Studies of The Opto-Electronic Chain for The LHCb RICH Upgrade

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Introduction

During my joint Ph.D. studies between the University of Ferrara (Italy) and the Institute of Nuclear Physics Polish Academy of Sciences (Poland), I had an opportunity to work in the LHCb experiment at CERN.

My research activities focused on the LHCb Ring-Imaging Cherenkov (RICH) detectors upgrade. The ultimate goal of my Ph.D. was to test the newly developed photodetection units, called the **Elementary Cells** (ECs).

For these reasons, I took part in the following activities:

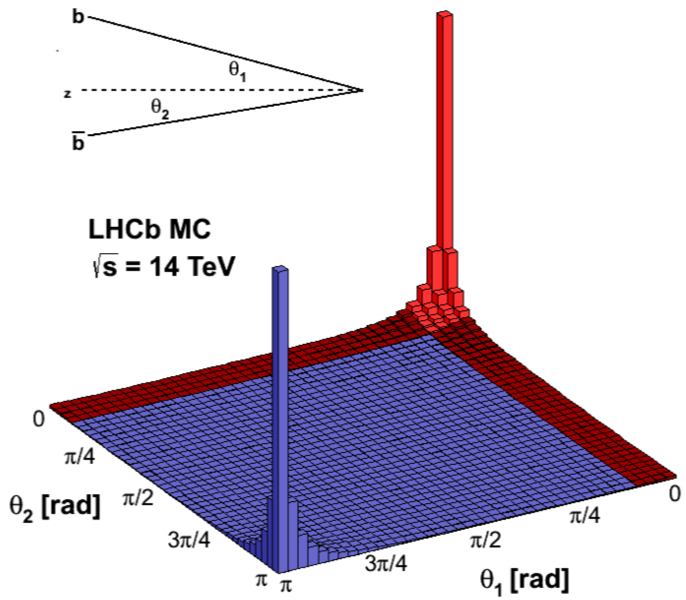
- Development of the experimental test setup for quality control of the ECs,
- Software development of the automated software for the ECs quality assurance,
- Hardware testing and assembly of the ECs,
- Quality control measurements of the ECs,
- Preparation of protocols and manuals,
- Preparation of scripts and offline data analysis,

In this presentation, I would like to show you the overview of the **Elementary Cell Quality Assurance** (ECQA) performed in Ferrara.

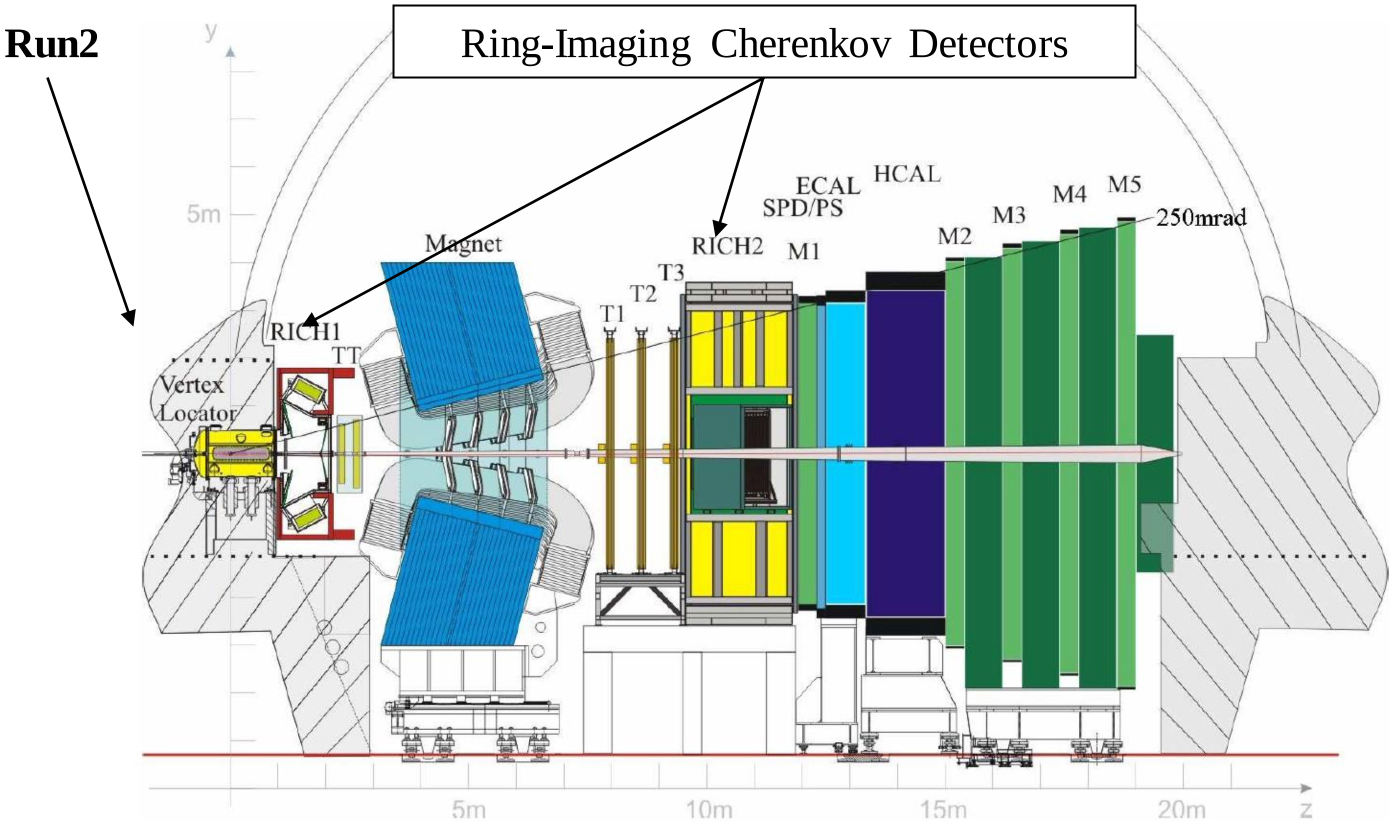
The LHCb Experiment at CERN
Overview

LHCb deals with heavy flavour physics

- General-purpose detector in forward region
- Goals:
  - Measure CP-violation in b-sector
  - Search for the rare decays
  - Exploit forward production of b-pairs with low angle
- Such studies can help to understand the matter-antimatter asymmetry in our Universe.



Run2



LHCb RICH detectors: RICH1 and RICH2

Particle Identification (PID)

- Separate charged hadrons to select decays of interest: kaons, pions and protons

The LHCb Experiment at CERN
Upgrade (1)

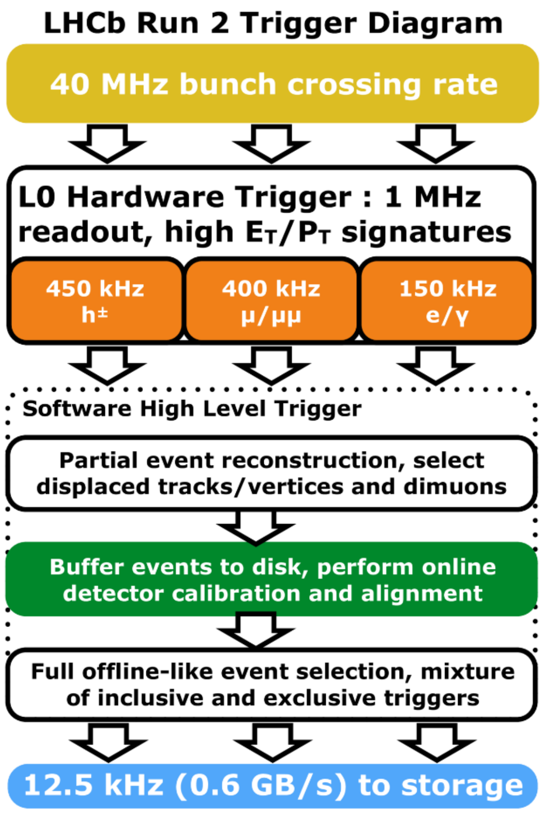
Reasons for the upgrade:

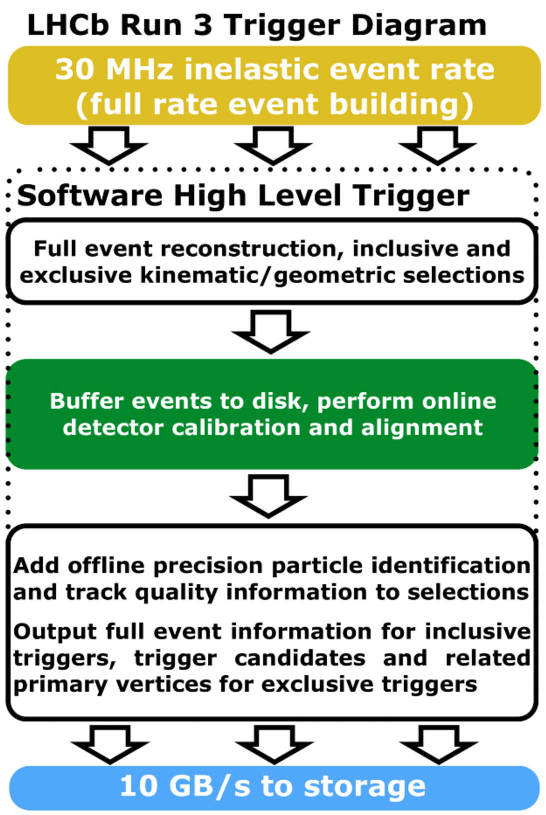
- More data to further challenge theoretical predictions
- Expose of detectors to radiation damage over years
- Bottleneck of Level-0 hardware trigger (1.1 MHz)
- Change in parameters → new geometry

LHCb Upgrade:

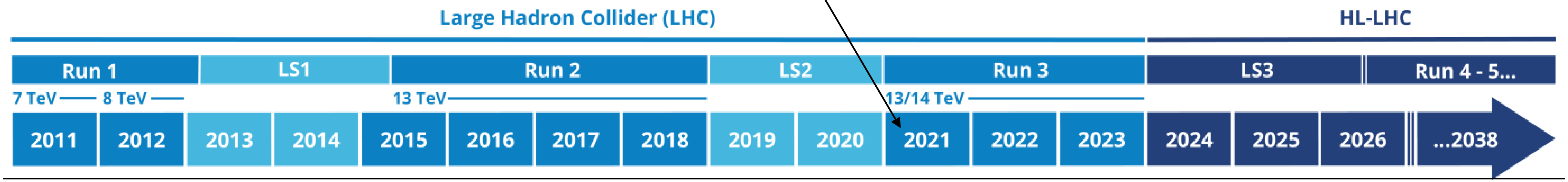
Luminosity	Data acquisition rate
$\mathcal{L} = 4 * 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$f = 1$ MHz
↓	↓
$\mathcal{L} = 2 * 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$f = 40$ MHz

- Replacement of L0 hardware trigger with software trigger
- Adjustments in geometry, change in read-out electronics





We are here

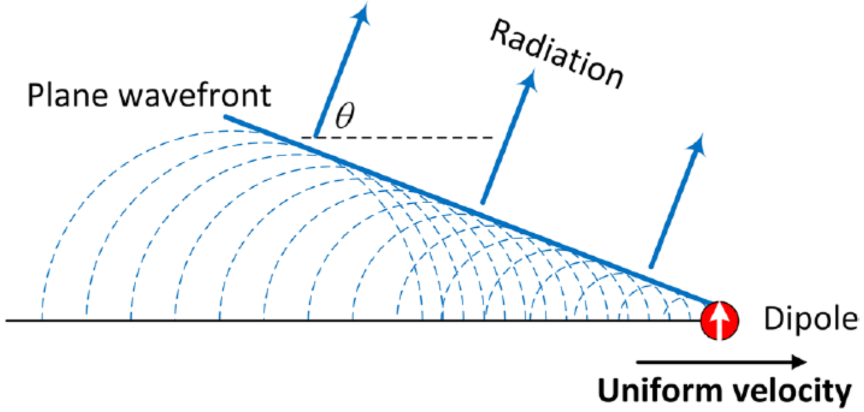


The LHCb Experiment at CERN
Cherenkov Radiation

- Charged particles faster than light in a dielectric medium

$$v_p = \frac{c}{n}, \qquad v > v_p$$

v_p - phase velocity of light
v - velocity of a particle



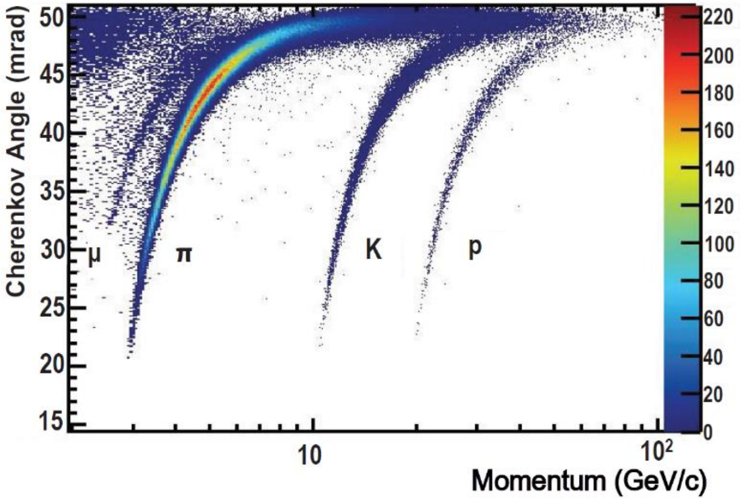
- Energy emitted as photons: **Cherenkov photons**
- Cherenkov angle:

$$\cos\theta = \frac{v_p}{v} = \frac{1}{\beta n}, \qquad \beta = \frac{v}{c}$$

- Mass of a particle:

$$\cos\theta = \frac{1}{n}\sqrt{\left(\frac{m}{p}\right)^2 + 1} \quad \rightarrow \quad m = p\sqrt{n^2\cos^2\theta - 1}$$

- Different characteristics of particles → precise identification



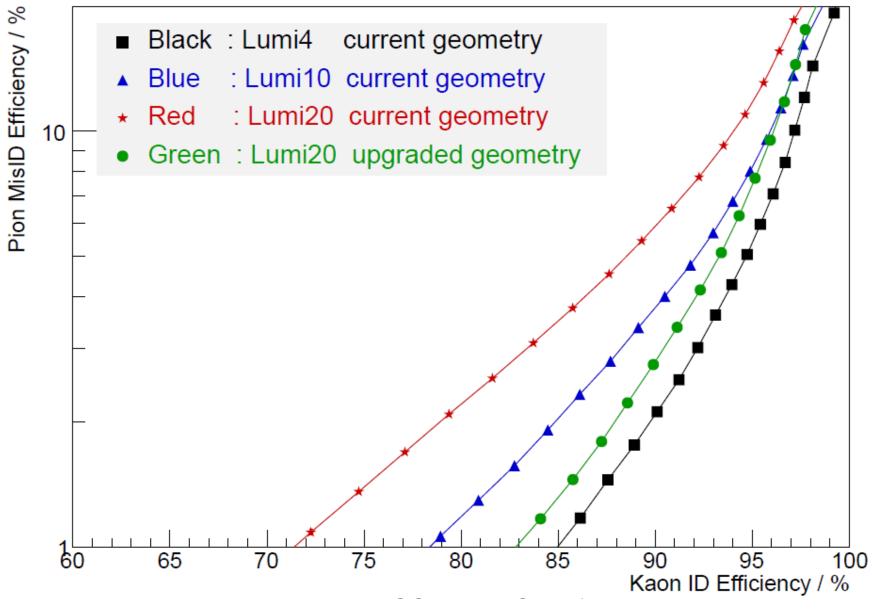
- Most particles in RICH detectors: protons, pions and kaons.

The LHCb Experiment at CERN
Importance of the PID

Channel	Branching fraction
$B_s^0 \to D_s^{\mp} K^{\pm}$	$(0.23 \pm 0.02) \times 10^{-3}$
$B_s^0 \to D_s^{-} \pi^{+}$	$(3.04 \pm 0.23) \times 10^{-3}$
$B^0 \to D^{-} \pi^{+}$	$(2.57 \pm 0.13) \times 10^{-3}$
$\overline{\Lambda}_b^0 \to \overline{\Lambda}_c^{-} \pi^{+}$	$(4.9 \pm 0.4) \times 10^{-3}$

→ signal ($B_s^0 \to D_s^{\mp} K^{\pm}$)

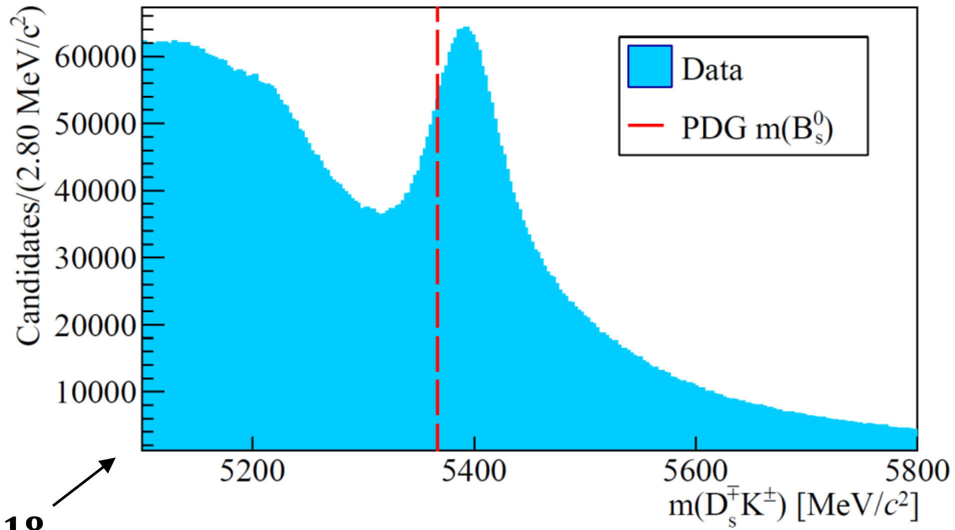
→ background contamination (other three channels)



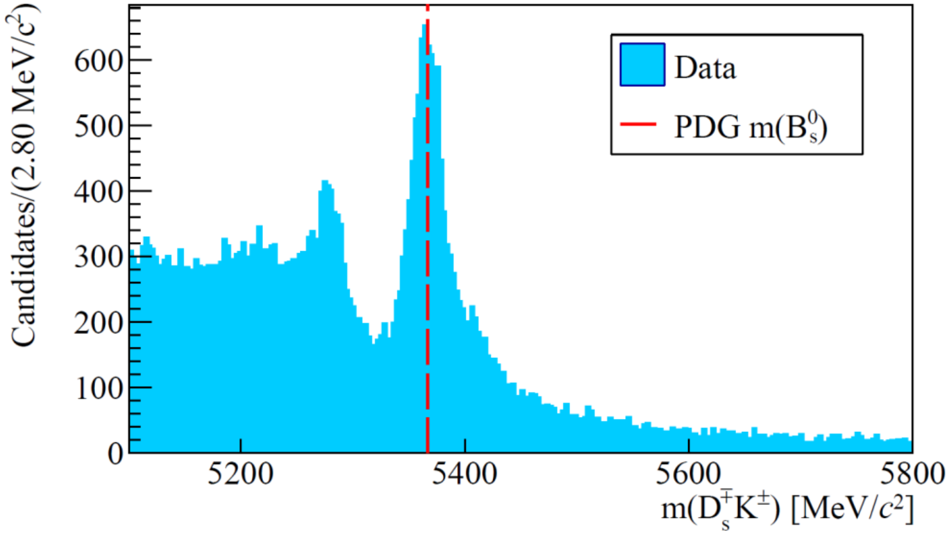
Lumi4 $3.9 * 10^{32}\ cm^{-2}s^{-1}$

Lumi10 $10 * 10^{32}\ cm^{-2}s^{-1}$

Lumi20 $20 * 10^{32}\ cm^{-2}s^{-1}$



Data from 2018



The LHCb RICH Detectors
Pre-upgraded

RICH1

- Acceptance: $25 - 300$ mrad
- Momentum range: $\sim 1 - 60$ GeV/c
- Refractive index: 1.0014 (C_4F_{10})

RICH2

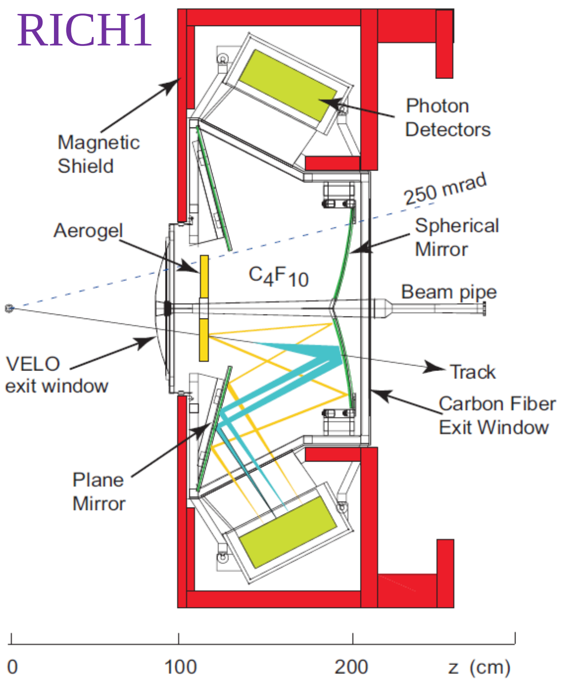
- Acceptance: $15 - 120$ mrad
- Momentum range: $\sim 15 - 100$ GeV/c
- Refractive index: 1.0005 (CF_4)

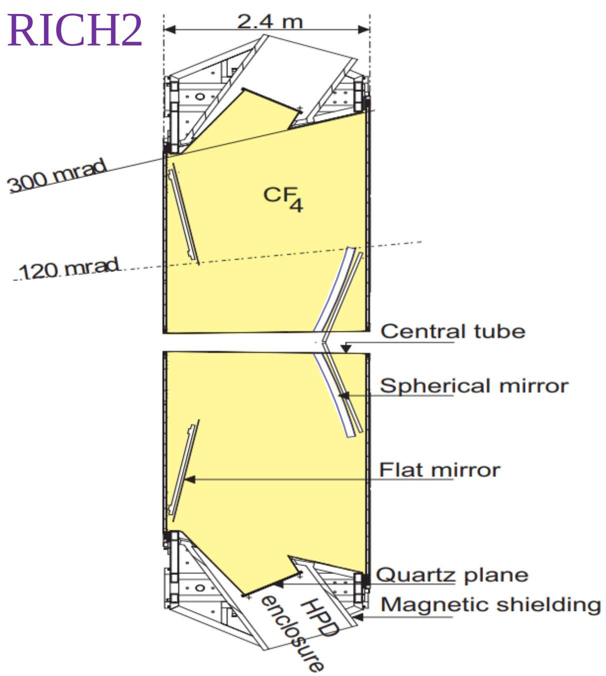
Optical system:

- **Hybrid Photon Detectors (HPDs)**
- Spherical mirrors and flat mirrors

HPDs:

- Vacuum photodetectors
- Accelerated photoelectrons dissipated in silicon
- Each HPD has 1024 pixels (32×32 matrix), each pixel's size: $500\ \mu\text{m} \times 500\ \mu\text{m}$
- Front-End (FE) electronics at 1 MHz bonded to pixel sensor





The LHCb RICH Detectors Upgrade Overview

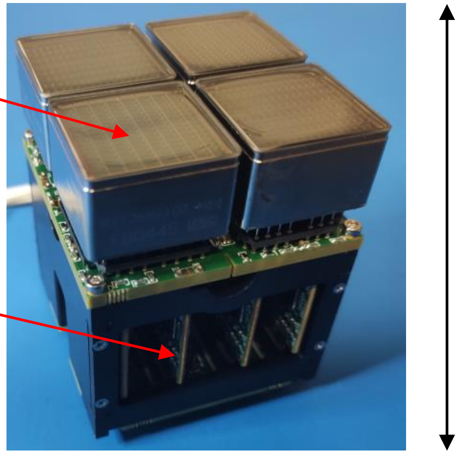
Change of the photon detectors:

- HPDs replaced by **Multi-Anode Photomultiplier Tubes (MaPMTs)**

Change in FE readout electronics:

- **CLARO** amplifier / discriminator ASIC
- FPGA-based digital boards
- GigaBit Transceiver (GBT) chip

New photon detection unit → **Elementary Cells (EC)**

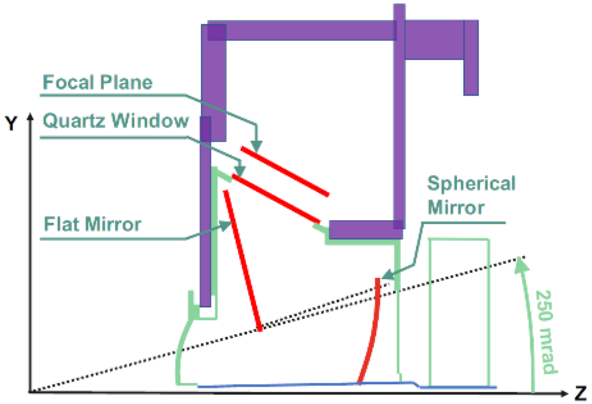


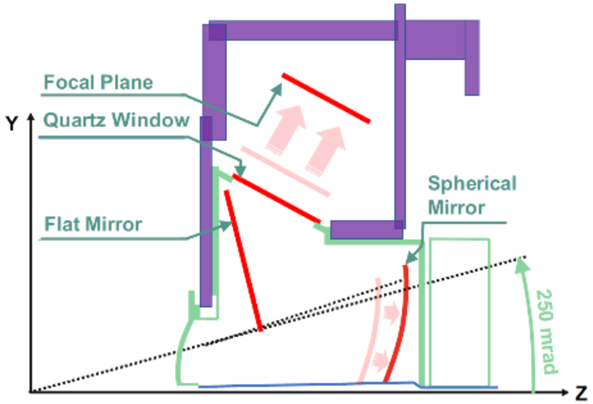
RICH1 modifications:

- Redesign of mechanics
  - new support
  - new cooling
- Optimization in optics
  - spherical mirrors focal length increase
  - spherical and plane mirrors repositioned

↓

peak occupancy < 30 %

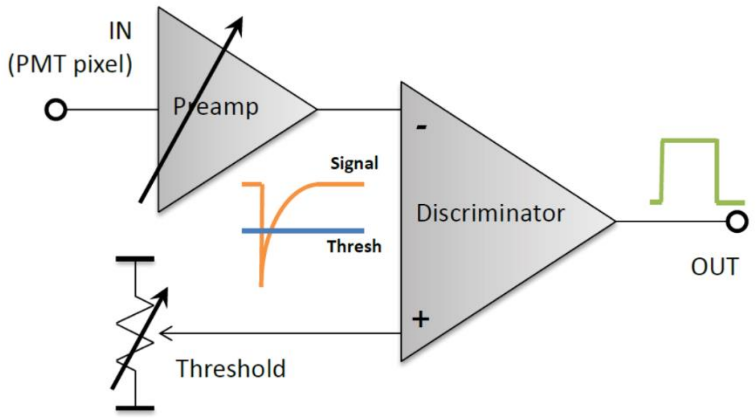


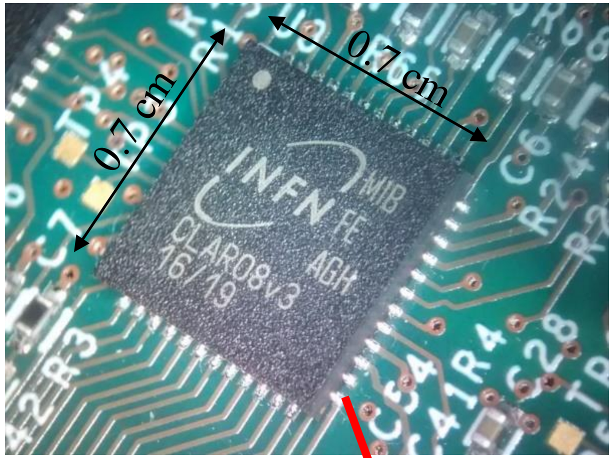


The LHCb RICH Detectors Upgrade
CLARO

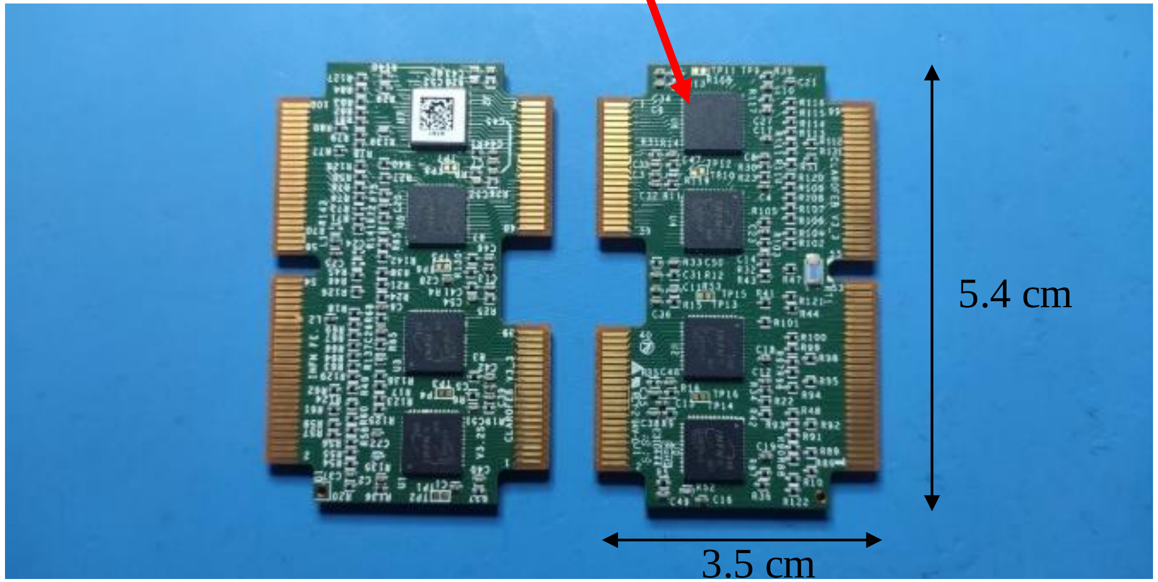
The CLARO chip:

- Designed by: AGH Kraków, INFN Ferrara, INFN Milano Bicocca
- **8 channel** amplifier / discriminator ASIC (0.35 µm CMOS, AMS)





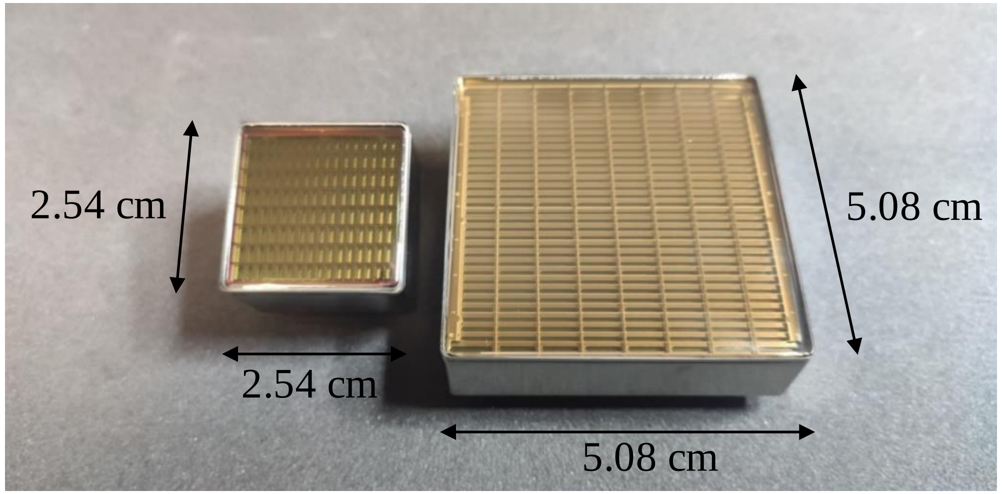
- Single photon counting with MaPMTs
- 40 MHz operation (recovery time < 25 ns)
- Low power consumption (<1 mW per channel)
- Radiation-tolerant
- Mounted on Front-End Board (FEB)
  - 8 chips per 1 FEB → 64 channels



The LHCb RICH Detectors Upgrade
Multi-Anode Photomultiplier Tube

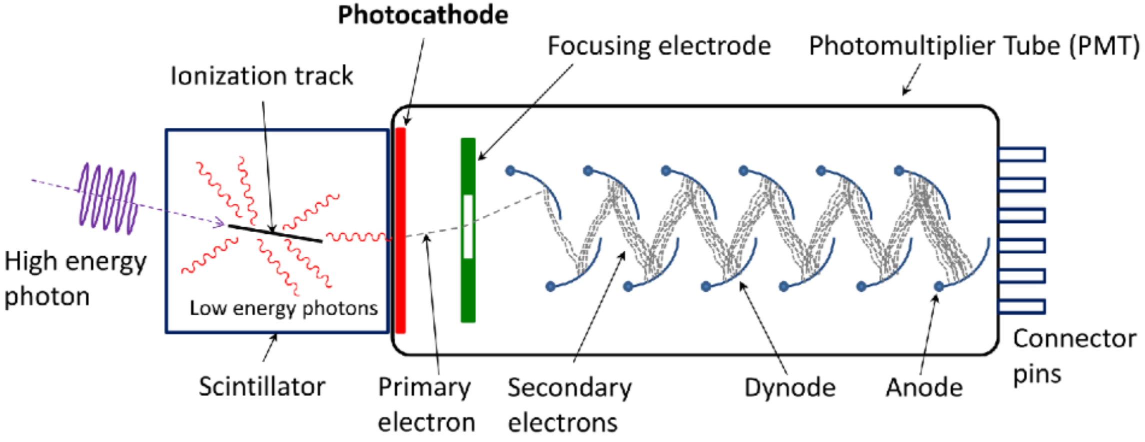
MaPMT:

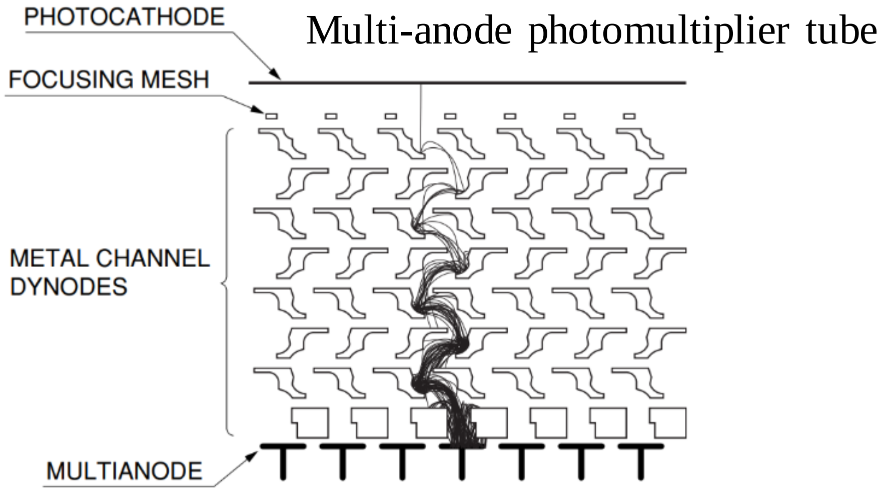
- Two types of MaPMTs designed by Hamammatsu Photonics:
  - **R13742 MaPMT** from R11265 series (1”) – **R-type**
  - **R13743 MaPMT** from R12699 series (2”) – **H-type**



- Single photon counting
- Large active area → 2.9 mm × 2.9 mm (R-type), 6 mm × 6 mm (H-type)
- 8 × 8 anode matrix → 64 silicon pixels
- Low dark count rate
- 12 stages of dynodes
- Typical gain of $10^6\ e^-$ at 1000 V

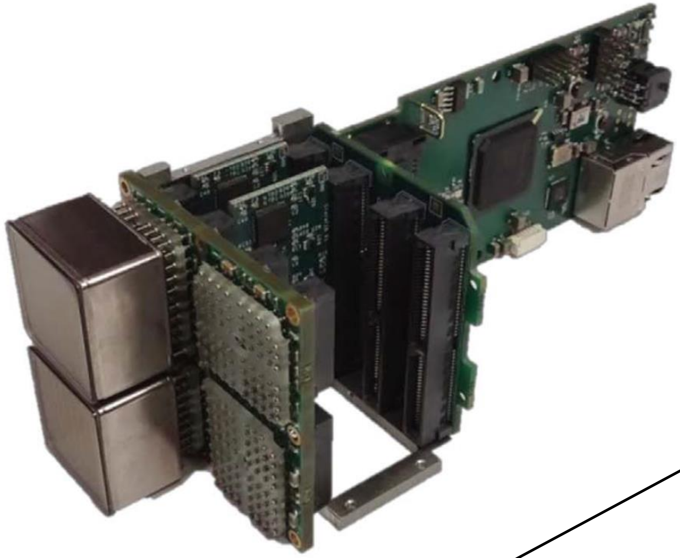
Singular photomultiplier tube



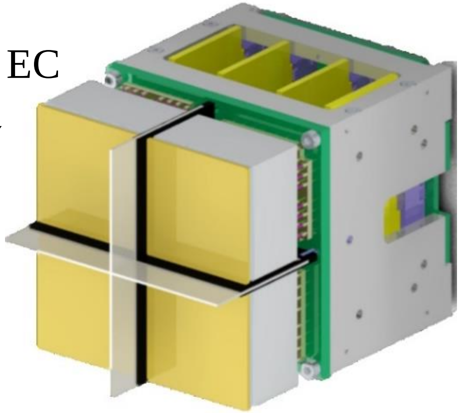


The LHCb RICH Detectors Upgrade
Elementary Cell

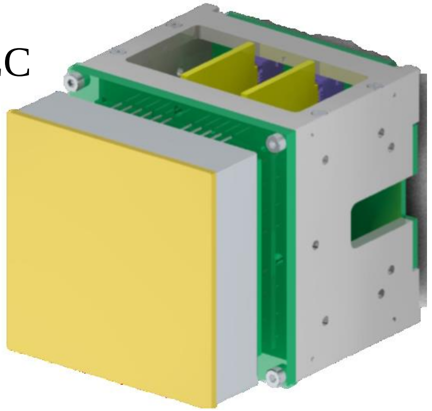
EC is the basic building unit of the RICH detection system.

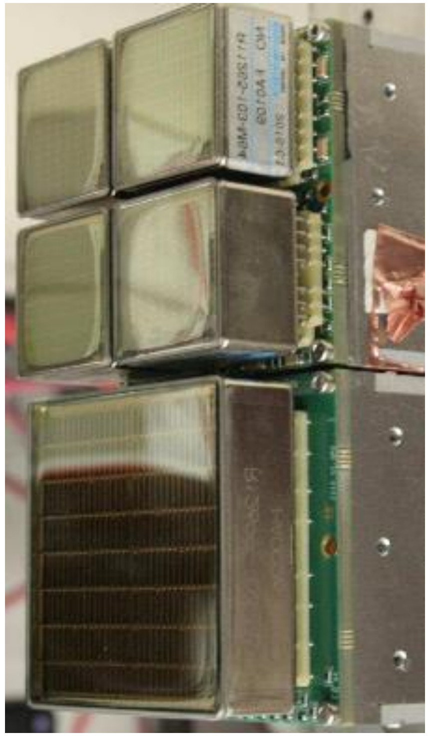


R-type EC



H-type EC



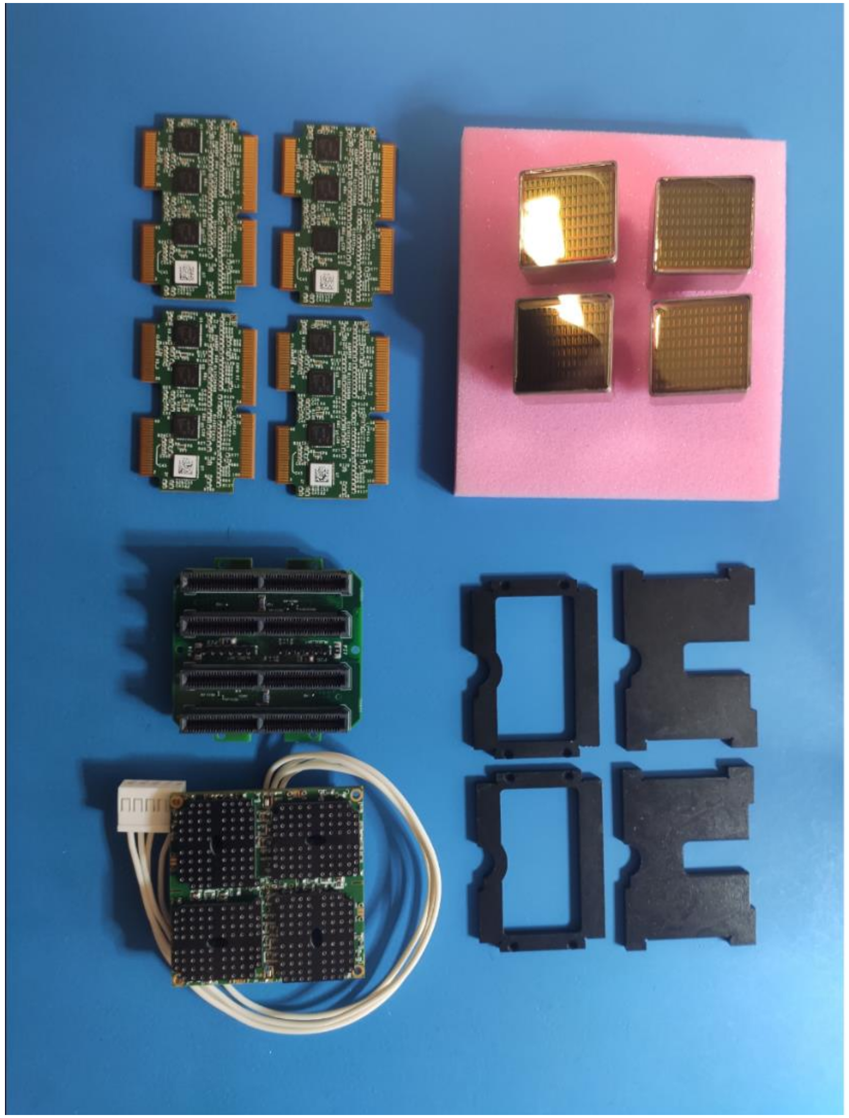


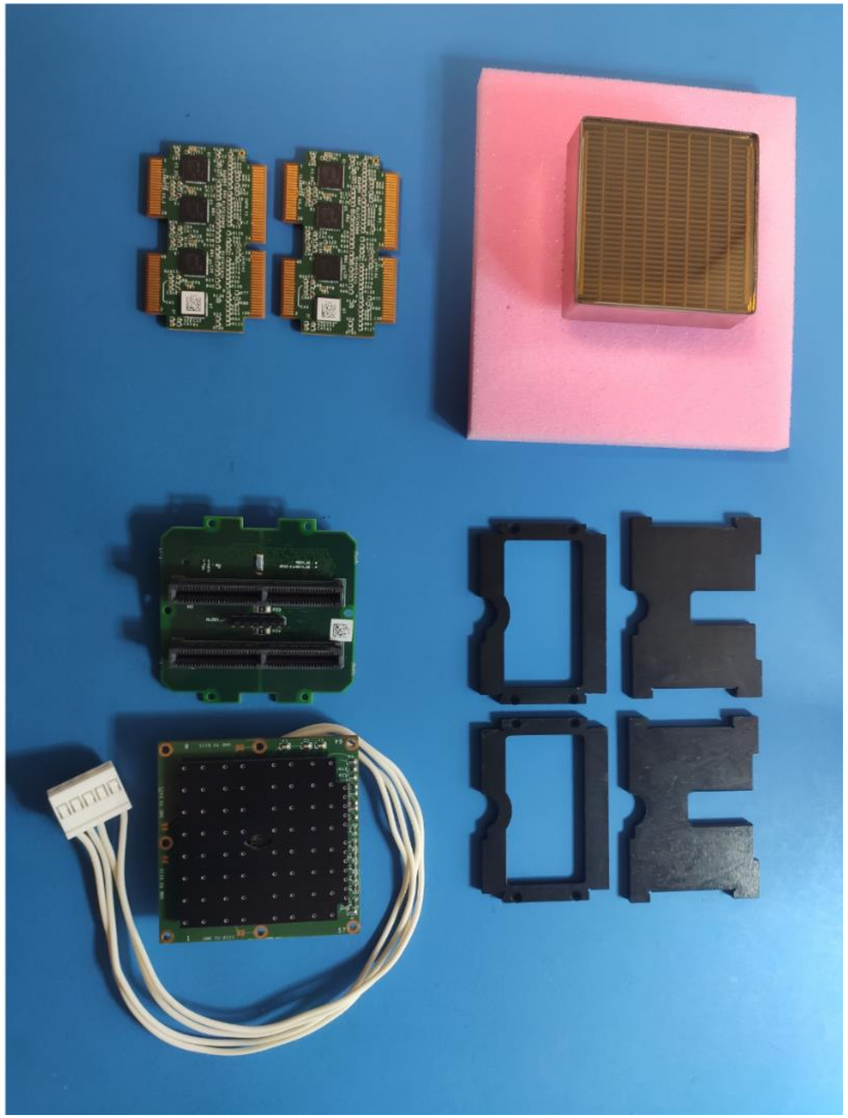
Components:

- 2x2 Hamamatsu R13742 (1”)
- 1x1 Hamamatsu R13743 (2”)
- Baseboard (Bb) interfacing MaPMTs with Front-End Boards (FEBs)
- 8 CLARO chips mounted on FEB
- Backboard (Bkb) interfacing FEBs with digital boards (DBs)
- DBs with FPGA readout logic and ethernet external connectivity

The LHCb RICH Detectors Upgrade
Components of Elementary Cell

R-type EC

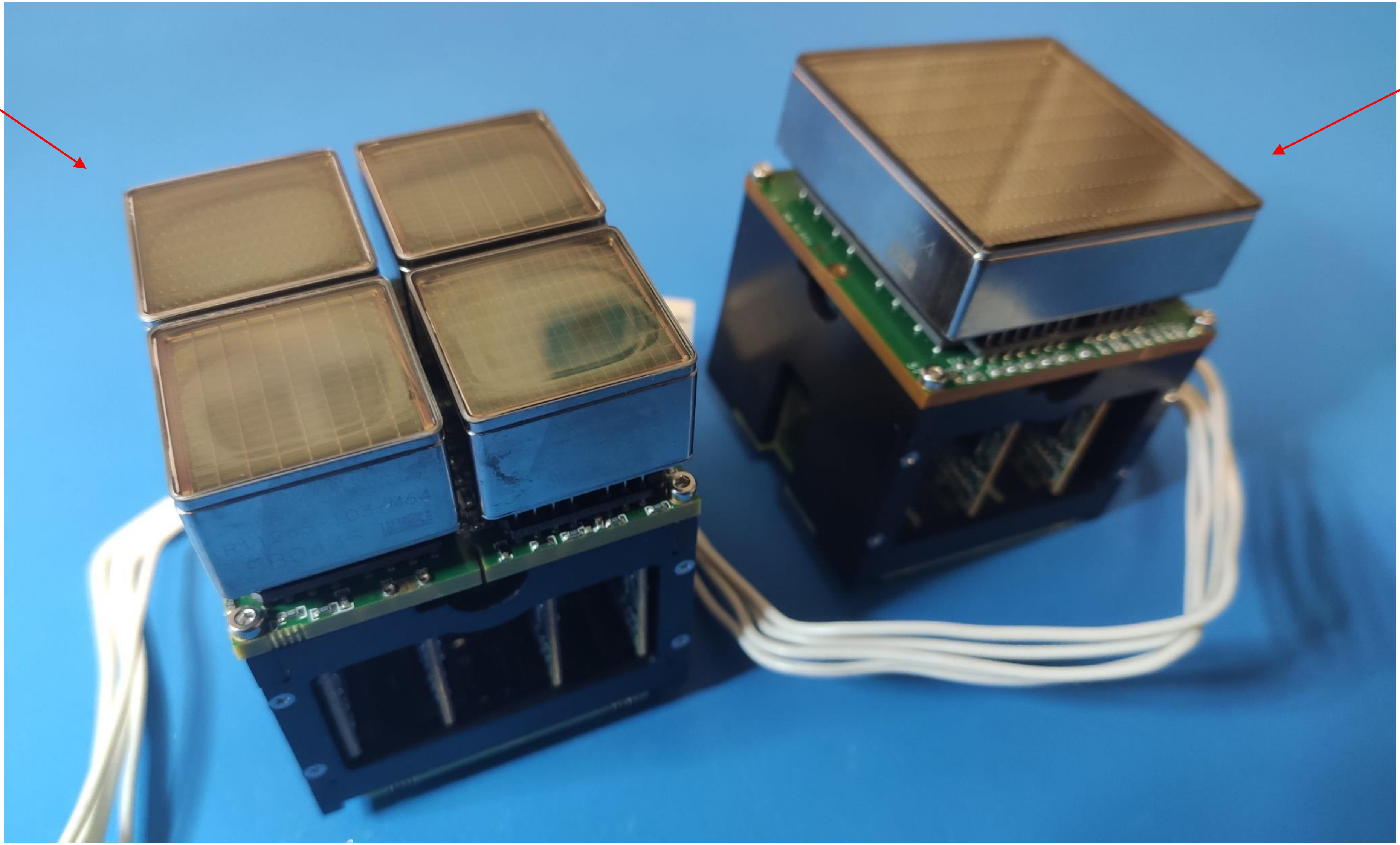




H-type EC

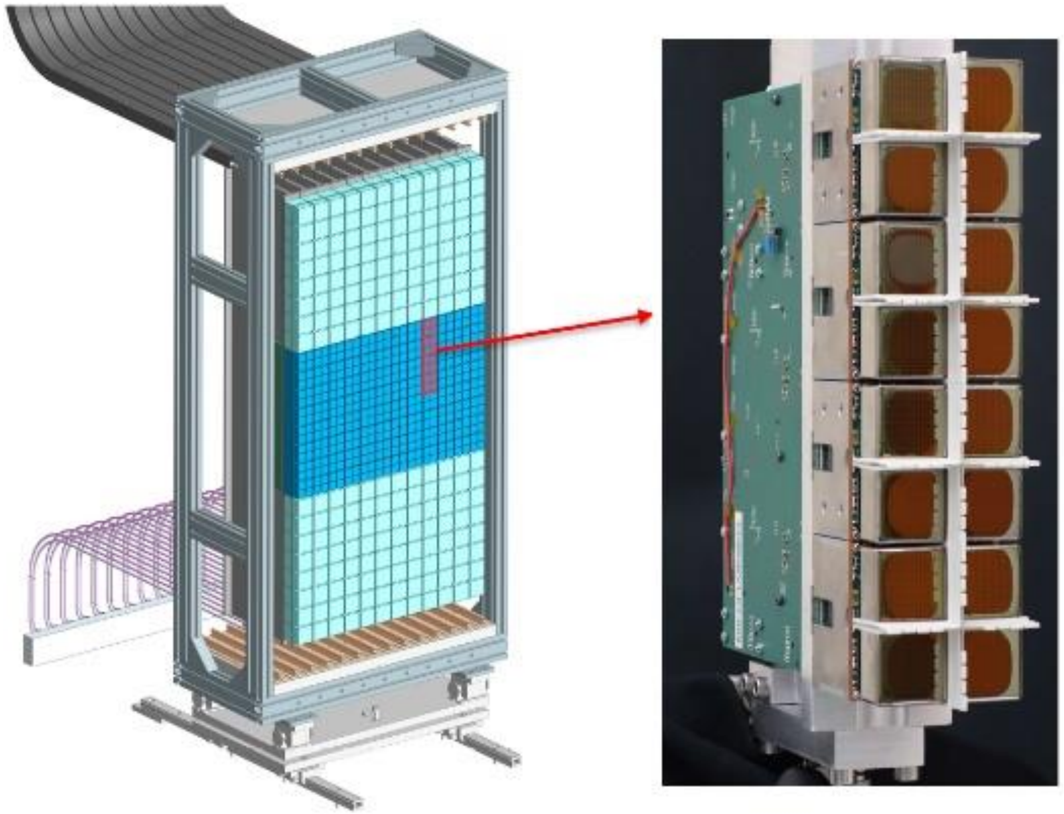
The LHCb RICH Detectors Upgrade
Assembled Elementary Cells

R-type EC



H-type EC

The LHCb RICH Detectors Upgrade
Photodetector Columns and Planes



	ECs		MaPMTs	
	R-Type	H-Type	R-Type	H-Type
RICH1	480	-	1920	-
RICH2	192	384	768	384
RICH1 + RICH2	672	384	2688	384
	1056		3072	

Elementary Cell Quality Assurance
Experimental Test Setup

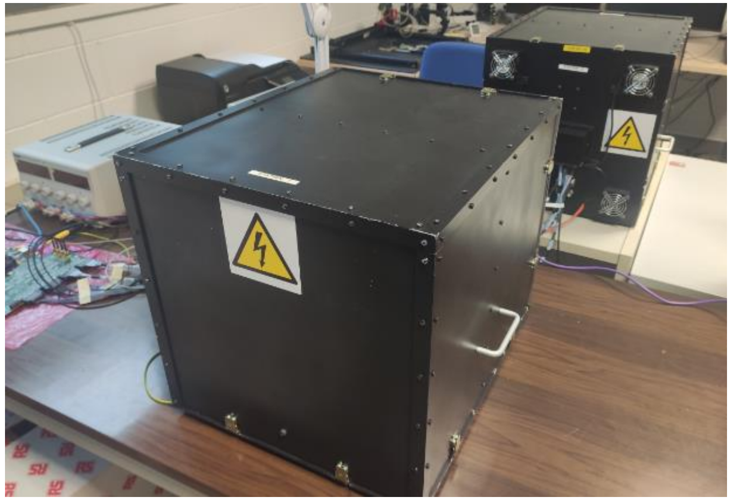
Authors: LHCb Ferrara Group (myself included)

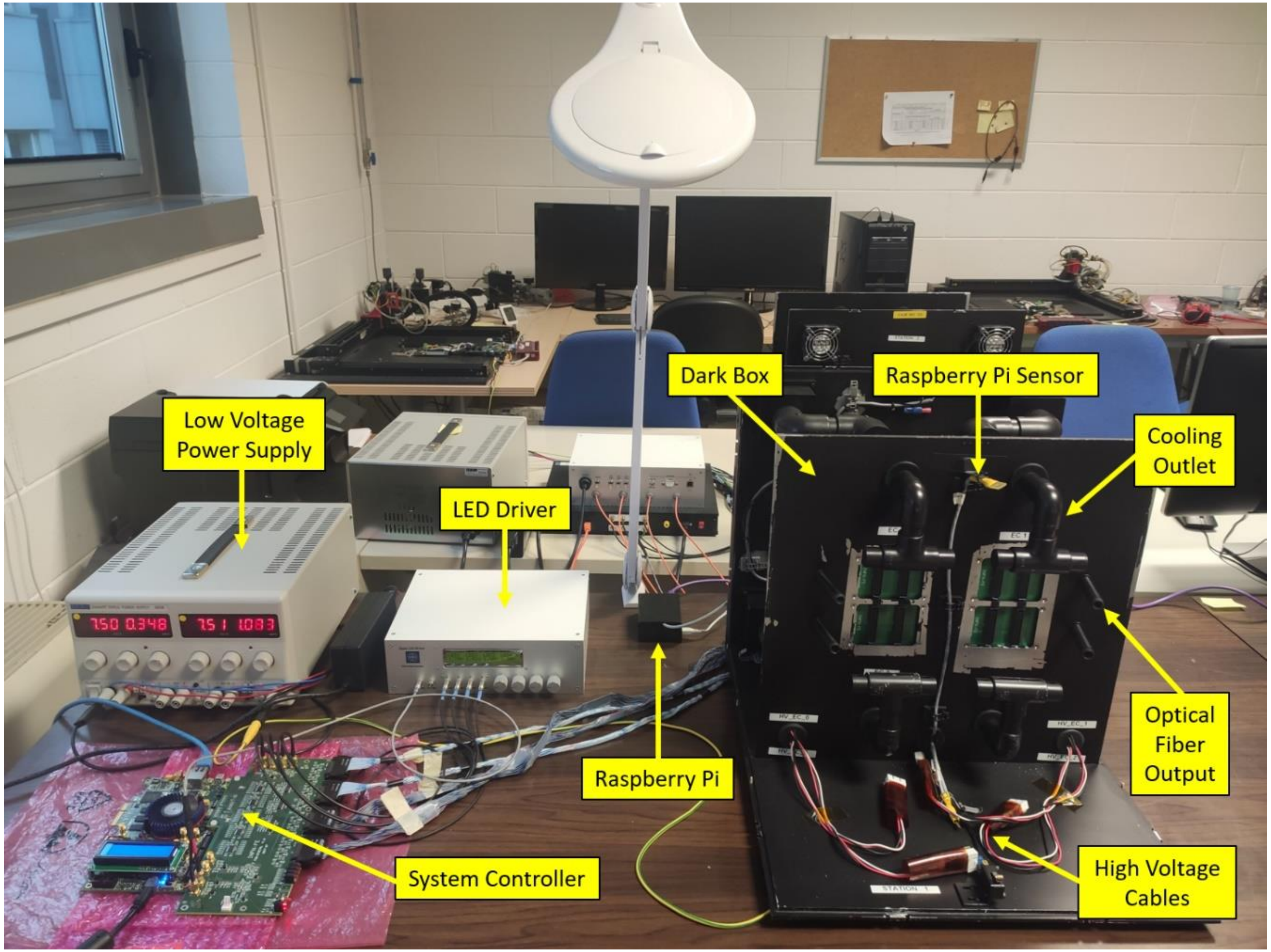
Test station:

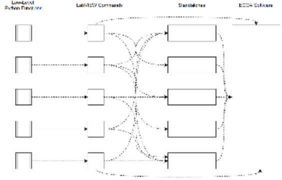
- Dark Box
- LV power supply
- LED driver
- System controller
- Raspberry Pi
- HV ISEG crate

Facilities:

- Ferrara – Station 1 and 2
- Edinburgh – Station 3 and 4



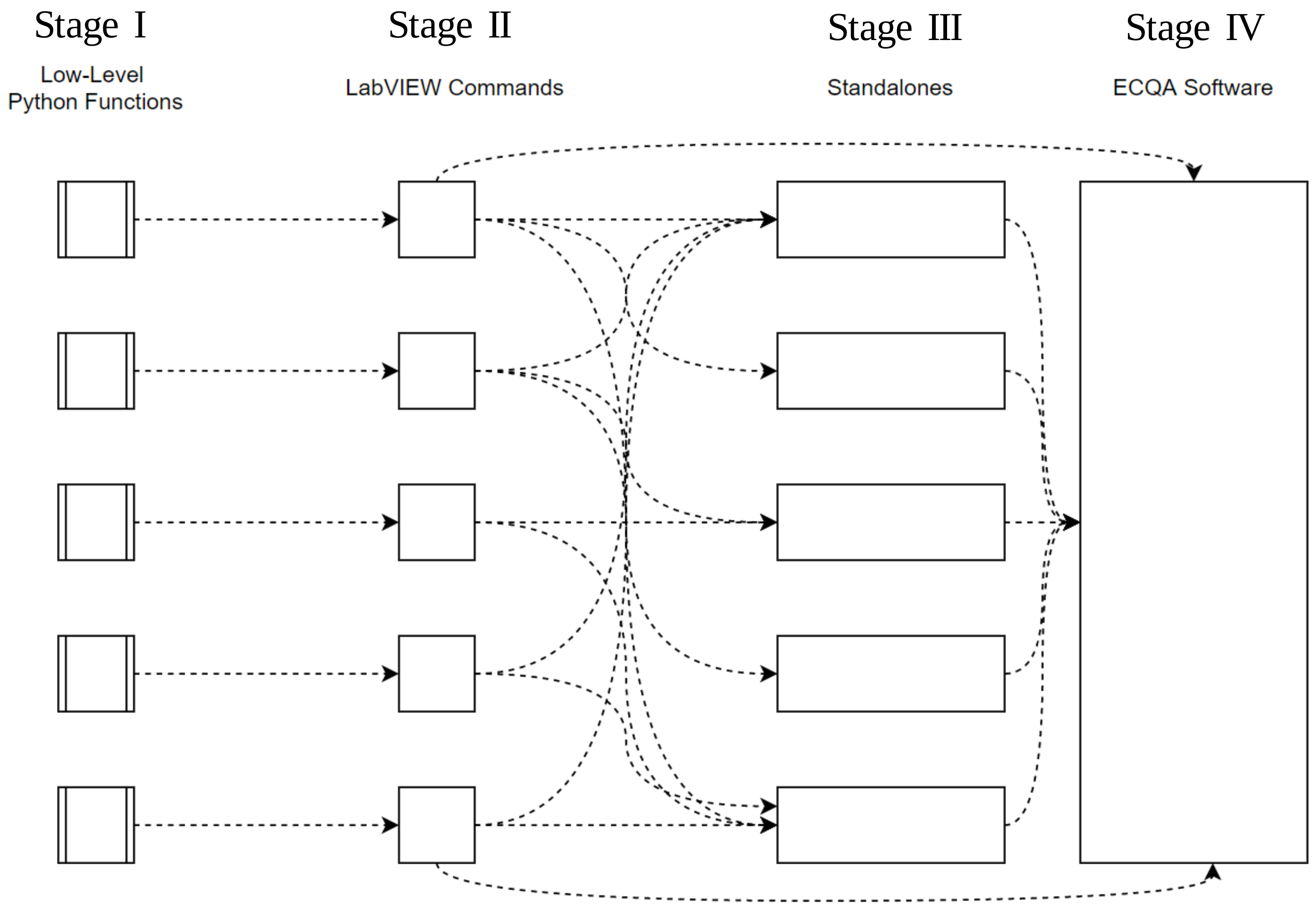


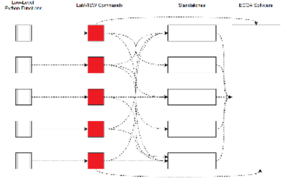


Elementary Cell Quality Assurance Software – Overview

Authors: Igor Ślazyk
Luca Minzoni
Edoardo Franzoso
Mirco Andreotti
Stefano Chiozzi

- Software development and debugging: nearly 2 years (2018-2019)
- Technologies: Python, C++ and LabVIEW



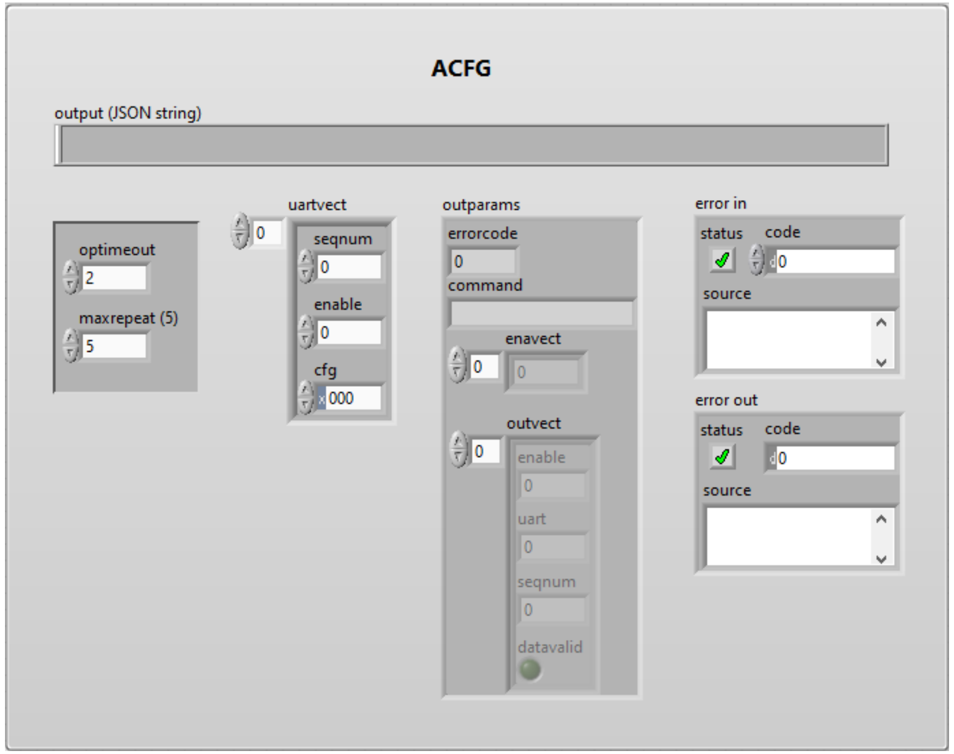


Elementary Cell Quality Assurance Software – Stage II (1)

Author: Igor Ślazyk

- The lowest level: python low-level functions
- Upper level of hierarchy: LabVIEW low-level sub-VIs (LabVIEW commands) based on the python low-level functions
- Communicates with hardware

LabVIEW → python → system controller → FPGAs → hardware



Communication:

- Python-LabVIEW interface

Read:

- Read hitcounts, counters, voltages, currents etc.

Write:

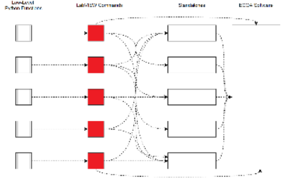
- Configuration of channels

Functionality:

- Selector of modules, power control, counter/hardware reset etc.

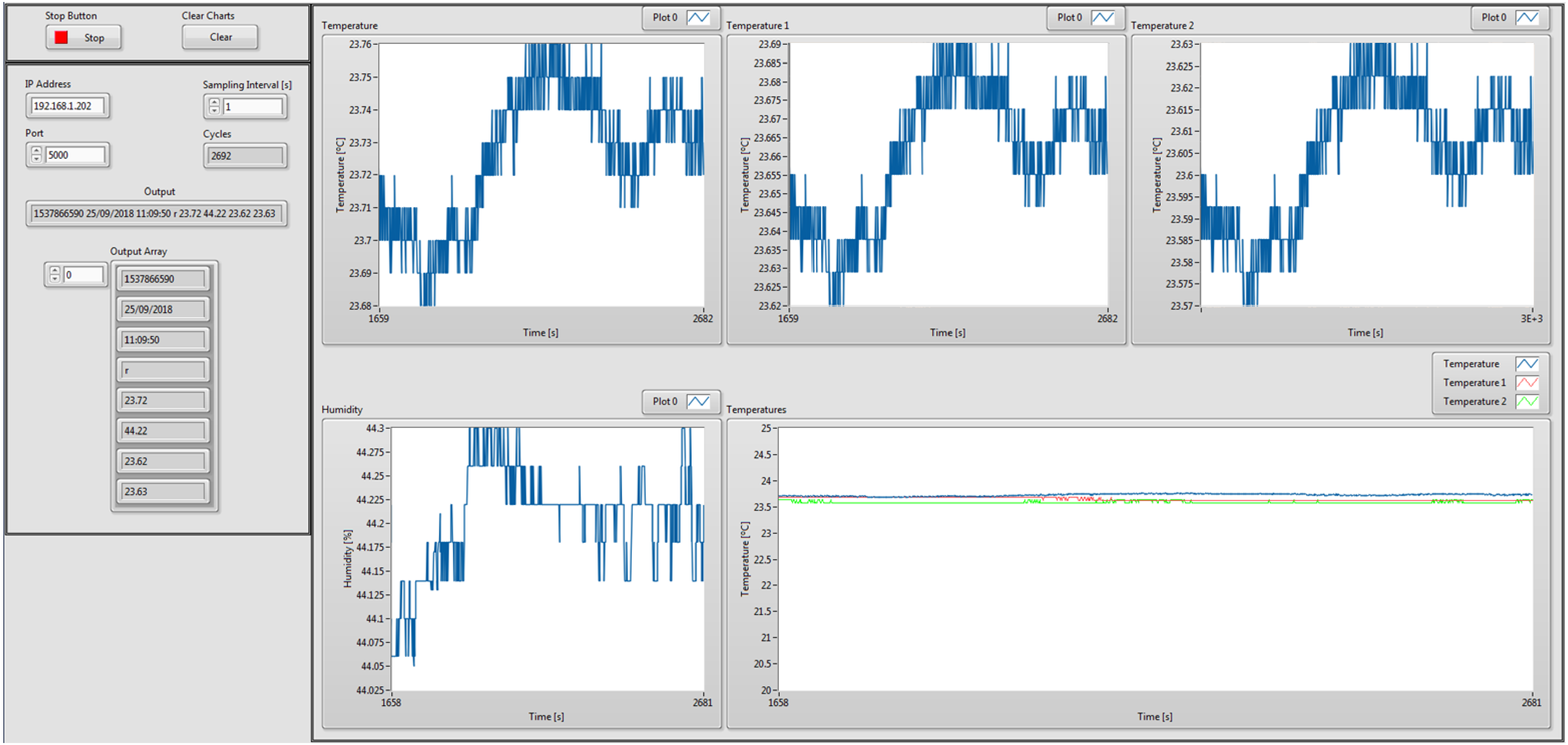
Temperature humidity reading software

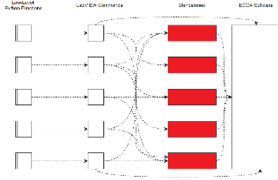
Over 30 low-level python functions and corresponding LabVIEW commands



Elementary Cell Quality Assurance Software – Stage II (2)

Author: Igor Ślazyk

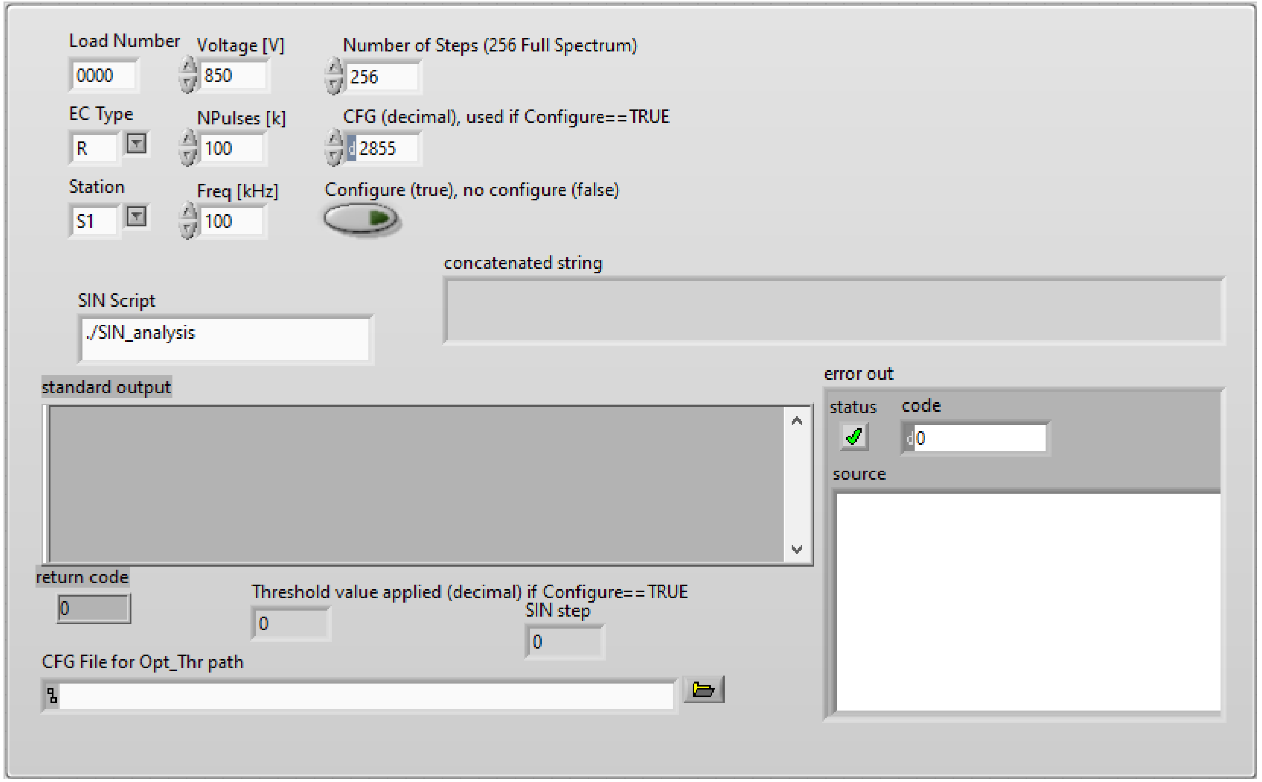




Elementary Cell Quality Assurance Software – Stage III

Authors: Igor Ślazyk
Luca Minzoni
Edoardo Franzoso

- Another upper level of hierarchy: Standalones based on the LabVIEW low-level sub-VIs
- Initial starting point of test measurements
- Semi-automated DAQ software
- Implemented data analysis scripts



Transition checker:

- Checking if transition is present for all the channels

Current measurements:

- Measurements of current and voltage

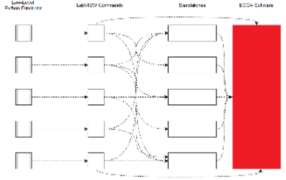
Quality assurance measurements:

- Digital-to-Analog Converter Scan
- Threshold Scan
- Dark Count Rate
- Signal-Induced Noise

Configuration loader:

- Loads optimized configuration acquired from Threshold Scan

7 standalones



Elementary Cell Quality Assurance Software – Stage IV (1)

Author: Mirco Andreotti

- Final level of hierarchy: ECQA software based on the Standalones and LabVIEW low-level sub-VIs
- Maximum efficiency point of test measurements
- Fully automated DAQ software

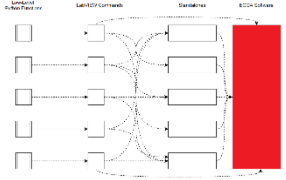
- Test parameters initialization for all measurements at the very beginning

- Control and monitoring:
  - High voltage
  - Environmental (temperature and humidity)

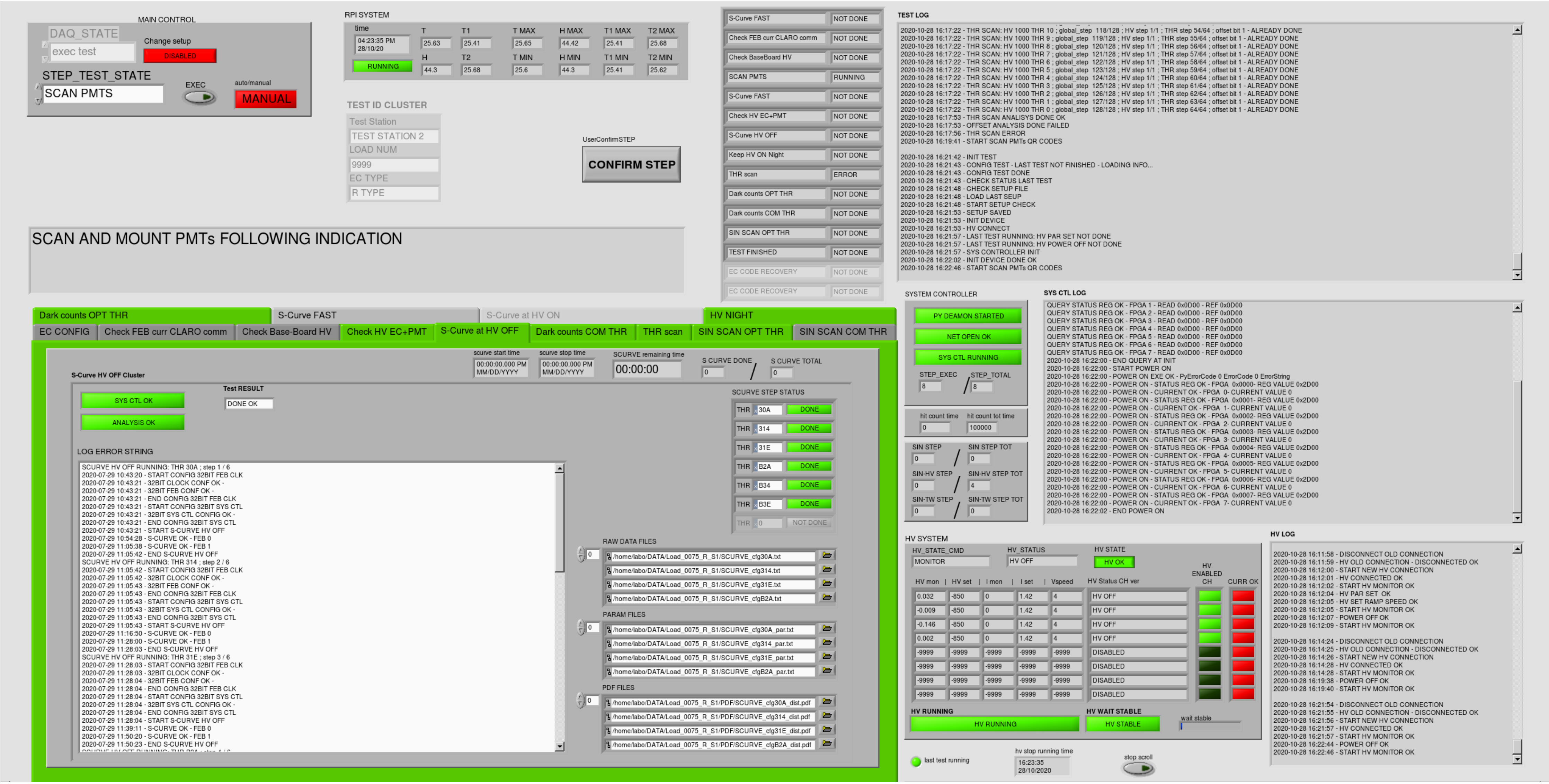
- Offline data analysis scripts launched automatically after each test

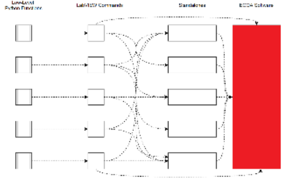
- Manual operation only in case of critical errors and during the mounting procedure of the ECs and MaPMTs

- Approximate procedure time: 18 hours

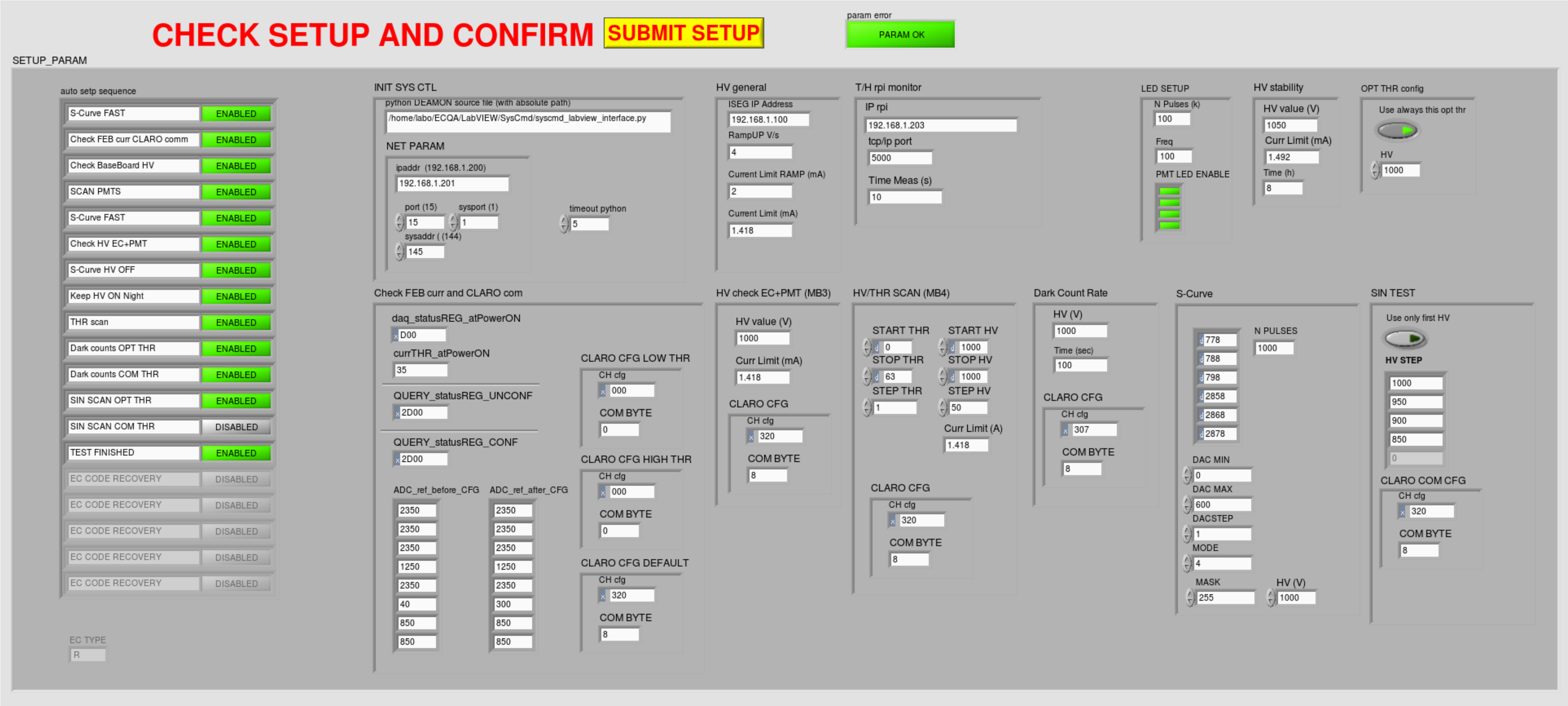


Elementary Cell Quality Assurance Software – Stage IV (2)





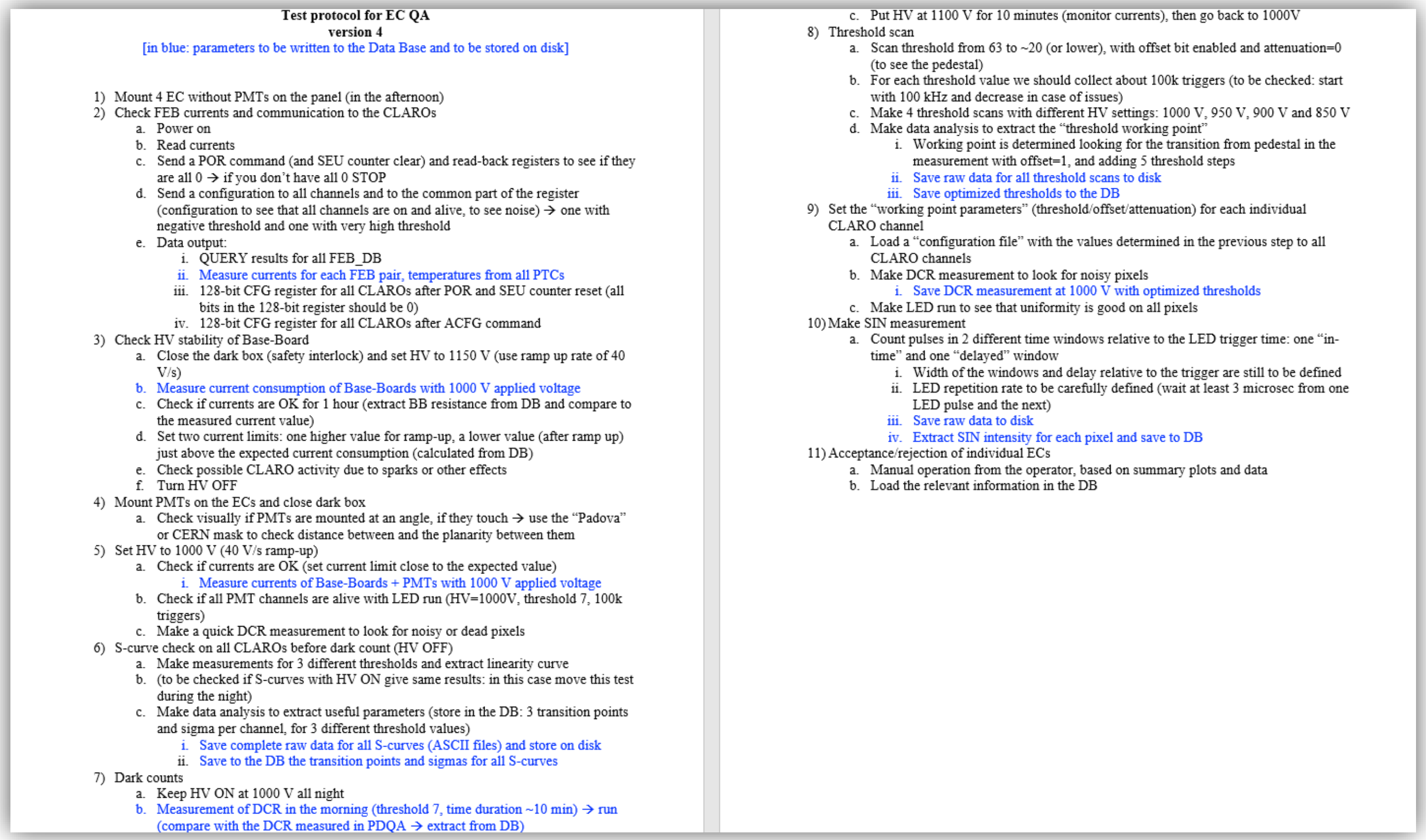
Elementary Cell Quality Assurance Software – Stage IV (3)



Elementary Cell Quality Assurance Protocol and Assembling Manual (1)

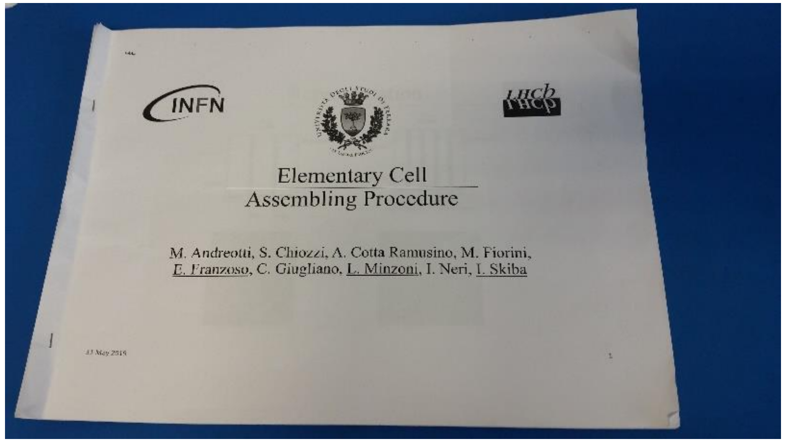
Author: Igor Ślazyk

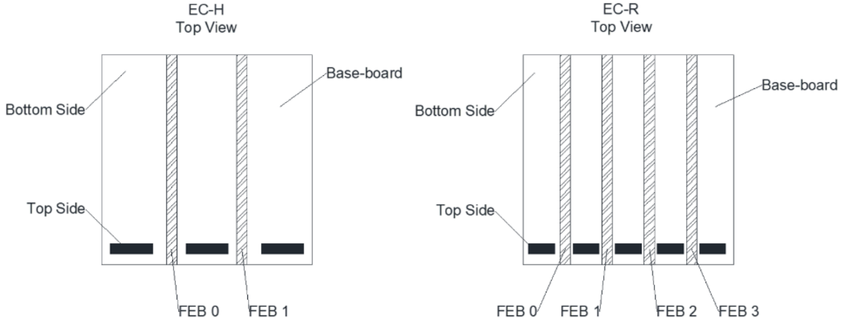
- Test protocol – a complete protocol used for the ECQA procedure
- Assembling manual – a complete guide to properly assembly ECs

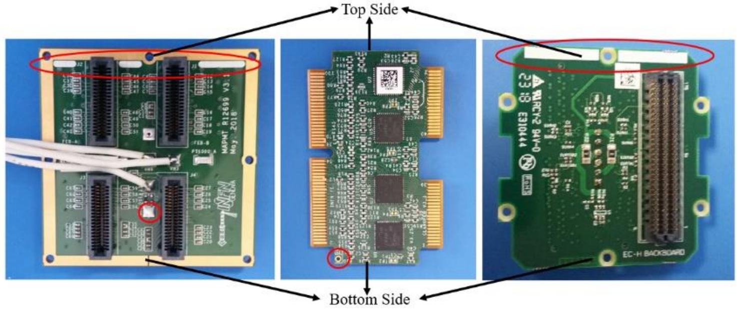


Test protocol for EC QA
version 4
[in blue: parameters to be written to the Data Base and to be stored on disk]

1) Mount 4 EC without PMTs on the panel (in the afternoon)
2) Check FEB currents and communication to the CLAROs
   a. Power on
   b. Read currents
   c. Send a POR command (and SEU counter clear) and read-back registers to see if they are all 0 → if you don't have all 0 STOP
   d. Send a configuration to all channels and to the common part of the register (configuration to see that all channels are on and alive, to see noise) → one with negative threshold and one with very high threshold
   e. Data output:
      i. QUERY results for all FEB_DB
      ii. Measure currents for each FEB pair, temperatures from all PTCs
      iii. 128-bit CFG register for all CLAROs after POR and SEU counter reset (all bits in the 128-bit register should be 0)
      iv. 128-bit CFG register for all CLAROs after ACFG command
3) Check HV stability of Base-Board
   a. Close the dark box (safety interlock) and set HV to 1150 V (use ramp up rate of 40 V/s)
   b. Measure current consumption of Base-Boards with 1000 V applied voltage
   c. Check if currents are OK for 1 hour (extract BB resistance from DB and compare to the measured current value)
   d. Set two current limits: one higher value for ramp-up, a lower value (after ramp up) just above the expected current consumption (calculated from DB)
   e. Check possible CLARO activity due to sparks or other effects
   f. Turn HV OFF
4) Mount PMTs on the ECs and close dark box
   a. Check visually if PMTs are mounted at an angle, if they touch → use the "Padova" or CERN mask to check distance between and the planarity between them
5) Set HV to 1000 V (40 V/s ramp-up)
   a. Check if currents are OK (set current limit close to the expected value)
      i. Measure currents of Base-Boards + PMTs with 1000 V applied voltage
   b. Check if all PMT channels are alive with LED run (HV=1000V, threshold 7, 100k triggers)
   c. Make a quick DCR measurement to look for noisy or dead pixels
6) S-curve check on all CLAROs before dark count (HV OFF)
   a. Make measurements for 3 different thresholds and extract linearity curve
   b. (to be checked if S-curves with HV ON give same results: in this case move this test during the night)
   c. Make data analysis to extract useful parameters (store in the DB: 3 transition points and sigma per channel, for 3 different threshold values)
      i. Save complete raw data for all S-curves (ASCII files) and store on disk
      ii. Save to the DB the transition points and sigmas for all S-curves
7) Dark counts
   a. Keep HV ON at 1000 V all night
   b. Measurement of DCR in the morning (threshold 7, time duration ~10 min) → run (compare with the DCR measured in PDQA → extract from DB)
   c. Put HV at 1100 V for 10 minutes (monitor currents), then go back to 1000V
8) Threshold scan
   a. Scan threshold from 63 to ~20 (or lower), with offset bit enabled and attenuation=0 (to see the pedestal)
   b. For each threshold value we should collect about 100k triggers (to be checked: start with 100 kHz and decrease in case of issues)
   c. Make 4 threshold scans with different HV settings: 1000 V, 950 V, 900 V and 850 V
   d. Make data analysis to extract the "threshold working point"
      i. Working point is determined looking for the transition from pedestal in the measurement with offset=1, and adding 5 threshold steps
      ii. Save raw data for all threshold scans to disk
      iii. Save optimized thresholds to the DB
9) Set the "working point parameters" (threshold/offset/attenuation) for each individual CLARO channel
   a. Load a "configuration file" with the values determined in the previous step to all CLARO channels
   b. Make DCR measurement to look for noisy pixels
      i. Save DCR measurement at 1000 V with optimized thresholds
   c. Make LED run to see that uniformity is good on all pixels
10) Make SIN measurement
   a. Count pulses in 2 different time windows relative to the LED trigger time: one "in-time" and one "delayed" window
      i. Width of the windows and delay relative to the trigger are still to be defined
      ii. LED repetition rate to be carefully defined (wait at least 3 microsec from one LED pulse and the next)
      iii. Save raw data to disk
      iv. Extract SIN intensity for each pixel and save to DB
11) Acceptance/rejection of individual ECs
   a. Manual operation from the operator, based on summary plots and data
   b. Load the relevant information in the DB



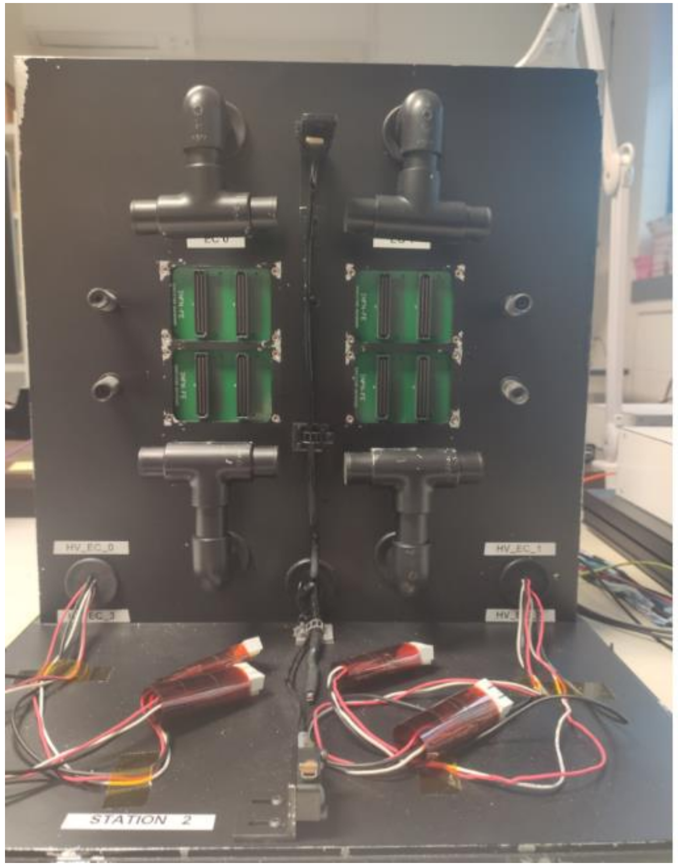


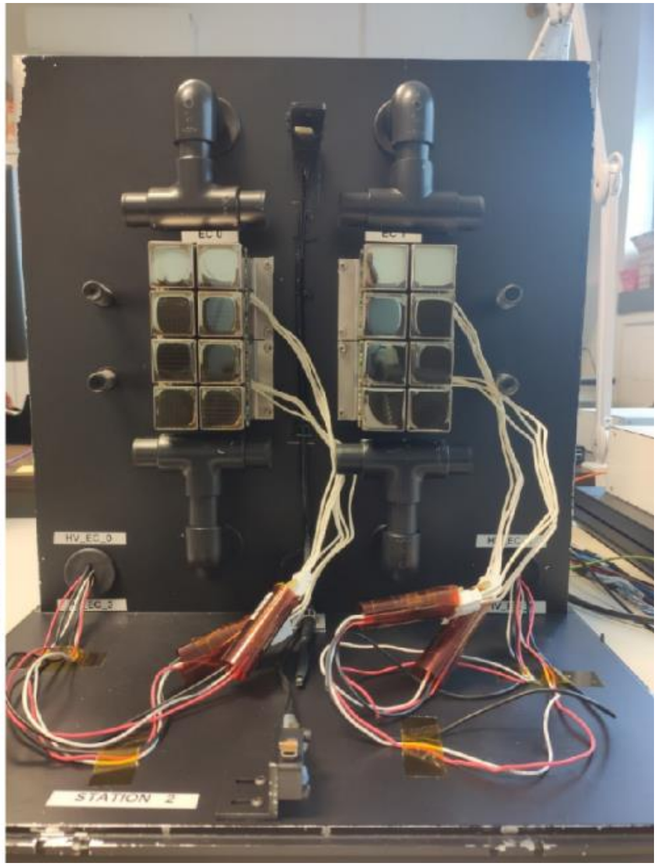


Author: Igor Ślazyk

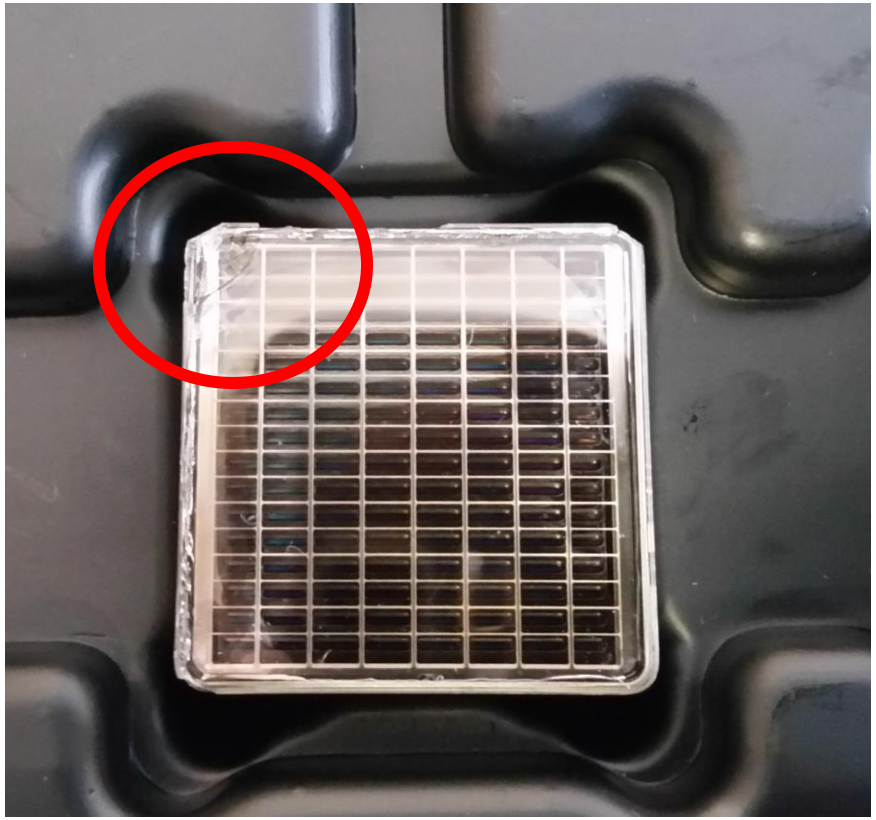
Procedure:

- Preparation of readout electronics for assembly
- Quick response (QR) code scanning
- Assembly – ECs without MaPMTs
- Mounting of ECs to test stations
- Test measurements on FE read-out electronics
- Preparation of MaPMTs according to grouping schemes
- Installation of MaPMTs with QR code scanning
- MaPMTs training – 10 hours
- Test measurements on MaPMTs
- Revision of obtained data
- Preparation of tested ECs for shipments to CERN





Elementary Cell Quality Assurance
Mistakes Were Made



Elementary Cell Quality Assurance
Offline Data Analysis

Authors: Igor Ślazyk
Luca Minzoni
Edoardo Franzoso

- Written in Python and C++

- Essential for revising obtained results

- Electronic (CLARO channel) and optical (MAPMT) mapping correlation

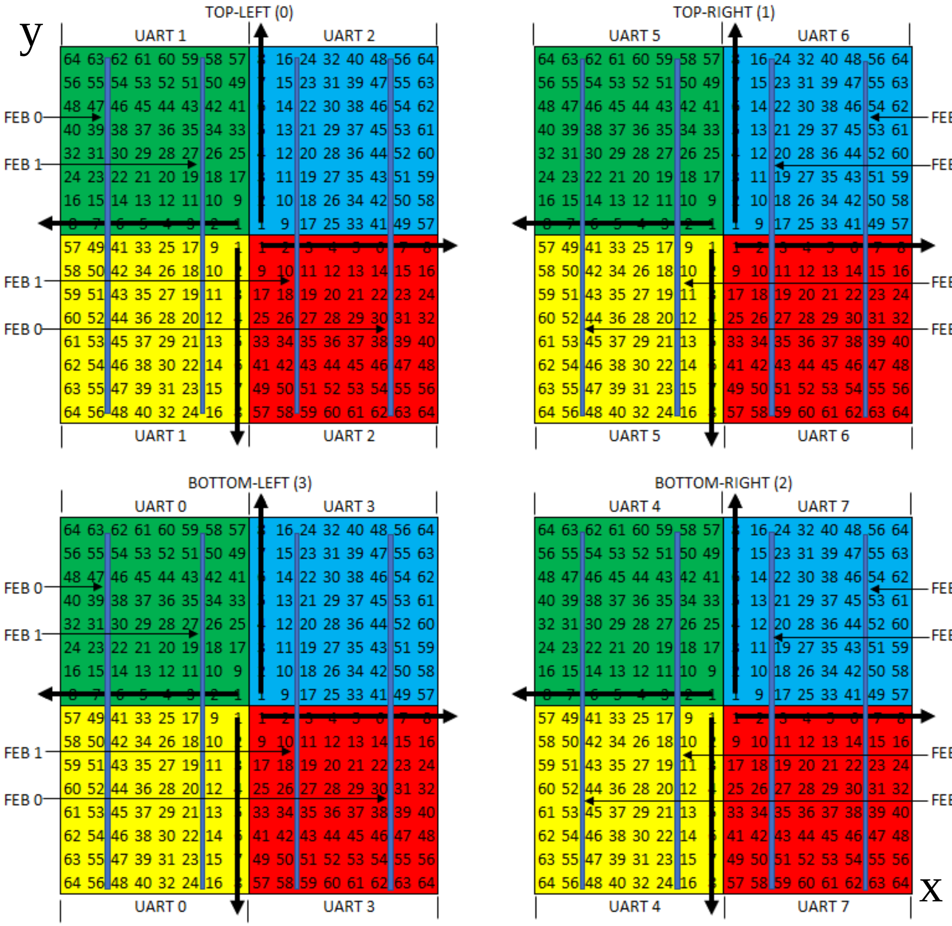
Analyses:

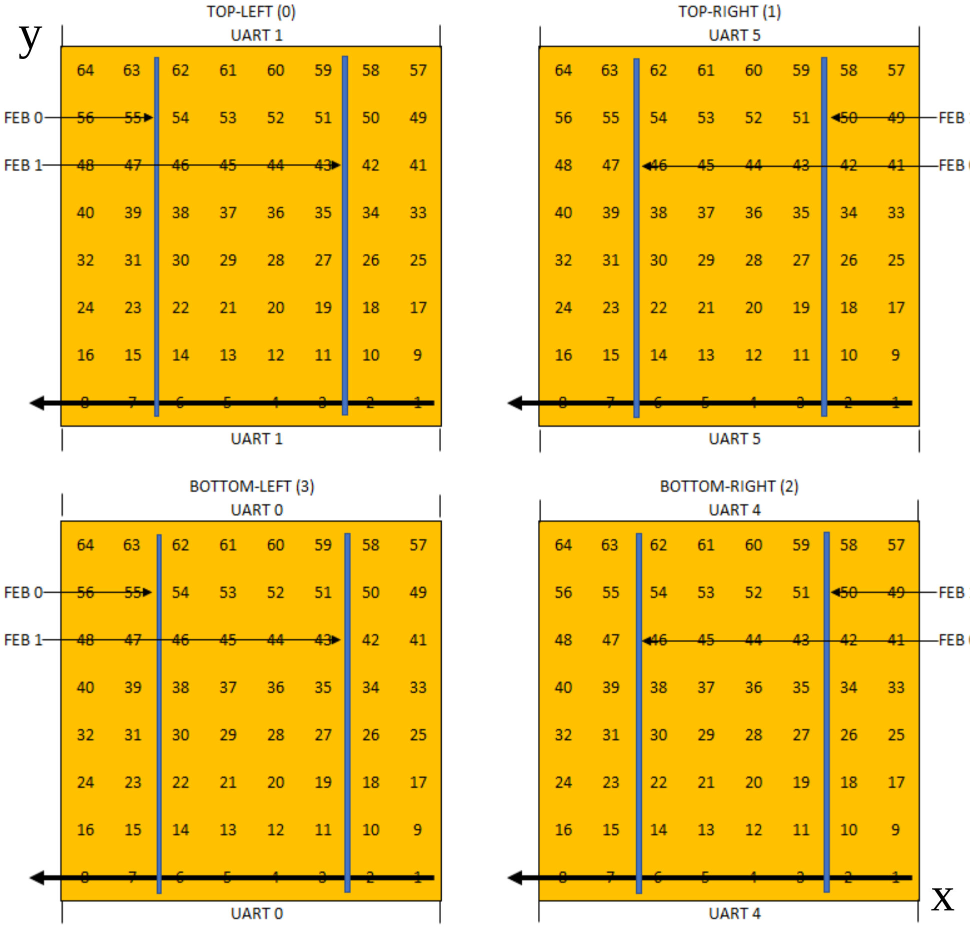
- Digital-to-Analog Converter (**DAC**) Scan
- Threshold (**THR**) Scan,
- Dark Count Rate (**DCR**),
- Signal Induced Noise (**SIN**).

Elementary Cell Quality Assurance Mapping (1)

R-type load (4 R-type ECs)

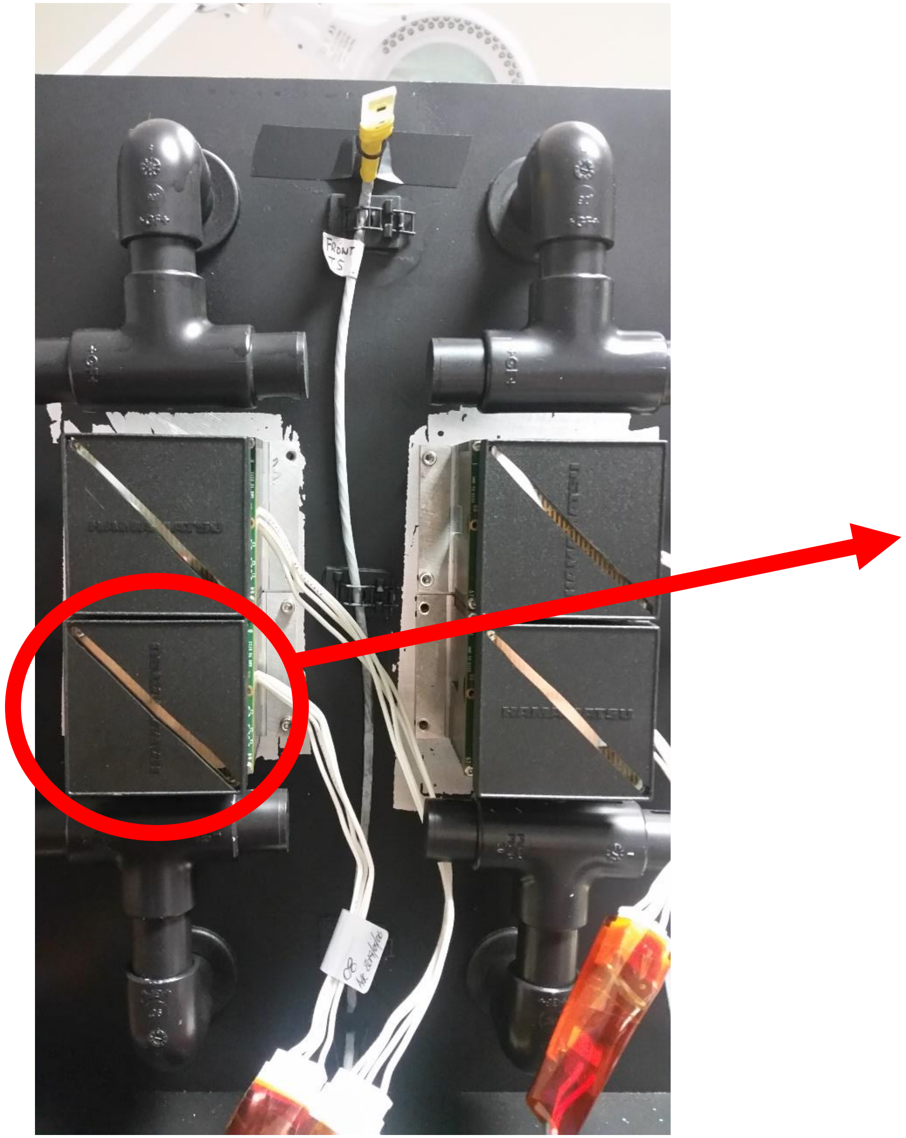
H-type load (4 H-type ECs)

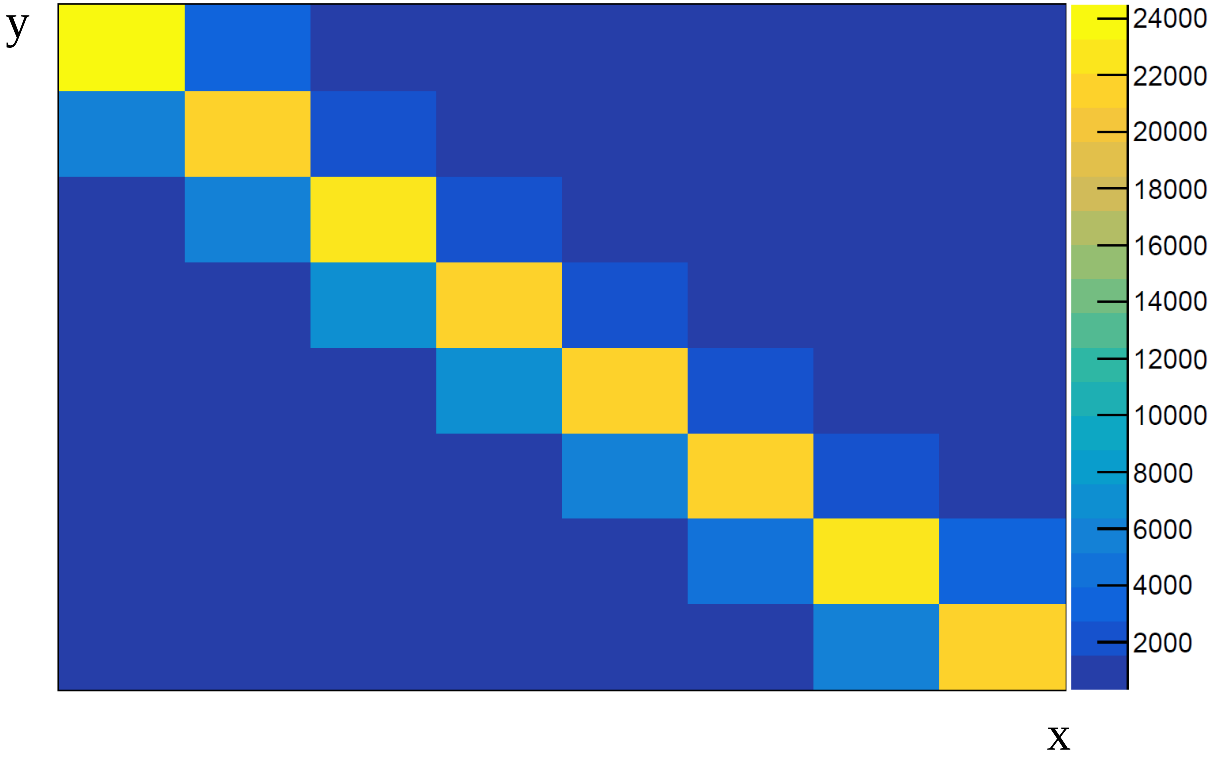




Elementary Cell Quality Assurance
Mapping (3)

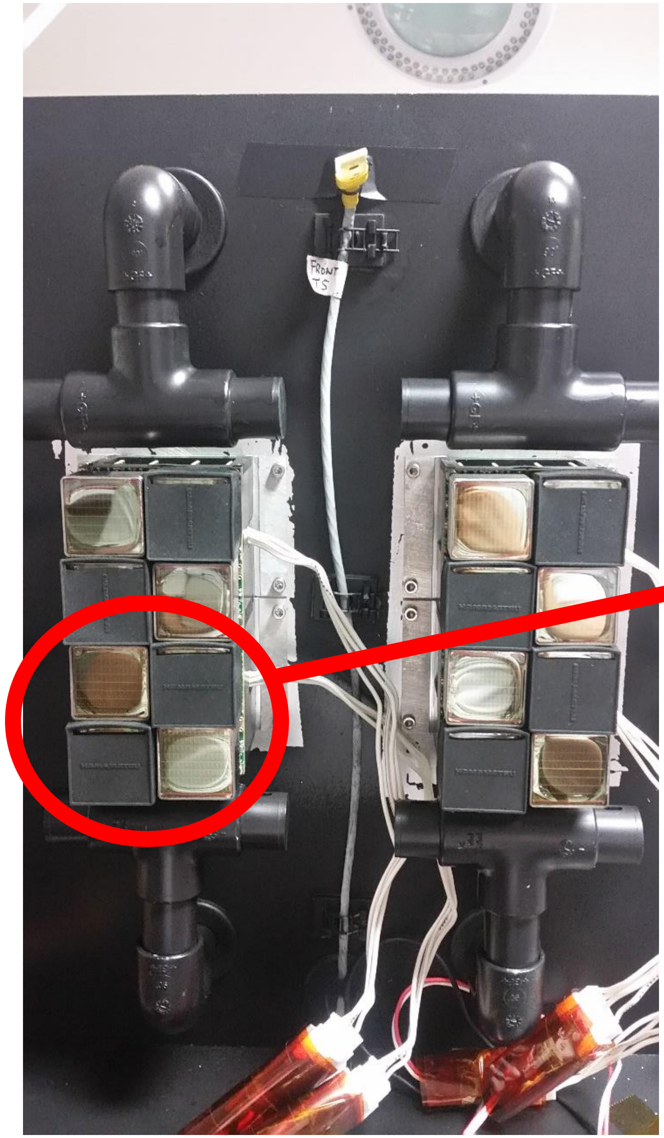
Author: Igor Ślazyk

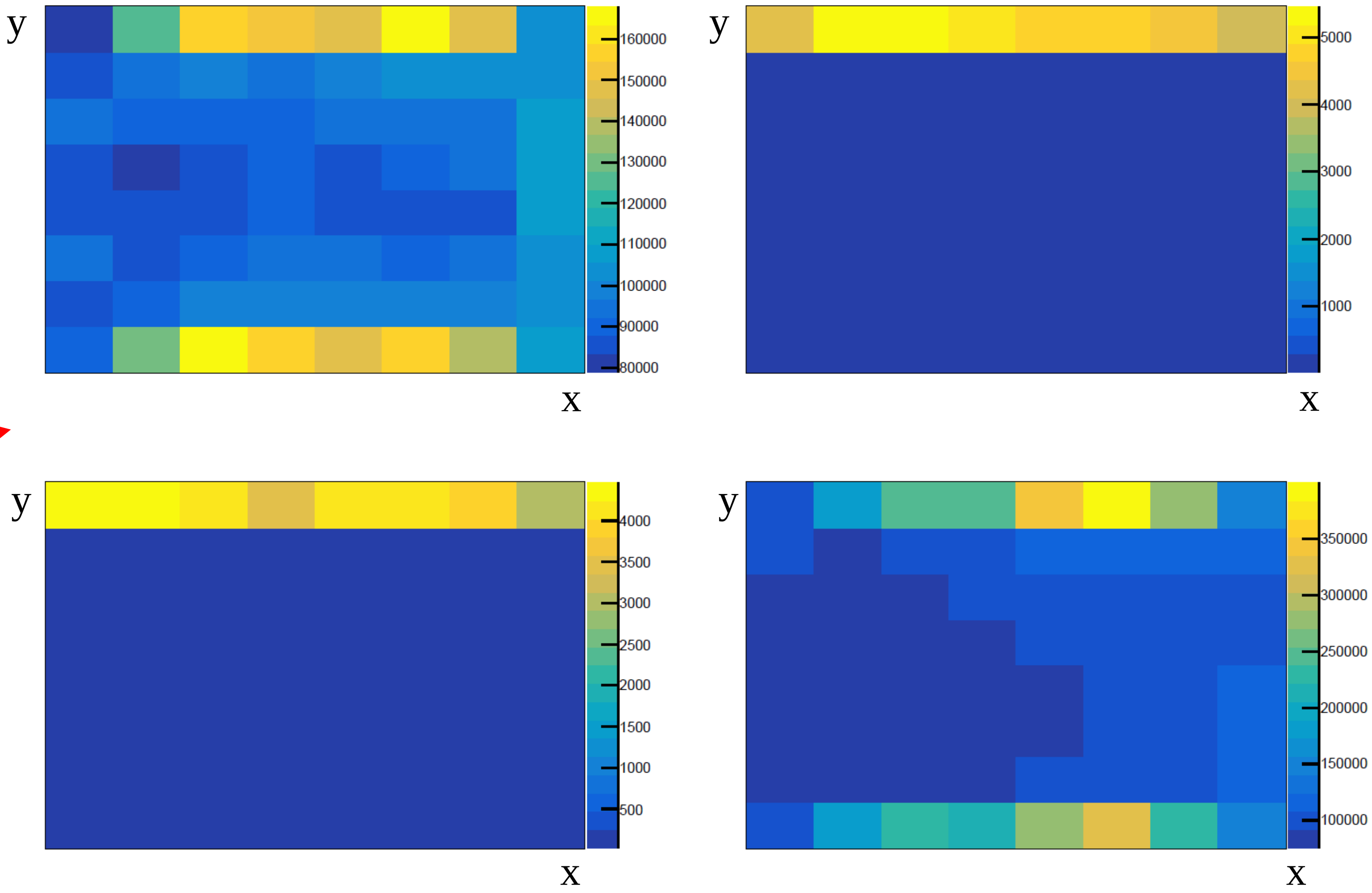




Author: Igor Ślazyk

Elementary Cell Quality Assurance Mapping (2)





Elementary Cell Quality Assurance
Digital-to-Analog Converter Scan (1)

- Used for the calibration of the CLARO channels

- Known charge Q_{inj} injected at fixed threshold

$Q_{inj} = DAC_{step} \times 1.22\ \text{mV} \times 640\text{fF} \cong DAC_{step} \times 4.874\ \text{ke}^{-}$

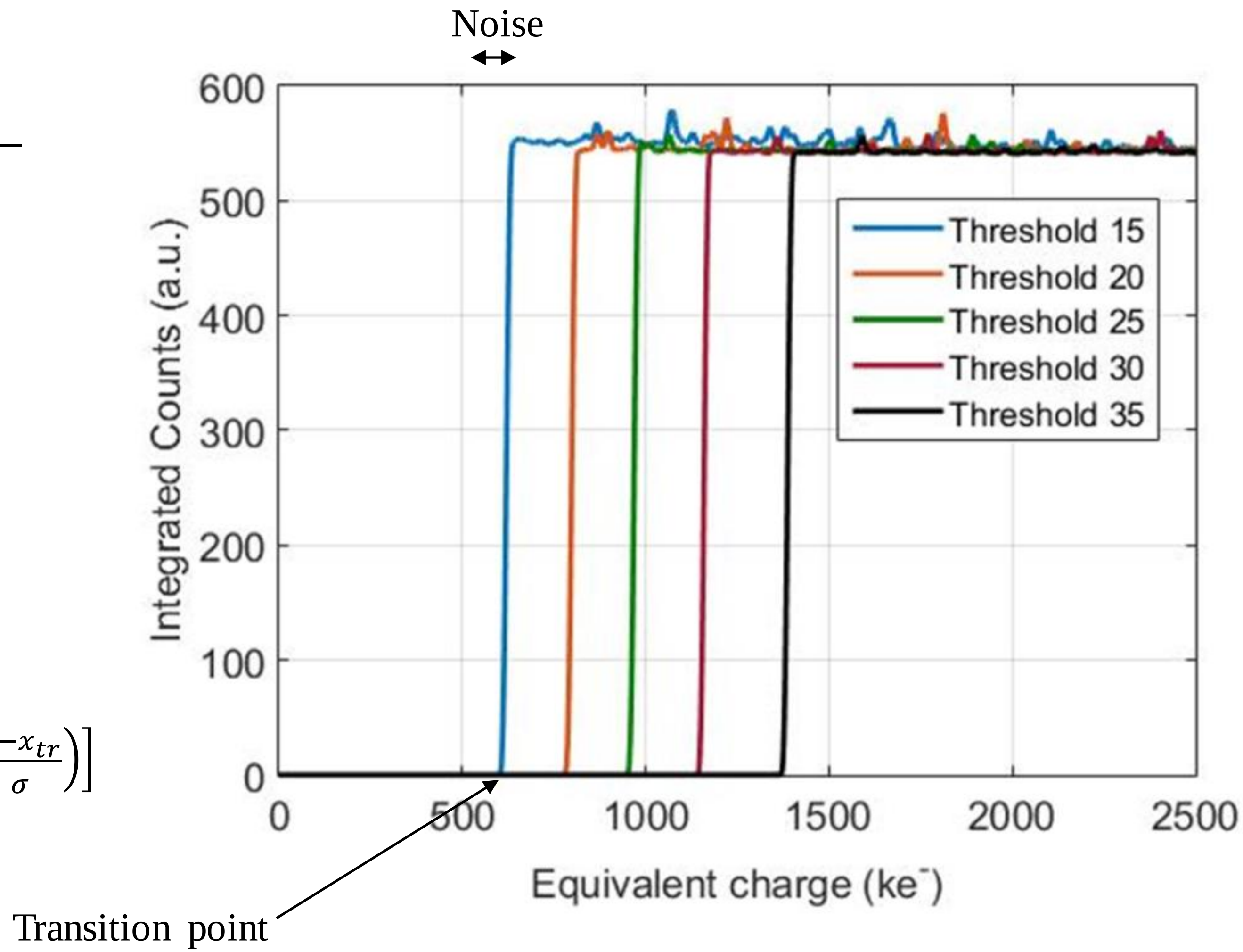
- Amplitude of the signal gradually increases

- If the charge is lower than the threshold → output **0**
- If the charge is higher than the threshold → output **1**

- Parameters of interest:
  - Transition point $\boldsymbol{x_{tr}}$
  - Noise $\boldsymbol{\sigma}$

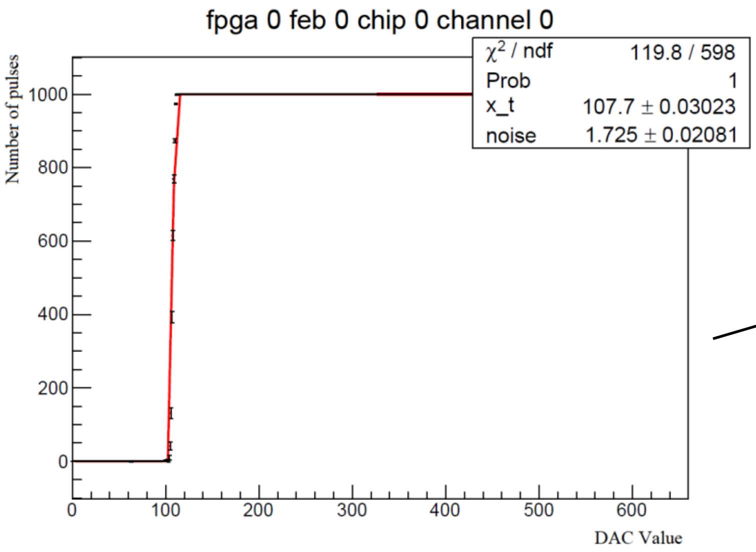
- Fitted using translated error function: $f(x) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{x - x_{tr}}{\sigma}\right)\right]$

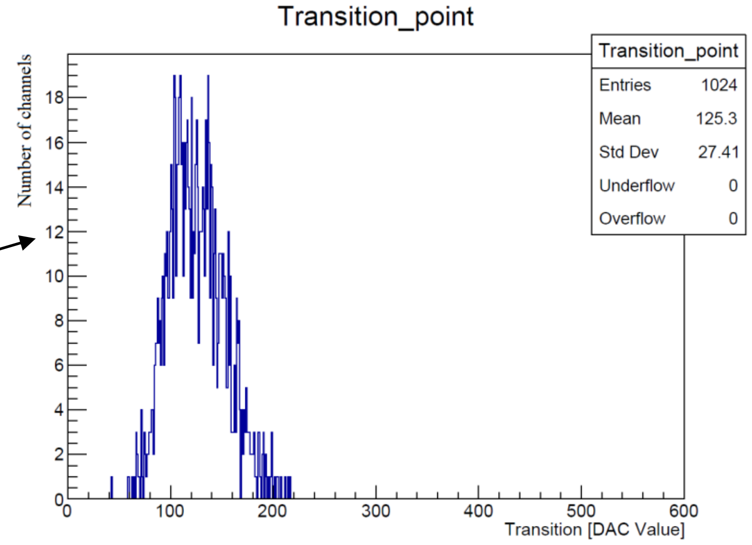
- DAC scan also referred as S-Curve test



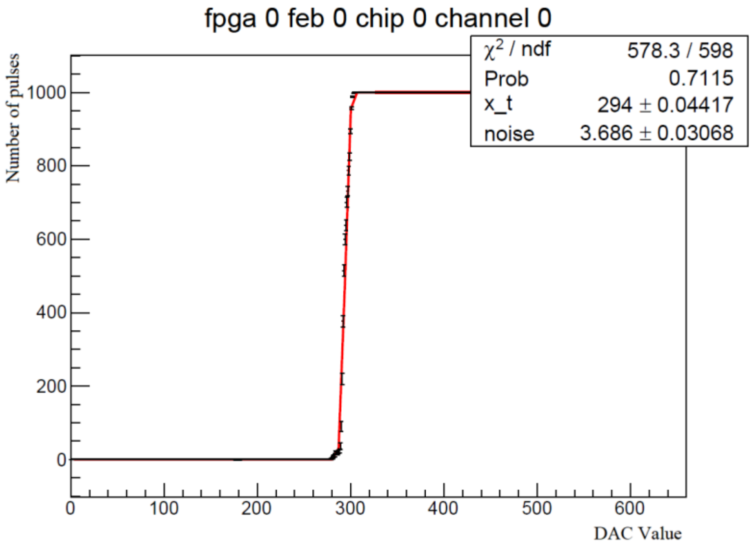
Elementary Cell Quality Assurance
Digital-to-Analog Converter Scan (2)

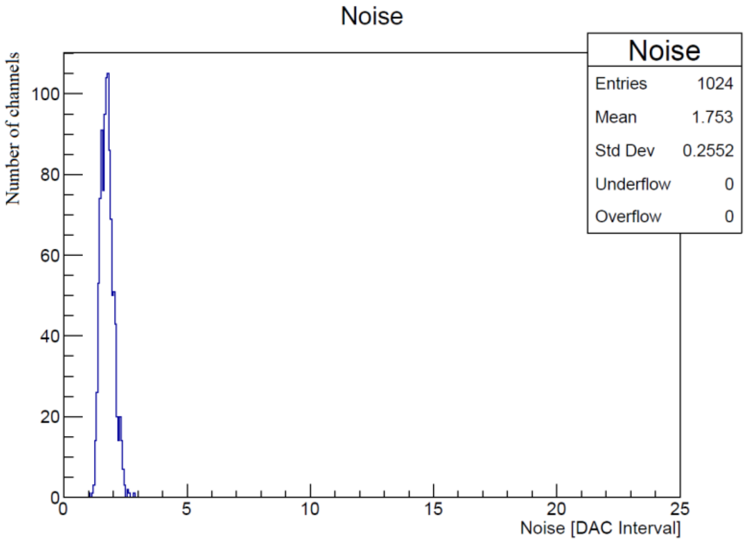
Threshold 10





Threshold 62





Elementary Cell Quality Assurance
Threshold Scan (1)

- Used for the calibration of the MaPMTs anodes

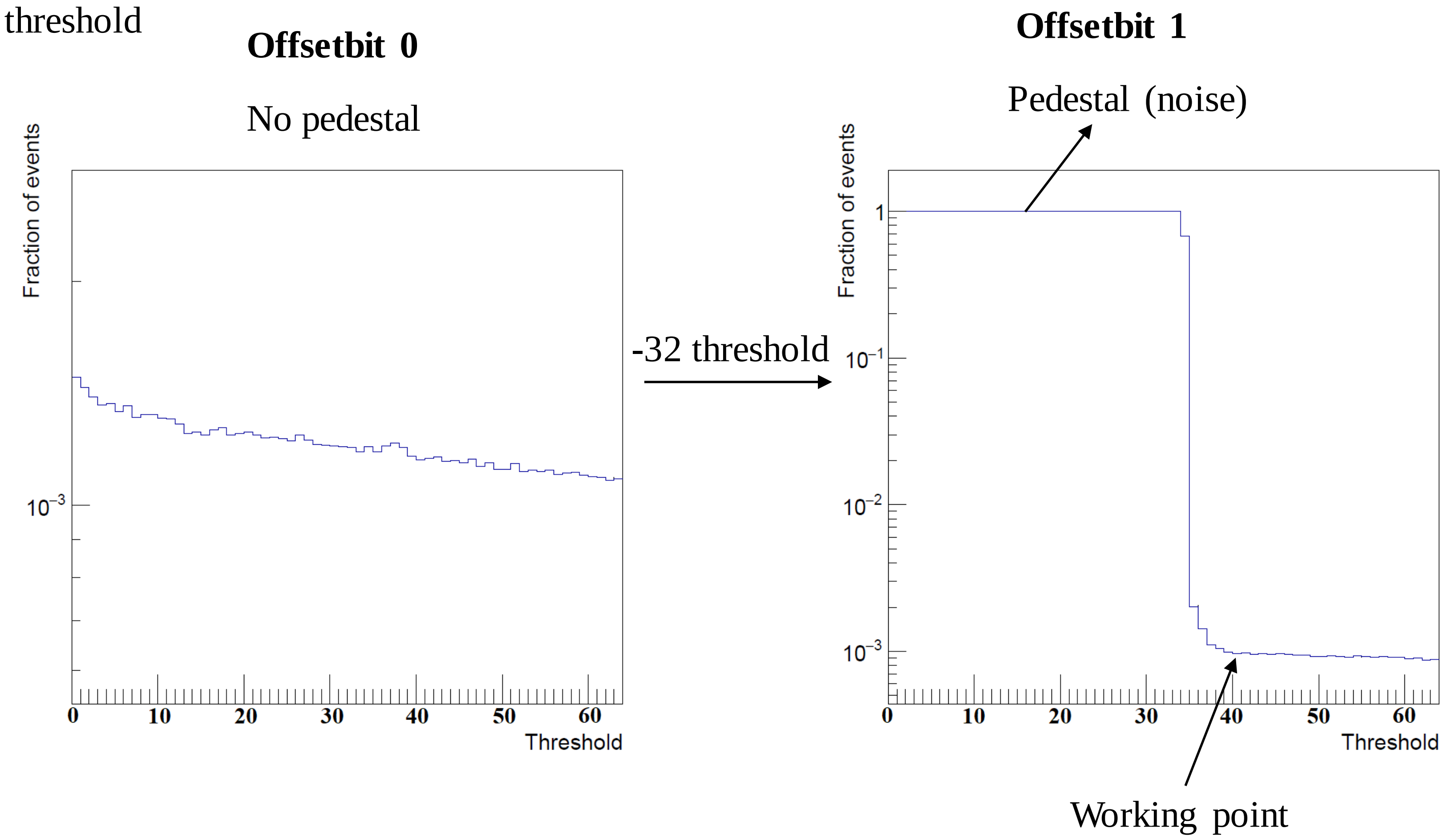
- Known charge Q_{inj} injected at decreasing threshold
- Amplitude of the signal fixed

- Distribution of above-threshold events

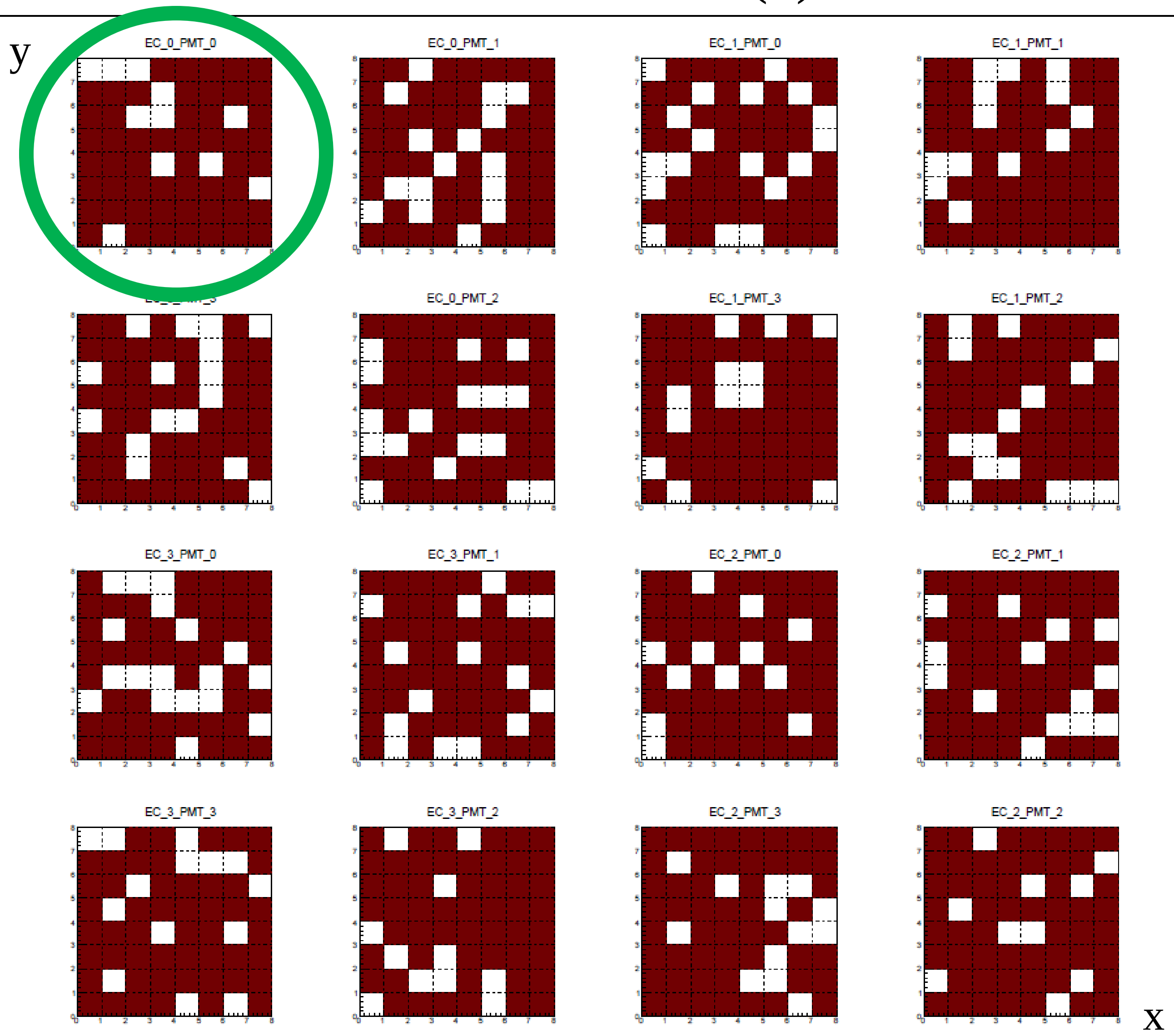
- Parameters of interest:
  - Working point $\boldsymbol{w_p}$

- At certain threshold (working point) the noise is well separated from the signal

- Offsetbit 0 and 1 – shifts threshold by -32

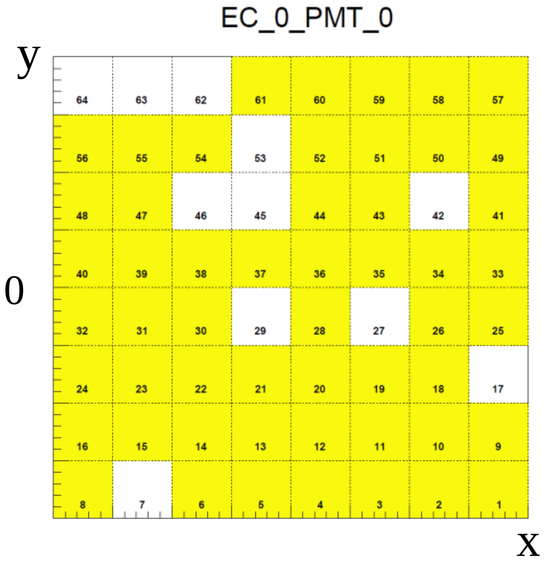


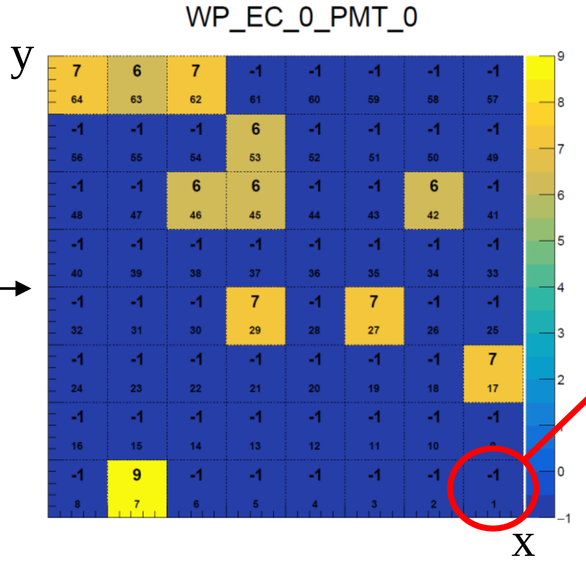
Elementary Cell Quality Assurance
Threshold Scan (2)

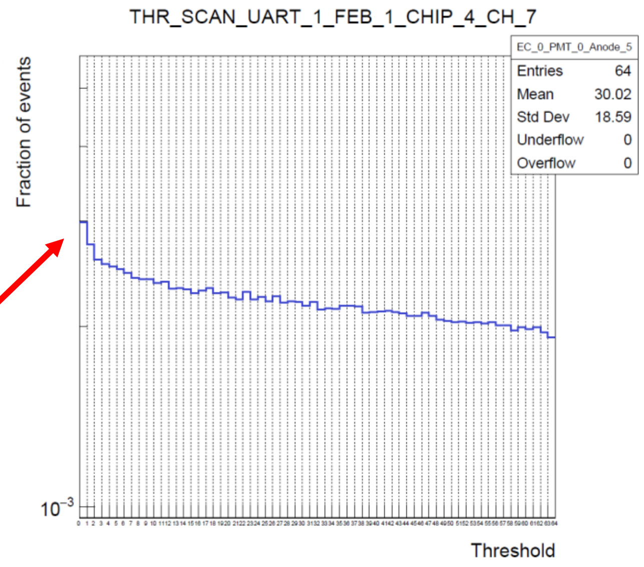


Elementary Cell Quality Assurance
Threshold Scan (3)

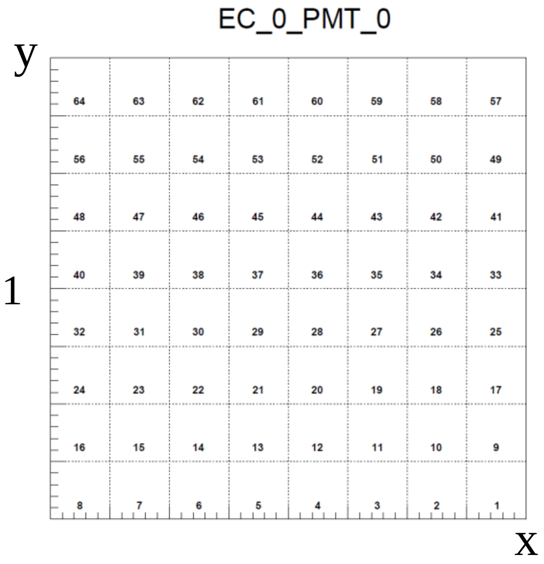
Offsetbit 0

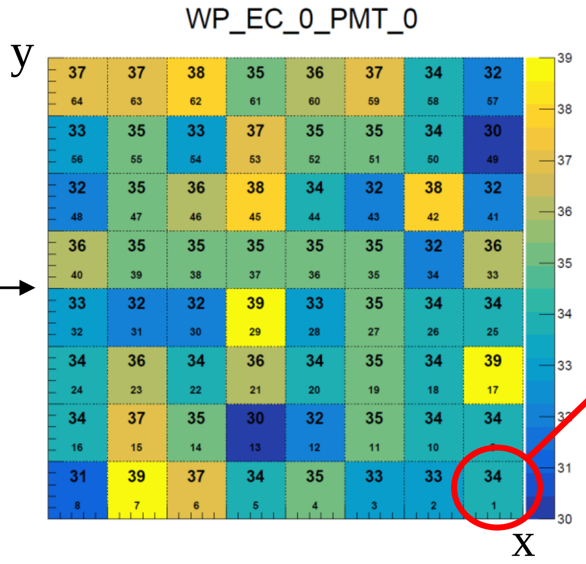


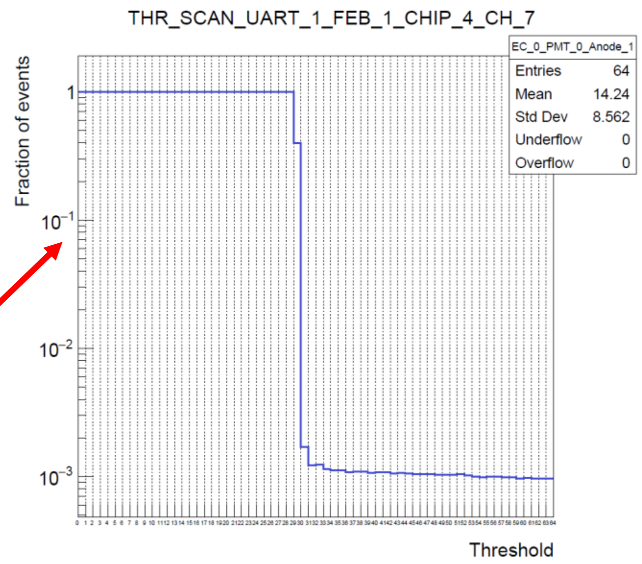




Offsetbit 1

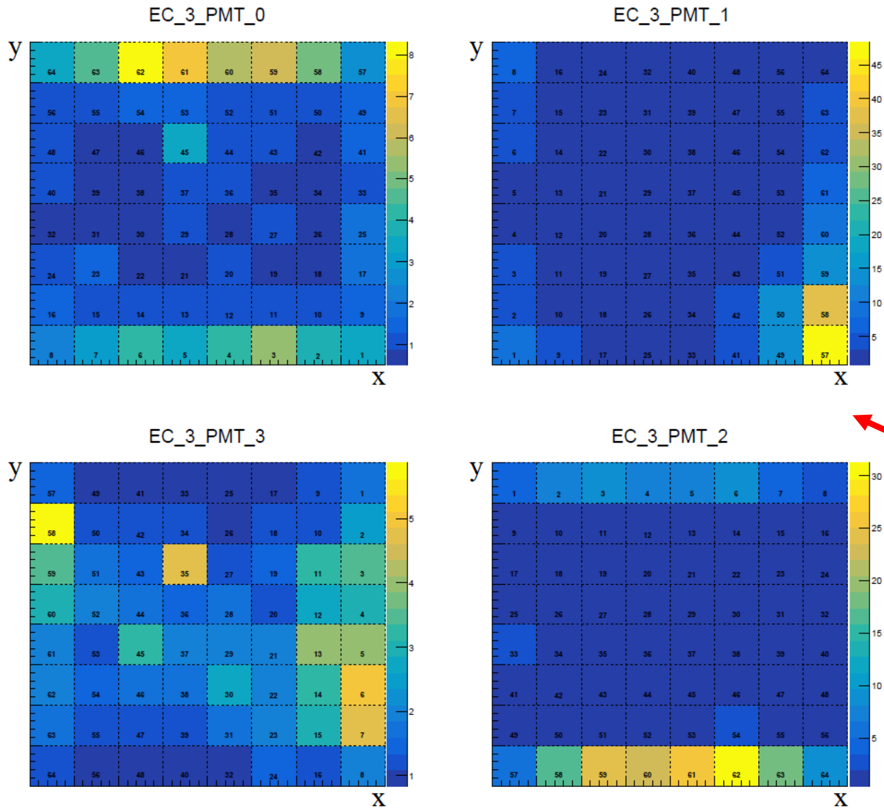






Elementary Cell Quality Assurance
Dark Count Rate

- Signals not generated by photon events
- Spontaneous electron emission (thermal emission)
- Used for the distinction of anodes with high counts
  - Should not exceed 1 kHz
- Used to check the uniformity of MaPMTs



Elementary Cell Quality Assurance
Signal Induced Noise (1)

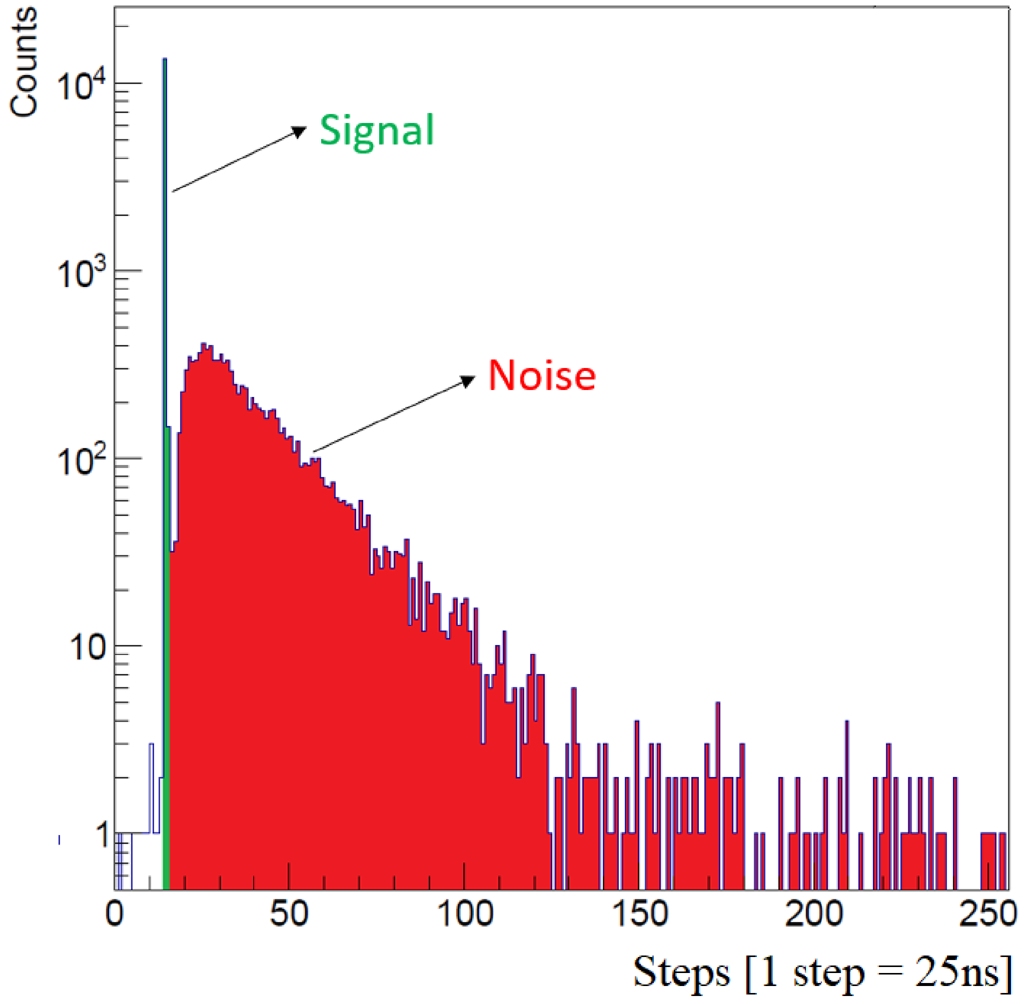
- Signals after the true signal
- Also referred as after-pulses
- Undesirable effect

- SIN step 14 – 15 [325 – 350ns] → signal
- SIN step 16 – 255 (350 – 6.375µs] → noise

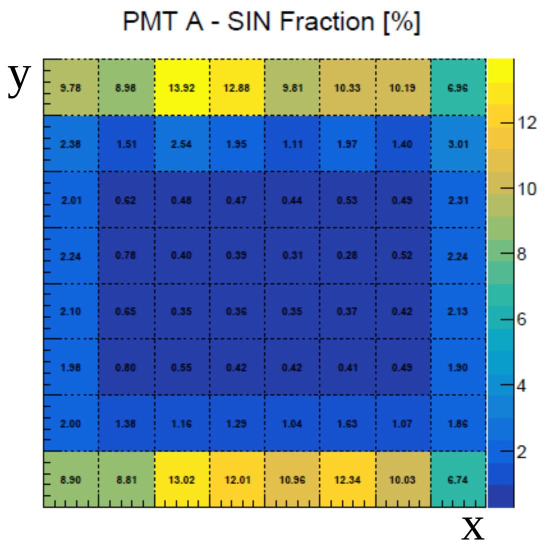
Parameters of interest:

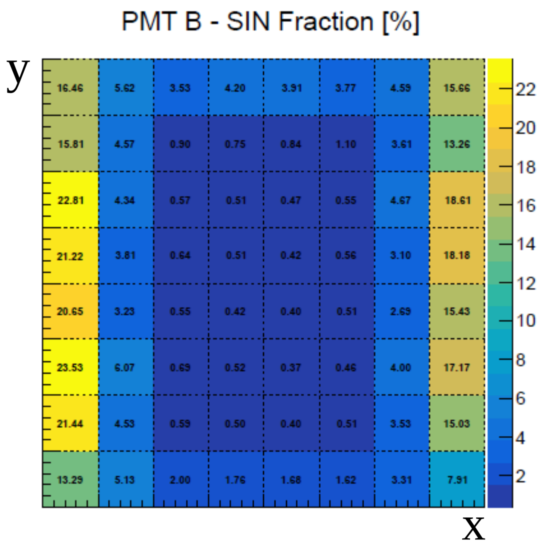
- $SIN\_Fraction = \frac{noise}{signal+noise}$
- $S/N\ Ratio = \frac{signal}{noise}$

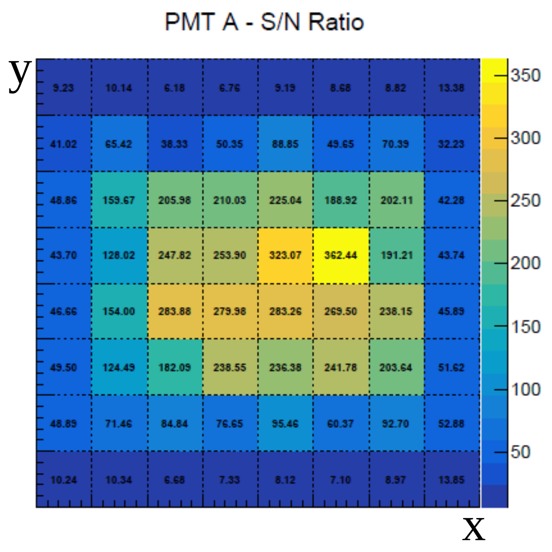
- For R-type ECs:
  - Hammamatsu introduced almost 200 so-called SIN-less MaPMTs
  - Since then, all other MaPMTs are referred as SIN-affected MaPMTs

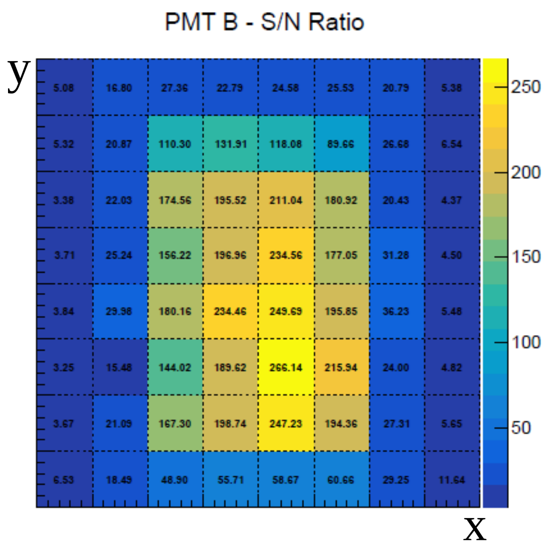


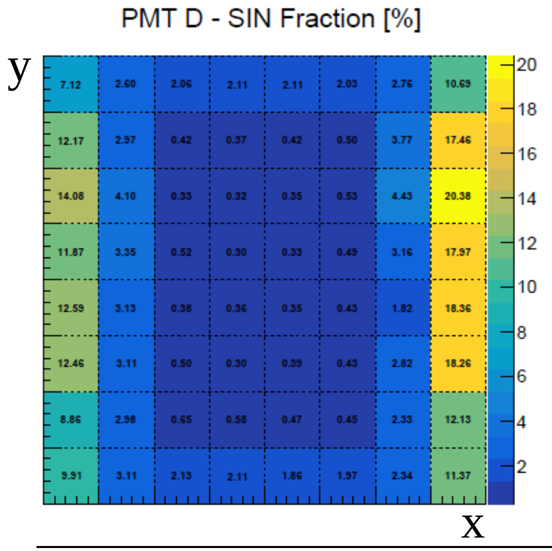
Elementary Cell Quality Assurance
Signal Induced Noise (2)

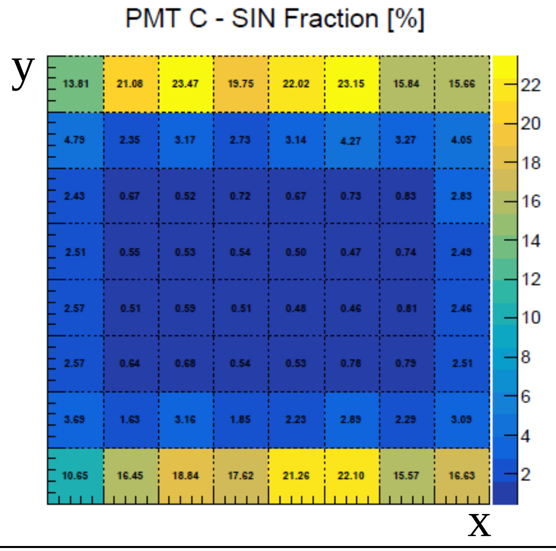


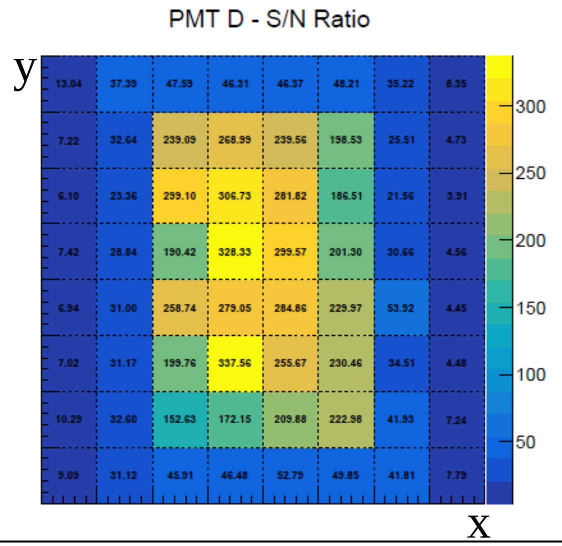


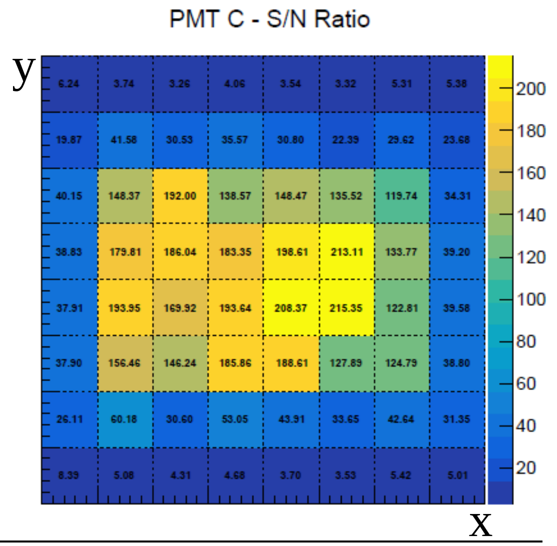






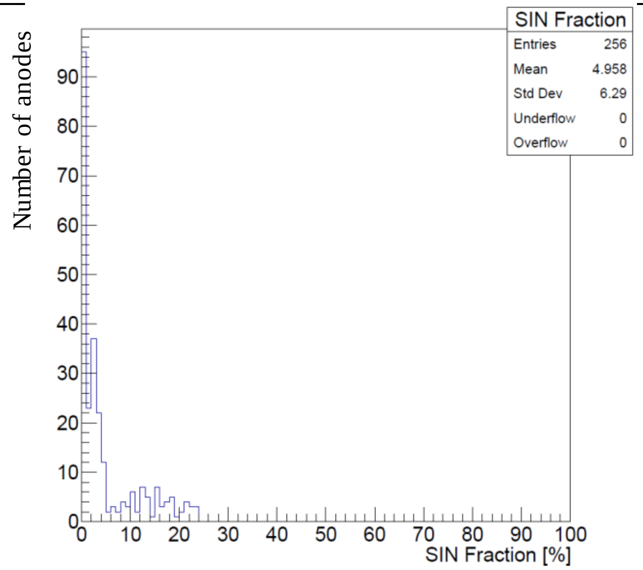


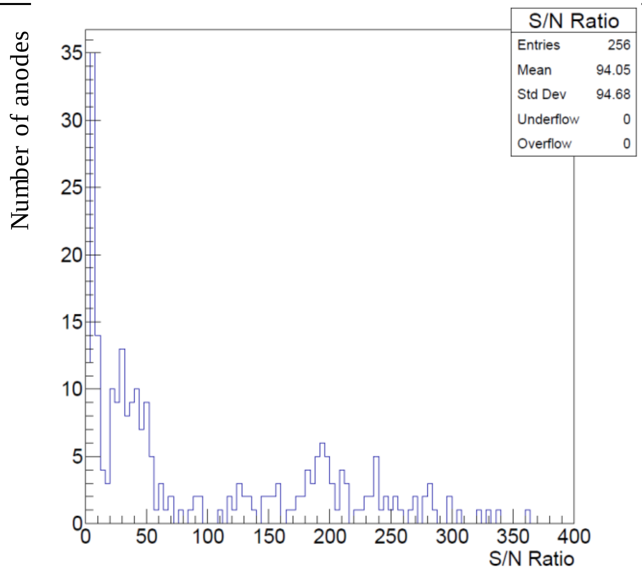




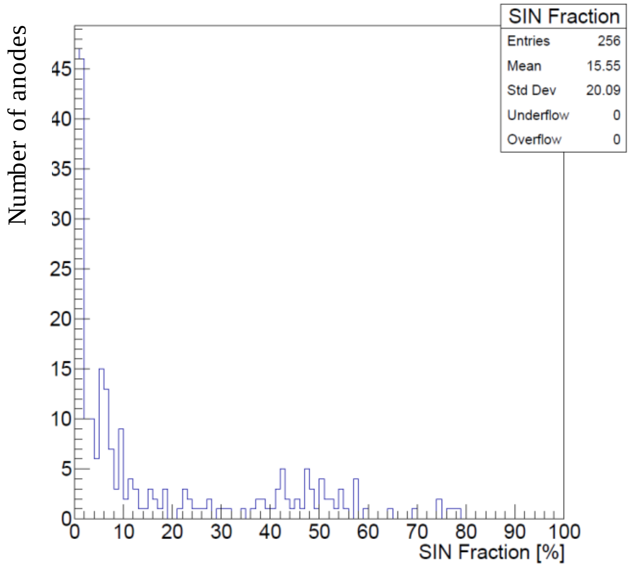
Elementary Cell Quality Assurance
Signal Induced Noise (3)

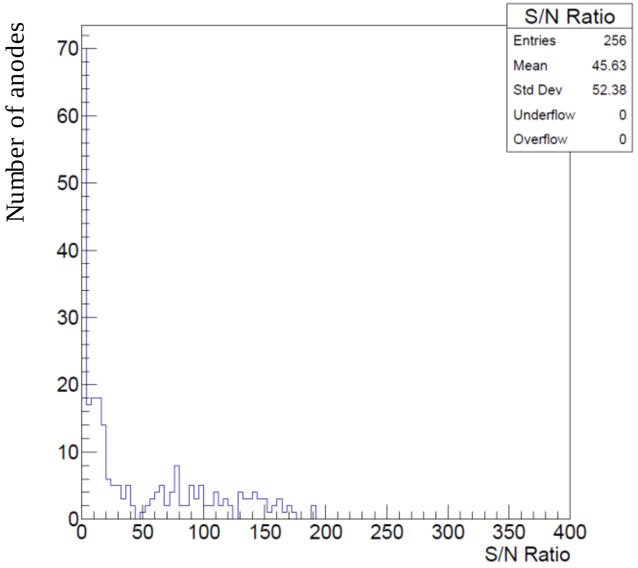
SIN-less EC





SIN-affected EC





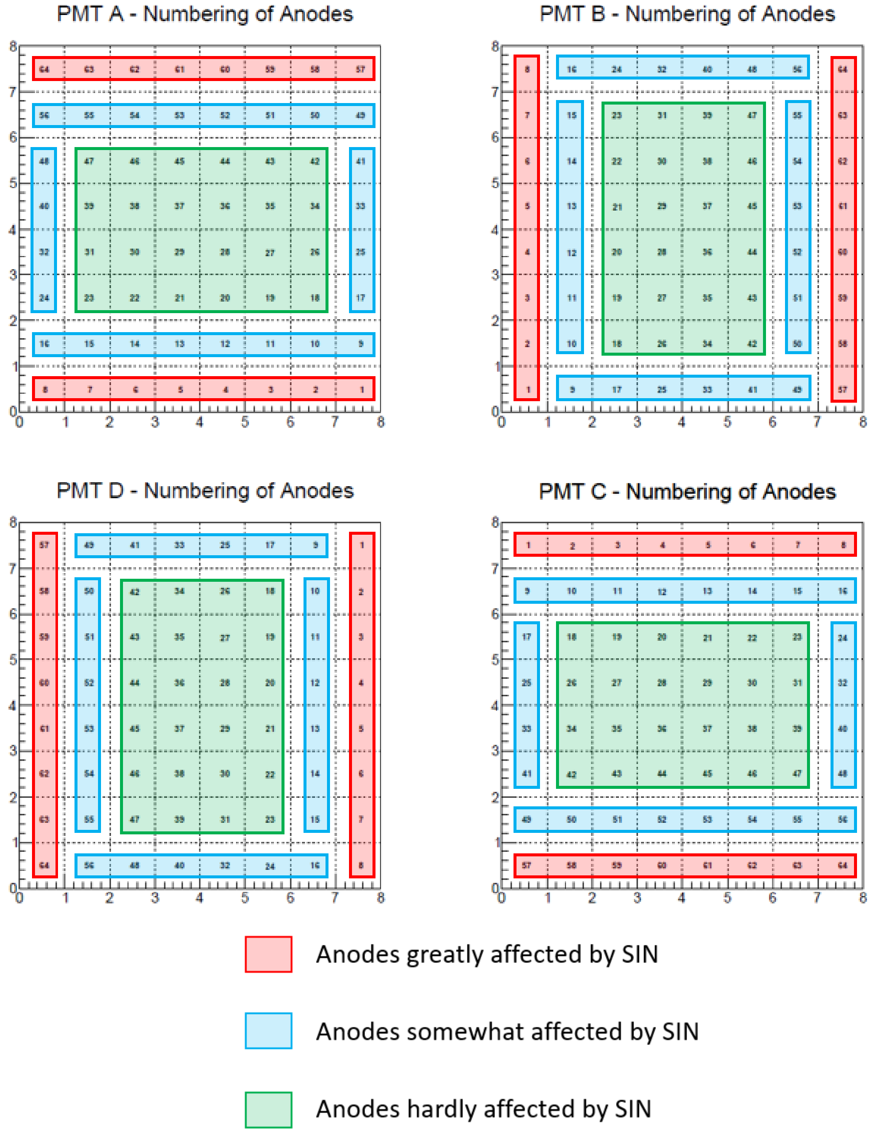
Elementary Cell Quality Assurance
Signal Induced Noise (4)

Author: Igor Ślazyk

12 SIN-affected ECs and 12 SIN-less ECs compared (48 PMTs – 3072 Anodes).

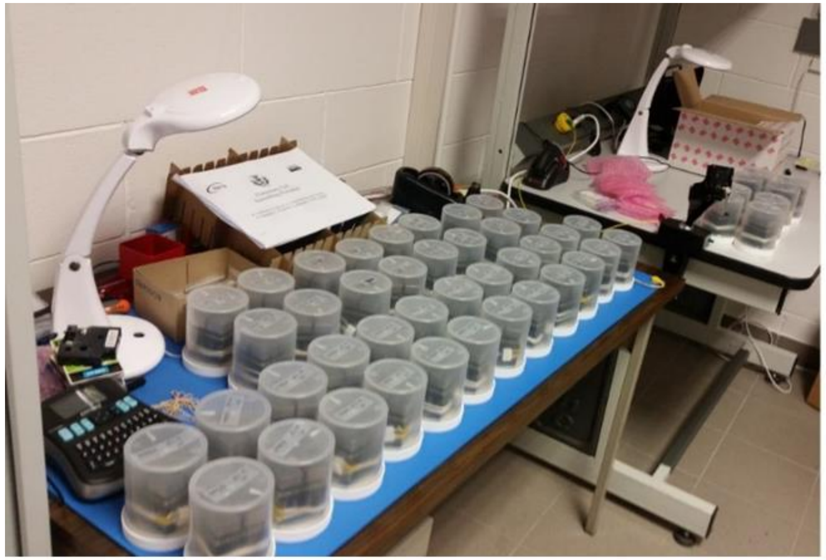
- Average SIN Fraction of SIN-less ECs compared to SIN-affected ECs is:
  - 52% lower (anodes hardly affected)
  - 64% lower (anodes somewhat affected)
  - 63% lower (anodes greatly affected)
  - 63% lower (all anodes)
- Average S/N Ratio of SIN-less ECs compared to SIN-affected ECs is:
  - 2 times higher (anodes hardly affected)
  - 2.25 times higher (anodes somewhat affected)
  - 3.95 times higher (anodes greatly affected)
  - 2.05 times higher (all anodes)

- **SIN greatly reduced in the SIN-less ECs**
- Advisable to be used in the regions with highest occupancy



Elementary Cell Quality Assurance
Shipments

Author: Igor Ślazyk



Conclusions

The ECQA in Ferrara finished successfully

- Experimental test setup proved to be reliable
- Fully automated software developed
- Quality control measurements fully completed
- Offline analysis scripts implemented in the final software
- Protocols and manuals produced
- SIN in SIN-less ECs proven to be substentially decreased
- Quality assurance results sent to CERN's database

- 581 ECs tested and sent to CERN (~55%):
    - 387 ECs of Type-R (~58%)
    - 194 ECs of Type-H (~51%)

- **RICH detectors should perform great in the future runs!**

Thank you for your attention

My Contribution

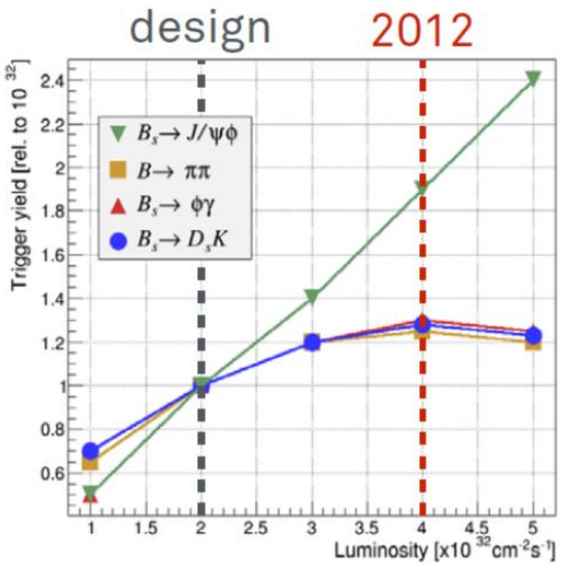
- Development and optimization of the test setup for quality control of the Elementary Cells
- Software development of the automated software for the Elementary Cells quality assurance
  - Python-LabVIEW Interface (Stage II)
  - LabVIEW Commands (Stage II)
  - Temperature and Humidity Read-Out Software (Stage II)
  - Standalones (Stage III)
  - Data analysis scripts (Stage III)
- Preparation of the test protocol and Elementary Cell assembly manual
- Hardware testing and assembly of the Elementary Cells
- Mapping tests
- Quality control measurements of the Elementary Cells
- Data analysis of the Elementary Cells quality assurance (SIN-less ECs)
- Minor data analysis on the example of the $B_s^0 \to D_s^{\mp} K^{\pm}$ decays
- Shipments to CERN

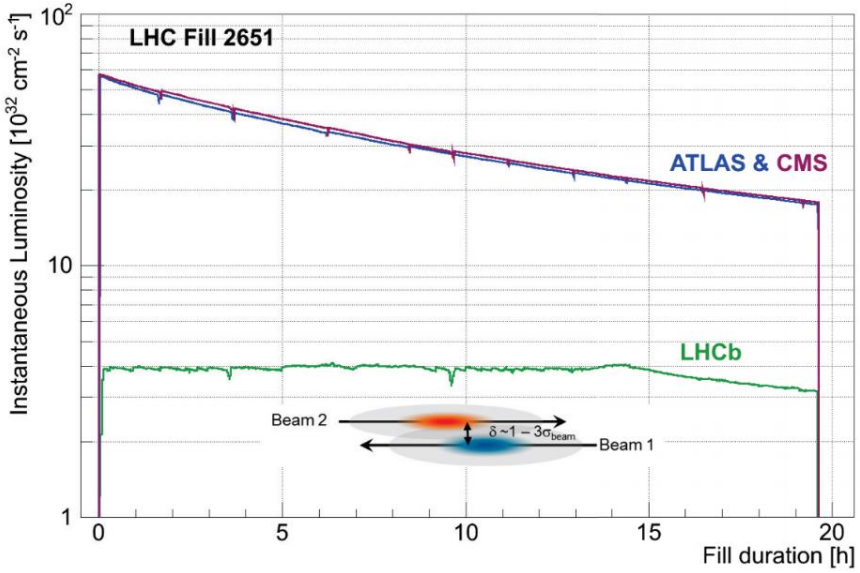
Backup

The LHCb Experiment at CERN
Upgrade (2)

Reasons for the upgrade:

- More data to further challenge theoretical predictions
- Expose of detectors to radiation damage over years
- Bottleneck of Level-0 hardware trigger (1.1 MHz)
- Change in parameters → new geometry





LHCb Upgrade:

Luminosity	Data acquisition rate
$\mathcal{L} = 4 * 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$f = 1.1$ MHz
↓	↓
$\mathcal{L} = 2 * 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$f = 40$ MHz

- Replacement of L0 hardware trigger with software trigger
- Adjustments in geometry, change in read-out electronics