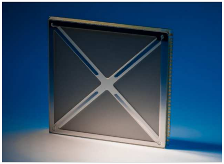
0.3C/cm^2

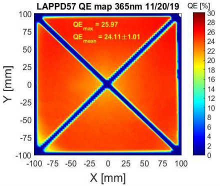
20C/cm^2

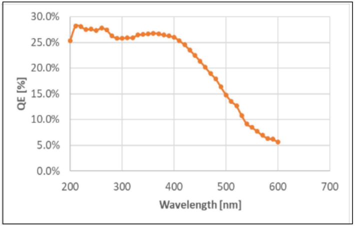
34C/cm^2



Large Area Picosecond PhotoDetector





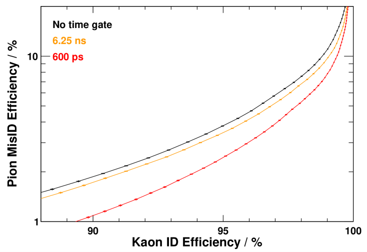


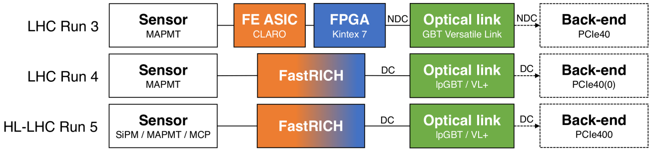
Fused Silica 3.8mm Window (LAPPD #63)

R&D to investigate possible options of low-gain MCPs: MCP-HPD [JINST 13 C12005 2018]

The plan for timing: LS3 enhancement

- timing concept new to LHCb but common amongst many systems for LHCb upgrade II
- anticipate ASIC development to LS3: introduce time stamp of photons
- FastRICH ASIC fast enough to be used in upgrade II
  $\Rightarrow$ timing in Run4 limited by photon detectors
- improvement in PID performance expected already in Run4
- LS3 PID TDR [CERN-LHCC-2023-005] approved in March 2024

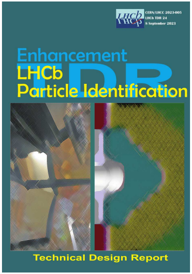



LHC Run 3 — **Sensor** MAPMT — **FE ASIC** CLARO — **FPGA** Kintex 7 — NDC — **Optical link** GBT Versatile Link — NDC — **Back-end** PCIe40

LHC Run 4 — **Sensor** MAPMT — **FastRICH** — DC — **Optical link** lpGBT / VL+ — DC — **Back-end** PCIe40(0)

HL-LHC Run 5 — **Sensor** SiPM / MAPMT / MCP — **FastRICH** — DC — **Optical link** lpGBT / VL+ — DC — **Back-end** PCIe400

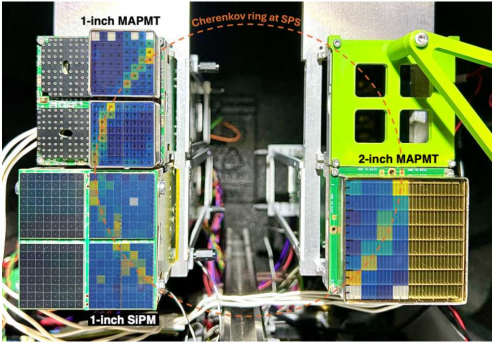
	Sensor [σ]	ASIC time walk	FE time gate	TDC time bin
LHC Run 3	150 ps	< 4 ns	6.25 ns	None
LHC Run 4	150 ps	CFD correction	2 ns	25 ps
HL-LHC Run 5	~ 50 ps	CFD correction	2 ns	25 ps

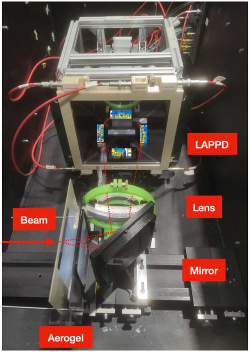

CERN/LHCC 2023-005
LHCb TDR 24
8 September 2023

Enhancement
LHCb
Particle Identification

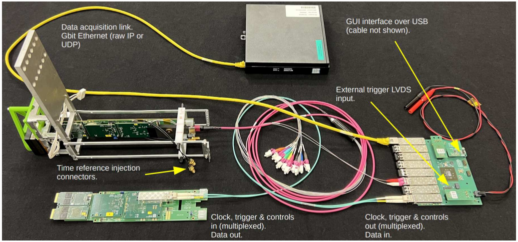
Technical Design Report

Test beam campaign





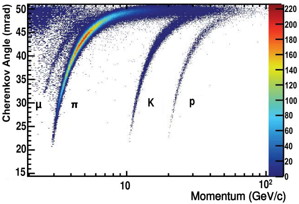
- intense testbeam campaign ongoing
- test prototype electronics for LS3 with MaPMTs currently operated in the RICH Upgrade
- test candidates for photon detection in Upgrade II



RICH performance: Cherenkov angle resolution

$$\Delta\beta/\beta = \Delta\theta_C \tan\theta_C,\ \text{where}\ \Delta\theta_C = \sigma_c/\sqrt{N_{ph}} + C_{\text{tracking,alignment,...}}$$

- σ_c is the resolution per single photon in a ring. The main contributions to keep under control (disk → ring) are:
  - emission point error due to the unknown emission point of the Cherenkov light: optimise the optics of the mirror system to focus the Cherenkov light
  - pixel size error due to the finite size of the photon detectors: choose photon detectors with optimal spatial granularity
  - chromatic error due to the radiator dispersion (different Cherenkov angles from the same track): appropriate choice of the radiator material to avoid large variations of the refractive index with the Cherenkov photons energy



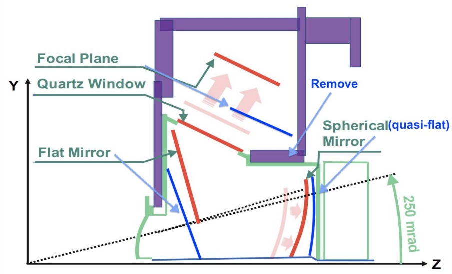
- photon yield (N_{ph}) as large as possible
- background counts as low as possible
- efficient pattern recognition keeping the peak occupancy under control (around 30%)

Emission Point error

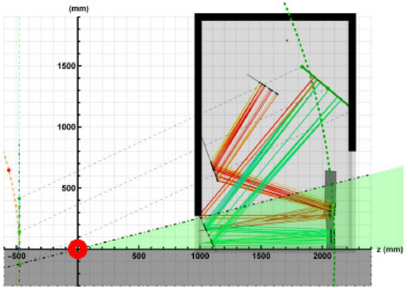
Road to the optimisation of the optics design:

- move flat mirrors in the acceptance ⇒ requires R&D on carbon fibre flat mirrors, light-weight supports and with good resistance to radiation ⇒ improve emission point error
- further increase in spherical mirror curvature radius ⇒ reduced occupancy and decreased pixel error

FTDR design for RICH1



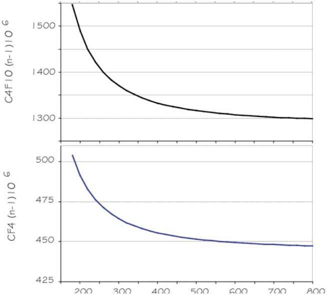
Split optics design for RICH1



Aim to reduce the emission point error: 0.38 mrad (Run3) → ∼ 0.13 mrad (Run5)

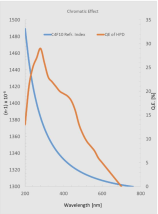
Optics optimisation less critical in RICH2 due to the lower occupancy and the already excellent Cherenkov angle resolution ⇒ optimisation ongoing and option of flat mirror in the acceptance under study

Chromatic error



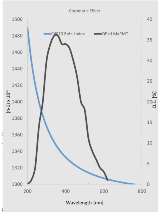
- fluorocarbon gases were chosen because of the relatively low chromatic dispersion
- C_4F_{10}: $n = 1.0014$ at 400 nm, gas vessel: $2 \times 3 \times 1\,\mathrm{m}^3$
- CF_4: $n = 1.0005$ at 400 nm, gas vessel: $100\,\mathrm{m}^3$
- the chromatic error depends on the convolution between the dispersion and the photon detector quantum efficiency (QE)
- R&D investigating photocathodes shifted towards the green to reduce single-photon chromatic error

Run 1 and 2



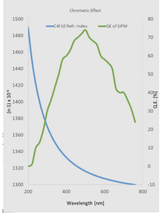
$\sigma^{\text{RICH1}}_{\text{chromatic}} = 0.84$ mrad
$\sigma^{\text{RICH2}}_{\text{chromatic}} = 0.48$ mrad

Run 3 and 4



$\sigma^{\text{RICH1}}_{\text{chromatic}} = 0.52$ mrad
$\sigma^{\text{RICH2}}_{\text{chromatic}} = 0.34$ mrad

Run 5 candidate



$\sigma^{\text{RICH1}}_{\text{chromatic}} = 0.11$ mrad
$\sigma^{\text{RICH2}}_{\text{chromatic}} = 0.10$ mrad

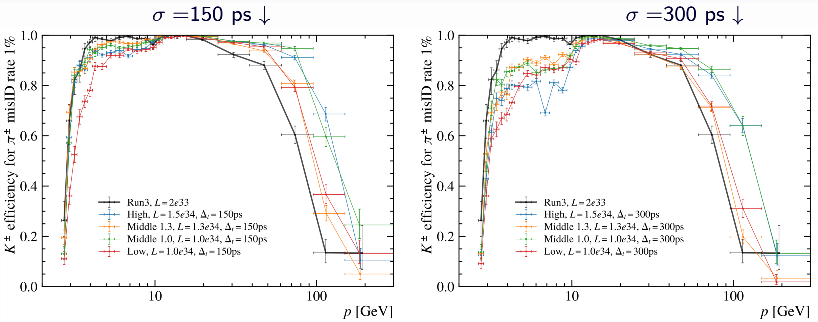
Aim to reduce the chromatic error:

0.59 mrad (Run3)
↓
0.28 mrad (Run5)

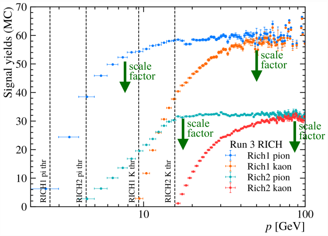
⇒ choice of the photon detector for RICH Upgrade II matched also with minimisation of chromatic uncertainty

PID Performance

σ =150 ps ↓ σ =300 ps ↓



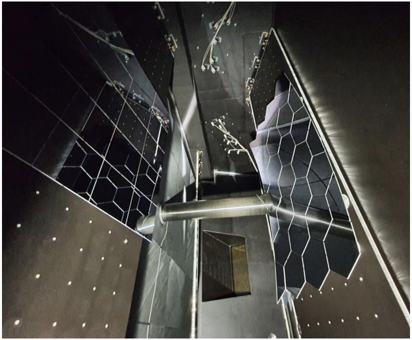
- different scenarios being considered to balance cost and performance at different values of instantaneous luminosity:
  - different timing capability
  - different pixel sizes
  - different optics designs
- timing plays a crucial role
- improvement of Cherenkov angle resolution in RICH2 leads to improvement in PID at high momentum



target improvement in resolution: RICH1 [0.82→0.38 mrad] - RICH2 [0.5→0.22 mrad]

Conclusions

- the operating conditions for the LHCb Upgrade II will result in unprecedented conditions for a RICH detector concerning high track and hit densities and radiation environment
- R&D ongoing on optics, radiators, photon detectors, fast electronics, mechanics to achieve the ultimate performance of a RICH detector in a hadronic environment
- very challenging programme with plenty of room for synergies with other R&D campaigns
- close collaboration with DRD4 programme in all areas



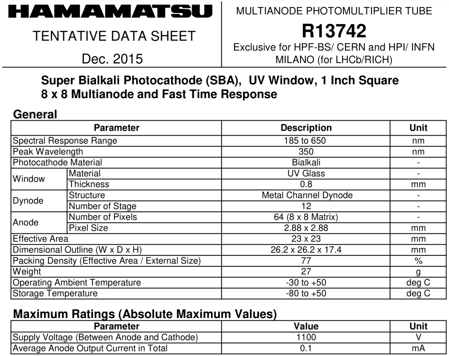
Photon detection at LHCb RICH in Run1&2

- HPDs equipped with embedded front-end electronics working at 1 MHz readout employed in Run1 and Run2
- MaPMTs with external readout at 40 MHz installed in LS2 and operated for Run3 and Run4
- R11265 and R12699 chosen for Upgrade I for the excellent active area ($\sim$ 80%), good spatial granularity $\mathcal{O}(10\text{mm}^2)$, and excellent response to detection rates up to $\mathcal{O}(100\ \text{MHz/cm}^2)$

- impressive quantum efficiency of 40% at 300 nm in average

Possible candidate MaPMT

- very reliable photon detector: state of the art currently installed in the RICH detectors
- limitations coming from pixels size: 2.8×2.8 mm^2 for R11265
- limitations coming from TTS$\sim$ 300 ps
- limitations coming form magnetic field tolerance
- limitations coming from maximum anodic current



HAMAMATSU

TENTATIVE DATA SHEET

Dec. 2015

MULTIANODE PHOTOMULTIPLIER TUBE

R13742

Exclusive for HPF-BS/ CERN and HPI/ INFN MILANO (for LHCb/RICH)

Super Bialkali Photocathode (SBA), UV Window, 1 Inch Square
8 x 8 Multianode and Fast Time Response

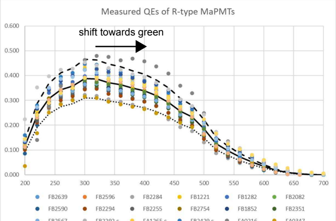
General

Parameter		Description	Unit
Spectral Response Range		185 to 650	nm
Peak Wavelength		350	nm
Photocathode Material		Bialkali	-
Window	Material	UV Glass	-
	Thickness	0.8	mm
Dynode	Structure	Metal Channel Dynode	-
	Number of Stage	12	-
Anode	Number of Pixels	64 (8 x 8 Matrix)	-
	Pixel Size	2.88 x 2.88	mm
Effective Area		23 x 23	mm
Dimensional Outline (W x D x H)		26.2 x 26.2 x 17.4	mm
Packing Density (Effective Area / External Size)		77	%
Weight		27	g
Operating Ambient Temperature		-30 to +50	deg C
Storage Temperature		-80 to +50	deg C

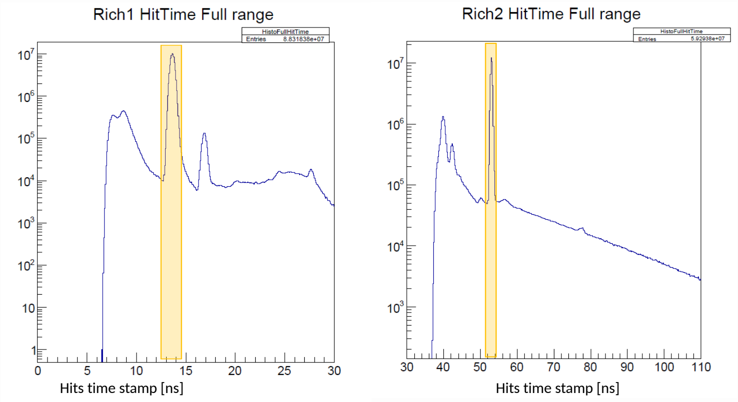
Maximum Ratings (Absolute Maximum Values)

Parameter	Value	Unit
Supply Voltage (Between Anode and Cathode)	1100	V
Average Anode Output Current in Total	0.1	mA

- very low noise
- excellent quantum efficiency: new version with green shifted spectrum produced and tested
- very good active area
- employable in low occupancy regions

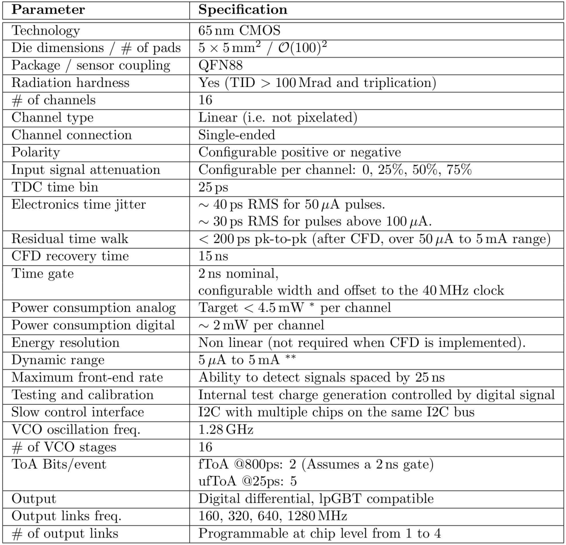


Front-end Electronics



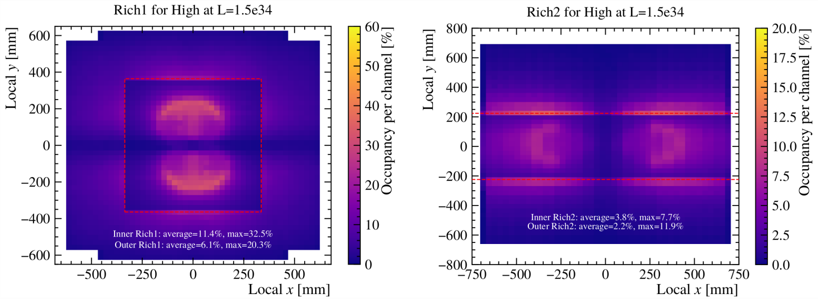
- ∼3 ns configurable time gating for suppression of out-of time hits
- better than 100 ps time-stamping and time-over-threshold measurement per photon (TDC) or constant-fraction discrimination to avoid the need for ToT and/or multi-level discrimination
- radiation tolerant ASIC
- High density, low power (few mW per channel)
- FastRICH ASIC under development

FastRICH



Parameter	**Specification**
Technology	65 nm CMOS
Die dimensions / # of pads	$5 \times 5\,\mathrm{mm}^2$ / $\mathcal{O}(100)^2$
Package / sensor coupling	QFN88
Radiation hardness	Yes (TID $>$ 100 Mrad and triplication)
# of channels	16
Channel type	Linear (i.e. not pixelated)
Channel connection	Single-ended
Polarity	Configurable positive or negative
Input signal attenuation	Configurable per channel: 0, 25%, 50%, 75%
TDC time bin	25 ps
Electronics time jitter	$\sim$ 40 ps RMS for 50 μA pulses. $\sim$ 30 ps RMS for pulses above 100 μA.
Residual time walk	$<$ 200 ps pk-to-pk (after CFD, over 50 μA to 5 mA range)
CFD recovery time	15 ns
Time gate	2 ns nominal, configurable width and offset to the 40 MHz clock
Power consumption analog	Target $<$ 4.5 mW * per channel
Power consumption digital	$\sim$ 2 mW per channel
Energy resolution	Non linear (not required when CFD is implemented).
Dynamic range	5 μA to 5 mA **
Maximum front-end rate	Ability to detect signals spaced by 25 ns
Testing and calibration	Internal test charge generation controlled by digital signal
Slow control interface	I2C with multiple chips on the same I2C bus
VCO oscillation freq.	1.28 GHz
# of VCO stages	16
ToA Bits/event	fToA @800ps: 2 (Assumes a 2 ns gate) ufToA @25ps: 5
Output	Digital differential, lpGBT compatible
Output links freq.	160, 320, 640, 1280 MHz
# of output links	Programmable at chip level from 1 to 4

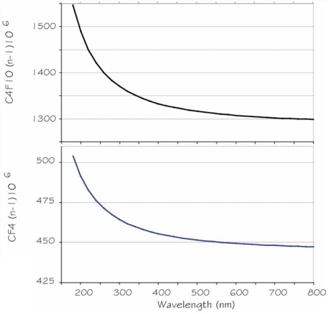
Expected Performance



Configuration		Overall [mrad]	Chromatic [mrad]	Emission pt. [mrad]	Pixel [mrad]	Yield
RICH1	MaPMT (Run 3)	0.82	0.59	0.38	0.46	62
	SiPM	0.51	0.28	0.37	0.22	65
	SiPM & geometry	0.38	0.28	0.13	0.22	52
RICH2	MaPMT (Run 3)	0.50	0.33	0.37	0.20	39
	SiPM	0.42	0.19	0.36	0.10	33
	SiPM & geometry	0.22	0.19	0.05	0.10	25

optimisation of sources of uncertainty to improve Cherenkov angle resolution and keep the peak occupancy under ∼ 30%

Radiators



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- CF_4: $n = 1.0005$ at 400 nm, gas vessel: $100\,\mathrm{m}^3$
- the chromatic error depends on the convolution between the dispersion and the photon detector quantum efficiency (QE)
- R&D investigating photocathodes shifted towards the green to reduce single-photon chromatic error

- fluorocarbon gases have large Global Warming Potential $\mathrm{GWP}(C_4F_{10}) = 8500\ CO_2$, $\mathrm{GWP}(CF_4) = 7000\ CO_2$
- could replace CF_4 (n=1.0005) with CO_2 (n=1.0004): photon yield ($\propto 1 - 1/n^2$) marginally lower, but worse chromaticity
- intense R&D and studies needed to find alternatives to C_4F_{10}, matching its refractive index and allowing operations in the LHCb environment
  see G. Hallewell's talk on radiators
- R&D on green coolants ongoing: see S. Jakobsen's talk