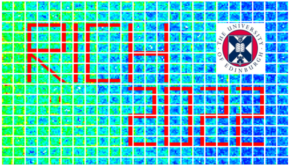
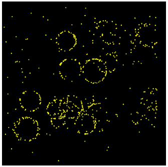




Characterisation and operations of the Multianode Photomultiplier Tubes for the LHCb RICH detectors

Giovanni Cavallero

CERN and Imperial College London

on behalf of the LHCb RICH collaboration

RICH 2022,
12-16 September, Edinburgh, UK

Outline

- requirements for the LHCb RICH photon detectors
- properties of the LHCb RICH Multianode Photomultiplier Tubes (MaPMTs)
- discovery and characterisation of a Signal Induced Noise
- MaPMT operations in LHC Run 3

Requirements for the LHCb RICH photon detectors

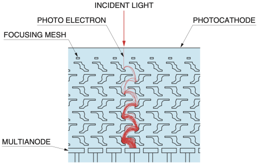
- single-photon detection at the 40 MHz LHC bunch crossing rate over a large area of ~ 4 m^2
- cope with detection rates of $\mathcal{O}(100$ MHz/cm$^2)$ in the high occupancy (central) region of RICH1 down to 5 MHz/cm^2 in the peripheral region of RICH2

  $\Rightarrow$ excellent active area ($\mathcal{O}(80\%)$) and spatial granularity ($\mathcal{O}(10$ mm$^2)$) to minimise inefficiencies and the pixel size error to separe overlapping rings
- appropriate gain ($> 10^6$) and quantum efficiency ($> 30\%$ at 300 nm) to maximise the photon yield per track and keep the chromatic uncertainty under control
- **low count rate ($\mathcal{O}$(kHz/cm^2)) caused by dark noise and other sources of internal instrumental noise** to allow an optimal pattern recognition to match hits to the corresponding charged track
- improved resiliance to the stray LHCb magnetic field and radiation hardness for 200 krad, 3×10^{12} 1 MeV n_{eq}/cm^2, 1.2×10^{12} HEH/cm^2

See Antonino Sergi's talk

The LHCb RICH photon detectors

Hamamatsu MaPMTs with 8 × 8 pixels



	R11265 (R13742)	R12699 (R13743)
size [mm^2]	26.2 × 26.2	52 × 52
pixel size [mm^2]	2.88 × 2.88	6 × 6
number of devices	2656	384
active area	77%	87%
average gain @ 1 kV	> 1 Me	
gain uniformity	1:4	1:3
peak/valley (P/V) ratio @ 1 kV	no more than 3 pixels with P/V< 1.3	
dark-count rate @ 1 kV	< 2.5 kHz/cm^2	
quantum efficiency	> 30% @ 300 nm	

Special series R13742 and R13743 respecting these technical specifications

The LHCb RICH photon detectors

Units with coarser granularity in the peripheral region of RICH2 allowing a **significant reduction in the number of MaPMT units and readout channels** (from 1536 to 384) with **negligible impact on the performance**

RICH1 Down MaPMT box

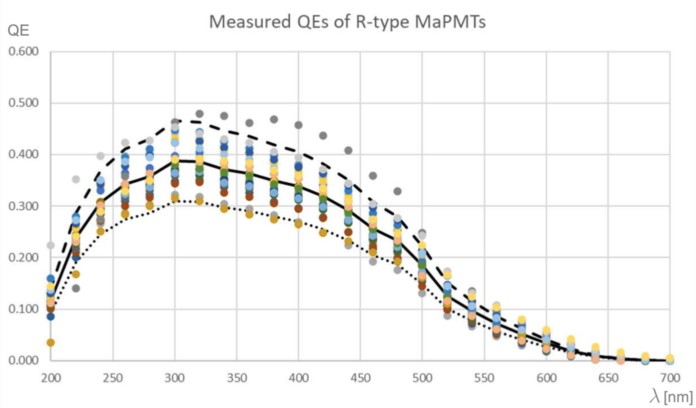
944 R13742 units (x 2)

RICH2 Left MaPMT box

384 R13743 and 192 R13742 units (x 2)

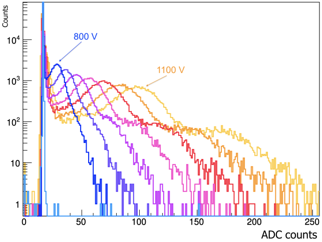
Quantum efficiency

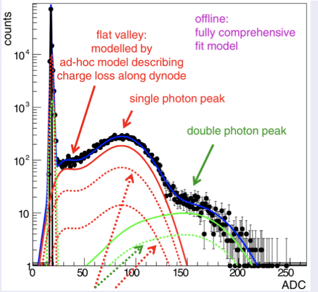
- quantum efficiency measured in a dedicated setup at CERN on a subsample of devices (technical specification from Hamamatsu on the Blue Sensitivity Index)
- UV-glass entrance window: sensitivity to single-photon between 200 and 600 nm
- **ultra bi-alkali photocathodes allow to reach an excellent quantum efficiency of 40% at 300 nm in average!**



Quality assurance measurements

Nucl. Instrum. Meth. A 876 (2017) 206-208





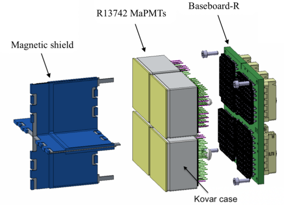
Signal + Contribution needed to describe right side of pedestal

- a total of **3500 units** have been qualified by two dedicated facilities in Edinburgh and Padova
- gain from 1100 → 800 V in steps of 50 V for all pixels
- in addition all the others technical specifications (peak to valley ratio, dark counts and uniformity) have been assured
- all data encoded in a custom WinCC-OA database
- **More details in Carmen Giugliano's poster**

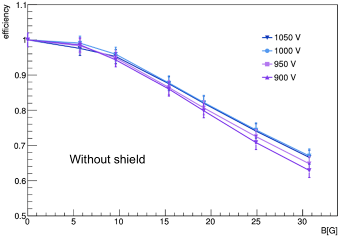
Behaviour in magnetic field

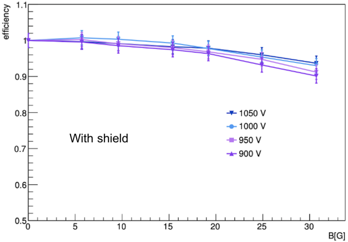
Nucl. Instrum. Meth. A 824 (2016) 21-23

- residual magnetic field from the LHCb dipole magnet of 30 G in RICH1 and 10 G in RICH2
- embedded Kovar case sufficient to shield against the RICH2 stray field



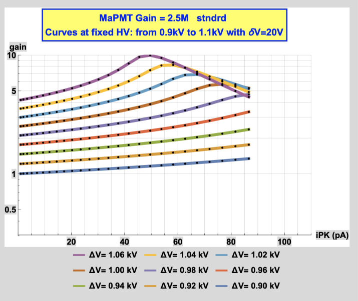
- dedicated mu-metal shield surrounding a group of four R13742 MaPMTs to recover drops in efficiency seen in **edge pixels** in presence of a **longitudinal field** parallel to the dynode structure

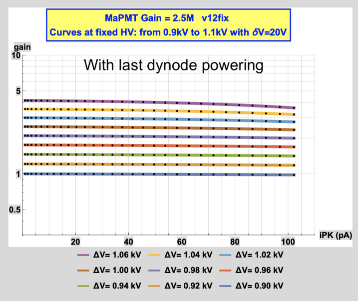




Anode current and gain linearity

- the maximum rating of the average anode current is 100 μA
- a dedicated LTSpice model of the 3 MΩ voltage divider and dynode chain shows that about 30 MaPMTs in the high occupancy (30% @ 40 MHz) region are close to this limit (if G = 1 Me)
- gain non-linearity due to the increase of the anode current and the changes in the interstage voltages





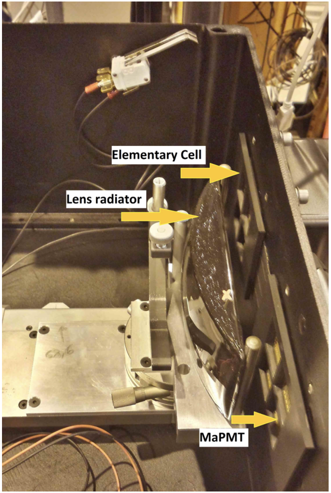
MaPMTs are operated powering the last dynode to keep constant the gain and to have a direct control on the average anode current by measuring the power supply currents

Tests on charged particle beams

JINST 12 (2017) 01, P01012

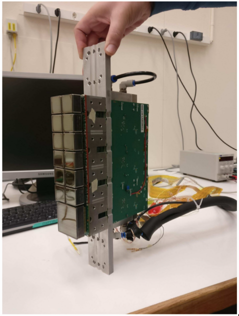
- first tests on a particle beam (mainly 180 GeV pions) in 2014 in the North Area of the Prevessin site at CERN
- well characterised optical setup allowing to perform data/simulation comparison, *e.g.* on the photon yield
- intense and continue testbeam campaigns up to 2018

	Data		Simulation		Analytical estimate
	mean	RMS	mean	RMS	mean
Total	13.4	3.8	13.1	2.9	-
PMT A	3.6	1.7	3.1	1.5	3.8
PMT B	3.3	1.6	3.1	1.5	4.1
PMT C	4.4	1.9	3.3	1.5	3.9
PMT D	4.2	1.8	3.3	1.5	4.1



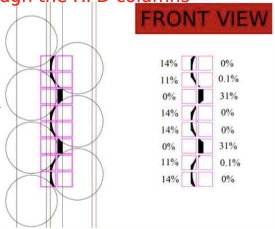
MaPMTs in the LHCb experiment during 2018 operations

Aim: test a photon detection module in a realistic environment



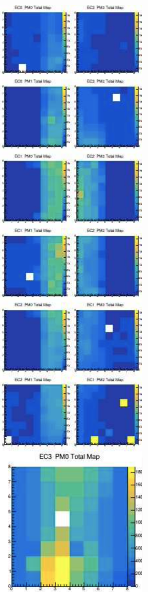
Idea →

Cherenkov light through the HPD columns



↓ Installation

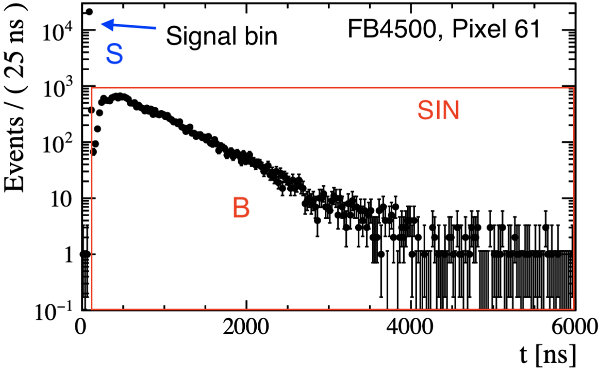
First collisions →



Observation of Signal Induced Noise (SIN)

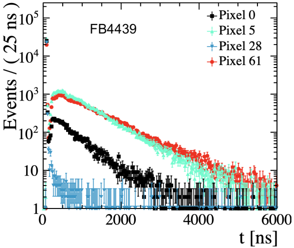
JINST 16 (2021) P11030

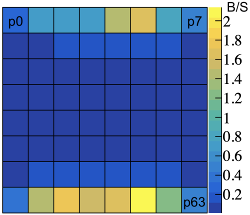
- first data acquired in an LHC collision scheme with isolated bunches (to synchronise the system) and with a 3 μs-wide acquisition window
- detection of **out-of-time hits** in R11265 tubes, delayed with respect to the expected arrival time of Cherenkov photons, indicating an unexpected source of noise
- characterised by the mean number of SIN pulses $\mu_{\text{SIN}} = B/S$



Localisation of SIN and device dependence

JINST 16 (2021) P11030





MaPMT	μ_{sin}^{0}	μ_{sin}^{5}	μ_{sin}^{28}	μ_{sin}^{61}
FB4439	0.2457 ± 0.0035	1.695 ± 0.013	0.0109 ± 0.0007	2.139 ± 0.018
FB2294	0.0745 ± 0.0012	0.3715 ± 0.0029	0.0076 ± 0.0004	0.491 ± 0.003
FB2312	0.132 ± 0.0017	0.747 ± 0.004	0.0081 ± 0.0004	2.231 ± 0.011
FB4500	0.266 ± 0.004	1.398 ± 0.012	0.0103 ± 0.0007	1.034 ± 0.010

- the localisation is a **general feature of SIN, but with absolute values of μ_{SIN} strongly depending on the device under consideration**
- weak correlation against the pixel gain, increasing at lower high-voltages
- no correlation with other MaPMT properties
- no connection between ageing effects and SIN and no significant changes when testing different voltage dividers

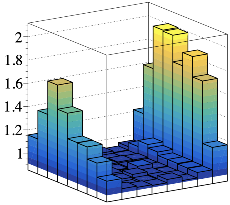
SIN and pile-up

JINST 16 (2021) P11030

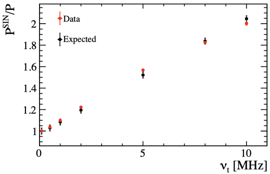
- SIN expected to produce pile-up effects in the high occupancy regions
- model developed and validated with measurements up to 10 MHz

Counting probability of Cherenkov light (ck)+SIN

$$P^{\mathrm{SIN}} = 1 - (1 - P_{\mathrm{ck}})e^{-\mu_{\mathrm{sin}} P_{\mathrm{ck}}}$$



(a)



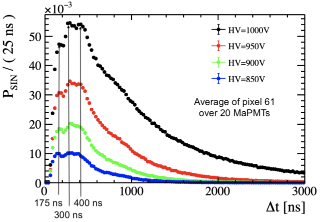
(b)

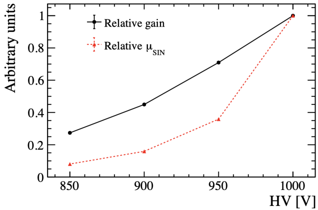
Figure 15: (a): ratio of detected counts at 10 MHz and 100 kHz for MaPMT FB3036. (b): ratio of the counting probabilities with and without SIN for pixel 61 of MaPMT FB3036, at different illumination rates, for the experimental (red) and expected (black) values. The mean number of SIN pulses is $\mu^{61}_{\mathrm{SIN}} = 4.329 \pm 0.031$.

Dependence on the HV

JINST 16 (2021) P11030

- per-bin probabilities presenting similar structures, usually due to ion feedback
- no observable shift in time as the the HV changes but still consistent with ion feedback given the size of an MaPMT: ~ 13 mm (2 mm) distance between the photocathode and the anode (first dynode)
- **exponential dependence on the HV**



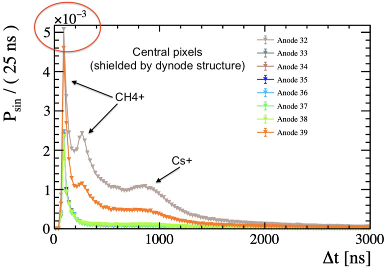


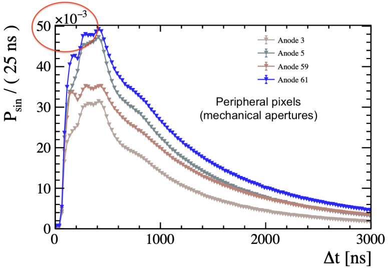
Assumption of uniform electric field
(but significant edge effects for peripheral pixels)

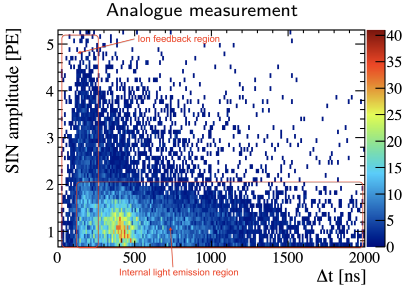
Ion	A [u]	$\Delta t_{\text{PK-Dy}}$ [ns] V=153.3 V	$\Delta t_{\text{PK-Dy}}$ [ns] V=130.3 V	$\Delta t_{\text{PK-An}}$ [ns] V=1000 V	$\Delta t_{\text{PK-An}}$ [ns] V=850 V
H_2^+	2.0	33.0	35.8	84.0	91.1
He^+	4.0	46.5	50.5	118.4	128.4
CH_4^+	16.0	93.1	101.0	237.0	257.1 ?
K^+	39.1	145.4	157.7	370.1	401.4
Sb^+	121.8	256.6	278.3	653.0	708.3
Cs^+	132.9	268.1	290.7	682.3	740.0

Interpretation

JINST 16 (2021) P11030





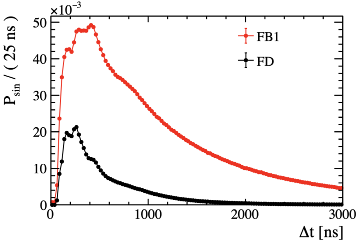


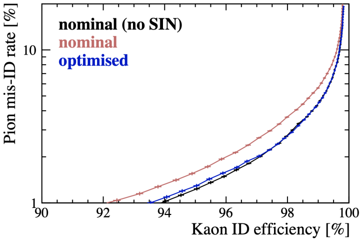
- exponential tail: **mechanism consistent with internal light emission and fluorescence decay**
- peaking structures shifted towards later times due to the convolution between ion feedback and light emission
- time gap of $\sim$ 200 ns $\Rightarrow$ SIN mainly initiated by ion feedback

Mitigation strategies

JINST 16 (2021) P11030

- a **new series (FD) of R11265 MaPMTs** has been produced in 2019 by Hamamatsu to reduce the contributions of SIN pulses by means of a change of the internal mechanical design of the tube ⇒ installed in the central region of RICH1
- exploit the strong dependance on the HV to operate at the **lowest possible HV** as a compromise between single-photon detection efficiency and low SIN rate
- exploit the prompt (time spread: $\mathcal{O}$(10 or 100 ps)) arrival time of Cherenkov photons on the photon detector planes to implement of a **6.25 ns time gate at the frontend readout** to increase the signal to noise ratio of a factor four (**see Floris Keizer's** talk)

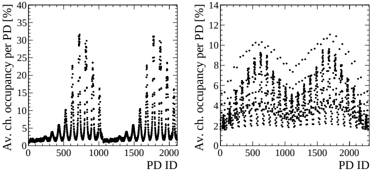




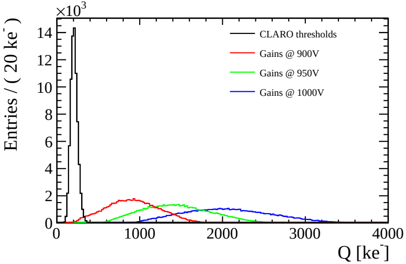
MaPMTs grouping in the photon detector planes

- one HV channel in common between a module of 16 MaPMTs $\Rightarrow$ choose MaPMTs with similar ($\Delta G/G \sim 10\%$) average gains
- equalisation of pixel gains across the photon detector planes (**total of $\sim$ 200k channels**) done through the optimisation of the high voltage setting and frontend thresholds
- high occupancy regions populated with SIN-mitigated tubes and care is taken on the chosen gain and high voltage setting to respect the maximum rating of the average anode current

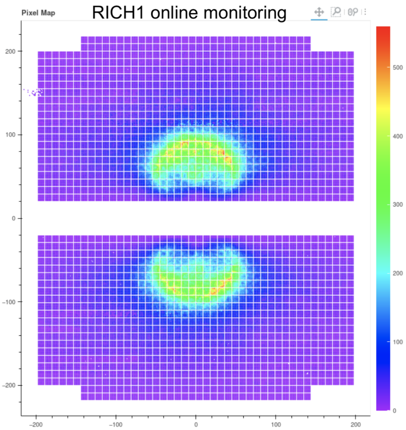
Simulation

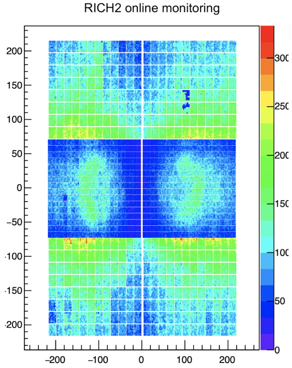


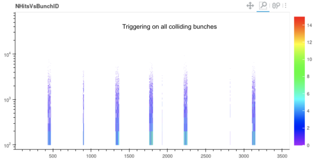
RICH2 calibration data

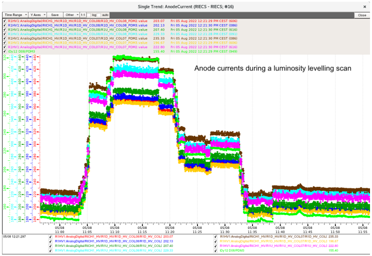


First operations in LHC Run 3



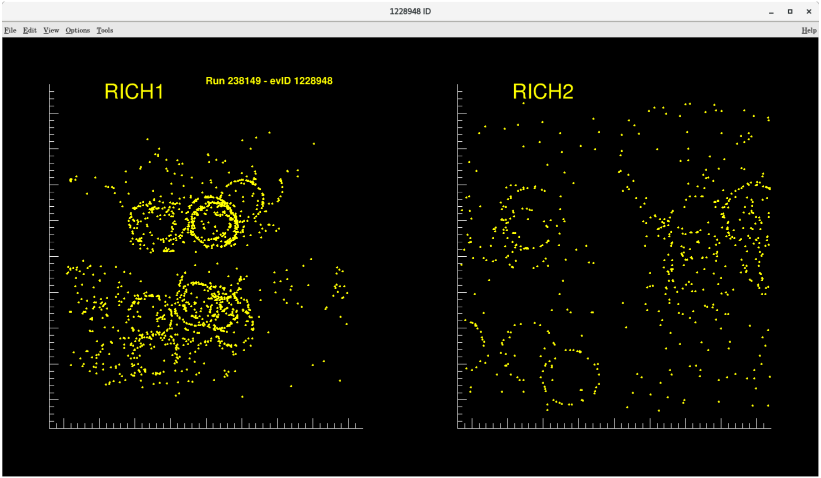






Conclusions

- a decade is now passed since the first tests done on the Hamamatsu R11265 and R12699 MaPMTs
- tests on the full production completed, comprising tests in the quality assurance facilities, with particle beams at CERN and operating the MaPMTs in LHCb in 2018
- discovery and characterisation of the SIN and mitigation strategies now in place
- we would like to aknowledge Hamamatsu for the fruitful collaboration across the years
- installation of the MaPMTs in both RICH1 and RICH2 is completed since the beginning of this year, and the first operations with Run 3 collisions are very promising from the point of view of the photon detectors performance


1228948 ID
File Edit View Options Tools
Help
RICH1
Run 238149 - evID 1228948
RICH2

Thanks!