

# The ePIC dual-radiator RICH detector

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## Abstract

The dual radiator Ring Imaging Cherenkov (dRICH) detector is required to provide continuous hadron identification from 3 GeV/c up to 50 GeV/c, and to supplement electron and positron identification from a few hundred MeV/c up to about 15 GeV/c, in the forward (ion-side) end-cap of the ePIC experiment. Such an extended momentum range imposes the use of two radiators, gas and aerogel. The common imaging system, that ensures compactness and cost-effectiveness, is based on SiPM sensors to work in high non-uniform magnetic field. During the R&D phase, the dual radiator principle and the single component performance have been validated. The status of the project is here presented. The design and technological choices are discussed together with the results obtained by laboratory characterization of the component demonstrators and by beam tests of the evolving prototypes.

**Keywords:** Single-photon detection, Ring-imaging Cherenkov detectors, Front-end electronics, Multi-anode PMT, Digital readout

## 1. dRICH at ePIC

The Electron-Ion Collider (EIC) at the Brookhaven National Laboratory (BNL), in Upton, NY, will be the first facility able to collide polarized electron and ion beams with a variable center-of-mass energy running from 30 GeV to 140 GeV [1] and at a luminosity in excess of  $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ . Spin control and energy range at EIC are ideal for the study of the strong-force dynamics that, despite leading to the ordinary nuclear structures (nucleons and nuclei), is still largely unexplored. The ePIC experiment has been designed in an almost hermetic layout to provide unprecedented features: high resolution at small transverse momenta to access information at a scale comparable to confinement, and excellent particle identification to access flavor sensitivity [2].

In the forward (ion side) endcap of ePIC, particle identification is obtained by a dual-radiator imaging Cherenkov detector (dRICH) plus a time-of-flight system covering low momenta up to about 2.5 GeV/c. In order to achieve an extended momentum reach up to 50 GeV/c, the dRICH simultaneously exploits two radiators, aerogel and gas, see Figure 1. Workable refractive indexes dictates a minimum thickness of 4 cm for the aerogel and O(1) m for the gas in order to ensure enough photon yield. Mirror focalisation is necessary to minimise the consequent uncertainty on the Cherenkov photon emission point. A common imaging system has been designed to ensure a compact and cost-effective layout. The dRICH has to provide open acceptance in the ePIC forward pseudo-rapidity range  $1.5 \lesssim \eta \lesssim 3.5$ , running from the beam pipe up to the detector barrel limits. The mirror array provides proper light focalization into six active areas which are located behind the shadow of the barrel detector and its support ring, close to the ePIC solenoid coils. In this region a nonuniform magnetic field up to 0.6T imposes the unprecedented use of silicon photomultiplier (SiPM) sensors.

The dRICH introduces several innovative technical solu-

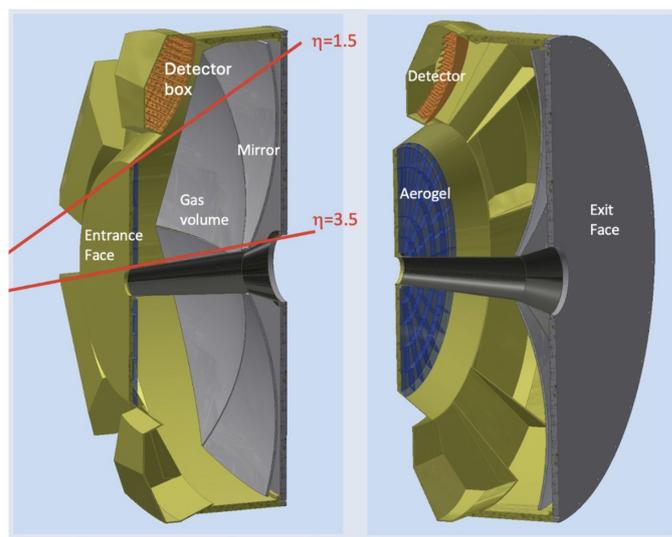


Figure 1: dRICH detector model with highlighted the major components.

tions to meet the stringent ePIC requirements. Among the most interesting here described are: world-record size of aerogel tiles at  $n=1.026$ ,  $\text{C}_2\text{F}_6$  radiator gas, SiPM sensor with in-situ annealing, light CFRP mirrors with optimized core, curved photon detection surface matching the mirror focal area, dedicated ALCOR precision-time digitization, streaming readout with ML assisted on-line data filtering.

## 2. dRICH Components

**Aerogel radiator.** An optimal aerogel refractive index  $n=1.020$  was suggested by the initial dRICH performance simulations. During R&D phase, several samples from Aerogel Factory (JP) at various refractive indexes ranging from  $n=1.015$  up to  $n=1.03$

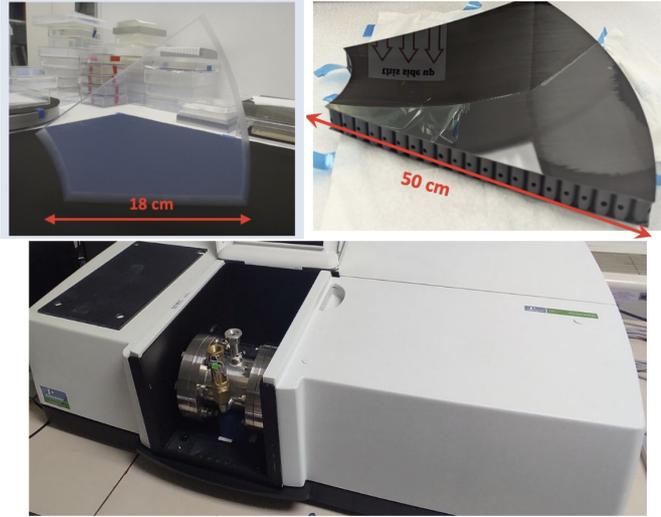


Figure 2: Example of aerogel tile produced with the dRICH baseline refractive index  $n=1.026$  and the reference dimensions of BELLE-II.

and with 2 cm thickness were characterized in laboratory. The samples were further evaluated with prototypes at the CERN test-beam facility, also in collaboration with ALICE3 [3]. The measurements indicate that the transparency values are typically above 70% at the wavelength of 400 nm, and the optical quality increases with wavelength with a maximum at  $n=1.03$ , a trend in line with previous developments. As a consequence of the optimization study matching data and simulations, the baseline refractive index  $n=1.026$  has been identified. With respect to the initial value, this choice provides a better overlap with FTOF due to the lower kaon momentum threshold ( $\approx 2.1$  GeV/c). At the same time, it preserves a momentum end-point well above the gas radiator threshold for kaons ( $\approx 12$  GeV/c) thanks to the higher photon yield that compensates the lower Cherenkov angle separation. The chromatic dispersion has been measured during the R&D phase to be  $dn/d\lambda = 6 \cdot 10^{-6} \text{ nm}^{-1}$  at 400 nm wavelength. An engineering study is now being pursued to define the maximum dimensions and best shaping of the aerogel tiles, in order to cover the dRICH entrance window, a disk of 90 cm radius around the central beam-pipe envelope, with minimized dead area. The reference maximum size of 18 cm, obtained at BELLE-II, has been successfully produced and water-jet cut in both squared and shaped versions, see top-left panel in Figure 2. A feasibility study is ongoing to increase these limits towards a side of 20 cm (or greater) to maximize the photon yield.

**Gas Radiator.** The selected reference gas radiator is hexafluoroethane ( $\text{C}_2\text{F}_6$ ), which matches the requirements being characterized by refractive index  $n = 1.00086$  at STP and excellent chromatic dispersion  $dn/d\lambda = 0.2 \cdot 10^{-6} \text{ nm}^{-1}$  at light wavelength  $\lambda = 350 \text{ nm}$ . The performance of  $\text{C}_2\text{F}_6$  has been validated with the dRICH prototype at the CERN test-beam facility [4]. With an optic arm similar to ePIC, a single photon-electron (SPE) resolution close to 1 mrad has been obtained, in line with expectations. The dRICH will be operated at atmospheric pres-

sure with standard techniques to limit the pressure gradients. Special attention is required for the gas system that should ensure purging and separation of the radiator gas with minimal losses, being  $\text{C}_2\text{F}_6$  a greenhouse gas with high global-warming power. The physical properties of  $\text{C}_2\text{F}_6$  are peculiar, with a boiling point at  $-78.1 \text{ C}$  that permits a single gaseous phase in all operations, but challenges a gas separation by liquefaction. An interesting option under study is the use  $\text{CO}_2$  as a stand-by gas during maintenance operations because can be liquefied prior of  $\text{C}_2\text{F}_6$  at manageable pressures ( $\approx 10 \text{ bar}$ ). The most promising alternative is the usage of separating membranes exploiting the low permeability to the large fluoro-carbon molecule, seconding a seminal separation test of  $\text{CF}_4$  from  $\text{CO}_2$  by LHCb using C0-C10 membranes from UBE Industries. Separation tests of  $\text{C}_2\text{F}_6$  are now ongoing at CERN with the help of experts. At the COMPASS monochromator setup, the transparency of  $\text{C}_2\text{F}_6$  has been measured to be greater than 98% in the near-UV wavelengths range from 170 nm to 220 nm, which is most sensitive to contaminants, after several ( $\approx 4$ ) years of storage in bottles. A system has been developed to measure the transparency in the visible light wavelength range from 200 nm to 900 nm, which best matches the SiPM sensor spectral response, based on a commercial photo-spectrometer and a compact high-pressure (up to 10 bar) chamber with transparent quartz windows, see bottom panel Figure 2. This will become part of the continuous monitoring tools installed in the high-pressure section of the dRICH gas system at ePIC. Measurements are ongoing to quantify the scintillation yield [5]. As a risk mitigation for greenhouse gases, alternate gas mixtures are under study at various pressures thanks to a pressurized dRICH prototype.

**Mirror.** The dRICH mirror array should cover a spherical surface with a radius of 2200 mm and an area of about  $10 \text{ m}^2$ . A mid-size demonstrator (of 60 cm diagonal) has been realized by Composite Mirror Applications (USA) with dRICH specifications, see top-right panel of Figure 2. The CFRP core structure has been optimized for preserving the surface shape accuracy and a light body: it adopts a light C-shaped cell structure (used by LHC-b) in the center, and a stronger cylindrical cell structure (used by CLAS12) on the edges. Before coating, the point-like source image test measures a D0 value, that represents a global surface quality estimator, of 1.8 mm, better than the specification of 2.5 mm. The same test indicates a radius of  $2254 \pm 5 \text{ mm}$ , slight above the request to be within 1% of the nominal value.

**SiPM Sensor.** The dRICH photon detector surface is shaped over a sphere of radius  $\approx 110 \text{ cm}$  to best approach the 3D focal area of the mirror array, see Figure 1. The SiPM sensor technology is selected for the photon detector. It ensures superior single-photon counting capability inside the ePIC magnetic field and compact dimensions suitable for tessellating a shaped active surface. The single SiPM sensor has a  $3 \times 3 \text{ mm}^2$  area to provide the necessary spatial resolution with an intrinsic time resolution better than 150 ps. Several sensors from different manufacturers have been tested in laboratory prior and after irradiation up to  $10^{10}$  1-MeV neutron equivalent  $n_{\text{eq}}$  flu-

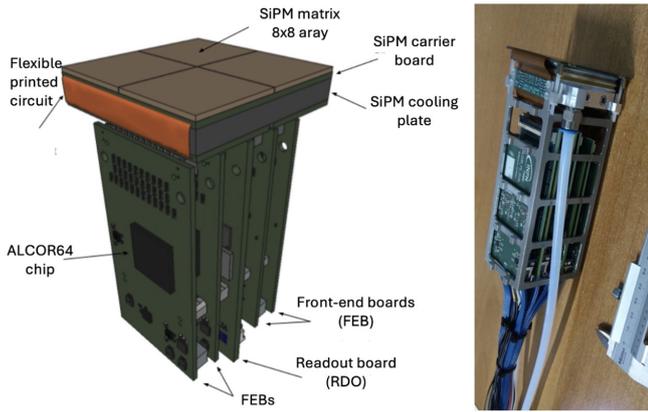


Figure 3: The PDU concept (left) and preliminary realization (right).

ence [6]. The measurements have sought for the best trade-off between high photon-detection efficiency (PDE), low dark-count rate and fast response. The current baseline is the Hamamatsu S13361-3075 sensor but further investigation is ongoing on potential faster SiPM with UV-enhanced sensitivity. To control the significant intrinsic dark-count (DCR) rate, the SiPMs will be operated at temperature  $\lesssim -30^\circ\text{C}$ . At the location of the dRICH photodetector a maximum (average) fluence of  $\Phi_{\text{eq}} = 6.4 (3.7) 10^7 \text{ cm}^{-2}/\text{fb}^{-1} n_{\text{eq}}$  is expected from e+p interactions at the highest center-of-mass energy of the EIC, accounting also for the beam induced-background. At these moderate radiation levels, no significant change in the SiPM working parameters is expected but a steady increase of the DCR. To reduce the effect of radiation damage, the SiPMs will be annealed at high-temperature. During the R&D phase, annealing in oven for several hours up to 150 C has been proven to cure about 97% of the damage. It was also demonstrated that annealing of SiPMs can be achieved exploiting the Joule effect with a comparable efficiency. In this case, the SiPM is forward biased, its micro-cells behave as directly polarized diodes, and the current flowing through their quenching resistors eventually heats up the entire device. A scheme has been developed in which frequent opportunistic annealing cycles can be performed on sub-fractions of the detector area, while full annealing cycles can be organized during the shutdown periods. Despite the temperature treatments, it is expected that a residual irreducible radiation damage (residual DCR) will build up during the dRICH lifetime. At least  $\sim 200 \text{ fb}^{-1}$  will be integrated before DCR increases to 300 kHz/ch, which is a conservative DCR reference value that has been shown to have marginal effects on the dRICH performance.

**ALCOR Readout.** The selected front-end ASIC is ALCOR [7], a customized 64-channel chip with coupling and rate capability optimized for SiPMs, and a ToT architecture with better than 50 ps (least significant bit) resolution. To minimize the volume within the dRICH envelope and to maximize the packing factor, the active area is organized in compact photodetector units (PDU), with approximate dimensions of  $52 \times 52 \times 140 \text{ mm}^3$ ,

integrating the readout with sub-zero cooling of the SiPMs as well as in-situ high-temperature annealing capability, see left panel of Figure 3. In particular, the PDU groups 256 SiPM channels with the ALCOR TDC readout provided by four front-end boards (FEB), one readout board (RDO) to interface with the ePIC data acquisition (DAQ) and detector control systems. A cooling block is placed in thermal contact with the back-side of the printed-circuit board hosting the SiPMs (carrier board) that is connected to the readout by flex kapton circuits. The fluid circulated through a closed loop by an external thermostat can be regulated to maintain the SiPMs at low temperature or pre-warm the sensors to sustain forward-bias annealing with reduced currents. The RDO concentrate all the functions (configuration, data-transfer, scrubbing) in the dimensions of a credit card. The preliminary 32-channel version of ALCOR has been used since years to support the SiPM characterization in conjunction with the ePIC driven readout. A prototype PDU mounting this version for ALCOR has been successfully realized and operated with dRICH prototypes at the CERN test-beam facility [8], see right panel of Figure 3. A new version of the ALCOR ASIC has been designed to extend the number of channels to 64 and integrate the chip inside a BGA package with a tape-out in the first months of 2025. The new chip and its upgraded FEB are now entering the evaluation phase.

**Streaming Readout.** The ePIC data-acquisition system utilizes the Felix-155 card as data-aggregator and works in streaming mode. The dRICH is one of the major contributor to the ePIC data throughput, because the significant DCR of SiPMs generates a sizeable stream of data that increases with the integrated luminosity. As explained above, the sensors are temperature treated in order never to exceed a maximum 300 kHz dark rate per channel. The corresponding maximum throughput rate of the entire dRICH is 1.3 Tbps assuming a modest  $\mathcal{O}(5)$  data reduction of the uninteresting DCR stream. This could be achieved via a shutter signal implemented in the front-end ASIC, to select a readout window around the EIC beam bunch interactions occurring every 10 ns, and/or via an external trigger derived from a scintillating signal or a calorimetry energy deposit. In conjunction, an online data reduction in dRICH DAMs, using machine-learning techniques to classify pure background events with no signal information, is under study with promising results [9].

**Mechanics.** A basic prototype has evolved in time to serve the dRICH R&D development for few years, see left panel of Figure 4. The gas vessel is a cylinder made of vacuum standards, to allow an efficient and safe gas exchange. The entrance flange can mount an external dark box separated from the inner gas volume by a UV-transparent lucite foil (or quartz window). An aerogel tile with possible additional UV filters, plus an array of alternative sensors and readout electronics, can be inserted into the dark box. Two mirrors inside the vessel have optimized focal lengths to image the Cherenkov light from the two radiators onto the limited active surface. The major achievements obtained during several test-beams have been the validation of the dual-radiator concept, the validation of the  $\text{C}_2\text{F}_6$  gas radia-

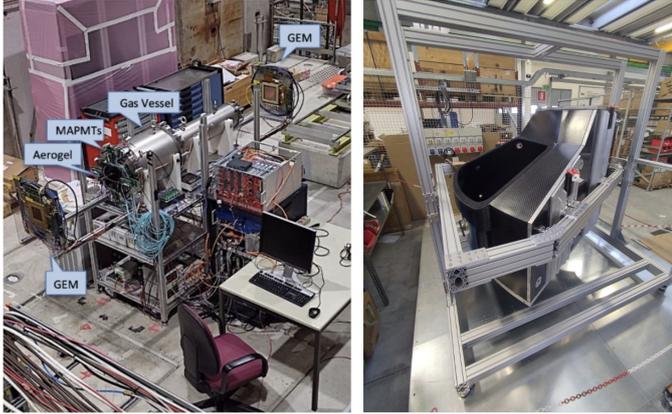


Figure 4: The basic (left) and real-scale (right) dRICH prototypes.

230 tor, the optimization of the aerogel refractive index, the perfor-  
 231 mance study of the SiPM-ALCOR readout chain, and the de-  
 232 velopment of an EIC-driven readout plane. The plane is being  
 233 progressively evolved to compare SiPM of different layout (e.g.  
 234 micro-cell size), upgraded versions of the readout electronics  
 235 and more and more realistic cooling and annealing systems. A  
 236 real-scale engineering article has been realized by Advanced  
 237 Composite Solutions (IT) with composite materials and a re-  
 238 alistic geometry (mimicking a dRICH sector), see right panel  
 239 of Figure 4. This is instrumental to validate the mechanical el-  
 240 ements and study the assembling details (e.g. of transparent  
 241 septa), the mechanical stability, the gas tightness, and the ther-  
 242 mal aspects. One of the major goals of the real-scale article  
 243 is also to reproduce the final ePIC working conditions, mount  
 244 an extended readout plane with the final PDU demonstrators,  
 245 operate realistic optical components as results of the ongoing  
 246 developments, and optimize the performance in a realistic off-  
 247 axis optics configuration. To this end, a commissioning with  
 248 cosmics is planned in winter 2026 and a performance test-beam  
 249 in spring 2026.

### 3. dRICH Performance

250 The dRICH model is part of the ePIC simulation frame-  
 251 work and allows complete performance studies taking into ac-  
 252 count quality of the track reconstruction, bent trajectories (by  
 253 magnetic field) and multiple scattering. The ePIC magnet coils  
 254 and the dRICH position has been optimized in order to mini-  
 255 mize the bending inside the radiator gas volume. The dRICH  
 256 has been designed in order to keep most of the contributions  
 257 to the SPE angle resolution close or below 0.5 mrad, a value  
 258 dictated by the tiny Cherenkov angle difference between pions  
 259 and kaons at 50 GeV/c in the radiator gas. The uncertainty on  
 260 the emission point remains the major contribution ( $\approx 1$  mrad)  
 261 to the SPE resolution of the radiator gas despite the mirror focal-  
 262 ization and the curved dRICH detector surface. The chromatic  
 263 error is well under control for gas but is the largest contribution  
 264 ( $\approx 2.5$  mrad) to the angular resolution for the aerogel. It lim-  
 265 its the aerogel momentum reach to something above 15 GeV/c,  
 266

267 a value well above the Cherenkov threshold of kaons in gas.  
 268 The mean number of recorded photons is about 18 for the ra-  
 269 diator gas and 12 for the aerogel for a particle with momen-  
 270 tum well above the Cherenkov threshold, and slightly varies  
 271 with the pseudo-rapidity due to the different path of the particle  
 272 within the radiators. In average, few charged particles per event  
 273 are expected to hit the detector. Simulations show that, with a  
 274 proper pattern recognition and photon path reconstruction, the  
 275 information of the two radiators can be combined to extend the  
 276 hadron momentum coverage of ePIC PID from the TOF  $\approx 2.5$   
 277 GeV/c upper momentum limit to above 50 GeV/c, and support  
 278 electron separation up to 15 GeV/c. In the most challenging  
 279 forward direction, an identification efficiency greater than 95 %  
 280 at a corresponding 5 % percent mis-identification probability, is  
 281 achieved in the upper momentum reach.

### 4. Conclusions

The dRICH project aims to provide effective particle iden-  
 tification in the forward endcap of ePIC. In order to meet the  
 stringent requirements, significant advances in several new tech-  
 nology solutions are being pursued with a vigorous develop-  
 ment program. The project has passed a 60% incremental de-  
 sign review in 2025 and is now rapidly moving towards a com-  
 plete TDR.

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