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Full Length Article

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 a high non-uniform magnetic field. During the R&D phase, the dual radiator principle and the single component performance have been validated. A status overview of the project is presented. The design and technological choices are discussed together with the results obtained from laboratory characterization of the component demonstrators and beam tests of the evolving prototypes.

1. dRICH at ePIC

The Electron-Ion Collider (EIC) at the Brookhaven National Laboratory (BNL), in Upton, NY, will be the first facility to collide polarized electron and ion (up to Pb) beams at a variable center-of-mass energy running from ≈20 GeV to ≈140 GeV [1] and at a luminosity in excess of $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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) end-cap of ePIC, particle identification is obtained by a dual-radiator ring-imaging Cherenkov detector (dRICH), complemented by a forward time-of-flight (FTOF) 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 Fig. 1. Practical refractive indexes dictate a minimum thickness of 4 cm for the aerogel and O(1) m for the gas in order to ensure sufficient photon yield. A focusing mirror system is required in order to optimize ring imaging accuracy despite the uncertainty of the 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 pseudorapidity range $1.5 \lesssim \eta \lesssim 3.5$, running from the beam pipe up to the detector barrel limits. The mirror system provides proper focusing of Cherenkov light onto 6 active sensor 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 non-uniform magnetic field up to 0.6 T necessitates the unprecedented use of silicon photomultiplier (SiPM) sensors for single photon detection.

The dRICH introduces several innovative technical solutions to meet the stringent ePIC requirements. Among the most interesting ones described here are: world-record size of aerogel tiles at n = 1.026, C_2F_6 radiator gas, SiPM sensor with in-situ annealing, light carbon-fiber 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 of 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 and with 2 cm thickness were characterized in laboratory tests, also in collaboration with ALICE3 [3]. The samples were further evaluated with prototypes at the CERN test-beam facility. The measurements indicate that the transparency values are typically above 70% at a wavelength of 400 nm, and that the optical quality increases with refractive index, reaching 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 of n = 1.026 has been selected. With respect to the initial value, this choice provides a better overlap with FTOF due to the lower kaon momentum threshold (≈2.1 GeV/c). At the same time, it preserves a momentum reach well above the gas radiator threshold for kaons (≈12 GeV/c), thanks to the higher photon yield that compensates the lower Cherenkov angle separation. The chromatic dispersion ($dn/d\lambda$) has been measured during the R&D phase to be $6 \cdot 10^{-6}\,\mathrm{nm}^{-1}$ 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 tile size of 18 cm, obtained at BELLE-II, has been successfully produced and water-jet cut in both squared and trapezoidal shaped versions, see top-left panel in Fig. 2. A feasibility study is ongoing to increase these limits towards a dimension of 20 cm (or greater) to maximize the photon yield.

Gas radiator. The selected reference gas radiator is hexafluoroethane (C_2F_6), which matches the requirements being characterized by refractive index n = 1.00086 at standard temperature and pressure (STP) and excellent chromatic dispersion $dn/d\lambda = 0.2 \cdot 10^{-6}\,\mathrm{nm}^{-1}$ at a wavelength of $\lambda = 350\,\mathrm{nm}$. The performance of C_2F_6 in terms of photon yield and Cherenkov angle resolution has been validated with the dRICH prototype at the CERN test-beam facility [4]. With an optic arm similar to ePIC, a single photoelectron (SPE) resolution close to 1 mrad has been obtained, in line with the expectations. The dRICH will be operated at atmospheric pressure applying standard techniques to limit the pressure gradients. Special attention is required for the gas

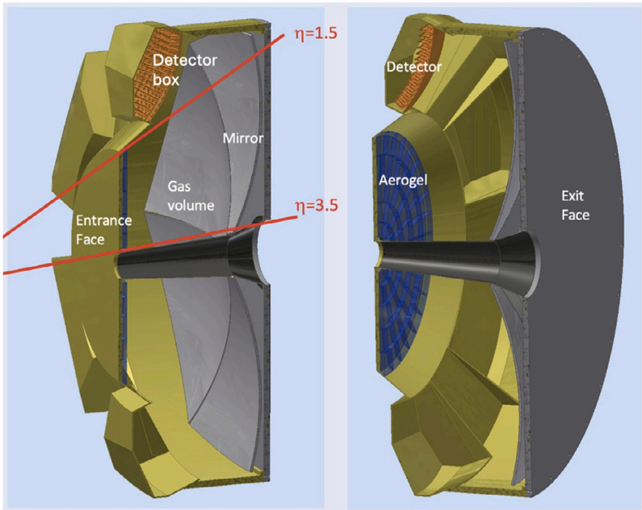

Fig. 1. dRICH detector model with major components highlighted.

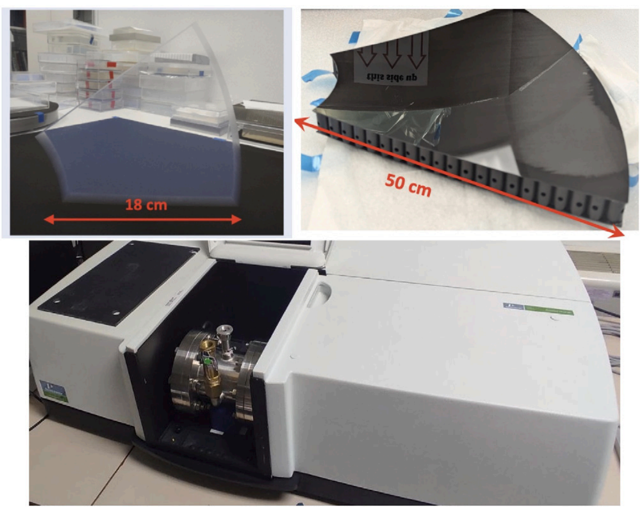

Fig. 2. (Top-left) Example of aerogel tile produced with the dRICH baseline refractive index n = 1.026 and the reference dimensions of BELLE-II. (Top-right) Mid-size CFRP mirror demonstrator with optimized core structure. (Bottom) Photo-spectrometer with compact high-pressure chamber for gas transparency measurements.

system that should ensure purging and separation of the radiator gas with minimal losses, given that C_2F_6 is a greenhouse gas with a high global-warming potential. The physical properties of C_2F_6 are peculiar, with a boiling point at −78.1°C that permits a single gaseous phase in all operations, but challenges a gas separation by liquefaction [5]. An interesting option under study is the use of CO_2 as a stand-by gas during maintenance operations because it can be liquefied prior to C_2F_6 at manageable pressures (≈ 10 bar). The most promising alternative is the usage of separating membranes exploiting the low permeability to the large fluoro-carbon molecule, following a seminal study by LHCb on the separation of CF_4 and CO_2 using C0-C10 membranes from UBE Industries. Separation tests of C_2F_6 are now ongoing at CERN with the help of experts. At the COMPASS monochromator setup, the transparency of C_2F_6 has been measured to be greater then 98% in the near-UV wavelengths ranging from 170 nm to 220 nm, which is most sensitive to contaminants, after several (≈4) years of storage in bottles. A system has been developed to measure the transparency in the near-visible wavelengths ranging 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 of Fig. 2. This system 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. Preliminary results indicate an emission peak at wavelengths around 300 nm that is twice larger then C_4F_{10} but twenty times lower than the problematic CF_4. 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 of 2200 mm radius and about 10 m^2 area. The carbon-fiber reinforced polymer (CFRP) technology is chosen as baseline for the mirror substrate to ensure the needed stiffness with minimum material budget. A mid-size demonstrator (of 60 cm diagonal) has been realized by Composite Mirror Applications (AZ, USA) with dRICH specifications, see top-right panel of Fig. 2. The CFRP core structure has been optimized to preserve surface shape accuracy and minimize structural mass at the level $\approx 5\ \mathrm{kg/m^2}$: it adopts a light C-shaped cell structure (used at LHCb) in the center, and a stronger cylindrical cell structure (used at CLAS12) on the edges. As noticeable in Fig. 2, the CFRP substrate optical surface is partially reflective even in absence of the Al+SiO_2 reflective layer deposition. Before such a 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 ± 5 mm, slight above the requirement to stay within 1% of the nominal value.

SiPM sensor. The dRICH photon detector surface is of spherical shape with radius ≈110 cm, matching closely the 3D focal area of the mirror system, see Fig. 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 $3 \times 3\,\mathrm{mm^2}$ 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^{11} 1-MeV neutron-equivalent (n_{eq}) fluence [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 SiPMs with UV-enhanced sensitivity. To control the significant intrinsic dark-count rate (DCR), the SiPMs will be operated at a temperature of $\lesssim -30$°C. At the location of the dRICH photodetector a maximum (average) fluence of $\Phi_{eq} = 6.4\ (3.7)\ 10^7\ \mathrm{cm^{-2}/fb^{-1}}\ n_{eq}$ 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 except for 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 using an 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 ∼200 fb^{-1} needs to be integrated before DCR increases to a reference limit of 300 kHz/ch, which is a conservative DCR value that has been shown to have marginal effects onto the dRICH performance. Preliminary tests with a pulsed-LED indicate that

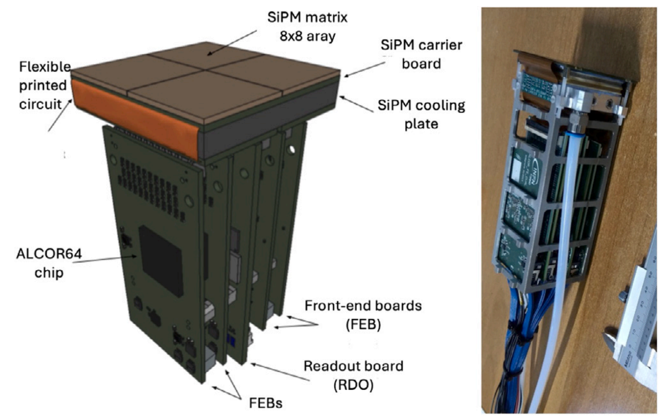

Fig. 3. The PDU concept (left) and preliminary realization (right).

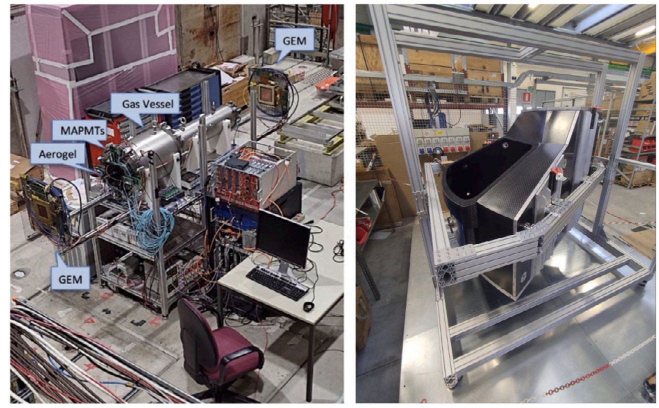

Fig. 4. The basic (left) and real-scale (right) dRICH prototypes.

no relative loss in PDE will be observed after a comparable integrated luminosity, i.e. irradiation up to 10^{10} n_{eq} and annealing at 150°C for few hundreds of hours.

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 time binning. The ALCOR chip implements a slew-rate measurement to correct time-walk effects and was proven to sustain a rate greater than 500 kHz per channel (almost twice the ePIC reference limit). The overall time resolution of the SiPM+ALCOR readout chain has been measured using single-photon laser events: it resulted compatible with ePIC requirements, being handily below 150 ps RMS and improving with SPAD size thanks to the larger signal and faster slew rates. 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 × 52 × 140 mm^3, integrating the readout with sub-zero temperature cooling of the SiPMs as well as in-situ high-temperature annealing capability, see left panel of Fig. 3. In particular, the PDU groups 256 SiPM channels with the ALCOR TDC readout provided by four front-end boards (FEB) and 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. A low-viscosity silicone fluid is circulated within the block, in a closed loop through an external thermostat, and 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 concentrates 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 of ALCOR has been successfully realized and operated with dRICH prototypes at the CERN test-beam facility, see right panel of Fig. 3, indicating capability of ring-imaging and particle identification suitable for ePIC [8]. 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 quarter 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 [9] as data-aggregator (DAM) 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 controlled and annealed in order never to exceed a maximum of 300 kHz dark rate per channel. The corresponding maximum throughput rate of the entire dRICH is 1.3 Tbps assuming a modest reduction of order O(5) of the uninteresting data caused by DCR. This could be achieved via a shutter signal implemented in the front-end ASIC, to select a readout window around the EIC beam bunch-crossing occurring every 10 ns, and/or via an external tagger 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 [10].

Mechanics. A basic prototype has evolved in time to serve the dRICH R&D development for few years, see left panel of Fig. 4. The gas vessel is a cylinder made of vacuum standards, to allow an efficient and safe gas exchange. An external dark box is mounted onto the upstream flange, and separated from the inner gas volume using 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 back 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 C_2F_6 gas radiator, the optimization of the aerogel refractive index, the performance study of the SiPM-ALCOR readout chain, and the development of an EIC-driven readout plane. The active plane is being progressively evolved to compare SiPM of different layout (e.g. micro-cell size), upgraded versions of the readout electronics and more realistic cooling and annealing systems. A real-scale engineering article of the dRICH vessel structure has been realized by Advanced Composite Solutions (IT) with composite materials and a realistic geometry (mimicking a dRICH sector), see right panel of Fig. 4. This is instrumental to validate the mechanical elements and study the assembling details (e.g. of transparent septa), the mechanical stability, the gas and light tightness, and the thermal aspects. One of the major goals of the real-scale article is also to reproduce the final ePIC working conditions, mount an extended readout plane with the final PDU demonstrators, operate realistic optical components as results of the ongoing developments, and optimize the performance in a realistic off-axis optics configuration. To this end, the mechanical support and its platform have been realized to allow a rotation from vertical (for maintenance and beam-test) to horizontal (for cosmic runs) position, and to facilitate the alignment at different projective angles with respect to the nominal interaction point, in order to mimic the pseudorapidity span at ePIC.

3. dRICH performance

The dRICH model is part of the ePIC simulation framework and allows complete performance studies taking into account: quality of the track reconstruction, bent trajectories (by magnetic field) and multiple scattering. The ePIC magnet coils and the dRICH position have been optimized in order to minimize the bending inside the radiator gas volume. The dRICH has been designed in order to keep most of the contributions to the SPE angle resolution close or below 0.5 mrad, a value dictated by the small Cherenkov angle difference between pions and kaons at 50 GeV/c in the radiator gas. The dRICH simulation model is regularly updated following the inputs derived from component characterization and beam tests to ensure realistic performance projections. The uncertainty on the emission point remains the major contribution (≈1 mrad) to the SPE resolution of the radiator gas despite the focusing mirror system, and the spherically shaped detector surface. The chromatic error is well under control for gas but is the largest contribution (≈2.5 mrad) to the angular resolution for the aerogel. It limits the aerogel momentum reach to something above 15 GeV/c, a value well above the Cherenkov threshold of kaons in gas. The photon yield slightly varies with the pseudo-rapidity due to the different path of the particle within the radiators. The mean number of recorded photons, estimated with conservative assumptions, is about 18 for the radiator gas and 14 for the aerogel for a particle with momentum well above the Cherenkov threshold. On average, few charged particles per event are expected to hit the detector. Simulations show that, with a preliminary pattern recognition and photon path reconstruction, the information of the two radiators can be combined to extend the hadron momentum coverage of ePIC PID from the FTOF ≈ 2.5 GeV/c upper momentum limit to above 50 GeV/c, and support electron separation up to 15 GeV/c [11]. In the most challenging forward direction, an identification efficiency greater than 95% at a corresponding 5% misidentification probability, is achieved in the upper momentum reach.

4. Conclusions

The dRICH project aims to provide efficient particle identification in the forward end-cap of ePIC. In order to meet the stringent requirements, significant advances in several new technology solutions are being pursued with a vigorous development program. The project has passed a 60% incremental design review in 2025 and is now rapidly moving towards a complete technical design report (TDR) and a timely construction start, with the goal to be ready for installation in the early thirties.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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