An integrated housing with active cooling for Silicon Photomultipliers arrays in next generation of Ring Imaging Cherenkov Detectors

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Outline

- **Motivation** Challenges of next-generation RICH detectors and SiPM/MPPC as baseline technology
- **Housing with active cooling** Ceramic prototypes, and validation through fluid/thermal mock-up tests
- **Outlook** Test beam plans and future developments

The role of RICH detectors in future colliders

- **Particle identification (PID)** is a key requirement for the physics programs at the EIC, HL-LHC, FCC-ee/hh and other future facilities.
- RICH detectors must ensure **excellent hadron separation** over a wide momentum range.
- **Next-generation colliders** impose more stringent requirements:
  - higher luminosities ⇒ increased occupancies and radiation doses,
  - very large detectors ⇒ extensive active areas,
  - tighter physics goals ⇒ improved performance with better Cherenkov resolution, enhanced spatial precision, optimized optical layouts, integration of timing information, and control of systematic effects.
- Technological innovation in **photodetectors** is crucial to meet these challenges (see talk by C. Chatterjee).

Next generation of RICH detectors at colliders: photodetector challenges

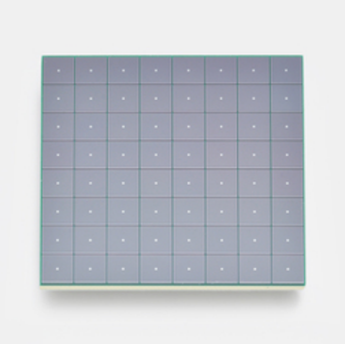
- **High single-photon detection efficiency** in the near-UV/visible domain
- **Fine granularity**: pixel size of $\sim$0.5–2.0 mm
- **Excellent timing performance**: $\mathcal{O}(100\text{ ps})$ or better, to suppress background and noise
- **Radiation hardness**: up to $\sim 3\times10^{13}$ neq/cm^2 (HL-LHC conditions)
- **Low random and correlated noise**: suppression of dark counts, cross-talk (internal/external), and afterpulsing
- **High-density front-end electronics**: low-power ASICs integrated close to the sensors to preserve signal integrity
- **Large active-area coverage**: from $\mathcal{O}(1\text{ m}^2)$ up to $\mathcal{O}(40\text{ m}^2)$, with close packing and high filling factor
- **Compact, lightweight, and robust structures** to host the sensors, readout boards, and ancillary systems

Which photodetector technology can meet these requirements?

RICH Photosensors: Silicon Photo-Multipliers (SiPM)

- Silicon Photo-Multipliers (SiPM) are already widely used in various fields (medical imaging, astroparticle physics, ...)
- Emerging as the **baseline solution** for next-generation RICH detectors

- **Key features:**
  - High photon detection efficiency (PDE) in the UV–visible range
  - Fine pixel granularity (down to sub-mm)
  - Excellent timing performance (tens of ps achievable)
  - Compact, robust, and cost-effective



Hamamatsu SiPM matrix

RICH Photosensors: Silicon Photo-Multipliers

- SiPMs address most requirements for future RICH detectors.
- Dedicated R&D is required to mitigate noise (random and correlated, high at ambient temperature) and to ensure radiation hardness (especially at hadronic colliders, where dark count rate increases with irradiation).
- **Mitigation strategies:**
  - shielding, whenever possible (i.e. outside acceptance)
  - improving SiPM intrinsic radiation hardness (for hadronic collider) $\Longrightarrow$new device designs in close collaboration with industrial partners
  - Using photon timing information to select in-time signal photons $\Longrightarrow$develop high-resolution dedicated electronics (see talk by F. Keizer)
  - Annealing $\Longrightarrow$develop systems and optimize recipes for in-situ annealing (see talk by N.Rubini)
  - operation at sub-zero temperatures $\Longrightarrow$**design and validate a suitable cooling system**

Photodetector Module Development

- We are developing a prototype module designed to house SiPM/MPPCs, featuring integrated active cooling.
- The design builds upon an existing modular unit, the LHCb-RICH Elementary Cell (EC), which currently houses MaPMTs for the LHCb-RICH Upgrade I [JINST **19** (2024) no.05, P05065].
- It shares many similarities with the module developed by INFN-BO for the ePIC dual-radiator RICH (see talk by N. Rubini).

LHCb-RICH photodetector plane

Photodetector Module Development

- This prototype might be of interest not only for the LHCb-RICH Upgrade II (see talk by C. Gotti) but also for other experiments, such as the ALADDIN experiment (see talk by E. Spadaro Norella), and it may serve as a starting point for the photodetector module of the future FCC-ee RICH detector, called ARC (see talk by S. Pezzulo).
- Development within the DRD4.3-Task 3 framework, exploiting synergies, experience, and knowledge from different groups of a full module (including cooling system and front-end electronics by INFN-BO with ALCOR chip by INFN-TO)
- The development of the module has also been included in the Otello project

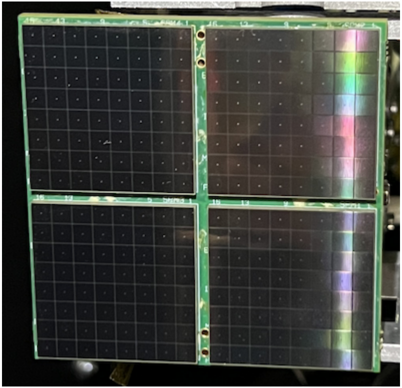
Housing Proposal for SiPM/MPPC

Main challenges:

- **Maximize geometric acceptance** of the entire photodetector array, ensuring an optimal filling factor both within each module and between modules.
- **Manage high channel density** arising from small pixel sizes (down to 0.5×0.5 mm for ARC), while ensuring proper handling by front-end and back-end electronics.
- **Integrate active local cooling** into the housing structure (for DCR suppression), aiming at $\lesssim -40^{\circ}$C.
  (the colder, the more difficult...)
- **Minimize material budget** (if necessary), carefully controlling the use of structural, electronic, and cooling materials to keep the total radiation length per module as low as possible.

SiPM BaseBoard Prototype (v1)

- A first prototype of the SiPM/MPPC BaseBoard (BBv1) has been designed, produced, and tested.
- It houses 4 SiPM/MPPC matrices, each with an 8 x 8 pixel array of 3 mm, using LGA packaging (Hamamatsu S13361-3050NE-08).
- **Main challenge:** achieving a high fill factor both inside the BB and between different BBs
- Tested in the laboratory with an analog electronics chain.



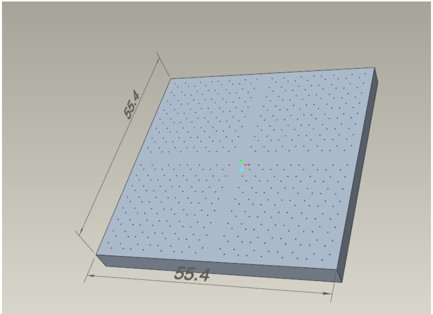
- It has also been used in LHCb/RICH Collaboration testbeams, partially equipped with a FastIC/picoTDC/lpGBT chain F.Keizer, proceedings

SiPM BB Prototype (v2) with active cooling (I)

- A new version of the BaseBoard (BBv2) includes an integrated active cooling.
- The cooling system is designed to cool the sensor region down to $-60°$C/$-80°$C.
- This solution keeps the sensors at tens of degrees below zero, while thermally insulating them from the front-end electronics.
- Several cooling technologies are in principle available, such as fluid micro-channels or miniature cryo-coolers. However, the current R&D focuses on two options: miniaturized Peltier coolers and **coolant-fluid ceramic interposers**.

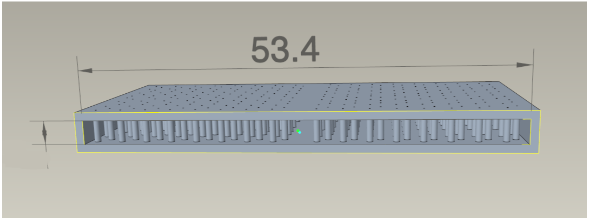
SiPM BB Prototype (v2) with active cooling (II)

- The new BaseBoard design integrates active cooling through a ceramic PCB with internal fluid circulation.
- The current version has a size of $\sim$2 $\times$ 2 inches, 3 mm thick
- It can house 4 Hamamatsu SiPM matrices (8$\times$8 pixels with 3 mm pixel size)



SiPM BB Prototype (v2) with active cooling(III)

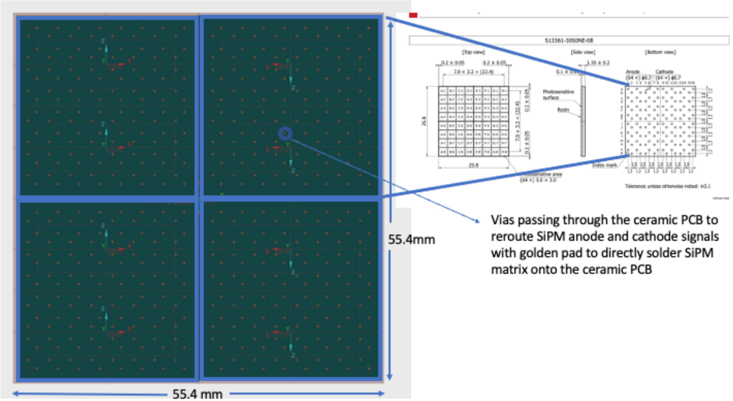
- The current design uses a hollow ceramic PCB that allows coolant to flow directly through it.
- Through-vias are used to route the SiPM/MPPC anode/cathode signals across the ceramic layer inside the supporting pillars.
- The design minimizes the analog signal length to the front-end electronics, preserving signal integrity and enhancing timing performance.



SiPM BB Prototype (v2) with active cooling(IV)

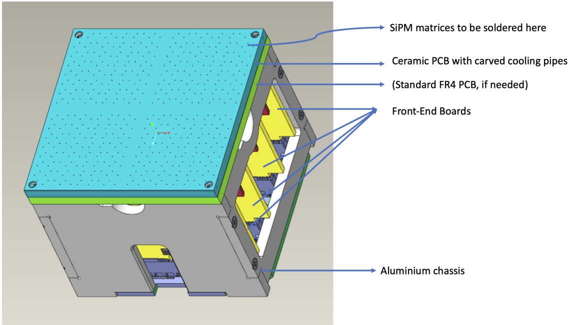
- SiPM/MPPC matrices are directly soldered onto the metallized pads of the ceramic PCB.

Top / Front Layer



SiPM BB Prototype (v2) with active cooling (V)

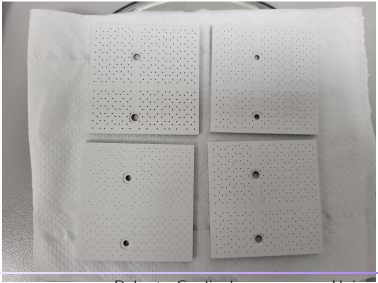
- An additional FR4 PCB can be included to provide some thermal insulation and structural stability. It also reroutes the signals to the back connector pins, where the Front-End Boards are attached.
- Thermal insulation is crucial to avoid the need for electronics qualification at low temperatures and to minimize the required cooling power (effectiveness tbd).

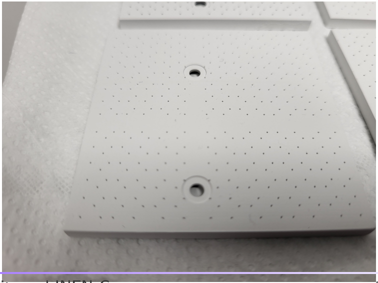


Adapted from LHCb-RICH Upgrade I EC [JINST **19** (2024) no.05, P05065]

First Ceramic Prototypes

- Collaboration with several companies for ceramic PCB production has already been established.
- 3D-printed aluminum nitride (AlN) ceramic prototypes without metallized vias have been ordered and produced; delivery is expected in the next few days (with a slight delay from the original schedule).
- R&D is ongoing to determine the minimum allowable diameter-to-length ratio for through-via metallization.
- Test samples with different via diameters (300, 400, and 500 μm) have been produced for metallization tests.



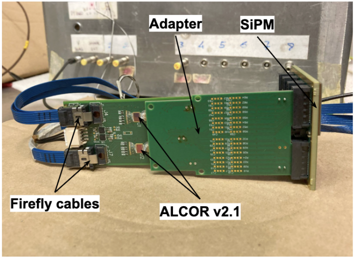


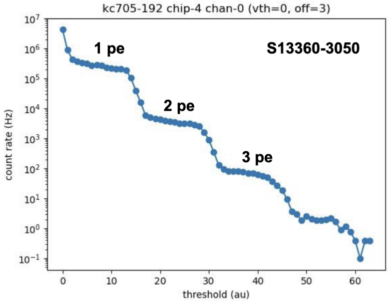
SiPM BB Prototype with Active Cooling (II)

- Once the ceramic samples are received and verified for conformity with the design, they will be sent to a company for metallization.
- After prototypes with metallized vias become available, signal integrity tests will be carried out.
- In parallel, thermal and fluid-dynamics simulations will be performed to validate and optimize the design, considering thickness, number and position of cooling fluid inlets/outlets, taking into account mechanical and space constraints.

SiPM BB Prototype with Active Cooling (III)

- Ceramic prototypes might be tested at the October 2025 DRD4 test beams, using a full prototype module read out by Front-End Boards (INFN-BO) equipped with the ALCOR chip (INFN-TO) (within the DRD4 Collaboration).



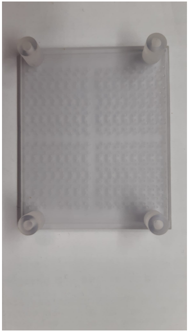
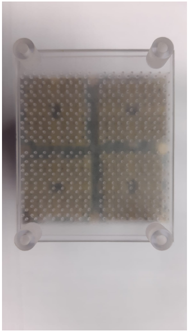
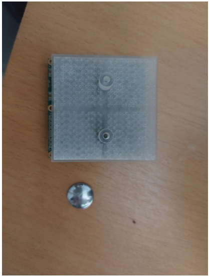
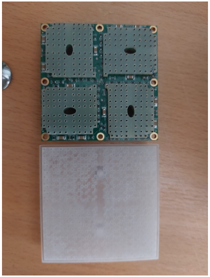


- In the meantime, thermal tests on plastic and metallic mockups have been carried out.
- These tests serve as preparation for the upcoming ceramic prototypes.

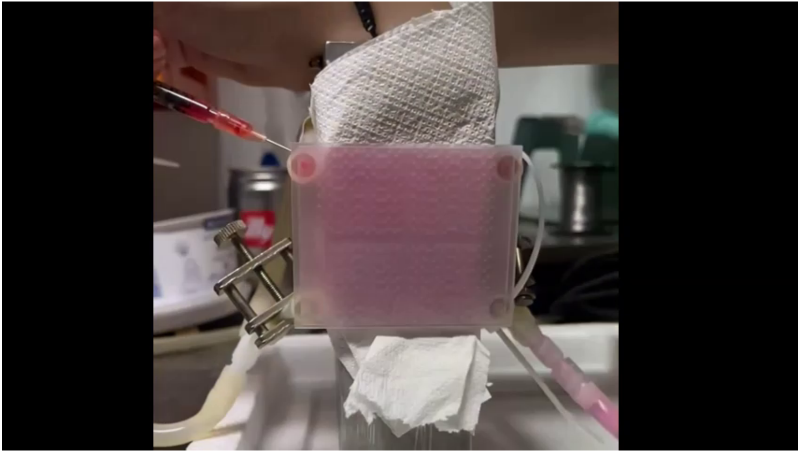
Thermal tests on 3D plastic mockups

3D-Printed Plastic Mockups

- Several 3D-printed plastic mockups have been produced.
- They were used to test and validate the circulation of the cooling fluid.

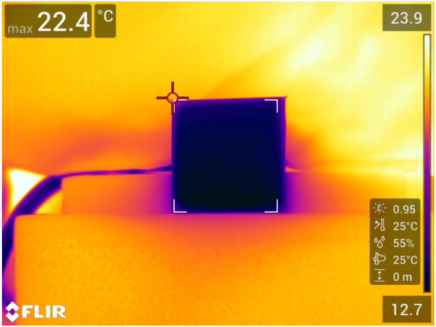





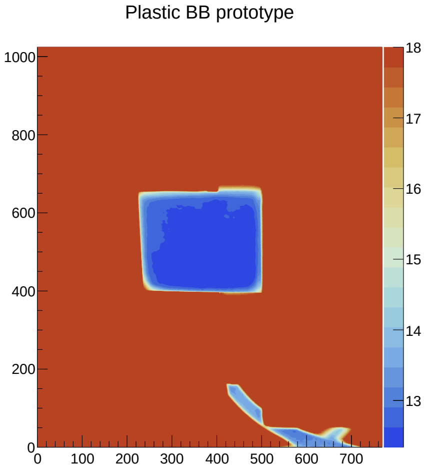
Plastic mockup: cooling fluid circulation



- Colored water circulates correctly throughout the full mockup.

Plastic mockup thermal measurements





- First tests have been performed with water at $\sim 12^{\circ}$C using a thermal camera to check temperature uniformity
- The prototype surface shows overall uniform temperature distribution.
- Corners are the most critical area and require careful optimization

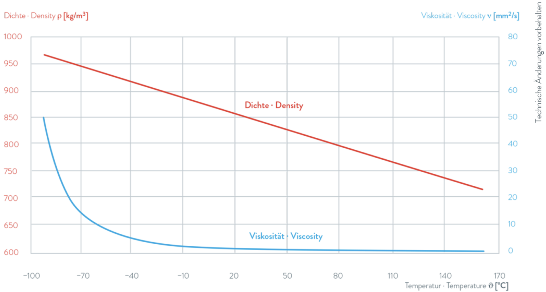
Thermal tests on 3D metallic mockups

Metal Mockups of the BB

- Two metal BB prototypes have been 3D printed with the same size and internal design as the ceramic PCB.
  - One in aluminium
  - One in **stainless steel 316L**
- The bottom surface has been **machined and polished**
- Most of the tests have been performed using the aluminium mockup since it has a thermal conductivity coefficient similar to the aluminum nitride

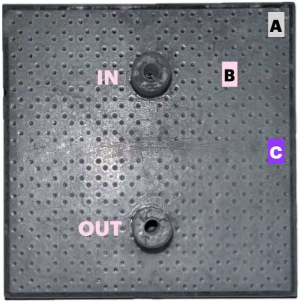
Tests at Low Temperatures

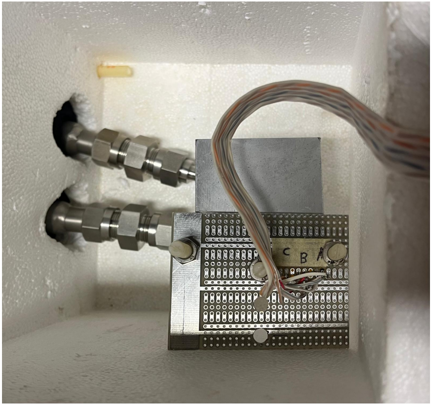
- Low-temperature tests have been performed using the metallic mockups.
- A Lauda chiller with silicone oil (Kryo95©) was used to reach temperatures down to $-80\,^{\circ}\mathrm{C}$.



Aluminium Mockup Tests (I)

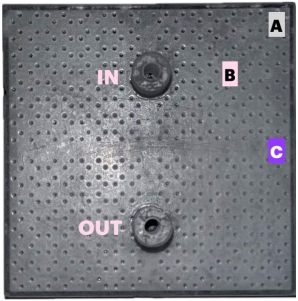
- Three PT1000 sensors measure the temperature at different positions (A, B, C) on the mockup.
- The system is placed inside a polystyrene box, with dry air pumped in to avoid condensation on the surface.

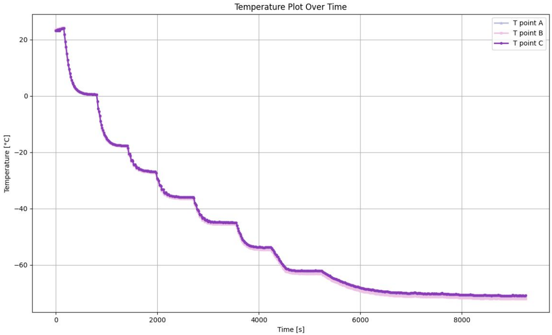




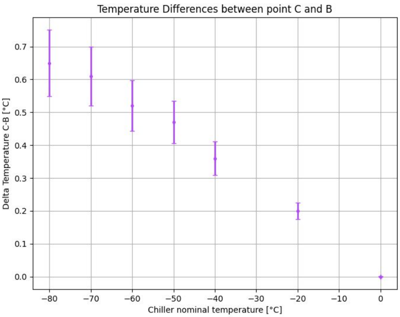
Aluminium Mock-up Tests (II)

- Chiller operated down to a minimum temperature of $-80°C$, in successive steps.





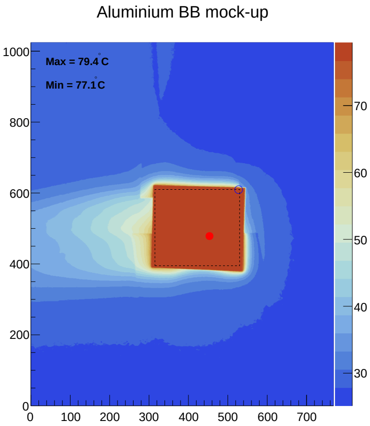
Aluminium mock-up results(I)



- Temperature uniformity along the surface seems ok: maximum difference between (A,B,C) points is $\lesssim 0.7^{\circ}\mathrm{C}$

Thermal Camera Measurements

- First thermal measurements using a thermocamera on the aluminium mock-up have been performed at high temperatures confirming the temperature uniformity
- The maximum temperature difference is $\lesssim 2^{\circ}$C.



Conclusions and Future Outlooks

- A new SiPM BaseBoard prototype with integrated active cooling has been designed
- Plastic and metallic mock-ups have been validated for fluid circulation and thermal behavior showing a good temperature uniformity.
- First ceramic prototypes have been produced; metallization and signal integrity tests are the next steps.
- Test beam validation with a full prototype module (equipped with ALCOR readout) is foreseen in 2025.
- Development of a new version with reduced pixel size (down to 2 mm $\times$ 2 mm) is on-going.

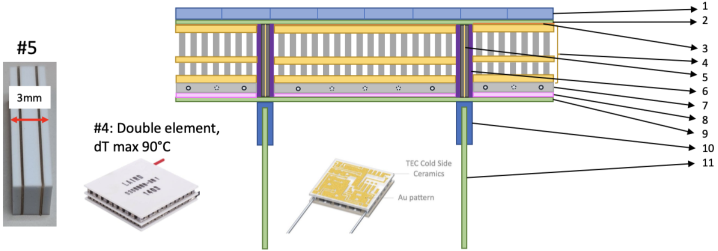
Spare

Thermal conductivity of materials

Material	k **[W/m·K]**	**Notes**
Aluminium (pure)	205–237	high, depends on purity
Carbon steel	45–60	moderate
Stainless steel (304/316)	14–17	very low
Aluminum Nitride (AlN)	150–180 (up to 200)	high, used in ceramic PCBs
Alumina (Al_2O_3, 96–99%)	20–30	depends on purity

First SiPM/MPPC BB prototype with active cooling (I) (2022)

- First prototype design using Peltier coolers

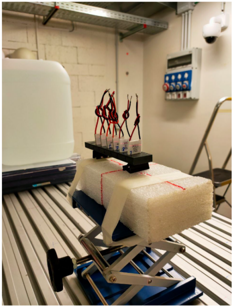


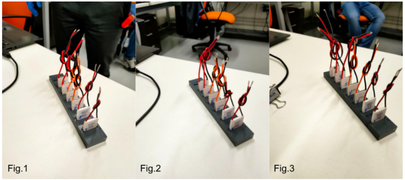
Legend:

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 (10^9neq/cm^2, 10^{10}neq/cm^2, 10^{11}neq/cm^2)
- Activation of the Peltier cell (not possible to test them after irradiation campaign)
- Issues with handling during any required maintenance of the detector
- However, Peltier cooling + in situ annaling is being used in CMS, so we will monitor the evolutions.



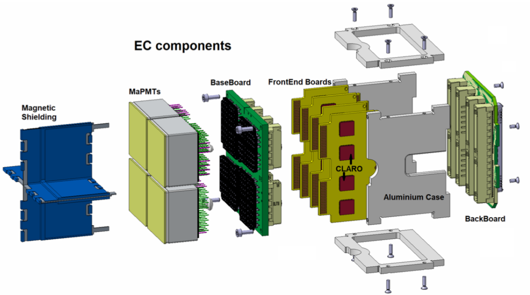


Pictures by Roberto Preghenella, irradiation campaign

in collaboration with EIC Bologna group (thanks!)

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.



MaPMT for LHCb/RICH Upgrade I 2