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The ARC compact RICH detector concept: design, simulations and prototype development

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Abstract: Particle Identification is a key requirement for future Higgs factories such as FCC-ee at Future Circular Collider. The ARC (Array of RICH Cells) detector is a compact and modular Ring Imaging Cherenkov (RICH) concept designed for π/K separation in the 1–40 GeV/c momentum range. It combines gas and aerogel radiators in independent cells equipped with mirrors and SiPM-based photon detectors. Simulation studies, including inverse ray-tracing reconstruction, confirm the expected photon yield and PID performance.

A key challenge for SiPM-based RICH systems is noise reduction. We present the development of a compact and scalable SiPM housing module integrating mechanical support, front-end compatibility, and active cooling. The design builds on the Elementary Cell concept of the LHCb RICH Upgrade and extends it with embedded thermal management at sensor level. Thermal modelling and prototype measurements demonstrate stable and uniform operation at temperatures down to −80°C. This approach provides a viable solution for low-noise SiPM modules for next-generation RICH detectors.

Keywords: Photon detectors for UV, visible and IR photons (solid-state); Cherenkov detectors; Detector cooling and thermo-stabilization; Cherenkov and transition radiation

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1 Introduction

Future electron-positron Higgs factories such as FCC-ee aim to deliver precision measurements of Higgs, electroweak, and flavour observables. Efficient identification of charged hadrons (π, K, p) in the momentum range 1–40 GeV$/c$ is essential to enhance flavour tagging and fully exploit large samples of Z decays. Since silicon tracking provides limited energy-loss discrimination in this regime, dedicated particle-identification detectors are required.

Ring Imaging Cherenkov (RICH) detectors provide a well-established solution, but their implementation in compact detectors is challenging due to volume and material constraints. The ARC (Array of RICH Cells) concept addresses this with a modular, low-mass architecture. A key element is the photon-detection plane, which must combine high efficiency, granularity, timing performance, and scalability. Silicon Photomultipliers (SiPMs) are a promising solution due to their compactness, magnetic-field insensitivity, and high efficiency, but dark count and correlated noise limit their use in single-photon applications. These effects can be mitigated by cooling and timing discrimination.

In this context, we present a compact SiPM module with integrated active cooling, enabling stable low-temperature operation while preserving high optical fill factor and scalability, together with the simulation and hardware development of the ARC detector, linking detector performance to photodetector design.

2 The ARC detector concept and geometry

The ARC detector implements a modular RICH architecture by tessellating the detector volume into optically independent cells arranged in barrel and endcap regions. Each cell acts as an independent optical unit while sharing a common radiator gas volume, enabling local optimization of the optical layout and uniform particle-identification performance.

The detector occupies a cylindrical volume with outer radius of about 2 m, length 4.4 m, and radial thickness of 20 cm, divided into a barrel and two endcaps tessellated with hexagonal cells (figure 1 Left). The mirror and photodetector layout has been optimized for these dimensions, while the modular concept remains scalable. Each cell (figure 1 Right) contains a gaseous radiator and a thin silica aerogel layer in front of the photon-detection plane. Charged particles from the interaction point emit Cherenkov photons in both media at an angle θ_C, determined by refractive index and velocity.

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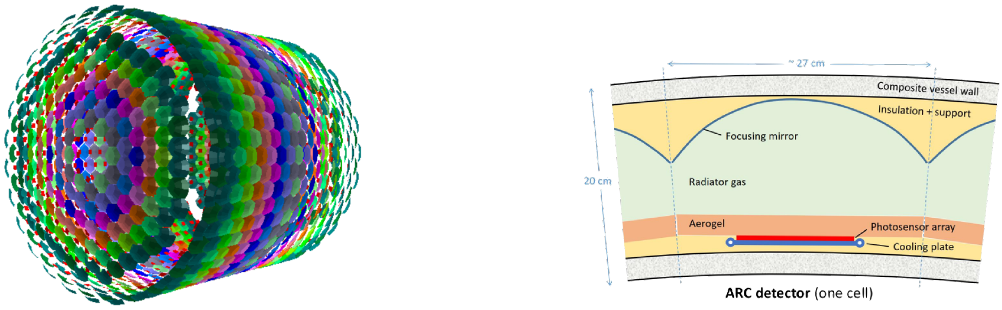

Figure 1. Overview of the ARC detector geometry and structure. Left: ARC detector layout showing mirrors and sensors only; colours identify homologous cells by symmetry. Right: schematic cross-section of a single ARC barrel cell.

A spherical mirror reflects and focuses the photons onto a SiPM-based detection plane, where the Cherenkov ring radius provides particle-mass discrimination given the track momentum.

The baseline gaseous radiator is C_4F_{10} at atmospheric pressure for its optical properties and photon yield, with alternatives such as xenon at up to 3 bar under study due to environmental concerns [1]. The aerogel radiator extends particle identification below $\sim$10 GeV/c and provides thermal insulation, enabling low-temperature operation of the SiPM plane to suppress dark counts while keeping the gas at room temperature. The SiPM arrays cover an active area of $8 \times 8\,\mathrm{cm}^2$ with $0.5 \times 0.5\,\mathrm{mm}^2$ pixels, ensuring high spatial granularity for precise Cherenkov-angle reconstruction.

3 Simulation and reconstruction

The ARC detector geometry is implemented using the DD4hep [2] framework and simulated with DDSim, the DD4hep interface to Geant4. Cherenkov-photon reconstruction is based on a local pattern-recognition algorithm [3], designed to associate detected photons with individual charged-particle tracks. This approach is suitable for FCC e^+e^- collisions, where track multiplicity is low and most ARC cells are empty or crossed by a single particle. The reconstruction is implemented in the Gaudi [4] framework, enabling full integration into the FCC-ee simulation and analysis chain.

For a given particle, the separation power between two mass hypotheses is computed from the reconstructed Cherenkov angle distributions:

$$N_\sigma = \frac{|\theta_2 - \theta_1|}{\sqrt{\left(\frac{\sigma_2}{\sqrt{N_2}}\right)^2 + \left(\frac{\sigma_1}{\sqrt{N_1}}\right)^2}}, \tag{3.1}$$

where $\theta_{1,2}$ are the mean reconstructed Cherenkov angles for two particle species, $\sigma_{1,2}$ are the single-photon standard deviations, and $N_{1,2}$ are the number of detected photons per track. For saturated tracks, the single-photon Cherenkov angle resolution and average detected photon yield obtained from the single-cell simulation are about 1.3 mrad and 14 detected photoelectrons per track for the C_4F_{10} gas radiator, and about 1.6 mrad and 7 detected photoelectrons per track for the aerogel radiator.

The ARC performance has been evaluated using full simulation for the combined configuration, which employs a C_4F_{10} gas radiator together with a 1 cm thick silica aerogel layer ($n = 1.03$ at 400 nm). Separation power N_σ is extracted from the reconstructed Cherenkov angle distributions. Figure 2

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shows the π/K separation as a function of momentum: the aerogel provides $> 3\sigma$ separation up to 13 GeV/c, while the gas radiator extends effective separation up to 40 GeV/c. This demonstrates that combining gas and aerogel radiators ensures continuous charged-hadron identification over the momentum range relevant for FCC-ee physics.

These results are based on single-cell simulations and do not yet include effects from the magnetic field or photon sharing between neighboring cells, which are under study. A solenoidal magnetic field of about 2 T is assumed. The field can affect the reconstruction through the curvature of the charged-particle trajectory in the radiator volume, in particular for low-momentum tracks. First preliminary studies show only a very small impact on the reconstructed Cherenkov-angle resolution.

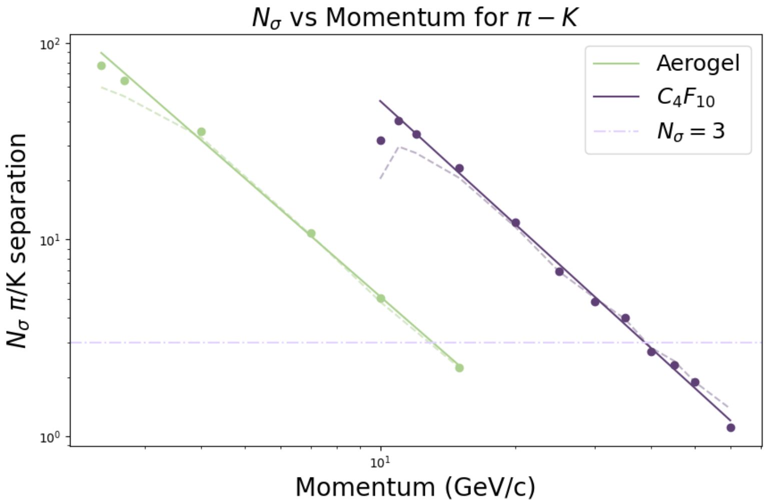

Figure 2. K/π separation power (N_σ) estimated from simulation as a function of momentum. The analytical N_σ is superimposed as a dashed line. The horizontal line indicates the $N_\sigma = 3$ threshold for effective particle separation.

4 Modular SiPM photodetector development and thermal validation

A modular tiling approach is adopted, inspired by RICH photodetector architectures such as the LHCb RICH Upgrade I Elementary Cell [5] and the ePIC dRICH at the Electron-Ion Collider [6], aiming for a compact, tileable unit integrating photosensors, mechanical support, and electrical routing while maintaining a high fill factor.

The baseboard incorporates active cooling within the sensor support, targeting −60 °C to −80 °C while thermally decoupling photosensors from front-end electronics to reduce cooling demands and relax ASIC constraints. Embedded coolant circulation within a hollow ceramic PCB (figure 3 Left) allows simplicity, scalability, and large-area tiling. The 2×2 in^2, 3 mm-thick substrate hosts four 8×8 SiPM matrices with 3×3 in^2 pixels (figure 3 Right), while metallized through-vias integrated in supporting pillars minimize analog path lengths, preserving signal integrity and timing.

Thermal tests on 3D-printed plastic and metallic mock-ups were performed to commission the cooling layout prior to ceramic production, focusing on coolant circulation and thermal performance. Tests on the plastic mock-up with dyed water confirmed continuous flow, identifying corner regions as critical for further optimization. An aluminium mock-up, used as a thermal surrogate for aluminium

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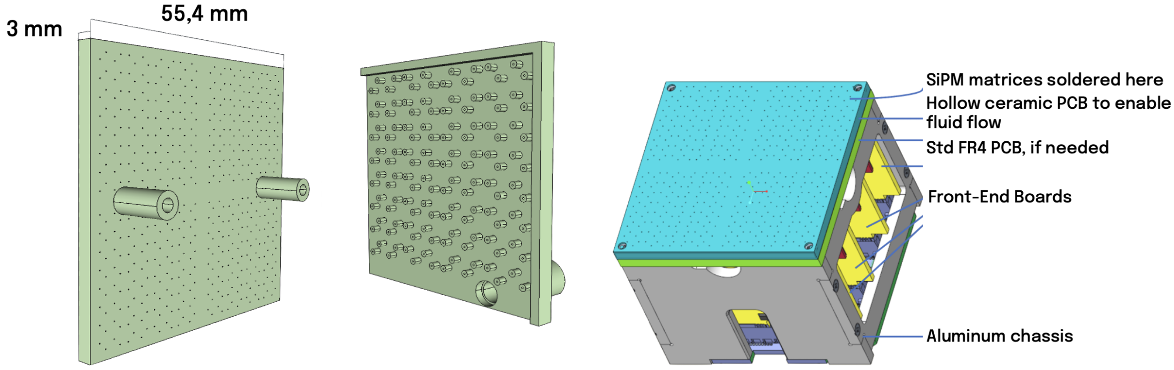

Figure 3. Prototype of the SiPM-based Elementary Cell. Left: baseboard concept based on a hollow ceramic PCB with embedded cooling channels. Right: layout of the modular photodetector unit integrating SiPM matrices, mechanical housing, and readout interface.

nitride (AlN), enabled a more realistic evaluation of thermal response. Measurements were carried out under both low- and high-temperature conditions to assess cooling efficiency, temperature gradients, and system stability.

Low-temperature tests employed a recirculating chiller with silicone oil, reaching coolant temperatures down to $-80\,^{\circ}$C. The setup was enclosed in polystyrene and flushed with dry air to prevent condensation (figure 4 Left). Three PT1000 sensors monitored surface temperature at different locations, showing good uniformity with a maximum difference $\lesssim 0.7\,^{\circ}$C in the coldest runs (figure 4 Right). Complementary high-temperature tests used heated water circulated by a thermostatic bath, with a thermal camera mapping the surface temperature. Variations across the baseboard remained below $\sim 2\,^{\circ}$C. These results validate the internal cooling-channel concept and support the transition to metallized ceramic prototypes with fully integrated readout electronics.

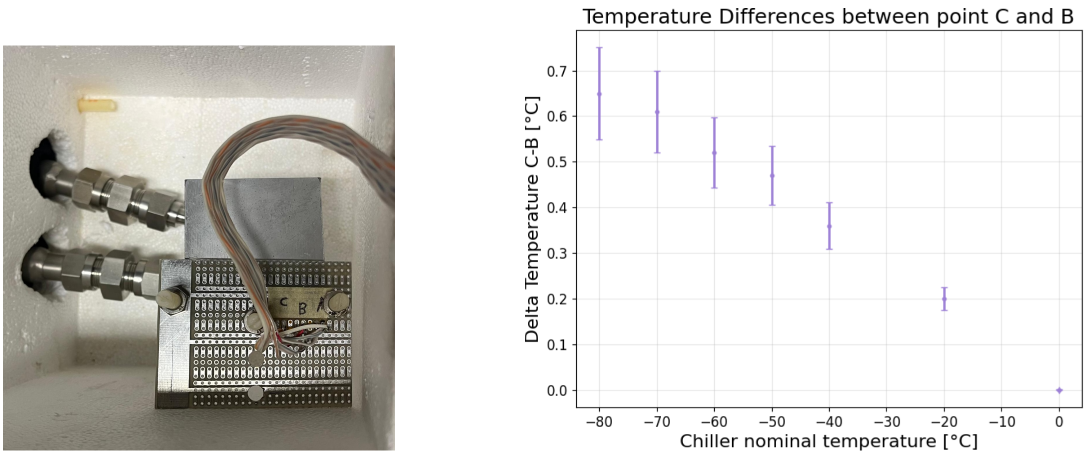

Figure 4. Low-temperature performance of the aluminium mock-up. Left: test configuration inside a polystyrene enclosure with dry air flushing to prevent condensation; PT1000 sensors (A, B, C) monitor surface temperature. Right: maximum temperature difference between sensors A, B, and C as a function of chiller fluid temperature down to $-80\,^{\circ}$C.

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5 Conclusions and future outlooks

A comprehensive R&D program toward a compact, low-noise SiPM-based photodetector module for next-generation RICH detectors has been presented in the context of the ARC concept.

On the hardware side, a new BaseBoard architecture based on a hollow ceramic PCB with embedded coolant circulation and via-based signal routing has been developed. Plastic and aluminium mock-ups validated the internal cooling-channel layout and thermal performance, demonstrating stable operation and temperature uniformity down to −80 °C. First AlN ceramic prototypes have been produced to validate the mechanical design, while dedicated R&D on through-via metallization and coolant integration is ongoing. Full metallization and signal-integrity validation constitute the next milestones. A beam-test of a fully integrated module, using ePIC dRICH [7] front-end boards with the ALCOR ASIC [8], is foreseen in 2026 within the DRD4 [9] framework. Further developments target reduced pixel sizes down to $2 \times 2\,\text{mm}^2$, enabling increased granularity for future applications.

In parallel, the ARC simulation framework has matured significantly. The reconstruction algorithm is being extended from single-cell studies to the full detector geometry, with performance for realistic physics events under evaluation. Ongoing developments include likelihood-based reconstruction and validation under more realistic conditions, including higher track multiplicity and magnetic-field effects. The combined progress in simulation and hardware R&D provides a coherent path toward the realization and experimental validation of a compact, scalable RICH system based on actively cooled SiPM technology.

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