



**Università
degli Studi
di Ferrara**

DOCTORAL COURSE IN:
PHYSICS

CYCLE XXXII

COORDINATOR Prof. Luppi Eleonora

*Experimental studies for the
validation of the
opto-electronic components
for the LHCb RICH Upgrade*

Scientific-Disciplinary Sector (SDS): FIS/01

Ph.D. Candidate:

Dott. Minzoni Luca

(signature)

Supervisor:

Prof. Fiorini Massimiliano

(signature)

Co-Supervisor:

Prof. Calabrese Roberto

(signature)

Years 2016 – 2019



Contents

1	The Large Hadron Collider	11
2	LHCb experiment	15
2.1	Overview	15
2.1.1	The VELO detector	18
2.1.2	The Tracker	20
2.1.3	The RICH detectors	24
2.1.4	The Calorimeter	25
2.1.5	The Muon Detector	26
2.1.6	Fixed-target collisions in LHCb	28
2.1.7	LHCb trigger	28
3	Physics at LHCb	31
4	LHCb RICH detectors at LHC	35
4.1	Cherenkov radiation	35
4.2	LHCb RICH system	37
4.2.1	RICH Detectors at LHCb	37
4.2.2	Particle identification requirements	38
4.2.3	RICH design	40
4.2.4	RICH performance	48
4.3	RICH upgrade overview	56
4.4	RICH Upgrade Technical design	61
4.4.1	MaPMT modularity and front-end mounting scheme	62
4.4.2	Upgraded RICH1 optical design	62
4.4.3	Upgraded RICH1 mechanics	66

4.4.4	Upgraded RICH2 optical design and mechanics	68
4.5	Performances of the LHCb RICH upgrade	69
4.5.1	Simulated data analysis	69
4.5.2	RICH upgrade simulation geometry	70
4.5.3	Simulation results	72
5	The LHCb RICH Upgrade Elementary Cell	75
5.1	The CLARO ASIC	75
5.1.1	CLARO technical design	76
5.1.2	CLARO characterization	78
5.1.3	The Front-End Board	81
5.2	Multi-anode PhotoMultiplier Tube	82
5.3	The Elementary Cell	84
6	Irradiation tests on the CLARO ASIC	89
6.1	Radiation effects on electronic devices	89
6.1.1	Lattice displacement and ionization effects	90
6.1.2	Single Event Effects	90
6.2	CLARO irradiation tests strategy	91
6.2.1	Ion irradiation	92
6.2.2	Proton irradiation	104
6.2.3	Mixed Field irradiation	109
6.3	Conclusions on the CLARO irradiations tests	112
7	RICH upgrade test-beam	113
7.1	Setup	113
7.1.1	Particle beam and monitoring tools	115
7.1.2	Cherenkov Radiator	115
7.1.3	Test-beam DAQ	117
7.2	Measurements	121
7.2.1	Cherenkov ring radius and Cherenkov angle reconstruction	121
7.2.2	Threshold scan	126
7.2.3	S-Curve	129

8	The LHCb RICH Upgrade Quality Assurance procedures	135
8.1	The CLARO QA procedure	136
8.1.1	CLARO QA data analysis	141
8.2	The Front-End Board QA procedure	146
8.3	The Elementary Cell QA procedure	152
8.3.1	Signal Induced Noise measurements and LED driver calibration	155
8.3.2	The ECQA test protocol	159
8.3.3	DAQ software	163
8.3.4	Data analysis	175
8.3.5	EC boxing and delivery	185
8.3.6	Database	186
9	Conclusions	189
A	Irradiation data analysis tools	193
B	Least-square circle fit	195
C	ECQA Mapping Scheme	197

Acronyms

ADC Analog-to-Digital Converter

ALICE A Large Ion Collider Experiment

AMS Austria Micro Systems

ASIC Application Specific Integrated Circuit

Bb Base Board

Bkb Back Board

BSM Beyond Standard Model

CERN Conseil Européen pour la Recherche Nucléaire

CHARM CERN High energy AcceleRator Mixed field (facility), CERN

CKM Cabibbo-kobayashi-Maskawa (matrix)

CMOS Complementary Metal-Oxide Semiconductor

CMS Compact Muon Solenoid (experiment)

CP Charge-Parity

DAQ Data Acquisition

DB Digital Board

DCR Dark Count Rate

EC Elementary Cell

ECAL Electromagnetic Calorimeter

ECQA Elementary Cell Quality Assurance

ECS Experimental Control System

EFF Event Filter Farm

EPDM Ethylene-Propylene Diene Monomer

FCNC Flavour Changing Neutral Current

FE Front-End

FEB Front-End Board

GBT Giga Bit

GEM Gas Electron Multiplier

GUI Graphical User Interface

HCAL Hadronic Calorimeter

HIF Heavy-Ion Facility, Louvain-La-Neuve (BE)

HLT High-Level Trigger

HSMC High Speed Mezzanine Card

HPD Hybrid Photodetector

HV High Voltage

IT Inner Tracker

LDR Low Dose Rate

L0 Level-0 (trigger)

LET Linear Energy Transfer

LEP Large Electron-Positron (collider)

LHC Large Hadron Collider

LHCb Large Hadron Collider beauty (experiment)

LLT Low-Level Trigger

LS Long Shutdown

LV Low Voltage

MaPMT	Multi-Anode Photomultiplier Tube
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MWPC	Multi-Wire Proportional Chamber
NP	New Physics
OT	Outer Tracker
PC	Polycarbonate
PD	Photon Detector
PDF	Probability Density Function
PDM	Photon Detection Module
PDMDB	Photon Detection Module Digital Board
PDQA	Photon Detector Quality Assurance
PID	Particle Identification
PMI	Polymethacrylimide
PS	Proton Synchrotron (accelerator)
PS	Pre Shower (LHCb calorimeter)
QR (code)	Quick Response (code)
RICH	Ring Imaging Cherenkov
SciFi/SFT	Scintillating Fibre (tracker)
SEB	Single Event Burnout
SEE	Single Event Effects
SEGR	Single Event Gate Rupture
SEL	Single Event Latchup
SES	Single Event Snapback
SET	Single Event Transient
SEU	Single Event Upset

SIRAD Silicon and RADiation (facility), Legnaro (IT)

SIN Signal Induced Noise

SiPM Silicon PhotoMultiplier

SM Standard Model

SMOG System for Measuring Overlap with Gas

SPD Scintillating Pad detector

SPI Serial Peripheral Interface

SPS Super Proton Synchrotron

TID Total Ionizing Dose

TPI Test Pulse Injector

TT Tracker Turicensis

UART Universal Asynchronous Receiver Transmitter

UT Upstream Tracker

VELO VERtex LOcator

VI Virtual Instrument

QA Quality Assurance

Introduction

In the initial phase of the Big Bang equal amounts of matter and anti-matter were created. However most of the created particles subsequently annihilated with their corresponding anti-particles producing photons. What is left of this annihilation process is the Cosmic Microwave Background, the 2.7 Kelvin radiation that fills the Universe. But not all of the matter underwent this annihilation process. A contribution to the observed asymmetry between matter and antimatter in the actual universe is to be associated to the CP-symmetry violation in the instants after the Big Bang.

The Charge Conjugation (C) operation transforms a particle in its anti-particle, conjugating all its quantum numbers. The Parity (P) operation reverse the handedness of the space. The CP operation is the product of C and P operations, and has the effects of transforming a particle in an antiparticle, inverting its space coordinates. In the Standard Model (SM), it has been demonstrated that the electromagnetic and strong interactions are invariant under the CP operation, but there are examples of decays involving weak interaction which are proven to violate the CP symmetry. The Cabibbo-Kobayashi-Maskawa (CKM) matrix describes the probability of transition for a given mass eigenstate to go in a weak interaction eigenstate. In this matrix we can recognize one of its free parameter as the source of the CP-symmetry violation in the SM. However, since this single source it's not enough to explain the asymmetry between matter and antimatter in the universe, new sources of CP violation must be present [1].

The LHCb experiment is designed to study evidences of CP violation in the hadronic environment of LHC and also to search for new CP violation mechanism in heavy flavour processes. LHCb proved to be able to search for signatures of physics "Beyond the Standard Model" (BSM) in rare decays and mixing involving b and c quarks. Most BSM models predict the existence of undiscovered heavy particles which, appearing in transitions mediated by loops, should lead to deviations from SM predictions in the values of some observables. LHCb goal is to uncover these changes by comparing SM

predictions for such observables with precision measurements. To increase the statistics on these rare processes, the LHCb collaboration decided to upgrade the experiment during the technical shutdown of 2019/2020 (Long Shutdown 2, LS2). My thesis work has been performed in the framework of the LHCb Ring Imaging Cherenkov (RICH) detector group, which is in charge for the RICH detector upgrade. The detector is responsible for the Particle Identification (PID) of charged hadrons, but the current setup has to be replaced in order to comply to the new LHC performances.

In Chapter 1 an overview of the Large Hadron Collider (LHC) is presented. In Chapters 2 and 3 an overview of the LHCb experiment and of the physics channels studied are presented. In Chapter 4 the LHCb RICH detector system is presented, with the current and the upgraded features. In Chapter 5 an overview of the Front-End (FE) electronics which will be used in the LHCb RICH Upgrade is presented.

The Ferrara RICH Upgrade group was responsible for the irradiation test on the FE electronics to be used in the upgrade to validate its radiation hardness. The facilities descriptions, the test methods and the results from the analysis of the data from these tests are reported in Chapter 6.

The LHCb RICH Upgrade prototype has been tested in a realistic environment on a beam line in the North-Area facility at CERN. The description of the setup and the results from the prototype data analysis are presented in Chapter 7.

In Chapter 8 are presented the results from the procedures developed by the LHCb RICH Upgrade group to validate the electronic components that will be installed in the upgraded RICH detectors. Three main components have been validated by a dedicated Quality Assurance (QA) procedure: the CLARO ASICs (CLARO QA), the FE Boards (FEBs QA) and the Elementary Cells (ECs QA).

Chapter 1

The Large Hadron Collider

The Large Hadron Collider (LHC) is the largest particle collider in the world. It was built by the Conseil Européen pour la Recherche Nucléaire (CERN) between 1998 and 2008. The collaboration includes 10,000 scientists from hundreds of universities and laboratories from more than 100 countries [2].

The accelerator is placed in a tunnel 27 km long, 3.8 m wide and with a depth ranging from 50 to 175 m under the France-Switzerland border near Geneva. The tunnel was previously used by the Large Electron-Positron Collider (LEP). In the tunnel two adjacent parallel beam lines are present, each containing a proton beam traveling in the opposite direction around the ring one respect to the other. LHC has four crossing points at which the proton collisions are performed, around which are positioned seven detectors, each of them designed to perform dedicated researches in the particle physics field. A total of 1,232 dipole magnets are used to keep the beams on their circular trajectory, while 392 quadrupole magnets are necessary to keep the beams focused, with stronger quadrupole magnets placed near to the intersection points used to increase the beam density, hence increasing the interaction cross-sections between the particles. A total of $\sim 10,000$ superconducting copper-clad niobium-titanium magnets are installed in LHC. 96 tonnes of superfluid helium-4 are needed to keep the magnets at the operating temperature of 1.9 K (-271.25°C).

First collisions have been performed in 2010 at an energy of 3.5 TeV per beam. During the period named Run II (2015-2018) it reached 6.5 TeV per beam (13 TeV total center of mass energy). At the end of 2018, it entered a two-year shutdown period during which many experiments will perform upgrades. During LHC operations, the CERN site draws roughly 200 MW

of electrical power from the French electrical grid. The LHC accelerator and detectors draw about 120 MW. When running at the energy of 6.5 TeV, the protons have a Lorentz factor of about 6,930 and move at about $0.999999990\,c$, which means 11,245 revolutions per second. The protons are grouped together into bunches and up to 2,808 bunches are injected in LHC for each run (which lasts between 5 and 24 hours), with 115×10^9 protons in each bunch. The bunch collision rate is 40 MHz with a luminosity of $2 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$. The particles are accelerated by steps, as shown in Figure 1.1. The first system is the linear particle accelerator LINAC 2 which accelerates the protons to 50-MeV. In the Proton Synchrotron Booster (PSB) the protons are accelerated to 1.4 GeV and then they are injected into the Proton Synchrotron (PS), where their energy reaches 26 GeV. Finally the Super Proton Synchrotron (SPS) increases their energy to 450 GeV before they are injected into the main ring. The main LHC physics program focuses on proton-proton collisions. However dedicated heavy-ion collisions running periods are performed. The baseline are lead ions. The lead ions used have an energy of 2.3 TeV per nucleon (or 522 TeV per ion). The aim of the heavy-ion program is to investigate the quark-gluon plasma.

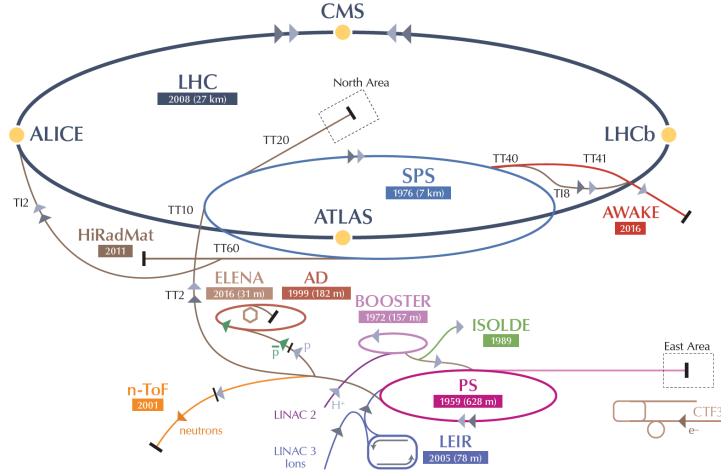


Figure 1.1: Scheme of the LHC accelerator complex (with date of installation and length) and of the experiments on it. CERN copyright.

Four main experiments are located at LHC: the ATLAS and the Compact Muon Solenoid (CMS) experiments are large general-purpose particle detectors. A Large Ion Collider Experiment (ALICE) and Large Hadron Collider beauty experiment (LHCb) have more specific design. ALICE focuses on QCD, and it has been designed to address the physics of strongly interacting

matter and the quark-gluon plasma at extreme values of energy density and temperature in nucleus-nucleus collisions. Besides running with Pb ions, the physics program includes collisions with lighter ions, lower energy running and dedicated proton-nucleus runs. LHCb study the asymmetry present in the universe between matter and anti-matter by searching New Physics (NP) contributions in rare CP symmetry violating processes/decays involving hadrons containing charm (c) and beauty (b) quarks.

Chapter 2

The LHCb experiment

2.1 Overview

LHCb is a single-arm spectrometer with a forward angular acceptance which covers the range 10-300 (250) mrad in the bending (non-bending) plane. The specific geometry of the detector is optimized to study high energies processes of b and $\bar{b}$ hadrons production, in which the particles are predominantly produced in the same forward or backward cone [3]. The detector covers a pseudorapidity (η) range of $2 < \eta < 5$. The charged particle momentum is measured by a high-precision tracking system, with a relative uncertainty which goes from 0.5% at the lowest measurable momentum to 1.0% at 200 GeV/c. The impact parameter, that is the minimum distance of a track to a primary vertex, is measured with a resolution of $(15 + 29/\text{pT}) \mu\text{m}$, where pT is the transverse (with respect to the beam) momentum component (in GeV/c) [4].

In Figure 2.1 the section of the LHCb experiment is shown. Most sub-detectors are assembled in two halves, referred to as the detector A- and C-sides, which can be moved out horizontally for assembly and maintenance purpose by providing access to the beam-pipe. A right-handed coordinate system is defined: the z axis is directed along the beam axis into the detector, y axis is vertical and x axis is horizontal. Cylindrical polar coordinates (r, z, ϕ) are defined accordingly.

The charged particles momentum measurement requires a warm dipole magnet. The LHCb magnet provides an integrated field of 4 Tm and deflects charged particles in the horizontal plane. Three dipole magnets are used to compensate the LHCb dipole effect on the LHC proton beams and to ensure a closed orbit for them. The tracking system is composed of many

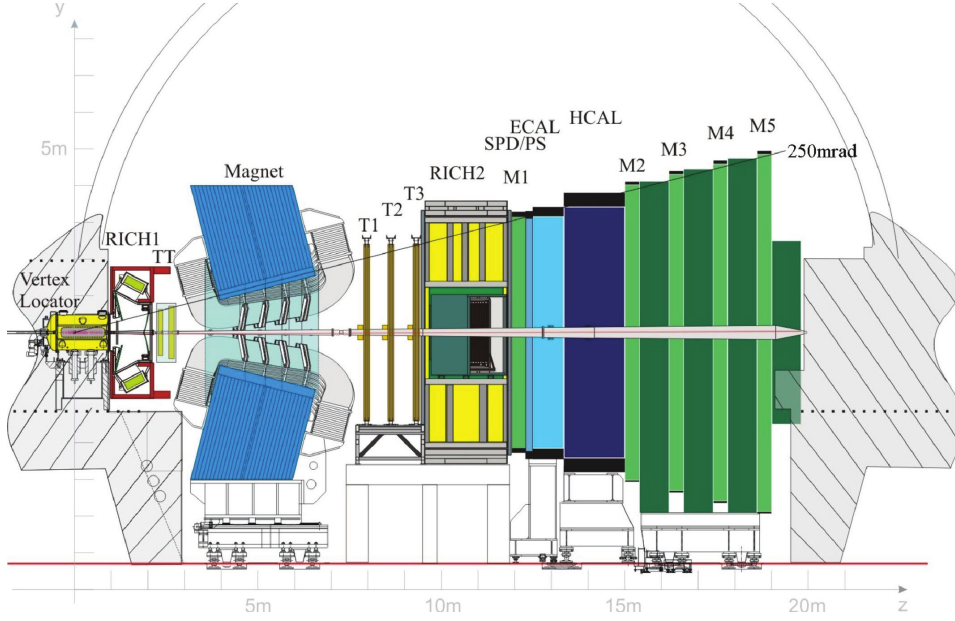


Figure 2.1: The section of the LHCb detector from its side.

sub-detectors: the VERtEX LOcator (VELO), a silicon-strip vertex detector surrounding the LHCb beam interaction region; the Tracker Turicensis (TT), a large-area silicon-strip detector located upstream of the LHCb dipole magnet; lastly, three stations of silicon-strip detectors placed downstream of the magnet, T1, T2, T3, each of them composed of two separate sub-detector, the Inner Tracker (IT), a silicon micro-strips detector, and the Outer Tracker (OT), a drift-tube gas detector. Charged hadron identification is performed by two Ring Imaging Cherenkov Detectors (RICH), RICH1 and RICH2. RICH1 is installed upstream the magnet while RICH2 is placed downstream of it. Both RICH detectors use gas as a radiator and they are mainly designed to separate π from K contribution in the decays of interest. The energy of electrons, photons and hadrons, as well as their spatial coordinates, is provided by a calorimeter system placed downstream of RICH2. Lastly, 5 muon stations are installed in the most downstream region of LHCb to detect muons produced in the collisions. Both the muon system and the calorimeter system provide information to the Level 0 (L0) trigger of the experiment for the selection of interesting events.

There are two fundamental parameters which define the LHCb performances: the luminosity, that is the ratio of the number of events detected in a fixed time interval to the interaction cross section, and the pile-up μ_{vis} , the average number of visible interactions per beam-beam crossing. The

value of luminosity in 2010 was $\sim 10^{28} \text{ cm}^{-2}\text{s}^{-1}$ and the pile-up was close to zero. During LHC Run I the LHCb operating conditions evolved, so that a luminosity of $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ with a pile-up of $\mu_{vis} \sim 2.5$ was reached. Despite the highest luminosity in 2010 being already 75% of the LHCb design luminosity ($2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$), the pile-up was larger than the design value of ~ 0.4 due to the low number of bunches in LHC. However, the trigger and reconstruction processes worked efficiently under such conditions, resulting in an increased detector occupancy due to pile-up, but with no side-effects on the physics output. The LHC beam energy was 3.5 TeV during 2010-2011. In the first months of 2011, the number of bunches in the machine was gradually increased to about 1300, the maximum possible with 50 ns bunch spacing. Since the number of bunches increased, the pile-up over the year decreased and LHCb took the majority of the data at a luminosity of $3.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. This value was 1.75 times more than the design luminosity. To compensate, in 2011 a luminosity levelling procedure was introduced. The procedure consists in adjusting the transverse overlap of the beams in proximity of the LHCb interaction point. During data taking the instantaneous luminosity can be kept stable to within 5% and the maximum overlap with head-on beams is reached only after 15 hours. The procedure minimizes the effects of luminosity decay for LHCb and makes possible to maintain the same trigger configuration during a fill, reducing systematic uncertainties due to changes in the detector occupancy.

In 2012 the LHC beam energy was increased to 4 TeV and since then LHCb is taking data at a luminosity of $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, twice the design luminosity. LHCb integrated luminosity recorded was 38 pb^{-1} in 2010, 1.11 fb^{-1} in 2011, 2.08 fb^{-1} in 2012. In 2015 the Run II started, with an increased center of mass energy of 13 TeV, 6.5 TeV per beam. The bunch crossing rate was 40 MHz, as it is today. The experiment collected 0.5 fb^{-1} in 2015, 1.6 fb^{-1} in 2016, 1.7 fb^{-1} in 2017 and 2.1 fb^{-1} in 2018 (Figure 2.2).

During the second long shutdown of the LHC, began in the first months of 2019, the LHCb experiment will be upgraded. After this upgrade the experiment will reach the luminosity of $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and will be read-out at the full rate of 40 MHz. To accomplish this, the LHCb hardware-based L0 trigger, which reduces the readout rate of the full detector to 1 MHz, will be removed. The event selection decisions will be taken by a flexible software trigger running in a CPU farm. Since new operating conditions will be applied, all sub-detectors of LHCb need to be re-designed to comply with a higher luminosity (5 times the Run II luminosity) and a higher data acquisition rate.

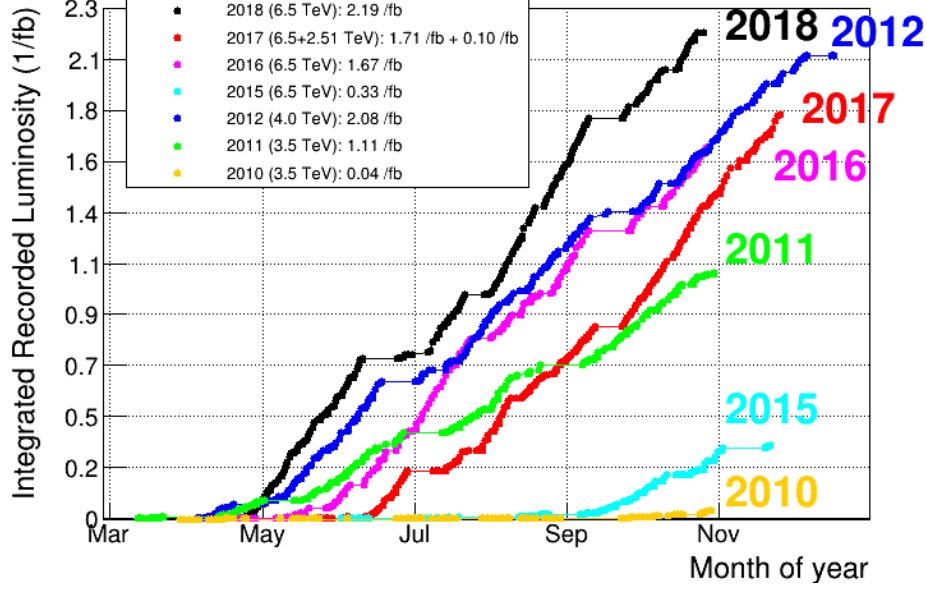


Figure 2.2: LHCb integrated luminosity during the years.

2.1.1 The VELO detector

The VELO, installed around the pp interaction region, covers a length of 1m and consists of 42 double sided modules supported by a carbon fibre paddle stan [5]. Each module is composed of two layers of silicon micro-strip sensors, one measuring the radial distance from the beam axis (R-sensor) and the other measuring the azimuthal angle (ϕ -sensor). Strip pitches width goes from $40\mu\text{m}$ for the R-sensor and $35.5\mu\text{m}$ for the ϕ -sensor in the region closer to the beam axis at the inner radius of 8.2 mm, to $101.6\mu\text{m}$ and $96.6\mu\text{m}$ for the R-sensor and the ϕ -sensor, respectively, in the outer region at the outer radius of 42 mm (Figures 2.3 and 2.4). These sensors operates at a temperature of -10°C and are cooled using a thermally conductive spine with a bi-phase CO_2 cooling system set at -30°C . The cooling blocks are attached to the module substrate base. During the injection of the LHC beams, the VELO modules are moved by 29 mm in the horizontal direction opposite to the beam pipe and are subsequently moved back once the beam is declared stable. Once the VELO is closed, the closest active strip is at 8.2 mm from the beam. This fully automated procedure has been developed to prevent fatal radiation damages to the VELO. The detector takes, on average, 210 seconds to close once stable beam conditions have been declared.

The VELO was installed inside the LHC vacuum vessel to achieve the best vertex resolution possible, and the sensors are separated from the LHC beams only by a $300\text{ }\mu\text{m}$ thin aluminum foil. In total, 170 thousand readout strips of the detector are read out by the custom-developed Beetle ASIC, which allows a maximum readout rate of 1.1MHz.

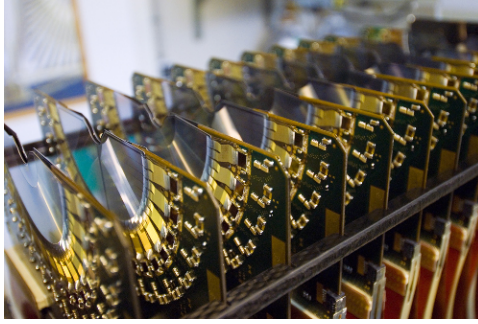


Figure 2.3: VELO silicon modules during assembly.

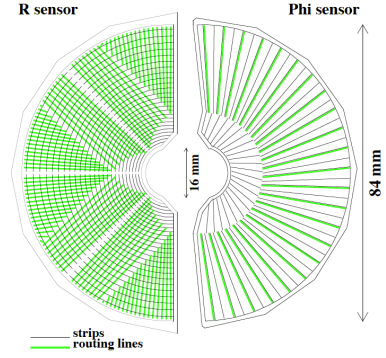


Figure 2.4: Schematic of R and ϕ sensors for a VELO module.

For the LHCb Upgrade the VELO detector has been redesigned [6]. The upgraded detector will be a pixel detector, and the current strip modules will be replaced. A new readout chip, the VeloPix ASIC, will be used to readout the $55 \times 55\text{ }\mu\text{m}^2$ silicon pixel sensors at a frequency of 40 MHz with 20.4Gb/s bandwidth [7]. A mechanical module concept for the upgrade is shown in Figure 2.5. The module design consists of a carbon-fibre structure on which a silicon micro-channel substrate is placed. The module has four silicon sensors, read out by twelve VeloPix ASICs which are glued directly onto the micro-channel base. With the VELO in closed position, a diamond shape is created with the sensors of opposing detector halves and the beam is passing through the centre of it.

The upgraded VELO will use thinner sensors and a thinner aluminum cover per each detector half. Also, in the closed position it will be 5.1 mm distant to the beam, 3.1 mm closer with respect to the actual position. With these features, the detector will have a more robust track reconstruction performance and an improved resolution with respect to the actual VELO. The upgraded VELO will use CO_2 kept at the temperature of -30°C as coolant, but it will flow directly under the major heat sources (like the VeloPix and other chips) via the micro-channels in the silicon substrate. A higher hit occupancy, due to increased particle flux, is foreseen. This will result in higher data rates coming from the detector and higher power consumption in the

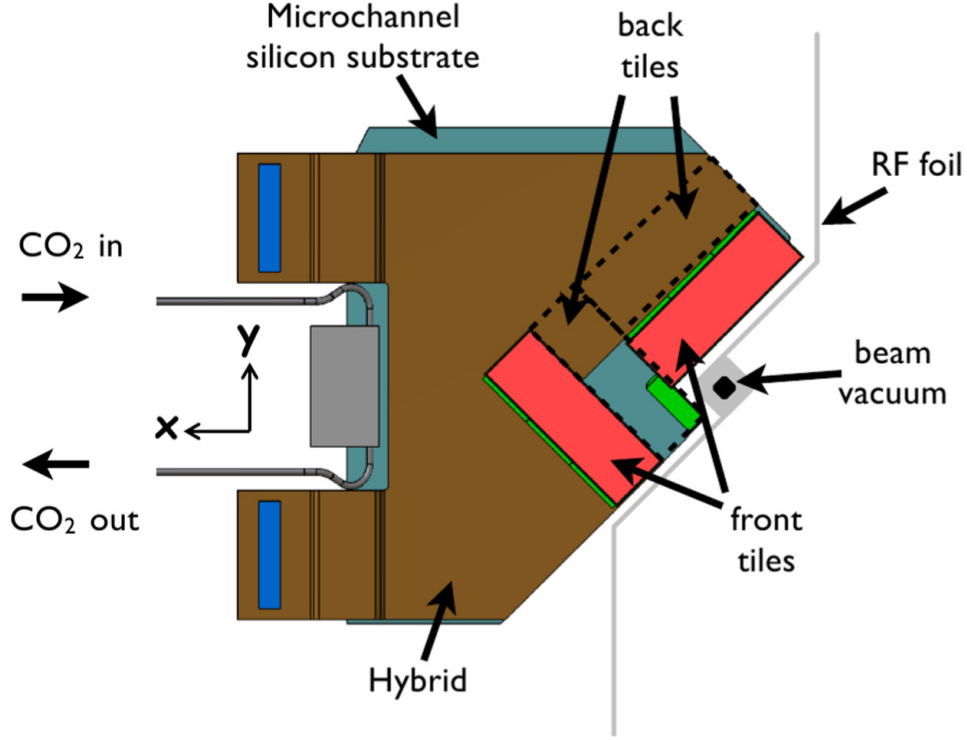


Figure 2.5: Schematic of one of the VELO modules that will be used in the upgrade.

front-end ASICs. It is estimated that the full VeloPix chip will consume $< 1.1 \text{ W/cm}^2$. The pixel sensors must operate at the temperature of -20°C in order to minimize the possibilities of thermal runaway triggered by radiation damage. In order to place the detector modules closer to the beam and to tolerate the higher luminosity foreseen for LHC Run III, the detector must be able to handle high radiation doses. The upgrade sensors are expected to receive a non-uniform radiation dose up to $8 \times 10^{15} \text{ 1-MeV} \cdot n_{eq}/\text{cm}^2$ during their lifetime. Despite the high dose, the sensors should retain a 99% hit efficiency at a bias voltage up to 1000V without suffering breakdown.

2.1.2 The Tracker

The TT tracking station consists of four planar layers of silicon microstrips detectors [8]. A total of 143 thousand strips are present, with a length of 40, 30, 20 or 10 cm and with a pitch of $183 \mu\text{m}$. Shorter strips were employed in the inner region of each detection layer, where particle densities

are highest, while longer strips were used in the outer region. The sensors are mounted on common cooling plate which is kept at 0°C , keeping the silicon strips temperature at 8°C . The strips are read out by the same ASIC used in the VELO [8]. The TT total active area is approximately 8 m^2 , 130 cm high and 150 cm wide. The four detection layers are arranged in a $x-u-v-x$ layout, with vertical strips in each of the two x layers, and strips rotated by a stereo angle of -5° and $+5^\circ$ in the u and v layers, respectively. The TT has to be replaced during the LHCb Upgrade. The currently employed silicon sensors would not sustain the high radiation dose in the post-upgrade LHCb environment, especially the inner detector region. With the actual read-out strip geometry the detector occupancy would be too high in the foreseen luminosity conditions. Lastly, the Beetle ASIC is not designed to run at 40 MHz read-out frequency and needs to be replaced. Since the FE on which the ASIC is installed is an integral part of the structure of the detector modules, the Beetle cannot be removed without damaging the modules themselves. The new Upstream Tracker (UT) will be installed during the upgrade. With this detector it will be possible to reconstruct long lived particles decaying after the VELO. The UT will be composed by 4 tracking layers employing silicon strip technology (Figure 2.6). The same $x-u-v-x$ layout as in TT will be used, with u and v layer rotated of -5° and $+5^\circ$ respectively. Given the positive experiences of Run I and Run II, the requirements about the clearance of the LHC beam-pipe have become more relaxed, hence the UT inner sensors will be closer to the beam pipe with respect to the actual tracker, increasing the geometrical acceptance. The detector geometry, the modules segmentation and the technology employed for the sensors is driven by the expected particle occupancy and radiation dose in the post-upgrade regime. The UT strips will run vertically, since the tracks are bent in the horizontal plane by the dipole magnet. In the outer region, the strips will be 99.5 mm long with $180\text{ }\mu\text{m}$ pitch, based on p^+ -in-n technology. The strips in the central region will be as long as the outer ones but 95 with μm pitch. Lastly, the closest strips to the beam will be 51.5 mm long, with $95\text{ }\mu\text{m}$ pitch. Both the inner and the central region strips will be based on n^+ -in-p technology in order to better sustain the radiation dose [9].

Two detector technologies are employed in the three tracking stations downstream of the magnet. The IT is a silicon micro-strip detector (Figure 2.7) with strips of $198\text{ }\mu\text{m}$ pitch. The IT detector covers a high cross-shaped region in the center of the three tracking stations T1-T3, with width of 125.6 cm and highness of 41.4 cm, for a total of approximately 4 m^2 . The A and C sides are $410\text{ }\mu\text{m}$ thick and each of them is composed of two different sensors

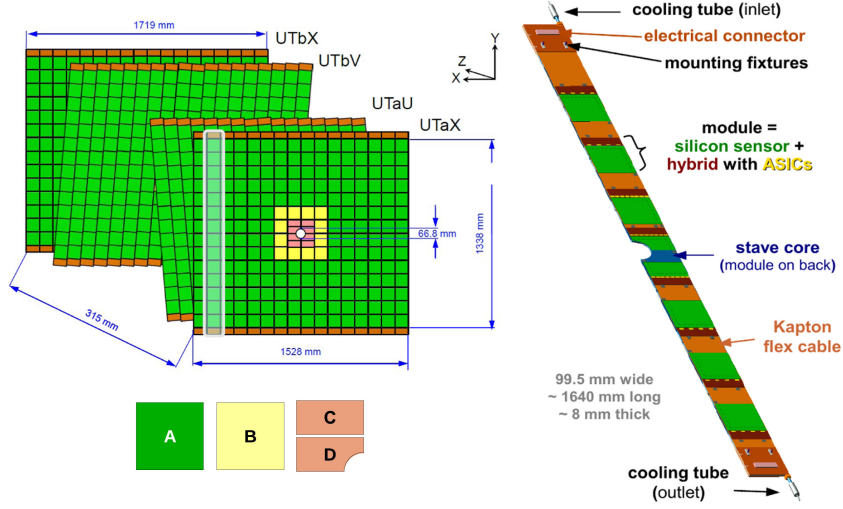


Figure 2.6: Left: UT geometry, looking downstream. Right: schematic of a silicon strip.

bonded together. The Top and Bottom sides are $320 \mu\text{m}$ thick and they are constituted of a single sensor. The readout for A and C side is 22 cm long, while for top and Bottom the readout is half as long. The cooling is the same as for the TT. The OT (Figure 2.8) is a straw drift-tube detector consisting of approximately 200 gas-tight modules with drift-time read-out. The gas, a mixture of Argon (70%), CO_2 (28.5%), and O_2 (1.5%), is chosen to obtain a spatial resolution of $200 \mu\text{m}$ and a drift time below 50 ns. The OT has four layers placed in an x - u - v - x layout, with a total active area of $597 \text{ cm} \times 485 \text{ cm}$. It is present in the outer region of the tracking stations. Both OT and IT have four detection layers per station, for a total of 54 thousand readout channels in the OT and 130 thousand readout channels in the IT. After traveling about 10 m in the LHCb from the VELO to the end of the three tracking stations, a particle has traversed about 60% of a radiation length and 20% of an absorption length. Charged particles require a minimum momentum of $1.5 \text{ GeV}/c$ to reach the tracking stations T1-T3.

The three downstream tracking stations would not sustain the higher occupancy in the post-upgrade running conditions, and the read-out electronics of both IT and OT are not designed to operate at 40 MHz. Hence, the actual tracking stations will be removed and a new detector will be installed: the Scintillating Fibre Tracker (SciFi Tracker/SFT). The SciFi will be used for track reconstruction after the magnet region, providing measurement of the particle momentum. It will have three stations (T1, T2, T3) placed between

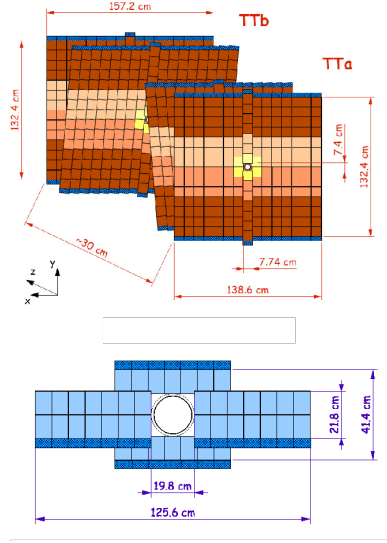


Figure 2.7: Top: the four TT planar stations. Bottom: the IT structure.

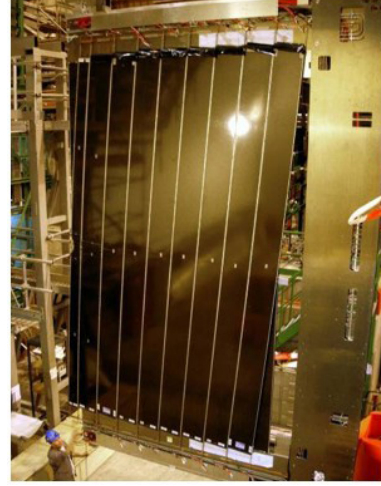


Figure 2.8: The OuterTracker during installation.

the LHCb dipole and the RICH2 detector. Each station is composed of four detection layers, for a total of 12 layers in the entire detector. Each station is centered at the same z -coordinate as the actual OT, with a 20 mm gap between the layers of a station. The beam pipe will pass through a circular hole in the centre of the layers. Again, the layers are arranged in an x - u - v - x layout with u and v layer rotated of -5° and $+5^\circ$ respectively. Each layer is composed of 12 modules, hence 144 modules will be used to build the detector.

The SciFi will use 2.4 m long plastic scintillating fibers with $250 \mu\text{m}$ diameter arranged on vertical layout [10]. Each of the detector layers will be composed of 8 sub-layers of fibers, for a total thickness of 1.35 mm and surface of about $6 \text{ m} \times 5 \text{ m}$. The fibers will be readout by 128-channels Silicon PhotoMultiplier detectors (SiPM) placed both on the top and bottom of the detector layers. SiPMs are highly susceptible at radiation damage and their Dark Count Rate (DCR) is strongly correlated to their temperature. To reduce both radiation effects and DCR the sensors will be cooled at the temperature of -40 C° . The UT and the SciFi detector will provide hits information for the track extrapolation in the range from the VELO to the RICH2 detector, reducing the number of fake reconstructed tracks by a factor 50-70%. As a consequence, the trigger timing will be largely improved.

2.1.3 The RICH detectors

Two Ring Imaging Cherenkov detectors (RICH1 and RICH2, Figure 2.9) are responsible for charged hadron identification in the momentum range 2 to 100 GeV/ c [11]. The upstream detector, RICH1, is designed to detect low momentum particles, from about 2 to 60 GeV/ c , and uses C₄F₁₀ gas as radiator medium for Cherenkov radiation production. The downstream detector, RICH2, is designed to cover the high momentum range, from 15 to 100 GeV/ c , and CF₄ gas is used as radiator medium. The angular acceptance of RICH1 is ± 25 mrad to ± 300 mrad (horizontal) and ± 250 mrad vertical, covering the LHCb acceptance. The angular acceptance of RICH2 is limited, covering the range from ± 15 mrad to ± 120 mrad (horizontal) and ± 100 mrad (vertical). This difference is due to the correlation between momentum and polar angle: a particle produced with high momentum has a smaller polar angle. In both RICH1 and RICH2 the Cherenkov photons produced in the gas are reflected by a system of plane and spherical mirrors and focused in ring images onto the photon detection planes, where the Hybrid Photon Detectors (HPDs) are installed. This type of photon detector was developed in collaboration with industry to be specifically used in the LHCb RICH system. The LHCb RICH system and its upgrade will be presented in detail in the next chapter.

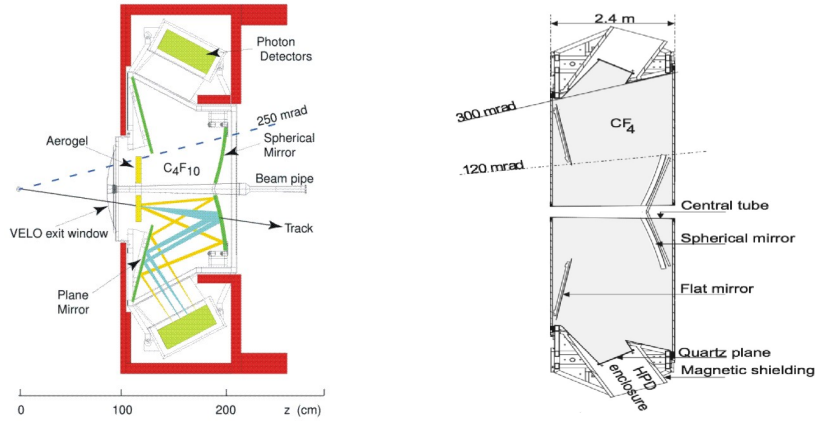


Figure 2.9: Schematic for RICH1 (left) and RICH2 (right) detectors in LHCb.

2.1.4 The Calorimeter

The calorimeter system, which provides the measurement of energies and positions of electrons, photons and hadrons, is composed of several sub-detectors: Scintillating Pad Detector (SPD), PreShower (PS), electromagnetic calorimeter shashlik type (ECAL), and hadronic calorimeter (HCAL). The system also selects candidates with high transverse energy for the first level trigger (L0) [12]. The SPD improves the separation between electrons and photons. A 15 mm lead converter, with a 2.5 radiation lengths (X_0) thickness, between the planes of rectangular scintillating pads of the SPD and the PS is placed. The background from charged pions is reduced by measuring the longitudinal partitioning of the electromagnetic shower in the PS detector and the main section of ECAL. The ECAL is composed of a sampling scintillator/lead structure with a 25 X_0 thickness. A schematic of the ECAL modules is reported in Figure 2.10. The detector has a lateral segmentation which takes into account possible variations in hit density up to two orders of magnitude over its surface. The ECAL segmentation is composed of three different sections and a corresponding projective geometry for the SPD and PS detectors is provided, so that their transverse dimensions scale with the distance from the interaction point. The square hole surrounding the beam-pipe limits the inner acceptance to projective polar angles $\theta_{x,y} > 25$ mrad, while the outer dimensions match projectively those of the tracking system. The HCAL, segmented into two zones with different lateral dimensions, uses iron as absorber material and scintillating tiles as active material. These tiles are parallel to the beam axis. Due to space constraints, the detector thickness is limited to 5.6 nuclear interaction lengths (λ_i).

The actual ECAL and HCAL granularity is sufficiently high to operate at the post-upgrade luminosity conditions, therefore both systems (modules, HV system and PMTs) will be kept as they are now. On the contrary, the PS/SPD systems, together with the lead converter, will be removed. The main role of the PS/SPD systems is to provide fast particle identification information to L0 trigger. With the upgrade, L0 will be removed hence the preshower detector can be removed. The ECAL and HCAL Front End (FE) boards will be replaced with new boards able to operate at 40 MHz. To prevent a too fast PMT aging at the post-upgrade luminosity running conditions, their gain will be reduced by a factor 5, increasing the sensitivity of the preamplifiers in the new FE boards accordingly. Radiation damage is affecting and will continue to affect mostly the inner part of the ECAL. The performance of the central ECAL modules should remain satisfactory

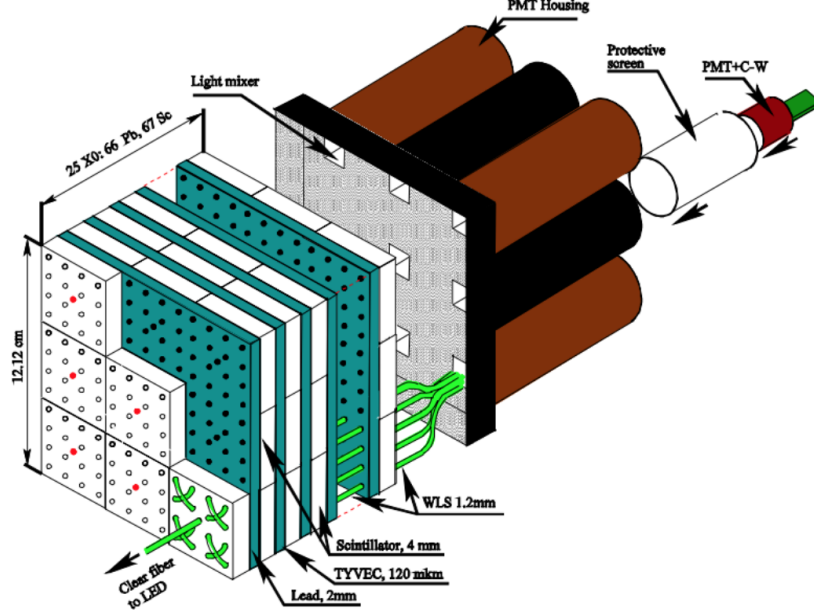


Figure 2.10: The ECAL modules grouping scheme in the current setup.

until $20\text{--}30 \text{ fb}^{-1}$ over the 50 fb^{-1} foreseen for LHCb Run III. A possible replacement of central modules during the LHC long shutdown LS3 of 2022–2023 is under study. HCAL modules will not remain operational until 50 fb^{-1} as well, but unlike ECAL modules they cannot be replaced. This implies that some of the HCAL central cells will lose functionality before the end of Run III. However, HCAL has been crucial to provide high p_T hadron information to L0, which will be removed. For other applications the lower efficiency or the absence of few HCAL central modules will not affect LHCb performances.

2.1.5 The Muon Detector

The muon detection system is responsible for muon identification and provides event selection information to the L0 trigger of the experiment. The system is composed of five rectangular stations (M1–M5): the first station, M1, is placed in the highest rate region and is equipped with triple Gas Electron Multiplier (GEM) detectors; M2–M4 are equipped with Multi Wire Proportional Chambers (MWPC), shown in Figure 2.11 [13]. A total of 1380 chambers are used, for a total area of 435 m^2 . Station M1 is placed in front of the calorimeters and provide information to improve the trigger measurements of p_T . Stations M2 to M5 are installed downstream of the

calorimeters and 80 cm thick iron absorbers are installed between them to select penetrating muons. The minimum momentum for a muon to cross the five regions is approximately 6 GeV/ c . Including the calorimeters, the absorbers total thickness is $20 \lambda_i$. The system with its five stations has a projective geometry. Each station is divided into four regions, R1 to R4, with increasing distance from the beam pipe. The segmentation scale of the regions R1, R2, R3, R4 is in the ratio 1:2:4:8. This geometry is such that the channels occupancy is comparable in each of the four regions of a given station.

The LHCb Muon detector Upgrade operations will mainly consist in the removal of M1, since the increased luminosity in Run III will require a redesign of the readout electronics to be operational with the 40 MHz bunch-crossing rate. Moreover, the front-end board control system will be redesigned to allow very fast detector configuration and monitor operations. Both these new features will solve the obsolescence problem for many of the current electronics components and will guarantee operation reliability during the high-luminosity phase.

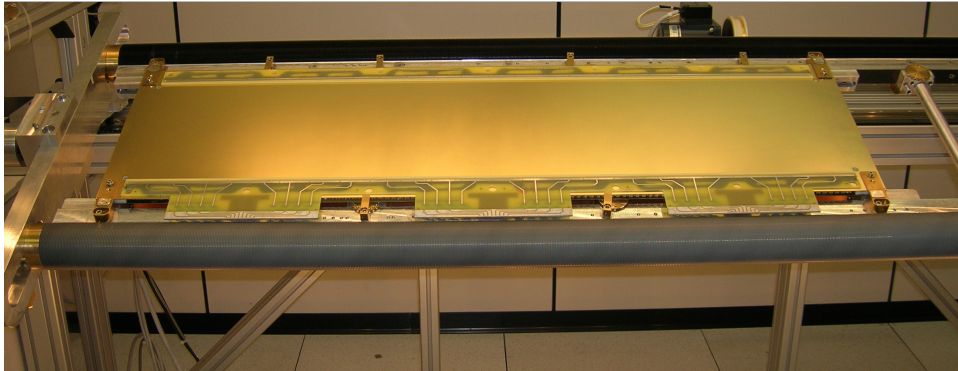


Figure 2.11: One of the LHCb Muon detector MWPC during assembly.

2.1.6 Fixed-target collisions in LHCb

The LHCb System for Measuring Overlap with Gas (SMOG) allows to inject small quantities of noble gases into the LHC vacuum vessel in the region of the LHCb VELO. The gas pressure in this region increases from about 10^{-9} mbar to 10^{-7} mbar. Its original purpose was to measure the trajectories of charged particles produced in the interactions between gas atoms and beam particles and to reconstruct the profiles of the circulating beams for a precise determination of the luminosity. However, collisions of beam protons or heavy ions on gas atoms open the possibility for a unique fixed-target physics program at the LHC collider. Since the start of Run II on 2015, data have been collected for protons colliding on Helium, Neon and Argon atoms at energies of 2.5, 4.0 and 6.5 GeV. Collisions of Lead ions on Neon atoms have been studied as well. The largest data sample, collected in p-Ne collisions at 2.5 GeV in 2017, corresponds to an integrated luminosity of 100 nb^{-1} .

An upgrade of the SMOG system has been proposed with installation foreseen during long shutdown LS2 [14]. A technical proposal [15] has been approved by the LHCb collaboration and it has been presented to the LHC machine committee in January 2019. For the upgrade a 20 cm long accumulation cell will be installed just upstream of the VELO, allowing for up to 100 times larger target densities, resulting in larger data samples. In addition, the density of the injected gas will be controlled with better precision, allowing for a more accurate determination of the luminosity conditions and a consequently more precise measurement of absolute cross sections.

2.1.7 LHCb trigger

The LHCb trigger system is divided into two sub-systems: the L0 and the High Level Trigger (HLT). The L0 trigger receives information from the calorimeter and muon system to reduce the event rate from the bunch-crossing rate of 40 MHz to 1.1 MHz, at which frequency the entire detector is readout. The L0 trigger is hardware implemented, while the HLT is a software application implemented in a farm, called Event Filter Farm (EFF), of around 20k parallel processing CPUs, where the event rate is reduced to around 12.5 kHz. For an efficient use of the resources of the farm, a fraction of the accepted events in the L0 trigger is processed by the HLT on disk during the time between fills.

The L0 trigger consists of three independent units: the L0-Muon trigger, the L0-Calorimeter trigger and the L0-PileUp trigger. The L0-PileUp

trigger is used to determine the luminosity in LHCb. This trigger system, synchronous with the LHC bunch crossing rate of 40 MHz, produces a total output limited to 1.1 MHz, that is the LHCb maximum read out rate possible. The total output rate is the sum of three different contributions: 500 kHz of hadron trigger, 400 kHz of muon triggers and approximately 150 kHz of photon and electron triggers, with an overlap of 10% on the individual triggers. Once the L0 selects an event, that event is transferred to one of the EFF processors. A total of 29,500 instances of the HLT run on the farm, each of them consisting of selection parameters for a specific class of events.

The HLT consists of two levels. The first level is called HLT1 and is a fast track-based trigger that runs online. Its output rate is of approximately 100 kHz and the data are first buffered on local disks then read by the second level trigger, HLT2. HLT2 is able to fully reconstruct the event after the sub-detector systems have been aligned and calibrated. The datasets produced by the LHCb trigger are then almost of the same quality as the ones produced offline. The requirement for this trigger strategy is that the same algorithms have to be used in the online and offline event reconstruction procedures, increasing the need for speed optimization.

The main aim of the LHCb trigger system is to select events in which beauty and charm hadrons are involved over a large range of decay time and momentum. The HLT software design allows for rapid adaptations to changes in running conditions. Inclusive selection criteria can be easily enabled to provide an efficient trigger for any beauty decay to charged particle. In Table 2.1 are reported typical trigger efficiencies for selected signals. For muonic b -decays we have higher efficiency with respect to hadronic b -decays. This is due to the hardware stage, which lowers the efficiency. The software component remains nevertheless efficient. Also, since the momentum spectra of the multi-body charm decays final state particles is softer, the efficiency for these processes is lower than the b -hadron one.

In order to be able to read-out the LHCb experiment at the 40 MHz bunch-crossing rate, the L0 trigger has to be removed during the upgrade [16]. It will be replaced with a software based Low Level Trigger (LLT) which will use limited information from muon and calorimeter systems to select high p_T candidates in the decay of interest. The output rate of LLT will be in the range 15-30 MHz. A fully software based HLT will be responsible for event reconstruction and selection of inclusive and exclusive kinematic and geometry. The HLT will also provide information to perform a run-by-run calibration of the LHCb detectors. Moreover, it will increase the precision in particle identification and will add track quality information to selections.

The HLT data flow output is expected to be 2-10GB/s to be stored.

Channel	L0	HLT1	HLT2
$D^+ \rightarrow K^- \pi^+ \pi^+$	44%	89%	91%
$D^{*+} \rightarrow D^0 \pi^+, D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$	49%	93%	30%
$B^0 \rightarrow K^+ \pi^-$	53%	97%	80%
$B^0 \rightarrow D^+ \pi^-, D^+ \rightarrow K^- \pi^+ \pi^+$	59%	98%	77%
$B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow \mu^+ \mu^-$	89%	92%	87%

Table 2.1: Whole trigger chain efficiencies of selected channels, normalized to the number of offline selected events. The configuration is the one of the 2012.

Chapter 3

Physics at LHCb

The successful operation of the Large Hadron Collider has led to a transformation of the high energy physics landscape [17]. The Higgs boson discovery completes the Standard Model (SM), a self-consistent theory that in principle could be valid up to the Planck scale [18, 19]. Even if the Higgs mass is not foreseen in the SM, particles predicted in theories that address this hierarchy problem, like the supersymmetry, have not been discovered yet. Measurements of the Higgs boson's properties, like its quantum numbers, production and decay modes, are consistent with the SM predictions, validating the model even more. The precision constraints measurements of W boson and top quark parameters like masses and effective weak mixing angle are in agreement with the SM. Studies of CP violation are consistent with the predictions based on the CKM quark mixing matrix, where a sole matter-antimatter asymmetry source is present [20, 21]; lastly, all determinations of the Unitarity Triangle properties fit together within the SM. The Unitarity Triangle is the graphical representation on the complex plane of the unitarity constraints on the off-diagonal terms of the CKM matrix. However, the search for physics beyond the SM has to continue. The hierarchy problem may be resolved in a theoretically way, at an energy scale so high that could not have been probed by any experiment. There is the need to understand the 95% of the Universe energy density that is not ordinary baryonic matter. The matter-antimatter asymmetry cannot be explained in the SM.

The LHCb experiment achieved amazing results during the Run1 (2010-12), continuing its successful operation in Run2 (2015-18), during which the higher cross-sections, thanks to the increased collision center of mass energy, and implementation of innovative online data processing strategies have led

to increases in the data samples to analyze. The flexible data-collection strategies of LHCb have expanded its physics program, for example allowing studies of dark sectors and collecting data from heavy ion and fixed target collisions.

Testing the SM through flavour physics precision measurements is fully complementary to searching for on-shell production of new particles in high energy processes. Beauty and charm hadrons decays and mixing are mediated by weak interaction massive gauge bosons (the W boson mass is about 80 GeV, the B mass is about 5 GeV). Possible unknown particles could contribute so that measured parameters like decay rates and CP violation asymmetries would be different from the SM predictions. The direct search for new particles is carried out in the TeV mass range at the LHC, while the flavour physics measurements can probe much higher mass scales since mixing and CP violation observables in the beauty and charm system probe scales from 10^3 to 10^5 TeV. Processes for which the SM contribution occurs through loop diagrams, that is flavour changing neutral currents (FCNC), are considered golden channels for eventual discoveries of physics beyond the SM. Processes like $B^0 - \bar{B}^0$, $B_s^0 - \bar{B}_s^0$ and $D^0 - \bar{D}^0$ mixing, as well as rare decays like $B \rightarrow \ell\ell$, $B \rightarrow X\ell\ell$ and $B \rightarrow X\gamma$ (where ℓ is a lepton and X is an hadronic system) are good candidates. Several anomalies reported by the LHCb experiment in these type of processes might anticipate a Beyond Standard Model (BSM) discovery. The angular distribution in $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decays is demonstrated to show a deviation from the SM value and branching fractions of $B^0 \rightarrow X\mu^+\mu^-$ decays are consistently below the SM predicted values [22, 23]. Additional contributions, beyond the SM ones, to the operators of the effective field theory might be the explanation for the measured values. Measurements of the branching fractions ratios of $B^0 \rightarrow X\mu^+\mu^-$ and $B^0 \rightarrow Xe^+e^-$ decays are also below the SM predictions.

In the charm sector, one of the most interesting observables is referred to as A_Γ . It quantifies the difference in the inverse effective lifetimes between D^0 and $\bar{D}^0$ decays to CP eigenstates like K^+K^- and $\pi^+\pi^-$, which are singly Cabibbo-suppressed. A nonzero value of A_Γ would be a sign of CP violation in charm mixing, which is expected to be at the $O(10^{-4})$ level, or less, in the SM. Differences between $A_\Gamma(D^0 \rightarrow K^+K^-)$ and $A_\Gamma(D^0 \rightarrow \pi^+\pi^-)$ would indicate time-integrated direct CP violation. An example of indirect CP violation study is the mixing and CP-violation parameters measurement in D^0 - $\bar{D}^0$ oscillations which can be accessed through the comparison of the decay-time-dependent ratio of $D^0 \rightarrow K^+\pi^-$ to $D^0 \rightarrow K^-\pi^+$ rates with its corresponding ratio of the charge-conjugate processes. The study of these

processes will particularly benefit from the excellent PID performances of the post-upgrade RICH detectors and the experiment will reach new world-leading precision in the estimation of the CP violation in charm physics.

The lepton universality might also be violated in charged-current weak interactions: the ratios of the branching fraction of $B \rightarrow X\tau\nu$ relative to that where the τ is replaced by a μ or e lepton is a channel of interest for this phenomenon. Results from LHCb on these modes, in which neutrinos are present, are consistent with those from BaBar and Belle (LHCb is world-leading for the other modes just discussed). A prudent interpretation has to be made since none of these measurements is individually above the 5σ threshold, but the consistency of the results has led to the explicit proposal of several models.

In Table 3.1 a summary of the current and the prospected sensitivities for the LHCb experiment is presented. The expected uncertainties in the "LHCb 2025" column have been calculated considering a total of 300 fb^{-1} of data collected before the start of Long Shutdown 3.

Observable	Current LHCb	LHCb 2025
EW Penguins		
$R_K(1 < q^2 < 6)\text{GeV}^2 c^4$	0.1 [24]	0.025
$R_{K^*}(1 < q^2 < 6)\text{GeV}^2 c^4$	0.1 [25]	0.031
R_ϕ, R_{pK}, R_π	-	0.08, 0.06, 0.18
CKM tests		
γ , with $B_s^0 \rightarrow D_s^+ K^-$	$(^{+17^\circ}_{-22^\circ})$ [26]	4°
γ , all modes	$(^{+5.0^\circ}_{-5.8^\circ})$ [27]	1.5°
$\sin 2\beta$, with $B^0 \rightarrow J/\psi K_s^0$	0.04 [28]	0.011
ϕ_s , with $B_s^0 \rightarrow J/\psi \phi$	49 mrad [29]	14 mrad
ϕ_s , with $B_s^0 \rightarrow D_s^+ D_s^-$	170 mrad [30]	35 mrad
ϕ_s^{sss} , with $B_s^0 \rightarrow \phi \phi$	154 mrad [31]	39 mrad
a_{sl}^s	33×10^{-4} [32]	10×10^{-4}
$ V_{ub} / V_{cb} $	6% [33]	3%
$B_s^0, B^0 \rightarrow \mu^+ \mu^-$		
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) / \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	90% [34]	34%
$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$	22% [34]	8%
$S_{\mu\mu}$	-	-
$b \rightarrow c \ell^- \bar{\nu}_\ell$ LUV studies		
$R(D^*)$	0.026 [35, 36]	0.0072
$R(J/\psi)$	0.24 [37]	0.071
Charm		
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [38]	1.7×10^{-4}
$A_\Gamma(\approx x \sin \phi)$	2.8×10^{-4} [39]	4.3×10^{-5}
$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$	13×10^{-4} [40]	3.2×10^{-4}
$x \sin \phi$ from multibody decays	-	$(K3\pi) 4.0 \times 10^{-5}$

Table 3.1: Summary of measurements sensitivities for LHCb flavour observables in the current and post-upgrade experimental conditions.

Chapter 4

LHCb RICH detectors at LHC

In this chapter the actual LHCb RICH detectors geometry and performances will be presented. An overview of the RICH upgrade will also be presented.

4.1 Cherenkov radiation

In quantum mechanics, a charged particle moving inside a polarizable medium excites the molecules of the medium to higher energy levels. Upon returning back to their ground state, the molecules re-emit photons as electromagnetic radiation. According to the Huygens principle, the emitted electromagnetic waves propagate spherically with a velocity v_p , phase velocity, given by the ratio between the speed of light in the vacuum c and the medium refractive index, n :

$$v_p = \frac{c}{n}. \quad (4.1)$$

If the particle moves with a velocity v greater than c/n , that is v_p , the emitted waves add up constructively leading to a coherent radiation emitted in a cone in the forward direction with respect the direction of motion of the particle. This radiation is called Cherenkov Radiation [41]. The angle of emission θ depends on the refractive index n of the dielectric and to the particle velocity v :

$$\cos\theta = \frac{1}{n\beta}, \quad (4.2)$$

where

$$\beta = \frac{v}{c}. \quad (4.3)$$

Figure 4.1 shows a schematic of the Cherenkov radiation emission process.

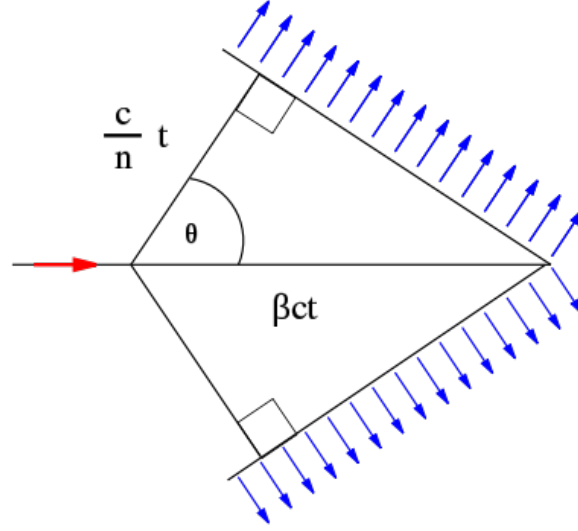


Figure 4.1: Relation between the particle's velocity, the refractive index of the medium and the resulting Cherenkov emission angle.

The refractive index of a medium n is defined as the ratio

$$n = \frac{c}{c_M}, \quad (4.4)$$

where c is the speed of the light in the vacuum and c_M is the speed of the light in that medium. The refractive index is also a function of the energy of the photons traversing the medium, E_γ , or equivalently their wavelength. In Equation (4.3) the dependence on the mass and the momentum of the particle can be made explicit:

$$\beta = \frac{v}{c} = \frac{cp}{E} = \frac{cp}{\sqrt{(cp)^2 + (c^2m)^2}} = \frac{1}{\sqrt{1 + (\frac{cm}{p})^2}}. \quad (4.5)$$

By measuring the Cherenkov angle θ and the momentum p of a particle we can calculate its mass m . In a standard accelerator based experiment p is measured by a magnetic spectrometer using tracking detectors and a magnet. The angle θ is measured by a Cherenkov detector. For a particle traversing the medium, if the condition $\beta = 1/n$ is satisfied, then the limit $\theta = 0$ is reached. This is defined as Cherenkov threshold. The Cherenkov

angle θ , given a fixed refractive index, has a maximum when β is almost 1, that is the ratio m/p is sufficiently small. This implies that particles with a very high momentum originates saturated tracks, the Cherenkov emission angle is a constant for all of them and no identification can be performed.

4.2 LHCb RICH system

In this section are described the current features of the LHCb RICH detectors and the performance.

4.2.1 RICH Detectors at LHCb

A Cherenkov detector is composed of three main components: a radiator medium to produce Cherenkov photons; a system of mirrors/lens to transport photons onto the photon-detectors, usually kept far from the beam pipe; lastly, the photodetector system.

A radiator medium is any medium with a refractive index. Amongst the most popular radiators used there are He, CO₂, silica aerogel, water or glass. It is fundamental to keep in mind that photons with different wavelength/energy experience a different refractive index of the medium. As a consequence, different Cherenkov photons generated by the same charged track can have different Cherenkov angles. This effect is known as Chromatic Error. There are some methods to reduce this effect, like filtering the low wavelength photons before they reach the photodetectors or choosing the right radiator medium. Alternatively, it is possible to measure the photons time of propagation from the point they are created to the photodetectors in order to estimate their wavelength and correct the Cherenkov angle for the Chromatic Error. The majority of the current Cherenkov detectors used in the most important particle physics experiment are sensitive to photons in the visible and part of UV spectrum. The detected photons wavelength λ_{ph} ranges from 135 nm to 800 nm, depending on the photodetectors used in the experiment.

The number of photons produced by a particle with charge Z along a length L can be estimated using the equation

$$N_{prod} = \frac{\alpha}{hc} Z^2 L \int \sin(\theta) dE_{ph}, \quad (4.6)$$

where $\frac{\alpha}{hc} = 370 \text{ eV}^{-1}\text{cm}^{-1}$, $E_{ph} = \frac{hc}{\lambda}$ and θ is the Cherenkov angle [41]. In the LHCb RICH detectors, the Cherenkov photons are produced in a gas

radiator and then reflected by a mirror system onto the photodetector plane separated from the gas enclosure by a quartz window. If the mirror reflectivity is $R(E_{ph})$, the quartz window has a transmission parameter $T(E_{ph})$ and the photodetectors have an efficiency $Q(E_{ph})$, then we obtain the number of photons detected

$$N_{det} = \frac{\alpha}{hc} Z^2 L \int RQT \sin(\theta)^2, dE_{ph} = N_0 L \sin(\theta_c)^2 \quad (4.7)$$

Here we assume θ_c as constant, average Cherenkov angle.

The LHCb RICH system, which is responsible for particle identification (PID) of charged hadrons in the momentum range 2-100 GeV/ c , is an essential tool for the study of hadronic final states and to make precision measurement of CP violation and rare decays of c and b hadrons[42, 43]. The tagging of particle-antiparticle depends on the b and $\bar{b}$ hadrons identification from their decay to charged kaons via the $b \rightarrow c \rightarrow s$ decay chain. This b and $\bar{b}$ hadrons identification is performed at the lower end of the LHCb RICH system momentum range. Also, LHCb RICH proton identification is helpful to the study of heavy-flavour baryonic states.

4.2.2 Particle identification requirements

The main role of the RICH detectors is to identify charged hadrons, like protons(π), kaons (K) or protons (p). In a flavour-physics experiment like LHCb, one of the strongest requirements for charged hadron identification is the reduction of the combinatorial background. Many of the decay modes of interest for LHCb of c and b hadrons involve hadronic multi-body final states where the most abundant produced charged particle is the π . To reduce the combinatorial background, the correct invariant mass of the decaying particles has to be reconstructed.

The PID information for hadrons are of vital importance to distinguish between different final states of decays with identical topology, like the two body hadronic decays $B \rightarrow h^+ h^-$, where h is a charged hadron. This kind of process is studied by LHCb in the context of CP violation. In this type of decay we have several contributions, like $B^0 \rightarrow \pi^+ \pi^-$ or $B_s^0 \rightarrow K^+ K^-$. Reconstructing a process like this using only the kinematic information and the vertex-related cuts would give us a signal which is the sum of all the possible contributions of this type. Therefore, a CP violation measurement for each of the different final states would be impossible unless with a very high statistics available. For a precise and exhaustive study of the CP vi-

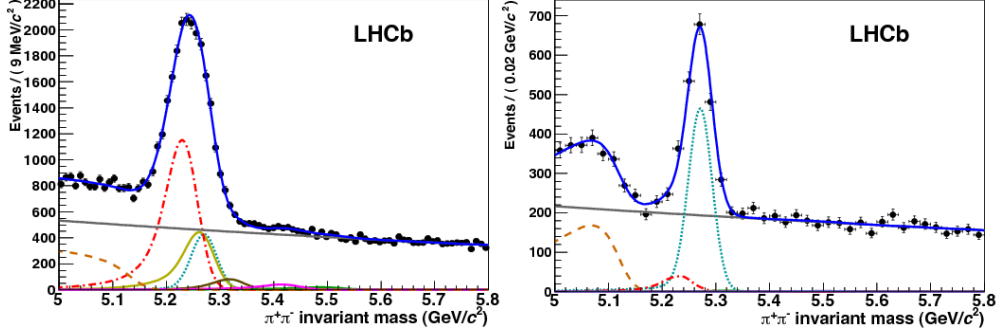


Figure 4.2: Distribution of the invariant mass in the $B \rightarrow h^+h^-$ decays in LHCb before (left) and after (right) applying the RICH PID. The selected signal of interest is the $B^0 \rightarrow \pi^+\pi^-$ decay, the light-blue dotted line, but the total distribution is the sum of all the contributions from other final states: $B^0 \rightarrow 3$ -body decays (orange dashed-dashed line), $B^0 \rightarrow \pi K$ (red dashed-dotted line), $V_s \rightarrow \pi K$ (brown line), $B_s \rightarrow KK$ (yellow line), $\Lambda_b \rightarrow pK$ (purple line) and $\Lambda_b \rightarrow \pi p$ (green line). All these contributions are heavily suppressed once a positive PID is performed, as shown in the right plot, and only the signal and the two more relevant background contributions are left. The solid grey line is the combinatorial background.

olation, the separation and identification of the different decay components is a fundamental requirement for the experiment, and this is achieved by using the highly efficient PID of the RICH. The effect of the PID is shown in Figure 4.2.

The charged hadrons identification is important for the particle flavour tagging of the experiment. In the study of CP asymmetries and in particle-antiparticle oscillation observation, the tag of the particle/antiparticle state which pairs the charged hadron gives us informations on the heavy-flavoured particles in the production state. In most cases, these heavy-flavoured particles are produced in pairs. One of the most efficient methods for the production state tagging is the identification of the charged kaons produced in the $b \rightarrow c \rightarrow s$ cascade decay. These kaons have a soft momentum distribution with an average of 10 GeV/c, therefore PID in a range down to few GeV/c can largely increase the tagging power of an experiment. However, since the typical momentum in a two body B decay is 50 GeV/c, to maintain a high reconstruction efficiency a PID up to at least 100 GeV/c is recommended. The lower momentum limit is 2 GeV/c because the experiment has to be able to identify particles from high multiplicity B decays. In addition,

particles below this momentum will not pass through the dipole magnetic field of the LHCb spectrometer (4 Tm).

4.2.3 RICH design

The actual LHCb RICH system consists of two detector: RICH1 and RICH2 [11]. RICH1 is placed upstream of the LHCb dipole magnet and it covers the full spectrometer angular acceptance of 25-300 mrad. The low angle acceptance limit is given by the size of the beam-pipe upstream the magnet. RICH1 is designed to cover the low-intermediate momentum range, 2-40 GeV/ c . The RICH2 detector is placed downstream of the LHCb dipole and its angular acceptance is 15-120 mrad. Since faster particles have higher probability to produce tracks at lower angles, RICH2 is designed to cover the high momentum range, 15-100 GeV/ c .



Figure 4.3: Picture of the RICH1 gas enclosure containing the flat and spherical mirrors (the interaction point is on the right). Also the beam-pipe crossing the detector is visible.

RICH1 (Figure 4.3) is placed as close as possible to the LHCb interaction region to reduce its physical size. The detector is placed immediately downstream of the VELO and, to minimize the material budget, its gas enclosure is directly sealed to the VELO vacuum tank. The exit window of RICH1 is a low-mass carbon-fibre/foam structure. High momentum tracks are less affected by the magnetic field, therefore RICH2 is placed downstream of the

magnet, right after the tracking system, in order to reduce the material for the charged tracks measurement. The RICH2 entrance and exit windows are foam sandwich constructions similar to the RICH1 exit window, covered with carbon-fibre and aluminum respectively.

The radiator media used in the LHCb RICH detectors are fluorocarbon gases at room temperature and atmospheric pressure: C_4F_{10} in RICH1 and CF_4 in RICH2. In RICH1 a 50 mm thick wall made of 16 tiles of silica aerogel was previously present, used as radiator medium for particles in the low momentum range 1.5-50 GeV/ c and to separate kaons from protons. It was removed after Run I since it has been found to be of reduced effectiveness at high luminosity, preventing the photons produced between the RICH1 entrance window and the aerogel layer to be detected. The refractive index for C_4F_{10} is 1.0012 and for CF_4 is 1.0005, both values measured at 0° , 101.325 kPa and for $\lambda = 400$ nm. A small percentage of CO_2 (5%) is added to the CF_4 to suppress scintillation effects in the gas. The refractive index of aerogel was 1.03 and the light scattering length was around 50 mm at 400 nm in pure N_2 atmosphere. To produce Cherenkov radiation in C_4F_{10} , kaons need to have a minimum momentum of 9.3 GeV/ c . Below this threshold, particles can be correctly identified as kaons and not misidentified as pions only in veto mode, namely by the lack of Cherenkov radiation associated to a track. Before the start of Run II small improvements in the gas radiators composition were implemented. A liquefying stage was added in RICH1 to purify the C_4F_{10} gas during the re-circulation, mainly removing nitrogen, while in RICH2 the CO_2 concentration has been increased to 10% to further reduce scintillation in the gas.

Both LHCb RICH detectors have a similar optical system. The Cherenkov photons are produced inside the radiator gases and then they are focused using tilted spherical mirrors, which project the 3D Cherenkov cone into a 2D ring image that is reflected out of the spectrometer acceptance. A set of secondary plane mirrors reflects again the light to focus the ring image on the photodetectors, located in two planes placed on either side of the beam pipe. The photodetectors are shielded from the residual B -field of the LHCb dipole magnet. RICH1 photodetector planes are placed above and under the beam pipe, while RICH 2 ones are placed on the right and on the left of the beam pipe, as shown in Figure 4.4. The choice for the RICH1 photodetectors placement was driven by the necessity of a more robust magnetic shielding with respect to RICH2 photodetectors, since they are close to the magnet. The RICH1 spherical mirrors consist of four quadrants on a carbon-fibre structure, while the RICH2 spherical mirrors and the flat mir-

rors of both detectors are tiled from smaller mirror elements with a thin glass substrate. RICH1 flat mirrors have 16 segments. RICH2 spherical and flat mirrors have 56 and 40 segments, respectively. The mirrors reflectivity is 90%, where this value is the average reflectivity over the wavelength region of interest (200-600 nm).

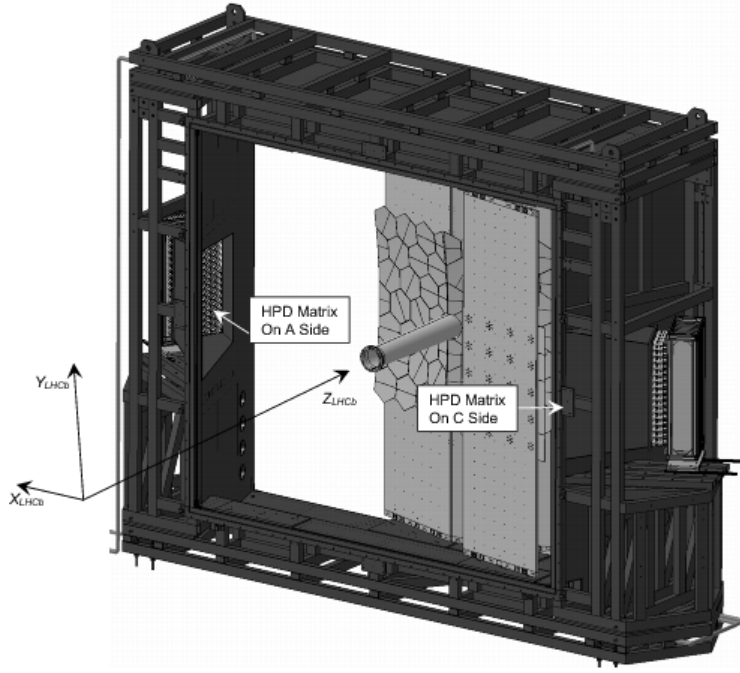


Figure 4.4: A scheme of RICH2 showing the beam pipe in the centre, the spherical mirrors and the HPD planes. One flat mirror has not been drawn to give a view of the HPD plane.

The Cherenkov photon cones produced by charged particles are focused into ring images onto the photodetector planes. A new type of photodetector tube was developed for the LHCb RICH system, in collaboration with industry. Called Hybrid photodetectors (HPDs, Figure 4.5), the devices are equipped with a 75 mm diameter active vacuum tubes, a quartz window and multi-alkali photocathode. Once emitted from the photocathode surface, the photoelectrons are accelerated at the potential difference of -16 kV onto a silicon pixel array, arranged in 32 columns and 32 rows for a total of 1024 pixels per HPD. These pixels cover a surface of $2.5 \text{ mm} \times 2.5 \text{ mm}$ at the photocathode level. A total of 484 HPDs have been installed on the four photodetector planes of the LHCb RICH, with two planes employed in each RICH. A total of 196 tubes are used in RICH1, while in RICH2 288 tubes

are used. A quartz window separate the radiator gas volume from the photodetector planes, and the photodetector regions have a CO_2 atmosphere. The HPD tube encloses the front-end electronics which is bump-bonded to the pixel sensor. This feature results in low electronic noise in the device (150 e^- RMS per pixel for a 5000 e^- signal). The tubes active area fraction is about 82% of the total and their quantum efficiency is 30% at 270 nm.



Figure 4.5: Left: single HPD, the ruler is 10 cm long. Right: Panel of HPDs inside RICH.

4.2.3.1 Calibration and alignment

The photon collection of the LHCb RICH system is maximized by synchronizing the HPD readout electronics with the LHC bunch crossing rate. This synchronization procedure is called *time alignment*. The *time alignment* procedure is not trivial due to the fact that each HPD has to be individually calibrated, since the drift time of the electrons within the silicon sensor is a parameter which varies for each device. The HPD readout electronics receives a trigger, consisting of a strobe pulse of 25 ns, distributed by the LHCb network through optic fibers. The trigger pulse is detected by the RICH system Level-0 (L0) boards, which are responsible for the triggering, the timing and the control of the RICH HPDs. A single L0 board is connected to and drives two HPDs which have been selected and paired because they have a similar timing properties, optimizing the *time alignment* procedure [44]. Three important parameters are defined in the *time alignment* procedure: the *turn-on* point, that is the delay between the optimal HPD readout efficiency and the strobe pulse timing at which we observe a 90%

efficiency of the peak photon collection; the *turn-off* point, that is the delay at which the timing profile drops below 90%; lastly, the midpoint, that is the average delay between these two values.

The LHCb RICH L0 boards global time alignment has been performed both before and during the RICH operations at LHC. The first time alignment has been performed using a pulsed laser in the absence of beam, and this resulted in a partial time alignment of the HPDs. The global time alignment has been performed using pp collisions and the first level trigger L0 of LHCb. In Figure 4.6 the distributions of the midpoints after the on-beam time alignment for RICH1 and RICH2 are reported. The RMS of the HPDs are approximately 1 ns.

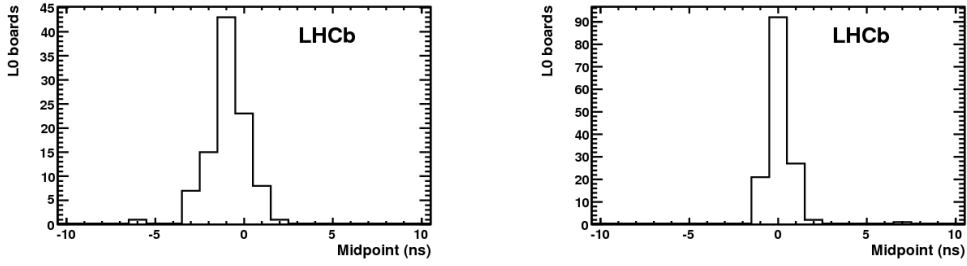


Figure 4.6: RICH1 (left) and RICH2 (right) midpoints distribution after on-beam time alignment procedure.

When a photoelectron is produced at the HPD photocathode, it must travel for 14 cm to reach the silicon anode and be detected. This relatively long path can be affected by the external residual magnetic field generated by the LHCb dipole magnet. To reduce this effect, a 0.8 mm thick cylindrical shield made of Mu-Metal[®] surrounds the tubes, but it is not possible to suppress all of the residual magnetic field. The magnetic field inside the HPDs is reduced from 65 (15) mT in RICH1 (RICH2) to a maximum value of 2.4 mT in RICH1, and 0.2-0.6 mT in RICH2. When the Cherenkov angle θ_{ch} is reconstructed from the photoelectrons hit coordinates on the HPDs sensor silicon matrix, the appropriate corrections are applied to the photoelectrons trajectory to obtain the correct result for θ_{ch} . The optimal θ_{ch} resolution in both RICH1 and RICH2 is achieved using a characterization procedure on the photodetectors to account for the effects of the LHCb dipole magnetic field. This procedure is different for the two detectors since they have different geometries and are affected by two different magnetic field configurations. In RICH1 two identical hardware arrangements, one for each of the HPD planes, have been implemented. Each system consists of an array of green LED mounted on a support covering the width of the HPD

boxes. On this support a total of 19 LED units have been installed, each of which is equipped with an array of 5×28 LEDs placed 2.5 mm apart one from another. The photons produced by each LED are channeled down by an individual collimator unit mounted at the level to the LED array, with aperture of 0.3 mm. The magnetic field distortion effects are then mapped by comparing the LED light spots position in magnet-on condition and magnet-off condition data. Studies on these data have shown that the net effect of the LHCb dipole residual magnetic field on the RICH1 HPDs is a rotation of the image around the central axis of the HPD and an expansion of the image itself. The magnetic distortion effects on the HPDs of the RICH2 detector is evaluated using a commercial light projector as light source to project a grid of light spots onto the HPDs plane. The light spots positions are analyzed using an algorithm that builds a cluster of hits for each HPD and then calculates the centre of the cluster. Using this technique a resolution better than the pixel size is obtained. The magnetic field distortion effects are evaluated by comparing the light spot positions with and without the magnetic field. These distortions mainly consist of small rotation ($\lesssim 0.1$ rad) of the light spots around the HPD axis. The rotation varies from HPD to HPD, depending on the HPD position. After the magnetic distortion evaluation and correction procedures, the resolution for RICH1 HPDs is $\sigma \simeq 0.2$ pixel (0.5 mm) with an irreducible pixel size resolution of 0.29 pixel (0.72 mm). For RICH2 the resolution after the correction is $\sigma \simeq 0.19$ pixel (0.47 mm), with same pixel size resolution as RICH1.

The spatial alignment of the LHCb detectors and their components is essential to correctly reconstruct the Cherenkov angle associated to the individual photons generated in the LHCb RICH system by the charged particles of interest. The resolution required for the components alignment is 0.1 mrad with respect to the LHCb tracking system. The alignment procedure is a sequential process involving several detectors components. First, the RICH system is aligned as a whole with the global LHCb coordinate system. Then each detector half is aligned, followed by each mirror segment. Lastly, all the HPDs are aligned. Aligning the HPDs means aligning their silicon sensors to the whole RICH detector, and to do this is necessary to know the position of the centre of each HPD photocathode on the anode. The silicon sensors alignment procedure is performed by mapping an image of the photocathode, without the need for Cherenkov angle reconstruction. The magnetic distortion corrections are taken into account at this point. After all these steps, the alignment procedure align the RICH detectors, the HPD panels and eventually the 4 (56) spherical and 16 (40) flat mirror segments in RICH

1 (RICH 2) using the reconstructed saturated Cherenkov angle of particles with $\beta \sim 1$. A misalignment of the RICH detector system produces a shift of the track projection points onto the HPDs plane from the centre of the corresponding Cherenkov ring generated in the RICH gas. The shift is calculated from the distribution of the Cherenkov angle, θ_c , as a function of ϕ , the azimuthal Cherenkov angle, defined as the angle of the pixel hit in the HPD panel coordinates system, the origin of which is the charged track projection coordinate. If the RICH system is correctly aligned, θ_c is expected to be independent on ϕ . The distribution of $\Delta\theta_c$ as a function of ϕ is represented in Figure 4.7, where $\Delta\theta_c$ is defined as $\theta_c - \theta_0$, with θ_0 the expected Cherenkov angle calculated using the gas refractive index and the charged track momentum. For each value of ϕ , a one dimensional histogram for $\Delta\theta_c$ is produced and then fitted with a Gaussian plus a polynomial background at second order. The mean value of each of these Gaussian fit for the values of ϕ is used to perform the fit of a sinusoidal distribution on the $\Delta\theta_c$ vs ϕ distribution:

$$\Delta\theta_c = \theta_x \cos(\phi) + \theta_y \sin(\phi), \quad (4.8)$$

where θ_x and θ_y correspond to a misalignment in the x and y direction, respectively, on the RICH HPD detector planes.

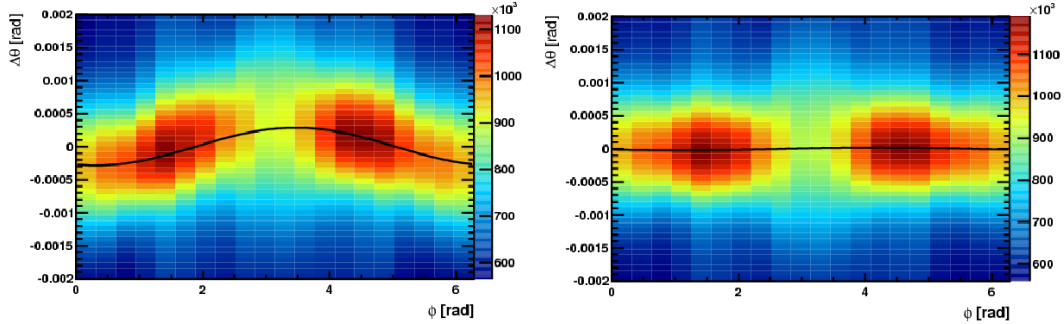


Figure 4.7: $\Delta\theta_c$ versus ϕ for one HPD panel of the RICH2 detector. The left-hand plot is obtained before applying the spatial alignment procedure, and the dependence on $\Delta\theta_c$ from the azimuthal angle is manifest. After the spatial alignment (right-hand plot) $\Delta\theta_c$ is much more uniformly distributed.

Since every photon is reflected by two different mirrors, only the photons which are definitely associated to unique spherical and flat mirror reflective paths combinations are used in the mirror segments alignment procedure. The LHCb RICH Cherenkov photons used in this procedure are the ones

which can be unambiguously associated to a given mirror pair and are emitted at both the start and the end of the gas radiator. If the mirror segments reflecting these photons are the same in both cases, then the photon trajectory is unequivocally identified and used for the mirror segments alignment. The RICH1 mirror arrangement allows for a sequential alignment approach as described above: the spherical mirrors are aligned first, followed by the planar mirrors. The sequential alignment is possible for RICH1 because photons reflected by a particular planar mirror have been reflected by a single spherical mirror. This is not the case of RICH2, in which the large number of spherical and planar mirror segments combinations makes the use of a sequential method impossible. The alignment procedure of the RICH2 mirror segments is performed using a set of equations simultaneously solved in order to extract all the alignment parameters of all the mirrors segments. One iteration of this method is necessary to reach the RICH2 mirrors alignment.

This is not the only monitoring system in the RICH detector. The position stability of the four segment of the spherical mirrors in RICH1 and of 20 of the mirror segments in RICH2 is monitored using laser beams and cameras [45]. To keep the mirrors correctly aligned, each monitored mirror is equipped with a system composed of optic fibers, a lens to focus the beam, a beam splitter, a mirror and a camera. The reference laser beam is directly focused on the camera, while the second laser beam is reflected onto the camera via the monitored mirror. The comparison of the light spots for the two laser beams provides information on any movements of the mirror with respect the correct alignment.

The gas radiator refractive index depends both on the temperature and on the pressure of the gas itself. It can change during the RICH operations and these changes affect the RICH performance. To monitor and calibrate the refractive index at the correct value, high momentum tracks are used to obtain a $\Delta\theta_c$ distribution peaked at zero. The calibration of the refractive index of the aerogel was performed using charged tracks with momentum $p > 10 \text{ GeV}/c$ required to be passing through each tile. It was found not to change as a function of time. The gas radiator purity is monitored by measuring the speed of sound in the gas using a 50 kHz ultrasonic range finder. The gas flow in and out the RICH detectors is monitored with a precision of about 1% for a binary gas mixture. A gas chromatograph is periodically used to obtain precise measurements of the gas purity.

The stability of the LHCb RICH detector Cherenkov angle resolution after all the corrections is depicted in Figure 4.8 . The time range covered

on the x -axis corresponds to about 8 months, hence it can be stated that the detectors exhibit a very stable behaviour.

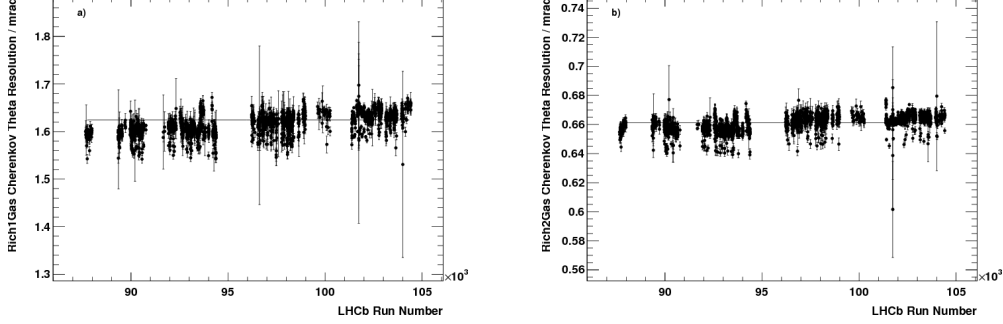


Figure 4.8: Cherenkov angle resolution as a function of run number for RICH1 (left) and RICH2 (right) detectors, after all the corrections have been applied.

4.2.4 RICH performance

In this section the LHCb RICH Data Reconstruction features are presented, together with the Cherenkov angle resolution and photon yield measurements. Lastly, the RICH PID features are reported.

4.2.4.1 Data reconstruction

The LHCb software has been developed using the Gaudi Framework which provides a versatile C++ Object Oriented framework. One of the major advantage of this framework is the flexibility and the configurability, which allow the use of the same software in different RICH applications, from the online monitoring to the use of the RICH in the final stages of the HLT, also providing the full offline event reconstruction. The first step in the data processing chain is the decode of raw data, as they are read out from the RICH system, to offline storage. A list with the HPDs pixels hit for each event is created, but to avoid excessively large events HPDs must have an occupancy lower than 20%. On average the HPDs occupancy is $\sim 1\%$. After this procedure, the photon hit coordinates on the HPD planes are reconstructed and several corrections are applied: the residual magnetic field distortions corrections, the HPDs alignment corrections and the HPDs electrostatic focusing parameters. The trajectory of each charged particle passing through the RICH radiator volumes can be determined using the information on the coordinate of the incoming particles provided by the

tracking systems. Once the particle trajectory is known, a computation of the photons emission points for each track can be performed, but the exact emission point for each photon remains unknown. As approximation, the mid-point of the particle path in the radiator is taken for Cherenkov angle calculations. The eligible candidate photons for each charged track are chosen by combining the measured photon hit positions and their approximated emission points. The Cherenkov angle θ_c and other quantities can be measured using all the previous information. Moreover, a full analytical solution of the RICH optics is used, which reconstructs the photon trajectory through the RICH optical system using the information on HPD and mirror/mirror segments alignment.

4.2.4.2 Cherenkov angle resolution

The resolution on the LHCb RICH Cherenkov angle measurement is obtained by fitting the $\Delta\theta_c$ distribution with a Gaussian function plus a polynomial function which takes into account the background. $\Delta\theta_c$ is calculated for each photon with respect to their measured track. In Figure 4.9 is reported the distribution for RICH2 single photon resolution during the first months of Run2. During Run1 the resolution was measured to be 1.618 ± 0.002 mrad and 0.68 ± 0.02 mrad for C_4F_{10} and CF_4 respectively, in good agreement with the values obtained from simulations of 1.52 ± 0.02 mrad in RICH1 and 0.68 ± 0.01 mrad in RICH2. In Run2 the average value for RICH1 has been determined to be 1.65 mrad and for RICH2 it was 0.67 mrad.

There are several sources of errors which negatively affects the Cherenkov angle resolution that must be taken into consideration. Since the refractive index of the RICH gases depends on the energy of the photons traversing them, a non-negligible spread of the Cherenkov angles measured in the detector will be present. This is called *Chromatic* error. The HPDs silicon sensor is a matrix of pixels with a finite granularity. This limits the detector resolution to the pixel dimensions and introduces an error on the pixel hit position of each photon on the silicon sensors of the HPDs. The net effect is an error on the reconstruction of the photon path in the gas. In addition, when reconstructing the photon track, there can be additional error sources in the reconstructed track parameters which affects the correct identification of the emission point of the photons. The reconstructed Cherenkov angles might be wrongly measured due to aberration in the focusing mirrors and to their tilt, which leads to a distortion of the true focal plane and results in a spread in the Cherenkov angle measurements. Moreover, due to the limited physical space in which the LHCb RICH detectors can operate, the

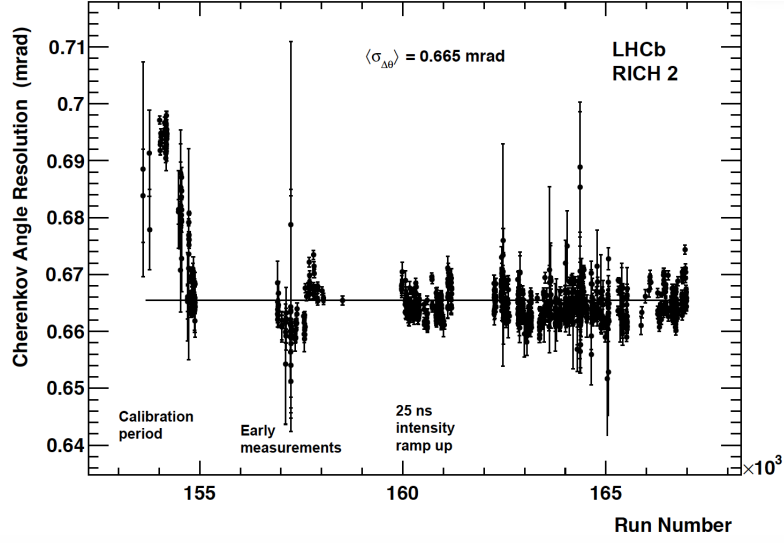


Figure 4.9: RICH2 single photon resolution during summer and early autumn of 2015. Each point is the resolution in one run with a maximum duration of one hour. The horizontal line is the average of all the runs after 155000.

used focal plane may not be the optimal focal plane for the photon reflection, resulting in a Cherenkov angle spread similar to the mirror aberration effect. Lastly, the hypothesis that all the Cherenkov photons are emitted from the mid-point of their track through the gas radiators contributes to the smearing of the reconstructed angle.

4.2.4.3 Photoelectron yield

The HPDs photoelectron yield N_{pe} is measured for two types of events in the LHCb RICH system. A *normal* event is representative of the nominal RICH operating conditions during LHCb data collection, without any requirements. An event is defined *ideal* when it has clean reconstructed tracks, the full Cherenkov ring has been detected and a very low photoelectron backgrounds is present. The *normal* event category does not use the RICH detectors in the selection of charged tracks, but uses an unbiased track sample of pions and kaons coming from the $D^0 \rightarrow \pi^+ K^-$ decays, where the D^0 is selected from the decays of $D^{*+} \rightarrow \pi^+ D^0$. To ensure that all the tracks have an almost saturated Cherenkov angle ($\beta \sim 1$), the tracks must have momenta $p_K > 37$ GeV/ c and $p_\pi > 30$ GeV/ c in the C_4F_{10} , $p_K > 74.8$ GeV/ c and $p_\pi > 40.4$ GeV/ c in the CF_4 , $p_K > 9.8$ GeV/ c and $p_\pi > 5$ GeV/ c in the aerogel. The *ideal* event category is composed of track sample

of muons selected from $pp \rightarrow pp\mu^+\mu^-$ events which are not required to have a visible primary vertex. The momenta of these track must satisfy the same conditions for the pions in the *normal* event category for all the radiators. Selection criteria are applied also on the track geometry, such that at least half of the Cherenkov cone associated to the selected tracks is fully projected onto the HPD panels and on the HPDs pixels. This requirement allows to select tracks for which the Cherenkov cone is not intersecting with the beam pipe and is not projecting outside the HPD acceptance regions and in the gaps between the HPDs.

N_{pe} is measured by fitting the $\Delta\theta_c$ distributions of the Cherenkov photoelectrons. Only photoelectron hits laying within the range $\Delta\theta_c \pm 5\sigma$ are retained, where σ is the total Cherenkov angle resolution. The distribution peak for the correctly associated photoelectrons to a track is around $\Delta\theta_c = 0$, and it is a Gaussian distribution. Other sources like background and tracks which are not of interest result in a non-peaking distribution. The first step to extract the photoelectron yield is to fit the distribution of all the $\Delta\theta_c$ aggregated for all the selected tracks using a probability density function (PDF) which is a combination of a Gaussian signal PDF and a quadratic background PDF. Then the distribution of the $\Delta\theta_c$ for a single track is fitted with a Gaussian signal PDF plus a linear background PDF. The mean value of the Gaussian PDF is fixed at zero, while its width is obtained from the aggregated $\Delta\theta_c$ distribution fit. Finally, the individual track photoelectron yield N_{pe} is determined as the total number of photoelectrons candidate under the Gaussian shape. The overall value of N_{pe} is evaluated as the average value of the N_{pe} per track distribution, and the error associated to this value is the one corresponding to the standard error on the average value. The N_{pe} calculations have been compared to the simulations to test the validity of the photoelectron yield measurement procedure. The samples which have been simulated are $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ decays and the same selection criteria as in the real data samples were applied. Moreover, the *ideal* data events track geometry selection criteria was applied on the simulated data set, obtaining a like-for-like comparison between *ideal* and simulated events. This like-for-like comparison between the true and the measured value of N_{pe} requires a constraint on the maximum number of track hits per event in the Scintillator Pad Detector (SPD), which provides a measurement of the charged track multiplicity of the event itself. The maximum number of allowed hits has been set to 50. In higher track multiplicity events a loss of detected photoelectrons has been observed, since in these events the RICH detectors exhibit a too high HPD occupancy. For example, in events with a number

of charged tracks > 500 , the occupancy is 20% in the RICH1 central region of the HPD panels. In these conditions N_{pe} is lower with respect to lower track multiplicity events because a pixel might be hit by multiple photons in a time shorter than the temporal resolution of the HPDs, hence only the first photoelectron would be detected while the others would be undetected during the dead time of the HPD electronics. This suppression of N_{pe} was not observed using the simulated data, because an analog HPD readout was emulated. The results are shown in Table 4.1. Using the simulated data sets the true and the calculated values of the photoelectron yield are in good agreement, therefore the accuracy of the calculation can be considered validated. The *ideal* events N_{pe} values are smaller than the simulated ones, and the *normal* events show values of N_{pe} smaller than *ideal* ones. This can be explained by the higher charged track multiplicity of the *normal* events which reduces N_{pe} . Also, the geometry cut applied to the *ideal* ones has the net effect to increase their value of N_{pe} .

Radiator	N_{pe} from data		N_{pe} from simulation	
	Tagged $D^0 \rightarrow K^- \pi^+$	$pp \rightarrow pp\mu^+\mu^-$	Calculated N_{pe}	True N_{pe}
C ₄ F ₁₀	20.4 ± 0.1	24.5 ± 0.3	28.3 ± 0.6	29.5 ± 0.5
CF ₄	15.8 ± 0.1	17.6 ± 0.2	22.7 ± 0.6	23.3 ± 0.5
Aerogel (now removed)	5.0 ± 3.0	4.3 ± 0.9	8.0 ± 0.6	6.8 ± 0.3

Table 4.1: Comparison of photoelectron yields determined from simulated data sets and real data sets, both *ideal* and *normal* events.

4.2.4.4 PID performance

The Cherenkov angle information is not sufficient by itself to determine the particle specie for each charged track detected. The track momentum, measured by the tracking system, is necessary to perform the identification of the particle leaving the track. The environment in which the RICH detectors operate is such that the HPDs experience a very high occupancy during the normal RICH operations (see Figure 4.10). To obtain the best reconstruction possible of the events of interest, an overall event log-likelihood algorithm is employed. When using this algorithm, all the tracks which are present in the event considered and in both the LHCb RICH detectors are analyzed simultaneously to obtain an optimal treatment of tracks for which the Cherenkov cones overlap.

The most abundant particles which are produced in the LHC pp collisions are the pions. For this reason the likelihood minimization procedure starts by assuming that all the particles involved in the processes under

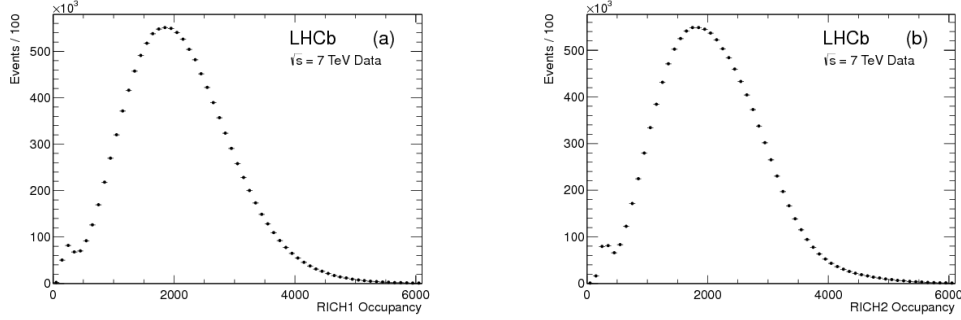


Figure 4.10: Occupancy (pixel hits per event) distribution for the HPDs of RICH1 (left) and of RICH2 (right).

study are pions. For this set of hypotheses the overall event likelihood is then computed with the information about the photon hits distribution, their associated tracks and errors. In the next step the likelihood for each track, one at a time, is recomputed changing the mass hypothesis to e, π, μ, K and p . All the other hypotheses remains the same as in the original hypothesis. The mass hypothesis resulting as the preferred value for a charged track is the one that gives the largest increase in the event likelihood. The procedure is repeated for every track until all the tracks have been set to their preferred value, that is when no further improvement in the likelihood can be found. The procedure performs a number of likelihood calculations which increases exponentially with the number of charged tracks detected. This large load of calculations can be stressful for the CPUs, given the large number of RICH HPD pixels and tracks. To reduce the number of combinations the procedure of minimization is modified. When searching for the track with the largest event likelihood improvement, the tracks are rearranged according to the likelihood change from the previous stage, so that the search in the next step starts with the track most likely to change its hypothesis. If the improvement for the first track likelihood is above a settable threshold, the search is stopped and that track hypothesis is changed. Moreover, when a track shows a clear preference for a mass hypothesis, after its hypothesis has been changed during a step, in the next iteration the track is removed from the procedure. Using these modifications to the likelihood minimization procedure the CPU resources required are largely reduced. The contribution of the background to the total RICH event likelihood is determined by comparing the expected signal for each HPD, which has been built from reconstructed charged tracks and their assigned mass hypotheses, with the detected signal. Any excess in the observed signal is defined as the HPD

background contribution. The entire procedure, that is likelihood minimization and background contribution calculation, can be run multiple times for a single event. However, it has been found that only two iterations of the algorithms are necessary to get convergent results.

Most of the times the LHCb RICH system will detect several Cherenkov rings for a single event and those rings will overlap with each other. There are also events for which a single Cherenkov ring from isolated tracks is detected, and those are an excellent data sample to test the RICH performance and to unequivocally reconstruct the Cherenkov angle. Using information from the C_4F_{10} RICH1 gas radiator in isolated track events ($\sim 2\%$ of the total) we can obtain the Cherenkov angle distribution as a function of the particle momentum, as shown in Figure 4.11. The distribution shows clearly separate bands, one for each type of particle detected, based on its mass.

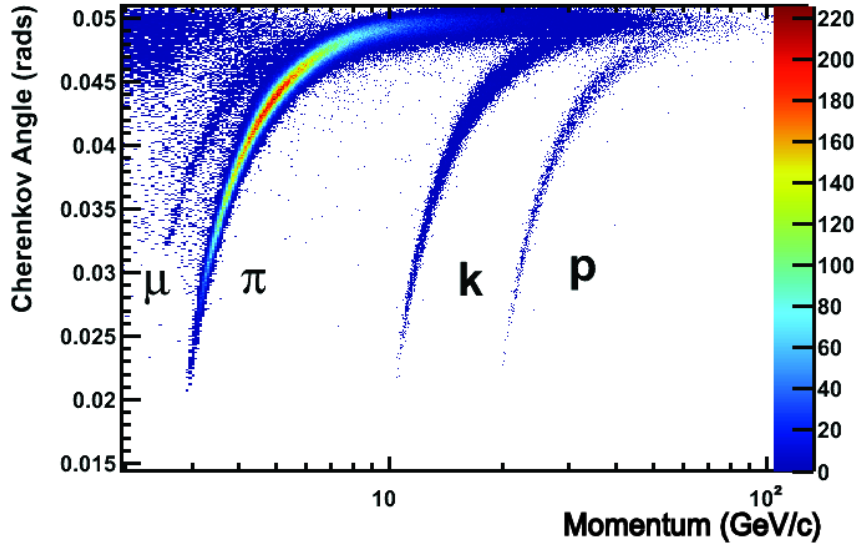


Figure 4.11: Reconstructed Cherenkov angle vs the particle momentum in the C_4F_{10} radiator for RICH1. Although the LHCb RICH detectors are designed to be hadrons detector, thanks to the excellent resolution of the RICH system a distinct muon band can be observed.

The PID calibration of the system is performed using high statistics data samples of pure $K^\pm$, $\pi^\pm$, p and $\bar{p}$ charged tracks. Only the tracks obtained by reconstructing exclusive decays using kinematic selections are retained, without the use of the RICH information in order to avoid a biased result. The decays of interest are: $K_S^0 \rightarrow \pi^+\pi^-$, $D^{*+} \rightarrow D^0(\pi^+K^-)\pi^+$ and

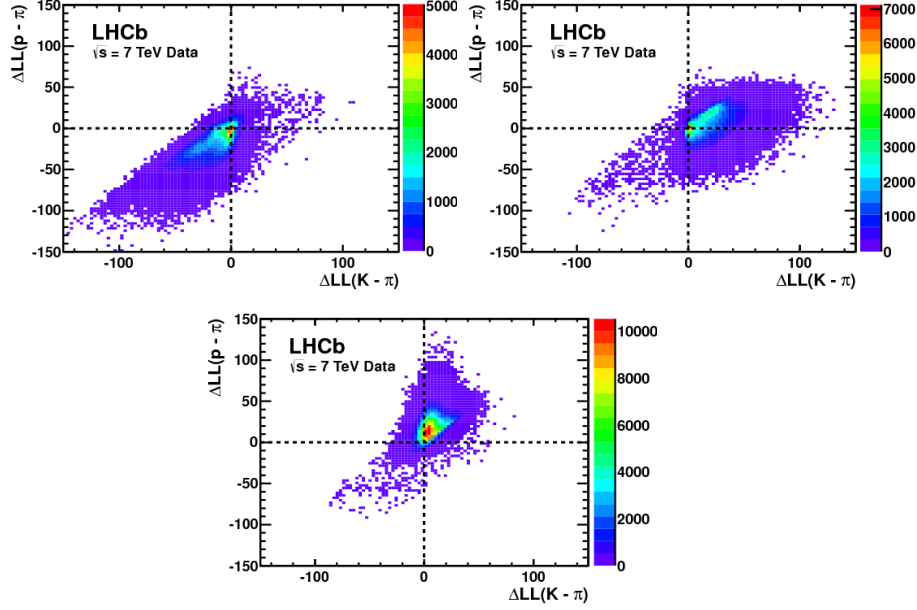


Figure 4.12: $\Delta\log\mathcal{L}(K-\pi)$ vs $\Delta\log\mathcal{L}(p-\pi)$ distribution for kaons (upper-right), pions (upper-left) and protons (bottom).

$\Lambda \rightarrow p\pi^-$. They have been chosen to ensure a set of final states compatible with the assess requirements for the RICH detectors PID calibration. While the high purity data samples can be simply obtained through purely kinematic requirements, the background must still be considered. In this procedure, the separation between signal and background is achieved using a likelihood technique, using the invariant mass of the decaying particles as discriminating variable. In Figure 4.12 the distribution of the total LHCb $\Delta\log\mathcal{L}(K-\pi)$ versus $\Delta\log\mathcal{L}(p-\pi)$ in a 2D plane is reported for the Run I data, in which each particle type is seen within a quadrant of the space. From the log-likelihood values obtained from the PID calibration, it is possible to perform an analysis on the particle misidentification rate in the LHCb RICH detectors.

In Figure 4.13 the rate of kaons identified as kaons, namely the kaon efficiency, is reported together with the pion misidentification rate, that is pions identified as kaons, as a function of particle momentum. The requirement apply is that the total LHCb likelihood for each track with the kaon mass hypothesis has to be larger than that the pion hypothesis, that is $\Delta\log\mathcal{L}(K-\pi) > 0$. Using this requirement we obtain a kaon efficiency and a pion misidentification fraction of 95% and 10% respectively. Using a stricter constraint, that is $\Delta\log\mathcal{L}(K-\pi) > 5$, we can achieve a reduced kaon efficiency fraction of

85% but with a significantly reduced pion misidentification fraction of 3%. In addition to the K/π separation, both p/K and p/π separations in the RICH system are fundamental for a complete and correct analysis at LHCb.

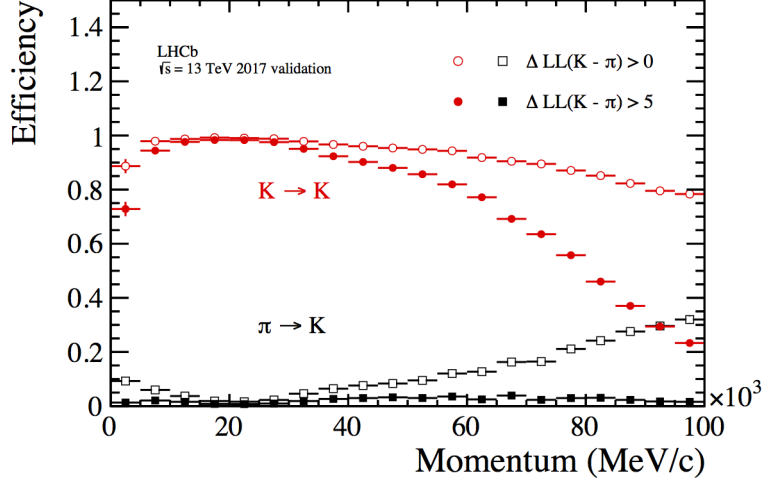


Figure 4.13: Kaon identification efficiency rate and pion misidentification rate measured on real LHCb data samples as a function of the charged tracks momenta. Two different conditions on $\Delta\log\mathcal{L}(K-\pi)$ have been imposed.

To quantify how well the RICH system performs, a comparison between calibration samples and the RICH PID can be performed. The calibration samples consists of pure particle samples of known species which can be obtained from well defined decay topologies without the use of the RICH [46]. In Table 4.2 the decays used in this process are reported.

Species	Low p and p_t	High p and p_t
$\pi^\pm$	$K_s^0 \rightarrow \pi^+\pi^-$	$D^* \rightarrow D^0(K^-\pi^+)\pi^+$
$K^\pm$	$D_s^+ \rightarrow K^+K^-\pi^+$	$D^* \rightarrow D^0(K^-\pi^+)\pi^+$
$p^\pm$	$\Lambda^0 \rightarrow p\pi^-$	$\Lambda^0 \rightarrow p\pi^-, \Lambda_c^+ \rightarrow K^-\pi^+$

Table 4.2: Well defined decay topologies well identified without the RICH system.

4.3 RICH upgrade overview

The LHCb upgrade will allow the experiment to run at the increased operating luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, which is five times the luminosity

kept during Run II. This will be possible only by removing the L0 trigger of the experiment, which reduces the data readout rate to 1 MHz for the full detector readout. After the upgrade and the L0 removal, the LHCb detector will be read out at 40 MHz, that is the LHC bunch crossing rate. To comply with the new operating conditions of luminosity and data readout frequency, most sub-detector electronics will be replaced. A new flexible software trigger will be implemented in the CPU farm and will take the decision on the events selection. As a consequence of the upgrade, the LHCb RICH photodetectors will be replaced, since the actual Hybrid Photodetectors (HPDs) have the 1 MHz read-out electronics embedded in the tube. The HPDs will be replaced with commercial Multi-Anode Photomultiplier tubes (MaPMTs) coupled to external read-out electronics. The chosen baseline tube for the upgrade is the 1-inch Hamamatsu[®] R13742 model from the R11265 series (also referred to as R-type MaPMT) that will be employed in RICH1 and in the highest occupancy regions of RICH2, which are the regions closest to the beam pipe. In the lowest occupancy regions of RICH2 the 2-inches Hamamatsu[®] R13743 model from the R12699 series will be used (also referred to as H-type MaPMT). The most relevant changes for RICH1 during the upgrade are the HPDs substitution and the installation of a new optical system that will increase the Cherenkov rings projection area onto the photodetectors planes and thus reducing the peak occupancy. For RICH 2, the most relevant change is the replacement of the actual photodetectors, together with small mechanical mounting and electronics optimization to comply with the increased luminosity. Alternative geometries for the upgraded RICH system have been studied, like using a single RICH detector with both radiators at the RICH 2 position. This layout could have the advantage to remove the entire RICH1 from the tracking system, reducing the material budget, but this would not give any advantage to the tracking or trigger systems. A modified version of the actual RICH1 detector was designed, with extended vertical size of the vessel obtained by excavating into the LHCb cavern floor. However a modification of the current shielding of the RICH vessel would require extensive studies to ensure that the trigger and the tracker of the experiment are not negatively affected. Hence, the actual two-RICH detectors layout will be retained during the LHCb upgrade [47, 48].

4.3.0.1 Photodetectors

The new LHCb RICH photodetectors must be able to resolve single photons having a wavelength in the range 200-600 nm (from low UV region

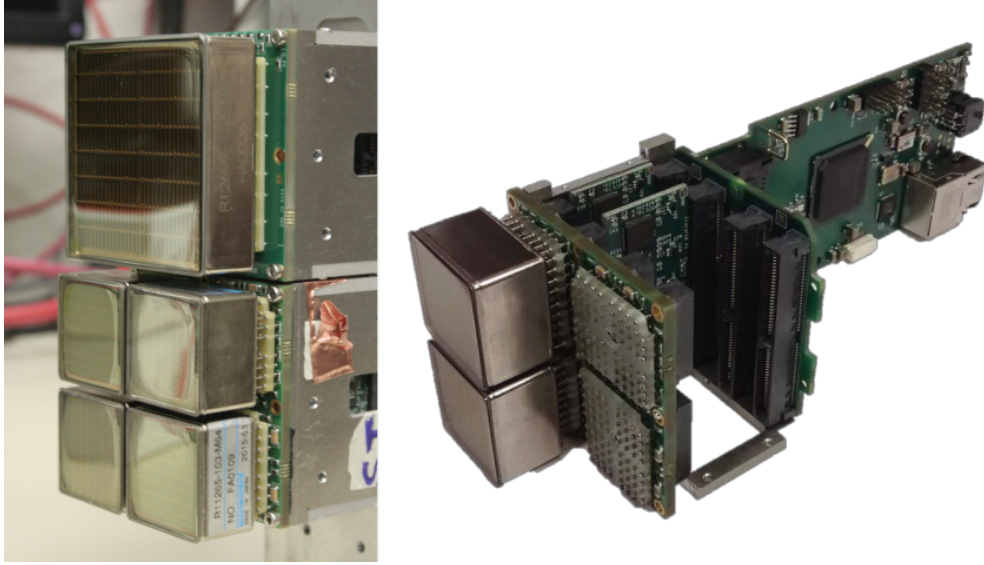


Figure 4.14: Right: the Hamamatsu[®] R13742 MaPMT mounted on a custom 2×2 socket board, specifically designed to be employed on the RICH upgrade, together with the data readout boards. Left: the R13742 and R13743 MaPMTs.

to orange visible region). In the detector regions where HPDs will experience the highest occupancy the pixel size is crucial. It should not exceed $3 \times 3 \text{ mm}^2$ to provide the spatial resolution needed to achieve the expected RICH PID performances. Additional requirements have to be fulfilled by the MaPMTs : they must have negligible cross-talk between neighboring pixels; they must exhibit a negligible dark current with respect to the signal intensity; they must not be affected by a magnetic field of up to 30 mT. The photodetector planes will cover an area of 1.6 m^2 in RICH1 and 2.1 m^2 in RICH2. The total number of MaPMTs required for the LHCb RICH system is 2700 R-type MaPMTs and 400 H-type MaPMTs. In Figure 4.14 is reported a picture of the two type of MaPMTs while in Figure 4.15 the RICH2 upgrade design is reported, where both type of MaPMTs will be employed. A total of 3100 and 450 R-type and H-type MaPMTs respectively have been tested in the dedicated MaPMT Quality Assurance (QA) procedure, in order to have a 12% of the total production as spare components. More details on the MaPMTs are reported in section 5.2.

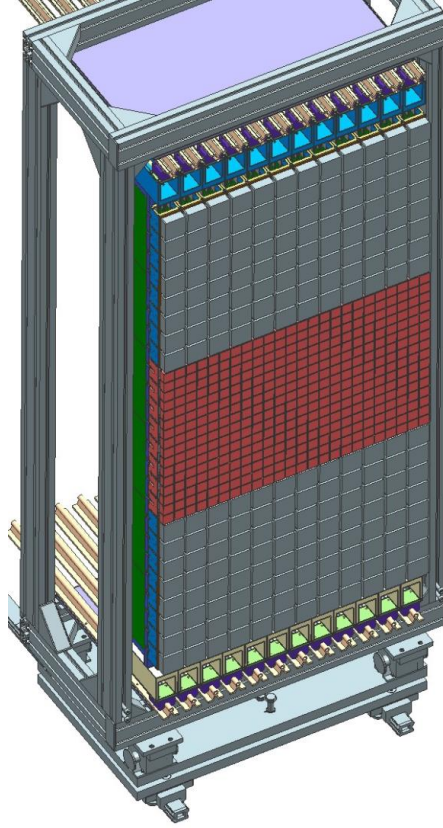


Figure 4.15: Design for the upgraded RICH2 detector, where both R13742 (red) and R13743 (grey) MaPMTs will be employed.

4.3.0.2 Readout electronics

The readout electronics of the RICH Upgrade MaPMT is designed to be conformed to the post-upgrade 40 MHz LHCb electronics architecture. The MaPMT-signal shaping, amplification, digitization and discrimination is performed by a custom ASIC FE chip. The ASIC is called CLARO8, is an 8 channel device where each channel is equipped of an analogue pulse shaper amplifier and a binary discriminator. The choice of a binary read-out technology requires to be possible to adjust the gain variation of the MaPMTs channel by channel. Moreover, a binary read-out is ideal to minimize the off-detector data throughput. A detailed report of the CLARO chip will be given in the next chapter. The CLARO ASICs are mounted on custom ASIC cards, the FEBs, which are plugged into the MaPMT baseboards. The LHCb operating environment is rich of ionizing particles, which may cause disruptive events inside the electronic components and negatively affect the

experiment operations. Therefore it is crucial that the RICH FE electronics is as much radiation tolerant as possible. The CLARO chip radiation hardness tests results will be reported in chapter 6. The signals coming from the MaPMT channels feed into the FEBs and then into the FPGA based digital boards. Each digital board serves four ECs. A schematic of the LHCb RICH Upgrade PDMDB is shown in Figure 4.16. The data will be then formatted for transmission via the giga-bit optical link (GBT) protocol by the four radiation tolerant digital board FPGAs.

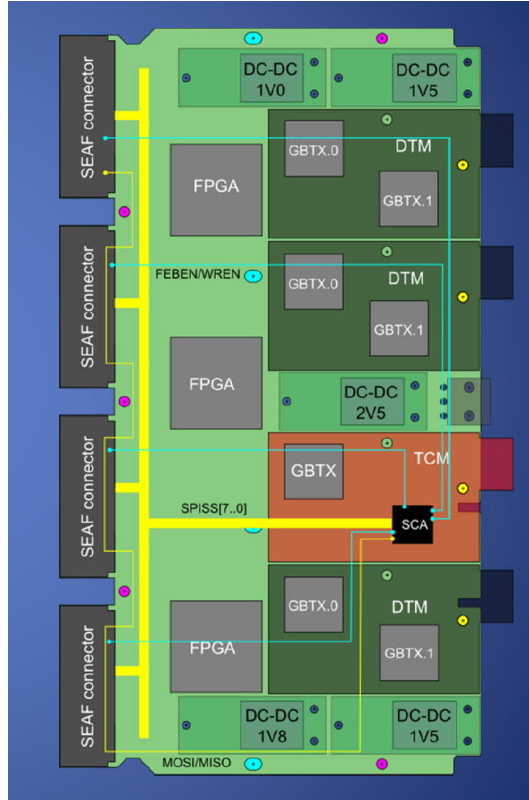


Figure 4.16: The schematic of the RICH Upgrade PDMDB which will read four ECs.

4.3.0.3 Mirrors and alignment

When LHCb will operate at the maximum post-upgrade luminosity conditions, the peak occupancy on the MaPMTs is expected to be over $\sim 30\%$, thus the PID performance will be significantly worsened. During the upgrade, the RICH1 optic system will be re-optimized to reduce the occupancy on the photodetectors planes below the 30% threshold. This will be pos-

sible by replacing the current spherical and plane mirrors and by increasing the radius of curvature of the detector spherical mirrors by $\sim \sqrt{2}$, from 2700 mm to 3800 mm. The RICH1 spherical mirror surface is segmented into four rectangular quadrants, each of them with size 750 mm $\times$ 650 mm. During the upgrade the mirrors will maintain the baseline technology of the current detector. Since the spherical mirrors are within the LHCb angular acceptance range, they will be made of a thin light-weight carbon fibre composite to reduce the material budget. On the other hand, the RICH1 upgrade flat mirrors are outside the LHCb angular acceptance range, therefore no special material budget requirements were imposed during their designing. The actual plane mirrors are made of SIMAX glass¹, and glass flat mirrors will be used also in the upgrade of RICH1. The main properties and parameters of the RICH1 flat and spherical mirrors are reported in Table 4.3, where the current and the foreseen post-upgrade performance are compared.

	Spherical RICH 1 current	Spherical RICH 1 upgrade specs	Flat RICH 1 current	Flat RICH 1 upgrade specs
Dimensions y [mm]	640	650	380.5	440
Dimensions x [mm]	835	750	347.5	370
Area [m ²]	2.1	2.0	2.1	2.6
Radius of curv. [mm]	2710	3800	$>6\times 10^5$	$>6\times 10^5$
Spot-size D^0 [mm]	1.2	<2.5	<2.5	<2.5
Thickness [mm]	33	33	8.0	6.0
Reflectivity	90%	$\geq 90\%$	90%	$\geq 90\%$
χ_0	1.2%	$<2\%$	-	-

Table 4.3: RICH1 mirrors specifications for the current detector and the expected ones after the LHCb upgrade.

4.4 RICH Upgrade Technical design

In this section the optical design and the mechanical changes for the LHCb RICH1 system upgrade is presented, together with a summary of the modifications that will be performed on the RICH2 detector. A description of the technical design of the electronics readout system and data acquisition is also presented.

¹<https://www.kavalier.cz/en/simax-professional/simax-glass.html>

4.4.1 MaPMT modularity and front-end mounting scheme

An equal modular arrangement for the MaPMTs and the FE readout boards will be used for both RICH1 and RICH2. The MaPMTs will be assembled into ECs, consisting either of 2×2 MaPMTs of the R13742 model (R-type EC) or 1×1 for the R13743 model. Four ECs in a line will form a PDM module (Figure 4.17). The MaPMTs of the EC are housed in custom SMD sockets in the PCB Base Board (Bb), where also the high-voltage dividers feeding the MaPMT dynodes and temperature sensors are placed. Inside the Bb copper layers act as dissipators to take out the heat produced by the high-voltage dividers. On its back side the Bb has a connector interface to the CLARO FEBs, each of them housing eight CLARO chips. Four/two FEBs per EC R-type/H-type are employed, which are placed between the Bb and the Backboard (Bkb), a second board which interfaces the FEB output to the FPGA based digital board. The Bb and the Bkb are mounted into a custom machined aluminum case, supported by two perpendicular aluminum plates (backbones) securing the digital board. The mechanical support structure on which the PDM will be mounted will also provide the thermal contact between the ECs and the cooling system. In Section 5.3 more details are provided. The magnetic shield surrounding the photodetector plane will reduce the magnetic field to a maximum value of 0.5 mT in RICH 2, and each elementary cell will be placed into an individual magnetic shield consisting in a square tube, of thickness 1 mm, made of high permeability material. This shield is expected to protrude up to 2.5 cm from the surface of the photocathode window, but they must not introduce a shadowing of the Cherenkov photons.

4.4.2 Upgraded RICH1 optical design

The photodetectors occupancy in the central regions of the RICH1 detectors after the upgrade will be excessively large due to the increased luminosity. Therefore the spherical mirrors will be replaced and their geometry has been modified by increasing the mirrors focal length by a factor $\sim \sqrt{2}$. This modification will halve the occupancy on the photodetector (PD) planes. A schematic of the changes is reported in Figure 4.18. The details are reported in Tables 4.4 and 4.5.

This geometry modification doesn't require an increasing in the area of the PD planes but, since the mirrors focal length is increased, the PD planes must be placed further away from the beam line to avoid a worsening in the Cherenkov angle resolution. This is allowed within the actual physical

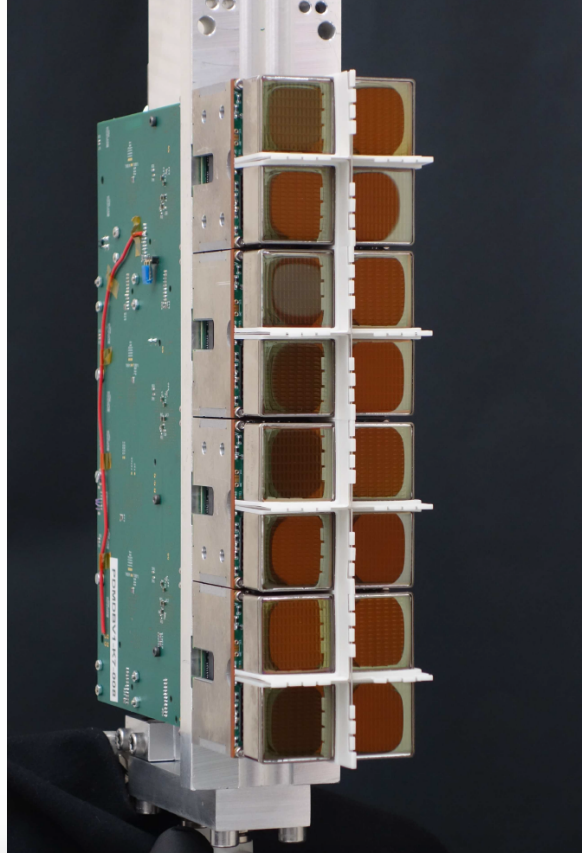


Figure 4.17: A PDM that will be installed in the upgraded RICH detectors, where four R-type ECs can be seen.

constraints of the RICH1 ironing shielding. In addition, the distance between the spherical mirrors and the plane mirrors can be extended in the z direction to increase the path of the tracks in the radiator. As a result more Cherenkov photons will be produced in the radiator and the spherical mirrors tilt will be reduced. All these modifications reduce the optical aberrations effects on the reconstructed Cherenkov angles and reduce the extension needed for the PD plane from the beam line with respect to the actual position. The overall volume of RICH1 will extend in the direction parallel to the beam line, between $z = 985$ mm and $z = 2245$ mm. The gas will occupy the volume between ~ 900 mm $\leq z \leq 2150$ mm, while all the surfaces of the optical system will be limited in z by: 1100 mm $\leq z \leq 2145$ mm. The acceptances however, both vertical and horizontal, will remain equal to the actual ones: 300 mrad horizontal and 250 mrad vertical.

A simplified geometry optics configuration for the new RICH system was

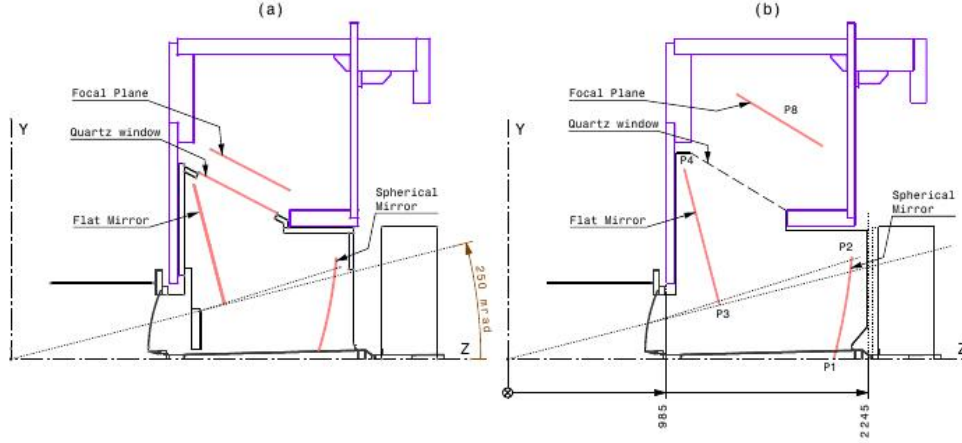


Figure 4.18: RICH1 geometries for the actual (left) and upgraded (right) optical system.

Centre of the spherical mirror	$z = -1640 \text{ mm}$	$y = +978 \text{ mm}$
Point 1	$z = +2032 \text{ mm}$	$y = 0 \text{ mm}$
Point 2	$z = +2145 \text{ mm}$	$y = +640 \text{ mm}$
Point 3	$z = +1320 \text{ mm}$	$y = +337 \text{ mm}$
Point 4	$z = +1100 \text{ mm}$	$y = +1189 \text{ mm}$
Point 8	$z = +1695 \text{ mm}$	$y = +1492 \text{ mm}$

Table 4.4: RICH1 post-upgrade optic parameters. The points P(n) can be seen in Figure /reffigure:mirpoint.

Normal of the plane mirror: angle with respect to the beam line.	14.5°
Normal of the PD plane: angle with respect to the beam line.	58.8°
Axis of the spherical mirror: angle with respect to the beam line.	10.0°
PD-assembly: size in the y - z plane (full geometrical acceptance).	$\approx 630 \text{ mm}$
PD-assembly: x -size (full geometrical acceptance).	$\approx 1380 \text{ mm}$

Table 4.5: RICH1 geometrical data for the PD plane and mirrors after the upgrade.

initially optimized stand-alone using a professional CAD software package

specific for optical applications.² Using this technique the setup performances have been studied and the various contributions to the total error on the Cherenkov angle resolution have been determined. After this stand-alone simulation the upgraded RICH optical layout was used in the full LHCb experiment simulation for a full performance evaluation. It has been shown that a small tilt on the spherical mirrors can minimize the contribution of emission-point error to the reconstructed Cherenkov angle resolution. However the essential condition is that all photons have to be reflected on the plane mirrors, which are located outside the geometrical acceptance of the RICH1 system. The plane mirrors tilt has been set in order to maximize the space behind the PD planes, where the MaPMT electronics and services have to be placed. The available volume behind the PD plane has a depth of 270 mm. Using this layout, the average photon angle of incidence on the PD plane is $(2.50 \pm 0.12)^\circ$ with a median magnification factor of (1.90 ± 0.02) mm/mrad.

4.4.2.1 Single photon Cherenkov angle resolution

In Table 4.6 are reported the three contributions to the reconstructed Cherenkov angle total error for the current RICH1, the upgraded RICH1 and the current RICH2. It can be seen that the three different contributions sum in quadrature, confirming that they are uncorrelated. The RICH upgrade operations are expected to reduce both the emission point error and the pixel size error, while no changes are expected on the chromatic error. This last contribution for the upgraded detector has been evaluated considering the MaPMTs with a borosilicate glass input window. A UV-glass input window for the photodetectors would have increased the number of detected photons by one third, but the error would have been up to 0.84 mrad [11].

	Current RICH 1	Upgraded RICH 1	Current RICH 2
Chromatic error	0.56 mrad	0.56 mrad	0.23 mrad
Pixel Size error	0.62 mrad	0.45 mrad	0.20 mrad
Emission point error	0.54 mrad	0.35 mrad	0.23 mrad
Total error	0.99 mrad	0.80 mrad	0.37 mrad

Table 4.6: Single photon reconstructed Cherenkov angle error contributions for the current RICH1, the current RICH2 and the upgraded RICH1.

²Optica 3, <http://www.opticasoftware.com> and Wolfram Mathematica 9, <http://www.wolfram.com/mathematica>.

Even if the new RICH system will have a better optical design with respect to the actual one, there are errors which are independent from the optical system: the measurement of the particle track and momentum, the photon background, the low-momentum particle tracks. A realistic post-upgrade LHCb particle environment must be accurately simulated to obtain a precise estimation of the true reconstructed Cherenkov angle resolution after the upgrade.

4.4.3 Upgraded RICH1 mechanics

The RICH1 mechanics is constrained by several requirements. The LHC shutdown (LS2) will have a duration limited to 18 months, which is not sufficient to remove and replace the currently used RICH1 magnetic shield nor to excavate concrete in the cavern. This is why the upgraded RICH1 mechanical design has to be compatible with the existing magnetic shield layout. The RICH1 gas enclosure must be extended, due to the increased focal length of the spherical mirrors. The quartz windows which isolates the radiator gas from the MaPMTs will be replaced as well. Moreover, the mirrors mounts will be replaced, together with the photodetector mounting frames and the sealed enclosure which houses the frames inside the magnetic shield.

4.4.3.1 Magnetic shield

The photodetectors are shielded from the LHCb dipole magnetic field by a magnetic shield (which is a box per each PD plane) but since now the PD planes are placed further away from the beam line, both photodetectors and electronic will have a limited space inside the magnetic shield. The magnetic shield boxes are two, placed one above and one below the beam pipe. They will reduce the magnetic field experienced by the MaPMT from 60 mT of the LHCb dipole magnet to about 2.5 mT. The boxes have a main part, mounted on the concrete wall/floor, and two side elements that can be removed for the insertion/extraction of the photodetectors.

4.4.3.2 Gas enclosure

The gas enclosure is required to be light tight and non-magnetic. In addition, it must provide the gas radiator containment and act as a stable platform for the mirrors. The gas pressure will be close to the atmospheric one, but it must withstand pressure differentials of ± 3 mbar without com-

promising the mirror alignment. The current RICH1 enclosure cannot be reused, but the new design will reuse some of its component, retaining most of the original design concepts. The enclosure is a six-sided box, where each face is closed by components with different requirement. The upstream face element must seal the RICH gas and must provide a light seal between the enclosure and the VELO exit window. Moreover, minimal force must be exerted on the VELO and the upstream wall. A direct sealing to the VELO will allow a material budget cut in the particles path. It seems possible to reuse the existing RICH1 seal, based on a stainless-steel bellows structure that allow thermal, pressure and vibration movements without generating significant forces on the RICH or the VELO of the order of ± 10 mm in the longitudinal direction and ± 1 mm in the transverse direction. The bottom and top faces are sealed by quartz windows to allow Cherenkov radiation to pass through and hit the PD planes. New windows have been designed and produced with design and specifications very similar to the existing ones. The downstream face is closed by a low-mass ($0.7\% \chi_0$) exit window, sealed to a fin on the beam pipe. The panel is made of carbon-fibre epoxy skins separated by a 16mm-thick polymethacrylimide (PMI) foam core. The side panels are designed to maximize the access for installation of the internal optical components.

4.4.3.3 Mirrors and mirror supports

Carbon fibre spherical mirrors, with an aluminum (Al) and magnesium fluoride (MgF_2) coating, completely satisfy all the requirements for RICH1 and have been successfully used in the current RICH system for the past years of LHCb operations. A suitable mirror manufacturer for the upgrade, also employed for the existing RICH1 detector, is the CMA company³. The mirror surface is built-up from carbon fibre layers pre-impregnated with cyanate ester resin, which are then placed over a borosilicate (Pyrex) glass mandrel which defines the shape of what will be the mirror reflective surface. The mirrors are then coated with a metallic reflective surface, protected with one or more thin transparent layers. The mirrors reflectivity depends on the coating material. In addition there are interference effects affecting the reflectivity, based on the thickness of the transparent layers. The thickness can be tuned to achieve the best reflectivity for a given wavelength range and photon angle of incidence. For the actual RICH1 spherical mirrors an Al coating coated with a MgF_2 layer was chosen and applied by the SESO

³Composite Mirror Applications, Inc., Tucson, AZ, USA; www.compositemirrors.com.³¹

company⁴. The carbon-fibre mirrors must be radiation tolerant. Prototype RICH1 spherical mirrors for the upgrade have been exposed to 10 kGy of Total Ionizing Dose (TID), approximately the expected dose for the Run III after the LHCb upgrade. However no deterioration of the mirror performances has been observed, as it hasn't been observed in the current RICH mirrors. The optical quality requirements for the RICH1 flat mirrors are similar to the spherical mirrors ones but, since the flat mirrors are installed outside the LHCb acceptance, they can be made from glass. For the RICH1 Upgrade new mirror segments will be manufactured. They will be assembled into two planes, one above and one below the LHC particle beam. Each plane will comprises eight rectangular mirrors with dimensions 370mm×440mm. A 3 mm spacing between each segment will result in a 1.5% loss in coverage. The dimensions of the RICH1 Upgrade flat mirrors will be larger (in the y-direction) than the actual flat mirrors. The flat mirrors will be fabricated using 6.0mm thick glass. For the existing glass mirrors, a coating of Al + SiO₂ + HfO₂ has been chosen for its UV reflectivity. For the RICH1 upgrade, the flat and the spherical mirrors mirror coating will be optimized for the angle of incidence of the Cherenkov photons resulting from the upgraded RICH1 optics and for the MaPMT quantum efficiency.

4.4.4 Upgraded RICH2 optical design and mechanics

The actual RICH2 optical layout is compatible with the expected luminosity after the LHCb upgrade, therefore its superstructure, its mirrors, the magnetic shields, the central tube, the entry, exit and the quartz windows will be retained, but a new mounting structure for the MaPMTs will be needed. The new opto-electronics chain will have to be compatible with the existent mechanical constraints. The RICH2 mirrors are required to maintain their optical performances for at least 20 years after their fabrication. To evaluate the aging effects on the mirrors coated glass specimen have been placed in the RICH2 gas enclosure since the LHC start up, and the most recent data did not show any sign of performances degradation. The 10 and more years of operation for the upgraded RICH2 components will add to the 8 years of operation up to LS2. The components used are polymer based, and are radiation resistant: polymethacrylimide (PMI) foam in the windows, polycarbonate (PC) for the mirror supports, carbon fibre epoxy composites of the central tube and the entry windows and rope-moulded Ethylene-Propylene Diene Monomer (EPDM) rubber for the assembly seal-

⁴Societe Europeenne de Systemes Optiques, Aix-en-Provence, France; www.seso.com.

ing. In addition, an epoxy glue for bounding many structures as the sandwich panels and mirrors support is used. The RICH 2 photodetector planes are 682 mm wide and 1300 mm high. The ECs will be arranged in 12 columns on the photodetector planes, placed side by side. To maintain a high photon detection efficiency, it is essential to minimize the tilt of this arrangement, while assuring the system integrity when maintenance is required. The foreseen clearance between columns will be of 1mm, while the column pitch will be of 56 mm. Each column could host 24 ECs. The support structure of the photodetector will be made of aluminum and anodized in black, with a kinematic system to align the photodetector matrix with respect to the optical system. To avoid any possible condensation on the cooled elements, the MaPMTs will be surrounded by a dry atmosphere of N_2 , with a gas flow of 250 l/h.

4.5 Performances of the LHCb RICH upgrade

The performance of the upgraded LHCb RICH system are simulated using the standard LHCb software framework, which is based on PYTHIA to generate pp collisions with different environmental conditions. The different beam configurations are listed in Table 4.7. The hadronic decays are described by EVTGEN, which also generates the final state radiation using PHOTOS. The toolkit GEANT4 implements the interactions between particles and the detector, together with its response. As defined in table 4.7, "Lumi4" refers to a luminosity of $3.9 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, that is the nominal running condition since 2012. "Lumi10" refers to $10 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and "Lumi20" to $20 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, that is the foreseen Run III luminosity. The studies on the MaPMTs occupancy and on the PID-efficiency are performed using $B_s^0 \rightarrow \phi\phi$ events generated considering the appropriate pile-up interactions. The performance plots include all tracks in the simulated event with a momentum range 1.5-100 GeV/ c and a transverse momentum of about 0.5 GeV/ c , with a polar angle range of 0-300 mrad. For each configuration, at least 210^4 events are simulated and reconstructed.

4.5.1 Simulated data analysis

The simulated Cherenkov photons production is regulated by GEANT4, which also regulates their path through the detector, their reflections and refractions at the optical boundaries and the consequently production of photoelectrons. In the LHCb database all the RICH system upgrade in-

Luminosity condition	Luminosity $\text{cm}^{-2}\text{s}^{-1}$	Number of beam bunches	L_B $\text{cm}^{-2}\text{s}^{-1}$	Beam energy (TeV)	ν
Lumi4	3.9×10^{32}	1300	0.302×10^{30}	4	2.5
Lumi10	10.0×10^{32}	2400	0.417×10^{30}	7	3.8
Lumi20	20.0×10^{32}	2400	0.834×10^{30}	7	7.6

Table 4.7: Parameters of the beam for the LHCb RICH upgrade simulation. L_B is defined as luminosity per bunch crossing and ν is the average number of pp interactions per bunch crossing.

formation about the geometry of the detector are contained, together with the materials and the optical properties of the RICH system components. The simulation and reconstruction program read these information together with information on the current RICH detector specifics, like the gas radiators refractive indices or the mirrors reflectivity parameter. The particle identification (PID) procedure is based on a log-likelihood algorithm which uses, as input, the reconstructed charged tracks from the hits in the tracking detectors and the digitized RICH hits. In the first step of the algorithm the particle is assumed to be a pion. Then, Cherenkov photons are generated following this hypothesis and their trajectories are traced through the RICH system onto the MaPMT planes. These signals are then compared with the GEANT4 generated photon hits and a likelihood function of the event is generated. This process is performed for all the mass hypotheses and the largest global likelihood is finally selected.

4.5.2 RICH upgrade simulation geometry

The overall geometry structure for the upgraded RICH is the same as that of the current system, but several detector components will be changed.

4.5.2.1 Photodetectors

The HPDs will be replaced by R13742 and R13743 Hamamatsu MaPMT models. The magnetic field shielding for the 1" MaPMTs in RICH1 will be provided by a local mu-metal cross installed on each EC. The dimensions of the modules and of the MaPMTs are given in Table 4.8. The MaPMTs detection efficiency is obtained from simulations by considering a super-bialkali photocathode and borosilicate window. In the simulations, the photodetector plane is equipped with MaPMTs to map the RICH system acceptance limit for Cherenkov photons originated from charged tracks and 90% global

MaPMT electronic readout efficiency is imposed.

Parameter	Value
R13742 Anode size	23.0 mm
R13742 Pixel size	2.875 mm
R13743 Anode size	48.5 mm
R13743 Pixel size	6 mm
Number of modules	
RICH 1	132 R-type
RICH 2	48 R-type + 96 H-type
Number of MaPMTs	
RICH 1	1920 R-type
RICH 2	768 R-type + 384 H-type

Table 4.8: Parameters of the R13742 and R13743 MaPMTs used in the simulation.

4.5.2.2 RICH 1 optical arrangement

The optical configuration for the upgraded RICH system has been re-defined and included in the simulations. The details are reported in Table 4.9 [49].

Parameter		Current Optics	Upgraded Optics
Primary mirror	Radius of curvature [mm]	2710	3650
	(x,y) of the centre of curvature [mm]	(841.2, -672.8)	(932.897, -1493.286)
Flat mirror	(y,z) of the horizontal edge near the beam line [mm]	(349.0, 1333.7)	(337.895, 1323.307)
	Tilt angle	250.2 mrad	256.56 mrad
Detector plane	Distance from the origin	1738.1 mm	2065.7 mm
	Tilt angle	480.9 mrad	562 mrad

Table 4.9: Main parameters of the upgraded RICH1 optics used in the simulations. All the tilts are with respect to the vertical y axis.

The overall length of the RICH1 gas enclosure in the beam line direction has been increased by ~ 100 mm towards the actual TT detector, hence the signal Cherenkov photons produced by each charged track has been increased by increasing the path length of the charged particles inside the radiator. The radius of curvature of the RICH1 primary spherical mirrors has been

increased from 2710 mm to 3650 mm and its position has been shifted 90 mm downstream. In addition, their angles of tilt and the flat mirrors position and orientation will be modified accordingly. In the simulation the positions of the iron magnetic shielding and the vertical extent of the RICH1 vessel are left unchanged. Two different configurations are defined: the *current geometry* is the actual LHCb geometry with the only difference of the HPDs replaced by the MaPMTs in the simulations, and the *upgrade geometry* is the upgraded optical configuration described above with the HPDs replaced by the MaPMTs.

4.5.3 Simulation results

In Table 4.10 is shown the Cherenkov photon yield generated by isolated tracks in the current and upgraded RICH detectors. The increased QE of the MaPMTs lead to an increased photon yield with the MaPMTs. In Figure 4.19 the occupancies on the photodetector planes are reported for the upgrade optical geometry of both RICH1 and RICH2 at Lumi20. The peak occupancy in RICH1 is now at 24% in a limited area of the MaPMT planes thanks to the increased curvature radius of the spherical mirrors.

Resolutions [mrad]	Current	Current	Upgraded	Upgraded
	RICH1 (MaPMTs)	RICH1 (HPDs)	RICH1 (R-type MaPMT)	RICH2 (R/H-type MaPMT)
Total resolution	1.12	1.50	0.75	0.42/0.61
Photon yield	32	34	42.4	23.08

Table 4.10: Single photon resolutions and photon yields for isolated tracks from the full simulation in the two RICH detectors with MaPMTs and HPDs.

The PID performance of the LHCb RICH system is defined in term of identification efficiency and misidentification rate, that is the ability of identifying a kaon as a kaon or the probability to identify a true pion as a kaon or another type of particle. These parameters are plotted one versus another for different values of the cut in the log-likelihood difference between kaon and pion mass hypotheses obtained from the PID algorithm. The cut allows to select between highly pure sample of kaons (or pions) at reduced detection efficiency or a highly efficient sample with an increased background. In Figure 4.20 the PID performance is plotted for the upgraded RICH geometry at Lumi20.

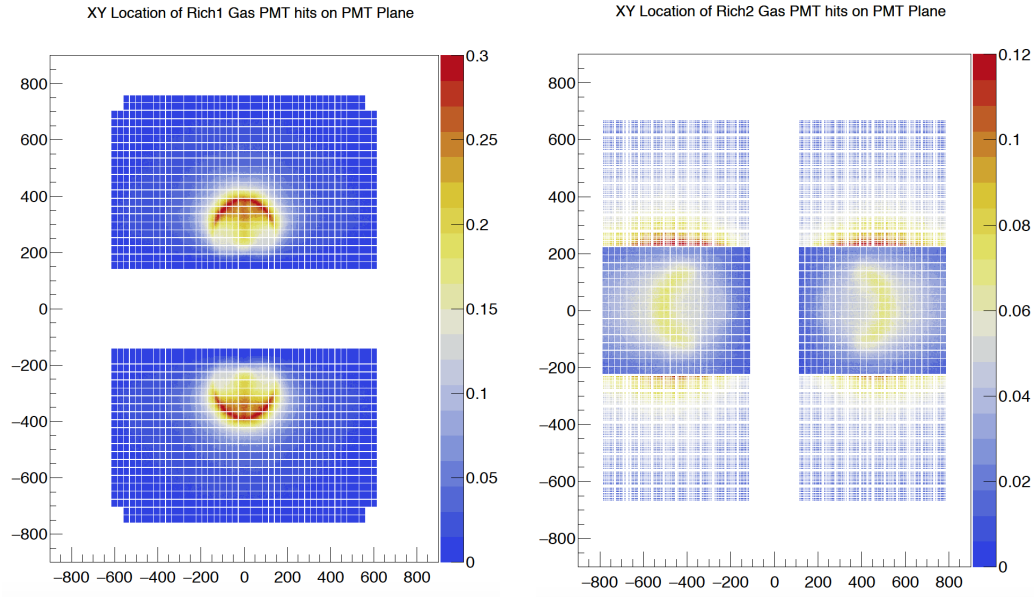


Figure 4.19: Occupancy of the RICH detectors in Lumi20 simulation conditions.

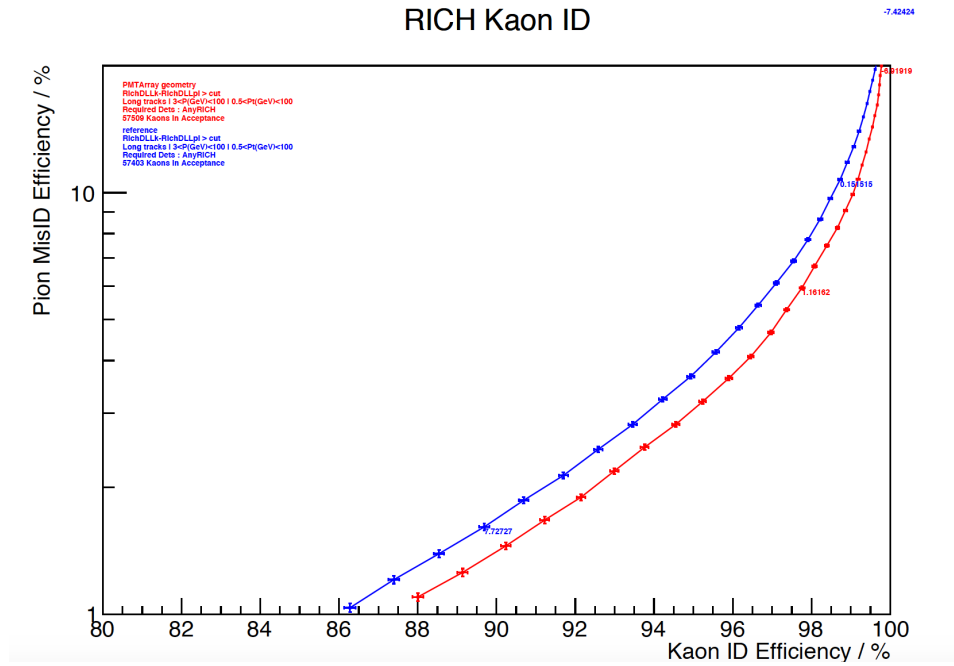


Figure 4.20: The PID performance of the current geometrical setup for Lumi20 conditions (blue) compared to the performance for the upgraded geometry at Lumi20 conditions (red).

Chapter 5

The LHCb RICH Upgrade Elementary Cell

The basic element of the LHCb RICH Upgrade is the EC, a compact structure containing the new photodetectors, the Hamamatsu[®] MaPMTs, and the FE readout electronics. The core of the EC readout chain is the CLARO ASIC. In this chapter a detailed overview of the CLARO, the MaPMTs and the EC are presented.

5.1 The CLARO ASIC

The CLARO is an 8 channel amplifier/discriminator ASIC designed to process input signals from 30 ke^- up to 20 Me^- . Each CLARO channel (a schematic of which is reported in Figure 5.1) is equipped with an analog charge amplifier and a discriminator. The amplifier converts the channel input current pulses into voltage signals, while the discriminator compares the signals at the amplifier output to a programmable threshold. A digital pulse is generated at the output of each channel when the signal exceeds the set threshold [50]. The input impedance of the front-end amplifier was minimized to reduce crosstalk effects amongst channels. The CLARO processes the signals and recovers to baseline in less than 25 ns (typical) - 40 ns (worst case), in order to cope with the expected LHCb RICH signal rate of 10^7 hits/s, with an expected peak occupancy on 27% in RICH1, and to minimize inefficiency and spillover. The RICH Upgrade detectors will be constituted of pixellated planes, where the photon sensors and electronics are close-packed in the ECs to maximize the active area. Hence the CLARO has been designed so that every channel has a power consumption below 1

mW/channel, eliminating the need for additional dedicated cooling. Another requirement for the FE electronics of the upgraded LHCb RICH detectors is to be able to tolerate the expected radiation dose for the post-upgrade LHCb environment. The foreseen radiation levels in the upgraded LHCb environment, at the RICH photodetector planes site, are up to 200 krad (2 kGy) Total Ionizing Dose (TID), which corresponds to $3 \times 10^{12} \text{ cm}^{-2}$ 1-MeV equivalent neutrons, and $1.2 \times 10^{12} \text{ cm}^{-2}$ hadron fluences above 20 MeV (High Energy Hadrons, HEH). These doses are referred to an integrated luminosity of 50 fb^{-1} expected to be collected in about 10 years of operation, including a safety factor of 2 [51].

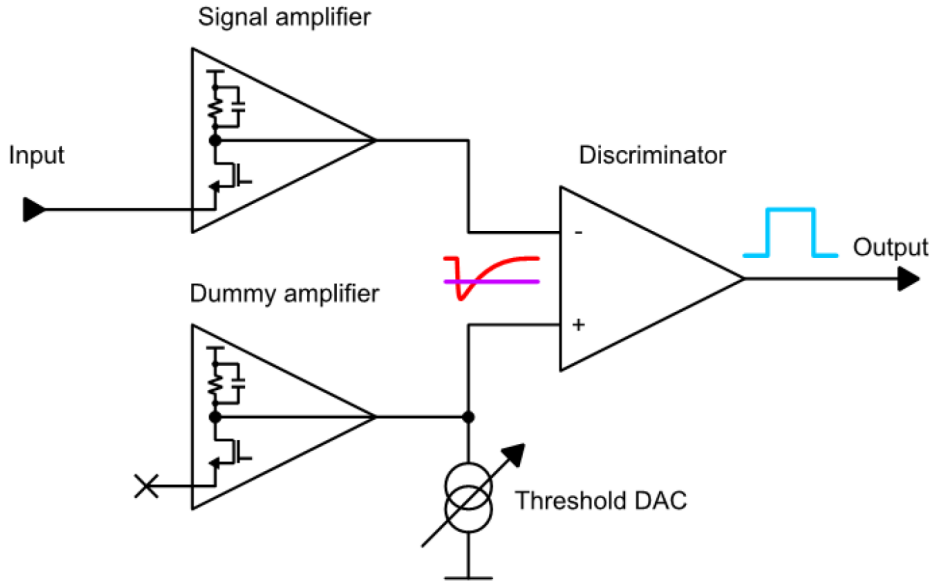


Figure 5.1: Diagram for a CLARO channel.

5.1.1 CLARO technical design

The CLARO has been designed in Austria Micro Systems (AMS) C35B4C3 technology (CMOS 0.35 μm)¹. This technology is available at low cost, with a high yield and high accuracy of simulation models. The critical feature of the technology is its radiation tolerance, which was nevertheless improved by several design techniques in order to satisfy the requirements. The chip and

¹Technology can be accessed by European research institutes through Europractice consortium. Full documentation provided by AMS on their ASIC website (asic.ams.com) with valid access credentials.

multiple power supply rails present on it are designed to operate at +2.5 V. The analog part power supplies (charge amplifier, threshold DAC and Power-On-Reset (POR) block) are named *avdd*, *agnd*. The configuration register dedicated power net is named *dvdd_core*. Disturbances can be generated in the comparators and the output pads. For this reason they are powered with nets (named *dvdd* and *dgnd*) isolated from *avdd* and *agnd*, but the digital nets are used to power the comparators in the analog block. The current drawn by the output pads is dependent on the signal rate and on the output load capacitance. For a load capacitance of 30 pF and a signal rate of 10^7 Hz the current will be 0.75 mA/channel, that is 6 mA/ch, while the comparators draw a bias current < 1 mA/chip in nominal conditions. There are 3 bits intended for the amplifier control: *ena*, *attn0* and *attn1*, whose values are stored in the configuration register. These bits correspond respectively to configuration bits 8, 7, 6 of each channel. The *ena* bit allows the input current pulses to pass to the integrating capacitor, so that the channel can be considered "on". The other two bits regulates the channel gain reductions by a factor $1/2^n$, with n given by the *attn0* and *attn1* bits: $1/2$ (*attn0*=1, *attn1*=0), $1/4$ (*attn0*=0, *attn1*=1) or $1/8$ (*attn0*=1, *attn1*=1). If all the three control bits are 0, then the bias current is cutoff, so that no current is drawn by the amplifier, the input voltage is 0 V and the input impedance is a few kW. If *ena*=0 but *attn0* or *attn1* are 1, the channel is still biased with input voltage = 0.5 V, the input impedance is low, but no signal exits the amplifier. Details on the CLARO channel configuration register are reported in section 5.1.1.1.

The configuration of the CLARO chip is stored in a 128 bit register accessible through a Serial Peripheral Interface (SPI). The register long term storage is protected against Single Event Upsets (SEUs), that is configuration register bit flip, by Triple Modular Redundancy (TMR). In the chip the register is stored in three copies in three different cells installed in different positions on the chip floor. The three register copies are compared to each other and if one of them has experienced a SEU the other two cells can recover the correct register/memory configuration. In the CLARO8v3, the latest version produced (and the one that will be used in the LHCb RICH Upgrade), the configuration/status register has been synthesized using the Radiation Hardened By Design (RHBD) digital cell library developed at the Instituto de Microelectronica de Sevilla IMSE-CNM [52, 53]. This type of cells have been specifically developed for the AMS 0.35um CMOS technology. Their main feature is the increased Linear Energy Transfer (LET) threshold at which an incident ion can trigger an overcurrent event called Single Event

Latchup (SEL) (more details in the next chapter). The use of these cells in place of the standard AMS logic library for the configuration/status register core produced a device able to sustain the expected radiation levels for the operations in the upgraded RICH1 and RICH2 regions of the LHCb experiment. A detailed overview of the irradiation test campaign on the CLARO is reported in the next chapter.

5.1.1.1 CLARO configuration register

In Table 5.1 the 12 bits of each CLARO channel configuration register are reported. The 6-bits threshold ranges from 0 to 63. The 2-bits attenuation reduces the channel gain. The channel enable bit switches the channel on/off (0/1). The hysteresis is a parameter which can be switched on/off with the corresponding bit and activates when the CLARO comparator triggers. If hysteresis is on, an offset of one threshold step ($\sim 30\text{ke}^-$) is summed at the signal amplifier output, as long as that output is high. This procedure is necessary to avoid output oscillations in channel with a threshold set too close to the baseline. The test pulse bit enable the injection of charge from the internal capacitors to perform characterization tests (see section 5.1.2.1). Lastly, the offset bit, when high, enables a shift of the CLARO channel thresholds by -32, allowing to access negative threshold values. This feature is used in the test reported in section 5.1.2.2.

Bit Position	Name	Type
11	Offset	R/W
10	Test Pulse Disable	R/W
9	Hysteresis On	R/W
8	Channel Enable	R/W
7:6	Attenuation	R/W
5:0	Threshold	R/W

Table 5.1: Configuration bits for each CLARO channel.

5.1.2 CLARO characterization

Two main tests are performed on the CLARO to characterize its performances: the S-Curve and the Threshold Scan tests. The S-Curve test is used to check the linear response of the channels to an input signal when changing the channel threshold. The Threshold Scan is used to evaluate

the threshold to be applied to each channel to achieve the best noise/signal discrimination.

5.1.2.1 The S-Curve test

In this test a train of n pulses with equal amplitude is sent to each of the CLARO channels input and the number of times the channels have been switched on (1 as output) is registered, then the signal amplitude is increased. The MaPMTs are not needed in this test, the signal is injected directly in the CLARO channels. Ideally we would obtain a step distribution, but because of the electronic noise the real distribution is s-shaped.

Two important parameters are obtained from this distribution. The transition point is defined as the x-coordinate (i.e. the number of electrons injected at the CLARO channel input) at which the S-Curve distribution reach half of its maximum height. It is more convenient to normalize the distribution to n , the number of pulses per step sent to the channel input during the test, so that the transition point becomes the x-coordinate at which the distribution reaches 0.5. The spread (or noise, or σ) of the distribution is defined as the width of the curve slope. Both of these parameters can be obtained by fitting the s-curve distribution with a translated Error Function (ERF). The ERF equation is defined as:

$$\text{ERF}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt, \quad (5.1)$$

while the translated ERF equation used to fit the distributions in the CLARO the S-Curve tests is:

$$f_{S-Curve}(x) = \frac{1}{2} [\text{ERF}(\frac{x - \text{TP}}{\sigma}) + 1]. \quad (5.2)$$

In Equation (5.2) TP is the transition point (x-coordinate) and σ is the slope of the distribution. An example of S-Curve with fit results can be seen in Figure 5.2, where the number of times the channel has switched on per each step vs the step signal amplitude is reported. The distribution has been normalized to the maximum number of pulses sent per step. The errors per each point correspond to 0.05, that is 5% of the maximum amplitude reached by the S-Curve. The reduced Chi-squared is very small and this might be due to an overestimation of the errors per point. However, the ultimate goal of the S-Curve test analysis is to obtain the distribution Transition Point using a fit, which can easily fail to converge. The large errors allow the fit to converge easily and make possible to correctly evaluate the transition point

for all the channels, since the use of different magnitude errors would not change the Transition Point value. Alternatively, the transition point can be evaluated with the Pattern Recognition method. This method will be discussed in the Test-Beam chapter.

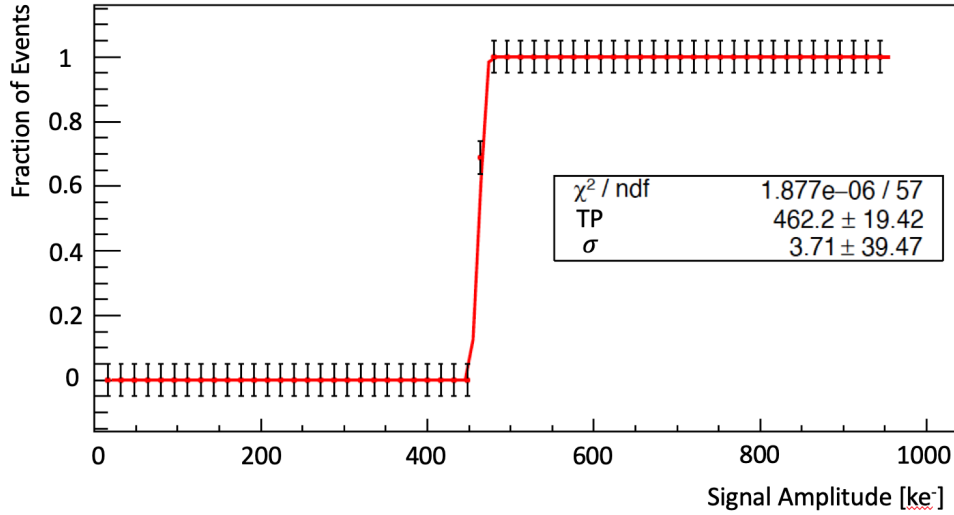


Figure 5.2: Example of S-Curve test for a CLARO channel. The parameters of interested are obtained by fitting the curve.

5.1.2.2 The Threshold Scan test

This test is performed with the MaPMTs powered on and an LED is used as signal source for the CLARO channels. While in the S-Curve the channel threshold was kept constant and the signal intensity was increased, in the Threshold Scan the signal coming from the MaPMTs is constant in amplitude but the channel threshold changes during the test. Starting at threshold 63, that is the maximum applicable threshold, the Data Acquisition (DAQ) system waits until a fixed number of triggers has been registered, then the threshold is decreased by one. This procedure is repeated until threshold 0 is reached. The obtained distribution is reported in Figure 5.3 and correspond to the integral distribution of the single photoelectron spectrum. The parameter of interest is the threshold at which correspond the rightmost edge of the pedestal. That is defined as the Working Point (WP) of the channel, since it correspond to the minimum between the pedestal and the first single photoelectron peak. If the channel threshold is set to the WP value the best discrimination between noise and signal is achieved. To be sure to cut-off all the electronic noise, it is better to set the WP a few (usually 5) threshold

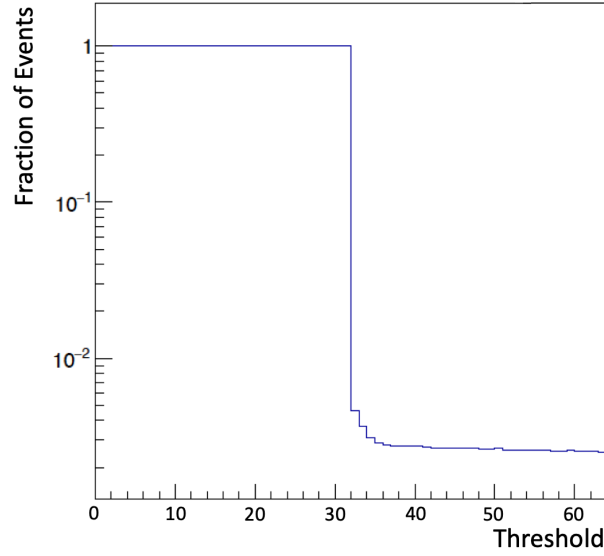


Figure 5.3: Threshold Scan distribution with for a CLARO channel having the Offsetbit set to 1. For this particular channel the edge of the pedestal correspond to threshold 32.

steps higher with respect to the pedestal edge. Few percentage of the signal is discriminated but almost all the noise is suppressed. Most of the CLARO channels don't exhibit the pedestal, even at threshold 0, if the Offset bit is not high. By setting this bit to 1 the channel threshold is shifted by -32. At this point the electronic pedestal is manifest in every channel when performing a Threshold Scan and the working point can be set correctly for all the channels.

5.1.3 The Front-End Board

The CLARO chip is the key component of the EC. A total of 8 CLAROs is needed to readout a single 64-channels MaPMT, and these 8 CLAROs are accommodated on the FEB. In Figure 5.4 the EC backboard (Bkb) of an R-Type EC is shown with three FEBs. On the FEB side there are four CLAROs, the other four are installed on the other side. On the FEBs a QR code is visible on the uppermost CLARO. The QR code is necessary for the FEB ID and to fast retrieve information on the FEB.

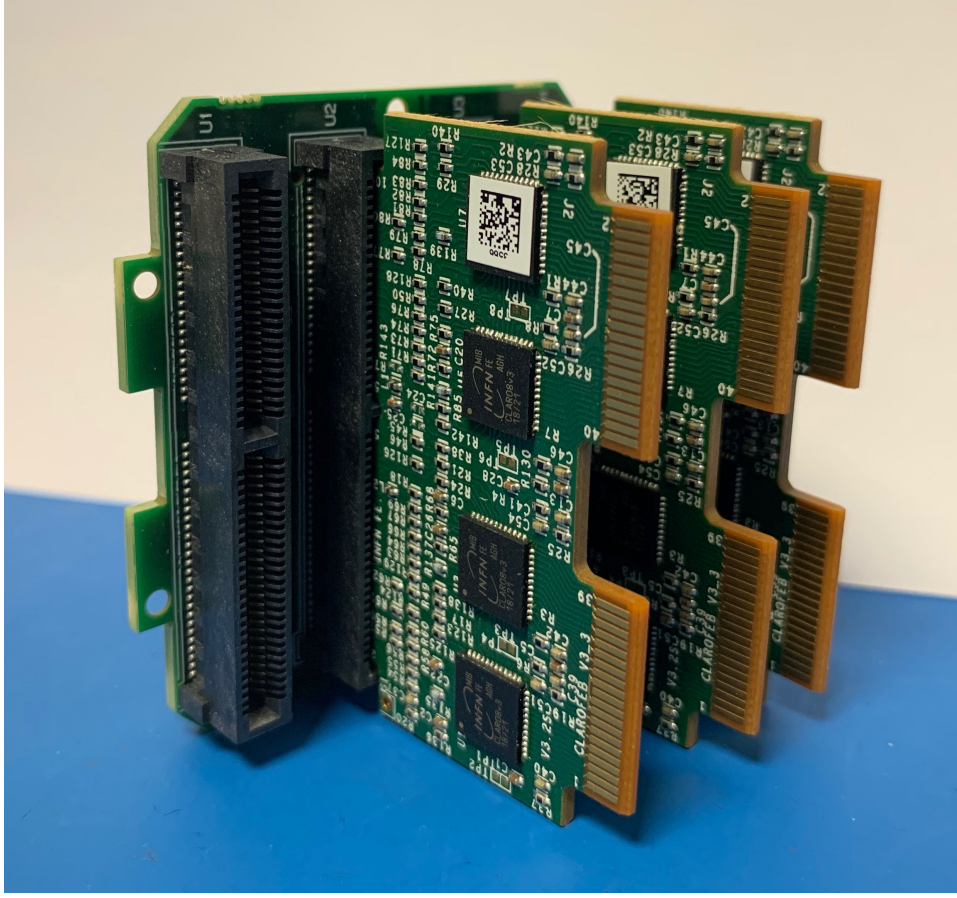


Figure 5.4: An R-Type EC backboard with three out of four FEB mounted on it. The FEB QR codes are visible on their top side. The socket for the FEB is clearly visible on the left-hand side of the picture.

5.2 Multi-anode PhotoMultiplier Tube

The baseline MaPMT used in the RICH upgrade is the R13742 MaPMT from Hamamatsu[®]. It is a 26.2 mm square device, with a 8×8 silicon pixel matrix and with an 0.8 mm thick UV/borosilicate entrance window. It is equipped with a SBA/UBA (super/ultra bi-alkali) photo-cathode and a tube with 12 stages of dynodes. Each device has a geometrical acceptance of 77%, with an active area for photon detection of $23 \times 23 \text{ mm}^2$. The standard MaPMT gain at 1 kV operating voltage is $10^6 e^-$, optimized for single photon detection². The photo-electron collection efficiency rate is 90% at the first dynode stage. The MaPMTs will be plugged into a 2×2 Bb to form the

²https://www.hamamatsu.com/resources/pdf/etd/R11265U_H11934_TPMH1336E.pdf

fundamental components of the RICH upgrade, the ECs. In the outer regions of RICH2, where the occupancy is lower with respect to RICH1 or the innermost regions of RICH2, the MaPMT model R13743 will be installed. Its active area is of $48.5 \times 48.5 \text{ mm}^2$ and, like the R13742 model, it has 8×8 silicon pixel matrix with a pixel size of $6 \times 6 \text{ mm}^2$. The photon entrance window is made of borosilicate glass, while the photocathode is made of a bialkali material. The R13743 tube has 10 stages of dynodes. The typical gain for the H-type MaPMT is of the order of $10^6 e^-$ at the operative voltage of 1 kV^3 . The MaPMTs will detect and convert single photons into charge signals of approximately 1 Me^- in 1 ns . The MaPMT gain is dependent on the bias voltage, ranging from 900 to 1100 V. A gain spread of 1:3 is tolerated between pixels of the same device. Additionally, a gain spread of 1:3 is also expected between different MaPMTs. This parameter can be compensated by adjusting the device voltage bias. On Figure 5.5 the two MaPMTs type used in the upgrade are shown.

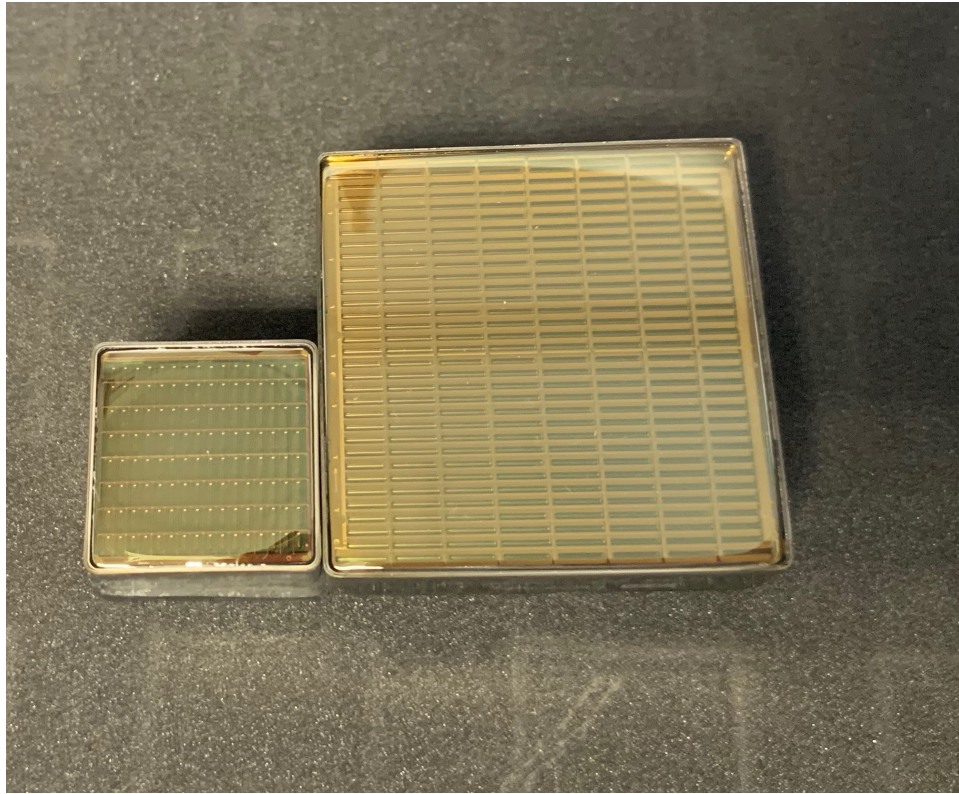


Figure 5.5: An R-Type MaPMT (left) next to an H-type MaPMT (right).

³https://www.hamamatsu.com/resources/pdf/etd/H12700_TPMH1348E.pdf

5.3 The Elementary Cell

The EC is the fundamental module in which the photodetectors and the readout electronics of the LHCb RICH Upgrade will be grouped. Based on the MaPMT type which is installed in the EC, the cell is named R- or H-type EC. Four/one R/H-type MaPMTs are installed on the custom frontal board of the EC, the Bb. The Bb has four/one socket to house the MaPMTs and interfaces the photodetectors with the CLARO ASIC. Also, it feeds the high voltage tension to the MaPMTs. The CLARO readout chip is installed in the FEBs, four FEBs for the R-type EC and two for the H-type EC. Even if the H-type EC has only one MaPMT, that is 64 channels, which could be readout by a single FEB, two half-FEBs are used instead. The unused CLARO channels have a 1 nF capacitance to ground at their output to suppress any possible signal at the CLARO outputs. At the back of the EC a third electronic board type is present, the Bkb, which connect the CLARO outputs at the FPGA-based digital boards. The R-type ECs in RICH1 will be equipped with a cross-shaped Mu-Metal[®] module, as shown in Figure 5.6, to reduce the intensity of the LHCb dipole residual magnetic field on the MaPMTs. The expected residual magnetic field intensity is 25 G in RICH1 and 5G in RICH2 ($1\text{G} = 10^{-4}\text{ T}$). The MaPMTs edge pixels experience an efficiency degradation of 50% at 30G. Using this kind of magnetic shield will allow a full efficiency recovery in the central pixels and a recovery $>85\%$ in the worst cases for pixels at the MaPMT edge. An aluminum case of cuboid shape contains the FEBs and act as a support for the Bb and the Bkb to be installed on. A picture of a disassembled EC is reported in Figure 5.7, while the assembled EC is shown in Figure 5.8.

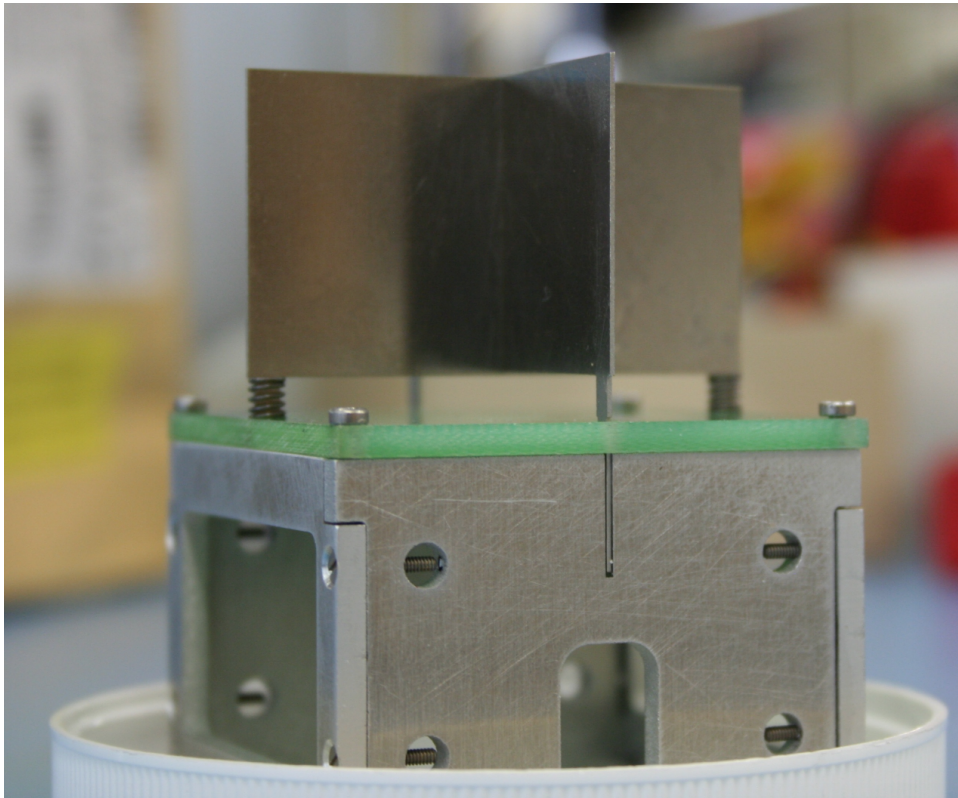


Figure 5.6: The Mu-Metal[®] magnetic shield installed in a R-type EC. The MaPMTs are not present.

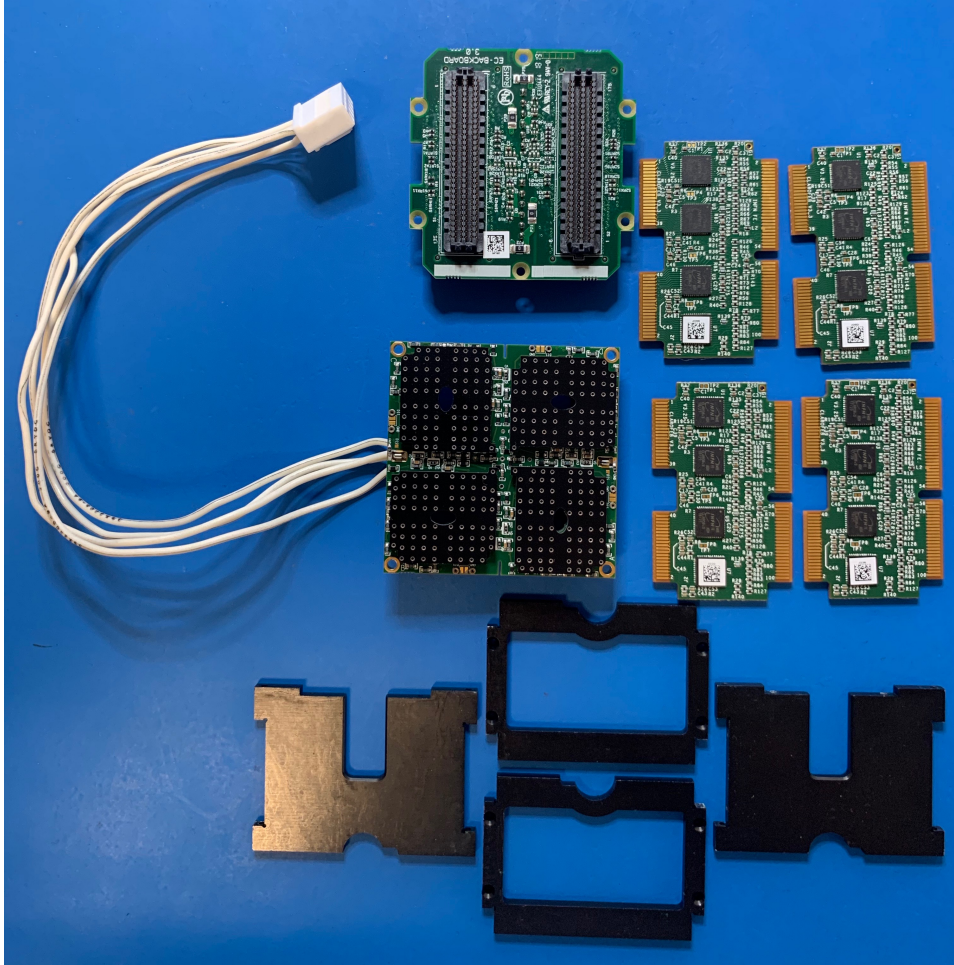


Figure 5.7: Components of an R-type EC. On the bottom side of the picture the four pieces of the aluminum case are present. On the right are the four FEBs, while on the top left is the back side of the Bkb (that connects to the digital board) and on bottom left the Bb with the four MaPMTs black socket.

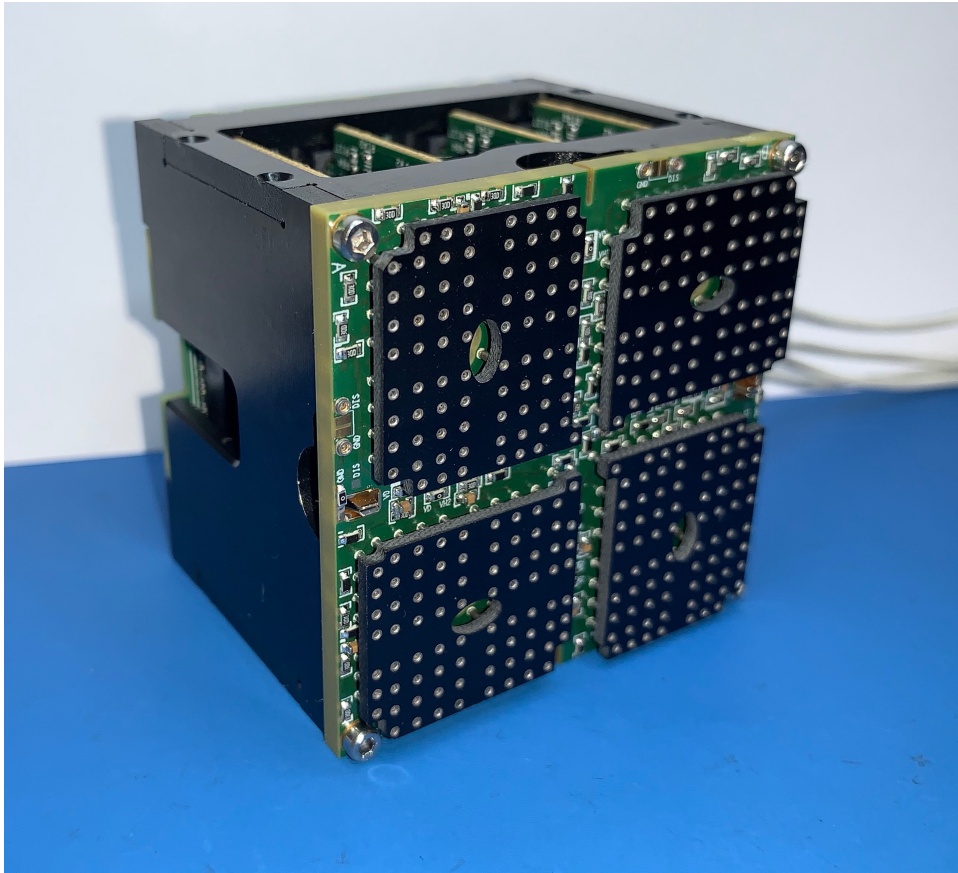


Figure 5.8: An R-Type EC completely assembled. Three of the four FEBs are visible on the top part of the EC.

Chapter 6

Irradiation tests on the CLARO ASIC

According to simulations for the LHCb RICH Upgrade environment, the worst-case value for the RICH1 photodetector region total ionising dose (TID) is 2 kGy (200 krad), corresponding to a neutron fluence of 3×10^{12} 1 MeV n_{eq}/cm^2 , and a High Energy Hadrons (HEH) fluence (defined as the time-integrated flux of hadrons above 20 MeV[54, 55]) of $1.2 \times 10^{12} \text{ cm}^2$. For this reason the CLARO chip has to be proven able to correctly operate when a high level of radiation is present. The chip has been tested using ions, protons and a mixed field in several facilities. In this chapter, first an overview of the radiation effects on electronic devices is presented. Then the CLARO irradiation tests and the tests results are presented.

6.1 Radiation effects on electronic devices

A single charged particle traversing an electronic device can create a shower of thousands of electrons, consequently causing electronic noise and signal spikes in the device. These effects have to be taken into account in the design of satellites and spacecraft (exposed to the space radiation without the atmosphere shielding) and in the design of nuclear power stations. To ensure the correct operation of the produced systems, manufacturers of sensors and integrated circuits employ methods of electronics radiation hardening [56].

6.1.1 Lattice displacement and ionization effects

Two main damage mechanisms affect the electronic devices. The lattice displacement is a permanent damage which consist in a change in the arrangement of the atoms in the crystal lattice of the device. This lattice displacement increases the number of recombination centers and reduce the number of minority carriers, resulting in a worsening of the analog properties of the affected semiconductor junctions. This effect is mainly caused by heavy particles like alpha particles, neutrons, protons, heavy ions and also high energy photons scattering on the lattice atoms. Higher doses over a short time period cause a softer damage with respect to same doses delivered at low intensity over a long time (Low Dose Rate, LDR).

Ionization effects are triggered by charged particles traversing the electronic device, together with the electronic current caused by ultraviolet and x-ray radiation. A charged particle can produce ionization effects even if its energy is too small to cause lattice displacement. These effects are usually transitory, mainly consisting of glitches and soft errors. However, they can have disruptive consequences on the device if they trigger other, more sever, damage mechanisms, like a latchup. A latchup is a short-circuit event occurring inside an integrated circuit. The cumulative damage of the device lattice caused by the Total Ionizing Dose (TID) over the exposition time is measured in rads ($1 \text{ rad} = 0.01 \text{ Gy} = 0.01 \text{ J/kg}$) and causes a gradual degradation of the device's performances. In devices based on CMOS technology the TID creates electron-hole pairs in the gate insulation layers, generating recombination noise current. Moreover, the holes trapped in the insulator lattice defects create an enduring gate biasing, influencing the transistors' threshold voltage. The accumulated charge can be sufficiently high so that the transistors is permanently open (or closed), leading to the device total loss.

6.1.2 Single Event Effects

When a high-energy particle travers a semiconductor device it creates an ionized track on its path. This ionization may cause soft or hard localized effects, like a bit flip in memory or a register of the device or a disruptive latchup and burnout. These effects are called Single Event Effects (SEE). There are several types of SEE in electronic devices.

A Single Event Transient (SET) is a soft, reversible error which occurs when the ionization event charge travers the circuit and it is detected as a spurious signal.

SEUs are triggered by a single ion interacting with the chip/sensor and consist of a bit-flip in the chip/sensor memory or register. It is a soft error which can be easily recovered thanks to tools like the Triple Modular Redundancy (TMR) (section 5.1.1). A single ion can also trigger a Multiple Bit Upset (MBU), which is a simultaneous SEU in several neighboring memory cells that cannot be recovered. If the SEU hit the control circuits of a complex system, such as a state machine, and set the device into an undefined state which needs a reset or a power cycle to recover, then the SEU is defined as Single Event Functional Interrupt (SEFI).

SELs are hard irreversible errors triggered by a heavy ion or a high-energy proton. A CMOS device comprises p-channel and n-channel transistors, but there might be parasitic PNP paths that are able to create low-impedance paths between the power supply rails when stimulated by incident radiation. This state is known as the latchup state. A latchup can cause permanent damage to the device due to the destructive high currents involved, but if no fatal events occur the normal functionality of the chip can be recovered when the device is power-cycled.

A Single Event Snapback (SES) is a hard error similar to SEL which is induced in N-channel MOS transistors when an ion hits close to the drain junction and triggers an avalanche multiplication of the charge carriers. After a SES the transistor then opens and stays opened.

Single Event Burnout (SEB) is another hard error which may occur in MOSFETs when the substrate under the source region becomes forward-biased and, at the same time, the drain-source voltage is higher than the breakdown voltage of the parasitic PNP structures. As a result a high current is generated and the consequent local overheating may destroy the device.

Single Event Gate Rupture (SEGR) is a serious event observed in power MOSFETs. It is triggered by a heavy ion hitting the gate region while a high voltage is applied to the gate itself. A breakdown happens in the gate insulating layer of silicon dioxide, which ultimately leads to local overheating and destruction of the gate region.

6.2 CLARO irradiation tests strategy

The CLARO8v3 chip radiation hardness has been intensively tested in several European irradiation facilities. A general strategy has been applied in every test. Multiple chips have been mounted on custom boards installed

in the dedicated facilities slots. Then the chips have been exposed to beams of ions, protons or to a mixed irradiation field to characterize their radiation tolerance in the radioactive spectrum and dose range foreseen in LHCb post-upgrade environment. During the irradiation tests the chips currents, the configuration register, the number of SEUs and SELs occurring in the ASICs and other parameters of interested have been constantly monitored to study the effects of the radiation on the devices. The data have been analyzed during and after the irradiation tests to ensure that the CLARO chip is able to correctly operate during and after the exposition to radiation.

6.2.1 Ion irradiation

Each ion is characterized by its LET, that is the energy deposited by the ionizing particle per unit distance, and by their range in silicon, that is the distance travelled in the material without straggling[57]. In electronic devices the ionization cause SEEs. The effective LET of an ion with a nominal LET ($LET_{nominal}$) depends on the angle of incidence of the ion on the chip following the Equation (6.1):

$$LET_{eff} = \frac{LET_{nominal}}{\cos\theta}, \quad (6.1)$$

where LET_{eff} is the ion effective LET when it hits the device under test at an angle θ with respect to the normal to the device surface. Using an incident angle θ different from 0 allows to access a finer spectrum of LET values to test the chip with the same ion. The SEUs and SELs cross section σ_{SEE} can be measured as a function of the ion LET from Equation (6.2):

$$\sigma_{SEE} = \frac{N_{SEE}}{F_{eff}}, \quad (6.2)$$

where N_{SEE} is the number of SEUs or SELs registered for the chip at a certain LET and F_{eff} is the effective fluence at an angle θ . The relation between the nominal beam fluence ($F_{nominal}$) and the fluence corrected for the angle of incidence θ (F_{eff}) is reported in Equation (6.3):

$$F_{eff} = F_{nominal} \cdot \cos\theta. \quad (6.3)$$

The CLARO has been tested using ion beams in two different facilities: the Heavy Ion Facility (HIF) at the Université Catholique de Louvain (UCL), in Louvain-La-Neuve (BE), and the INFN SIRAD facility, at Laboratori Nazionali di Legnaro (LNL), in Legnaro (IT). In the next sections details on the two tests are presented, together with the data analysis results.

6.2.1.1 CLARO irradiation tests in Louvain-La-Neuve

On October 2017 the Ferrara RICH Upgrade group performed the test on the CLARO in Louvain-La-Neuve Heavy-Ion-Facility (HIF) using charged ions accelerated by the facility cyclotron.

After an evaluation and assessment period in the mid-1990s, ESA sponsored the installation of a permanent heavy ion beam line at the CYCLOTRON of LOUvain-la-NEuve (CYCLONE) at the Université Catholique De Louvain-La-Neuve (UCL). The beam line has been used for SEE testing on electronic devices since 1996 by the space and the High Energy Physics (HEP) communities. The HIF uses the multi-particle, variable-energy cyclotron CYCLONE, able to accelerate protons up to 75 MeV, light and heavy ions up to the Xenon from 0.6 to 27.5 MeV/a.m.u. and it's equipped with an external Electron Cyclotron Resonance (ECR) ion source and beam transport system to provide the heavy ion beams. The produced beam flux ranges between a few particles/(s·cm²) and 1.5×10^4 particles/(s·cm²). The beam flux can be tuned from the user station using injection grids (for a constant attenuation factor) or by inflector bias variations (for intermediates values). The beam homogeneity is $\pm 10\%$ on a 25 mm diameter. The list of available ions is reported at the link in footnote¹.

Three different CLARO chips, mounted on three different boards, have been irradiated during this test. They have been numbered as boards 40, 41 and 42. The boards have been placed on a support in the vacuum chamber and they have been connected to the read out system by a cable system passing through services installed on the chamber wall (Figure 6.1). The support can be moved in 3D, allowing to select which chip to irradiate and at which angle. The chips have been irradiated at angles 0°, 30°, 40°. The DAQ system was based on an ALTERA MAX10 FPGA master board, configured to implement a telnet server to send command strings to the CLARO chips and able to readout the ASICs. The number of SEUs is constantly monitored for each CLARO.

At the end of the test is possible to plot the number of SEUs as a function of the irradiation time for a particular ion, as shown in Figure 6.2. The SEU cross-section is then evaluated for each ion and each board, and then they are plotted to form the distribution shown in Figure 6.3. Each point of the distribution is a board for a specific ion. The details on the error bars calculation for the SEE cross-sections are reported in Appendix A (used also

¹<https://uclouvain.be/en/research-institutes/irmp/crc/parameters-and-available-particles.html>

for the Legnaro irradiation test data analysis). Under the LET threshold of 20 MeV/mg/cm² (which correspond to the 20 MeV used in the High Energy Hadron fluence definition) no SEU has been registered, and when the LET is increased a plateau is reached for which the SEU cross-section no longer increases as the LET increase. Every time a SEU occurred in one of the chip registries during the test, the ASICs were always able to recover the correct configuration. A distribution for the SEL cross-section can be analogously obtained. The result is shown in Figure 6.4. The SELs occurred only for the $^{103}\text{Rh}^{31+}$ ion, at 30° and 40°, and for the $^{124}\text{Xe}^{35+}$ ion at all angles. These were the highest LET ion configurations applicable during the test, and for the LHCb RICH Upgraded environment such high LET are not foreseen. The TID absorbed by each CLARO per each different ion is reported in Table 6.1. The TID of reference for the RICH upgrade is 200 krad.

Ion	TID Board40 (10 ⁴ rad)	TID Board41 (10 ⁴ rad)	TID Board42 (10 ⁴ rad)
^{58}Ni	2.54	2.54	2.54
^{84}Kr	2.15	2.15	2.15
^{103}Rh	0.33	0.7	0.75
^{124}Xe	NA	1.20	1.12

Table 6.1: TID (per ion used) received by the CLAROs during the irradiation test in Louvain-La-Neuve.

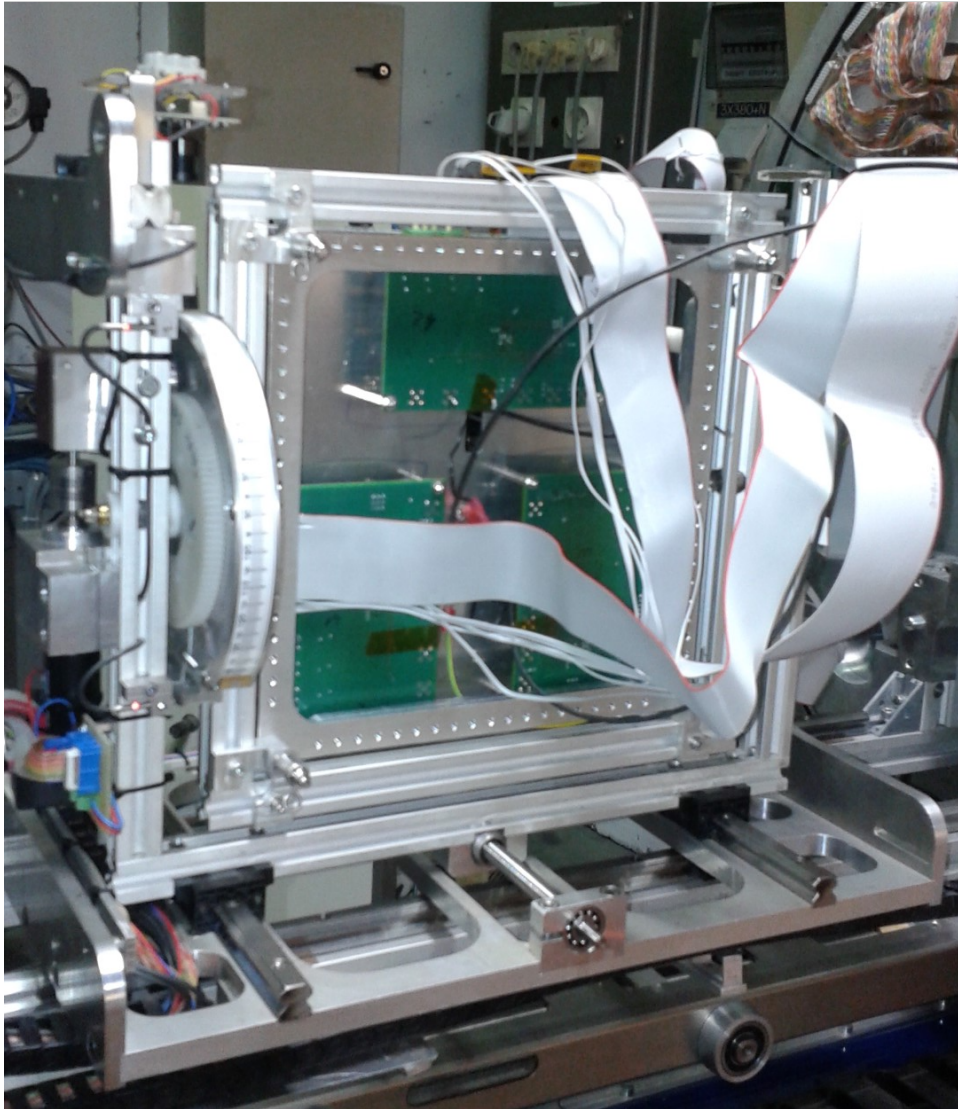


Figure 6.1: The three boards hosting the CLARO chips tested at Louvain-La-Neuve. They have been mounted onto the movable support inside the facility vacuum chamber. The ring showing the tilt angle with respect to the incident beam is visible on the left of the boards support.

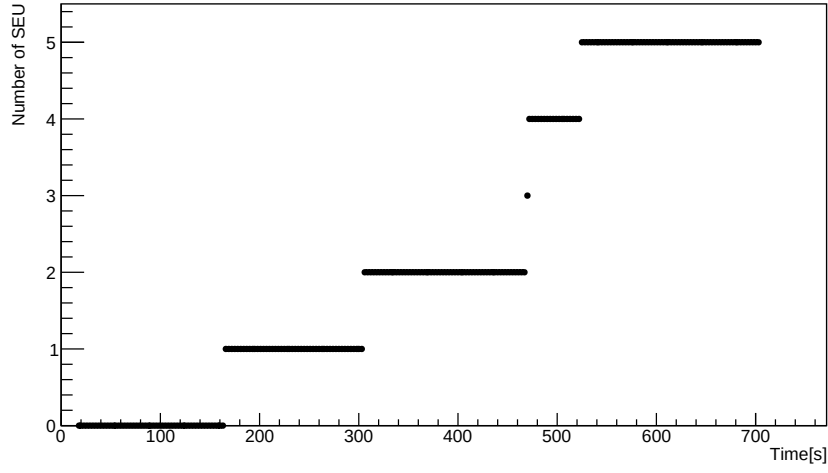


Figure 6.2: Typical plot for SEU occurring in one CLARO vs the irradiation time (ion Nickel, $\theta = 0$, $LET_{effective} = 20.4 \text{ MeV/mg/cm}^2$).

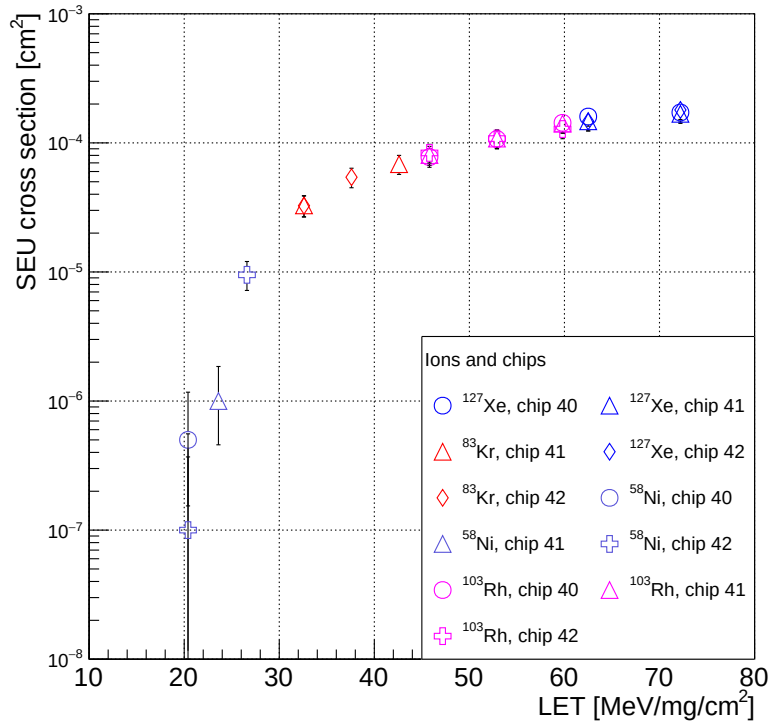


Figure 6.3: SEU cross section distribution for the CLARO ion irradiation test at Louvain-La-Neuve HIF.

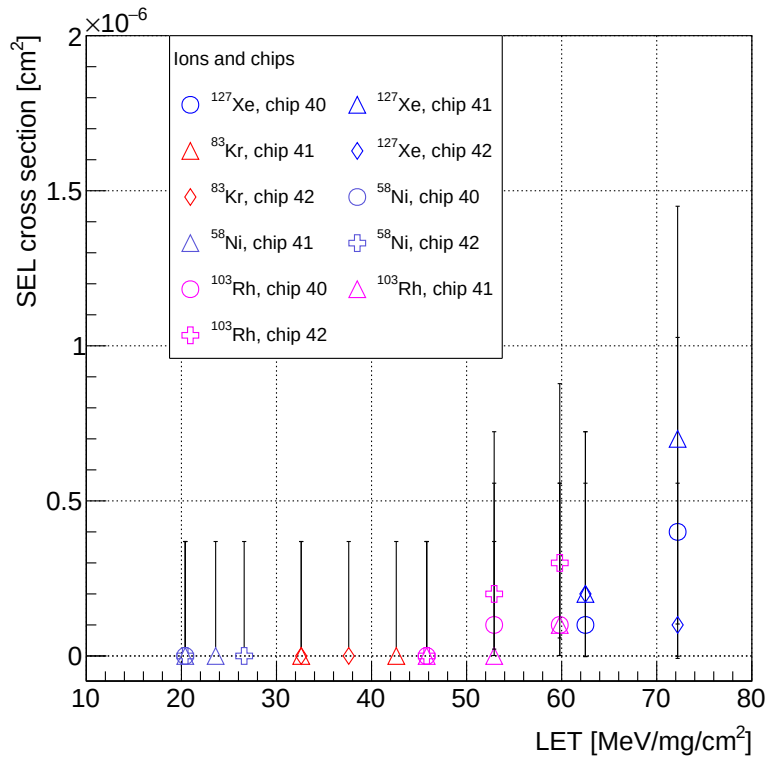


Figure 6.4: SEL cross section distribution for the CLARO ion irradiation test at Louvain-La-Neuve HIF.

6.2.1.2 CLARO irradiation tests in Legnaro

On November 2018 the Ferrara RICH Upgrade group performed an irradiation test with ions at the Silicon and Radiation (SIRAD) facility of Legnaro.

The facility has been designed to study bulk damage and SEE in semiconductor devices and electronic systems developed for high energy physics and space applications. The facility is also equipped with an Ion Electron Emission Microscope (IEEM) to map the sensitivity of electronic devices/systems to single ion impacts. The SIRAD facility is located at the INFN Tandem accelerator (Van Der Graaf type), which is equipped with two strippers and able to run up to 15 MV maximum voltage. The Tandem High Voltage Terminal (HVT), which exceeds 14.5 MV positive voltage as the maximum operational electrostatic value, is located at the center, and along the longitudinal axis, of the horizontal tank which is filled with insulation gas (SF_6 , sulfur hexafluoride) at the nominal pressure of 7 atm. The evacuated beam pipe and the accelerating column, which support the central terminal voltage, extend from both terminal sides for the whole tank length. An operational scheme of Tandem, displaying the main components, is shown in Figure 6.5. Ions are generated from an external source and then extracted with a positive charge state ($q = +1$). Before entering the Tandem accelerator the ions traverse a charge-exchange region in which, via electronic affinity, they receive two electrons from the Cesium gas which they interact with. They exit the Cesium gas with a net negative charge state ($q=-1$). At this point the ions enter the low energy side of the Tandem and are accelerated towards the HVT at $V_T = +14.5$ MV. Inside the Faraday cage ions traverse a thin carbon foil called stripper which absorbs a small beam current fraction. With this device the ions can be stripped by a large number of electrons ($q'=+10/+20$ based on the ion type and acquired energy). The ions then leave the HVT with a positive charged state, hence they experience a repulsive electrostatic forces from HVT and undergo a second acceleration process (hence the name "Tandem") in the second half of the accelerator. Because of the higher charge state, the energy $E = q'VT$ acquired in the second Tandem half is much larger to the energy acquired in the first half. At the Tandem exit (Figure 6.6) particle are driven using a magnetic deflectors and lenses system and then distributed by a switching magnet towards the selected irradiation target station. If the magnetic dipole is switched off, the beam can be driven to the linear accelerator of the facility ALPI, in which a further acceleration is applied and higher energies are reached. More details, together with the list of available ions in SIRAD and associated LET are

reported at the link in footnote².

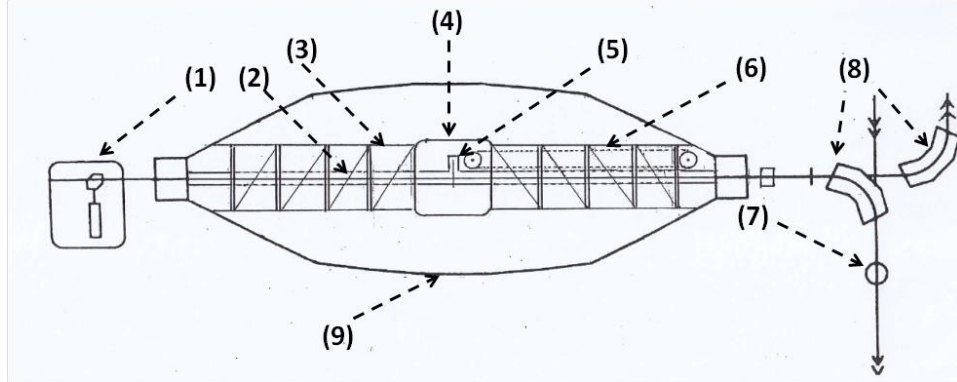


Figure 6.5: Schematic of the Legnaro Tandem accelerator: the ion source platform (1); the accelerating pipe (2); the column (3) supporting the high voltage terminal (4), where the ion beam stripping station is placed (5); the laddertron charging belt (6); the beam diagnostic station (7); the bending magnets (8); enclosure tank filled in SF_6 gas(9).

Four different CLARO chips have been irradiated during this test. They were named CLARO0, CLARO1, CLARO2, CLARO3 and they were installed on a custom electronic board. The board has been then placed inside the SIRAD vacuum chamber (see Figure 6.7), where a movable stage allows to select which chip to hit with the beam and which incidence angle to set between target and beam. The chips have been tilted at 0° , 30° , 40° and, only for the chlorine, the lowest LET ion, at 50° to exceed the minimum LET threshold of 20 MeV/mg/cm^2 . The data have been acquired via a custom readout system based on the NI CompactRIO (CRIO) controller, an industrial-grade embedded controller which combines a processor running NI Linux Real-Time, one FPGA and a modular I/O with vision, motion and display capabilities.

As for the Louvain-La-Neuve irradiation test data, we can obtain the SEU cross-section vs ion LET distribution (Figure 6.8). No SEL occurred in the Legnaro irradiation hence no distribution can be obtained. The TID absorbed by the CLAROs per each ion is reported in Table 6.2.

²http://sirad.pd.infn.it/SIRAD_IF/Documents_PDF/SIRAD_TechnicalCharacteristics_2014-10-01.pdf



Figure 6.6: The output Tandem accelerator vacuum pipe: the void pumps, as well as the quadrupoles magnetic lenses, which let the beam focused along the beam axis, are visible.

Ion	TID CLARO1 (10^4 rad)	TID CLARO2 (10^4 rad)	TID CLARO3 (10^4 rad)	TID CLARO4 (10^4 rad)
^{35}Cl	NA	NA	NA	0.64
^{48}Ti	1.21	1.21	1.29	1.21
^{58}Ni	1.67	1.67	1.67	1.67
^{79}Br	2.06	2.33	2.32	2.33
^{107}Ag	3.44	3.18	3.16	3.16
^{127}I	4.44	3.46	3.46	4.46

Table 6.2: TID received by the CLAROs during the ion test in Legnaro.

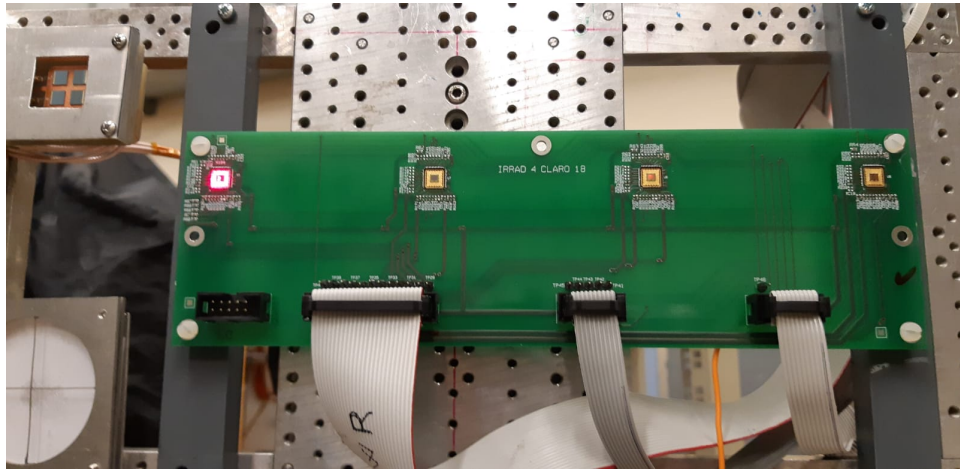


Figure 6.7: The four CLAROs used in the 2018 irradiation test in Legnaro. The board on which they are installed is mounted on the vacuum chamber support. The leftmost CLARO is illuminated by the alignment laser. On the upper left corner the diode system for the beam fluence calibration is shown.

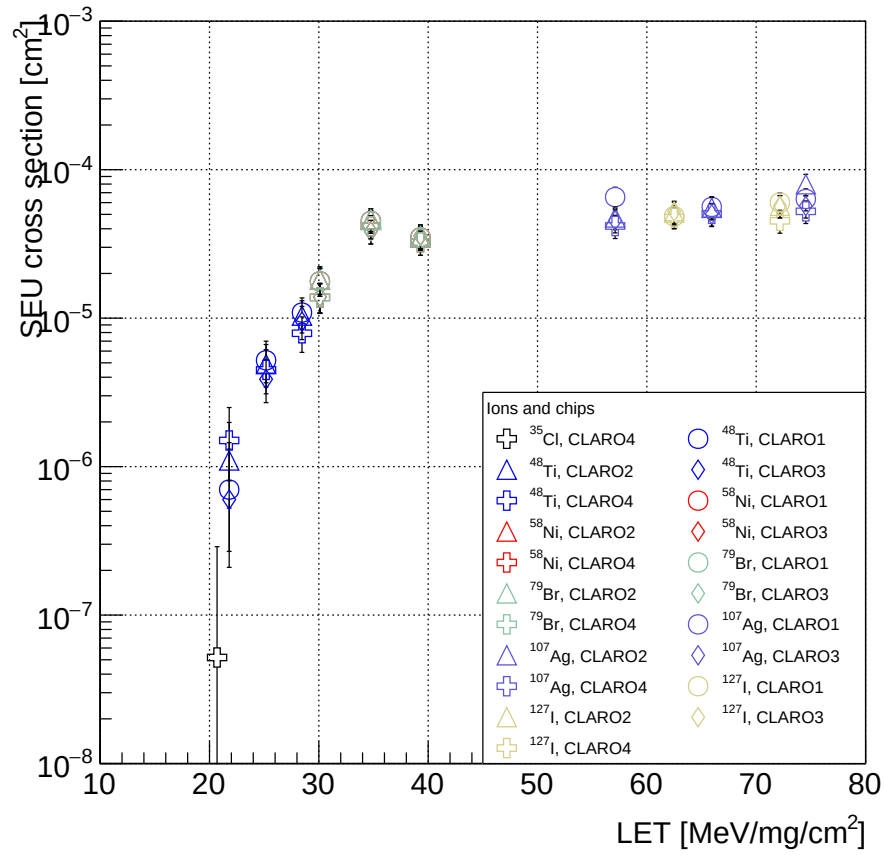


Figure 6.8: SEU cross section distribution for the CLARO ion irradiation test at Legnaro SIRAD.

6.2.1.3 Summary of the ion irradiation tests results

We can observe that the distributions in Figures 6.3 and 6.8 have the same shape, the same lower LET threshold for SEU to happen at ~ 20 MeV/mg/cm² but a different behaviour at higher LET. The SEU cross-section for the Legnaro CLAROs is lower by a factor 2 for LET > 50 MeV/mg/cm². This difference is due to the fact that the CLAROs used in the two irradiation tests have been produced in different batches, hence some differences in the production procedure may have slightly changed the chip properties between different production batches. The summary list of the ions parameters used in the two irradiation tests are reported in Table 6.3. It can be stated that the CLARO chip has been proven to be able to operate correctly when exposed to high TID levels.

Louvain Ion	LET _{eff} [MeV/mg/cm ²]	Range[μ m Si]
⁵⁸ Ni	20.4	100.5
⁸⁴ Kr	32.4	94.2
¹⁰³ Rh	45.8	87.3
¹²⁴ Xe	62.5	73.1
Legnaro Ion	LET _{eff} [MeV/mg/cm ²]	Range[μ m Si]
³⁵ Cl	13.3	43.6
⁴⁸ Ti	21.8	34.8
⁵⁸ Ni	30.1	32.7
⁷⁹ Br	42.0	29.7
¹⁰⁷ Ag	57.1	25.5
¹²⁷ I	62.4	26.7

Table 6.3: Summary list of the ions used in the CLARO irradiation tests main parameters.

6.2.2 Proton irradiation

On October 2018 the Ferrara LHCb RICH Upgrade group performed an irradiation test on the CLARO ASICs using the proton beam of the CERN IRRAD facility (Figure 6.9).

The facility is located on the CERN T8 beam-line in the PS East Hall where a 24GeV/c momentum primary proton beam is extracted from the PS ring. The proton beam is extracted in spills of maximum 5.0×10^{11} protons. During the CLARO irradiation test the spills were on average of 1.9×10^{11} particles. The beam intensity depends on the number of spills per PS super-cycle (CPS). The beam size relevant for proton irradiation experiments, on horizontal and vertical planes, ranges from 5mm to 15mm RMS. The designated space (of approximately 500m²) for irradiation tests is located in the south part of the PS experimental area. The test zone is shared between the proton IRRAD, upstream of the beam, and the CHARM mixed-field facility, implemented downstream (Figure 6.10). A description of the CHARM facility will be given in the next section. The IRRAD bunker dimensions define the available space for the installation of the irradiation equipment, consisting in a remote-controlled shuttle and tables. The bunker dimensions are 3.2m×18.0m×2.4m (W × L × H) for a total volume of 140m³. The shielding walls and roof are made of standard concrete and cast iron blocks. To limit the neutron sky-shine, a 5.6m thick roof of concrete blocks has been built for the IRRAD facility. Standard room temperature (RT) and humidity conditions are maintained during operations inside the bunker. The IRRAD bunker is split in three sub-areas according to the nature of the samples to be irradiated. In between each of these irradiation sub-areas an 80cm thick concrete wall (with a hole for the beam to pass through) is present in order to reduce the radiation background during the tests, minimizing the ambient dose received by the operators during the accesses to the area. In order to further minimize the collateral radiation produced by the proton beam interaction with the air, two vacuum beam-pipes are installed in the zones between the installed irradiation systems. It is possible to separate the IRRAD facility in two main areas: the area accessible during beam operation, consisting of the control room, the technical area, the storage area and Buffer Zone and the Dewar cooling vessel delivery area, and the area not accessible during beam operation that is the Irradiation Bunker and the access chicane. The access to the Irradiation Bunker and the chicane is forbidden during beam operations due to the presence of significant radiations. To operate the irradiated samples during beam operations, a shuttle named IRRAD1, that is a remote-controlled conveyor moving on a rail sys-

tem, allows the positioning of small objects (typically passive components and/or silicon detector test-samples) on the beam without the need of human access into the area. This system performs an X-Y alignment with a precision of $\pm 0.1\text{mm}$ with respect to the beam direction. The shuttle runs across the facility shielding blocks for a length of about 10m inside a conduit of $400 \times 400\text{mm}^2$. The maximum volume available for irradiation on the shuttle is $50 \times 50 \times 200\text{mm}^3$ for a weight of 1kg. The size of the beam spot on the shuttle system is 5-7mm RMS but it can be changed according to the different beam focusing options.

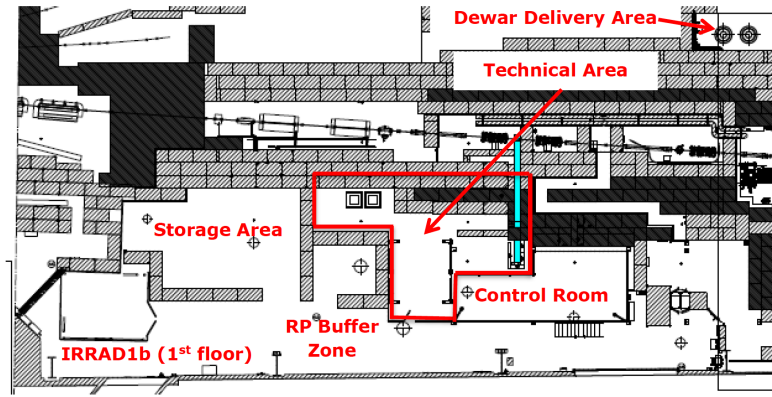


Figure 6.9: Schematic of the IRRAD facility.

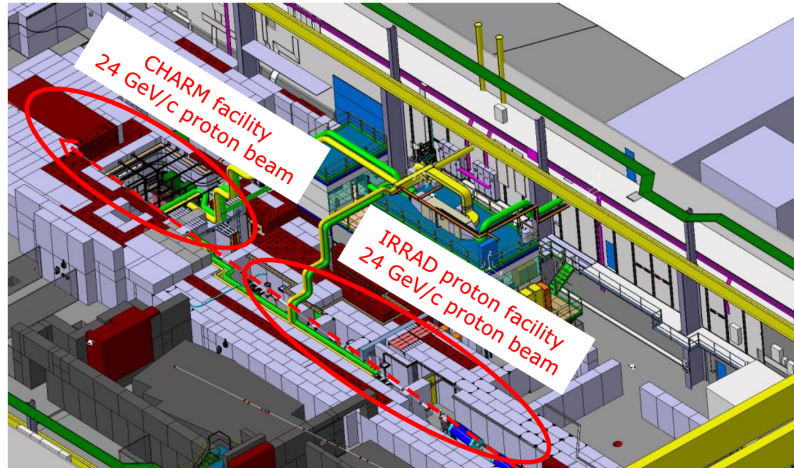


Figure 6.10: A 3D model of the CERN PS East Hall T8 beam-line, where both the IRRAD and the CHARM facilities are located.

During the test a total of 19 CLARO chips have been tested, 16 from

the latest production batch at that time and three that were already tested at IRRAD in November 2017. The CLARO arrangement during the test is reported in Figure 6.11. The setup was moved in four different positions (P1-P4) so that a line of CLAROs was irradiated. For the positions P1-P3 the line consisted of one CLAROs from 2017 test and three from the latest production batch. For P4 the line was composed by four new CLAROs. Here, like for the Legnaro ion irradiation test, the NI Compact RIO (CRIO) controller has been used for data acquisition.

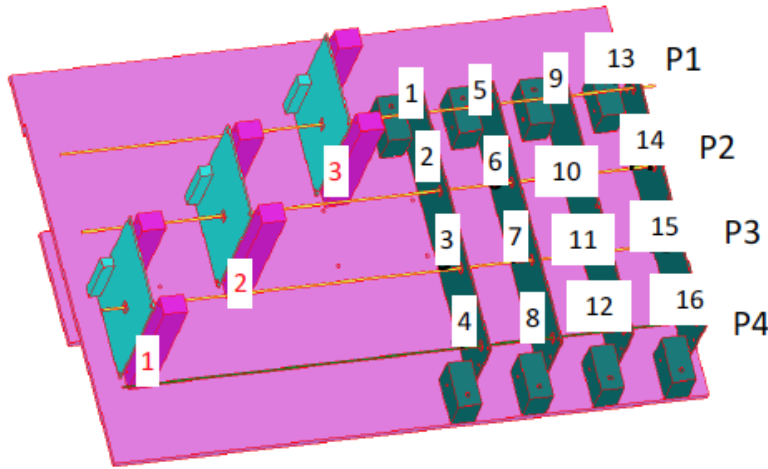


Figure 6.11: A 3D model of the setup for the CLARO proton irradiation.

The most important parameters which have been monitored are the CLARO currents (analog, digital and digital core), the SEUs and the SELs, together with the chip register configuration. A typical plot for the three currents as a function of the irradiation time of a CLARO is reported in Figure 6.12. It is possible to see the effects of the beam on the currents: when the chip is on the beam (colored bands on the plots) the currents are slightly increased. As soon as the chip is out of the proton beam the current returns to the nominal value. A SEL, which in fact is an overcurrent event, can occur for each of the three CLARO currents. An overcurrent event is flagged as SEL if the current stays above 10mA for more than 10 seconds. During the test no SEL occurred in the CLAROs. For one of the chips the digital current went above 10mA for 1 ms, then it adjusted to the typical value. This kind of event is classified as an overcurrent glitch and does not pose a danger for the CLARO operations.

The number of SEU on the chips was constantly monitored and a plot of

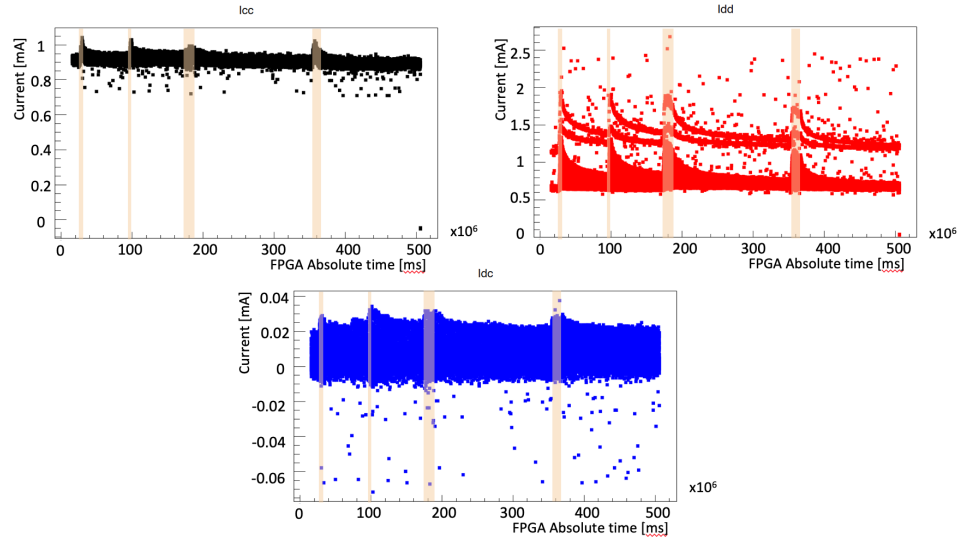


Figure 6.12: CLARO currents (analog in black, digital in red, digital core in blue) for one of the CLAROs used in the October 2018 proton irradiation test.

the cumulative number of SEUs vs the irradiation time can be obtained for each CLARO. A typical plot is reported in Figure 6.13. The number of SEU in the chip stays constant as long as the chip is not irradiated, but increases linearly as soon as the setup is moved and the chip is hit by the proton beam. The total dose received by the CLAROs per position is reported in Table 6.4, calculated using the Equation A.2 reported in Appendix A. The rate of SEU per chip per Mrad received can be calculated and the results are reported in Table 6.5. Like in the ion irradiation test, the SEU were not affecting the CLARO operations. After a SEU the ASICs were always able to recover the correct configuration.

	P1	P2	P3	P4
DOSE [Mrad]	12.46	12.57	12.67	13.92

Table 6.4: Total dose received by the CLAROs on each position on the IRRAD proton irradiation test.

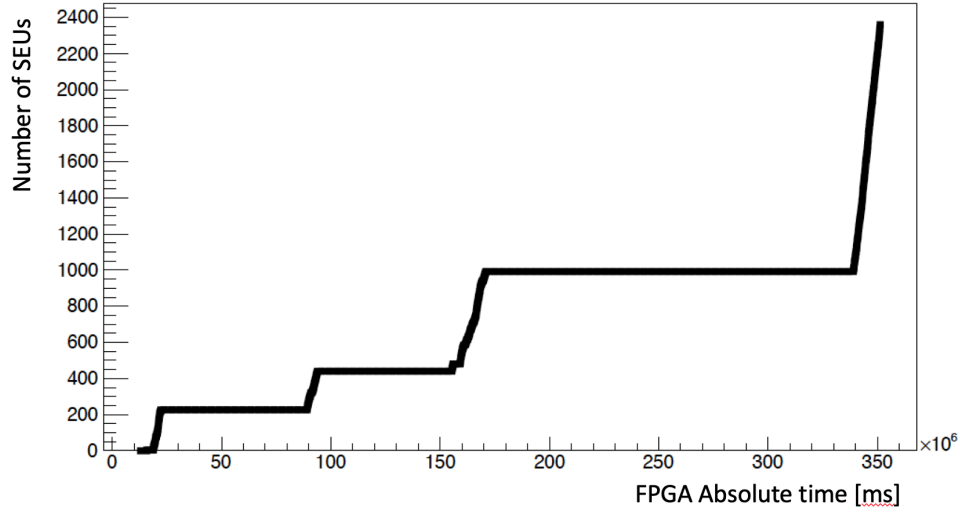


Figure 6.13: Cumulative CLARO SEU number vs irradiation time, measured by the CRIO FPGA.

CLARO#	SEU	Dose[Mrad]	SEU·Mrad ⁻¹
1	1789	12.46	143.58
2	2015	12.57	160.30
3	1682	12.67	132.75
4	2007	13.92	144.18
5	1748	12.46	140.29
6	1937	12.57	154.09
7	1749	12.67	138.04
8	1793	13.92	128.81
9	1766	12.46	141.73
10	1735	12.57	138.03
11	1928	12.67	152.17
12	1915	13.92	137.57
13	1725	12.46	138.44
14	1679	12.57	133.57
15	1599	12.67	126.20
16	1760	13.92	126.44

Table 6.5: Total dose received by the CLAROs on each position on the IRRAD proton irradiation test.

6.2.3 Mixed Field irradiation

On July 2016 the Ferrara LHCb RICH Upgrade group performed an irradiation test on the CLARO ASICs at the CERN CHARM facility (Figure 6.14).

CHARM (CERN High energy AcceleRator Mixed field) features a wide spectrum of radiation types and energies (called mixed-field radiation environments where protons, neutrons, pions, gamma photons etc.. are present), and puts at user disposal the space to test large equipment ($2m^3 \cdot 10^3$ kg, along with the precise monitoring equipment needed) and even the possibility to adjust the environment using mobile shielding. In CHARM is possible to recreate any of the radiation environments found in the LHC accelerator chain. The radiation is created by colliding a beam against a fixed target (copper, aluminum or an aluminum sieve, depending on the required intensity). The facility is located just downstream of the IRRAD facility, exploit its proton beam, which would be otherwise dumped. The beam parameters are the same as the IRRAD facility parameters, since it's the same beam. In order to minimize radiation exposure, the equipment to be tested must be installed in the irradiated area without human intervention. This is made possible by using a custom semi-remote lifting and transport vehicle which drives the heavy equipment from the user accessible area into the irradiation area. The equipment service cables are attached to a rail on the ceiling which follows the same track and they will be connected through a patch-panel to the user's control and DAQ system. In the LHC tunnel there are two different radiation environments: one in the tunnel itself, where particles with very high energy are present, and the other in the contiguous shielded areas, where the energy spectrum is dominated by neutrons. CHARM is able to accurately simulate all these environments.

During the test 16 CLAROs have been exposed to the CHARM mixed field. They have been installed on an electronic board as shown in Figure 6.15. Like for the Legnaro ion irradiation and the IRRAD proton irradiation tests, the NI Compact RIO (CRIO) controller has been used for data acquisition. During the irradiation tests the three CLARO currents, the SEU and SEL have been monitored. The total dose absorbed by the chips during the test is 800 Gy, or equivalently $9 \cdot 10^{12}$ 1 MeV n_{eq} , and $3.7 \cdot 10^{12}$ HEH $_{eq}$. The total number of SEU per chip is reported in Table 6.6. No SEL occurred. The number of SEU occurred in these chips is much lower with respect to the ion and proton irradiation tests one because of the much lower absorbed dose, and the chips operations were not affected by the SEU.

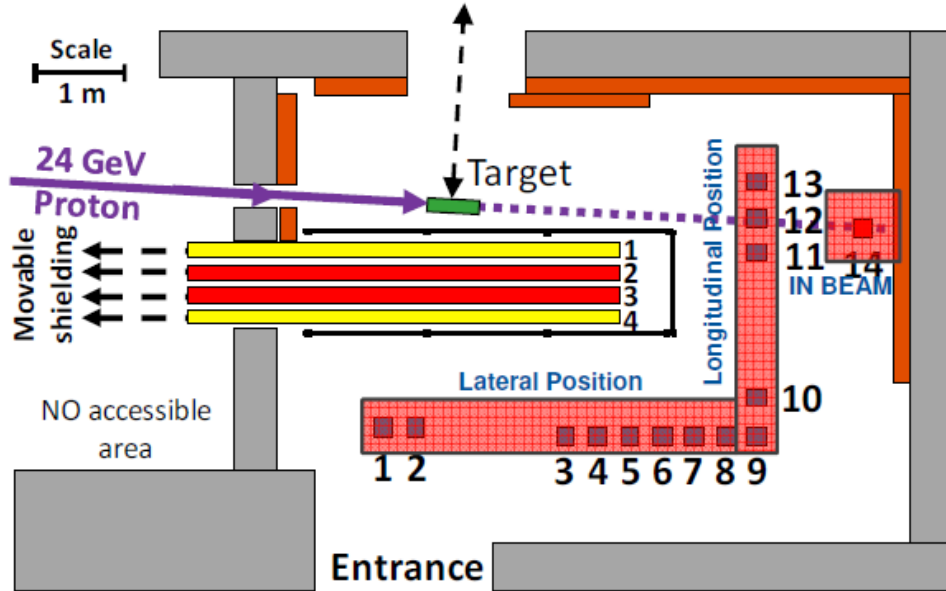


Figure 6.14: Schematic of the CHARM facility at CERN.

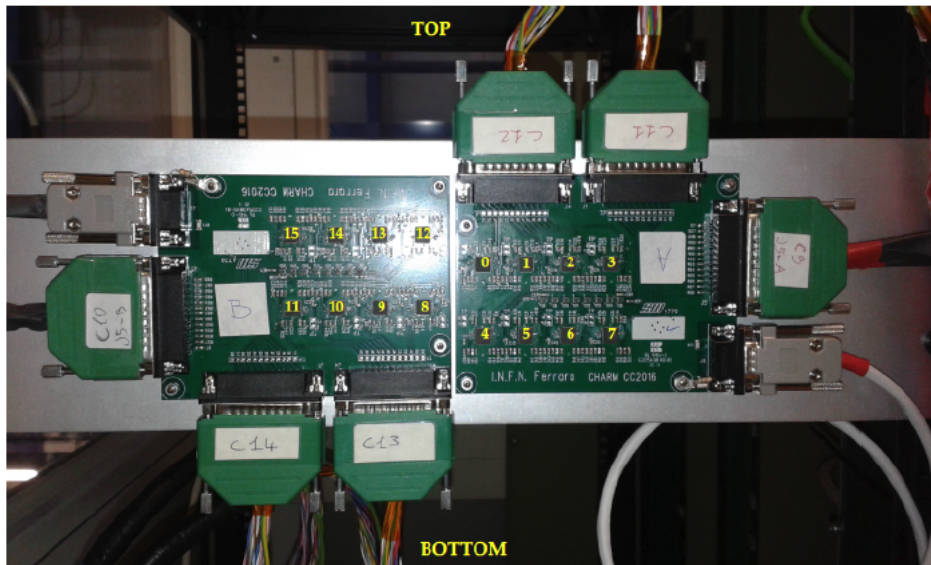


Figure 6.15: CLARO CHARM irradiation setup.

CLARO#	SEU
1	2
2	2
3	9
4	6
5	6
6	4
7	7
8	8
9	7
10	7
11	5
12	4
13	2
14	12
15	10
16	8

Table 6.6: SEU occurred in the CLARO chips used in the CHARM irradiation test.

6.3 Conclusions on the CLARO irradiations tests

The CLARO has been intensively tested using ions, protons and a mixed field as sources of radiation. The TID at which the CLAROs have been exposed during these tests ranges from 10^4 to 10^7 rad, delivered within a few hours/days. This has to be compared to the worst-case scenario of 2×10^5 rad expected for the whole upgrade phase (50 fb^{-1}).

Despite the extreme conditions in which the CLAROs have been tested, they were able to correctly operate and recover from every SEU. A limited amount of SELs occurred only for the highest LET ions and a power-cycle of the devices was able to restore their operations. The CLARO currents maintained a regular behaviour during the tests, increasing when the devices were exposed to the beam and returning to their nominal values once out of the beam.

From these results it can be stated that the CLARO satisfies all the radiation hardness requirements and will be able to correctly operate in the upgraded LHCb detector environment.

Chapter 7

RICH upgrade test-beam

In June and October 2017 two tests-beam have been performed at the H8 beam line at the SPS North Area (CERN Prévessin). The goal was the study of the performance of four fully populated final ECs using the prototype for the Upgraded LHCb RICH Detector. In particular, the MaPMTs, the mechanical housing and the CLARO v3 FE assemblies have been tested, together with the full optoelectronic chain and DAQ system in a realistic upgrade environment.

7.1 Setup

Several institutes contribute to the LHCb RICH collaboration: CERN, the University of Glasgow, the Imperial College, the Rutherford Laboratory, the H. H. Wills Physics Laboratory, the University of Birmingham, the University of Ferrara, the University of Genova, the University of Milano-Bicocca, the University of Edinburgh, the University of Oxford and the University of Cambridge.

In both tests-beam the setup was almost identical (Figure 7.1). In June four R-type ECs have been installed in the prototype, while in October two R-type and two H-type ECs have been initially installed but the test was concluded using four R-type ECs. The latest version of the FEBs (v3) mounting the CLAROV3, have been used in the ECs. The ECs have been mounted on a prototype Photon Detection Module (PDM) to simulate the ECs operational conditions in the upgraded RICH detector. The PDM is mounted on a water cooled cold-bar, which provides the mechanical support and the cooling to the four ECs installed. Moreover, the cold-bar is installed on a translation stage, MICOS MT-85 motion controller and stepper motor drive, with a load

capacity up to 20 kg. The setup temperature is constantly monitored by the ELMB interface and PT100 and PT1000 sensors. The CLARO data readout has been performed by two PDM Digital Boards (PDMDBs) connected to the EC Bkb. The PDMDBs then transmit the data to the DAQ system, called miniDAQ, via optical link. The ground connections for the test-beam is provided by copper braids installed on the cold bar. Both the DBs ground and the metal plate on the backboards are connected to the copper braids. The entire setup is enclosed in a light-tight polypropylene box (also named dark box) that provides thermally insulation for the system. The humidity level is controlled using molecular nitrogen injected in the box. The high voltage and low voltage hardware is composed of the CAEN SY1527 crate, the A1735N HV board with 12 floating channels 1.5 kV/7 mA for the MaP-MTs power supply and the A1517A LV board, with 6 floating channels 7 V/4 A for DBs power supply.

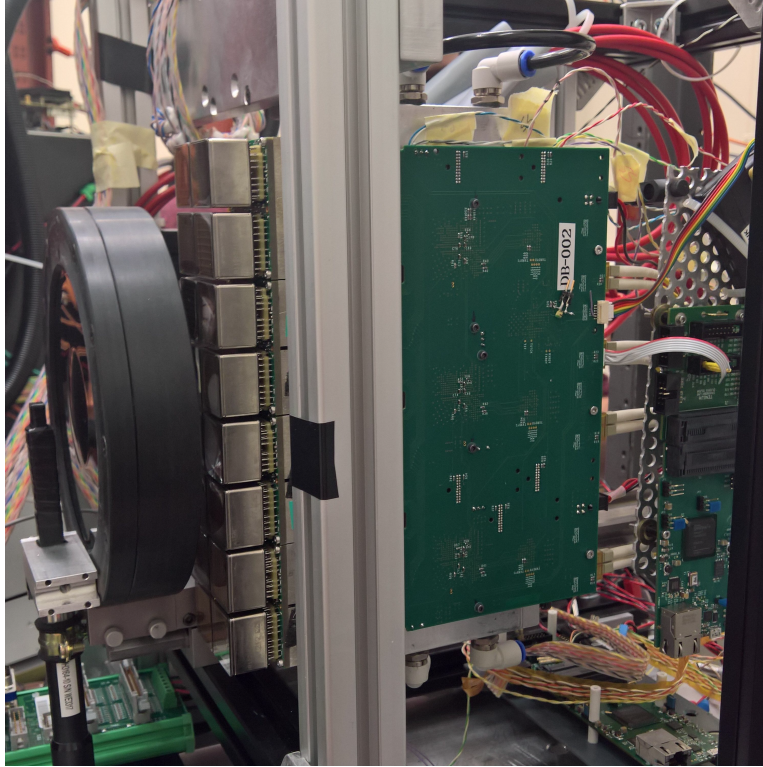


Figure 7.1: The cold bar with four R-type ECs. On the right the lens is visible, surrounded by its black plastic support. On the right the PDMDB is attached to the ECs backboards.

7.1.1 Particle beam and monitoring tools

The beam used for these tests-beam is a secondary beam generated by the collision of the CERN Super Proton Synchrotron beam with a target. This collision generates a beam of 180 GeV/ c positively charged hadrons: 67% protons, 30% pions and 3% kaons. A small background of muons is also present. The beam is divided in spills of about 10^5 - 10^7 particles and these spills last for 3-5 s. Two pairs of orthogonal scintillators are installed in the dark box, one upstream and one downstream the lens used as Cherenkov radiator. These scintillators, each with sensitive area of $8 \times 12 \text{ mm}^2$ and overlapping area per pair of $8 \times 8 \text{ mm}^2$, are used to generate beam trigger signals when the limit threshold is exceeded within a pre-set time window. During the data taking the LHCb VELO tracker was also present at a distance of 1230 mm upstream of the RICH prototype. This tracker provides information on the beam profile width and on the beam direction on the x - y plane, which is measured over 75 mm, that is the distance between the first and the last tracking stage of the VELO tracker. A second tracker has been used during the tests-beam. This tracker consists of two tracking stations with four read-out modules each plus a spare module (Figure 7.2). In each module two silicon strip sensors are present, rotated one respect to the other of 40 mrad stereo angle. The silicon sensors strips have an active area of $64 \times 128 \text{ mm}$ with 50 μm x -resolution and 400 μm y -resolution using the stereo angle. The sensors are from the ATLAS Silicon Tracker (SCT) and they are read out by the ATLAS ABCD ASICs connected to the LHCb RICH DBs equipped with an adapted firmware. The data are sent to DAQ system via 100 MBit Ethernet link connection. The beam trigger signals coming from the RICH scintillators, the RICH tracker and the VELO tracker are combined to obtained detailed information on the beam.

7.1.2 Cherenkov Radiator

The radiator element employed in the tests-beam is a plano-convex lens¹, in which Cherenkov photons are generated. The lens substrate is made of N-BK7, one of the most common technical optical glass, which shows good scratch resistance with low amount of inclusions and it is almost free of bubbles. This material has an high linear optical transmission in the visible range down to 350nm. Moreover, because of stable chemical properties of N-BK7, no special treatments are required to grind and polish the material.

¹<http://www.edmundoptics.com/optics/optical-lenses/plano-convex-pcx-spherical-singlet-lenses/large-pcx-condenser-lenses/27509/>

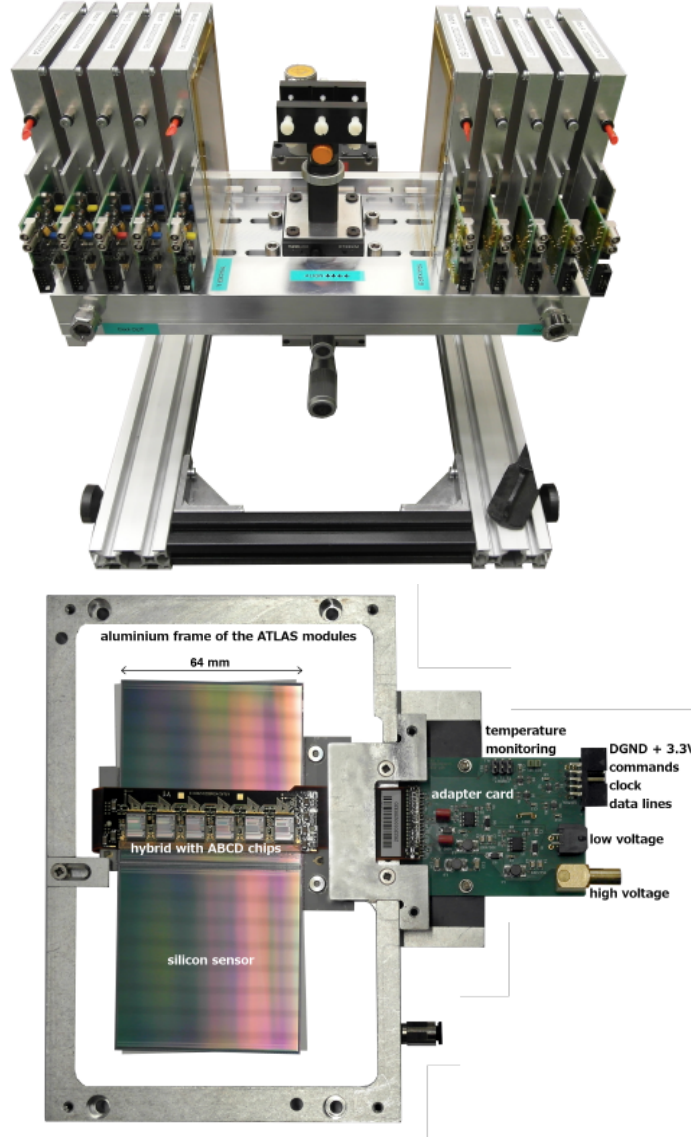


Figure 7.2: Top: the tracker developed by the LHCb RICH Upgrade group for the 2017 tests-beam. Bottom: detailed view of a silicon module and read-out electronics.

Its average refractive index is $n_{lens} = 1.57$. The beam enters orthogonally the lens in its centre. The photons generated in the region of the lens closer to the flat surface are absorbed by a circular layer of black coating attached to the flat surface of the lens. This feature enhances the resolution of the reconstructed Cherenkov angle. The photons generated in the first 12.5 mm

of the lens are internally reflected from the flat surface onto the focusing mirror surface attached to the spherical part of the lens, and then reflected on the upstream photodetector plane. The spherical reflective coating has an annular shape to minimize the background photon reflection, and black silicon covers the remaining area of the spherical part to absorb photons which do not hit the reflective coating. A schematic model of the lens is shown in Figure 7.3.

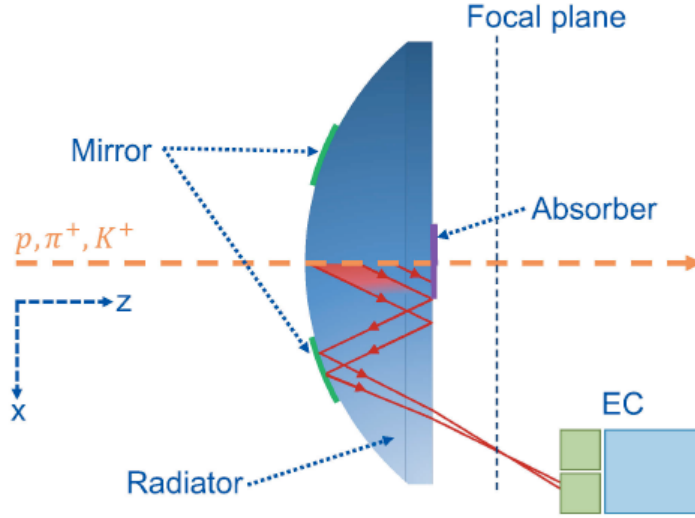


Figure 7.3: Schematic of the lens. The photons path inside the lens is represented by the black lines.

7.1.3 Test-beam DAQ

The LHCb Experimental Control System (ECS) contains the entire experiment control, the monitoring and all the components from the infrastructure equipment to the data acquisition. The LHCb ECS is a distributed system, based on a commercial Supervisory Control and Data Acquisition (SCADA) system, that is WinCC OA, and several custom developed components[58, 59]. WinCC provides several features which are very important for the LHCb ECS: user interfaces, data archiving, a centrally managed alarm screen to handle alarms. The WinCC open architecture makes possible to customize every aspect of the system to better fit the user needs. The LHCb ECS is built as a tree-like control hierarchy structure based on a Finite State Machine (FSM) tree. Commands which are sent from a level of the system are propagated all the way down to the lower leafs which ex-

ecute the actions requested. Then the state of the end-nodes at the bottom of the system is propagated up to the topmost node. The state of the entire LHCb experiment is always visible and can be controlled from a single place. The DAQ system for the tests-beam has been developed in the exact same way using WinCC and a dedicated user-friendly Graphical User Interface (GUI) has been designed to control and monitor the RICH Upgrade prototype in an efficient way. A GUI is an interface that allows users to interact with electronic devices through graphical icons. The top level of the RICH tests-beam WinCC project allows to control the system HV, the Detector Control System (DCS) and the DAQ system. From the top level panel the user can descend into the panels dedicated to each section of the system and operate specific actions for that section. The state of each part of the system is continuously propagated to the top level and the user can correct errors/problems by navigating into the section which is in ERROR state. The top level panel directly shows information on the actual data taking conditions so the user can easily monitor the data acquisition.

7.1.3.1 MiniDAQ

Many new electronics components and systems have been developed for the LHCb Upgrade. All of them will have to be controlled, monitored and integrated into the ECS. The MiniDAQ has been designed to be the development platform for all the monitoring and control activities of the new front-end and the new readout electronics of the sub-detectors. The LHCb MiniDAQ system has two levels: a hardware platform and the corresponding software suite to control and to monitor the hardware. The hardware consists of a CPU server housing a PCIExpress card named PCIe40. The PCIe40 is the core component of the upgraded LHCb Online system, providing the interface to the connected electronics and is used to read-out the data. The PCIe40 can have up to 48 bi-directional optical links implementing the GBT protocol, can operate at 4.6 Gbps and it's able to transmit up to 100 Gbps of data through the PCIe lanes. It's equipped with Arria 10 FPGA with 1.15 million cells. Thanks to the programmable component flexibility, depending on the firmware loaded into the FPGA, the PCIe40 board can be used for different tasks: readout board (TELL40); readout supervisor (Super ODIN); controls interface (SOL40) to the connected electronics. Thanks to the large number of logic cells in the FPGA the board can be programmed to execute all the above functions, but with a reduced number of instantiated links. The integrated firmware is called MiniDAQ firmware. The MiniDAQ is a powerful tool for stand-alone development which facilitates a

distributed and de-centralized development of the different detector groups control system. The technology developed by the different detector groups using the MiniDAQ framework can easily be integrated into the final LHCb ECS and this will facilitate the commissioning of the upgraded detector in 2020/21. For this reason the MiniDAQ has been used in the development of the RICH Upgrade test-beam control system. In June 2017 the MiniDAQ v1 (MiniDAQ1) has been used, while in October both the MiniDAQ v1 and MiniDAQ v2 (MiniDAQ2) has been used in a special setup: the MiniDAQ1 has been used to read the beam trigger information and to forward them to the MiniDAQ2, while the MiniDAQ2 was used for the PDMDB data read-out. The LHCb RICH Upgrade group was the first group in LHCb to use a functional and complete upgrade acquisition system with the MiniDAQ in a realistic environment.

7.1.3.2 Cherenkov Ring display

The DAQ GUI includes an online monitoring system developed using Java which provides readout information from the MaPMT sockets and displays it on the monitor in real time, as shown in Figure 7.4. Each pixel is an MaPMT channel, which correspond to a CLARO chip channel, and the different colours shows the number of hits in each pixel in the integrated acquisition time. However, each MaPMTs has a different hits map colour scale. A Cherenkov ring is clearly visible on the MaPMTs. When the ring is deliberately de-focused it spreads over more channels. Some pixels outside the ring Cherenkov ring are red, which means the associated CLARO channels are detecting electronic noise. That is because a common threshold has been set to all the CLARO channels and the ones which are detecting the noise have the threshold set on the pedestal. The white pixels correspond to channels which could have not been configured properly.

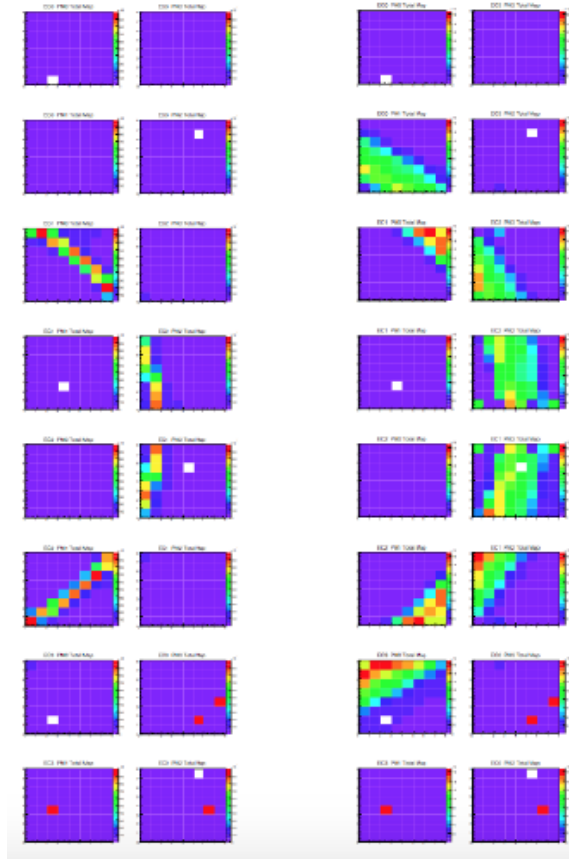


Figure 7.4: DAQ GUI used in the test beam. The Cherenkov ring is detected using the optimal optical setting on the left, while on the right it has been de-focused.

7.2 Measurements

In this section the reconstruction procedure for the Cherenkov angle and radius measurements and the CLARO characterization tests with the upgraded RICH prototype setup are presented.

7.2.1 Cherenkov ring radius and Cherenkov angle reconstruction

The study of the Cherenkov ring in the LHCb RICH Upgrade prototype is performed in two steps. The first step consists in a Monte Carlo simulation of the system using a dedicated software which replicates the geometry of the setup. In the simulation the Cherenkov photons are generated at a fixed Cherenkov angle depending on the setup geometry and on the radiator medium parameters, then a reconstruction procedure is implemented to obtain the Cherenkov angle from the simulated hits. The simulated Cherenkov angles and the reconstructed one are expected to be equal, within the uncertainties. From the reconstruction procedure it's possible to evaluate the three main Cherenkov angle contributions: the Emission Point error, the Chromatic error and the Pixel error. This last contribution arises from the different angle evaluation when considering the exact photon-hit coordinates in the MaPMT pixels (which is unknown for the real data) or the hit pixel centre. The data coming from the prototype are analyzed using the same software, after the simulation has been performed. The photon-hit map of the MaPMTs for a particular run is processed to measure the Cherenkov ring radius. For each event, that is a particle passing through the radiator and generating Cherenkov photons, the centre of the Cherenkov ring can be found by averaging over the photon-hits coordinates. Alternatively, the projection of the nominal z -axis, the beam axis, on the MaPMT plane can be considered as the centre. The Cherenkov radius is then measured taking the distance of a single photon hit from the circle center previously found. For each event a single radius value is found by averaging over all the photon hits in the event. Alternatively, the Cherenkov radius can be measured using the least-square circle fit method (Appendix B). The reconstruction procedure also provides the measurement of the Cherenkov angle. In Figure 7.5 is represented the reconstruction model used in the software. Before the data analysis is performed a simulation map is created which contains the sample of photon paths corresponding to each pixel in each MaPMT. This map provides the coordinates of the point E_T , the true Cherenkov photon emission point on the particle track, the internal reflection points T and M

in the lens, the photon exit point X and the true pixel photon hit point H on the MaPMT, together with the center P of the corresponding pixel hit by a photon for each pixel of the system. The true lens focal plane is the plane F shown in figure. Due to dimension constraint, the plane N is used instead. The fictitious plane G is the plane N translated to the true photon trajectory so that the path $X-H$ is equal to $X-K$. Using this information, the photon path projections D and K on the true focal plane F and the imaged MaPMT plane G are obtained. The point C is the actual center of curvature of the lens, E_M is the imaged Cherenkov photon emission point and E_R is the imaged radiator centre.

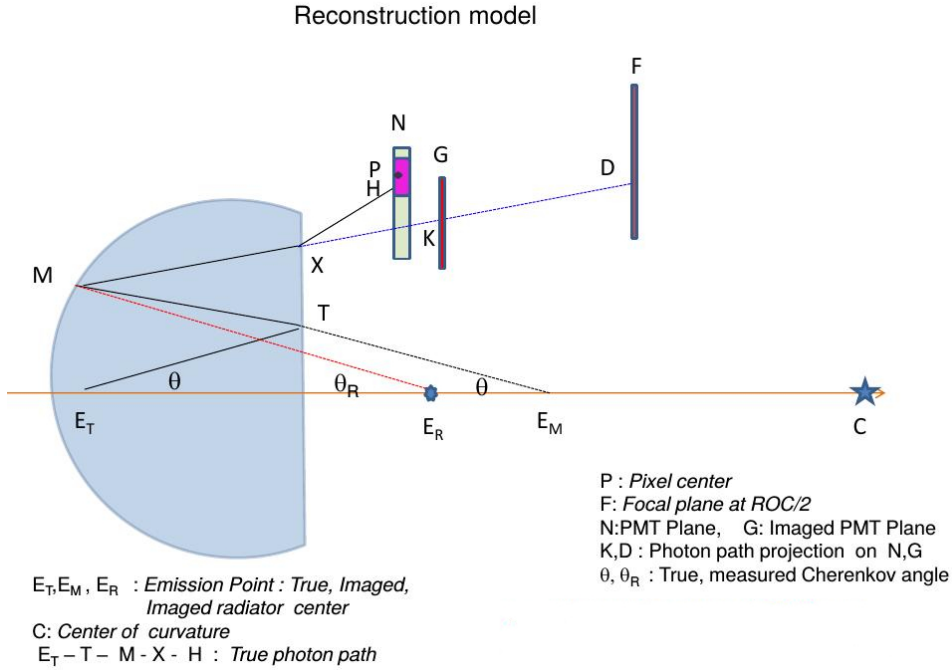


Figure 7.5: Schematic of the reconstruction geometry model used in the software to measure the Cherenkov angle from the LHCb RICH Upgrade prototype data.

The reconstruction procedure is identical for both the simulated and the real data. From the event photon hit map we obtain the point D for each pixel hit in the event. Since D , M , C and E_R are coplanar a quartic equation can be employed to obtain the point M for each photon track and consequently measure the Cherenkov angle θ_R between the beam axis and the line $M-E_R$. The true Cherenkov angle θ measurement cannot be obtained, at least for real data, because in the reconstruction process every photon is

assumed to be emitted from the center of the radiator medium, i.e. from E_R . The difference between the true and measured Cherenkov angle is accounted in the Emission Point error contribution. The Cherenkov ring radius is measured, for each photon hit, as the distance of that hit from the centre of the ring. The centre of the ring can be set to a nominal value (i.e. the z -axis) or can be evaluated using the average of the coordinates of the photon hits for each event. Alternatively, the Cherenkov ring radius can be obtained using the least square circle fit method (appendix B). The ring radius value is slightly different depending on the decision to consider the real or the imaged MaPMT plane. This is due to the refraction effect on the outgoing photons from the lens. Hence the Cherenkov ring radius measured in the real MaPMT plane is larger than the radius measured in the imaged plane. In order to obtain more realistic measurements of the Cherenkov radius and angle, a random point on the pixel hit by a Cherenkov photon can be considered instead of the pixel center, moving the points K and D accordingly.

The reconstructed Cherenkov angle is affected by the three main error sources described above, which can be evaluated using the simulated data.

The Emission Point contribution is due to the emission point approximation and to the unfocused reflected photons, since the true focal plane cannot be used and the photons are reflected onto a non-optimal (from the optical focus point of view) surface. This error contribution is evaluated by reconstructing the Cherenkov angle for Monte Carlo data using the true photon hit point (a parameter available only for the simulated data) and by setting the refractive index of the radiator lens to its average value (constant).

The Chromatic Error is due to the different wavelengths of the Cherenkov photons that experience different refractive indices in the radiator medium. To evaluate this contribution, the Cherenkov angle is reconstructed using the true hit point of the simulated data and their true emission point. Hence, the only uncertainty left can be ascribed to the chromatic contribution.

Lastly, the Cherenkov angle is reconstructed using both a random point on the pixel hit and the true hit point on the pixel and the distribution of the difference between the two measure is obtained. This error is defined as the Pixel contribution and it is used to evaluate the effect of the finite granularity of the photon detection system.

In Figure 7.6 the three distributions used to evaluate the Cherenkov angle resolution contributions are reported. In the Emission Point and in the Chromatic Error distributions a two-peak structure is visible, due to the pixel size effect being too dominant. Nonetheless, the Cherenkov angle contributions can be correctly evaluated by fitting the distributions with a

Gaussian PDF using ROOT. For each plot a stat-box is present, where several parameters are reported. The first three parameters are automatically generated by ROOT when creating an histogram: the number of data in the histogram (Entries), the histogram average value (Mean) and the data spread around it (RMS). Then the ROOT fit parameters are reported: first the reduced Chi-squared of the fit, then the three Gaussian PDF parameters with errors. In this case we have the Gaussian PDF amplitude (Constant), the average value (Mean) and the Standard Deviation (Sigma). The Standard Deviation parameter of the obtained fit function is the Cherenkov angle resolution contribution.

The Cherenkov ring radius has been measured on the image G plane using a random pixel point on the pixel hit, and the beam center has been calculated by averaging on the hit points coordinates. The obtained value from the real data is compatible to the one of the simulation. The Cherenkov ring radius has also been calculated using the least square circle fit method on the actual MaPMTs plane. The mean value for the radius in this case is bigger than the one of the previous measurement because of the refraction effect on the photons when exiting the lens. Its mean value is compatible with the one of the Monte Carlo data reconstructed Cherenkov ring radius on the actual plane. From both the simulated and the real data is possible to extract the average number of hit per event, that is the average number of emitted Cherenkov photon per particle that radiates in the lens. The values for the reconstructed Cherenkov angle, for the three Cherenkov angle contributions and for the Cherenkov radius in the different cases are reported in Table 7.1.

Measure	Real Data	MC
Cherenkov angle [rad]	0.8738 ± 0.02392	0.8787 ± 0.02387
Emission point contribution [rad]	/	0.01306
Chromatic contribution [rad]	/	0.01049
Pixel contribution [rad]	/	0.01696
Total contribution [rad]	/	0.02384
Cherenkov radius (image MaPMT plane) [mm]	57.15 ± 1.57	56.99 ± 1.46
Cherenkov radius (actual MaPMT plane) [mm]	61.05 ± 1.85	60.76 ± 1.79
Cherenkov photons per particle	33.3	32.8

Table 7.1: Cherenkov ring and angle measurements from the LHCb RICH Upgrade prototype data using the reconstruction software.

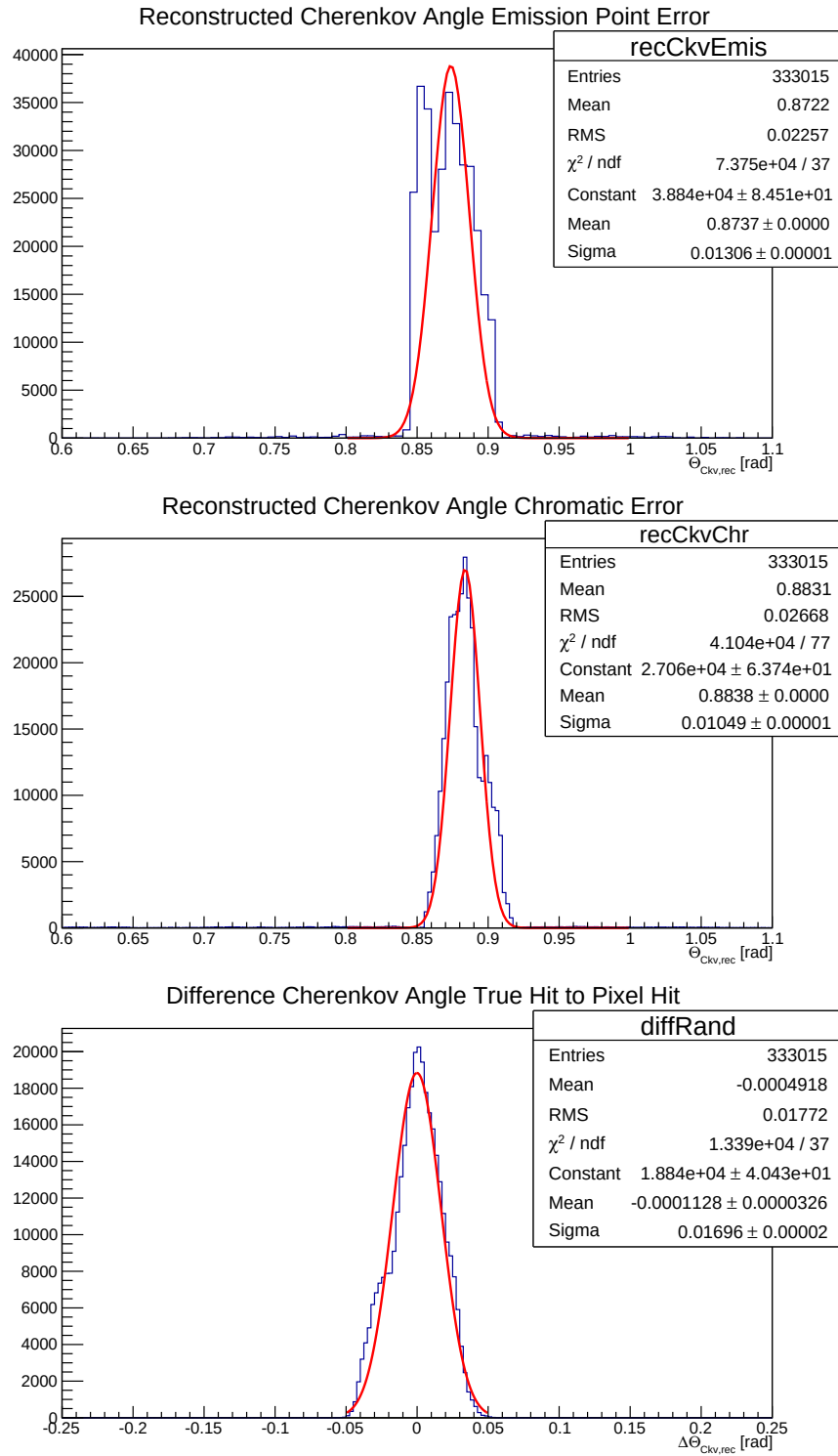


Figure 7.6: Cherenkov angle contributions obtained from the reconstruction software for the LHCb RICH Upgrade prototype.

7.2.2 Threshold scan

The Threshold Scans at the tests-beam have been performed using both the beam or a LED as a light source. The LED has been placed in the box in front of the MaPMTs, facing the wall of the box where a white sheet of paper was attached to uniformly reflect the LED photons onto the MaPMTs plane. The aim of this test is to find the optimal thresholds (or working point) for each CLARO channel in the prototype using the upgrade full opto-electronic chain in a realistic environment. The optimal threshold is the CLARO threshold at which most of the noise is cut-off and a very little portion of the true physical signal is excluded. Even though the measurement is performed in the same way with both the LED and the beam, the LED provides a uniform illumination on the MaPMTs plane and we can expect that each channel approximately register the same hits number. When using the beam the CLARO channels corresponding to the MaPMTs pixels on the Cherenkov ring will have a way bigger number of hits with respect to the others, albeit every channel will have a non-zero hits number for a long-enough Cherenkov light exposition. During the tests-beam both Threshold Scans with the beam and with the LED have been acquired, but the CLARO optimal threshold per channel has been extracted using the LED as light source to obtain uniform and high enough illumination over all the MaPMTs pixel. The Threshold Scans have been taken at the MaPMTs operative voltage of 950 V, 1000 V and 1050 V to analyze the variation of the MaPMTs gain with the voltage. The expected result is a shift of the first photoelectron peak to higher threshold values for increased voltage. Each scan starts at threshold zero and finishes at threshold 63. The threshold value is changed once the maximum number of trigger events has been collected. The number of trigger event is set in the DAQ GUI and its registered value in each run is based on the combined information coming from the VELO and the RICH trackers. For a precise study of the noise distribution (that is the pedestal), the Offset bit of the CLARO channels has been set to 1. This option performs a shift of the threshold value of -32. Only when using this option it becomes possible to obtain the detailed shape of the pedestal for every channel. For some channels a portion of the first photoelectron peak is visible as well. Without seeing the pedestal for a CLARO channel it's impossible to set the optimized threshold for that channel. In Figure 7.7 is reported a typical Threshold Scan histogram. Each bin correspond to a threshold value and its height corresponds to the number of times in which the channel has been switched on during an event (that is a trigger count). The histogram has been then normalized to the maximum number of collected events, as set on

the DAQ GUI, hence the maximum bin height becomes 1.

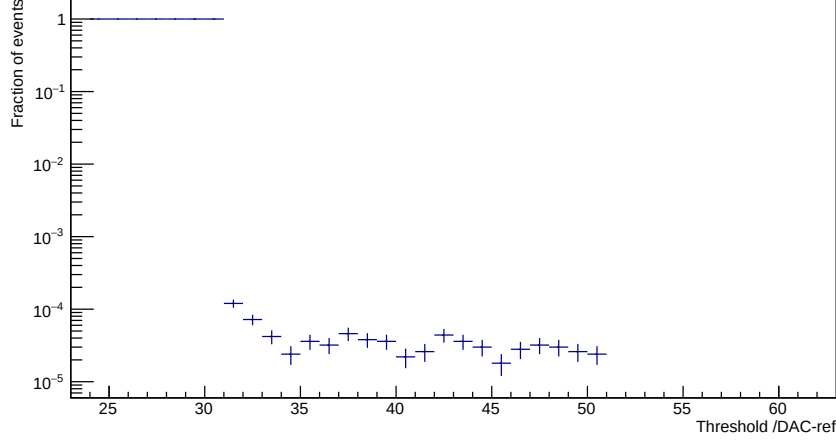


Figure 7.7: Typical threshold scan distribution obtained during the tests-beam.

The obtained threshold scan distribution is the integral form of the typical photoelectron spectrum shown in Figure 7.8. The expected distribution presents several peaks: the leftmost peak is the pedestal, generated by the electronic noise of the CLARO channel; at the right-hand-side of the pedestal there will be a peak corresponding to the signal generated by a single photoelectron emitted from the MaPMT's pixel when hit by a photon.

To obtain the parameters of the threshold scan distribution a fir procedure using ROOT on dedicated scripts has been developed. The fit function is a linear combination of Complementary Error Function (ERFC) Probability Density Functions (PDFs). The Error Function $\text{ERF}(x)$ PDF is defined in Equation (5.1) and correspond to the integral of the Gaussian PDF. The $\text{ERFC}(x)$ PDF is defined as:

$$\text{ERFC}(x) = 1 - \text{ERF}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt \quad (7.1)$$

A direct connection therefore exist between the Gaussian PDF and the $\text{ERFC}(x)$ PDF.

The PDF used to fir the Threshold Scans from tests-beam data has been built by taking into account one contribution for the pedestal and a contribution for each possible photoelectron peaks up to a maximum of three peaks. The four $\text{ERFC}(x)$ PDFs are weighted by a Poisson distribution probability coefficient proportional to the average number of photoelectrons produced in

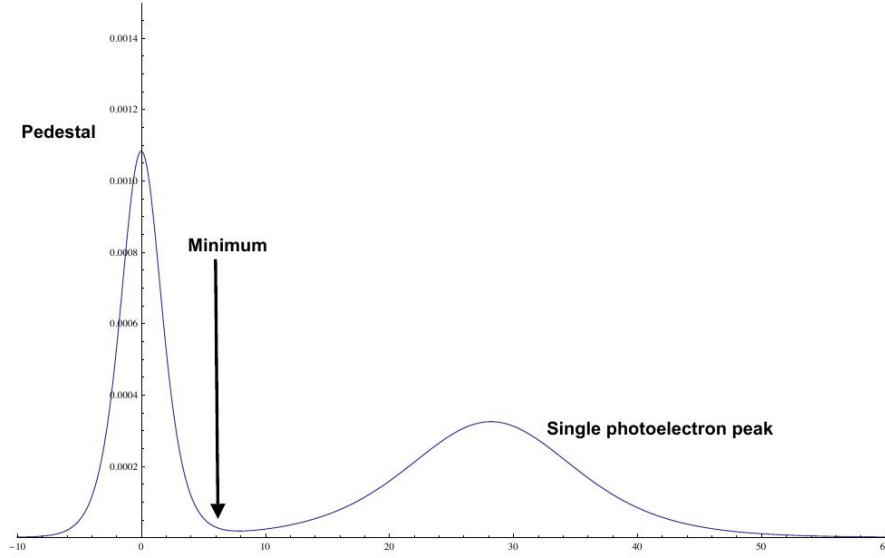


Figure 7.8: Schematic of the single photoelectron spectrum, that is the expected signal spectrum for the CLARO channels. Additional peaks can be found at higher threshold values, corresponding to multiple photoelectrons emitted per MaPMT photon hit.

the MaPMTs channels per photon hit in the entire test. The photoelectron number depends on the MaPMTs parameters like QE, cross-talk, conversion efficiency, as well as on the light source (LED) intensity. The FIT PDF equation is the following:

$$\begin{aligned} \text{FIT}_{\text{ThresholdScan}}(x) = & \frac{p6 \cdot P(0, p0)}{2} \text{ERFC} \left(\frac{x - p3}{p4} \right) \\ & + \sum_{n=1}^3 P(n, p0) \cdot \text{ERFC} \left(\frac{(x - n)p1}{p2\sqrt{n} + p5} \right), \end{aligned} \quad (7.2)$$

where $P(n, p0)$ is the Poisson probability to obtain n events given $p0$ average number of events.

The fit PDF has seven free parameters to be determined with the fit.

The parameter $p0$ is the average number of emitted photoelectron per photon hit. It has been calculated assuming a Poissonian emission probability for the photoelectrons inside the MaPMTs pixels.

The parameter $p1$ is the x-coordinate, that is the threshold, of the n -th peak transition point. The product $n \cdot p1$ is necessary to correctly fit the

multiple photoelectron peaks which are supposed to be found at constant distance $p1$ one from the others.

The parameter $p2$ is the slope of the photoelectron peaks, where the $\sqrt{n}$ factor is considered since a bigger spread for the peak at higher signal intensity is expected.

The parameter $p3$ is the x-coordinate, that is the threshold, at which the pedestal, considered standalone, would reach half of its height. We can call this parameter the pedestal transition point, in complete analogy with an S-Curve test.

The parameter $p4$ is the pedestal slope. The sum in the equation runs on the possible number of photoelectrons emitted, up to a maximum of three.

Lastly, $p5$ and $p6$ parameters are respectively the vertical offset and the amplitude of the distribution.

The most important parameter obtained during the test is the pedestal transition point from which the channel optimized threshold can be set. However, given the complexity of the used function, the fit efficiency is less than 100% and for some channels it fails. The study of the Threshold Scan fit function is still ongoing.

A simpler analytical method to extract the channel optimized threshold is to identify the pedestal right-most edge, that is the threshold at which the distribution height goes from 1 to the user-set value <1 , then the optimized threshold is set as that value plus 5 threshold steps. The downside is that no other information on the channel spectrum is obtained from the test. This last technique is used in the EC Quality Assurance procedure that will be discussed later in the thesis.

7.2.3 S-Curve

The S-Curve test is necessary to study the behaviour of the CLARO channels and to check the expected proportionality between the applied threshold and the transition point position. The S-Curve is performed with the MaP-MTs switched off. The signal is injected in each CLARO channel from the DBs 8-bit DAC. The DAC step size is of about 16 ke^- (considering the internal capacity of the CLARO of $\sim 640 \text{ fF}$) for a total of 256 steps. The channels have a fixed threshold for each different acquisition, and acquisitions at different threshold have been taken. Per each test step the maximum number of signals, which has been set in the DAQ GUI panel, is sent to CLARO test inputs. The digital board registers the number of times that every channel has switched on for that DAC step compared to the total number of signals

injected and then increases the signal amplitude. What is expected is that the channels are more likely to be switched on as the signal amplitude increases. As a result we obtain an s-shaped signal distribution, the transition point of which can be used to adjust the optimal operative threshold of each channel. The distribution is normalized to the maximum number of signal injected per DAC step. If the threshold applied to the channel is increased, the transition point is expected to be found at higher signal amplitude. The linear response of the CLARO channel can be verified by reporting the transition point variation as a function of the channel threshold. The spread of the distribution is expected to increase as well when the threshold increases, since a higher injected signal means a higher noise in the system. In Figure 7.9 is shown the typical S-Curve distribution for a CLARO channel. The relative big error on the fit parameters is due to the very steep transition (usually one or two DAC steps) which makes it difficult to perform the fit: the distribution is more similar to a step function than to an S-Curve.

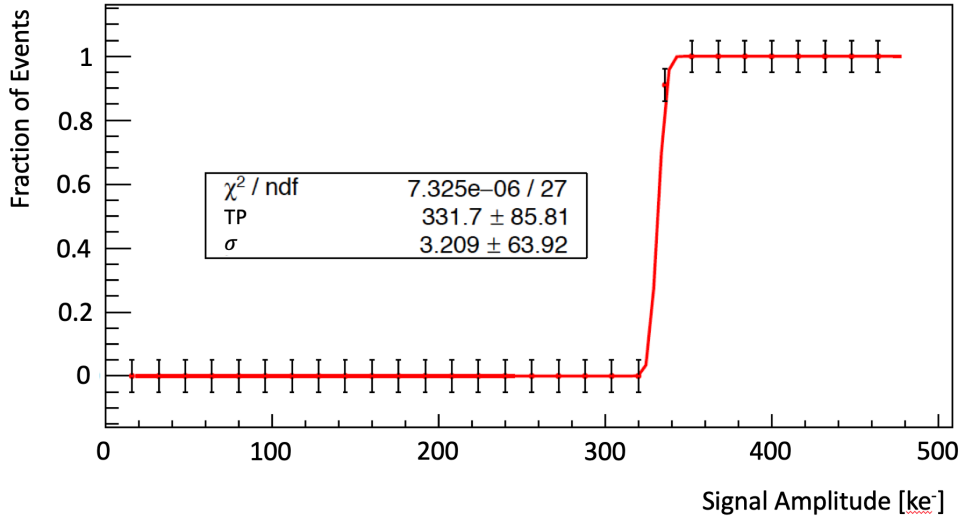


Figure 7.9: Typical S-Curve distribution obtained during the test-beam S-Curve tests.

The distribution is expected to be an S-curve, that is the integral of a Gaussian distribution. A fit technique as for the Threshold Scans can be used to extract the parameters of interest. The fit function used (red) is the translated ERF PDF reported in Equation (5.2). The error associated to each point has been evaluated to account for electronics oscillations and deviations from the expected distribution.

The S-Curve tests are performed at fixed threshold. Data at different

thresholds have been acquired to study the variation of the transition point as a function of the applied threshold. In Figure 7.10 is shown the linear behaviour of the transition point, obtained from the fit of the S-Curve at the corresponding threshold, as a function of the channel applied threshold. The error associated to each point is obtained from the fit itself. The linearity plot can be fitted with a linear function to obtain two parameters (in ke^-) per channel: the channel offset threshold, that is the fit y-axis intercept and it's named p0 on the plot, which is an intrinsic feature different per each channel; the slope of the linear fit which represent the number of ke^- per threshold step for that channel, p1 on the plot. The offset threshold is the reason why it's possible to see the pedestal only for some channels when running a threshold scan with the offset bit at 0. Two CLARO channels set at the same threshold with the same input signal amplitude might exhibit a different behaviour because the offset thresholds they have are very different from one another. It is therefore important to fully characterize the CLARO channels and register all of their parameters.

Even if the function used to obtain the S-Curve transition point and slope is simpler with respect to the Threshold Scans one, the fit may not succeed 100% of the time. This might happen for different reasons: the channel might be problematic (non monotonous distribution, the channel is dead and doesn't count, the channel is noisy and register a number of counts higher than the maximum set in the DAQ GUI...) or, as it can be seen in Figure 7.9, the distribution obtained is so steep that a correct evaluation of the parameters can't be performed. In particular, the slope is

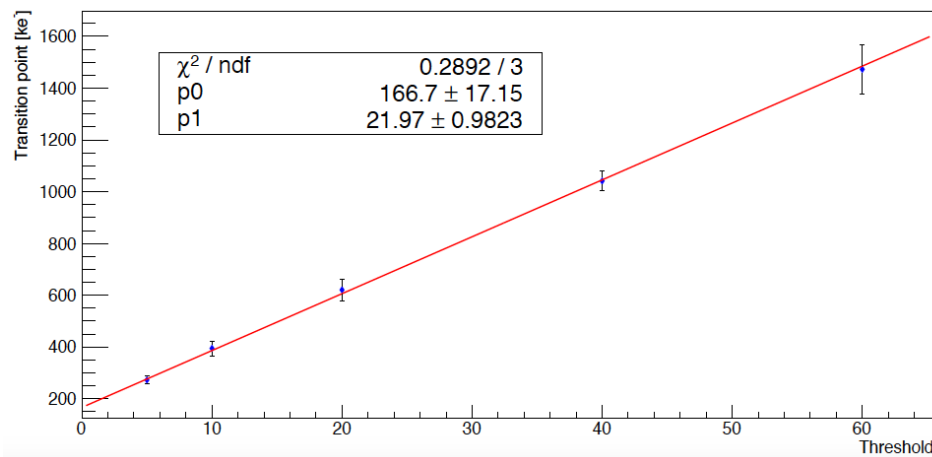


Figure 7.10: Linearity plot obtained for a CLARO channel during the tests-beam S-Curve tests.

underestimated. In the data acquired during the tests-beam all the S-Curve tests shows this feature, and that is due to the DB DAC resolution. For this reason a different evaluation method for both transition point and slope has been developed, called Pattern Recognition.

As reported in Figure 7.11, two limits are set in the S-Curve transition region. The transition point for that channel will be the x-coordinate of the point in between the last point below the lower limit and the first point above the upper limit. An upper limit for the slope is then evaluated by counting in how many DAC steps the transition happens (usually one or two DAC steps). The Pattern Recognition method is more reliable because it doesn't require to converge like a fit. The downside is that eventual problems have to be found "manually" by adding controls and exceptions to the analysis algorithm, while with the fit we can use the reduced Chi-square parameter to spot possible problematic channels.

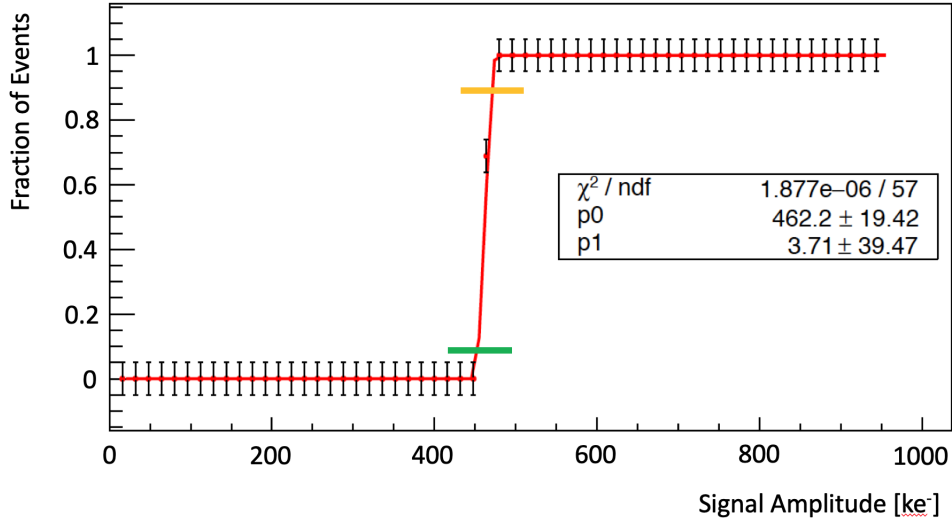
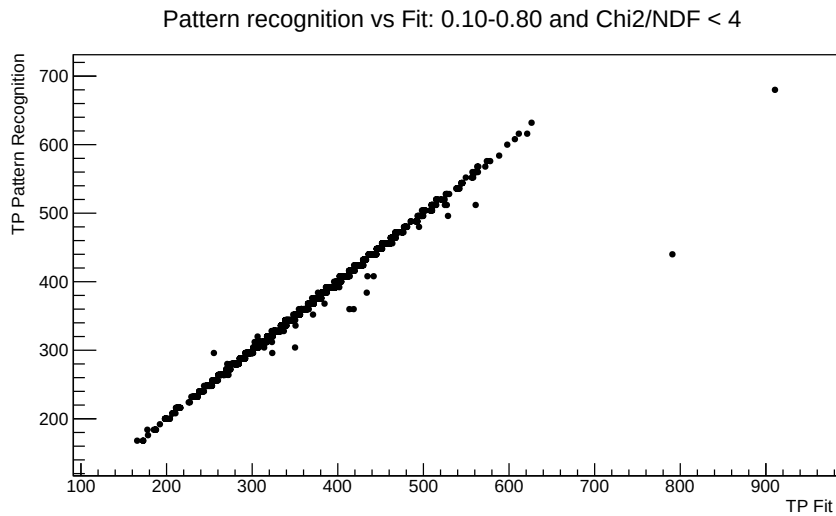


Figure 7.11: Visualization of the Pattern Recognition method, with the lower limit (green) and the upper limit (yellow).

A comparison between the transition point obtained from the fit and this method has been performed. For the Pattern Recognition method different limits have been set. Only channels for which the reduced Chi-square < 4 from the fit have been taken into account. In Figure 7.12 the transition points evaluated with the Pattern Recognition are plotted as a function of their correspondent value obtained from the fit. Two different pairs of upper and lower limits are set while the condition on the reduced Chi-square is fixed. If the transition point is found to be identical in the two methods the

obtained distribution would be a line. We can see few outlier channels in the distribution with Pattern Recognition limits 0.10-0.80 (top plot), probably being underestimated in the Pattern Recognition method with respect to the fit. When the limits are reduced to 0.20-0.70 (bottom plot) the distribution converge to a line, except for two problematic channels for which the fit failed, while the value found with the Pattern Recognition method is in the same range as the others.



Both method can be used when analyzing the S-Curves. The Pattern Recognition method is more reliable and easier when it comes to evaluate the transition points, but can't be used to correctly evaluate the S-Curve slope. Possible problematic channels can be spot by controls and exceptions handling inserted manually in the analysis algorithm. The fit gives a complete overview of the S-Curve parameters, when enough DAC resolution is available, but requires a correct initialization of the parameters to converge. The reduced Chi-square is a powerful tool to check for errors and problematic channels but an in-depth analysis of the problems is required anyway.

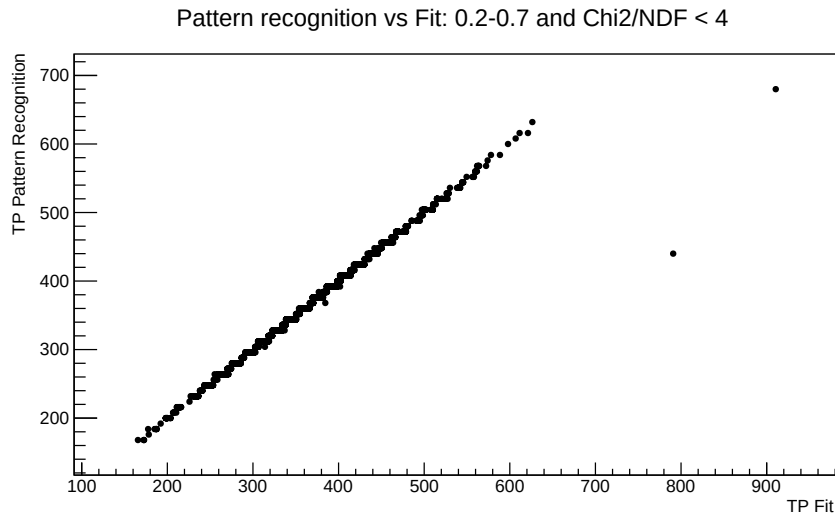


Figure 7.12: Distributions obtained for the comparison of the transition point evaluated using the Pattern Recognition and the fit. By choosing different upper and lower limit for the Pattern Recognition method the transition point value obtained can be adjusted.

Chapter 8

The LHCb RICH Upgrade Quality Assurance procedures

The Ferrara LHCb RICH Upgrade Group has been accounted responsible for the Quality Assurance procedure on the entire CLARO ASIC and FEBs production for the experiment upgrade. In addition, the group has been accounted responsible for the QA procedure on half of the ECs production for the upgrade. The Edinburgh RICH Upgrade group is responsible for the QA on the other half of the RICH EC production. For the upgrade the total number of CLARO needed is 32'000, and 40'000 have been produced taking into account spare components. After being tested with a dedicated QA procedure, the ASICs have been sent to Studioemme[®], the italian company¹ responsible for the FEBs production, where they have been soldered on the FEBs. The boards have then been tested at the company site using the QA setup and procedure developed by the Ferrara RICH Upgrade group, and then they have been sent at CERN where a random sample quality check has been performed. For the EC QA procedure the required components (MaPMTs, metal chassis, FEBs, Bkbs and Bbs) are sent to Ferrara where the ECs are assembled using a well-defined mounting protocol and then tested. The EC which pass the QA procedure are then shipped at CERN where they will be installed in the new RICH detectors.

In this chapter first the CLARO QA procedure, then the FEB QA procedure and finally the EC QA procedure will be presented in details.

¹<https://www.studioemme.it/en/>

8.1 The CLARO QA procedure

The validation of the entire CLARO production for the LHCb RICH Upgrade took place in Ferrara using two identical test stations and a dedicated test protocol.

The QA procedure is performed by a pick-and-place test station (Figure 8.1) controlled by a Windows OS based PC running the control software designed using National Instrument LabVIEW (Figure 8.2). The hardware part of the station consists of a motorized XY (horizontal plane) gantry system, model G-LSQ450B450B-T4-K0048², and a motorized linear stage used for the Z (vertical) direction, model LSM050B-T4³. Both the XY and the Z systems are produced from Zaber[®] company. The XY system is able to move for 450 mm×450 mm with an accuracy of 45 μm per movement, with accuracy of 4 μm when repeating the movement. The maximum movement speed is of 120 mm/s. The Z system can travel for 50 mm with an accuracy of 15 μm per movement, with accuracy of 4 μm when repeating the movement. The maximum movement speed is of 104 mm/s. The ASICs to be tested are placed on a tray put on the test station floor. The QA test is performed on one chip at a time. The movable stage travels to the selected chip position and pick it up using a pneumatic suction cup (produced by SMC[®], model ZPR06UNK6-06-A8⁴), releasing it on a socket designed to improve the alignment of the chip with the test socket. After being picked up again, with an improved XY alignment, the chip is released onto the test socket where the QA test is performed. The setup pressure sensor regulates the force exerted on the chips during the procedure in order to avoid any kind of damage. The test socket is housed in a custom CLARO burn-in card, an electronic board designed by the institutes INFN Ferrara, INFN Milano-Bicocca and the AGH of Krakow. The board is then read-out by an Altera MAX10 FPGA development kit board connected via ethernet to the control PC. A plastic peg has been used to keep the CLAROs under test in the correct position in the test socket. The use of the peg has been proven useful to reduce communication/contact problems between the ASICs and the burn-in card.

The test protocol has been developed in such a way that all the CLARO parameters are analyzed to spot any possible problem. During the QA test all the data acquired are recorded in a dedicated log file per chip.

²<https://www.zaber.com/products/xy-xyz-gantry-systems/G-LSQ/details/G-LSQ450B450B-T4>

³<https://www.zaber.com/products/linear-stages/LSM/details/LSM050B-T4/features>

⁴<https://uk.rs-online.com/web/p/suction-cups/2273705/>

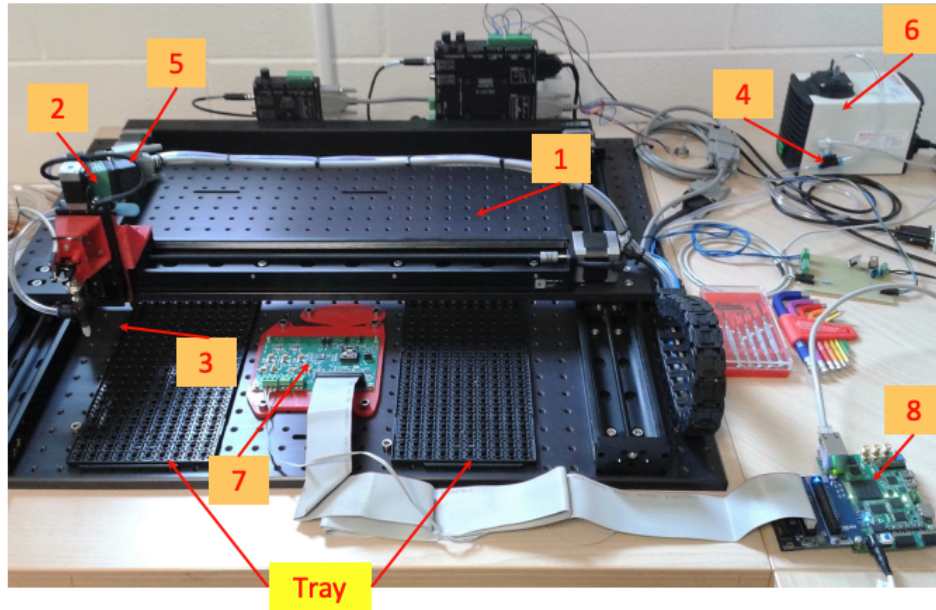


Figure 8.1: CLARO QA station (Station1) for the validation of the LHCb RICH Upgrade ASIC. The XYZ motorized system for the pick-and-place procedure (1) uses a pneumatic suction cup (2), an air compressor (6) and a pressor sensor (3) to move the CLAROs from the left-hand side tray to the test socket on the CLARO burn-in card(7). The system vacuum is regulated by a dedicated valve (4) and pump (5). The DAQ is driven by the ALTERA MAX10 FPGA development kit (8).

1. Power Up and current measurement:

right after the ASIC is put on the test socket it is powered up and the three currents (analog, digital, digital core) are measured as the average of three samples of each current acquired in two seconds. If any of the current measurements exceeds the limit threshold, set at 10mA for the analog current and 4 mA for the two digital currents, then the eight channels level out, that is the voltage measured at the channels output, is measured by taking 10 sample in 1 second, the configuration channels configuration is read-out (it should be zero for all the channels since no configuration has been sent to the channels yet) and saved. The chip is then powered off and put aside, since the test is considered failed. If the current measurements don't exceed the threshold the test can continue.

2. Configuration R/W:

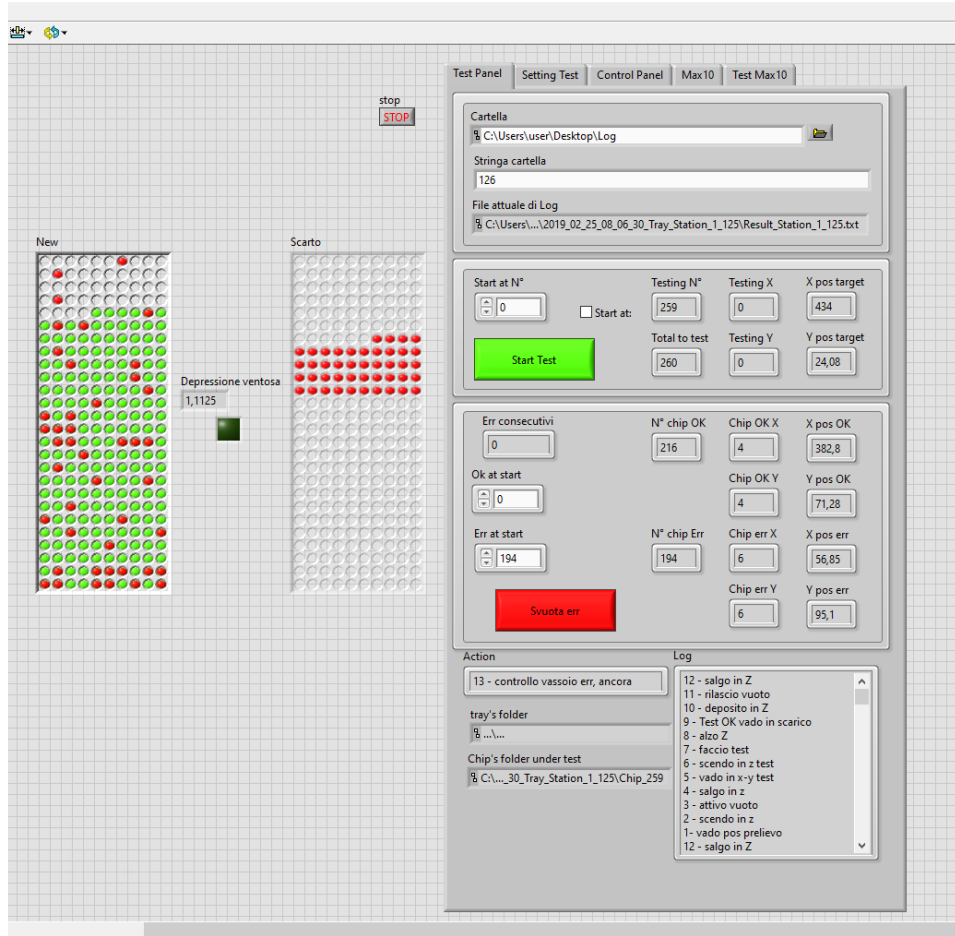


Figure 8.2: CLARO QA test software overview. On the left-hand side of the panel an overview of the current tray test is reported: the chips are picked from the left-hand side tray and the ones which don't pass the test are put in the right-hand side tray, flagged as red in both trays. On the right-hand side of the panel the control/monitor tool allows to check the status of the current test, of the actual set parameters and allows to change parameters of the test setup (XYZ system) and of the test protocol.

the chip channels configuration is read-out (as before, it is expected to be zero for all channels but the test is not considered failed if otherwise) and the first configuration is sent to all the channels. The hexadecimal configuration code used for the 12-bits of the register is 0x314. As reported in Table 5.1, this configuration enables the channel, set its Hysteresis on and its threshold at 20. Any time a WRITE command is sent to the configuration register, during the entire test, a read-back

cycle is performed and a communication error message is generated if the read-back data doesn't match the data sent in the WRITE command. If this happens the chip QA test is considered failed.

3. Current measurement:

the next step is the measurement of the three currents, using the same method and limit threshold as before. If any of them is above the corresponding threshold the chip QA test is considered failed. It is important to measure the currents again because this time the CLARO channels are configured, which means the driven current is expected to be higher than in the previous evaluation. The eight channels level out are also measured and they must be above 2.1 V for the test to continue.

4. SEU simulation:

after these measurements a Single Event Upset (SEU) simulation test is performed. During this test a fixed number of SEUs are simulated in the chip register and the CLARO SEU counter has to detect a number of SEU identical to the number of simulated events. If that is not the case the chip QA test is considered failed.

5. Pulse test:

at this stage of the test a pulse test is performed in two steps. In the first step charge is injected in all eight CLARO channels in trains of 1000 pulses. Several patterns of enabled channels are used during this phase of the QA test: first all channels are enabled with configuration 0x314; then only the channels 0, 2, 4 and 6 are enabled with configuration 0x314 while the disabled channels configuration is set to 0x23F (that is channel disabled, Hysteresis on and threshold 63); after that only the channels 1, 3, 5 and 7 are enabled with configuration 0x314 while the disabled channels configuration is set to 0x23F; lastly all channels are disabled with register configuration set at 0x214, that is channel disabled, Hysteresis on and threshold 20. These different configurations and patterns are useful to check In the second step a single pulse is sent via the dedicated CLARO *tp_input* pin with all the CLARO channels enabled. A rising edge of the CMOS 2.5V signal connected to this pin triggers the injection of charge at the input of the enabled channels. The test is considered passed if all CLARO channels register the correct number of pulses sent (0 if the channel is disabled). The chip QA test is considered failed otherwise.

6. POR test:

a Power-On Reset (POR) cycle is performed through SPI. The POR generator has been designed to reset the flip flops of the TMR protected part of the configuration registers. After the action is completed the configuration is read-back and, if not all CLARO channels have configuration at 0, the chip QA test is considered not passed.

7. S-Curve test:

the QA test continues with the S-Curve test. The test is performed for only one channel at a time, set at threshold 20, while all the other channels are disabled. 1001 pulses are sent to the CLARO channel per each DAC step, ranging from 0 to 1000 (0-1000 mV) with 1 mV step and 0.5 pF input capacitance. However, the range on which the channel transition point has to be found is reduced to the values 100-280 mV. This range has been set since the majority of the channel transition points is found between these two values, as shown in the CLARO QA data analysis section. Channels with a transition point out of this range would contribute to inhomogenize the CLARO production performances. The algorithm to find the S-Curve parameters has 3 steps: first a binary search is performed in the range 100-280 mV to search a number of hit count different from 0 and 1001; starting from that value a fine scan is performed, decreasing the DAC value in steps of 2 mV until the output count is found to be 0 for two consecutive steps; lastly the scan is performed as above but increasing the DAC value in step of 2 mV, searching 1001 pulses. The S-Curve test is considered passed if the transition point found on that channel, obtained by fitting the distribution using a LabView routine, is between 100 and 280 mV, and then a file is generated containing the DAC values and the hitcounts in the fine scan range together with the transition point and slope (also obtained by the fit) values of the channel.

8. Offset scan test:

the next step is the Offset scan test, used to evaluate the optimal threshold for the CLARO channels by detecting the electronic noise pedestal. It's equivalent to a Threshold Scan but without the MaPMT signals. The test is performed on one channel at time. The DAC value fixed at 1280 mV but no signal is injected in the CLARO channel. The procedure is the following: one channel at a time is enabled, Hysteresis on, configured with Offset bit 1 and threshold 37 (0xB25 in hexadecimal) while the other channels are disabled (0x23F as be-

fore). The threshold of the channel under test is lowered (in steps of 1 threshold) until the output of the CLARO channel goes into saturation (hitcount read is FFFF). That threshold is defined as the Offset threshold for the channel. The Offset scan test is considered passed if the point of saturation is between 37 and 23 threshold value. At this point, if no errors occurred, the test is finished and the chip is placed in the tray it came from.

If during a chip test an error of any kind occurs (some value is over the limit threshold, or a test fails) the test is performed again on the chip from the start, and this can be repeated other two times. The CLARO chip is not moved by the pick-and-place robot arm between the tests, but it is released and re-pressed on by the plastic peg which is keeping it in position. If the CLARO chip fails the test for 3 consecutive times it is moved to a second tray, named error tray, placed next to the first tray, and it will be fully tested again up to a maximum of two times. The time needed to perform the full test sequence is: 10 s for power on sequence and pulse testing, 8 x 10 s to perform the S-Curve test, 10 s for the Offset scan and 60 s for all the movements and the alignment procedure, for a total of 160 seconds if no errors occur.

8.1.1 CLARO QA data analysis

Before starting the CLARO QA procedure an analysis has been performed to validate the two test stations and to ensure that the results coming from one station are comparable to the other station results. A tray with 180 chips has been tested using the QA procedure in both stations and the results have been compared. In Figure 8.3 are reported the transition point distributions for the two stations. The number of entry is the number of tested channels. The parameters Mean and Std Dev in the stat-box are given by ROOT when creating the histogram. The parameters Overflow and Underflow are calculated by ROOT and they simply are the number of data out of the histogram x-axis limits, respectively over the maximum or above the minimum histogram x value. These parameters are useful to check that all the analyzed data are reported in the histogram. Some CLARO channels were problematic during the test in one of the two stations, and only the channels which have been correctly tested on both stations are reported in the distributions. The average value for the transition point is almost identical in the two stations, while on the station named Station2 the distribution presents a slightly bigger width due to about ten outlier channels.

However, except for those channels, all the transition points are in the limit 100-280 in the DAC ref. scale which correspond to 100-280 mV, hence the threshold imposed in the QA procedure. A similar plot can be obtained also for the S-Curve spread, or sigma (Figure 8.4). This last distribution suggests that for a tens of channels in Station2 the measured electronic noise is slightly higher with respect to the noise in Station1. However the transition point is correctly evaluated also for the channels with an higher sigma, and no selection criteria is applied on the channel noise during the QA procedure.

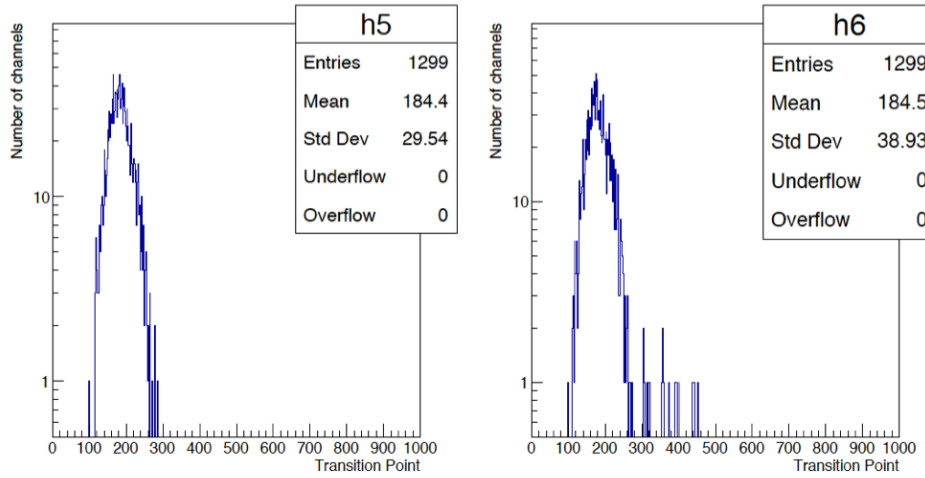


Figure 8.3: Pre-QA data analysis on the CLARO chips, transition point distribution obtained using C++ ROOT script. Left: Station1 data. Right: Station2 data.

The S-Curve transition points and the sigmas reported in these plots are obtained by a dedicated analysis C++ script with CERN ROOT, which fits the S-Curve distributions using the function (5.2) reported in Section 5.1.2.1. The same plots can be obtained using the LabVIEW routine implemented in the CLARO QA procedure (Figure 8.5 and Figure 8.6). This type of analysis has been performed to ensure that the LabVIEW routine is correctly evaluating the S-Curve parameters by comparing it to an analysis tool of well-known efficiency that is ROOT. The distribution obtained using the LabVIEW report the exact same MEAN value for the transition point with a difference of $\sim 0.3\%/4\%$ on the distribution spread for Station1/2. We can therefore use the LabVIEW routine for the S-Curve parameters extrapolation.

The results coming from the two CLARO QA test stations have been considered comparable, hence the QA procedure has been performed using them both.

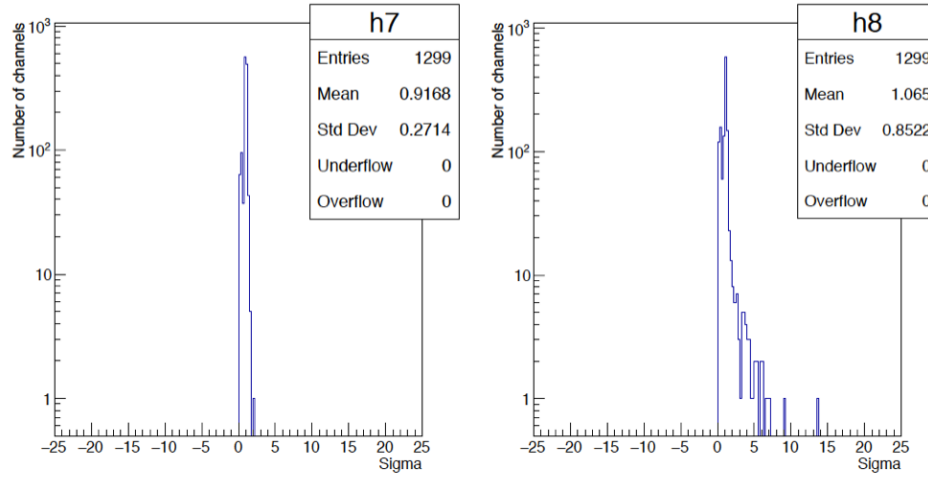


Figure 8.4: Pre-QA data analysis on the CLARO chips, sigma distribution obtained using C++ ROOT script. Left: Station1 data. Right: Station2 data.

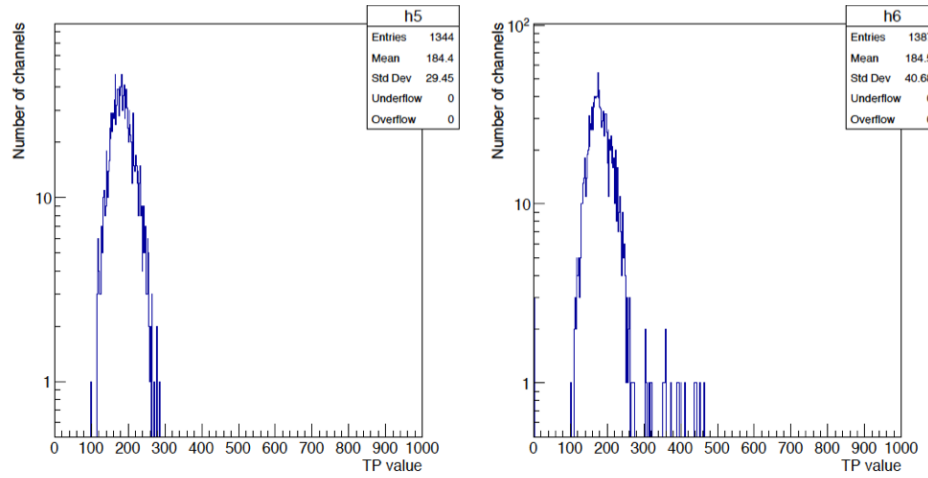


Figure 8.5: Pre-QA data analysis on the CLARO chips, transition point distribution obtained using LabVIEW routine. The results are almost identical with respect to the C++ ROOT script analysis. Left: Station1 data. Right: Station2 data.

A detailed analysis has been performed on 9044 CLARO ASICs tested using the QA procedure. In Figure 8.7 are reported the transition point and sigma results from the analysis of the chips, which have been correctly tested at the first try during the procedure. In the transition point distribution (left-

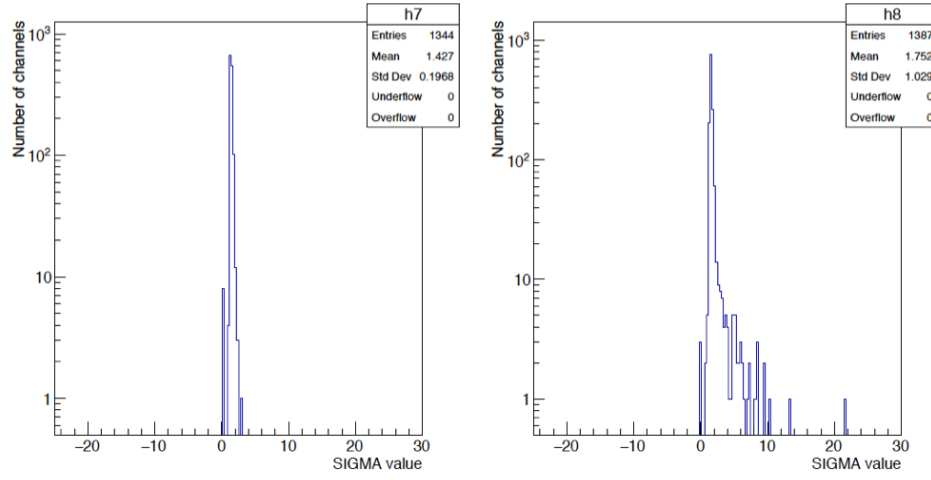


Figure 8.6: Pre-QA data analysis on the CLARO chips, sigma distribution obtained using LabVIEW routine. Left: Station1 data. Right: Station2 data.

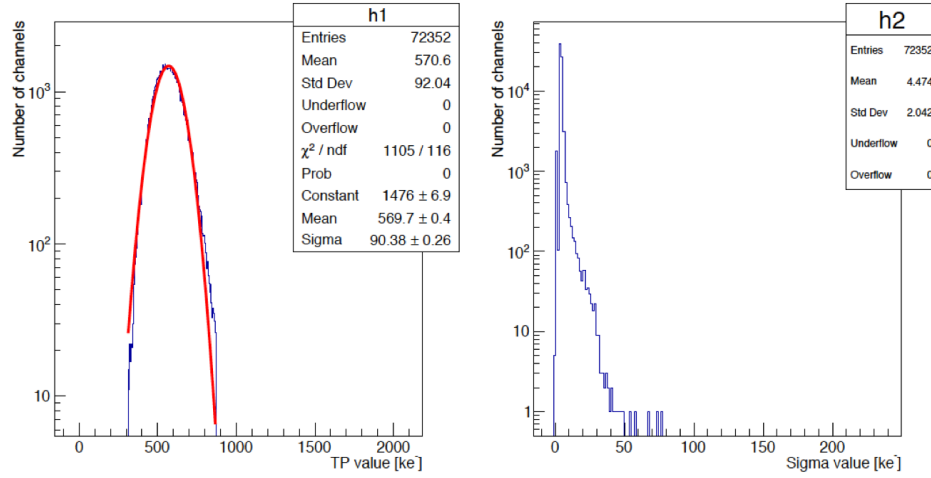


Figure 8.7: CLARO QA data analysis on 9044 CLARO chips tested using the QA procedure. Left: transition point distribution, which has been fitted with a Gaussian PDF to extract the average value. Right: sigma distribution.

hand side) we can see the cut edges at the 100-280 mV limits, or, in charge, $\sim 312\text{-}874 \text{ ke}^-$. It is important to notice that all the chips which failed the QA tests have been tested again up to a maximum of two times in case they continue to fail the test. The re-tests are performed days later one from another. This procedure has been applied to avoid the discard of good chips

which fail the test because of causes independent from the chips (e.g. dust on the test socket or natural parameters oscillations). In numbers, 75.61% of the CLARO chips have passed the QA test on the first try and 58.54% of the retested chips passed the QA test after a single re-test. Therefore after a single re-test iteration the good chips yield is of 89.89%. The final CLARO chip yield is close to 95% when considering two retest iterations.

8.2 The Front-End Board QA procedure

The CLAROs passing the QA procedure are assembled on the FEBs, which are the components used in the LHCb RICH Upgrade ECs. The FEBs produced are validated using a test setup developed by the Ferrara RICH Upgrade group before being assembled in the ECs. The FEBs are inserted in the Bkbs, which are then plugged into the test setup socket. The test setup (Figure 8.8) consists of four DBs, each one hosting two ALTERA MAX10 FPGAs. This type of DB is also used in the EC QA procedure, explained in the next section. Each FPGA controls two FEBs, hence up to four Bkbs (16/8 FEBs depending if the Bkbs are R/H-type) can be tested at once. The DBs are equipped with a 12-bit, 8-channels ADC per FPGA used to monitor the total current in the two corresponding FEBs, the temperatures of the two FEBs, of the Bkb and, once the ECs is assembled, of the Bb, and lastly to monitor the `vdd_core` tension (CLARO power tension) of all the CLAROs per each FEB.

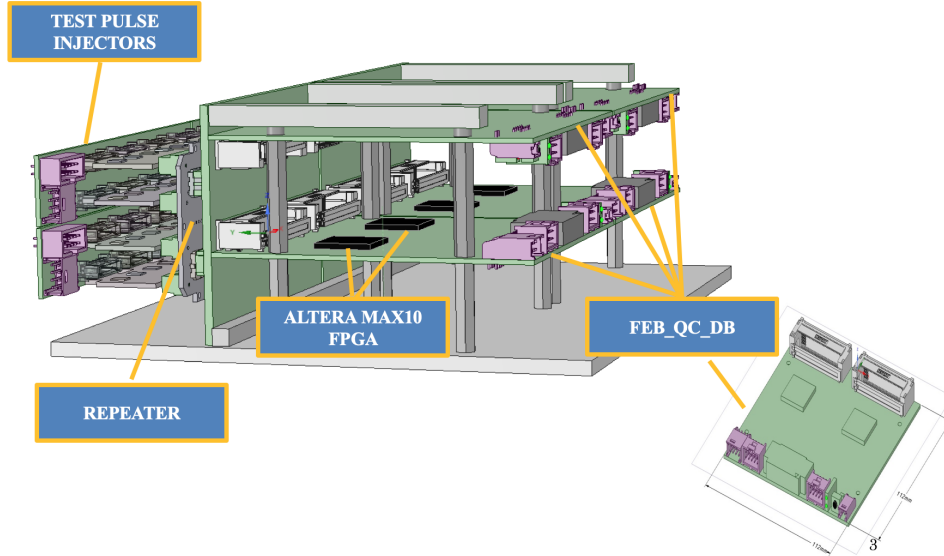


Figure 8.8: 3D model of the FEB QA setup with all its components. The repeaters are connectors used to avoid the deterioration of the DB connectors. On the left-hand side of the figure the DB measures are reported.

The communication between the FEBs and the MAX10 FPGA is performed via SPI protocol through the Bkb. A system controller works as the main controller for two DBs using high-speed mezzanine card connectors (HSMC) and an external cable-adaptor board. The system controller,

based on Cyclone V GT FPGA development board (5CGTFD9E5F35C7N, 1152-pin FBGA) is connected to the Host PC via Gbit Ethernet interface. The DB dialog with the system controller through an interconnection UART module. UART (Universal Asynchronous Receiver/Transmitter) is a physical circuit in a microcontroller which main purpose is to transmit and receive serial data. Each DB is equipped with two UART module, one per FPGA. Lastly, to perform S-Curve tests on the FEBs, a custom board called Test Pulse Injector (TPI) has been designed to feed signal into the CLARO channels. A single TPI board provides signal for four FEBs on two half Bkbs, as shown in Figure 8.9. It's possible to control the setup from the PC using dedicated python scripts which send the appropriate commands to perform each action. Three identical setup have been produced and distributed: one is in Ferrara, one at CERN and one at the production site, Studioemme[®] company. The CLAROs are sent from Ferrara to the company which solder them on the FEBs and produces also the Bkbs. Then the FEBs assembled on the Bkbs are tested using the setup provided by the Ferrara group. The valid ones are sent to CERN where a random sample check is performed.

All the FEBs main parameters are examined during the QA test by following a dedicated test protocol.

1. Power Up:

in the first test step the CLARO chips are switched on.

2. STATUS_1:

the FEBs current (measured for the FEBs couple for that UART), the temperatures and the VDD tensions (which is the CLAROs operative tension) are read-out by the DB ADC and the values are registered. The typical value for the CLARO VDD is 850 mV, while the typical value for the FEB currents with non-configured CLAROs is ~ 3 mA, increasing to ~ 30 mA when the CLAROs are configured. Higher values for these parameters trigger errors and the test is not passed.

3. CONFIG:

the third step is necessary to check that all the CLAROs are correctly configurable. The configuration 0x314 (threshold 20, channel enabled and Hysteresis on) is sent to each channel and then the channel configuration is read back to check that it has been correctly configured. In addition, a reset is sent to the nPOR pin of all CLAROs to reset the chip channels configuration, after which a read back of the channels

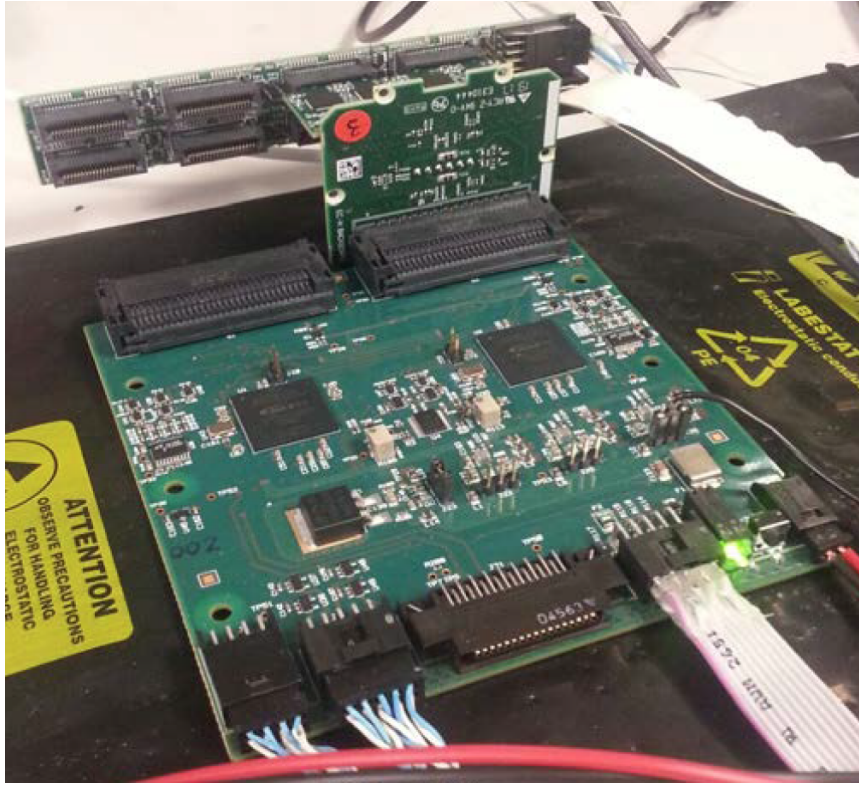


Figure 8.9: A digital board used in the FEB QA procedure. A Bkb with a FEB is connected to the FPGA UART connector on the right-hand side of the picture, and the TPI is attached to the FEB.

configuration is performed to check that the reset has worked correctly. If not, the test is not passed.

4. STATUS_2:

the fourth step performs the same actions as STATUS_1.

5. S-Curve test:

an S-Curve test is performed, in two parts, in parallel on all the MAX10 FPGA on up to 8 FEBs. A single chip per FEB is tested so that a maximum of 8 chips at a time are tested. First the signal is injected only in the even channels of the selected CLARO (S_CURVE_EVEN). The injection is performed through the even input pins and the value of the hitcounts through all of the CLARO channels output pins is read out. 1000 pulses are sent for each DAC step in the range 0x000-0x0F8 (0-300 mV, where 300 mV corresponds to approximately 2 Me^- injected

with a 1pF input capacitance) with a step size of 0x002 (~ 2.4 mV). A fit using the error function PDF is performed on the obtained S-Curve distribution. Warning messages are generated by the data processing function if the counts on the first DAC step are not 0 and/or on the last step are not 1000, or if the fit fails. However, these warnings do not stop the execution of the test but they are used to determine the outcome of the acceptance test. The transition points of the S-Curves for each active CLARO channel are registered in an output summary file. During this part of the test, the presence of crosstalk is verified by monitoring the odd channel hitcounts, which have to be zero. The S-Curve test, with the same parameters, is then performed on the odd channels. If one or more channels don't have the transition the test is considered not passed.

6. S_CURVE_TP:

an S-Curve test is performed on 8 channels at a time by injecting signal in them using the TP_IN pin, on the Bkb side, and then reading out the value of their hitcounts. A total of 1000 pulses per DAC step are sent. All the channels are configured with configuration 0x314, the signal is injected in the range 0x03C-0x192 (72-500 mV) with a DAC step of 0x002 (~ 2.4 mV). If one or more channels don't have the transition the test is considered not passed.

7. SEU simulation:

a SEU simulation test is then performed, where a fixed number of events is simulated in each chip and a check is performed to verify that the CLARO internal SEU counter correctly registered them.

8. STATUS_3:

equal to STATUS_1 and STATUS_2 but with the channels configured. The FEBs current is expected to higher at this stage of the test with respect to the first step.

The required time to test four Bkbs is 15 minutes. This time is independent on the Bkb type, R or H, and on the correspondent number of FEBs tested because the test parallelization is on the eight FPGAs.

A dedicated analysis has been performed on the S-Curve data coming from 36 of the first produced FEBs. For the test a 10-bit DAC, with a 1pF injection capacitor, as been used. Four type of S-Curve, named A,B,C and D, have been performed on each chip with different enabled channels

combination and different range and resolution of the injected signal: the A/B S-Curves are defined as a coarse scan, where 1000 pulses have been injected in the range 0x000-0x0F8 with a DAC step of 0x008 (0-1.2V, DAC step 40 mV), while C/D are defined as fine scan with 1000 pulses and signal range 0x001-0x030 with DAC step 0x002 (5-234 mV and DAC step 10 mV). All channels are enabled during the test but on A/C S-Curves the signal is injected only in odd channels while on B/D S-Curves the signal is injected in the even channels. The transition point distributions obtained for the CLARO channels of these FEBs in both fine and coarse scans are reported in Figure 8.10. In the coarse scan distribution (left) it's possible to see that the number of entries, i.e. of channel transition points, corresponds to almost 37 FEBs and not 36. This effect is due to the crosstalk between a odd and an even channel: only one of the two is pulsed at a time but if the signal injected has a very high amplitude, as in happens at the end of the coarse S-Curves, the signal propagates in the non-pulsed channel and a transition point is registered even if it should not. If the signal injected has a lower intensity, as in the fine S-Curves, the number of detected transition points is the nominal one. A fit using a gaussian PDF has been performed to extract the average transition point and to compare it with the CLARO QA value. The results are reported in Table 8.1. While the transition point value difference is of the order of 1% in the two tests, the distribution spread on the FEB QA results is 15% larger with respect to the CLARO QA tests, probably because of small differences in the signal injection parameters.

Test	Transition average value [ke^-]
CLARO QA	569.7 ± 90.4
FEB QA	576.9 ± 106.3

Table 8.1: Average transition point value comparison between the CLARO QA and the FEB QA results.

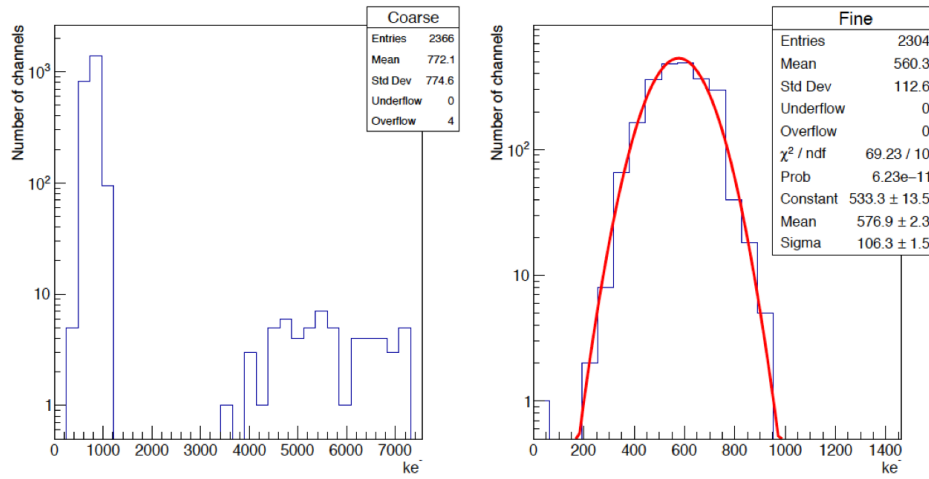


Figure 8.10: Results from the S-Curve data of 36 of the first produced FEBs for the LHCb RICH Upgrade. Left: coarse scan results, where the crosstalk is happening. Right: fine scan results. The transition point for a malfunctioning channel was close to zero, as it can be seen in the left corner of the right-hand plot.

8.3 The Elementary Cell QA procedure

The EC is the main component for the LHCb RICH Upgrade. It consists of the MaPMTs (4/1 R/H-type), of several electronic components (the FEBs, the Bb, where the MaPMTs are housed, interfacing them with the CLAROs, the Bkb interfacing the CLAROs with the DBs) and an aluminum case to contain them. Each electronic component of the EC and the MaPMTs are labeled using an adhesive QR code containing an ID code for that component. The electronic components and the case are assembled together following a well-established assembling procedure. After being assembled the QA test is performed on the EC to validate it. If the EC pass the test it is sent to CERN to be installed on the new RICH detector. The ECQA is performed using two identical test stations in both Ferrara (Station ID 1 and 2) and Edinburgh (Station ID 3 and 4). Each test station consists of a light-tight box (dark box) in which the ECs are mounted during the test. It has to be light-tight since the MaPMTs are switched on during the procedure. Inside the box up to four ECs can be mounted at the same time, as shown in Figure 8.11. They are connected to the same setup used for the FEB QA procedure (four DBs, eight UART connectors, a system controller placed outside of the box), which has been installed on the middle wall of the box. This wall stops possible photons coming from the service holes in the back of the box from reaching the MaPMTs placed on the other side of it. However, light is injected inside the box, in a controlled way, using an LED driver placed outside of it to perform tests with the MaPMTs. Four optic fibers are connected to the LED driver, entering the box and ending in the area of the box in which the ECs are mounted, facing the box wall. A mirror is mounted on that wall, so that the photons injected trough the fibers are reflected by the mirror onto the EC MaPMTs. The MaPMTs are connected to the high voltage (HV) crate, ISEG ECH 242⁵ equipped with an ISEG crate controller model CC24 Master⁶ and two 8-channels HV power supply ISEG boards EHS 8020n_SHV⁷. A single crate is used in each test location to pilot the HV for the two test stations. A load of 4 ECs uses 4 channels of the HV board, one per each Bb. The MaPMTs are air-cooled by a fan system providing a continue airflow: air flows in the vertical direction directly onto the MaPMTs and on the Bbs from the lower part of the box, being then aspirated from the upper side of the box just right-after it passes the MaPMTs. The cooling is also provided for the DBs. The fans, together with the DBs, are powered

⁵https://iseg-hv.com/files/media/iseg_manual_ECH24x_en_20.pdf

⁶https://iseg-hv.com/files/media/iseg_manual_CC2x_en_14.pdf

⁷<https://iseg-hv.com/en/products/detail/EHS>

by a low voltage (LV) power supply, Aim TTi EX354RT⁸, placed outside the box. The environmental temperature and humidity are monitored using a Raspberry Pi system which creates a log file on which the environmental parameters are registered every 10 seconds. The entire system is controlled by a CENTOS7 OS PC running a DAQ control software designed in National Instrument LabVIEW 2017 64-bit.

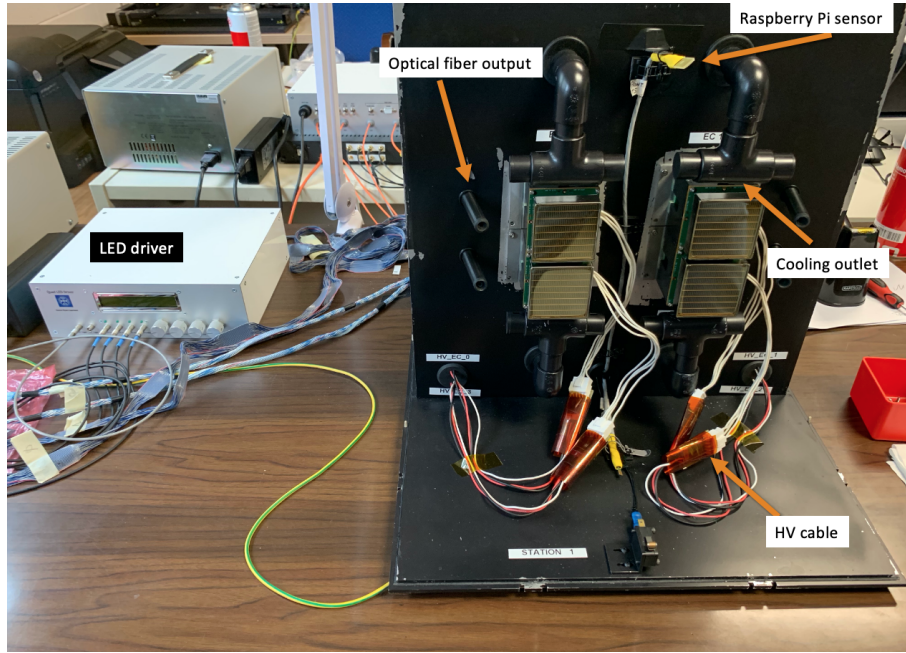


Figure 8.11: Picture of the ECQA setup, Station1, where four EC H-type are mounted in the box. On the left, the LED driver is visible.

In Figure 8.12 the numbering scheme for the ECQA setup is reported, while in Figure 8.13 the numbering scheme of the CLAROs on the FEB is reported. The QR code of the FEB is always placed on the CLARO 7.

Every set of ECs tested in the box is called "Load" and a four-digit sequential Load Number is associate to it. The Load Number sequence is separate for each of the four stations. Up to four ECs of the same type can be tested in the same load (to test a full four-ECs load is preferable to an incomplete load, for testing-time efficiency) and the QA data are saved in a load-specific folder, the name of which also specify the test station used and the type of EC tested (e.g. Load_0000_R_S1 is the folder for the Load Number 0000 of R-type EC tested on the station 1, which is in Ferrara). When mounted in the dark-box, the ECs are numbered from 0 to 3 based on

⁸<https://www.aimtti.com/product-category/dc-power-supplies/aim-ex-rseries>

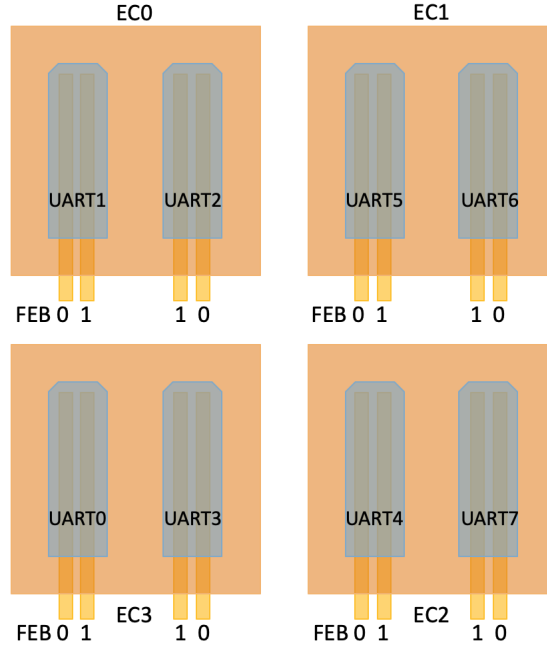


Figure 8.12: Schematic of the numbering scheme for the ECQA main components. The ECs of the load are numbered from 0 to 3 starting from the top-left going clockwise, the UART are named from 0 to 7 and each one of them is connected to two FEBs, 0 and 1, the numbering of which is inverted for UART connectors rotated of 180° one respect to the others.

their position, from the top-left going clockwise. The MaPMTs of an R-type EC are also identified based on their position, from A to D or from 0 to 3 starting from the top-left one going clockwise. For an H-type MaPMT this identification is not needed.

Inside the load folder two subfolders are present: QR_Codes and PDF. In the QR_Codes folder a file per each EC of the load is generated containing all the service and hardware info of the cell. This file is created during the assembling procedure when scanning the components QR codes. First date, time and location of the assembling are reported, together with the name of the person assembling the EC. Then the QR codes of Baseboard, FEBs and Backboard are written, after which the Load Number, the Station ID and the EC position in that Load are reported. Lastly, the QR codes of the MaPMTs are written. In the PDF folder all the plots produced during the data analysis are stored, and they are checked by the users to control no errors are present. In every data file generated the date and time of the test is registered, together with the most relevant setup settings used for the test

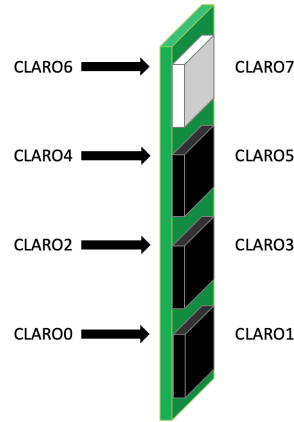


Figure 8.13: Scheme representing the numbering convention for the CLAROs on the FEB. Since it is in perspective, half of the CLAROs are hidden in the scheme but they are soldered on the FEB in a specular way with respect to the visible ones. On the CLARO7 the QR code is present.

after which the data file has been created.

Before describing the ECQA test protocol, the Signal Induced Noise (SIN) test measurement will be described.

8.3.1 Signal Induced Noise measurements and LED driver calibration

The MaPMTs produced for the LHCb RICH Upgrade are affected by after-pulses, named SIN. This effect is more evident in the anodes numbered 1-8 and 57-64, following the scheme reported in Figure 8.14, and almost absent in the central anodes. To evaluate the after-pulse magnitude a dedicated test has been developed and implemented in the ECQA procedure. This test can be performed on the full ECs load. The MaPMT operative voltage is set to a fixed value in the range 850-1000V. The system perform a scan: starting from a delay of 0 ns, it reads the CLARO hitcounts registered in an integrated interval of 25 ns, then in the next step the delay is incremented of 25 ns, covering a time range from 0 to 6.4 μ s (256 steps). The LED driver is used as signal source and it is set to send 100k pulses at a rate of 100kHz for each test step. The result is reported in Figure 8.15. The highest peak of the distribution is present at the steps 14, with a second high peak in the step 15 (these two steps correspond to the 350-375 ns interval), and corresponds to the true signal from the LED driver. The counts after it are SIN, and

they last until the very end of the time range.

R-Type Top Left & H-Type								R-Type Top Right							
64	63	62	61	60	59	58	57	8	16	24	32	40	48	56	64
56	55	54	53	52	51	50	49	7	15	23	31	39	47	55	63
48	47	46	45	44	43	42	41	6	14	22	30	38	46	54	62
40	39	38	37	36	35	34	33	5	13	21	29	37	45	53	61
32	31	30	29	28	27	26	25	4	12	20	28	36	44	52	60
24	23	22	21	20	19	18	17	3	11	19	27	35	43	51	59
16	15	14	13	12	11	10	9	2	10	18	26	34	42	50	58
8	7	6	5	4	3	2	1	1	9	17	25	33	41	49	57
57	49	41	33	25	17	9	1	1	2	3	4	5	6	7	8
58	50	42	34	26	18	10	2	9	10	11	12	13	14	15	16
59	51	43	35	27	19	11	3	17	18	19	20	21	22	23	24
60	52	44	36	28	20	12	4	25	26	27	28	29	30	31	32
61	53	45	37	29	21	13	5	33	34	35	36	37	38	39	40
62	54	46	38	30	22	14	6	41	42	43	44	45	46	47	48
63	55	47	39	31	23	15	7	49	50	51	52	53	54	55	56
64	56	48	40	32	24	16	8	57	58	59	60	61	62	63	64
R-Type Bot Left								R-Type Bot Right							

Figure 8.14: Numbering scheme for the MaPMT anodes on the EC, where the observer is imagined facing the MaPMTs window. To notice that the numbering scheme for the R-type top-left MaPMT is the same as for an H-type MaPMT. The Anode 1 is always at the centre of the R-type EC. This implies that, going from 0 to 3, one MaPMT is rotated of 90° clockwise with respect to the previous one.

Several tests have been performed and it has been found that the highest number of counts is, in almost all the tests, at the step 14. For a very small number of anodes it has been found that the step 15 was the one with the highest number of counts. Hence the LED signal is considered as the sum of the hitcounts in the steps 14 and 15. In the steps 0-13 (0-325 ns) zero to few counts are detected, and they are counts due to the natural noise inside the MaPMTs (dark counts). Everything else, in the range 16-255 (400 ns - $6.4 \mu\text{s}$) is considered SIN. Two main parameters are extracted for each MaPMT anode during the ECQA procedure: the signal intensity and the SIN intensity, defined as the integral of the hitcounts in the SIN test step range 14-15 and 16-255, respectively. A useful visualization of the SIN

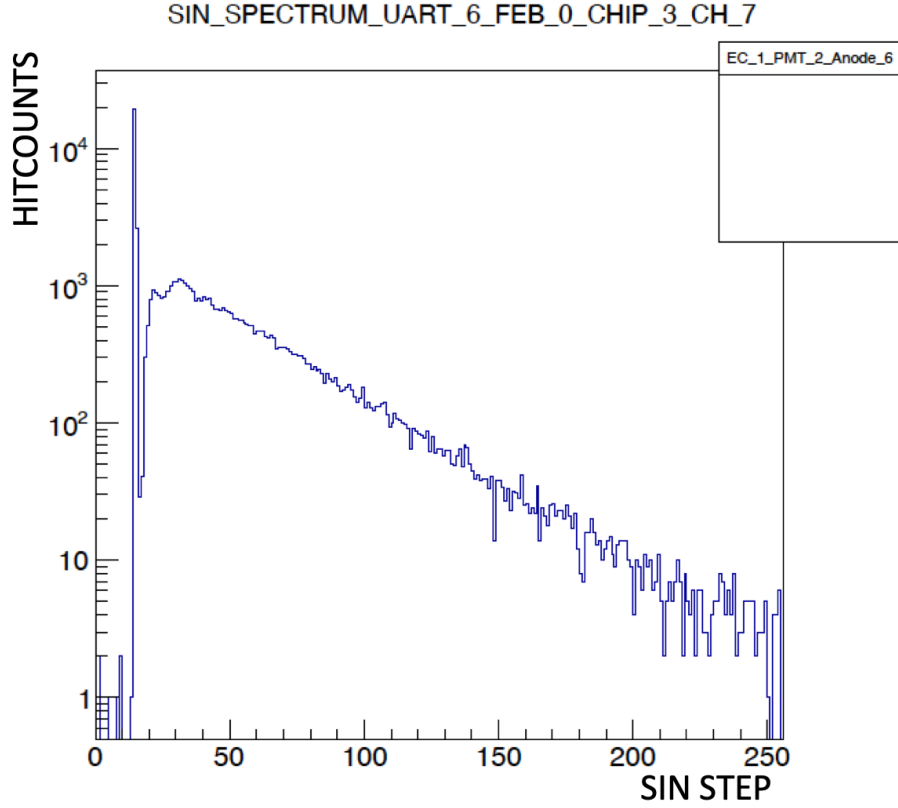


Figure 8.15: SIN distribution for a MaPMT anode. The association between CLARO channels, MaPMT anode and EC is explicitly reported in the distribution and histogram titles.

effects on the MaPMTs can be obtained using a 2D histogram representing the MaPMTs anodes where each histogram bin height is the ratio defined in Equation (8.1):

$$\frac{SIN_{Intensity}}{SIN_{Intensity} + Signal_{Intensity}}, \quad (8.1)$$

that is the SIN fraction on an anode with respect to the total signals registered in the full time window. An example is reported in Figure 8.16. The SIN fraction is high on the anodes 1-8 and 57-64, on the neighboring rows is at half of that value and in the center is almost absent. The value of the SIN fraction on the MaPMTs anode is not a parameter for which an EC can be considered faulty. The EC with the highest SIN fraction will be placed in the RICH regions at lower occupancy. the Hamamatsu[®] company already produced 150 new SIN-less MaPMTs which have already been tested

in Padova University and they will arrive in Ferrara for an in-depth SIN analysis. These new MaPMTs will replace the ones already produced with the highest SIN fractions.

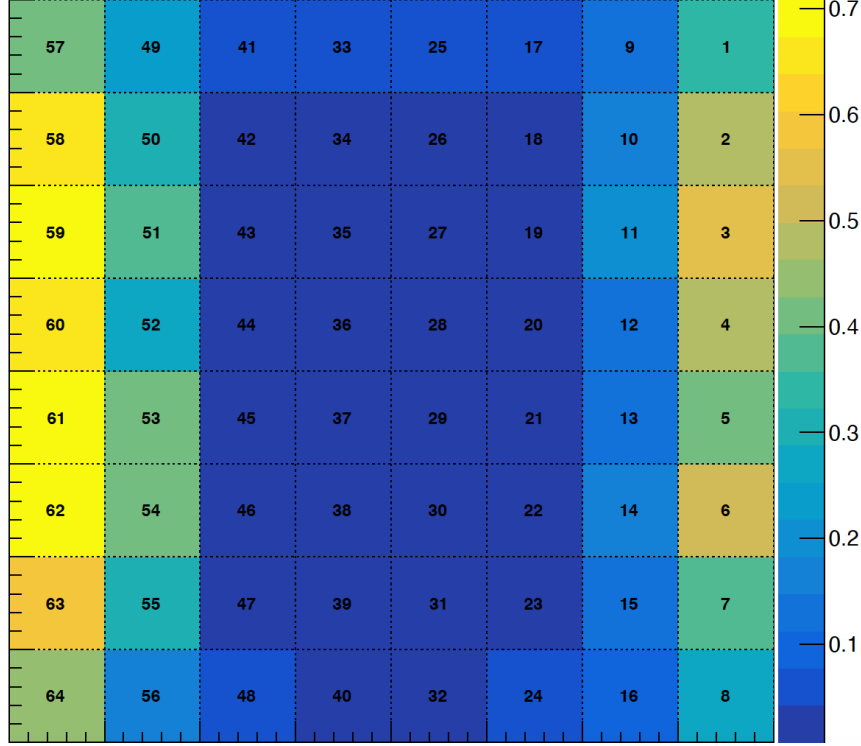


Figure 8.16: 2D histogram for an R-type MaPMT showing the SIN fraction per each anode. The number reported on each histogram bin is the anode number following the scheme of figure 8.14.

Using the data obtained from the SIN measurement it has been possible to calibrate the LED driver operative voltage in order to suppress the 2-3 photons emission events in the LED. For an R-type EC the average signal intensity (hitocunts in SIN test step 14-15) on the four MaPMTs has been measured as a function of the LED operative voltage and reported on a graph, together with the four-MaPMTs average. The results are shown in Figure 8.17, where the signal intensity increases as the LED voltage increases, as expected. The photon emission for an LED is regulated by the Poisson distribution. By setting the expected number of occurrences to 0.1, that is a 10% efficiency, the number of events with >2 photon emitted is almost zero. Therefore, since the number of pulses set for the LED driver is 10k, the optimal value for the LED operative voltage is the one at which we register,

on average, 1k pulses. This voltage is found to be 1.8V, which has been applied to all four the LED driver channels.

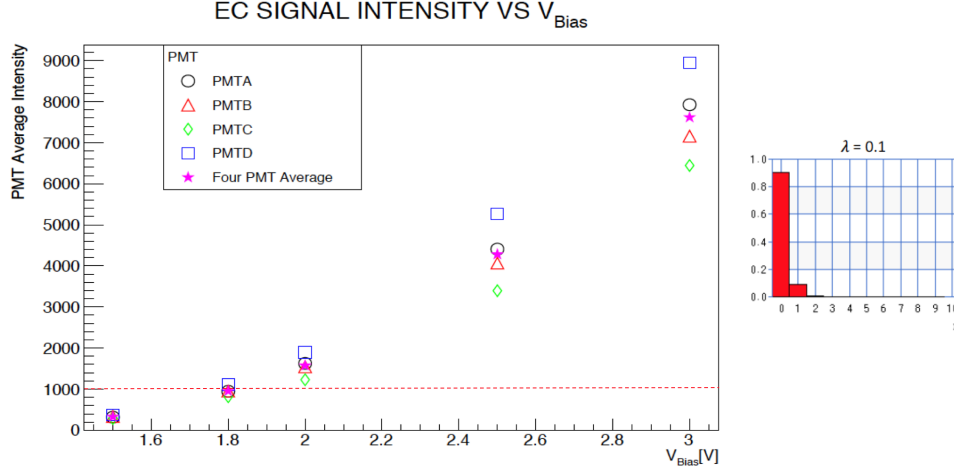


Figure 8.17: On the left, average signal intensity per MaPMT of the EC as a function of the applied LED driver voltage. On the right, the Poisson distribution optimized to suppress events of multi-photons emission.

8.3.2 The ECQA test protocol

After being assembled, a new load of ECs is mounted on the dark box without MaPMTs. The control software open the connection between the PC and the system controller, starts the python daemon (which allows to send commands to the system controller to perform the tests) and power on the CLAROs. Also it establish the connection with the HV crate and with the Raspberry Pi system, which start monitoring the voltages and currents of the MaPMTs and the environmental parameters, respectively.

1. S-Curve Comm Check:

the first test performed is a very fast coarse S-Curve (step 0x032, ~60.5 mV), named S-Curve Comm Check, whose sole purpose is to verify that a transition happens in every CLARO channel, hence assuring that no communication problems with the ASICs are present. A dedicated C++ scripts verifies that the first point (low signal intensity) has less than 5 counts and the last point (high signal intensity) has more than 950 counts, where 1000 pulses are the maximum number of pulses sent per DAC step, in every channel S-Curve. The thresholds of 5 and 950 have been chosen to account for possible counts oscillations in the

channel during the test. The script checks also if a channel is dead, that is counts always 0, or if its noisy counting always 1000 or more, or if the S-Curve is not monotonous and oscillations are present in the distribution. If any of this problem appears in one or more channels the corresponding EC is dismounted from the box, their connectors are cleaned using compressed air and the test is performed again. A communication error in electronic devices might only be due to a little bit of dust on the connectors, but if the problem persists the FEB corresponding to the defective channel is replaced (its QR code in the file is replaced as well) and the test is performed again. The defective FEB is then put aside for a future test on the FEB QA setup.

2. POR, SEU reset and ADC channels read:

a SEU counter reset and a Power-On reset are sent to the CLARO chips and the eight FPGAs ADC channels (FEB0 and FEB1, Bkb and two Bb temperatures, the FEB couple current and the CLARO VDD for the two FEBs) are read out and their value are registered in a file named LV_noconf.txt in the correspondent load folder. The file is named noconf since no configuration has been applied to the CLAROs yet. Then a configuration (0x314, but it doesn't really matter since no data from CLAROs is acquired) is sent to the CLARO channels and the ADC channels are read out again, this time being saved in a file named LV_conf.txt, since this time the CLAROs are configured.

3. HV measurement (without MaPMTs):

on the next step of the test protocol the HV is switched on at 1000V. After a waiting of 1 minute, to let the currents stabilize, the Bbs currents are measured and registered in a dedicated file, named HV_nopmt.txt, since no MaPMTs have been installed yet. The tension of the four HV channels is registered as well. Then the HV is switched off.

4. MaPMTs mounting + S-Curve Comm Check:

the MaPMTs are mounted in the ECs, after their QR codes have been scanned. An S-Curve Comm Check is performed to ensure that the mounting of the MaPMTs has not created communication problems with the CLAROs. If the test is ok the dark box is finally closed, otherwise the problem has to be investigated as before.

5. HV measurement (with MaPMTs):

the HV is switched on at 1000V (40V/s ramp-up speed) and the Bbs currents are monitored for 1 minute, after which the average value of

the currents for the four HV channels are calculated and registered in the HV_pmt.txt file together with the HV tensions. Then the HV is set to 1050V (40V/s ramp-up speed) and the currents are monitored for 1 minute. Then the average value for the Bb currents at 1050V is extracted and will be used to set the HV crate current limit during the night. Then the HV is switched off.

6. S-Curve test:

an S-Curve test is performed on all the CLAROs (range 0-725 mV, step 1.2 mV) using six different configurations: the channels are always enabled, as well as the Hysteresis, but the channel thresholds are sent to 10, 20, 30 with Offset bit 0 (configuration 0x30A, 0x314 and 0x31E respectively) and 42, 52, 62 with the Offset bit 1 (configuration 0xB2A, 0xB34 and 0xB3E respectively). Right after the data have been acquired a python script finds the transition point for each channel using the fit method. It also produces PDF plots of the S-Curve for each channel and cumulative distributions of both transition point and S-Curve spread for all the channels of the load per each different CLARO configuration. If a channel doesn't have the transition an error message is produced but the procedure doesn't stop. Only at the very end of the test the user checks the data and decide if an EC is to be put aside or not. The channels transition points and spreads are also stored in a dedicated text file. More details on the data analysis will be given in the next section.

7. 1050 V stand-by:

after the S-Curve test the ECs are left with the HV set at 1050V for 10 hours. This procedure is necessary to reduce the electronic noise (dark counts) inside the MaPMTs, since they have been tested 2-3 years ago in the Photon Detector Quality Assurance (PDQA) and since then they have been in boxes waiting for the ECQA.

8. Threshold Scan test:

the first test to be performed after the 10 hours at 1050V is the Threshold Scan. The HV is set at 1000V, all the channels are enabled, the Hysteresis bit is 1 and the threshold ranges from 63 to 0. This test is performed twice, with Offset bit at 0 and 1. The LED driver is set to send 100k pulses at 100kHz per threshold step. A C++ script is launched at the end of the test to analyze the data and extract, for each channel, the threshold corresponding to the pedestal.

From there, five threshold steps are added and that is considered the channel working point, which is registered in a dedicated text file. For the Offset bit 0 threshold scans only a small number of channels will have the pedestal, while for the others the working point evaluation cannot be done using this script. A separate script may provide the pedestal position also for the Offset bit 0 files. The procedure is explained in the Threshold Scan data analysis section. As in the S-Curve tests, also in the Threshold Scan test a channel without transition or which gives another error doesn't stop the procedure, but triggers an error message.

9. Dark Count Rate measurement:

the MaPMTs Dark Count Rate (DCR), that is the rate of registered counts without any light source on the PMTs, is measured with the HV set at 1000V. First all CLAROs are configured with threshold 7 and the DCR is measured in a 100s time window, then the CLARO channels are configured at their optimal threshold obtained from the previous Threshold Scan test and the DCR is measured in a 100s time window. A C++ script perform the data analysis and produces 2D histogram plots with the DCR of the MaPMTs. A threshold is set for which the DCR of a channel has to be lower than 1 kHz, otherwise an error message is generated. This threshold is given by the production parameters guaranteed by the Hamamatsu® company.

10. SIN test:

lastly the SIN test is performed at four different MaPMTs operative voltages (1000V, 950V, 900V, 850V), since the SIN intensity strongly depends on the MaPMT tension. In this test the CLAROs are configured at their optimal thresholds. After the data have been taken, a C++ script is launched which performs the analysis and produces the PDF plots containing the MaPMTs 2D histograms and the SIN spectrum for every channel. No limit threshold is set on the SIN or signal intensity in this test.

The operator, at the end of the test, can check the data plots and the system log to decide whether or not to accept or reject an EC. A log file is generated at the beginning of the test and all the outputs from all the several sub-VIs of the control software are registered in it. The total time of the test is ~ 12 hours but, since a 10 hours waiting time is set and 2 hours are needed to assemble the ECs and mount them, together with the MaPMTs, an entire day is required to test a full load.

8.3.3 DAQ software

The DAQ control software has been developed in NI LabVIEW 2017 64-bit. A python daemon is launched when the control software starts so that dedicated DAQ python scripts can be executed via LabVIEW through low-level functions specifically built for this purpose. The python scripts are the same used in the FEB QA setup and provide the basic functions to operate with the system controller and the CLAROs (e.g. open/close connection between PC and system controller, CLARO power on/off, CLARO configuration register read/write, ADC channels read). These low-level functions are the core of the Virtual Instruments (VI) used to performed the QA tests on the ECs. In the first step of the software development a standalone VI for each type of measurement present in the test protocol has been developed: ADC channels read, S-Curve tests (Comm Check and standard), Threshold Scan, SIN and DCR measurement. These VIs perform the measurement for which they have been developed and then they stop, no automatization in the ECQA process has been implemented in this stage of the software development. Hence, the user has to run all the VIs separately and manually to perform all the tests in the test protocol. In addition to the standalone measurement VIs, a VI has been developed to scan the components QR codes and generate the files containing the ECs information, together with a configurator VI. This Vi has been developed to read the file containing the working points for all the Load channels found with the threshold scans data analysis and to configure each channel to its optimal threshold, so that the ECQA tests with the optimized thresholds can be performed. The connection to the system controller and the python daemon start are manually initialized using the `syscmd_open_ECQA.vi` and the `command_NET_OPEN_ECQA.vi` low-level functions reported in Figure 8.18. The `syscmd_open` function launches the python daemon and has to be executed first, then the `command_NET_OPEN` can be executed, in which the system controller IP address has to be inserted together with the communication ports.

Before the test starts the user has to set several parameters in the VIs, some of which are present in every standalone VI and others are specific for each test.

The Load Number, the EC Type and the Station are parameters to be set in every VI and they determine the path at which the data file is saved, because the load data folder name depends on these parameters. Since an H-type EC load has a complete different anode/CLARO channels mapping scheme and 1/4 of the channels with respect to an R-type load, the information on the EC type is propagated to the analysis script running at the end

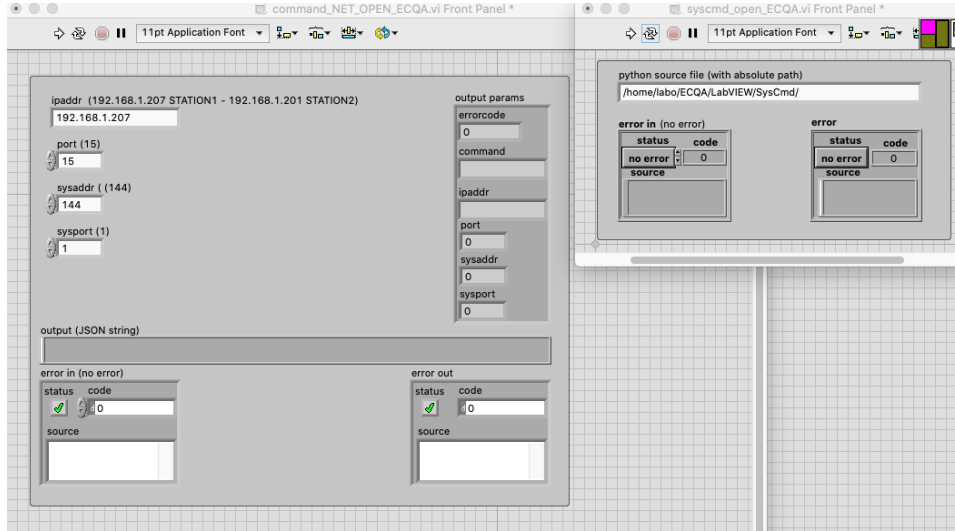


Figure 8.18: The control panel of the two low-level VIs used to open the connection with the system controller (left) and to start the python daemon (right).

of the test so that the correct number of the channels is analyzed and the right mapping scheme is applied. Two LED driver parameters can be set for the tests using it (SIN and Threshold Scan): the number of pulses to be sent in each test step and the frequency. The LED driver parameters are also set for the DCR measurement, even if the light is not used for the test, to define the temporization of the test (e.g. setting 100k pulses at 1kHz set the DCR acquisition time to 100s). The values of these two parameters are written in the data file header for reference. For Threshold Scan, DCR and SIN measurements the voltage at which the test is performed is to be set. However, this does not act as a control for the system voltage, but just as an indicator. The value set there is written in the data file header for reference. For this first phase of the ECQA DAQ software development the system HV is controlled using the ISEG crate web browser interface.

In Figure 8.19 the control panel of the standalone VI for the ADC channels and HV channels read is shown. In the "Voltage Type to measure" control is possible to select LV or HV. Selecting LV the DBs ADC channels are read out, while using HV the ISEG crate channels are read out and the current and tension values are reported in the eight indicators in the bottom left corner. Also, selecting LV/HV will change the first part of the data file name (LV_ or HV_). The second part is determined by the two boolean selectors under the "Voltage Type to measure" control. The upper

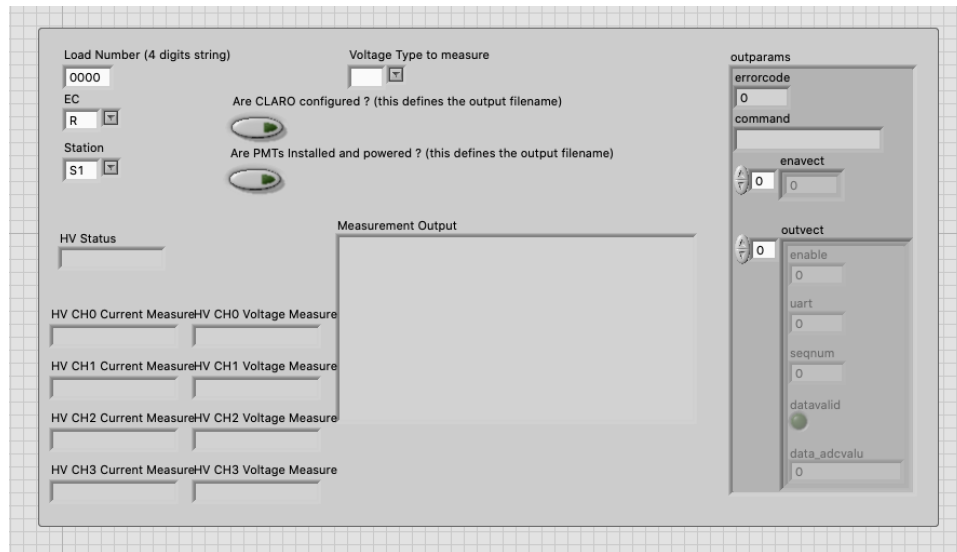


Figure 8.19: The control panel for the ADC channels and HV channels read standalone VI.

boolean ("Are CLARO configured?") control refers to the ADC channels reading, which is performed before and after the CLAROs configuration. If the CLAROs are not configured (control is 0), the ADC channels are read out and the data are written to the file `LV_noconf.txt`. If the CLAROs are configured (control is 1) the ADC channels are read out and the data are written to the file `LV_conf.txt`. The lower boolean ("Are PMTs Installed and powered?") refers to the HV channels reading, performed at 1000V with and without the MaPMTs on the ECs. Depending on the boolean state (0/1) the HV data are written to the file named `HV_nopmt.txt`/`HV_pmt.txt`. The indicator "Measurement output" will show the data written to the data file, header included. The "outparameters" cluster contains the ADC channels reading, together with the error state of the acquisition (0 means no errors).

In Figure 8.20 the control panel of the standalone VI for the S-Curve Comm Check test is shown. The only parameters to be set are the general Load information and the output files names: the raw data file (named `"S_Curve_Comm_Check.txt"` in the figure) contains the S-Curve data for all the channels, while the log file (named `"S_Curve_Comm_Check_log.txt"` in the figure) contains the analysis script output which is also shown in the "S-Curve Check errors" window. The "concatenated string" indicator is used to check the command line executed to run the C++ script to analyze the raw data file, in case there are problems with the path. The "Channel configuration" indicator shows the channel threshold applied for the test (in

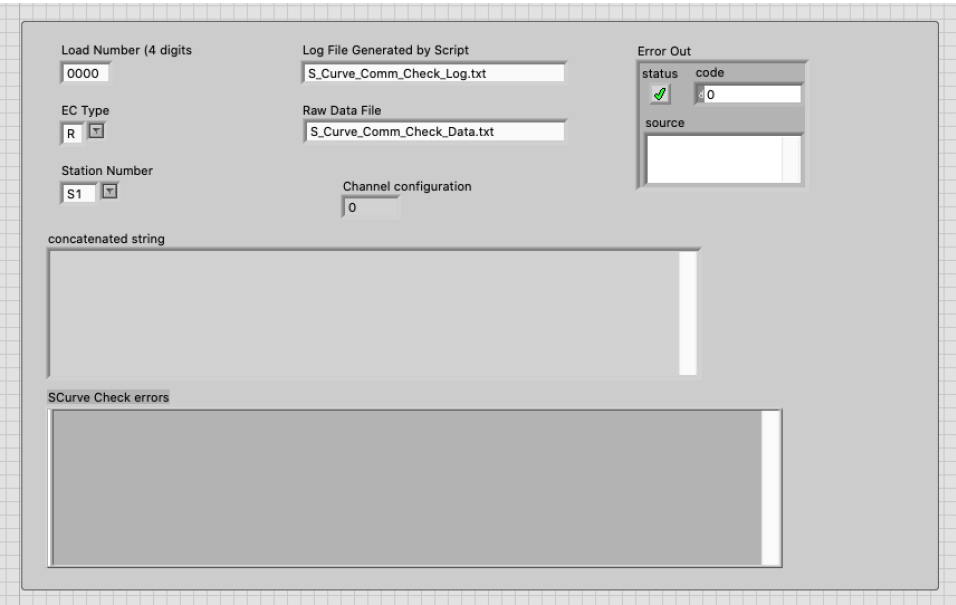


Figure 8.20: The control panel for the S-Curve Comm Check test standalone VI.

decimal code) and the "Error Out" window returns the error state of the test execution.

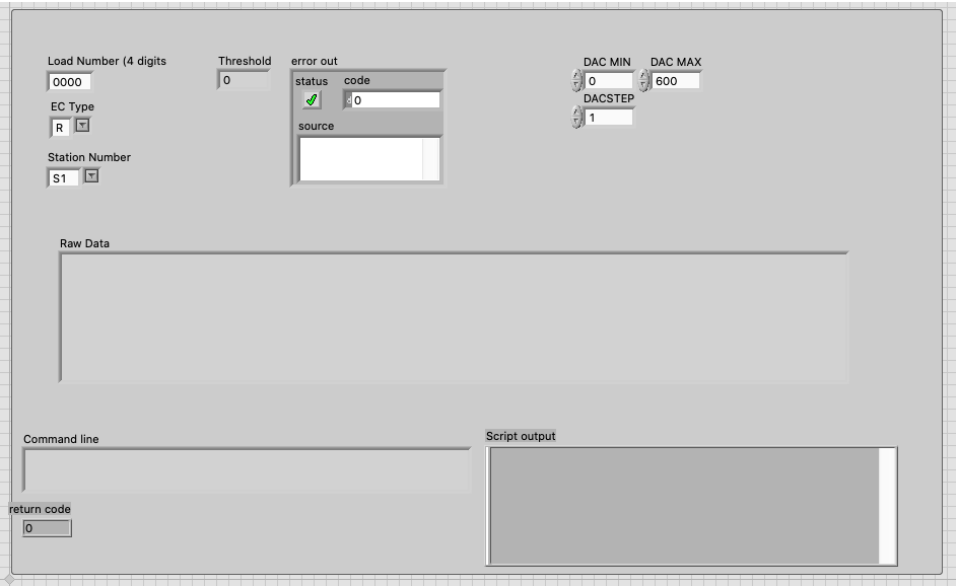


Figure 8.21: The control panel for the S-Curve test standalone VI.

In Figure 8.21 the control panel of the standalone VI for the standard S-

Curve test is shown. The minimum and maximum DAC limits have to be set, together with the DAC step. The "Threshold" indicator shows the applied threshold to the CLARO channels. "error out" returns the test execution error state, while "return code" returns the analysis script execution error state. The indicators "Raw Data" and "Command line" report the raw data to be written on the data file and the command line executed to run the C++ script to analyze the raw data file, respectively, and "Script output" reports the analysis script output.

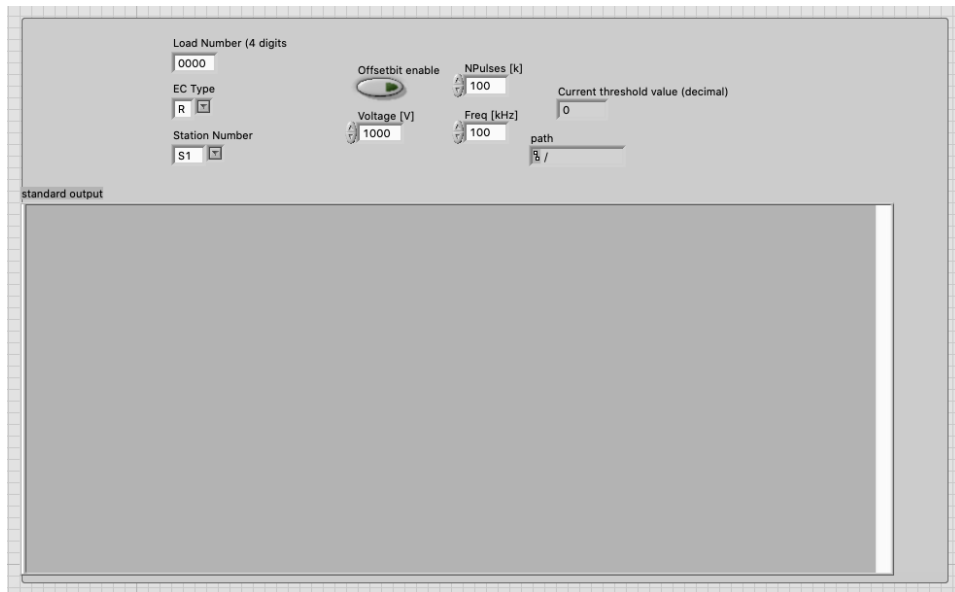


Figure 8.22: The control panel for the Threshold Scan test standalone VI.

In Figure 8.22 the control panel of the standalone VI for the Threshold Scan test is shown. The CLARO Offset bit can be set to 0 or 1 using the dedicated boolean control, while the threshold applied, shown in the "Current threshold value" indicator in decimal code, is always from 0 to 63 with a step of 1. The "path" indicator shows the path used to save the optimized threshold file generated by the analysis script, the output of which is reported in the "standard output" window.

In Figure 8.23 the control panel of the standalone Vi for the SIN test is shown. The number of 25 ns steps in which the test is performed can be set in the "Number of Steps" control. The "SIN step" indicator shows the current step number, to monitor the progression of the test. The CLAROs for this test can be configured to a common threshold using the "CFG (decimal)" control and setting the "Configure" boolean to the true state. The threshold value applied in this case is reported in the "Threshold value applied" indic-

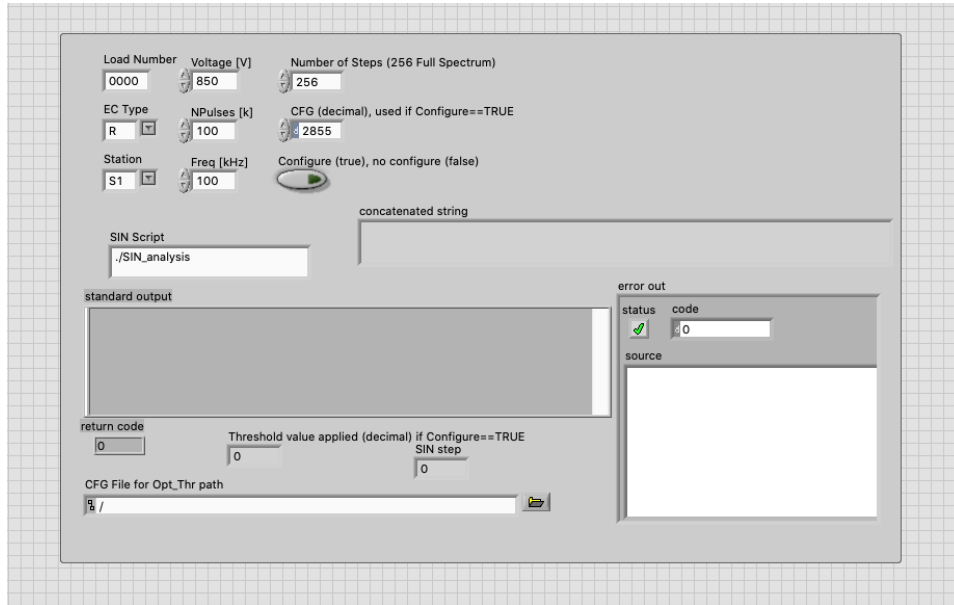


Figure 8.23: The control panel for the SIN test standalone VI.

ator at the bottom of the panel. If the boolean control is in the false state, no configuration is sent to the CLAROs, so that the optimized threshold configuration can be used (sent before starting the SIN test using the dedicated configurator VI). The path to the optimized threshold file used to configure the CLAROs before the SIN test can be put in the "CFG File" control path window at the bottom of the panel, and that path will be inserted in the data file header for reference. The "SIN Script" control allows to specify the analysis script to be used, the output of which is reported in the "standard output" window and the "return code" indicator returns the analysis script execution error state. In the "concatenated string" window the command line executed to run the C++ script to analyze the raw data file is reported. The "error out" cluster contains information on the status of the test.

In Figure 8.24 the control panel of the standalone Vi to perform DCR measurement is reported. As for the SIN VI, a common CLARO configuration can be set for all the chips using the "Configure" boolean control, and the configuration set in the "Configuration" control is set for all the ASICs. The analysis script name is set in the "DCR Script" control, while the script output and its execution state are reported in the indicators named "standard output" and "return code", respectively. The "concatenated string" indicator shows the command string sent to execute the analysis script.

In Figure 8.25 the configurator VI control panel is shown. Two files have

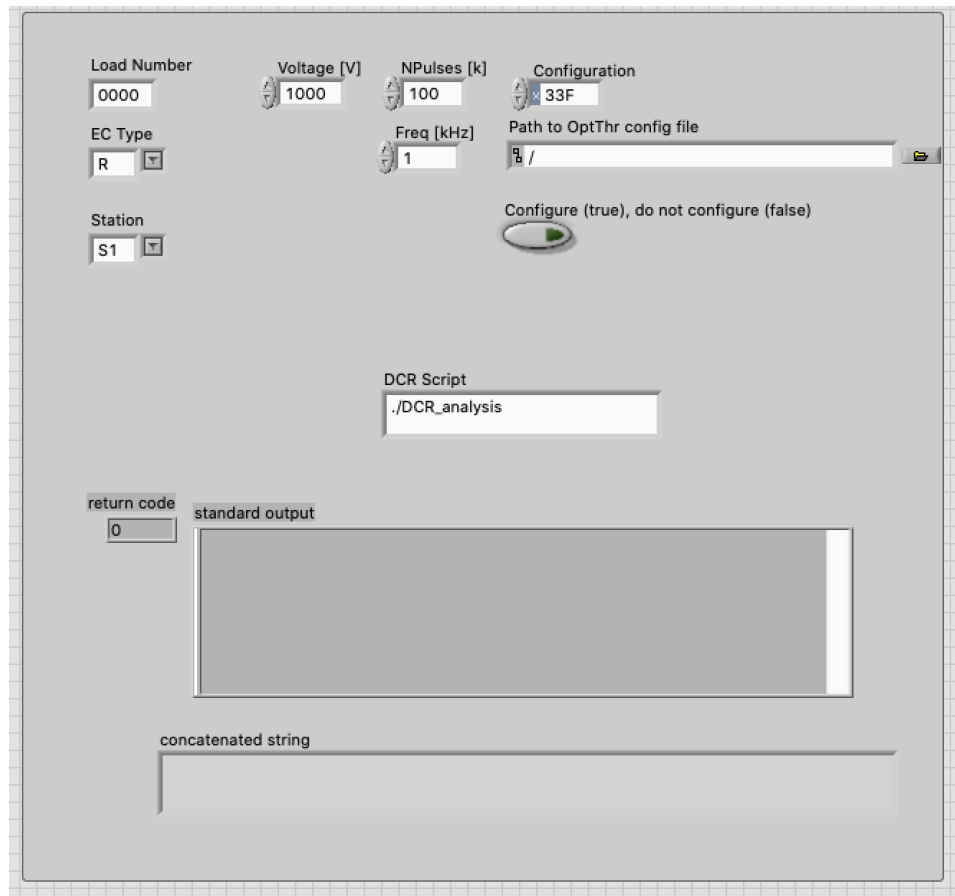


Figure 8.24: The control panel for the DCR test standalone VI.

to be selected: the file in the upper control is a default configuration file, while the lower one is the optimized threshold file to load into the setup. The VI reads these two files and write the appropriate configuration to each chip. The EC type has to be specified. After all the chips have been configured, their configuration is read out and compared to the one that has been sent to them. The "WRITE CFG" and "READ CFG" indicators show in real time which configuration has been sent to a chip and what is read out from it. The chip being read out is identified using the three indicators "UART", "FEB" and "CHIP". If for one or more channel the configuration sent and the configuration read out don't match an error is generated in the "Error" window.

After all these standalone VIs have been developed and used to perform the ECQA tests on 50 loads using the two Ferrara test stations, a state machine has been developed (always with LabVIEW) to perform the full test

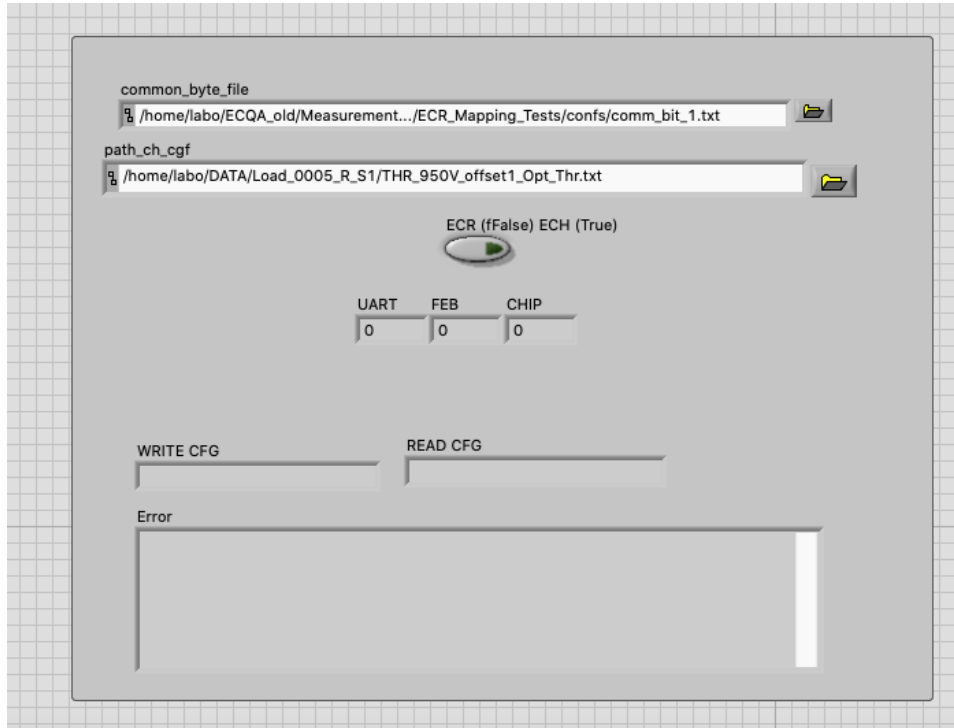


Figure 8.25: The control panel for the configurator VI.

protocol in an automatic way. The state machine uses the standalone VIs as sub-VIs, so the file output and the data analysis don't change, but every measurement is launched automatically following the test protocol without the user intervention. The user has to assemble the EC scanning the component using the EC_scan standalone VI (Figure 8.26), mount them on the box, start the state machine and wait until the measurements without the MaPMTs are performed. If everything is ok (currents under limit threshold, CLARO communication is fine) then the MaPMTs can be scanned directly from the state machine control panel and their code will be appended to the appropriate EC file containing all its component QR codes. After this operation the box can be closed and the tests continue until completion, the next day. The main upside of the state machine is that all the system parameters are constantly monitored like the CLARO configuration register, which is read out every time a new one is written (this was not implemented in the standalone VIs for time constraints) or the system HV, controlled and monitored directly from LabVIEW. The automatization of the procedure also reduces the possibility of errors by the users and the dead times between the measurements.

In Figure 8.27 the control panel of the ECQA state machine is shown. Each phase of the test protocol has a separate tab in the bottom-left window, from the MaPMTs scan to the measurements, for which dedicated indicators have been inserted in the correspondent tab to show possible error messages during the tests. After a test protocol step has finished, the "CONFIRM STEP" control has to be pressed to pass at the next step. In the top-left corner the "MAIN CONTROL" panel allows to select which phase of the test execute, when running in MANUAL mode, and to change from MANUAL to AUTO. Every test can be repeated as many time as the user needs, in case of problems. If the AUTO mode is selected, the state machine will perform all the steps reported in the window on the right-hand side of the "CONFIRM STEP" control. The test protocol steps to be performed, together with the setup parameters, are chosen before the test starts using the dedicate panel shown in Figure 8.28, where all the measurements parameters, the threshold for the LV and HV currents, the system controller, LED driver and Raspberry Pi settings can be modified following the user needs. On the left-hand side of the "CONFIRM STEP" button the Load information have to be inserted before starting the test. On top of this panel, the environmental information (temperature and humidity of the two sensors in the box with maximum and minimum values registered) are reported and constantly monitored throughout the test. On the left-hand side of the window the system controller and HV control/ monitor panels are present, which report the state of the connections with the system controller and with the ISEG crate, respectively. The python daemon state (which has been launched automatically when the test starts, as well as the system controller communication opening) is monitored as well. Three log windows are used to check the system controller activity, the ISEG crate activity and the test general activity. The logs are written in the Load folder in dedicated log files.

Operator	Location	EC Type	Load Number (4 digits)	Station Number																												
Igor	Ferrara		0000	1																												
			EC Position																													
ELEMENTARY CELL																																
<table border="1"> <tr> <td colspan="2">Backboard</td> </tr> <tr> <td colspan="2"></td> </tr> <tr> <td>FEB I</td> <td>FEB II</td> </tr> <tr> <td></td> <td></td> </tr> <tr> <td>FEB III</td> <td>FEB IV</td> </tr> <tr> <td></td> <td></td> </tr> <tr> <td>Baseboard</td> <td></td> </tr> <tr> <td></td> <td></td> </tr> <tr> <td colspan="2">ID EC (Backboard)</td> </tr> <tr> <td colspan="2"></td> </tr> <tr> <td>PMT A</td> <td>PMT B</td> </tr> <tr> <td></td> <td></td> </tr> <tr> <td>PMT D</td> <td>PMT C</td> </tr> <tr> <td></td> <td></td> </tr> </table>					Backboard				FEB I	FEB II			FEB III	FEB IV			Baseboard				ID EC (Backboard)				PMT A	PMT B			PMT D	PMT C		
Backboard																																
FEB I	FEB II																															
FEB III	FEB IV																															
Baseboard																																
ID EC (Backboard)																																
PMT A	PMT B																															
PMT D	PMT C																															

Figure 8.26: The control panel of the VI for the scan of the QR codes of the EC components.

Figure 8.27: The control panel of the finite state machine for the automatic ECQA procedure.

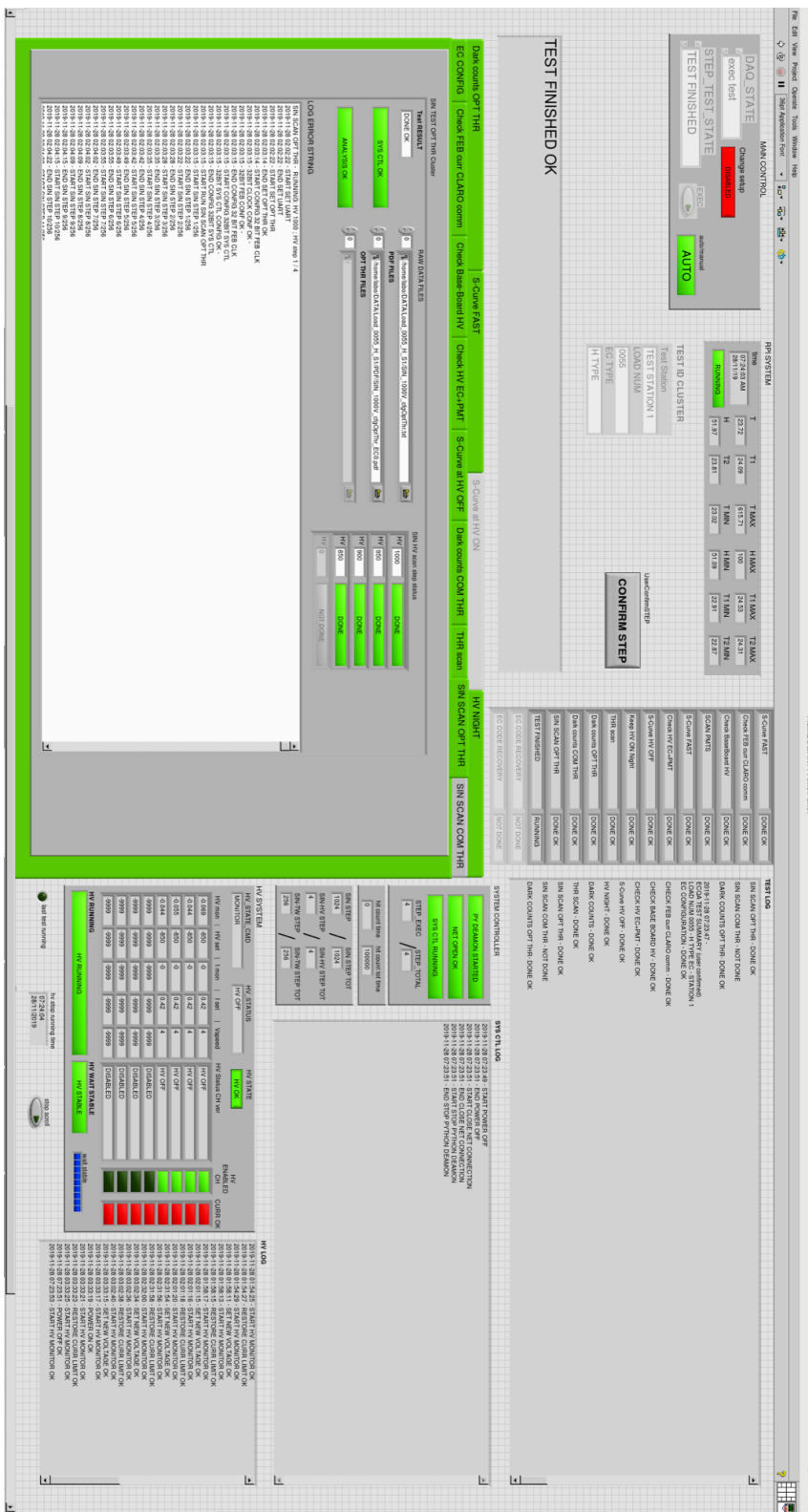
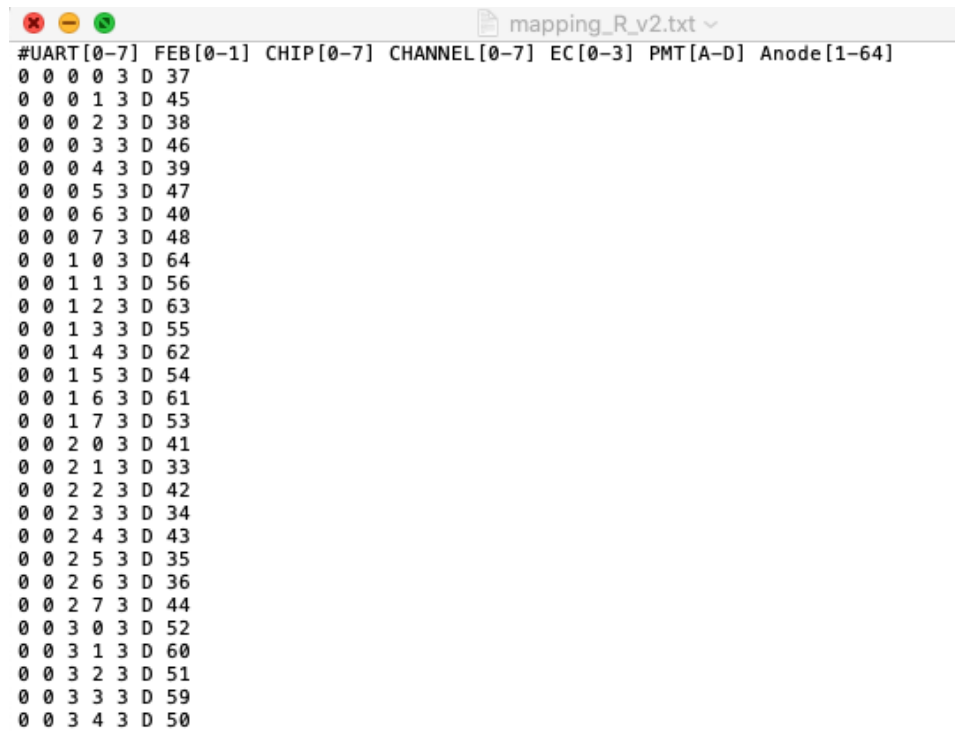


Figure 8.28: The finite state machine parameters settings panel.

[illegible]

8.3.4 Data analysis

The data analysis on the ECQA measurements is performed right after a test has finished using a dedicated script for each different measurement. The scripts are launched directly via LabVIEW. All the scripts use two mapping file, one for the R-type ECs and one for the H-type ECs, to correctly associate a CLARO channel to the right MaPMT anode on the correct EC. A portion of the R-type mapping file is shown in Figure 8.29. A one-line header is put to facilitate the file readability. The channel ID (UART FEB CHIP CHANNEL) is associated to its anode (1-64) of its MaPMT (A-D) of its EC (0-3). The H-type file is almost identical, except for the fact the only one MaPMT is present per EC so there is no need for the sixth file column. Using these files the 2D histogram plots can be produced with the correct physical anode-CLARO channel (optical-electronical) association.



#UART[0-7]	FEB[0-1]	CHIP[0-7]	CHANNEL[0-7]	EC[0-3]	PMT[A-D]	Anode[1-64]
0	0	0	0	3	D	37
0	0	0	1	3	D	45
0	0	0	2	3	D	38
0	0	0	3	3	D	46
0	0	0	4	3	D	39
0	0	0	5	3	D	47
0	0	0	6	3	D	40
0	0	0	7	3	D	48
0	0	1	0	3	D	64
0	0	1	1	3	D	56
0	0	1	2	3	D	63
0	0	1	3	3	D	55
0	0	1	4	3	D	62
0	0	1	5	3	D	54
0	0	1	6	3	D	61
0	0	1	7	3	D	53
0	0	2	0	3	D	41
0	0	2	1	3	D	33
0	0	2	2	3	D	42
0	0	2	3	3	D	34
0	0	2	4	3	D	43
0	0	2	5	3	D	35
0	0	2	6	3	D	36
0	0	2	7	3	D	44
0	0	3	0	3	D	52
0	0	3	1	3	D	60
0	0	3	2	3	D	51
0	0	3	3	3	D	59
0	0	3	4	3	D	50

Figure 8.29: The R-type EC mapping file used by the analysis scripts to correctly map the CLARO channels and produce 2D histograms.

The S-Curve Comm Check analysis is performed using a C++ script which reads the raw data file. The purpose of the analysis is just to check that every channel has a transition and that all the channels are behaving properly. For this reason the script check that the channel hitcounts at the first DAC step are smaller than 5 and that at the last DAC step are bigger than 950, over a total of 1000 pulses sent per DAC step. As said in the test protocol explanation, these limits are set to account for possible small fluctuations in the channel hitcounts. The script also checks if a channel is always at 0 hitcounts or at >1000 hitcounts, being dead in the first case and noisy in the second case. If any of these cases happen a text error is generated and propagated to the VI error window and saved in the log file. No plots/distributions are produced in this analysis.

The standard S-Curve analysis is performed using a python scripts which reads the raw data. Using the standard S-Curve fit function (Equation (5.2)) with ROOT, the transition point and the sigma for each channel are obtained. The fit Chi-square parameter is used to spot possible problems in the channels. The script generates a PDF file for each raw data file (in total six S-Curve data files, for six different configurations, are produced during the ECQA procedure). The title of these files is SCURVE_cfgXXX_dist.pdf, where XXX is the CLARO channel configuration for that raw data file (0x314, 0x30A, 0x31E, 0xB2A, 0xB34, 0xB3E). In the file two histograms are produced, which are the transition point and sigma distribution for all the channels of that load. Then the S-Curve distributions for all the channels are produced in the file. In Figure 8.30 the transition point and sigma distributions for a load are reported. The configuration applied in this case was 0x30A (threshold 10). The number of entries is 1024 that is all the channels had a transition. In Figure 8.31 the S-Curve distribution for a single channel is reported. A log file is generated by the script, containing any errors found in the test (no transitions, noisy/dead channels), together with a parameter file containing, per each channel, the transition point and the sigma (in DAC units), the errors on these two parameters given by the ROOT fit and lastly the four channel ID parameters. A further analysis is performed on the S-Curve data to extract the linearity parameters of the channels: the channel transition points at different thresholds are reported in a graph as a function of the applied threshold, then a linear fit with ROOT is performed to find the slope and the y-axis intercept of the line. The slope of the line is the gain of the channel, that is the number of ke^- per threshold step, while the y-axis intercept is the channel offset in ke^- . Both parameters are extracted for each channel for its full characterization.

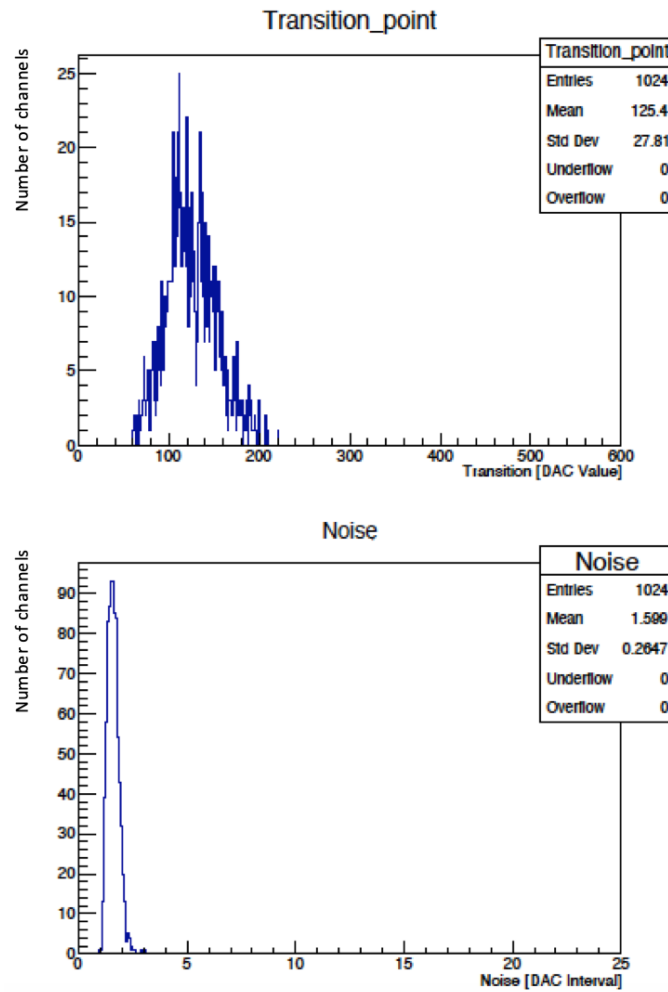


Figure 8.30: Transition point and sigma distribution for a full 4 ECs load R-type, generated by the S-Curve python analysis script.

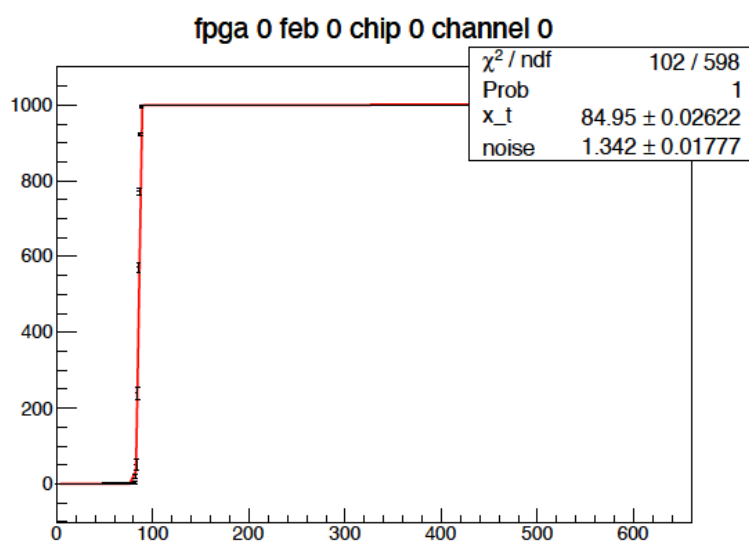


Figure 8.31: S-Curve distribution for a single CLARO channel obtained during the ECQA procedure. The channel ID is in the title of the graph. The fit parameters are reported in the top-right corner.

The Threshold Scan analysis is performed using a C++ script. The main purpose of this test is to find the optimized thresholds (or working points) for all the channels of the load. This is done by searching for the channel pedestal edge in the threshold scan distribution and setting five threshold steps above that point. In addition, checks are performed to ensure that every channel is active (no 0 counts), that the transition happens in all channels, that there are no channels with a normalized number of counts > 1 . The output of the script consist of a PDF file for each MaPMT of the load, a PDF containing the errors overview for the entire load and two text files, a log and the optimized threshold file. The error overview PDF (Figure 8.32) is a single plot containing a 2D 8×8 ROOT histogram for each MaPMT of the load. If during the test a channel has a problem (no pedestal found, dead/noisy channel) the correspondent bin on the histogram is filled, otherwise it stays blank. This allows the user to quickly check the data quality of the test.

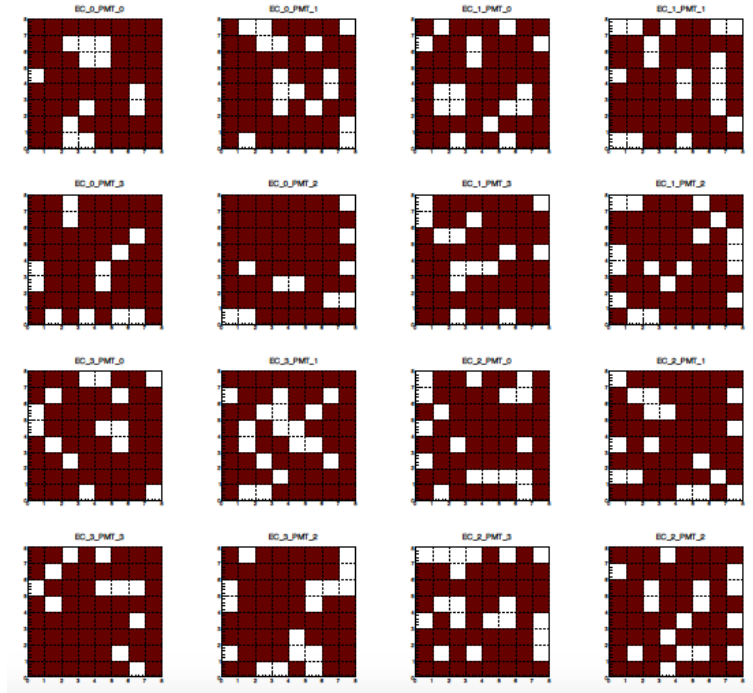


Figure 8.32: 2D histogram error overview for a threshold scan test. This test was performed with the CLAROs Offset bit at 0, hence most of the channels do not exhibit the pedestal and they are marked as defective in this plot.

In the single-MaPMT PDF files a 2D histogram with the found working point per channel is reported, as shown in Figure 8.33. This plot helps the

user to have an overview of the system behaviour in this test. After that, the single channel Threshold Scan distributions are reported (Figure 8.34). The association between electronics (UART FEB CHIP CHANNEL) and optics (ANODE MaPMT EC) is explicit in each plot to check that no mapping error is performed.

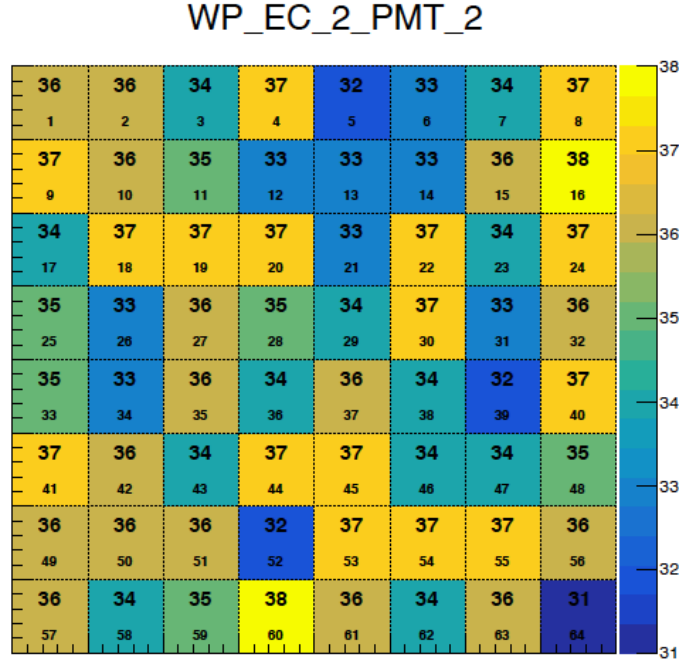


Figure 8.33: 2D histogram showing the found working points for all the channels of the MaPMT 2 (C) of the EC 2 (bottom-right).

The log file text file contains any errors found in the test (no transitions, noisy/dead channels). The optimized thresholds file contains a line for each channel. In each line the channel ID parameters are written, followed by the configuration (in decimal) to set that channel at the previously found optimized threshold with the Offset bit 1. The last element is the optimized threshold explicitly written, to help the user to read the file. The configurator VI reads this file and set the channel identified by the first four line parameters at the configuration found in column "CHANNEL-CFG".

The optimized thresholds are calculated also for the Offset bit 0 threshold scan files, even if the pedestal is not present in most channels. This is done using a dedicated algorithm which compares the Threshold Scan distributions for each channel obtained at Offset bit 0 and 1 and searches for the threshold at which the two distributions better overlap. The algorithm op-

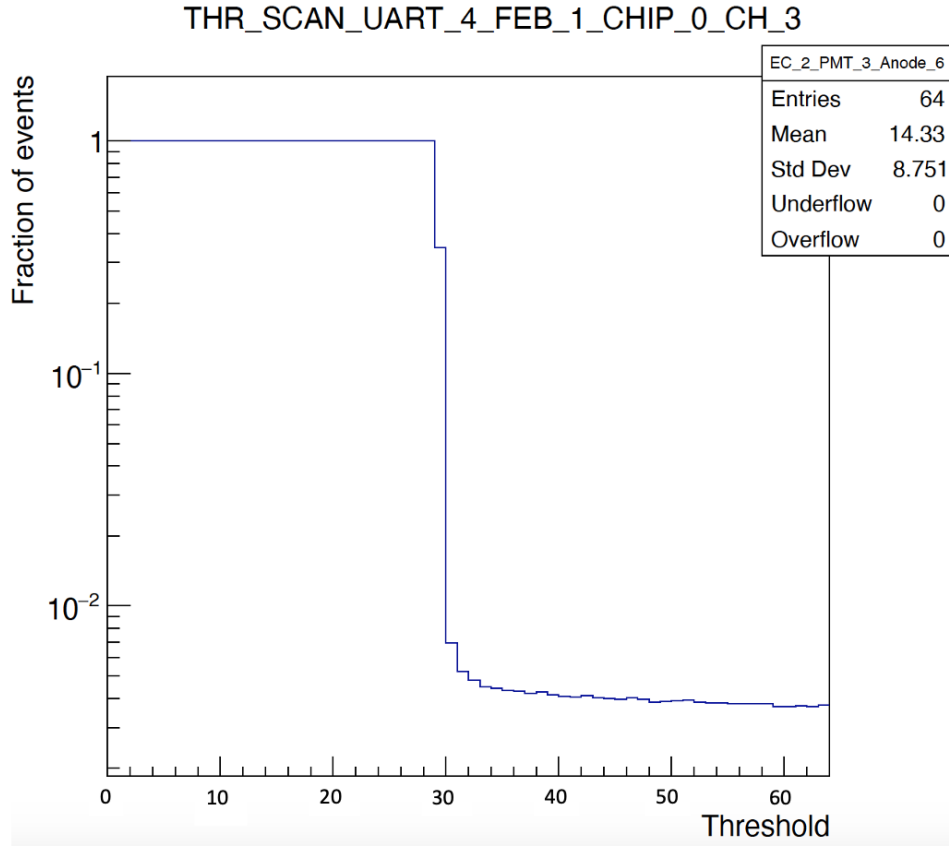


Figure 8.34: Typical Threshold Scan distribution for the CLARO channels in the ECQA procedure.

erates on the threshold range [19,42] for the Offset bit 1 distribution and [1,20] on the Offset bit 0 distribution. The content of the bin of the Offset bit 1 distribution C_1 is compared to the content of each bin in the Offset bit 0 distribution range C_0 using the formula:

$$\sum_{k=1}^{20} \frac{(C_1 - C_0 k)^2}{C_1}, \quad (8.2)$$

and the value obtained is put in a histogram for the bin referred to the C_1 bin threshold reference in the range [19,42]. The result is shown in Figure 8.35. The threshold at which the minimum in the distribution is found corresponds to the threshold offset of the channel, that is the actual shift operated by the Offset bit. Using this value is possible to evaluate the optimized threshold for the Offset bit 0 Threshold Scan distributions from the Offset bit 1 distributions.

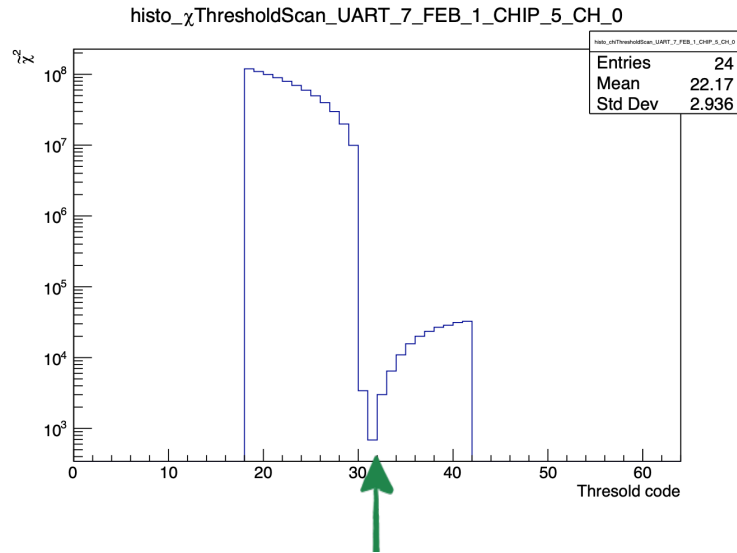


Figure 8.35: Distribution obtained for a CLARO channel for the threshold offset calculation. For this particular channel the action of the Offset bit is to shift the threshold by 32, that is the standard value.

The SIN data analysis is performed by a C++ script. The output consist of a PDF file per each MaPMTs in the load and of a single text file. The PDF contains three 2D histograms 8×8 which represent the MaPMT. The height of each bin is a different SIN parameter for each histogram: in the first one the "TOTAL" intensity is used, that is the sum of all the counts in the entire SIN spectrum for that channel; in the second one, the "SIGNAL" intensity is used, that is the total number of counts in the steps 14-15, corresponding to the true LED signal; lastly, the "SIN" fraction is used, defined in Equation 8.1. Using these three overview plots it's possible to monitor the SIN contribution for the MaPMTs while also monitoring the anodes uniformity. Then the SIN distributions for all the channels of that MaPMTs are reported in the PDF. AN example of these plots are shown in Figure 8.36.

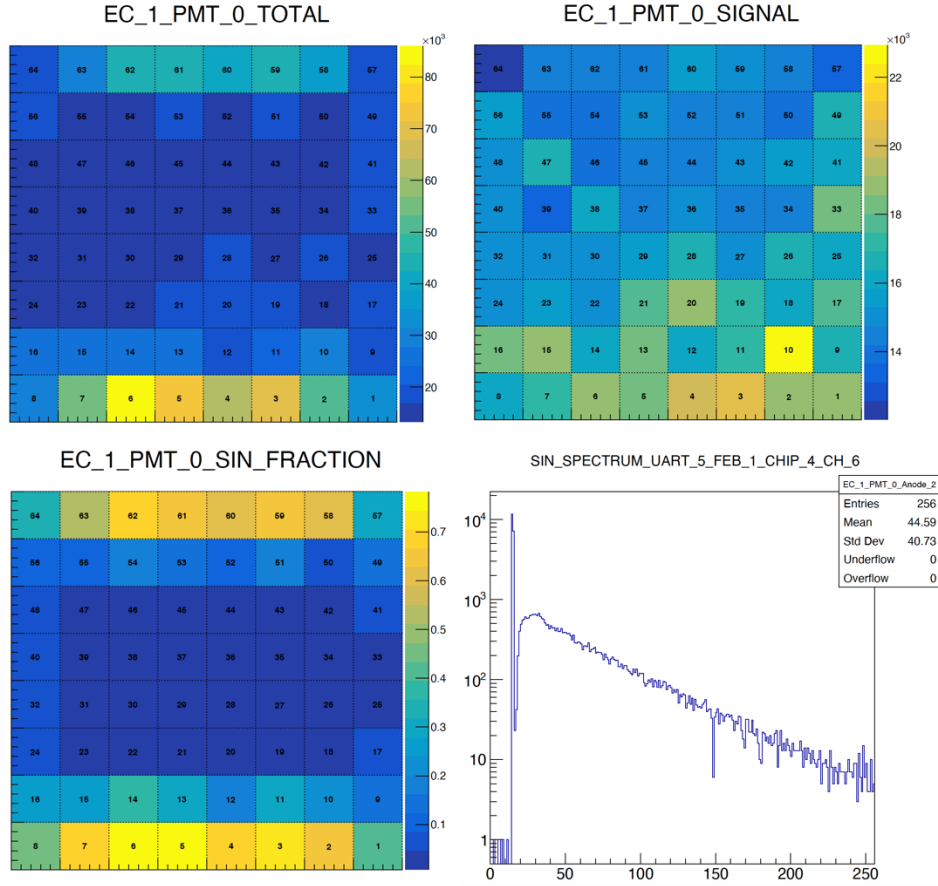


Figure 8.36: The three overview 2D histograms produced for the SIN analysis of a MaPMT, together with the SIN spectrum for a channel. Also here the connection between channel ID and MaPMT anode is explicit in the histogram title.

The DCR data analysis is performed by a C++ script. The script produces an error message if the DCR for a channel is over 1kHz. The output consists of a PDF file per EC of the load and a the log text file in which the script output is registered. The PDF file contains two set of 2D histograms representing the MaPMTs of the load. The first set of histograms is an error overview histogram, like the one in Figure 8.32, in which the MaPMTs anodes are colored only if the DCR for that anode is $> 1\text{kHz}$. In the second set of histograms the DCR for all the MaPMTs anodes are reported (Figure 8.37).

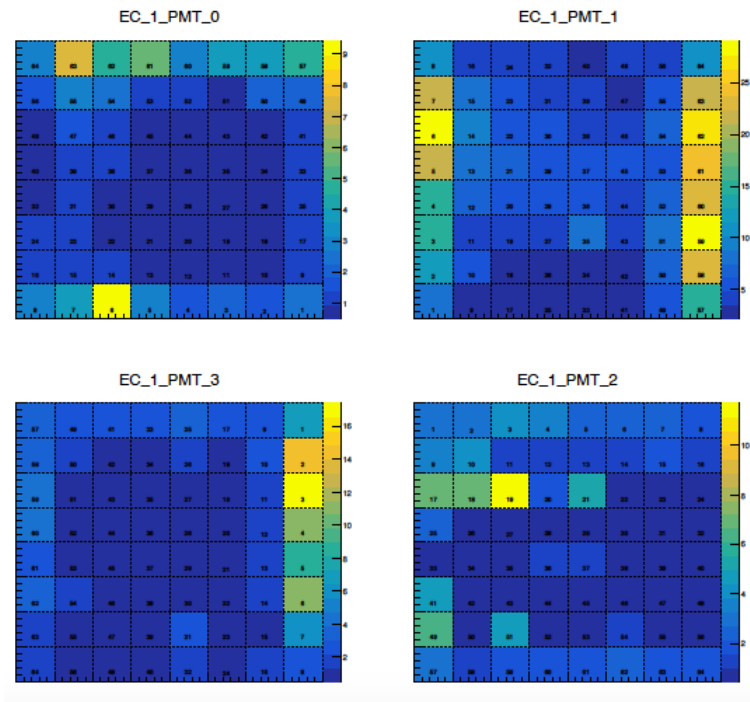


Figure 8.37: DCR plot for an R-type EC. The SIN contributions on the outer channels are present also in this kind of measurement. The number of the anode is reported on the corresponding bin.

8.3.5 EC boxing and delivery

After an EC has been tested and no problems have been spotted on it, a barcode is attached to its side (for a fast identification of the cell) and it's put in a plastic jar⁹ which has been customized so that the EC aluminum

⁹<https://export.rsdelivers.com/product/rs-pro/jwp0500p/rs-pro-lab-bottles-storage-bottle-pp-500ml/4781703>

case back part can be screwed to the jar cap. The jar is then kept always with the cap facing the floor and the MaPMTs facing upwards, as shown in Figure 8.38. This prevent the MaPMTs to detach due to possible vibrations/movements during the transport. The jar are then put in a Korrvu cardboard box¹⁰ equipped with a support with plastic membranes (Figure 8.39) which keep the EC spaced from the box. A maximum of two ECs can be put in the same box. A maximum of 40 boxes (80 ECs) are then shipped to CERN using a wooden box, in which the EC are always kept in the correct orientation.



Figure 8.38: The H-type EC screwed to the plastic jar cap ready to be sent to CERN. The barcode is visible on its side and a label with the EC load number and the station used to test it is placed on the jar bottom, which is facing upwards.

8.3.6 Database

The ECs main parameters are saved in text files which will be loaded into the LHCb database. A file per each EC is provided at the end of the ECQA procedure, and the file name is the barcode attached to the EC at the end of the tests, so that the EC parameters can be quickly retrieved.

In the file the general information on the EC are first reported, a line for each different element: EC barcode; date, time, place of the test, operator assembling the cell, station number ID, EC position in the load and Load Number. Then the EC components QR codes are reported: Bkb, FEBs and Bb following the scanning order, followed by the MaPMTs codes. The environmental temperature average registered during the tests is then inserted. After that, the eight ADC channel values taken from the LV_conf.txt measurement file are inserted. Lastly, the DCR for each MaPMT of the EC is reported. After these EC parameters the parameters per single channel are

¹⁰<https://sealedair.com/product-care/product-care-products/suspension-packaging>



Figure 8.39: EC jar in the Korrvu packaging ready to be sent to CERN.

inserted: S-Curve linearity slope and y-axis intercept for both the Offset bit 0 and 1 measurements (4 parameters); pedestal and optimized threshold for both the Offset bit 0 and 1 measurements (4 parameters); the Signal Intensity and the SIN intensity for the four SIN measurements, taken at 1000V, 950V, 900V, 850V (8 parameters). The different channels parameters line are separated by a default string.

Chapter 9

Conclusions

In this thesis I presented the validation tests performed on the optoelectronic chain which will be used in the LHCb RICH upgraded detector.

The CLARO ASIC, the core component of the RICH Upgrade electronics, has been tested in the most advanced European irradiation facilities using charged ion beams, proton beams and mixed irradiation field to ensure that it is able to operate on the foreseen environment of the upgraded LHCb experiment, for which the Total Ionizing Dose (TID) expected in the Run III + IV (2021-2029) is 200 krad, 3×10^{12} 1 MeV n_{eq}/cm^2 . The CLARO has been tested for Single Event Effects (SEE) in the ions test, performed at the Heavy Ion Facility (HIF) of Louvain-La-Neuve (BE) and at the Silicon and RADiation (SIRAD) facility in Legnaro (IT). From the data analysis of these ion test the Single Event Upset (SEU) and Single Event Latchup (SEL) cross-sections of the CLARO as a function of the ion Linear Energy Transfer (LET) have been measured. The LET threshold for SEU cross section has been found to be 20 MeV/mg/cm² in both tests. SEL occurred in the Louvain-La-Neuve tests with a LET > 50 MeV/mg/cm², but in Legnaro no SEL happened in the same LET range. At the IRRAD facility (CERN) the ASIC has been tested using a 24 GeV/ c proton beam up to a TID of ~ 14 Mrad. The SEU rate per Mrad has been measured for each tested CLARO, with values in the range 130-160 SEU·Mrad⁻¹. No SEL happened during this test. Lastly, the CLARO has been exposed to a mixed radioactive field in the CERN CHARM facility. The field, recreating a realistic LHCb environment possible, was mainly composed of protons, neutrons, pions and gamma photons but suffers from low particle rates, limited by the radiation protection rules. The TID absorbed by each CLARO was 80 krad. Due to the low TID the number of SEU was low (maximum 12) and no SEL

occurred. Given the performances in the aforementioned irradiation tests, the CLARO has been defined as suitable to operate in the required post-upgrade conditions in LHCb.

The LHCb RICH Upgrade prototype has been tested at the North-Area at CERN using a 180 GeV/ c charged hadron beam. Aim of the test was to test the full opto-electronic chain in a realistic environment using the miniDAQ as a data readout system. The prototype was composed of four full Elementary Cells (ECs), the compact structure with the CLAROs and the Multi-Anode Photo Multiplier Tubes (MaPMTs), mounted on a movable water-cooled structure placed inside a light-tight box, in which a borosilicate-glass lens is used as a radiator medium for Cherenkov photons. Using a dedicated software was possible to reconstruct the Cherenkov ring radius and angle and obtain an estimate of the three main contributions to the Cherenkov angle resolution (Chromatic error, Pixel Size error and Emission Point error). Then several runs of S-Curve tests and Threshold Scan tests have been performed on the setup and the data have been analyzed to fully characterize the CLARO behaviour in a system structurally close to the upgraded LHCb RICH setup.

In the last part of the thesis the validation tests on the CLARO chips, standalone and mounted on the Front-End Boards (FEBs), and on the ECs are presented. The components have been validated using dedicated Quality Assurance (QA) procedures. The entire CLARO production has been tested in Ferrara using two identical pick-and-place test stations, designed and produced in Ferrara, and a dedicated test protocol. The data from the preliminary QA tests have been analyzed to ensure both stations produced the same results and to characterize the tests stations, together with the CLARO so that the appropriate parameter's cuts during the procedure could have been applied. Then an analysis on the QA data of $\sim 1/4$ of the CLARO production has been performed to ensure everything was performed correctly. The results from this analysis were in agreement with the expected results from the used QA test protocol. The CLARO passing the QA procedure have been sent to the company responsible for the FEBs and Backboard (Bkb) production. The CLARO have been soldered on the FEBs and the boards have been tested on the company site using a dedicated setup designed and produced by the Ferrara RICH Upgrade group using a dedicated test protocol. The CLARO data coming from a portion of the first FEBs produced have been analyzed and compared to the results obtained from the CLARO QA data analysis results. This analysis has shown a good agreement between the results obtained from the two QA tests. All the electronic and optical

components have been assembled in ECs which are being tested in Ferrara and Edinburgh. Two test stations are present in Ferrara, each one composed of a light-tight box, a DAQ system and a LED driver to perform tests on the ECs with light. Up to four ECs can be tested at the same time using a test station. The DAQ software has been designed using NI LabVIEW, first developing standalone VIs to perform single measurements of the QA procedure and then developing a state machine able to perform the full test protocol sequence in an automatic way. Dedicated analysis scripts have been developed for each different measurement and the data obtained from the analysis have been collected in dedicated files per each EC to collect its most important parameters to be loaded into the LHCb database. These data represent a first level characterization of the ECs, which of course has to be performed again once the EC is mounted on the upgraded RICH detector.

All the tested ECs will be mounted on the upgraded RICH detectors (some of the RICH2 ECs have already been mounted) and during 2020 the upgraded RICH commissioning will start. Following this schedule it will be possible to start the data taking on March 2021, as expected.

Appendix A

Irradiation data analysis tools

The data from the irradiation tests on the CLARO chips have been analyzed following the European Space Components Coordination (ESCC) guidelines[57]. The Total Ionizing Dose (TID) D in rad absorbed by a silicon device when irradiated with an ion is calculated from formula (A.1):

$$D = F_{eff} \times LET_{eff} \times 1.6 \cdot 10^{-5}, \quad (A.1)$$

where F_{eff} is the effective particle fluence, measured in ions/cm², and LET_{eff} is the ion effective Linear Energy Transfer expressed in MeV/mg/cm². For the proton irradiation the dose D in rad has been calculated using the formula (6.2):

$$D = F_{eff} \times 2.666 \cdot 10^{-10} \text{Gy} \cdot \text{particle/cm}^2 \quad (A.2)$$

where F_{eff} is the effective particle fluence, measured in ions/cm² [60].

The Single Event Effects (SEE) cross-section σ is given by equation (6.2) already seen in section 6.2.1:

$$\sigma_{SEE} = \frac{N_{SEE}}{F_{eff}}, \quad (A.3)$$

where N is the number of events and F_{eff} the effective fluence. The uncertainty on this cross-section is given by equation (A.4):

$$\frac{\delta\sigma}{\sigma} = \sqrt{\left(\frac{\delta N}{N}\right)^2 + \left(\frac{\delta F}{F}\right)^2}, \quad (A.4)$$

which can be also written as equation (A.5):

$$\delta\sigma \times F = \sqrt{(\delta N)^2 + (N \times \frac{\delta F}{F})^2}, \quad (\text{A.5})$$

The term $\delta F/F$ is the uncertainty on the measured fluence, which was set to 15% for this thesis calculations. The term δN is the variance on the measured number of SEE. Assuming that SEE are random, the probability for one of them to happen follows a Poissonian distribution. Hence the variance on N is calculated from the Chi-Square distribution for a given confidence level. The variance has been calculated using the Excel functions reported below as a function of the confidence level CL. For the calculations in this thesis the CL was set to 95%. The lower limit of the confidence interval on N , Lower- N , is calculated as following:

- If no SEE occurred ($N = 0$), the lower limit Lower- N is set to 0;
- If $N > 0$, Lower- N is given by equation (A.6):

$$\text{Lower-}N = 0.5 \times \text{CHISQ.INV}((1 - \text{CL})/2, 2 \times N); \quad (\text{A.6})$$

the function CHISQ.INV returns the inverse of the left-tailed probability of the chi-squared distribution¹.

The upper limit of the confidence interval on N , Upper- N , is calculated as following:

- For all cases, that is $N \geq 0$, Upper- N is given by equation (A.7):

$$\text{Upper-}N = 0.5 \times \text{CHISQ.INV.RT}((1 - \text{CL})/2, 2 \times (N + 1)); \quad (\text{A.7})$$

the function CHISQ.INV.RT returns the inverse of the right-tailed probability of the chi-squared distribution². If $N=0$ the Upper- N depends on the confidence level.

¹<https://www.excelfunctions.net/excel-chisq-inv-function.html>

²<https://www.excelfunctions.net/excel-chisq-inv-rt-function.html>

Appendix B

Least-square circle fit

The following method allows to find the best circle, using the least square method, that fits a set of points $\{(x_i, y_i) | 0 \leq i \leq N\}$ [61]. Define

$$\bar{x} = \frac{1}{N} \sum_i x_i, \quad \bar{y} = \frac{1}{N} \sum_i y_i, \quad (\text{B.1})$$

and let $u_i = x_i - \bar{x}$, $v_i = y_i - \bar{y}$ for $0 \leq i \leq N$. The problem is first solved in the (u, v) coordinates and then it's transformed back into (x, y) coordinates. The circle center coordinates are (u_c, v_c) and its radius is R . We have to minimize the parameter $S = \sum_i (g(u_i, v_i))^2$, where $g(u, v) = (u - u_c)^2 + (v - v_c)^2 - \alpha$, $\alpha = R^2$. To do that, we differentiate $S(\alpha, u_c, v_c)$:

$$\frac{\partial S}{\partial \alpha} = 2 \sum_i g(u_i, v_i) \frac{\partial g}{\partial \alpha}(u_i, v_i) = -2 \sum_i g(u_i, v_i). \quad (\text{B.2})$$

The derivative is zero if, and only if,

$$\sum_i g(u_i, v_i) = 0. \quad (\text{B.3})$$

Using (B.3), we can obtain

$$\begin{aligned} \frac{\partial S}{\partial u_c} &= 2 \sum_i g(u_i, v_i) \frac{\partial g}{\partial u_c}(u_i, v_i) \\ &= 2 \sum_i g(u_i, v_i) 2(u_i - u_c)(-1) \\ &= -4 \sum_i u_i g(u_i, v_i) + 4u_c \sum_i g(u_i, v_i). \end{aligned} \quad (\text{B.4})$$

In presence of (B.3), $\partial S / \partial u_c = 0$ is verified only if

$$\sum_i u_i g(u_i, v_i) = 0, \quad (\text{B.5})$$

and, in a similar way, for $\partial S/\partial v_c = 0$

$$\sum_i v_i g(u_i, v_i) = 0. \quad (\text{B.6})$$

By expanding equation (B.5) we can obtain

$$\sum_i u_i [u_i^2 - 2u_i u_c + u_c^2 + v_i^2 - 2v_i v_c + v_c^2 - \alpha] = 0. \quad (\text{B.7})$$

By defining $S_u = \sum_i u_i$, $S_{uu} = \sum_i u_i^2$, etc., we can rewrite the previous equation (B.7) as

$$S_{uuu} - 2u_c S_{uu} + u_c^2 S_u + S_{uvv} - 2v_c S_{uv} + v_c^2 S_u - \alpha S_u = 0, \quad (\text{B.8})$$

but $S_u = 0$, and thus

$$u_c S_{uu} + v_c S_{uv} = \frac{1}{2}(S_{uuu} + S_{uvv}), \quad (\text{B.9})$$

and similarly from equation B.6, since $S_v = 0$, we can obtain

$$u_c S_{uv} + v_c S_{vv} = \frac{1}{2}(S_{vvv} + S_{vuu}). \quad (\text{B.10})$$

By simultaneously solving (B.9) and (B.10) we can obtain (u_c, v_c) and then the circle center coordinate back in the (x, y) coordinate system: $(x_c, y_c) = (u_c, v_c) + (\bar{x}, \bar{y})$. To obtain the radius R , the equation B.3 has to be expanded and using $S_u = S_v = 0$ we obtain

$$N(u_c^2 + v_c^2 - \alpha) + S_{uu} + S_{vv} = 0, \quad (\text{B.11})$$

and thus

$$\alpha = u_c^2 + v_c^2 + \frac{S_{uu} + S_{vv}}{N}. \quad (\text{B.12})$$

The radius R is $R = \sqrt{\alpha}$.

Appendix C

ECQA Mapping Scheme

In this appendix the detailed mapping between the CLAROs channel on the Front-End Boards (FEBs) and the Multi-Anode Photo Multiplier Tubes (MaPMTs) anode in the Elementary Cells (ECs) is reported. In figure C.1 the mapping scheme for an R-type EC is reported. The same scheme is valid for each R-type EC. The UART information is missing because every R-type EC of the load has different UART connectors associated: 0 and 3 for the EC3 (bottom-left), 1 and 2 for the EC0 (top-left), 4 and 7 for the EC2 (bottom-right) and 5 and 6 for the EC1 (top-right).

In figure C.2 the mapping scheme for an H-type EC is reported. The same scheme is valid for each H-type EC. The UART information is missing because every H-type EC of the load has different UART connectors associated: 0 for the EC3 (bottom-left), 1 for the EC0 (top-left), 4 for the EC2 (bottom-right) and 5 for the EC1 (top-right).

Figure C.1: Scheme representing the association between MaPMTs anodes (green = MaPMT A, pink = MaPMT B, yellow = MaPMT C, blue = MaPMT D) and CLARO channels on the FEBs for an R-type EC. On the top side the CLARO channels at which the anodes are connected are reported, with the channel ID parameters at which the channel is associated (FEB and CHIP). On the bottom side the MaPMT anode numbering convention is reported.

FE80 CHIP7 CH7	FE80 CHIP7 CH6	FE80 CHIP6 CH0	FE80 CHIP6 CH1	FE81 CHIP7 CH7	FE81 CHIP6 CH1	FE81 CHIP6 CH0	FE82 CHIP7 CH7	FE82 CHIP7 CH6	FE82 CHIP6 CH0	FE82 CHIP6 CH1	FE83 CHIP7 CH7	FE83 CHIP6 CH1	FE83 CHIP6 CH0
FE80 CHIP7 CH5	FE80 CHIP7 CH4	FE80 CHIP6 CH2	FE80 CHIP6 CH3	FE81 CHIP7 CH4	FE81 CHIP7 CH5	FE81 CHIP6 CH2	FE82 CHIP7 CH5	FE82 CHIP7 CH4	FE82 CHIP6 CH2	FE82 CHIP6 CH3	FE83 CHIP7 CH4	FE83 CHIP6 CH2	FE83 CHIP6 CH3
FE80 CHIP7 CH1	FE80 CHIP7 CH0	FE80 CHIP6 CH5	FE80 CHIP6 CH4	FE81 CHIP7 CH0	FE81 CHIP7 CH1	FE81 CHIP6 CH3	FE82 CHIP7 CH1	FE82 CHIP7 CH0	FE82 CHIP6 CH4	FE82 CHIP6 CH5	FE83 CHIP7 CH0	FE83 CHIP6 CH3	FE83 CHIP6 CH4
FE80 CHIP6 CH6	FE80 CHIP6 CH7	FE80 CHIP4 CH0	FE80 CHIP4 CH1	FE81 CHIP6 CH7	FE81 CHIP6 CH6	FE81 CHIP4 CH0	FE82 CHIP6 CH6	FE82 CHIP6 CH7	FE82 CHIP4 CH0	FE82 CHIP4 CH1	FE83 CHIP6 CH7	FE83 CHIP4 CH0	FE83 CHIP4 CH1
FE80 CHIP5 CH4	FE80 CHIP5 CH5	FE80 CHIP4 CH3	FE80 CHIP4 CH2	FE81 CHIP5 CH4	FE81 CHIP5 CH5	FE81 CHIP4 CH2	FE82 CHIP5 CH4	FE82 CHIP5 CH5	FE82 CHIP4 CH3	FE82 CHIP4 CH4	FE83 CHIP5 CH4	FE83 CHIP4 CH2	FE83 CHIP4 CH3
FE80 CHIP5 CH2	FE80 CHIP5 CH3	FE80 CHIP4 CH5	FE80 CHIP4 CH4	FE81 CHIP5 CH2	FE81 CHIP5 CH3	FE81 CHIP4 CH3	FE82 CHIP5 CH2	FE82 CHIP5 CH3	FE82 CHIP4 CH5	FE82 CHIP4 CH6	FE83 CHIP5 CH2	FE83 CHIP4 CH4	FE83 CHIP4 CH5
FE80 CHIP5 CH0	FE80 CHIP5 CH1	FE80 CHIP4 CH7	FE80 CHIP4 CH6	FE81 CHIP5 CH1	FE81 CHIP5 CH0	FE81 CHIP4 CH7	FE82 CHIP5 CH0	FE82 CHIP5 CH1	FE82 CHIP4 CH7	FE82 CHIP4 CH6	FE83 CHIP5 CH0	FE83 CHIP4 CH6	FE83 CHIP4 CH7
FE80 CHIP3 CH7	FE80 CHIP3 CH6	FE80 CHIP2 CH0	FE80 CHIP2 CH1	FE81 CHIP3 CH7	FE81 CHIP2 CH1	FE81 CHIP2 CH0	FE82 CHIP3 CH7	FE82 CHIP3 CH6	FE82 CHIP2 CH0	FE82 CHIP2 CH1	FE83 CHIP3 CH7	FE83 CHIP2 CH1	FE83 CHIP2 CH0
FE80 CHIP3 CH5	FE80 CHIP3 CH4	FE80 CHIP2 CH2	FE80 CHIP2 CH3	FE81 CHIP3 CH5	FE81 CHIP2 CH2	FE81 CHIP2 CH3	FE82 CHIP3 CH5	FE82 CHIP3 CH4	FE82 CHIP2 CH2	FE82 CHIP2 CH3	FE83 CHIP3 CH5	FE83 CHIP2 CH2	FE83 CHIP2 CH3
FE80 CHIP3 CH3	FE80 CHIP3 CH2	FE80 CHIP2 CH4	FE80 CHIP2 CH5	FE81 CHIP3 CH2	FE81 CHIP2 CH4	FE81 CHIP2 CH5	FE82 CHIP3 CH2	FE82 CHIP3 CH3	FE82 CHIP2 CH4	FE82 CHIP2 CH5	FE83 CHIP3 CH2	FE83 CHIP2 CH4	FE83 CHIP2 CH5
FE80 CHIP3 CH1	FE80 CHIP3 CH0	FE80 CHIP2 CH7	FE80 CHIP2 CH6	FE81 CHIP3 CH1	FE81 CHIP2 CH6	FE81 CHIP2 CH7	FE82 CHIP3 CH1	FE82 CHIP3 CH0	FE82 CHIP2 CH6	FE82 CHIP2 CH7	FE83 CHIP3 CH1	FE83 CHIP2 CH6	FE83 CHIP2 CH7
FE80 CHIP1 CH6	FE80 CHIP1 CH7	FE80 CHIP0 CH1	FE80 CHIP0 CH2	FE81 CHIP1 CH6	FE81 CHIP0 CH2	FE81 CHIP0 CH1	FE82 CHIP1 CH6	FE82 CHIP1 CH7	FE82 CHIP0 CH1	FE82 CHIP0 CH2	FE83 CHIP1 CH6	FE83 CHIP0 CH1	FE83 CHIP0 CH2
FE80 CHIP1 CH4	FE80 CHIP1 CH5	FE80 CHIP0 CH3	FE80 CHIP0 CH4	FE81 CHIP1 CH4	FE81 CHIP0 CH3	FE81 CHIP0 CH4	FE82 CHIP1 CH4	FE82 CHIP1 CH5	FE82 CHIP0 CH3	FE82 CHIP0 CH4	FE83 CHIP1 CH4	FE83 CHIP0 CH2	FE83 CHIP0 CH3
FE80 CHIP1 CH2	FE80 CHIP1 CH3	FE80 CHIP0 CH5	FE80 CHIP0 CH6	FE81 CHIP1 CH2	FE81 CHIP0 CH5	FE81 CHIP0 CH6	FE82 CHIP1 CH2	FE82 CHIP1 CH3	FE82 CHIP0 CH5	FE82 CHIP0 CH6	FE83 CHIP1 CH2	FE83 CHIP0 CH3	FE83 CHIP0 CH4
FE80 CHIP1 CH0	FE80 CHIP1 CH1	FE80 CHIP0 CH7	FE80 CHIP0 CH6	FE81 CHIP1 CH0	FE81 CHIP0 CH7	FE81 CHIP0 CH6	FE82 CHIP1 CH0	FE82 CHIP1 CH1	FE82 CHIP0 CH7	FE82 CHIP0 CH6	FE83 CHIP1 CH0	FE83 CHIP0 CH6	FE83 CHIP0 CH7
64	63	62	61	60	59	58	8	16	24	32	40	48	56
56	55	54	53	52	51	50	7	15	23	31	39	47	55
48	47	46	45	44	43	42	6	14	22	30	38	46	54
40	39	38	37	36	35	34	5	13	21	29	37	45	53
32	31	30	29	28	27	26	4	12	20	28	36	44	52
24	23	22	21	20	19	18	3	11	19	27	35	43	51
16	15	14	13	12	11	10	2	10	18	26	34	42	50
8	7	6	5	4	3	2	1	9	17	25	33	41	49
57	49	41	33	25	17	9	1	2	3	4	5	6	7
58	50	42	34	26	18	10	9	10	11	12	13	14	15
59	51	43	35	27	19	11	17	18	19	20	21	22	23
60	52	44	36	28	20	12	25	26	27	28	29	30	31
61	53	45	37	29	21	13	33	34	35	36	37	38	39
62	54	46	38	30	22	14	41	42	43	44	45	46	47
63	55	47	39	31	23	15	49	50	51	52	53	54	55
64	56	48	40	32	24	16	57	58	59	60	61	62	63
													64

FEB0 CHIP7 CH7	FEB0 CHIP7 CH5	FEB0 CHIP6 CH2	FEB0 CHIP6 CH0	FEB1 CHIP7 CH7	FEB1 CHIP7 CH5	FEB1 CHIP6 CH2	FEB1 CHIP6 CH0
FEB0 CHIP7 CH1	FEB0 CHIP7 CH0	FEB0 CHIP6 CH7	FEB0 CHIP6 CH6	FEB1 CHIP7 CH1	FEB1 CHIP7 CH0	FEB1 CHIP6 CH7	FEB1 CHIP6 CH6
FEB0 CHIP5 CH6	FEB0 CHIP5 CH4	FEB0 CHIP4 CH3	FEB0 CHIP4 CH1	FEB1 CHIP5 CH6	FEB1 CHIP5 CH4	FEB1 CHIP4 CH3	FEB1 CHIP4 CH1
FEB0 CHIP5 CH2	FEB0 CHIP5 CH0	FEB0 CHIP4 CH7	FEB0 CHIP4 CH5	FEB1 CHIP5 CH2	FEB1 CHIP5 CH0	FEB1 CHIP4 CH7	FEB1 CHIP4 CH5
FEB0 CHIP3 CH5	FEB0 CHIP3 CH7	FEB0 CHIP2 CH0	FEB0 CHIP2 CH2	FEB1 CHIP3 CH5	FEB1 CHIP3 CH7	FEB1 CHIP2 CH0	FEB1 CHIP2 CH2
FEB0 CHIP3 CH1	FEB0 CHIP3 CH3	FEB0 CHIP2 CH4	FEB0 CHIP2 CH6	FEB1 CHIP3 CH1	FEB1 CHIP3 CH3	FEB1 CHIP2 CH4	FEB1 CHIP2 CH6
FEB0 CHIP1 CH6	FEB0 CHIP1 CH7	FEB0 CH1P0 CH0	FEB0 CH1P0 CH1	FEB1 CHIP1 CH6	FEB1 CHIP1 CH7	FEB1 CH1P0 CH0	FEB1 CH1P0 CH1
FEB0 CHIP1 CH0	FEB0 CHIP1 CH2	FEB0 CH1P0 CH5	FEB0 CH1P0 CH7	FEB1 CHIP1 CH0	FEB1 CHIP1 CH2	FEB1 CH1P0 CH5	FEB1 CH1P0 CH7

64	63	62	61	60	59	58	57
56	55	54	53	52	51	50	49
48	47	46	45	44	43	42	41
40	39	38	37	36	35	34	33
32	31	30	29	28	27	26	25
24	23	22	21	20	19	18	17
16	15	14	13	12	11	10	9
8	7	6	5	4	3	2	1

Figure C.2: Scheme representing the association between the single MaPMT anodes and CLARO channels on the FEBs for an H-type EC. On the top side the CLARO channels at which the anodes are connected are reported, with the channel ID parameters at which the channel is associated (FEB and CHIP). On the bottom side the MaPMT anode numbering convention is reported.

List of Tables

2.1	Whole trigger chain efficiencies of selected channels, normalized to the number of offline selected events. The configuration is the one of the 2012.	30
3.1	Summary of measurements sensitivities for LHCb flavour observables in the current and post-upgrade experimental conditions.	34
4.1	Comparison of photoelectron yields determined from simulated data sets and real data sets, both <i>ideal</i> and <i>normal</i> events.	52
4.2	Well defined decay topologies well identified without the RICH system.	56
4.3	RICH1 mirrors specifications for the current detector and the expected ones after the LHCb upgrade.	61
4.4	RICH1 post-upgrade optic parameters. The points P(n) can be seen in Figure /reffigure:mirpoint.	64
4.5	RICH1 geometrical data for the PD plane and mirrors after the upgrade.	64
4.6	Single photon reconstructed Cherenkov angle error contributions for the current RICH1, the current RICH2 and the upgraded RICH1.	65
4.7	Parameters of the beam for the LHCb RICH upgrade simulation. L_B is defined as luminosity per bunch crossing and ν is the average number of pp interactions per bunch crossing. . .	70
4.8	Parameters of the R13742 and R13743 MaPMTs used in the simulation.	71
4.9	Main parameters of the upgraded RICH1 optics used in the simulations. All the tilts are with respect to the vertical y axis. . .	71

4.10	Single photon resolutions and photon yields for isolated tracks from the full simulation in the two RICH detectors with MaP-MTs and HPDs.	72
5.1	Configuration bits for each CLARO channel.	78
6.1	TID (per ion used) received by the CLAROs during the irradiation test in Louvain-La-Neuve.	94
6.2	TID received by the CLAROs during the ion test in Legnaro.	100
6.3	Summary list of the ions used in the CLARO irradiation tests main parameters.	103
6.4	Total dose received by the CLAROs on each position on the IRRAD proton irradiation test.	107
6.5	Total dose received by the CLAROs on each position on the IRRAD proton irradiation test.	108
6.6	SEU occurred in the CLARO chips used in the CHARM irradiation test.	111
7.1	Cherenkov ring and angle measurements from the LHCb RICH Upgrade prototype data using the reconstruction software.	124
8.1	Average transition point value comparison between the CLARO QA and the FEB QA results.	150

List of Figures

1.1	Scheme of the LHC accelerator complex (with date of installation and length) and of the experiments on it. CERN copyright.	12
2.1	The section of the LHCb detector from its side.	16
2.2	LHCb integrated luminosity during the years.	18
2.3	VELO silicon modules during assembly.	19
2.4	Schematic of R and ϕ sensors for a VELO module.	19
2.5	Schematic of one of the VELO modules that will be used in the upgrade.	20
2.6	Left: UT geometry, looking downstream. Right: schematic of a silicon strip.	22
2.7	Top: the four TT planar stations. Bottom: the IT structure.	23
2.8	The OuterTracker during installation.	23
2.9	Schematic for RICH1 (left) and RICH2 (right) detectors in LHCb.	24
2.10	The ECAL modules grouping scheme in the current setup.	26
2.11	One of the LHCb Moun detector MWPC during assembly.	27
4.1	Relation between the particle's velocity, the refractive index of the medium and the resulting Cherenkov emission angle.	36

- 4.2 Distribution of the invariant mass in the $B \rightarrow h^+ h^-$ decays in LHCb before (left) and after (right) applying the RICH PID. The selected signal of interest is the $B^0 \rightarrow \pi^+ \pi^-$ decay, the light-blue dotted line, but the total distribution is the sum of all the contributions from other final states: $B^0 \rightarrow 3\text{-body}$ decays (orange dashed-dashed line), $B^0 \rightarrow \pi K$ (red dashed-dotted line), $V_s \rightarrow \pi K$ (brown line), $B_s \rightarrow KK$ (yellow line), $\Lambda_b \rightarrow pK$ (purple line) and $\Lambda_b \rightarrow \pi p$ (green line). All these contributions are heavily suppressed once a positive PID is performed, as shown in the right plot, and only the signal and the two more relevant background contributions are left. The solid grey line is the combinatorial background. 39
- 4.3 Picture of the RICH1 gas enclosure containing the flat and spherical mirrors (the interaction point is on the right). Also the beam-pipe crossing the detector is visible. 40
- 4.4 A scheme of RICH2 showing the beam pipe in the centre, the spherical mirrors and the HPD planes. One flat mirror has not been drawn to give a view of the HPD plane. 42
- 4.5 Left: single HPD, the ruler is 10 cm long. Right: Panel of HPDs inside RICH. 43
- 4.6 RICH1 (left) and RICH2 (right) midpoints distribution after on-beam time alignment procedure. 44
- 4.7 $\Delta\theta_c$ versus ϕ for one HDP panel of the RICH2 detector. The left-hand plot is obtained before applying the spatial alignment procedure, and the dependence on $\Delta\theta_c$ from the azimuthal angle is manifest. After the spatial alignment (right-hand plot) $\Delta\theta_c$ is much more uniformly distributed. 46
- 4.8 Cherenkov angle resolution as a function of run number for RICH1 (left) and RICH2 (right) detectors, after all the corrections have been applied. 48
- 4.9 RICH2 single photon resolution during summer and early autumn of 2015. Each point is the resolution in one run with a maximum duration of one hour. The horizontal line is the average of all the runs after 155000. 50
- 4.10 Occupancy (pixel hits per event) distribution for the HPDs of RICH1 (left) and of RICH2 (right). 53

4.11	Reconstructed Cherenkov angle vs the particle momentum in the C_4F_{10} radiator for RICH1. Although the LHCb RICH detectors are designed to be hadrons detector, thanks to the excellent resolution of the RICH system a distinct muon band can be observed.	54
4.12	$\Delta\log\mathcal{L}(K-\pi)$ vs $\Delta\log\mathcal{L}(p-\pi)$ distribution for kaons (upper-right), pions (upper-left) and protons (bottom).	55
4.13	Kaon identification efficiency rate and pion misidentification rate measured on real LHCb data samples as a function of the charged tracks momenta. Two different conditions on $\Delta\log\mathcal{L}(K-\pi)$ have been imposed.	56
4.14	Right: the Hamamatsu [®] R13742 MaPMT mounted on a custom 2×2 socket board, specifically designed to be employed on the RICH upgrade, together with the data readout boards. Left: the R13742 and R13743 MaPMTs.	58
4.15	Design for the upgraded RICH2 detector, where both R13742 (red) and R13743 (grey) MaPMTs will be employed.	59
4.16	The schematic of the RICH Upgrade PDMDB which will read four ECs.	60
4.17	A PDM that will be installed in the upgraded RICH detectors, where four R-type ECs can be seen.	63
4.18	RICH1 geometries for the actual (left) and upgraded (right) optical system.	64
4.19	Occupancy of the RICH detectors in Lumi20 simulation conditions.	73
4.20	The PID performance of the current geometrical setup for Lumi20 conditions (blue) compared to the performance for the upgraded geometry at Lumi20 conditions (red).	73
5.1	Diagram for a CLARO channel.	76
5.2	Example of S-Curve test for a CLARO channel. The parameters of interested are obtained by fitting the curve.	80
5.3	Threshold Scan distribution with for a CLARO channel having the Offsetbit set to 1. For this particular channel the edge of the pedestal correspond to threshold 32.	81

5.4	An R-Type EC backboard with three out of four FEB mounted on it. The FEB QR codes are visible on their top side. The socket for the FEB is clearly visible on the left-hand side of the picture.	82
5.5	An R-Type MaPMT (left) next to an H-type MaPMT (right).	83
5.6	The Mu-Metal [®] magnetic shield installed in a R-type EC. The MaPMTs are not present.	85
5.7	Components of an R-type EC. On the bottom side of the picture the four pieces of the aluminum case are present. On the right are the four FEBs, while on the top left is the back side of the Bkb (that connects to the digital board) and on bottom left the Bb with the four MaPMTs black socket. . . .	86
5.8	An R-Type EC completely assembled. Three of the four FEBs are visible on the top part of the EC.	87
6.1	The three boards hosting the CLARO chips tested at Louvain-La-Neuve. They have been mounted onto the movable support inside the facility vacuum chamber. The ring showing the tilt angle with respect to the incident beam is visible on the left of the boards support.	95
6.2	Typical plot for SEU occurring in one CLARO vs the irradiation time (ion Nickel, $\theta = 0$, $LET_{effective} = 20.4 \text{ MeV/mg/cm}^2$).	96
6.3	SEU cross section distribution for the CLARO ion irradiation test at Louvain-La-Neuve HIF.	96
6.4	SEL cross section distribution for the CLARO ion irradiation test at Louvain-La-Neuve HIF.	97
6.5	Schematic of the Legnaro Tandem accelerator: the ion source platform (1); the accelerating pipe (2); the column (3) supporting the high voltage terminal (4), where the ion beam stripping station is placed (5); the laddertron charging belt (6); the beam diagnostic station (7); the bending magnets (8); enclosure tank filled in SF ₆ gas(9).	99
6.6	The output Tandem accelerator vacuum pipe: the void pumps, as well as the quadrupoles magnetic lenses, which let the beam focused along the beam axis, are visible.	100

6.7	The four CLAROs used in the 2018 irradiation test in Legnaro. The board on which they are installed is mounted on the vacuum chamber support. The leftmost CLARO is illuminated by the alignment laser. On the upper left corner the diode system for the beam fluence calibration is shown.	101
6.8	SEU cross section distribution for the CLARO ion irradiation test at Legnaro SIRAD.	102
6.9	Schematic of the IRRAD facility.	105
6.10	A 3D model of the CERN PS East Hall T8 beam-line, where both the IRRAD and the CHARM facilities are located. . . .	105
6.11	A 3D model of the setup for the CLARO proton irradiation. .	106
6.12	CLARO currents (analog in black, digital in red, digital core in blue) for one of the CLAROs used in the October 2018 proton irradiation test.	107
6.13	Cumulative CLARO SEU number vs irradiation time, measured by the CRIO FPGA.	108
6.14	Schematic of the CHARM facility at CERN.	110
6.15	CLARO CHARM irradiation setup.	110
7.1	The cold bar with four R-type ECs. On the right the lens is visible, surrounded by its black plastic support. On the right the PDMDB is attached to the ECs backboards.	114
7.2	Top: the tracker developed by the LHCb RICH Upgrade group for the 2017 tests-beam. Bottom: detailed view of a silicon module and read-out electronics.	116
7.3	Schematic of the lens. The photons path inside the lens is represented by the black lines.	117
7.4	DAQ GUI used in the test beam. The Cherenkov ring is detected using the optimal optical setting on the left, while on the right it has been de-focused.	120
7.5	Schematic of the reconstruction geometry model used in the software to measure the Cherenkov angle from the LHCb RICH Upgrade prototype data.	122
7.6	Cherenkov angle contributions obtained from the reconstruction software for the LHCb RICH Upgrade prototype. . . .	125
7.7	Typical threshold scan distribution obtained during the tests-beam.	127

- 7.8 Schematic of the single photoelectron spectrum, that is the expected signal spectrum for the CLARO channels. Additional peaks can be found at higher threshold values, corresponding to multiple photoelectrons emitted per MaPMT photon hit. 128
- 7.9 Typical S-Curve distribution obtained during the test-beam S-Curve tests. 130
- 7.10 Linearity plot obtained for a CLARO channel during the test-beam S-Curve tests. 131
- 7.11 Visualization of the Pattern Recognition method, with the lower limit (green) and the upper limit (yellow). 132
- 7.12 Distributions obtained for the comparison of the transition point evaluated using the Pattern Recognition and the fit. By choosing different upper and lower limit for the Pattern Recognition method the transition point value obtained can be adjusted. 134
- 8.1 CLARO QA station (Station1) for the validation of the LHCb RICH Upgrade ASIC. The XYZ motorized system for the pick-and-place procedure (1) uses a pneumatic suction cup (2), an air compressor (6) and a pressor sensor (3) to move the CLAROs from the left-hand side tray to the test socket on the CLARO burn-in card(7). The system vacuum is regulated by a dedicated valve (4) and pump (5). The DAQ is driven by the ALTERA MAX10 FPGA development kit (8). 137
- 8.2 CLARO QA test software overview. On the left-hand side of the panel an overview of the current tray test is reported: the chips are picked from the left-hand side tray and the ones which don't pass the test are put in the right-hand side tray, flagged as red in both trays. On the right-hand side of the panel the control/monitor tool allows to check the status of the current test, of the actual set parameters and allows to change parameters of the test setup (XYZ system) and of the test protocol. 138
- 8.3 Pre-QA data analysis on the CLARO chips, transition point distribution obtained using C++ ROOT script. Left: Station1 data. Right: Station2 data. 142

-
- 8.4 Pre-QA data analysis on the CLARO chips, sigma distribution obtained using C++ ROOT script. Left: Station1 data. Right: Station2 data. 143
- 8.5 Pre-QA data analysis on the CLARO chips, transition point distribution obtained using LabVIEW routine. The results are almost identical with respect to the C++ ROOT script analysis. Left: Station1 data. Right: Station2 data. 143
- 8.6 Pre-QA data analysis on the CLARO chips, sigma distribution obtained using LabVIEW routine. Left: Station1 data. Right: Station2 data. 144
- 8.7 CLARO QA data analysis on 9044 CLARO chips tested using the QA procedure. Left: transition point distribution, which has been fitted with a Gaussian PDF to extract the average value. Right: sigma distribution. 144
- 8.8 3D model of the FEB QA setup with all its components. The repeaters are connectors used to avoid the deterioration of the DB connectors. On the left-hand side of the figure the DB measures are reported. 146
- 8.9 A digital board used in the FEB QA procedure. A Bkb with a FEB is connected to the FPGA UART connector on the right-hand side of the picture, and the TPI is attached to the FEB. 148
- 8.10 Results from the S-Curve data of 36 of the first produced FEBs for the LHCb RICH Upgrade. Left: coarse scan results, where the crosstalk is happening. Right: fine scan results. The transition point for a malfunctioning channel was close to zero, as it can be seen in the left corner of the right-hand plot. 151
- 8.11 Picture of the ECQA setup, Station1, where four EC H-type are mounted in the box. On the left, the LED driver is visible. 153
- 8.12 Schematic of the numbering scheme for the ECQA main components. The ECs of the load are numbered from 0 to 3 starting from the top-left going clockwise, the UART are named from 0 to 7 and each one of them is connected to two FEBs, 0 and 1, the numbering of which is inverted for UART connectors rotated of 180° one respect to the others. 154

8.13	Scheme representing the numbering convention for the CLAROs on the FEB. Since it is in perspective, half of the CLAROs are hidden in the scheme but they are soldered on the FEB in a specular way with respect to the visible ones. On the CLARO7 the QR code is present.	155
8.14	Numbering scheme for the MaPMT anodes on the EC, where the observer is imagined facing the MaPMTs window. To notice that the numbering scheme for the R-type top-left MaPMT is the same as for an H-type MaPMT. The Anode 1 is always at the centre of the R-type EC. This implies that, going from 0 to 3, one MaPMT is rotated of 90° clockwise with respect to the previous one.	156
8.15	SIN distribution for a MaPMT anode. The association between CLARO channels, MaPMT anode and EC is explicitly reported in the distribution and histogram titles.	157
8.16	2D histogram for an R-type MaPMT showing the SIN fraction per each anode. The number reported on each histogram bin is the anode number following the scheme of figure 8.14. . . .	158
8.17	On the left, average signal intensity per MaPMT of the EC as a function of the applied LED driver voltage. On the right, the Poisson distribution optimized to suppress events of multi-photons emission.	159
8.18	The control panel of the two low-level VIs used to open the connection with the system controller (left) and to start the python daemon (right).	164
8.19	The control panel for the ADC channels and HV channels read standalone VI.	165
8.20	The control panel for the S-Curve Comm Check test standalone VI.	166
8.21	The control panel for the S-Curve test standalone VI.	166
8.22	The control panel for the Threshold Scan test standalone VI.	167
8.23	The control panel for the SIN test standalone VI.	168
8.24	The control panel for the DCR test standalone VI.	169
8.25	The control panel for the configurator VI.	170
8.26	The control panel of the VI for the scan of the QR codes of the EC components.	172

8.27	The control panel of the finite state machine for the automatic ECQA procedure.	173
8.28	The finite state machine parameters settings panel.	174
8.29	The R-type EC mapping file used by the analysis scripts to correctly map the CLARO channels and produce 2D histograms.	175
8.30	Transition point and sigma distribution for a full 4 ECs load R-type, generated by the S-Curve python analysis script. . . .	177
8.31	S-Curve distribution for a single CLARO channel obtained during the ECQA procedure. The channel ID is in the title of the graph. The fit parameters are reported in the top-right corner.	178
8.32	2D histogram error overview for a threshold scan test. This test was performed with the CLAROs Offset bit at 0, hence most of the channels do not exhibit the pedestal and they are marked as defective in this plot.	179
8.33	2D histogram showing the found working points for all the channels of the MaPMT 2 (C) of the EC 2 (bottom-right). . .	180
8.34	Typical Threshold Scan distribution for the CLARO channels in the ECQA procedure.	181
8.35	Distribution obtained for a CLARO channel for the threshold offset calculation. For this particular channel the action of the Offset bit is to shift the threshold by 32, that is the standard value.	182
8.36	The three overview 2D histograms produced for the SIN analysis of a MaPMT, together with the SIN spectrum for a channel. Also here the connection between channel ID and MaPMT anode is explicit in the histogram title.	184
8.37	DCR plot for an R-type EC. The SIN contributions on the outer channels are present also in this kind of measurement. The number of the anode is reported on the corresponding bin.	185
8.38	The H-type EC screwed to the plastic jar cap ready to be sent to CERN. The barcode is visible on its side and a label with the EC load number and the station used to test it is placed on the jar bottom, which is facing upwards.	186
8.39	EC jar in the Korrvu packaging ready to be sent to CERN. .	187

-
- C.1 Scheme representing the association between MaPMTs anodes (green = MaPMT A, pink = MaPMT B, yellow = MaPMT C, blue = MaPMT D) and CLARO channels on the FEBs for an R-type EC. On the top side the CLARO channels at which the anodes are connected are reported, with the channel ID parameters at which the channel is associated (FEB and CHIP). On the bottom side the MaPMT anode numbering convention is reported. 198
- C.2 Scheme representing the association between the single MaPMT anodes and CLARO channels on the FEBs for an H-type EC. On the top side the CLARO channels at which the anodes are connected are reported, with the channel ID parameters at which the channel is associated (FEB and CHIP). On the bottom side the MaPMT anode numbering convention is reported. 199

Bibliography

- [1] A. D. Sakharov, “Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe,” *Journal of Experimental and Theoretical Physics Letters (JETP Letters)*, no. 5, pp. 24–27, 1967.
- [2] L. Evans and P. Bryant, “LHC machine,” *Journal of instrumentation*, vol. 3, no. 08, p. S08001, 2008.
- [3] LHCb Collaboration, “LHCb detector performance,” *International Journal of Modern Physics A*, vol. 30, no. 07, p. 1530022, 2015.
- [4] O. Steinkamp, LHCb Collaboration, *et al.*, “LHCb upgrades,” in *Journal of Physics: Conference Series*, vol. 1271, p. 012010, IOP Publishing, 2019.
- [5] I. Bediaga *et al.*, “LHCb VELO upgrade technical design report,” 2013.
- [6] K. Hennessy, “LHCb VELO upgrade,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 845, pp. 97–100, 2017.
- [7] T. Poikela *et al.*, “VeloPix: the pixel ASIC for the LHCb upgrade,” *Journal of Instrumentation*, vol. 10, no. 01, p. C01057, 2015.
- [8] LHCb Collaboration *et al.*, “LHCb tracker upgrade technical design report,” tech. rep., 2014.
- [9] A. Piucci, “The LHCb Upgrade,” in *Journal of Physics: Conference Series*, vol. 878, p. 012012, IOP Publishing, 2017.
- [10] T. Kirn, LHCb Collaboration, *et al.*, “SciFi: a large scintillating fibre tracker for LHCb,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 845, pp. 481–485, 2017.

- [11] LHCb Collaboration *et al.*, “LHCb PID upgrade technical design report,” tech. rep., 2013.
- [12] Y. Guz, “LHCb Calorimeter Upgrade,” tech. rep., 2013.
- [13] A. Cardini, “The LHCb Muon Upgrade,” *Journal of Instrumentation*, vol. 9, no. 02, p. C02014, 2014.
- [14] A. Bursche *et al.*, “Physics opportunities with the fixed-target program of the LHCb experiment using an unpolarized gas target,” tech. rep., 2018.
- [15] P. Di Nezza, “The SMOG2 project,” tech. rep., 2018.
- [16] LHCb Collaboration *et al.*, “LHCb trigger and online upgrade technical design report,” *CERN, CERN-LHCC-2014-016*, 2014.
- [17] I. Bediaga *et al.*, “Physics case for an LHCb Upgrade II-Opportunities in flavour physics, and beyond, in the HL-LHC era,” *arXiv preprint arXiv:1808.08865*, 2018.
- [18] G. Aad, T. Abajyan, B. Abbott, J. Abdallah, S. A. Khalek, A. A. Abdelalim, O. Abdinov, R. Aben, B. Abi, M. Abolins, *et al.*, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” *Physics Letters B*, vol. 716, no. 1, pp. 1–29, 2012.
- [19] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, *et al.*, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” *Physics Letters B*, vol. 716, no. 1, pp. 30–61, 2012.
- [20] N. Cabibbo, “Unitary symmetry and leptonic decays,” *Physical Review Letters*, vol. 10, no. 12, p. 531, 1963.
- [21] M. Kobayashi and T. Maskawa, “CP-violation in the renormalizable theory of weak interaction 1973 Prog,” *Theor. Phys*, vol. 49, p. 652.
- [22] R. Aaij, B. Adeva, M. Adinolfi, C. Adrover, A. Affolder, Z. Ajaltouni, J. Albrecht, F. Alessio, M. Alexander, S. Ali, *et al.*, “Measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+ \mu^-$ decays at the LHCb experiment,” *Physical review letters*, vol. 111, no. 10, p. 101805, 2013.

- [23] T. CMS, L. Collaborations, V. Khachatryan, A. Sirunyan, A. Tumasyan, W. Adam, T. Bergauer, M. Dragicevic, J. Erö, M. Friedl, *et al.*, “Observation of the rare $B_s^0 \rightarrow \mu^+ \mu^-$ decay from the combined analysis of CMS and LHCb data,” *arXiv preprint arXiv:1411.4413*, 2014.
- [24] R. Aaij, B. Adeva, M. Adinolfi, A. Affolder, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, *et al.*, “Test of lepton universality using $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays,” *Physical review letters*, vol. 113, no. 15, p. 151601, 2014.
- [25] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, G. Alkhazov, *et al.*, “Test of lepton universality with $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decays,” *Journal of High Energy Physics*, vol. 2017, no. 8, p. 55, 2017.
- [26] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, A. A. Albero, S. Ali, *et al.*, “Measurement of CP asymmetry in $B_s^0 \rightarrow D_s^\mp K^\pm$ decays,” *Journal of High Energy Physics*, vol. 2018, no. 3, p. 59, 2018.
- [27] L. collaboration *et al.*, “Update of the LHCb combination of the CKM angle γ using $B \rightarrow DK$ decays,” *LHCb-CONF-2018-002*.
- [28] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, A. A. Albero, S. Ali, *et al.*, “Measurement of CP violation in $B^0 \rightarrow J/\psi K_S^0$ and $B^0 \rightarrow \psi(2S) K_S^0$ decays,” *Journal of High Energy Physics*, vol. 2017, no. 11, p. 170, 2017.
- [29] R. Aaij, B. Adeva, M. Adinolfi, A. Affolder, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, *et al.*, “Precision measurement of CP violation in $B_s^0 \rightarrow J/\psi K^+ K^-$ decays,” *Physical review letters*, vol. 114, no. 4, p. 041801, 2015.
- [30] R. Aaij, C. A. Beteta, B. Adeva, M. Adinolfi, A. Affolder, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, *et al.*, “Measurement of the CP-violating phase ϕ_s in $\bar{B}_s^0 \rightarrow D_s^+ D_s^-$ decays,” *Physical review letters*, vol. 113, no. 21, p. 211801, 2014.
- [31] R. Aaij, B. Adeva, M. Adinolfi, A. Affolder, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, *et al.*, “Measurement of CP violation in $B_s^0 \rightarrow \phi \phi$ decays,” *Physical Review D*, vol. 90, no. 5, p. 052011, 2014.

- [32] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, G. Alkhazov, *et al.*, “Measurement of the CP asymmetry in $B_s^0 - \bar{B}_s^0$ mixing,” *Physical review letters*, vol. 117, no. 6, p. 061803, 2016.
- [33] R. Aaij, B. Adeva, M. Adinolfi, A. Affolder, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, *et al.*, “Determination of the quark coupling strength $|V_{ub}|$ using baryonic decays,” *Nature Physics*, vol. 11, no. 9, pp. 743–747, 2015.
- [34] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, G. Alkhazov, *et al.*, “Measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ branching fraction and effective lifetime and search for $B^0 \rightarrow \mu^+ \mu^-$ decays,” *Physical review letters*, vol. 118, no. 19, p. 191801, 2017.
- [35] R. Aaij, B. Adeva, M. Adinolfi, A. Affolder, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, *et al.*, “Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$,” *Physical review letters*, vol. 115, no. 11, p. 111803, 2015.
- [36] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, A. A. Alberro, S. Ali, *et al.*, “Test of lepton flavor universality by the measurement of the $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ branching fraction using three-prong τ decays,” *Physical Review D*, vol. 97, no. 7, p. 072013, 2018.
- [37] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, A. A. Alberro, S. Ali, *et al.*, “Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau) / \mathcal{B}(B_c^+ J/\psi \mu^+ \nu_\mu)$,” *Physical review letters*, vol. 120, no. 12, p. 121801, 2018.
- [38] R. Aaij, C. A. Beteta, B. Adeva, M. Adinolfi, A. Affolder, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, *et al.*, “Measurement of the difference of time-integrated CP asymmetries in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays,” *Physical review letters*, vol. 116, no. 19, p. 191601, 2016.
- [39] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, S. Ali, G. Alkhazov, *et al.*, “Measurement of the CP violation parameter A_Γ in $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays,” *Physical review letters*, vol. 118, no. 26, p. 261803, 2017.

- [40] R. Aaij, B. Adeva, M. Adinolfi, Z. Ajaltouni, S. Akar, J. Albrecht, F. Alessio, M. Alexander, A. A. Albero, S. Ali, *et al.*, “Updated determination of $D^0 - \bar{D}^0$ mixing and CP violation parameters with $D^0 \rightarrow K^+\pi^-$ decays,” *Physical Review D*, vol. 97, no. 3, p. 031101, 2018.
- [41] W. R. Leo, *Techniques for nuclear and particle physics experiments: a how-to approach*. Springer Science & Business Media, 2012.
- [42] M. Adinolfi *et al.*, “Performance of the LHCb RICH detector at the LHC,” *The European Physical Journal C*, vol. 73, no. 5, p. 2431, 2013.
- [43] A. Papanestis, C. D’Ambrosio, LHCb RICH collaboration, *et al.*, “Performance of the LHCb RICH detectors during the LHC Run II,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 876, pp. 221–224, 2017.
- [44] H. Jibo, “Real-time calibration and alignment of the LHCb RICH detectors,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 876, pp. 13–16, 2017.
- [45] W. Baldini *et al.*, “LHCb alignment strategy,” tech. rep., 2006.
- [46] O. Lupton *et al.*, “Calibration samples for particle identification at LHCb in Run 2,” tech. rep., 2016.
- [47] M. Adinolfi *et al.*, “LHCb Upgraded RICH 1 Engineering Design Review Report,” tech. rep., 2016.
- [48] P. J. Garsed *et al.*, “LHCb Upgraded RICH 2 Engineering Design Review Report,” tech. rep., 2016.
- [49] B. Malecki, “Update on the simulation numbering scheme.” URL: https://indico.cern.ch/event/830911/contributions/3480366/attachments/1869342/3075345/BartoszMalecki_NumberingScheme.pdf, 6 2019.
- [50] M. Baszczyk *et al.*, “CLARO8V3 Extended Manual Rev 0.4.” Internal note, 2016.
- [51] M. Fiorini, “The Upgrade of the LHCb RICH detectors.” URL: https://rich2018.org/indico/event/1/contributions/12/attachments/71/117/Fiorini_-_RICH2018.pdf, 2018.

- [52] J. Ramos-Martos *et al.*, “SEE characterization of the AMS 0.35 μm CMOS technology,” 2013.
- [53] J. Ramos-Martos *et al.*, “Radiation characterization of the austriamicrosystems 0.35 μm CMOS technology,” in *2011 12th European Conference on Radiation and Its Effects on Components and Systems*, pp. 806–811, IEEE, 2011.
- [54] K. Roed *et al.* *IEEE Transactions on Nuclear Science*, vol. 58, 932-938, ISSN 0018-9499, 2011.
- [55] K. Roed *et al.* *IEEE Transactions on Nuclear Science*, vol. 59, 1040-1047, ISSN 0018-9499, 2012.
- [56] G. C. Messenger and M. S. Ash, “The effects of radiation on electronic systems,” 1986.
- [57] E. ESA and S. B. S. No, “25100: Single event effects test method and guidelines,” *ESA, Noordwijk, Netherlands*, vol. 1005, 1995.
- [58] C. Gaspar and B. Franek *IEEE Transactions on Nuclear Science*, vol. 53 No.3, 974-979, 2006.
- [59] L. G. Cardoso *et al.*, “LHCb MiniDAQ control system,” in *EPJ Web of Conferences*, vol. 214, p. 01005, EDP Sciences, 2019.
- [60] F. Ravotti, “Dosimetry techniques and radiation test facilities for total ionizing dose testing,” *IEEE Transactions on Nuclear Science*, vol. 65, no. 8, pp. 1440–1464, 2018.
- [61] R. Bullock, “Least-square circle fit.” URL: https://dtcenter.org/met/users/docs/write_ups/circle_fit.pdf, 2017.