The LHCb RICH for Upgrade II

Quick clarification:

Present RICH 1, %Xo is 4.5% (see PID TDR for Upgrade I);

Present VELO %Xo is 21.3% plus the VELO Exit window 6.8% (from VELO TDR and Matt pres.).

RICH System PID Requirements in Upgrade II (DRAFT)

Main specifications of the system to maintain the same performance as previous

1. Keep peak Occupancies (time and space) < 30%
2. Improve Single Photon Cherenkov Angle precision to < 0.5 mrad
3. Provide the system with timing (25ps) capabilities (event gating and photon ToA*) and limit as much as possible the overall bandwidth of the system (see Floris presentation)
4. Provide RICH1 and RICH2 with green gases (or a leak-less system…)

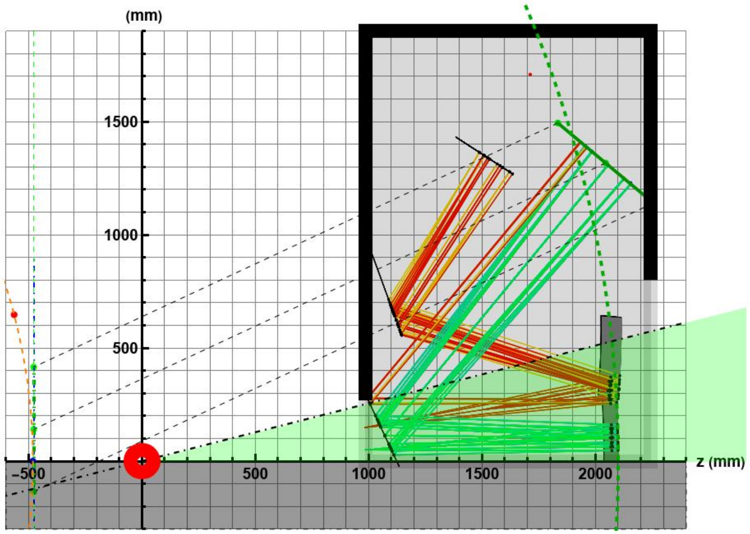
* Time of Arrival

1. Occupancies in the RICH System are very dis-uniform;

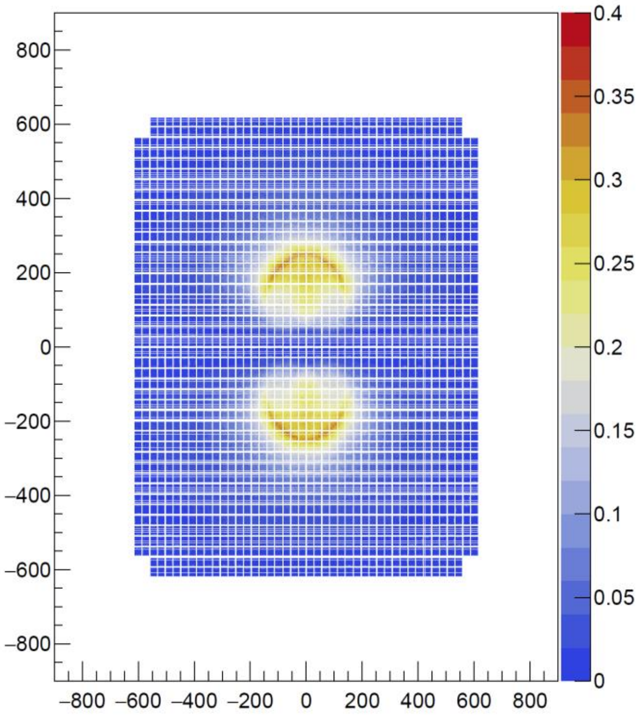
The high occupancy region in RICH1 is only ~10% of the total:

study new optical layouts;

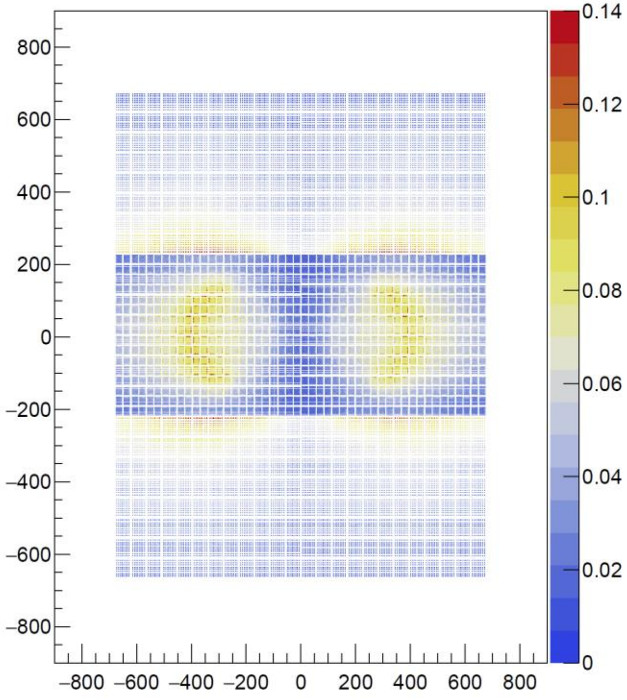
work on a variable granularity system.



Genova



Rich1 : Av. channel occupancy XY map



Rich2 : Av. channel occupancy XY map

2. Optical Systems and associated R&D

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

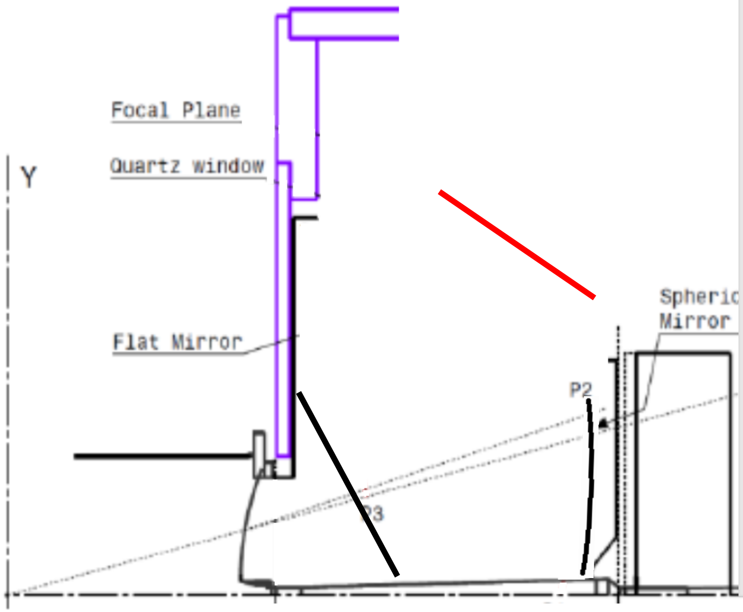
Further reduce chromatic uncertainty
- by tuning the gas
- by selectively absorbing unwanted UV photons
- by further moving the photodetector sensitive region towards the green
- by increasing photodetector QE

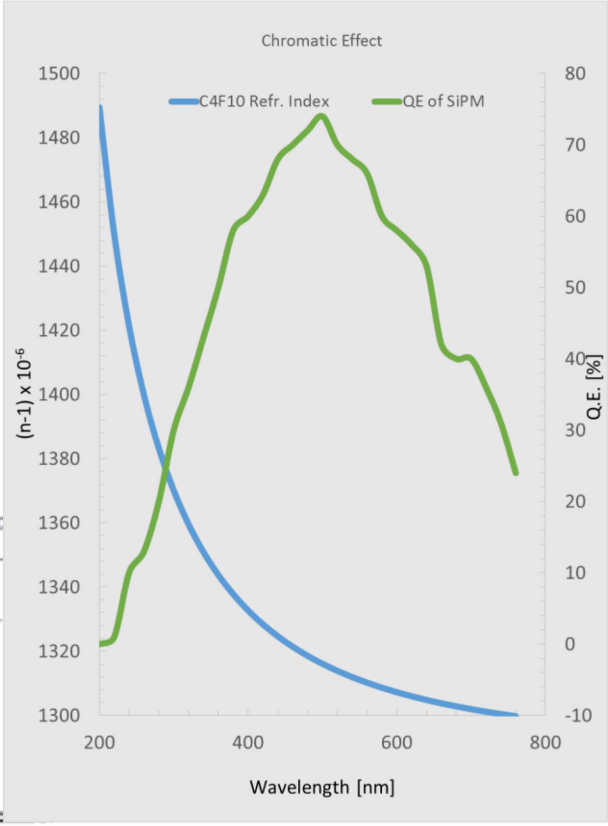
Optical Performance and Photon Yields

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

Detector Version	RICH-1 Upg2
Avr. Phel. Yield	60 - 40
Single Photon Errors [mrad]	
Chromatic	0.24
Pixel	0.15
Emission Point	0.1
Track resolution	?
Overall	0.3

Upg2

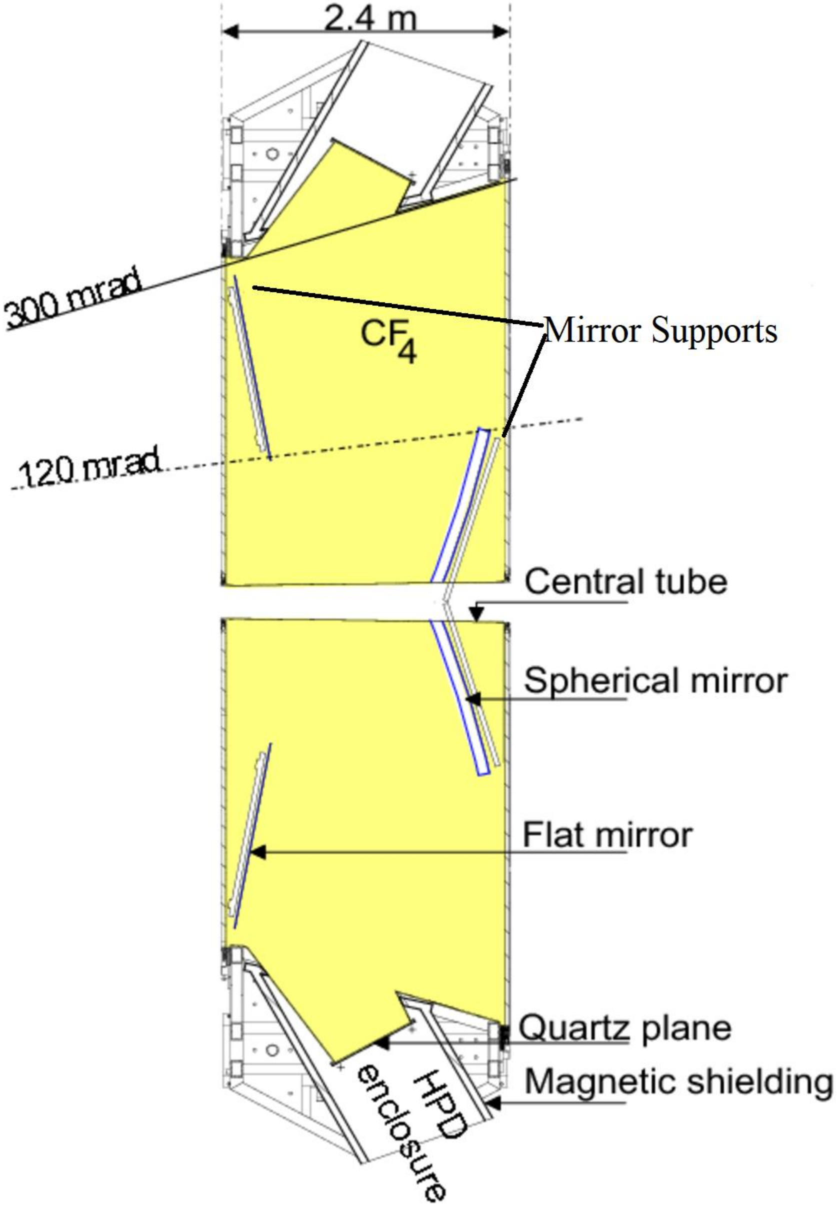


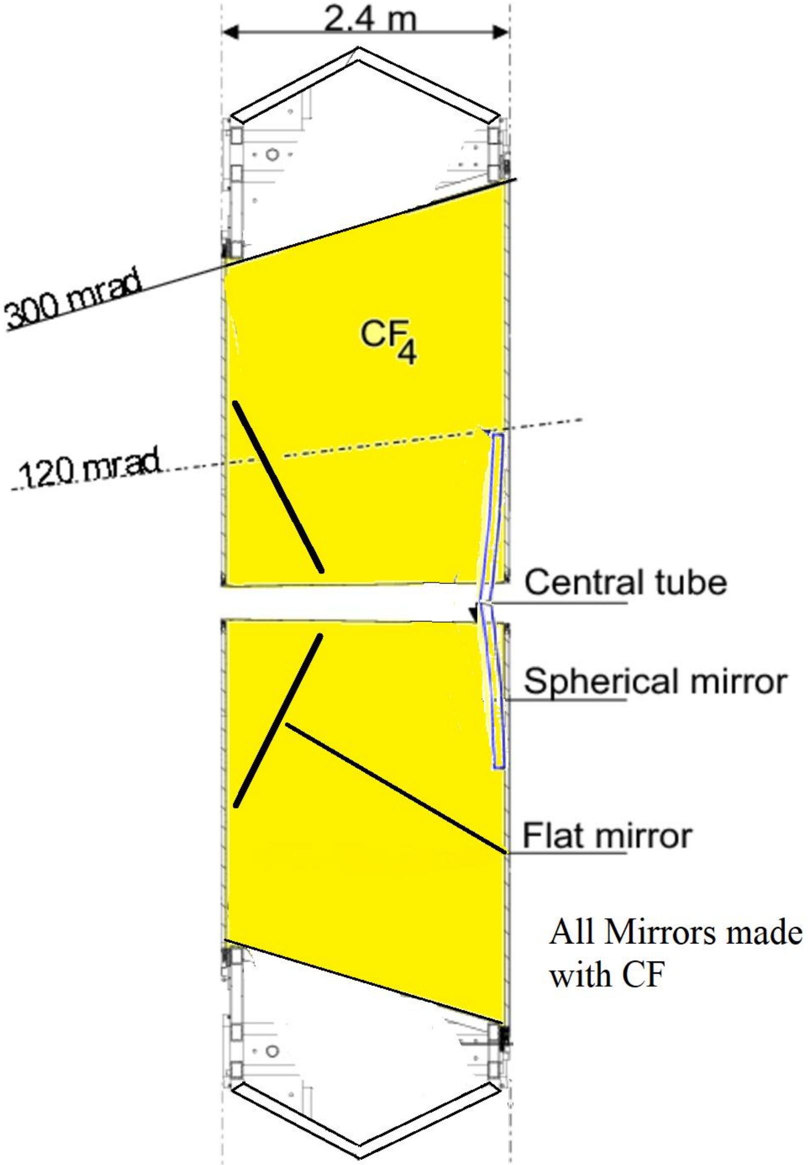


Reduce chromatic by choosing a photodetector with a "green-shifted" QE curve (and filter the shorter wavelengths)

Chromatic depends on the overlap between dispersion and photodet. QE (this example of a SiPM QE is rather from literature than realistic, QE between 50% and 60% would be closer to reality)

RICH 2 would also evolve …





All Mirrors made with CF

Simulated Optical Performance and Photon Yields

For Upg2, $\boldsymbol{\sigma_{\vartheta} \lesssim 0.5mrad}$

Radiator	C_4F_{10}			CF_4	
Detector Version	RICH-1 Current (HPD)	RICH-1 Upg1	RICH-1 Upg2	RICH-2 Upg1	RICH-2 Upg2
Avr. Ph.Electron Yield	25 (30)*	40 (rms=8)	40 - 30	22 (rms=5)	30 - 20
Single Photon Errors [mrad]					
Chromatic	0.84	0.58	0.24 – 0.18	0.31	~0.1
Pixel	0.9	0.44	0.15	0.20	0.07
Emission Point	0.8	0.37	0.1	0.27	0.05
Track resolution	0.4	?0.4?	?0.4?	?0.4?	?0.4?
Overall	1.52	0.9	0.5 (0.3 – 0.2)	0.60	0.42 (0.13)

*Value from data (expected); ** see Bartosz, https://indico.cern.ch/event/982426/

3. Use of Timing in Upgrade II

At the front-end (FastRICH):

1. A 1 to 2 ns time gate is applied with a fixed, configurable latency with respect to the LHC clock.
2. Within this time gate, the ToA of the photon signal will be read out with a time bin of 25 ps width.

4. Photodetector, Time-Sensitive Electronic System and associated R&D

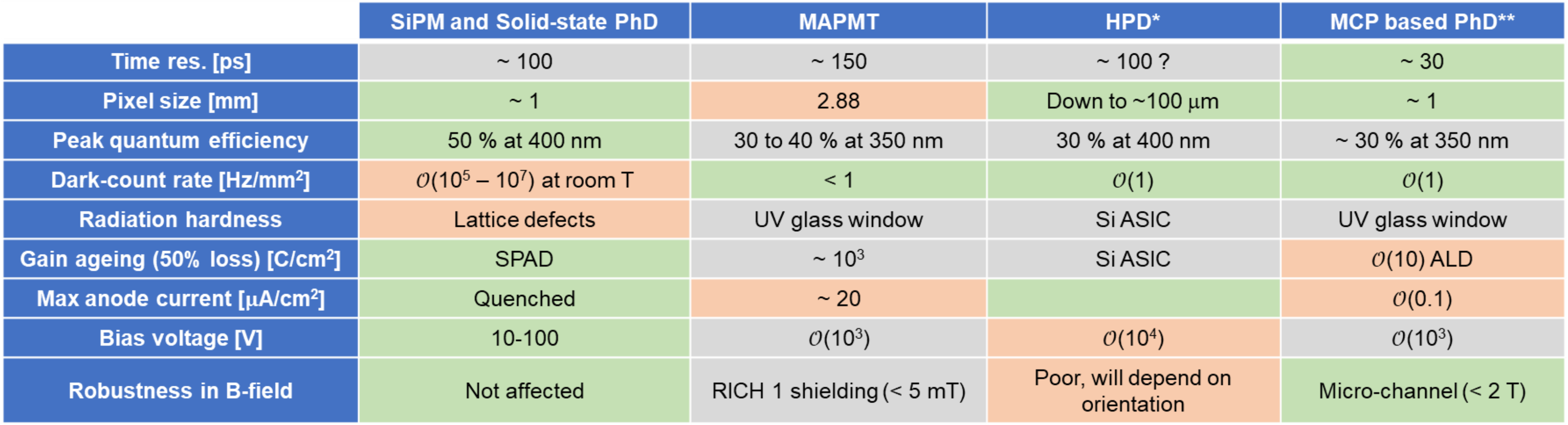
Improve space and time resolutions;

Photodetector development, tests and choice;

Development of micro-lenses array;

New optoelectronic chain geometry (compatible with cooling).

Upgrade II will have a new sensor installed with better time resolution.
Several options all with pros and cons, e.g. SiPM and MCP detectors.



	SiPM and Solid-state PhD	MAPMT	HPD*	MCP based PhD**
Time res. [ps]	~ 100	~ 150	~ 100 ?	~ 30
Pixel size [mm]	~ 1	2.88	Down to ~100 µm	~ 1
Peak quantum efficiency	50 % at 400 nm	30 to 40 % at 350 nm	30 % at 400 nm	~ 30 % at 350 nm
Dark-count rate [Hz/mm^2]	$\mathcal{O}(10^5 – 10^7)$ at room T	< 1	$\mathcal{O}(1)$	$\mathcal{O}(1)$
Radiation hardness	Lattice defects	UV glass window	Si ASIC	UV glass window
Gain ageing (50% loss) [C/cm^2]	SPAD	~ 10^3	Si ASIC	$\mathcal{O}(10)$ ALD
Max anode current [µA/cm^2]	Quenched	~ 20		$\mathcal{O}(0.1)$
Bias voltage [V]	10-100	$\mathcal{O}(10^3)$	$\mathcal{O}(10^4)$	$\mathcal{O}(10^3)$
Robustness in B-field	Not affected	RICH 1 shielding (< 5 mT)	Poor, will depend on orientation	Micro-channel (< 2 T)

* Include Pixel-HPDs, Timepix-HPDs, A-HPDs,…

** Include MCP-PMT, Image Intensifiers, MCP-ASIC HPDs, LAAPD, …

Strategy towards Upgrade II

First Enhancement in LS3 and then full Upgrade in LS4

- -LS3:
  - Change of the complete opto-electronic chain (Floris presentation)
- -LS4:
  - Change everything else (in the region of high occupancy?).

Down-scoped proposal for Upgrade II

Run 5, 25 ns, up to 10^{34} cm^{-2} s^{-1}, 2032 onwards (and perhaps even $\eta < 4.8$)

- Down-scope of the down-scoped proposal:

  MaPMTs perhaps still ok in low occupancy regions (but a bit slow);

  SiPMs/MCPs in high occ. regions of RICH1;

  New electronics (FastRICH). New optical system for both RICHes.

- High-end down-scoped proposal (example):

  SiPMs* everywhere;

  Use of lenses arrays, to adapt for different occupancies;

  New electronics (FastRICH). New optical system for both RICHes.

- Possible to discuss anything in between these two downgrades … Need Simulation!!!

* The choice of sensor is still open, this is only an example

For LS3 Enhancements

In bracket and red, institutes which are already actively working on the specific activity or/and have given such indications at meetings/by e-mail:

- General mechanics, optics and services (CERN, Imperial, Padova)
- FastRICH design and development (Barcelona, Cambridge, CERN, Ferrara, Genova)
- EC/FastRICH cooling (CERN, Edinburgh, Genova, Imperial, Padova)
- FastRICH characterization (Bucharest, Cambridge, CERN, Ljubljana, Padova, Perugia)
- Overall frontend topology (Cambridge, CERN, Ferrara, Genova)
- New PDM modularity (Bucharest, Cambridge, CERN, Edinburgh, Ferrara, Imperial)
- DAQ (Cambridge, CERN, Genova)
- QA of all the different new parts and the “enhanced ECs” (Bucharest, CERN, Edinburgh, Ferrara, Ljubljana, Padova, Perugia, Rutherford)
- New Control Systems (Cambridge, Edinburgh, Genova, Ferrara, Perugia, Rutherford)

- New Software, Simulation, Data Quality Monitoring, Performance and Physics (Cambridge, CERN, Genova, Milano, Oxford, Rutherford)
  - - RTA Engagement (integration into HLT2 and perhaps HLT1).
    - Simulation (which covers both detector, Gauss, and readout simulation, Boole)
    - Integration of timing info into reconstruction sequence
    - Decoding support
    - Online monitoring tasks
    - Online alignment and calibration
    - Data Quality Aspects
    - PID Performance Monitoring and Physics

- Commissioning (Bucharest, CERN, Edinburgh, Ferrara, Genova, Imperial)
- Calibration, alignment and monitoring systems (CERN, Genova, Perugia)
- Radiation (Bucharest, Ljubljana, Padova)
- Test beams (more or less all of us)
- Compliance with LHCb (CERN, …

This list is not exhaustive nor exclusive.

Robust R&D activities for LHCb RICH Upgrade II:

Full simulations with new optical schemes (and without the shielding…);

Photodetector development, tests and choice;

New optoelectronic chain geometry (compatible with cooling);

New mechanics (and cooling/cryo) systems;

New light-weight optics for both RICHes;

Development of micro-lenses array;

New green extended photocathodes;

Neutron shields;

DAQ aspects (compression, bandwidth, format, etc);

PID aspects (global algorithm, others?);

Study the long-term behavior and characteristics of the system;

Possible first prototype to be inserted in RICH2 system already during LS3 …

…..

Robust R&D activities for LHCb RICH Upgrade II:

Very well coordinated in all our collaboration institutes and countries: CERN, IT, RO, SL, UK:

For the general orientations, please visit (https://indico.cern.ch/event/1222213/).

For details of the most recent studies and activities, please visit (https://indico.cern.ch/event/1271273/).

Here a few slides to highlight the great interest, motivation and professionalism of our collaborators*.

*I hope I’ll be forgiven if I do not show all the available material…

R&D on Photosensors

Almost all labs are getting instrumentation and custom set-ups for testing Photosensors

Conclusions

In Ferrara

- We can peform SiPM characterization down to LN2 temperature in LN2 vapour through a dedicated custom system;
- We tested so far 4 different HPK models:

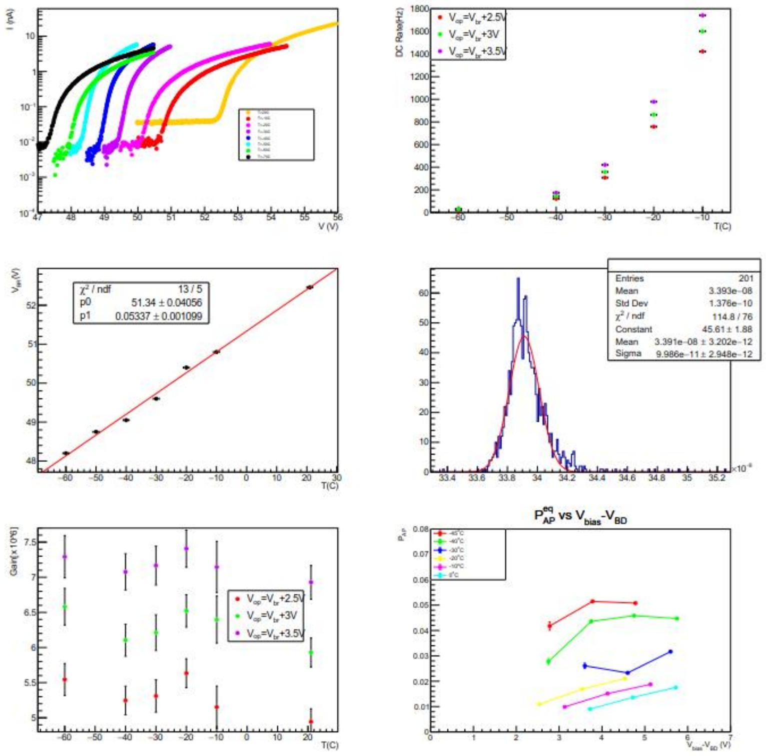
	13360-3025CS	13360-3025PE	14160-3015PS	13081-050CS
Pitch(um)	25	25	15	50
Area(mm^2)	3x3	3x3	3x3	1x1
DCR @-120, +5OV (Hz/mm^2)	0.77	0.15	0.47	2

- DCR behaviour with burst effect (random train of pulses at kHz);
- DCR decreses from MHz at room temperature down to Hz at -120°;
- We are currently testing other SiPM models.

For the near future:

- We plan to test these sensors after different dose irradiation;
- We plan to test the irradiated sensors after different annealing procedure;
- We are setting-up a setup for temporal measurements with UV laser pulses.

SiPM characterization/validation with focus on the local cooling design [Upgrade II]



Genova

LAPPD and MCPs Characterization (timing)

The Large Area Picosecond PhotoDetector

LAPPD (INCOM US)

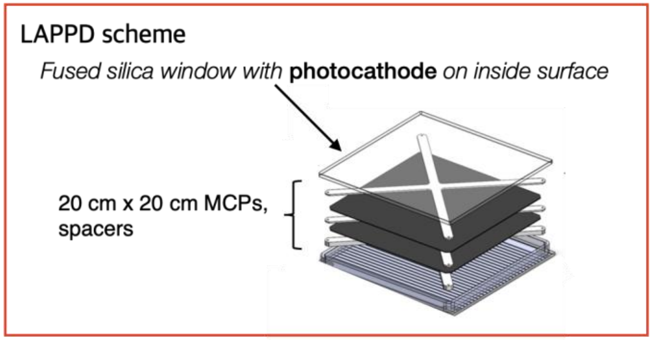
Micro Channel Plate photomultiplier, Dimension 20 x 20 cm^2

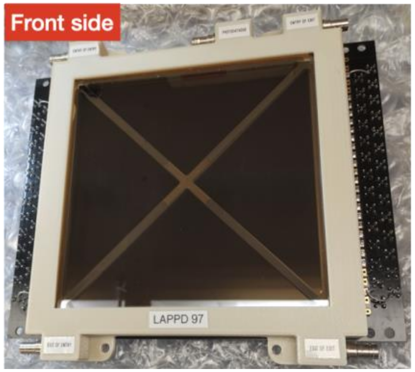
Advantages:

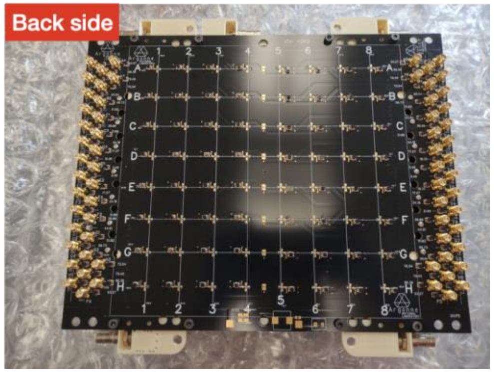
- Time resolution lower than 60 ps
- High gain (~ 10^7)
- capable of imaging single photons

Gen II LAPPD 97 @ Edinburgh

- Gen II LAPPD, pixel readout
- Spectral response 160-650 nm
- 5 taps for independent voltage control of the photocathode and entry/exit of each MCP
- readout board used for testing so far as directly provided from INCOM, pixel Pitch to pitch distance 25 mm, effective dimension 24 x 24 mm^2

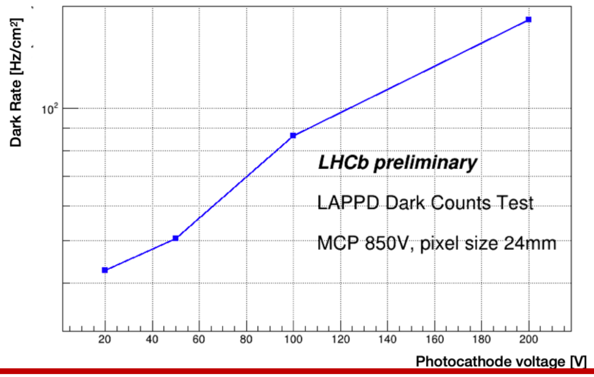




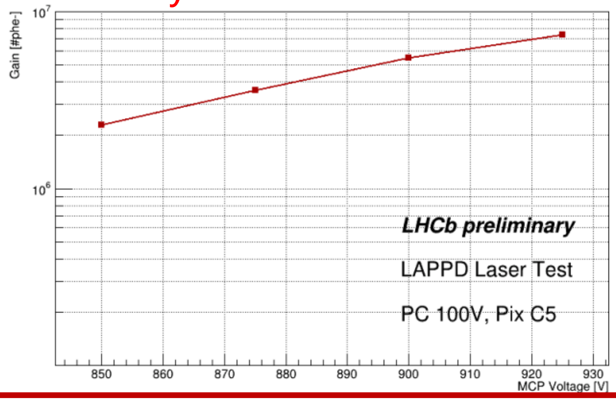


Overview of the measurements in Edinburgh

Dark counts



Gain study

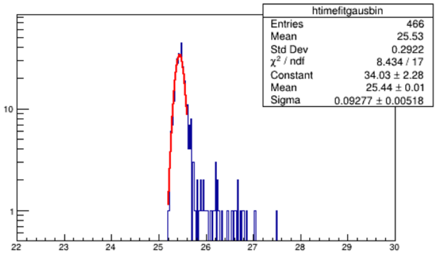


- ➢ Single photoelectron condition
- ➢ Laser frequency 5kHz

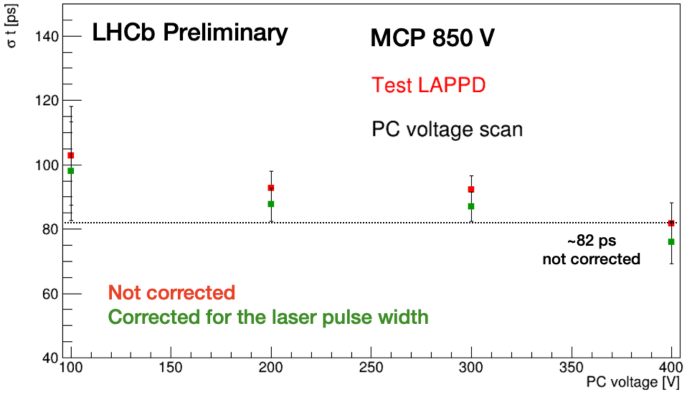
Time resolution

Extracted from Gaussian fit
to the time difference Signal-Laser trigger

Example time distribution PC@200V



Time Signal-Time reference [ns]



- ➢ Single photoelectron condition
- ➢ Laser frequency 5kHz

Milano Bicocca

MCP studies

- Comparison between MaPMT (R13742) and MCP-PMT (R10754)
- from Hamamatsu
- R10754 has 4x4 pixels in 1’’x1’’ (≈5 mm pixel side)
- MCP saturates above ≈100 kHz/mm2

https://doi.org/10.1088/1748-0221/15/10/P10031

Single photon time resolution of photodetectors at high rate: Hamamatsu R13742 MaPMT and R10754 MCP-PMT

M. Calvi[1,2], S. Capelli[1,2], P. Carniti[1,2], C. Gotti[2] and G. Pessina[2]

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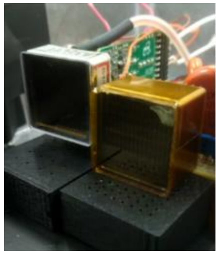
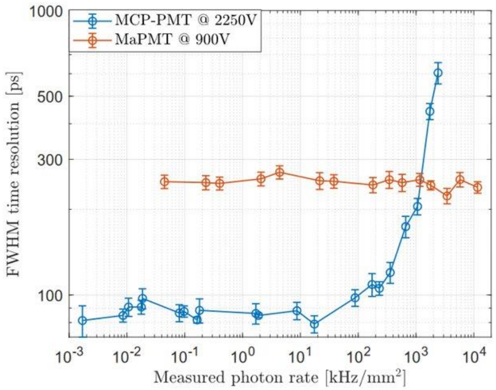
Journal of Instrumentation, Volume 15, October 2020

Citation M. Calvi *et al* 2020 *JINST* **15** P10031

DOI 10.1088/1748-0221/15/10/P10031





- Study of the Photek Auratek-Square MCP-PMT (15um pores)
- Pixel size down to ≈1x1 mm2, but significant charge sharing
- MCP saturates above ≈100 kHz/mm2

https://doi.org/10.1088/1748-0221/17/11/P11009

Single photon counting performance of the Auratek-Square MCP-PMT

M. Calvi[1,2], S. Capelli[1,2], P. Carniti[1,2], C. Gotti[2] and G. Pessina[2]

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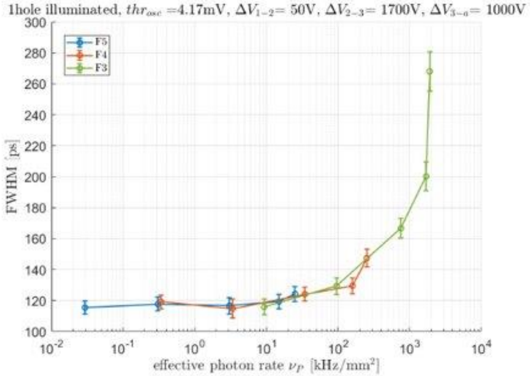
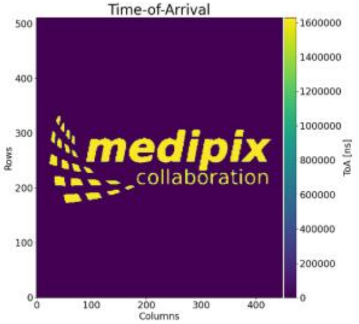


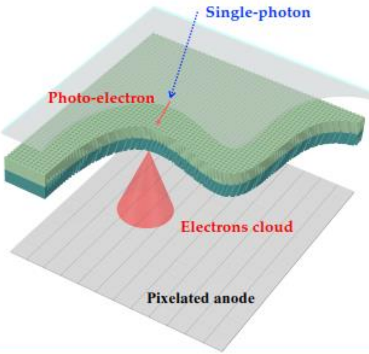
Next steps

focused on development of low gain, high rate MCP-PMTs and development of readout electronics for a low gain MCP.

Hybrid MCP development

- Hybrid vacuum photo-detector development (INFN, UniFE, CERN)
  - Photocathode + MCP multiplication + Timepix4 anode in vacuum tube
- Timepix4 prod.: v0 (Q1-2020), v1 (Q4-2020), v2 (Q4-2021), v3 (Q1-2023)
  - v2 bare ASIC extensively tested; first tests with Si sensor in summer 2022
- Activities
  - C++ software development for ASIC configuration, DAQ and analysis
  - Development of FPGA-based control board
  - Development of ceramic carrier (signal integrity simulation)
  - Power measurements and cooling system development
  - Calibrations with laser, radioactive sources, test pulses
- Issues
  - Extremely long procurement times or production delays for many critical components
- Prototype detectors expected early 2024
  - Beam tests with Cherenkov radiator
  - Measurements in life science applications



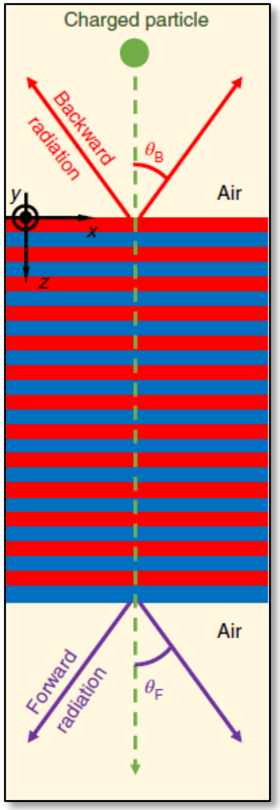


JINST 13 C12005 2018

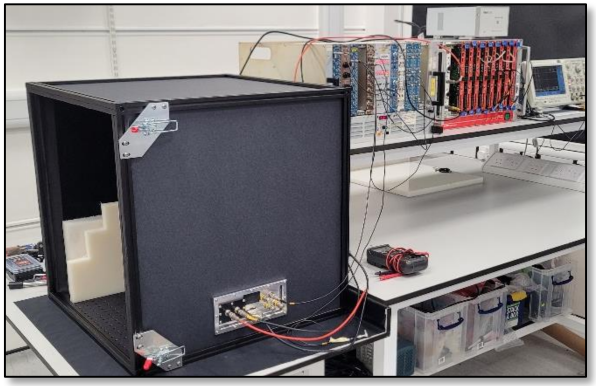
R&D on radiators

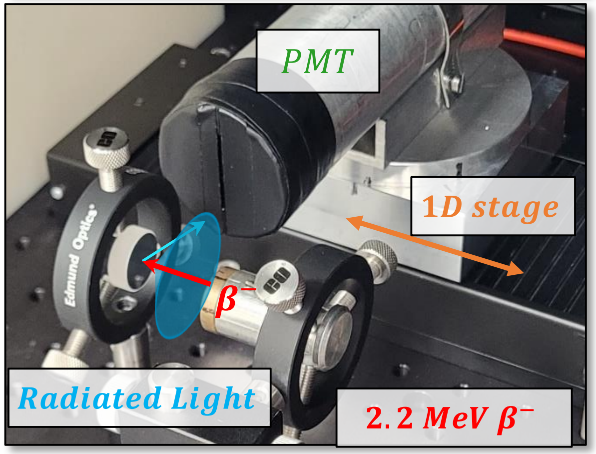
Using Metamaterials for PID

- ❑ Goals: exploit backward **T**ransition **R**adiation (TR) from **metamaterials** for PID.
  - $\theta_{TR} \propto \vec{v}_{particle}$
  - Replace RICH gas radiators with metamaterials
  - Re-imagine RICH geometry in upgraded LHCb
- ❑ Lab setup to search for TR:
  - Sr^{90} source: 2.2MeV electrons
  - Sample: Thorlabs BB03-E02 dielectric mirror
- ❑ Provide design inputs for custom metamaterials sample, fabricated at Imperial College
  - Can specify refractive index tailored to our use cases
  - Computational support also from collaboration with Prof. Ortwin Hess & postdoc (Trinity & Imperial)



Nature Phys **14**, 816–821 (2018)

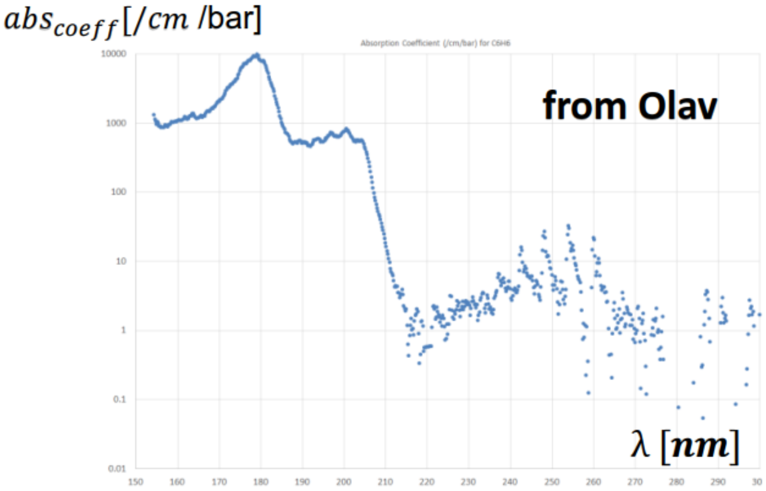




Benzene – introduction

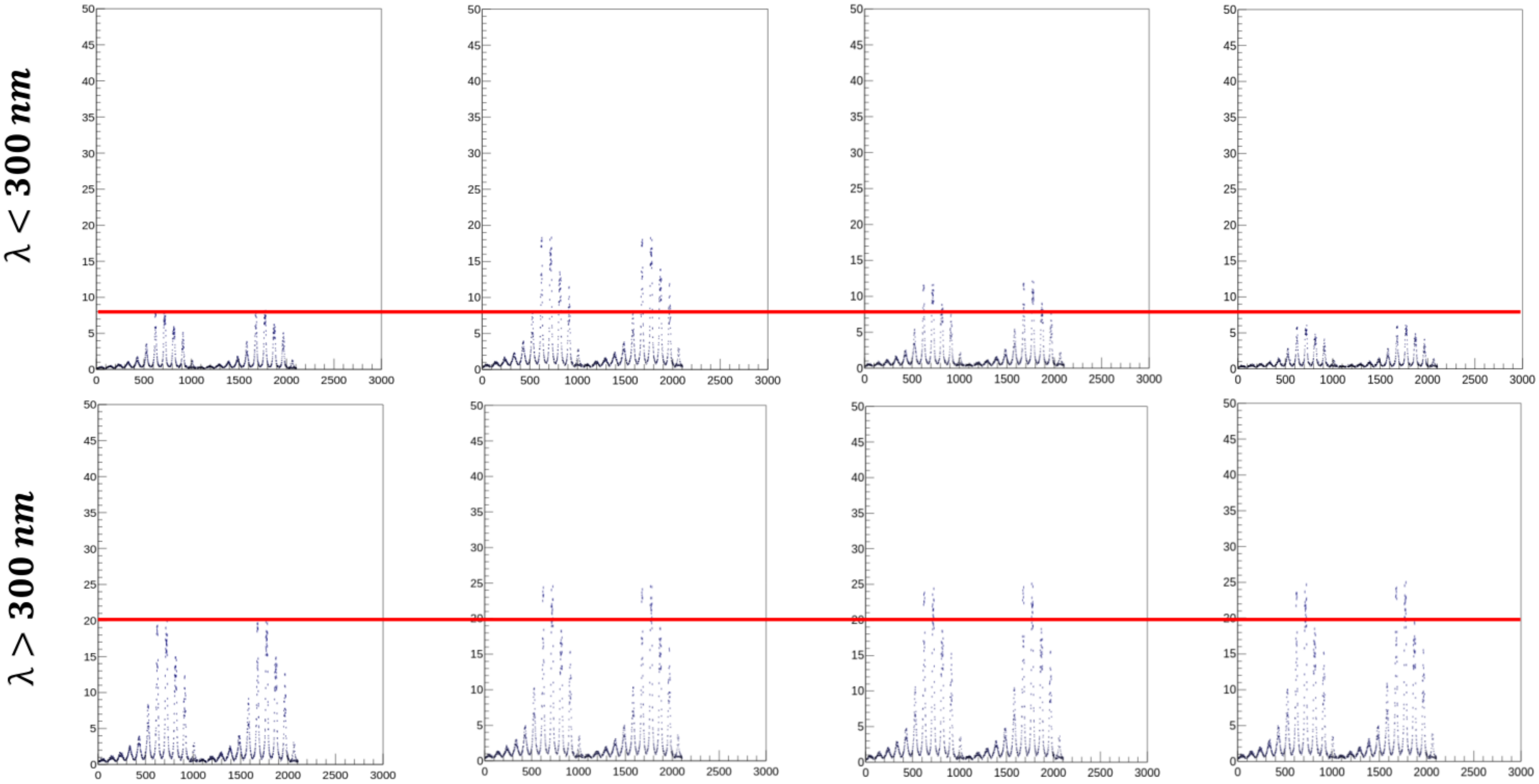
- **Benzene** can be used to **filter the low-wavelength photons away**.
  - Assign the benzene absorption properties to the existing gas radiator in the simulation, in the range < 300 nm (no absorption above this value).
  - Can it help to mitigate the occupancy increase? → **CHECKED**
  - How will it affect the PID? → **CHECKED**

- **Benzene fractions for R2** given in the plot labels should be interpreted as e.g. **`equivalent to 0.1% in R1`**.
  - The actual fractions for R2 are divided by a factor of 3 (due to the different optical paths in both R1/R2).



Benzene (occupancy, Gauss) (WL regions, R1)

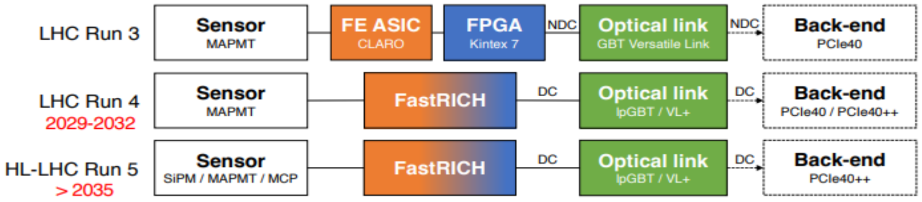
reference **sim updates (new QE)** **benzene (0.1%)** **benzene (0.5%)**



Adding between **0.1-0.5%** of benzene in R1 **reduces the occupancy in the low-WL region to a level comparable to the `reference`**. The high-WL region is not affected by adding benzene (as expected).

R&D on electronics

Upgrade 2 RICH FE roadmap



LHC Run 3	**Sensor** MAPMT	**FE ASIC** CLARO	**FPGA** Kintex 7	NDC	**Optical link** GBT Versatile Link	NDC	**Back-end** PCIe40
LHC Run 4 2029-2032	**Sensor** MAPMT	**FastRICH**		DC	**Optical link** lpGBT / VL+	DC	**Back-end** PCIe40 / PCIe40++
HL-LHC Run 5 > 2035	**Sensor** SiPM / MAPMT / MCP	**FastRICH**		DC	**Optical link** lpGBT / VL+	DC	**Back-end** PCIe40++

Cambridge Upgrade 2 interests

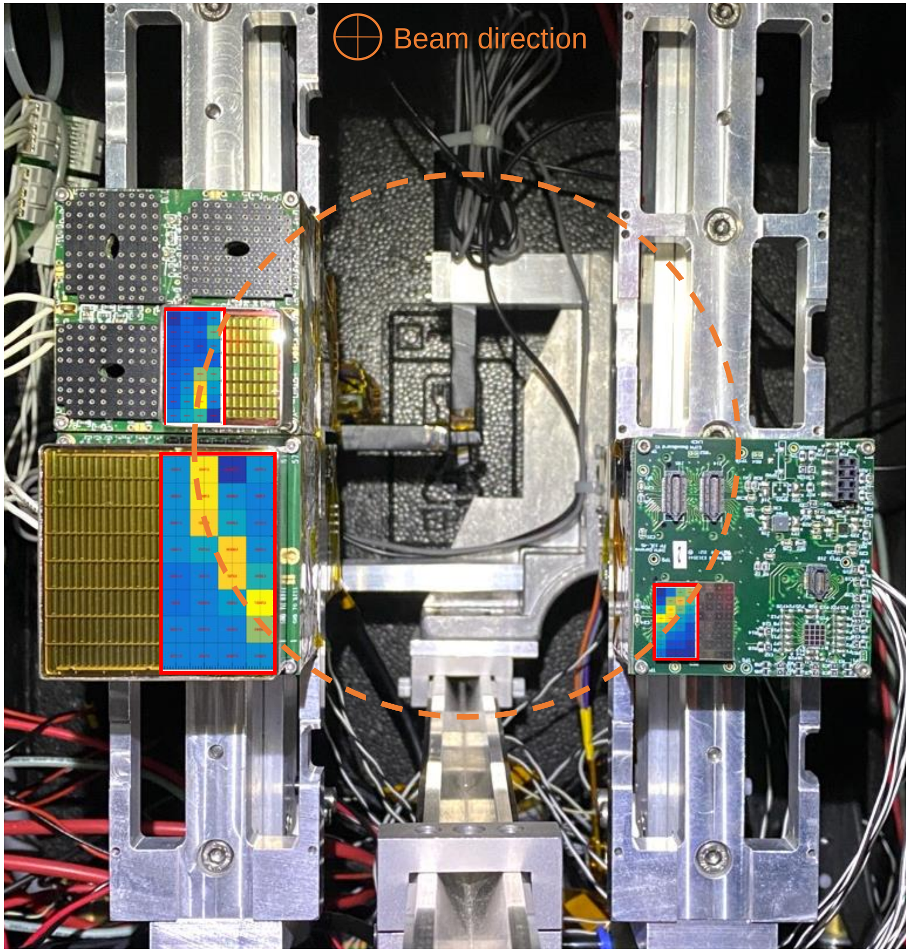
- Electronics
  - Specification, development, prototyping, production, testing and commissioning of FE electronics and read-out architectures for Run 4.
  - Further refinement of electronics adapted to new sensors for Run 5 (higher granularity, better time-resolution)
  - Specification, development, proyotyping, production, testing and commissioning of FE electronics and read-out architectures for Run 5.
  - Testing and characterisation of timing performance of front-end electronics in the laboratory and beam facilities.
  - Read-out system support for laboratory, beam test, and irradiation campaigns.
- Software
  - Detector optimisation and design through simulation and integration with LHCb simulation
  - Development of new reconstruction algorithms and with new architectures
  - Integration with RTA
  - Optimisation of algorithms for resource usage
  - Monitoring alignment and calibration

SPS beam tests of prototype fast-timing chain

Valuable information was collected on fast-timing techniques, FastIC operation, sensor coupling, clock and signal distribution etc.

Superimposed hit maps show detected arcs from the Cherenkov ring (orange-dotted line) during beam tests.
Analyses of timing performance are ongoing with preliminary best estimate of ~ 230 ps SPTR for MAPMTs (approaching the 150 ps TTS),
with scope for further improvements in the analyses, track reference timestamp, etc.

R&D is foreseen to evolve to larger sensor areas and demonstrate cryogenically-cooled SiPM arrays readout by the fast-timing chain based on the FastRICH (FastIC) ASIC.
Furthermore, an LAPPD will be tested using Cherenkov rings generated by novel aerogel tiles.

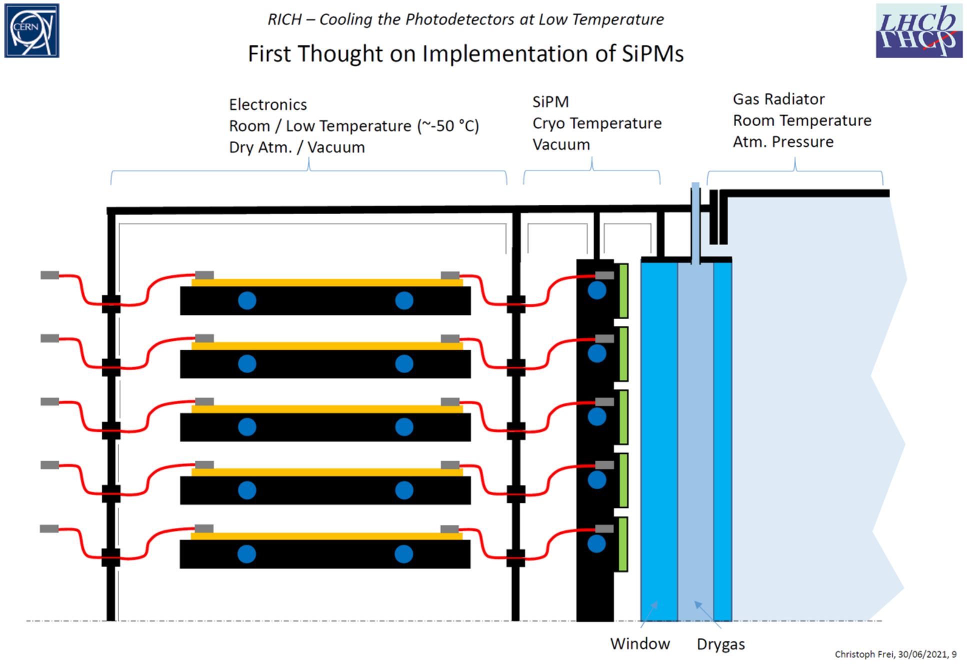


R&D on mechanics, cooling, cryo, etc…

Low temperature / cryogenic cooling of photon detectors

R&D into compact vessel structures has started and several meetings held with the cryogenics experts at CERN (TE-CRG-CI).

- One of the ideas could be to use two specially-coated quartz windows separated by a vacuum.
- Exploring synergies with other LHCb sub-detectors.
- Design of a lab/testbeam demonstrator is far advanced.



RICH – Cooling the Photodetectors at Low Temperature

First Thought on Implementation of SiPMs

Electronics
Room / Low Temperature (~-50 °C)
Dry Atm. / Vacuum

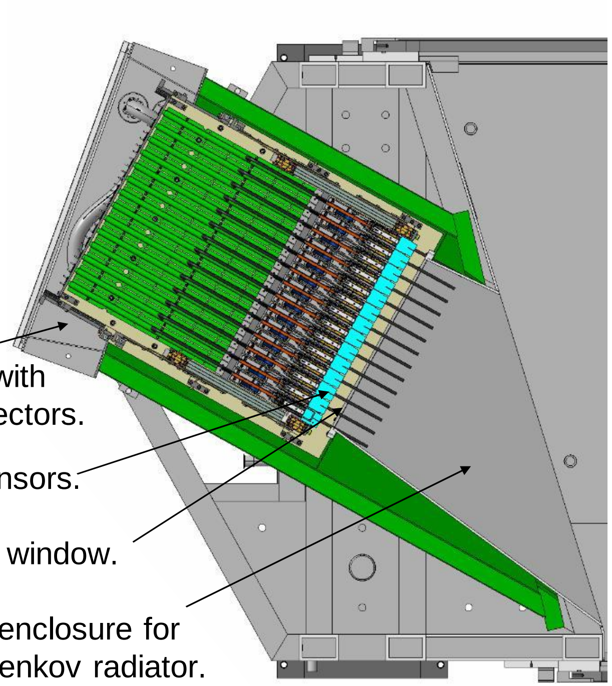
SiPM
Cryo Temperature
Vacuum

Gas Radiator
Room Temperature
Atm. Pressure

Window

Drygas

Christoph Frei, 30/06/2021, 9



Enclosure with photon detectors.

Photon sensors.

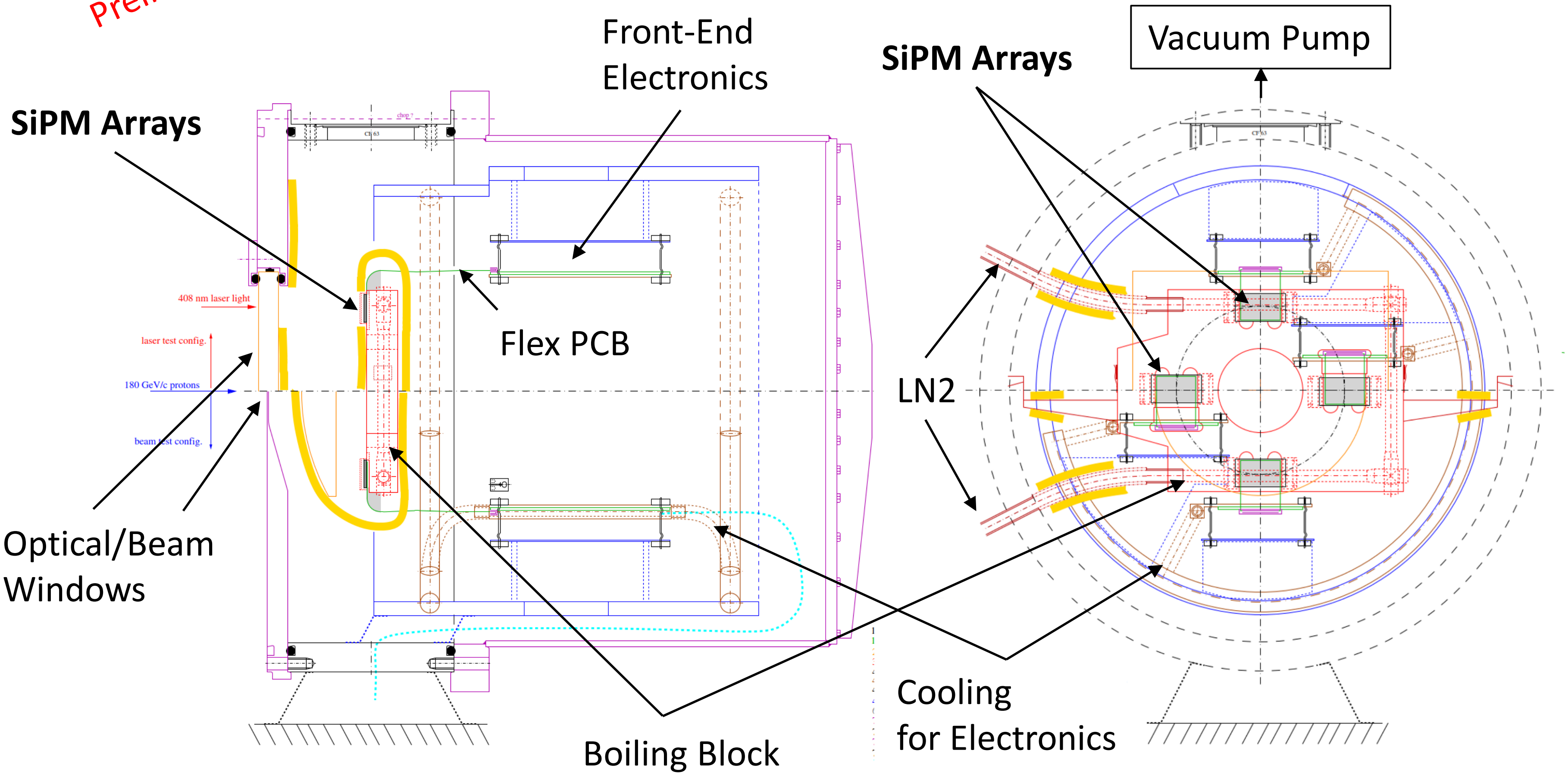
Quartz window.

Gas enclosure for Cherenkov radiator.

https://indico.cern.ch/event/1175130/

Cryostat for Characterizing SiPMs Arrays in Testbeam Facility and Lab

Preliminary



SiPM Arrays

Front-End
Electronics

SiPM Arrays

Vacuum Pump

Flex PCB

LN2

Optical/Beam
Windows

Boiling Block

Cooling
for Electronics

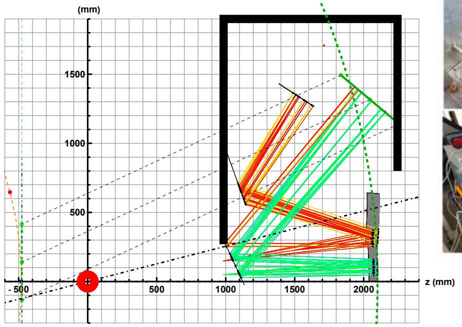
[Piet Wertelaers]

R&D on optical schemes and hardware

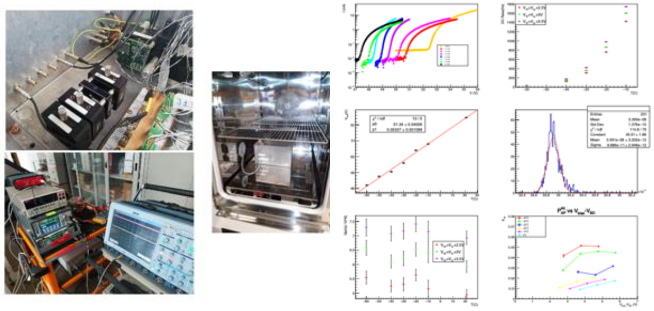
LS4 (Upgrade 2) – Genova's activities and interests

- Design of the new optical layout
- Optics technologies studies (lightweight mirrors in acceptance).
- SiPM characterization/validation with focus on the local cooling design.
- Design, development and production of the new BaseBoard and EC++ housing for sensors with integrated local cooling.
- DAQ firmware development
- Detector Control System (TBC).
- Calibration/Alignment/Monitoring
- Detector Simulation.
- Reconstruction, pattern recognition and analysis.
- Physics performance of the RICH detector.

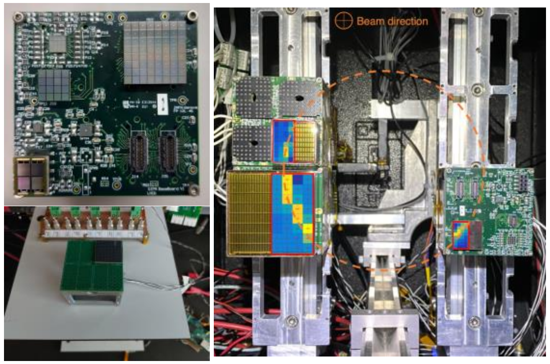
New optical layout to minimize the aberrations, reduce the occupancy by longer focal length, split to deal with large occupancy dynamic range



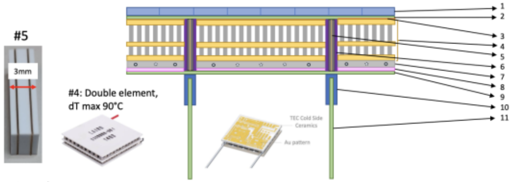
SiPM characterization/validation setup and measurements



SiPM housing BaseBoards already produced and tested both in lab and during testbeams



Development of new SiPM housing BaseBoards with integrated local cooling



Legend:

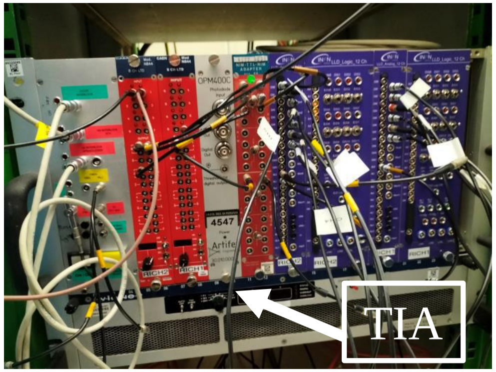
1. SiPM matrix (8 x 8 S13361-3050NE-08)
2. SiPM signals fan-out PCB
3. Silicon conductive paste with high thermal conductivity
4. Two Stages Peltier cell (2nd stage with doubled thickness compared to the first, to keep the same useful cold area)
5. Silicon rubber with vertical gold wires (SiPM to FEB fan-out)
6. Silicon rubber holder
7. Metal heatsink with possible liquid cooling
8. Thermal insulator
9. Baseboard PCB
10. Front-End Board connector
11. Fron-End Board

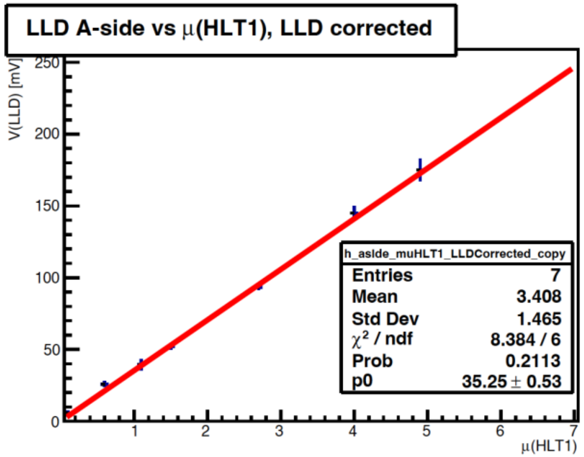
R&D on monitoring and calibration hardware

Calibration and monitoring

- **Calibration:**
  Ready to work together with Genova group on their idea to develop a calibration system based on Rayleigh scattering (see previous slide for the setup)

- **Monitoring:**
  For the 2024 data taking we will install two TIA (Trans Impedance Amplifier) in the readout chain of as many LLDs.
  We usually use such device to characterize and calibrate the LLDs, this will allow to further improve the sensitivity of LLD as **luminosity monitor,** without compromising the LLD main functionality.





Perugia group

Radiation Issues

LHCb-Romanian team and activities in LHCb RICH Upgrade II

❑ Bucharest Team in LHCb Upgrade program – envisioned R&D activities and tasks, for 2024 - 2034:

1. Design, produce, and test Digital Boards, more explicitly their Motherboards – for both LS3 and LS4;
2. Characterization of FastRICH chips when operating with new Photon Counter arrays with higher granularity;
3. Irradiation campaign of FastRICH, Photon Counters (e.g., SiPMs), EC prototypes – both for LS3 and LS4;
4. Precise measurement of radiation effects and annealing for SiPM and Photon Counters in general:
    - ○ Investigate the feasibility to operate commercial Photon Counters in hard radiation environments,
    - ○ E.g., implement mitigation procedures to reduce the dark counts in SiPMs besides reducing the operating temperature;
5. Contribute to the mass testing of: FEB, Digital Board plugins, ECs.
6. Contribute to the construction and commissioning of new RICH detectors.

Irradiation possibilities @ TRIGA nuclear reactor

Institut "Jožef Stefan", Ljubljana, Slovenija

JSI TRIGA nuclear reactor:

- max. power 250kW
- Neutron fluxes up to 3.57×10^{12} n/cm2/s

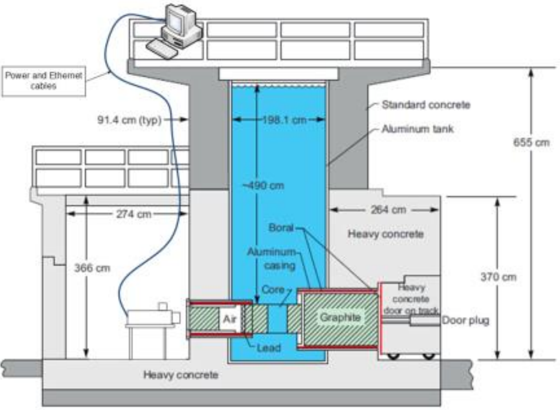
https://ric.ijs.si/en/info-za-uporabnike/

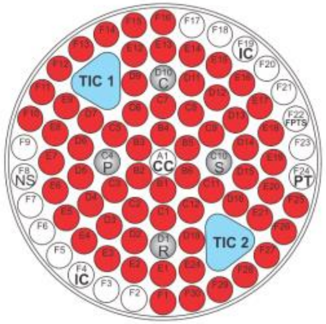
Irradiation of samples

- Directly in the reactor core
- Side channels - approx 20x20 cm2 (trolley)

2000 samples/year
for LHC experiments

- 1st criticality: 31st May, 1966
- P_{max}
  - 250 kW (steady state)
  - 1 GW (pulse)
- Fuel
  - UZrH (12 wt. % U)
  - E= 20 %





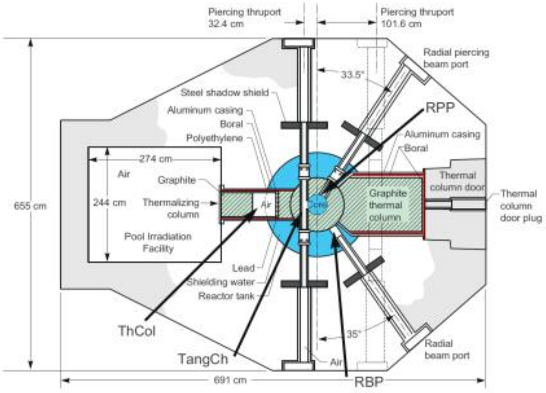


Fig. 2. TRIGA reactor at JSI, top view (Jeraj and Ravnik, 1999).

Ljubljana

Radiation damage studies plans

- Electronics for Upg Ib
  - Study SEE with ions from TANDEM and TANDEM+ALPI
  - Collaboration with Lubjana group
  - TANDEM allows irradiation scanning ionic species with LET in the range 1-40MeV/(mg/cm2)
  - TANDEM+ALPI irradiation allows a single specie of ions (Xe) with high energy (O(1GeV))
- Sensors for Upg II
  - Irradiated SiPM (Hamamatsu) avalable from Belle II group flux=10^{11} 1MeV neq/cm2
  - Investigating a neutron source @ Legnaro (^{7}Li)should reach higher doses, to be checked allowed limits from radioprotection

Padova

Every laboratory is designing and producing new test set-ups for components and system characterization and Quality Control

Software, Pattern Recognition, etc…

STFC – RAL

- Simulation:
  - Extensive activity on simulation for Run 3, 4 & 5
  - Simulation of testbeams
- Testing of SiPMs:
  - New lab setup for testing SiPMs
  - Plans for irradiation and evaluation
  - Could extend to other photon detectors
- Testing of boards for testbeams and prototypes for LS3 enhancements
  - Some experience with lpGBT
  - Activity to start soon

Spares

3. Use of Timing in Upgrade II

Profit from the unique property of our RICHes, that is the common arrival time of photons

Owing to the prompt Cherenkov radiation and focusing optics of the RICH detectors, all the Cherenkov photons from a given primary vertex arrive at the photon detectors within a small time-interval of a few picoseconds and the time spread can be corrected to $\sigma_{\text{RICH,software}}<5$ ps by adding the LHCb tracking information in the RICH reconstruction algorithms.

Exploiting this unique feature results in several decisive advantages, like a large reduction of occupancies on the detector arrays, an increased efficiency (and a decreased mis-identification probability) and ultimately would allow the present system (in terms of volumes) to withstand luminosities in excess of 10^{34} $\text{cm}^{-2}\text{s}^{-1}$.

Furthermore, the time-of-arrival (ToA) information of the Cherenkov photons can be used to associate photons and tracks to primary vertices, which significantly reduces the combinatorial background in the whole experiment (not only the RICH system). This is expected to have strong benefits for the particle identification and LHCb performance, as demonstrated by exhaustive simulation studies.

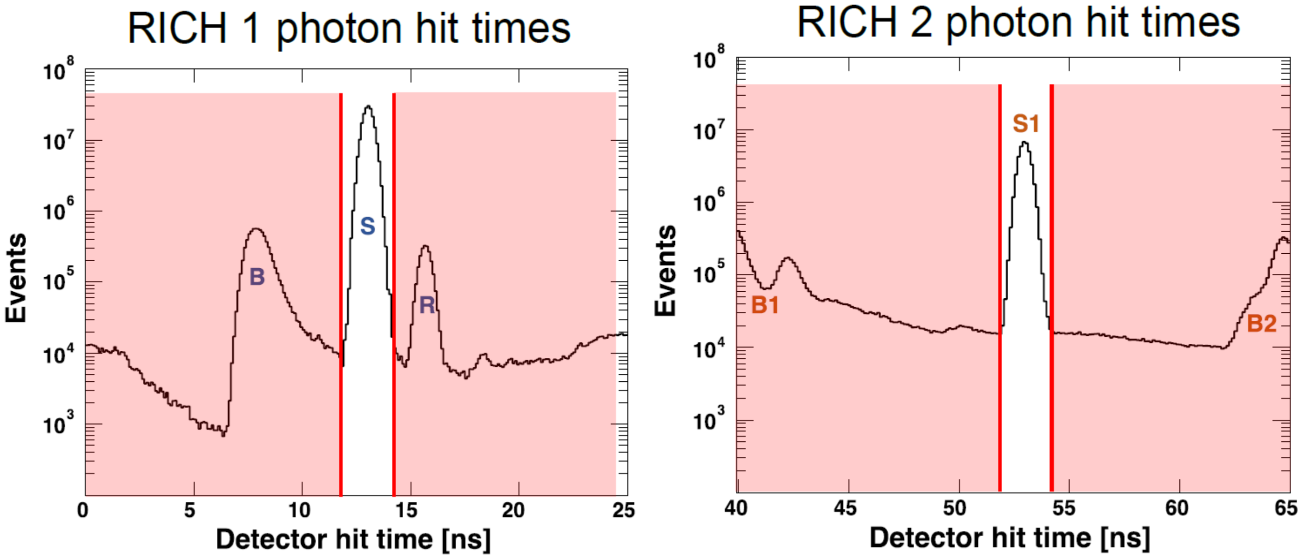
3. Use of Timing in Upgrade II

1): Front-end hardware gate

The time gate operates like a shutter as shown in the image below, retaining all hits that arrive between the opening and closing of the gate. The dominating time scale is σ_{PV} ~ 210 ps and a conservative time gate of 1 to 2 ns should be chosen, since no primary vertices should be excluded.

The gate has two effects, which both decrease the bandwidth. Firstly, it reduces the number of bits required to encode a hit. Secondly, it eliminates out-of-time background hits from the photon sensor and beam interactions.

RICH photon detector hit times, showing the signal (S) as well as background peaks (B,R). The red-shaded area can be removed by a time gate in the FE ASIC. Please, note that here the background is purely due to particle interactions and does not take in account the added noise due to the opto-electronic chain.



3. Use of Timing in Upgrade II

(2): ToA within the gate

A ToA information of approximately 25 ps with CFD would match well with the aimed RICH sensor resolutions for Upgrade II.

Strategy towards Upgrade II

First Enhancement in LS3 and then full Upgrade in LS4

The LS3 Enhancement sets the right order of magnitude for timing in the readout electronics:

- Build expertise with fast timing, bandwidth optimization and integrated designs.
- ASIC solution is the way forward for future radiation hardness.
- Compact integrated circuits with low power consumption.
- Verify simulation studies, optimise t-zero reconstruction algorithms and study resolutions in the relatively ‘friendly’ low-luminosity environment.

Run 4 will give us important information towards Upgrade II :

- 4x more PVs,
- but 2-3x better sensor resolution,
- challenging next step!

Work on new and specific pattern recognition algorithms