Development of an integrated housing for SIPM for future Ring Imaging Cherenkov (RICH) detectors

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on behalf of the Genova's group

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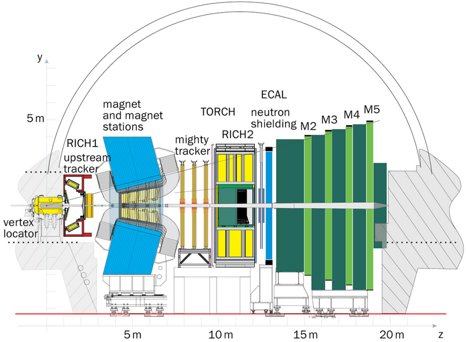
Overview

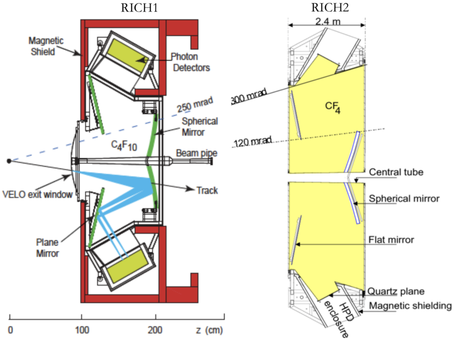
- The housing of photo-sensors for future RICH detectors is a complex task, regardless of the sensor choice, due to the **many requirements**. In order to save on the required resources and simplify the design, **different functions should be possibly integrated all together**.
- **This led to the development of the, today operational, LHCb/RICH focal surface photo-sensor array, for Hamamatsu MAPMT.**
- For the LHCb/RICH Upgrade II, for the Run 5 of the LHC, the MaPMT will be replaced since they do not fully fulfill the detector requirements. A possible candidate sensor is Silicon Photo-Multiplier (SiPM)
- For SIPM-like sensors, some sort of **active cooling** is required to keep the sensors at low temperatures of many tens of centigrade degrees below zero.
- For the LHCb/RICH Upgrade II, for the Run 5 of the LHC at CERN, **several possibilities are being investigated**. A **local cooling** strategy is being considered, to cool down a region as small as possible around the sensor only, exploiting the industrial technologies existing today for cooling of solid state devices by many applications.

The LHCb experiment at LHC



- Forward spectrometer covering pseudorapidity range $\eta \in (2 \div 5)$
- Experiment dedicated to precise measurements of heavy flavour physics
- Very good momentum resolution
- Excellent impact parameter and decay time resolution
- Particle Identification capabilities

The LHCb/RICH detector



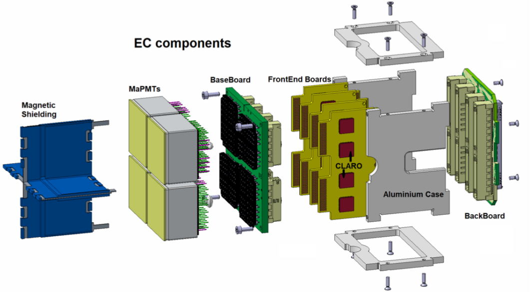
- Two RICH detectors
  - RICH 1 (C_4F_{10}): upstream, 2 GeV/c - 60 GeV/c over 25 mrad - 300 mrad
  - RICH 2 (CF_4): downstream, 30 GeV/c - 100 GeV/c over 15 mrad - 120 mrad

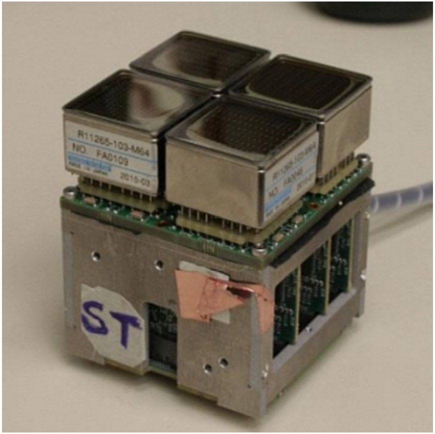
Housing photo-sensors: LHCb/RICH at LHC

- Main requirements for the photo-sensor housing, regardless of the sensor choice, include the following:
    - structural stability to house and secure in place the sensor, the read-out boards as well as any other ancillary system;
    - **close-packing with large and uniform filling factor** on a large surface
    - **provide electrical connections** from/to the sensors, **thermal dissipation** functionalities for heat transfer to the cooling system and electromagnetic shielding
    - provide support for possible optical components (lenses and/or optical filter) and for components for calibration systems
    - ease of access for repair and maintenance.
- A **modular solution**, based on fully autonomous functional units, is preferred, for ease of construction, maintenance and repair
- In order to save on the required resources and simplify the design, **different functions should be possibly integrated together**.

MaPMT for LHCb/RICH Upgrade I

- Modular unit: Elementary Cell (EC) which consists of
  - A Base-Board (BB) with custom sockets to house the MaPMTs. It provides power, common High Voltage (HV) to the photocathodes of the MaPMTs, resistor divider chain(s) which supply potential(s) to the dynodes and connect the MaPMT anodes to the Front-End Boards.
  - Front-End Boards, each equipped with eight CLARO chips.
  - A backboard, which interfaces the FEBs to the Digital Board for configuration and read out.

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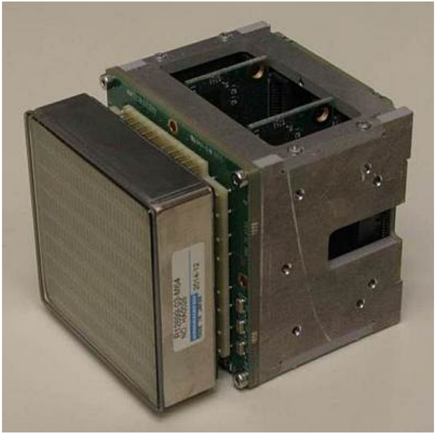
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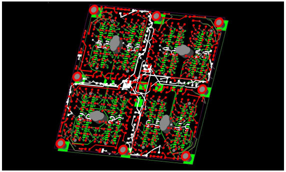
Base-Board Passive Cooling Design

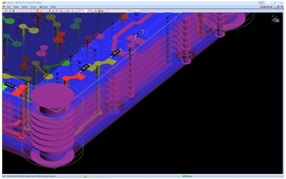
- Base-Board: thick $(3.1\,\mathrm{mm})$ PCB
- Relevant for cooling is the internal structure, designed on purpose.
- Copper layers $(6 \times 0.105\,\mathrm{mm})$

The internal structure of the Base-Board: 3D view of the electrical routing.



Metalized holes connected to the case for fixing and heat exchange.

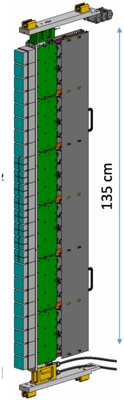
The internal structure of the BB: 3D view of the passive internal copper layer

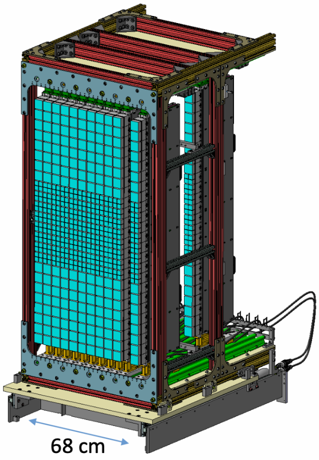


NB: old prototype, not the final routing and thermal layers design.

LHCb/RICH upgrade-I

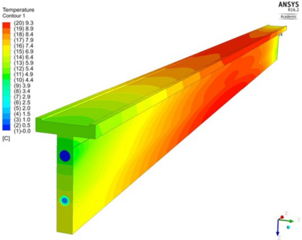
- The ECs are arranged in columns.
- Columns of EC form the PhotoDetector plane assembly

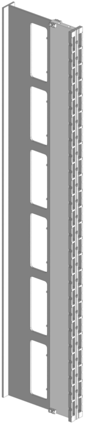


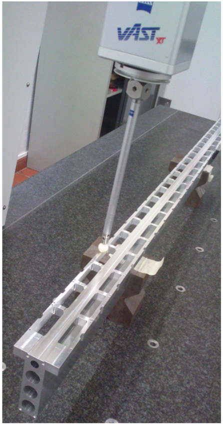


LHCb/RICH upgrade-I 2

- The structural backbone of the columns is an aluminum T-piece (called cold-bar)
- The EC Aluminum case is connected to the cold-bar which has two ducts for coolant circulation, for effective passive cooling.
- Maximum temperature of the MaPMT: $35^\circ\,\mathrm{C}$ (to avoid high dark-count rates and degradation of the MaPMT photocathode).



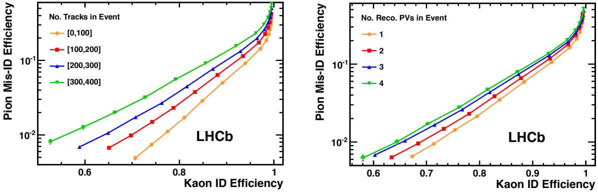




RICH in Upgrade II

- PID capability of charged hadrons fundamental in the LHCb physics program
- PID performance known to be affected by high detector occupancy

First data from Run1



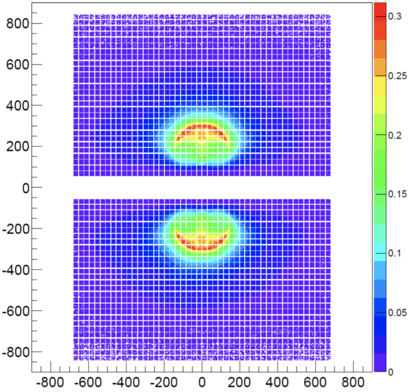
- Goal: Keep/improve the current performance for Upgrade II at the HL-LHC extending also the high-momentum limit

RICH in Upgrade II

- Maximum occupancy (in limited regions of RICH1) in 2022: ~ 0.3; known to be manageable from Run-1 and Run-2
- In Upgrade II:
  - far too high occupancy in the detector (in particular in the central region of RICH1): without any change wrt the Upgrade I detector, occupancies in excess of 100% are expected in RICH1
  - need to improve the currently relatively large overall Cherenkov resolution

$$\sigma_\theta = \sigma_{\text{focusing}} \oplus \sigma_{\text{chromatic}} \oplus \sigma_{\text{pixelsize}}$$

Occupancy
in RICH1 for Upgrade I



Design strategy for Upgrade II

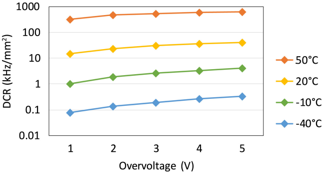
Reduce occupancy	Reduce the angular granularity pixel size and/or focal length. Readout timing information: time-resolved RICH New optical design to spread out high-occupancy region
Improve photon yield	Sensors with enhanced PDE and large active area fraction
Improve pixel size uncertainty	Reduce the pixel size
Improve chromatic uncertainty	Sensors with enhanced red-shifted PDE Choice the gas radiator
Improve focusing uncertainty	Optical design and lightweight optics fabrication technologies
Keep low background/noise	Narrow time bins in readout
Keep low noise	If SiPM: cool it down.

New photo-sensor/photo-detector development

- For the Upgrade II, the MultiAnode-PMT (MaPMT) do not completely fulfill requirements, in particular pixel size ($3\,\mathrm{mm}$) and time resolution ($\sim 200\,\mathrm{ps}$).
- Possible candidate photosensors for replacement are SiPMs.
- SiPM have the potential to meet all the the requirements after a vigorous R&D program targeted to LHCb/RICH:
  - improving intrinsic radiation hardness $\Longrightarrow$ work in strict contact with industrial partners;
  - enable operating at low enough temperature (plus, possibly, annealing) $\Longrightarrow$study a suitable cooling system.
  - After that: shape the geometry of the design to obtain a large and uniform filling factor for the active areas.
- Need to characterize, improve and design for: correlated noise, time-response, low-temperature, radiation tolerance, light collection system, engineering....
- Synergies among several LHCb/RICH groups and with other experiments to fully characterize SiPM.

SiPM well-known limitations

- High Dark Count rate (DCR) and correlated noise (cross-talk, after pulses, ...)
- DCR depends on temperature, it can be mitigated by cooling



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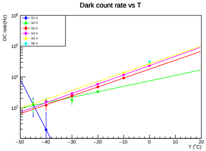
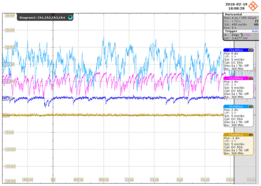
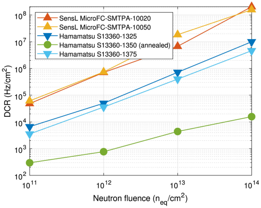


[CERN-THESIS-2021-034.pdf]

- DCR depends heavily on irradiation
- It can be mitigated by cooling and annealing





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SiPM for the LHCb/RICH

Additional mitigation strategies exist, not related to the sensor nor to the cooling system

- The foreseen measurement of arrival times introduces short bins in time which, adding to the space bins given by pixels, helps a lot with DCR suppression, making DCR less critical.
- In addition, the possibility of reducing radiation levels using neutron shielding around (parts of) the RICH is under investigation, in synergy with other LHCb detectors.
- Moreover, DCR adverse effects can be mitigated by using micro-lensing to reduce the physical SiPM area while keeping the effective pixel size in the range of ≈ 1 mm to avoid too many channels, and reducing sensor capacitance.

Housing for SiPM for LHCb/RICH Upgrade II

- A new housing PCB is needed for integration of SiPM in the current electro-mechanical structure
- Main **challenges**
    - **maximize the geometry acceptance** of the full PhotoDetector array (filling factor inside every module and among different modules)
    - **managing the high channel density**, due to the smaller pixel size, for all the front-end/back-end readout electronics.
    - **integrate** into the Elementary-Cell an **active local cooling** with the other ancillary services.
- Some possible **simplifications** in LHCb/RICH:
  photo-detector outside the LHCb acceptance: limited material-budget issues.

LHCb/RICH SiPM Cooling

- The approach used for the housing of the MAPMT proved **very successful**. Therefore, we plan to continue to pursue it, by changing passive into active cooling.
- Local strategy of cooling for Upgrade II
  - It depends on the required SiPM temperature
  - Basic idea is to cool down a region as small as possible around the sensor only, providing thermal insulation as close as possible to the sensor, thus minimizing the mass to cool and avoid problems with low temperatures of nearby objects, such as the radiator gases, using multiple cooling stages with several technologies

Local cooling concept: new housing

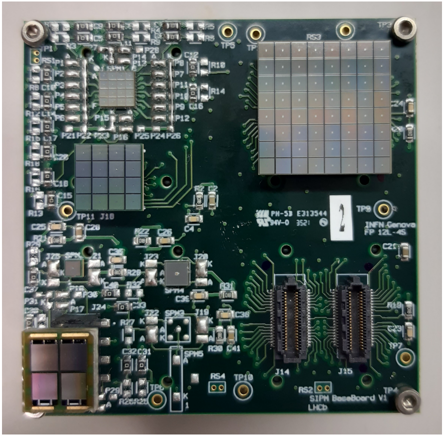
- Cooling of solid state devices is today targeted by many applications, also at the industrial/commercial level.
- Possible technologies include
  - miniaturized active Peltier coolers
  - fluid mini-channel cooling
  - fluid micro-channel cooling technologies
  - heat-pipe
  - miniature cryo-coolers
  - ...
- Options for similar problems have been studied in LHCb.
- We are in the process to try to figure out the most promising approach
- Any of these technologies are to be integrated as much as possible in the housing or nearby. Cold fingers, capable to extract enough power, need to be placed as close as possible to the housing.

Development Plan for Local Cooling

- Expert-advised market survey for available technologies.
- Modify the Base-Board to host SiPM instead of MAPMT (done) and test different SiPM (on-going).
- Base-Board with full geometrical acceptance SiPM coverage (done) and test of SiPM matrices (on-going).
- Thermal cooling measurements (on-going), and comparison with thermal simulations, aimed at a reliable thermal model
- First prototype with integrated cooling design in 2024.

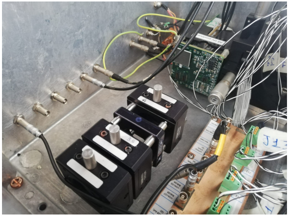
SiPM Evaluation Base-Board

- A first evaluation Base-Board housing SiPM already produced
- Fully compatible with the Upgrade I EC housing
- Housing various SiPM types (including Hamamatsu and FBK SiPM) for test purposes
- Possibility of reading both positive or negative SiPM signals (to be more flexible for the readout electronics)
- Tested successfully both in laboratory and in Autumn 2021/July 2022 testbeam periods

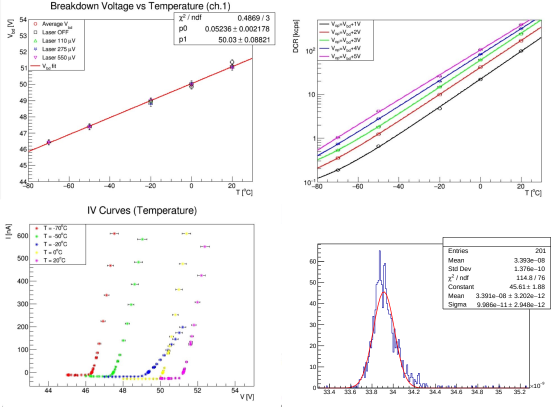


SiPM Base-Board prototypes: test in lab

- Fully automatic setup able to measure IV-curves/gain/DC rate/time resolution/...
- System setup includes a laser with ps pulses, fast pre-amplifiers, a multichannel digitizer, several multimeters, an oscilloscope



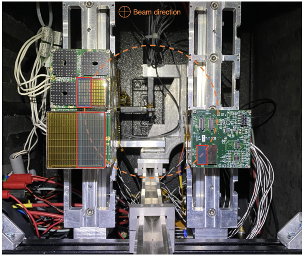
Plots from Simon Ghizzo's thesis

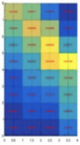


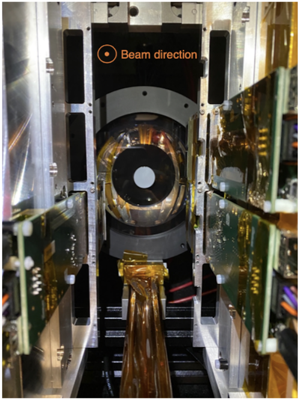
"Characterization of Silicon Photodetectors for future upgrades of Particle Identification Cherenkov detectors in extreme irradiated environments at Belle II/LHCb experiments" External supervisors: Doct. Ezio Torassa, Prof. Hidekazu Kakuno

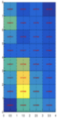
TestBeam with SiPM Base-Board

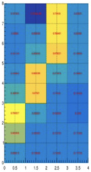
- First test on beam of the opto-electronic chain with fast-timing information using the new SiPM Base-Board





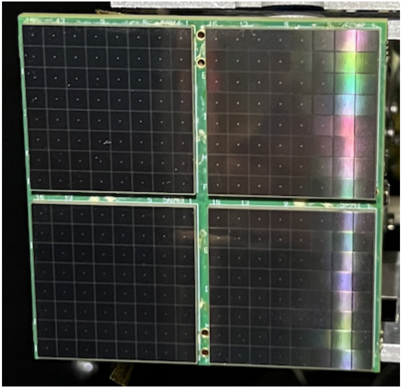






SiPM Base-Board prototype

- A prototype of the Base-Board housing SiPM has been designed, produced and successfully tested
- It houses 4 SiPM matrices with LGA (Hamamatsu S13361-3050NE-08)
- Main technological challenges:
  - achieved a high fill factor
- It has been tested both in laboratory and in this year testbeam period



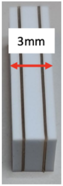
First SiPM BB prototype with active cooling

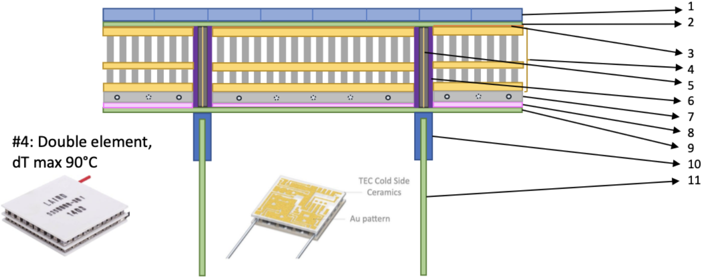
- New version currently under design will include some pioneering prototype for active cooling

First SiPM BB prototype with active cooling (I)

- First design using Peltier coolers

#5



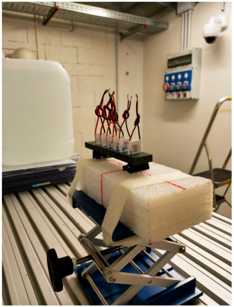

#4: Double element, dT max 90°C

Legend:

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

Radiation hardness tests of Peltier coolers

- Radiation hardness campaign has been performed to verify any possible performance degradation ($10^9 \mathrm{neq/cm^2}$, $10^{10} \mathrm{neq/cm^2}$, $10^{11} \mathrm{neq/cm^2}$)
- Activation of the Peltier cell (not yet possible to test them after irradiation campaign)
- Issues with handling during any required maintenance of the detector



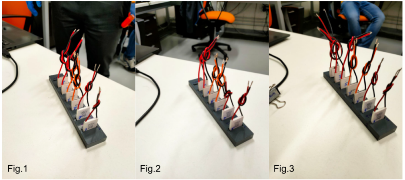


Fig.1 Fig.2 Fig.3

Pictures by Roberto Preghenella, irradiation campaign in collaboration with EIC Bologna group (thanks!)

First SiPM BB prototype with active cooling (II)

- New design includes a ceramic PCB with mini-channel cooling pipes (∼1 mm diameter) directly carved into the ceramic plate

  Idea taken from Dohle, R. et al. Journal of Microelectronics and Electronic Packaging. 15. 86-94.

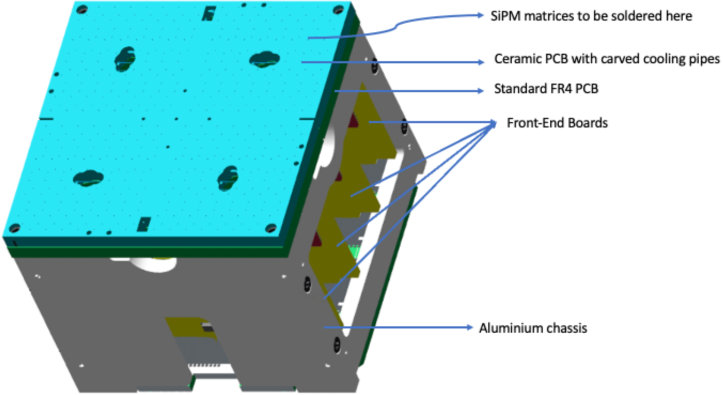
  10.4071/imaps.562590, presented by Alberto Gola at CERN/DRD4 Community Meeting

  https://indico.cern.ch/event/1263731

- SiPM matrix is directly soldered to pads on the metalized layer of the ceramic PCB
- PCB through vias for SiPMs anodes/cathodes signals passing through the ceramic PCB
- Standard PCB to reroute signals to the back connectors pins (where Front-End Boards are plugged)

SiPM Ceramic PCB with integrated cooling

Full EC

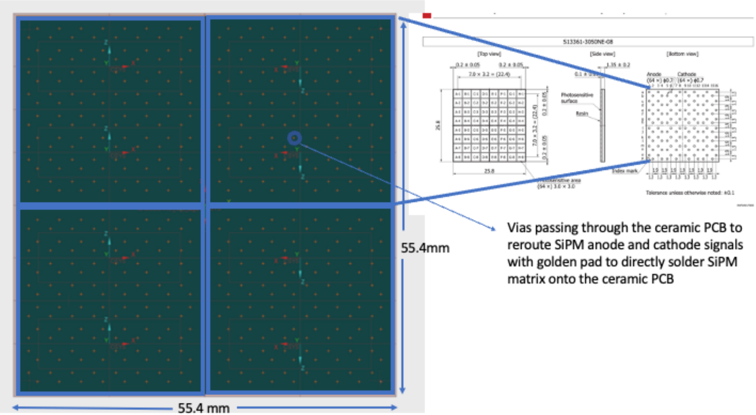


Ceramic PCBs

- Several cooling pipe design are currently under investigation
- Feasibility of few tight requirements to be assessed with the manufacturing company (in particular pass through vias with the required size, required tolerances between vias cooling-pipes)
- Thermal measurements to define power requirements on-going
- Thermal and fluid dynamics simulations to be performed to validate and optimize the cooling pipe design (pipe section size/length/cooling pipe design/number of cooling fluid inlets/outlets) taking into account mechanical and space constraints
- Campaign of tests in the lab of the prototype to be performed (thermal measurements, signal integrity measurements, ...)

SiPM Ceramic PCB with integrated cooling

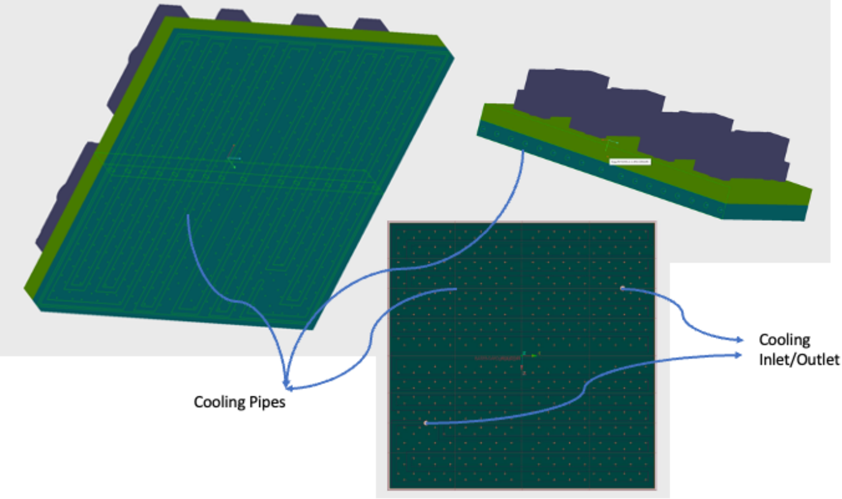
Top/Front layer



Vias passing through the ceramic PCB to reroute SiPM anode and cathode signals with golden pad to directly solder SiPM matrix onto the ceramic PCB

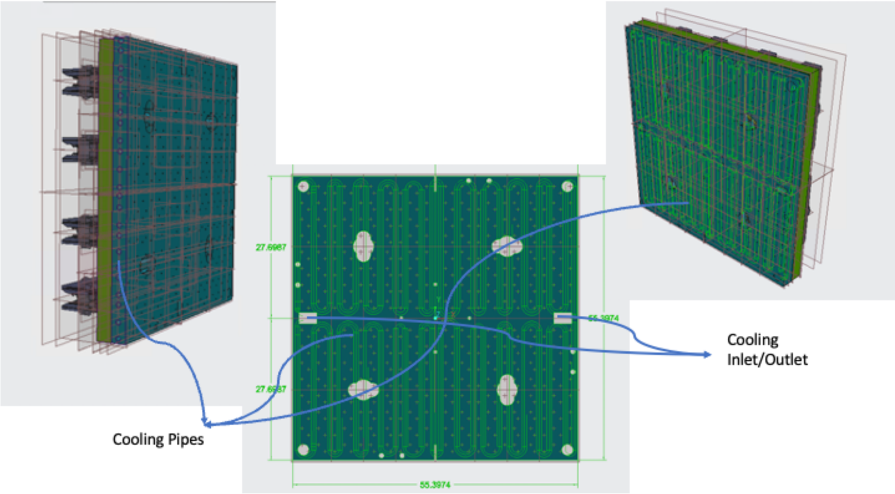
SiPM Ceramic PCB with integrated cooling

Internal layer: possible design of cooling pipes carved in the ceramic



SiPM Ceramic PCB with integrated cooling

Internal layer: another possible design of cooling pipes

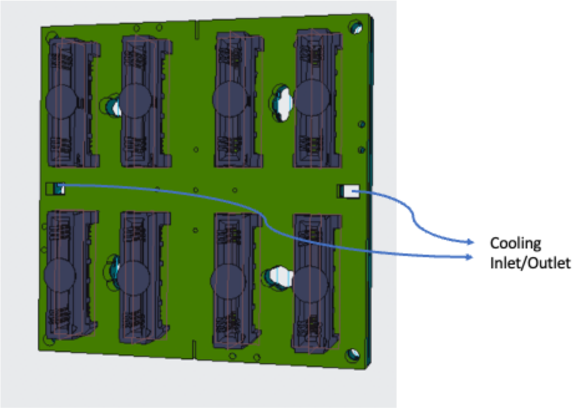


Cooling Pipes

Cooling Inlet/Outlet

SiPM Ceramic PCB with integrated cooling

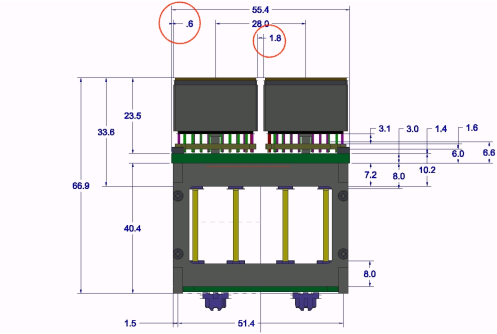
Bottom/Back layer: cooling pipes inlet(s) and outlet(s) in the ceramic



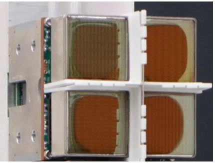
Conclusions

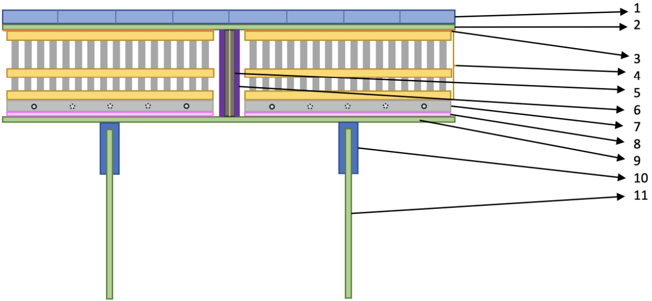
- Start from the robust design for MAPMT and try to adapt it.
- From MAPMT to SiPM: no challenge (with the same pixel size)
- From passive to active cooling: it looks like challenging, whatever strategy, either local or global cooling.
- SiPM Base-Boards (without cooling) already produced and tested both in lab and in testbeams
- Design of a BaseBoard with integrated cooling on-going: to be produced in 2024
- A full campaign of thermal tests foreseen next year

Spare Slides



Magnetic Shielding is not drawn.





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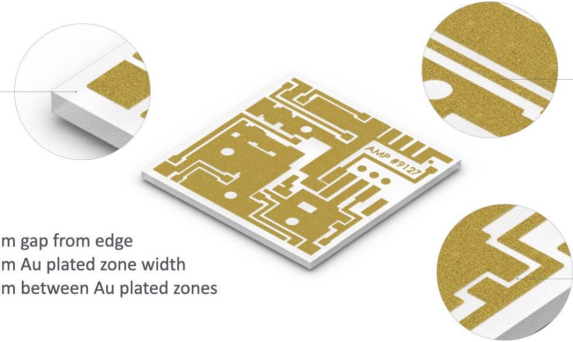
7. Metal heatsink with possible liquid cooling
8. Thermal insulator
9. Baseboard PCB
10. Front-End Board connector
11. Fron-End Board

LHCb/RICH SiPM Cooling Requirements

- Need to cool down both the sensors (SiPM) and the electronics
- Large PhotoDetector Area: 4 planes, $\sim 1\,\mathrm{m}^2/\mathrm{planes}$ each
- Large optical window, $\sim 1\,\mathrm{m}^2$ separating the gas radiator from the PDA Asssembly
- Volume of the PDA: $1.5 \times 0.7 \times 0.5\,\mathrm{m}^3$
- Considering a pixel size of $1\,\mathrm{mm}^2$ (30%) + $9\,\mathrm{mm}^2$ (70%) the estimated number of channels: ~ 400000/plane
- Power estimate for electronics (FastRICH + TDC: $5 \div 10\,\mathrm{mW}$/channel + other components): $\sim 5\,\mathrm{kW}$/plane

THREE BASIC DESIGN RULES FOR AU PATTERNS

There is a simple rule “3x100um”. The shape and complexity of Au pattern can be any then



Min 100um
gap from edge

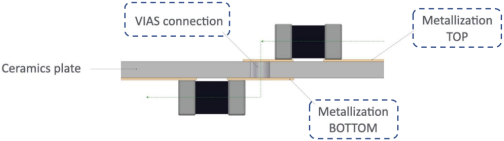
Min 100um
Au zone width

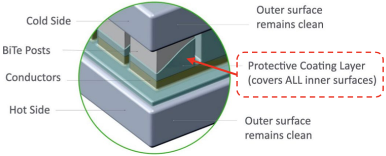
Min 100um
distance between

1. Min 100um gap from edge
2. Min 100um Au plated zone width
3. Min 100um between Au plated zones

Au pattern can be applied to one or both sides of the ceramic substrate.

For application with Dew Point and condensation risks, TEC can be provided with a protective coating





The connection between AU patterns on each side can be created using VIAs

Cooling requirements for Upgrade I - RICH1

Number of circuits (loops):	2
Nominal heat power:	$2 \times 3.45\,\mathrm{kW}$
Max. temperature of the photon detectors:	$< 35\,^\circ\mathrm{C}$
Max. temperature of electronics	$< 50\,^\circ\mathrm{C}$
Coolant:	Fluorinated fluid: 3M Novec$^{\mathrm{TM}}$ 649, 7100 or C_6F_{14}
Heat transfer medium:	Liquid mono-phase
Minimum temperature at the PDA inlet:	$\sim 11\,^\circ\mathrm{C}$
Temperature difference of the coolant (PDA outlet), ΔT:	$5\,^\circ\mathrm{C}$
Maximum pressure at the PDA inlet:	$< 2\,\mathrm{bar}$
Pressure drop in the PDA:	$\sim 0.7\,\mathrm{bar}$
Leak rate, in total:	$< 0.05\,\mathrm{l/day}$
Typical flow of the coolant:	$1750\,\mathrm{l/h}$

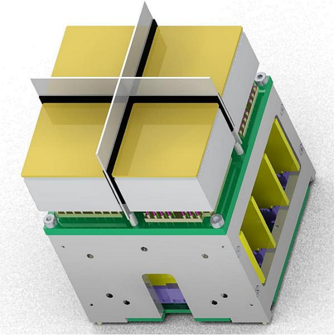
Component	Power
Digital Boards, LV (7 V, 3.4 A):	6 kW
Front-end ASIC Boards (0.128 W/board)	250 W
The high voltage divider boards	650 W
Total power per Column	311 W
Total power	6.9 kW

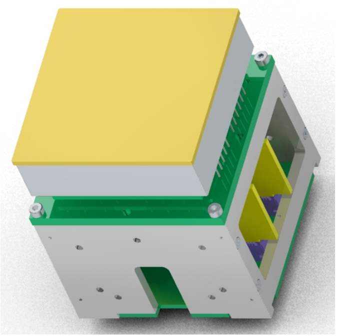
Cooling requirements for Upgrade I - RICH2

Number of circuits (loops):	2
Nominal heat power:	$2 \times 2.1\,\mathrm{kW}$
Max. temperature of the photon detectors:	$< 35\,^\circ\mathrm{C}$
Max. temperature of electronics	$< 50\,^\circ\mathrm{C}$
Coolant (Fluorinated fluid) [9]:	3M Novec$^{\mathrm{TM}}$ 649, 7100 or C_6F_{14}
Heat transfer medium:	Liquid mono-phase
Minimum temperature at the PDA inlet:	$\sim 11\,^\circ\mathrm{C}$
Temperature difference of the coolant (PDA), $\Delta T_{inlet-outlet}$:	$5\,^\circ\mathrm{C}$
Maximum pressure at the PDA inlet:	$< 2\,\mathrm{bar}$
Pressure drop in the PDA:	$\sim 0.7\,\mathrm{bar}$
Leak rate, in total:	$< 0.05\,\mathrm{l/day}$
Typical flow of the coolant:	$1060\,\mathrm{l/h}$

Component	Power
Digital Boards, LV (7 V, 3.4 A):	3.6 kW
Front-end ASIC Boards (0.128 W/board)	150 W
The high voltage divider boards	650 W
Total power per Column	175 W
Total power	4.2 kW

MaPMT for LHCb/RICH Upgrade I

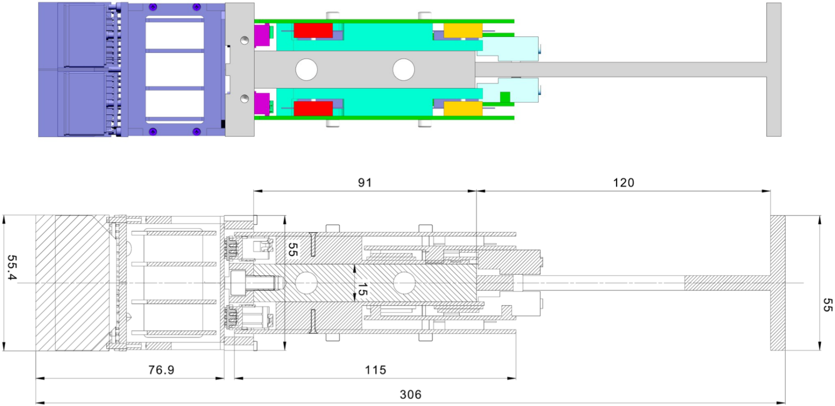




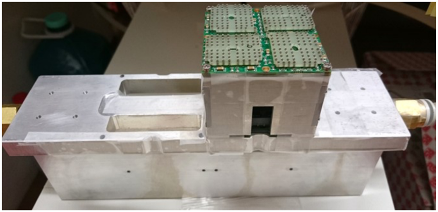
MaPMT for LHCb/RICH Upgrade I

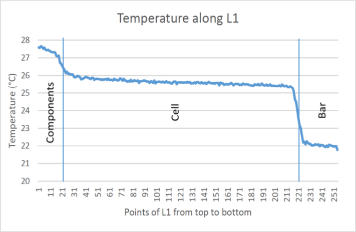
Bare Aluminium (Alu) case

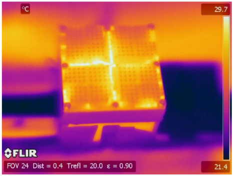
LHCb/RICH upgrade-I cooling system

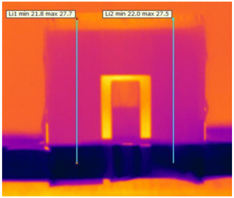


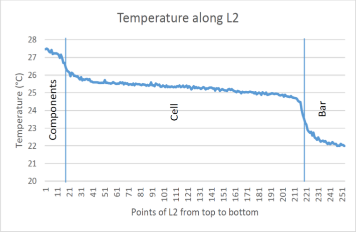
LHCb/RICH upgrade-I cooling system











Detector Design for Upgrade II

- Main requirements
  - Single-photon Cherenkov angle uncertainty $\sigma \lesssim 0.4/0.2\,\mathrm{mrad}$ (RICH1/RICH2)
    a factor 2 better than expected for Run3
  - Number of detected photons per saturated track: $\gtrsim$ 40/30 (RICH1/RICH2)
  - Maximum signal occupancy ≈ 0.2 (space and time bins)
  - Signal/noise ratio: average Dark Count Rate occupancy ≈ 0.001 (space and time bins); plus cross-talk, after-pulse.....
  - Provide the system with timing capabilities (event gating and photon ToD)
  - Active area fraction: $\gtrsim$ 0.8.
  - Integrate the detector with its own system for monitoring and calibration, to improve the systematic uncertainties.
  - Plus, of course, many other requirements: recovery time, robustness to magnetic fields (could remove magnetic shield in RICH1 freeing space), feasibility of large-area implementation, uniformity, stability, rad-hardness, ageing, cooling, bandwidth limit, greenify whatever possible......

Detector Design for Upgrade II 2

- All this require and translates into the following sub-systems requirements.
    - New optical design.
    - New photo-sensors.
    - New readout for a time-resolved RICH.
    - New calibration/monitoring system with sub-ns precision and relative/absolute detector efficiency online measurement/calibration.
    - New radiator gases? TBD.
    - Aerogel? TBD.