Simulation Study for Particle Identification with the dRICH of the ePIC Experiment at the EIC

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Abstract

The dual-radiator Imaging Cherenkov detector (dRICH) is a key component of the forward particle identification system for the ePIC experiment at the Electron-Ion Collider (EIC). This study evaluates the dRICH performance using Geant4 simulations in the context of the global ePIC simulation stack, focusing on the optimization of the aerogel radiator and the impact of sensor noise. We compare two aerogel configurations: the initial design (n=1.019) and the current default (n=1.026). The latter, characterized by improved optical properties and a higher refractive index, demonstrates enhanced $\pi - K$ separation at high momenta, effectively extending the operational overlap with the C_2F_6 gas radiator. Additionally, the study investigates the impact of Silicon Photomultiplier (SiPM) dark noise, showing that a 300 kHz noise rate leads to a moderate reduction (approximately 1.5 GeV/c) in the 3σ separation threshold. These results validate the current dRICH design and quantify the purity levels achievable for both radiators under expected experimental conditions.

Keywords: ePIC, RICH, radiator gas, aerogel, simulation

1. Introduction

The ePIC experiment at the Electron–Ion Collider (EIC) is an approved project under realization at Brookhaven National Laboratory (BNL), USA. It aims to address key questions on how nucleon properties such as mass and spin emerge from partons and their interactions, and how partons are distributed in momentum and position space. The EIC will also study the interactions of color-charged quarks, gluons, and jets with nuclear matter. Central questions include how confined hadronic states emerge from quarks and gluons, how quark–gluon interactions generate nuclear binding, how the nuclear environment modifies parton dynamics and correlations, and how gluon densities in nuclei evolve toward saturation at high energies, potentially giving rise to a universal gluonic phase of matter in nuclei and nucleons. To explore such elaborate physics, the requirements on the accelerator and the detector are state-of-the-art. High polarization ($\sim$ 70%) for electron and light nuclei

beams, availability of heavy ions up to Uranium, high luminosity (peak value around 10^{33} to 10^{34} cm^{2}s^{-1}), high centre of mass energy (20-140 GeV) makes the EIC an ultimate machine to study the fundamental aspect of QCD and hadronic physics. The detector has to general purpose to deliver the whole EIC physics program; almost hermetic coverage and compact setup are key challenges for such multipurpose ambitious detector design. The requirements for EIC have been described in detail in the common effort by the physics community interested in the EIC physics, known as the Yellow report [1]. In the Yellow report the role of the particle identification (PID) detectors in delivering the physics of EIC has been considered fundamental. Such an elaborate PID could not be delivered by a single PID technology. Therefore, several technologies have been identified to deliver the PID requirements altogether. A dual radiator Ring Imaging CHerenkov (dRICH) counter in the forward direction will provide at three sigma pion level, kaon-pion

separation from few hundred MeV/c up to 50 GeV/c. Two radiators will provide a continuos PID over a wide acceptance; pseudorapidity range between 1.5 to 3.5. It will support the identification of the scattered electrons of Deep Inelastic Scattering (DIS) events by pion rejection, therefore complementing the calorimeter systems, particularly at low momenta, up to 15 GeV/c. The aerogel radiator will provide particle identification in the lower momentum end and the C_2F_6 gaseous radiator in the higher momentum range up to 50 GeV/c, with substantial overlap between the two ranges. The RICH design is based on six identical arrangements of spherical mirrors and photosensor sectors where the SiPMS are arranged so to form a pseudo-spherical surface. Each mirror focuses reflected photons onto the corresponding photosensor area. Sophisticated simulation serves as a fundamental block of the detector construction. For the ePIC dRICH an extensive simulation campaign is ongoing. In this study, we discuss the results of several simulation studies performed with the official dRICH simulation stack and using single particle Monte-Carlo events.

2. Simulation software scheme

The ePIC software scheme is complex and multi-layered. To simulate the hits, the geometry of the detector is described in the DD4hep framework [2], and the simulated data is generated using Geant4 [3]; for our studies related to generation of Cherenkov photons we use the [4] plugin of DD4hep. The simulated hits are then reconstructed using an indirect ray tracing method [5] to obtain the Cherenkov angle. This standalone code based on C++ is a part of the ePIC reconstruction framework EICRecon [6]. EICRecon is a framework based on JANA2 [7]. Due to our status of integration, the data model of our simulation studies strictly follows the data model of the ePIC experiment [8], which is based on PODIO [9] and EDM4hep[10].

The final output for the characterization studies of the sub-detector systems is fully customized by the users. For example, in figure 1 it can be seen how the reconstructed squared mass of charged particles varies as a function of momentum. The combined information provided by the two radiators can be appreciated. The mass has been computed using the dRICH Cherenkov angle information. The simulation framework has also been extensively utilized for some the critical parameter optimizations and impact studies, as those reported here. Several other important studies are being performed and have been reported elsewhere [11].

3. Improving Aerogel Performance

The aerogel radiator of the dRICH provides particle identification (PID) at low momentum, specifically where the charged particles are below the Cherenkov threshold of the gas radiator. The threshold for positive kaon identification in the C_2F_6 radiator is approximately 12 GeV/c. Therefore, to ensure substantial overlap with the gas radiator, the aerogel must provide 3σ separation well above 12 GeV/c. In this study, the parameters of two aerogel samples were used for a comparative performance
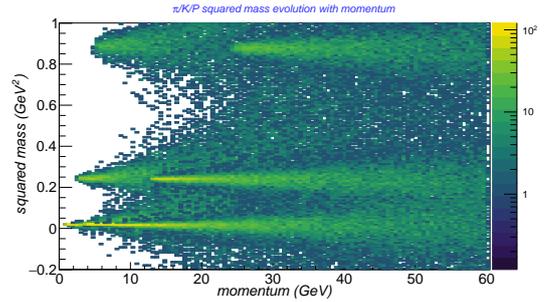

Figure 1: Reconstructed m^2 as a function of momentum for single particle events in the dRICH simulation environment. The plot was produce using the n=1.019 aerogel.

analysis. The first sample, originally planned for the ePIC experiment, has an average refractive index of 1.019[12]; the second, with an index of 1.026, is the new current default for the detector. The radiator is planned to be 4 cm thick. An aerogel radiator with a higher refractive index increases the number of detected photons, thereby enhancing pattern recognition; however, saturation occurs at a lower momentum. The new aerogel also features improved optical properties, with an optimized Rayleigh scattering length that improves the resolution of the reconstructed single-photoelectron Cherenkov angle. Overall, the second aerogel allows for better particle discrimination at higher momenta, extending the overlapping range with the gas radiator. In figure 2, the separation $\pi - K$ in number of standard deviation $N\sigma$ is plotted as a function of momentum at a fixed pseudorapidity. The number of detected photons is also heavily influenced by the pseudorapidity due to geometric acceptance: at $\eta = 2.0$, the ring is typically fully contained within a single sensor sector. At higher values of η, performance is modulated by the "shadowing" effect of the beam pipe and the splitting of rings across multiple sensor sectors as they are reflected by nearby mirrors.
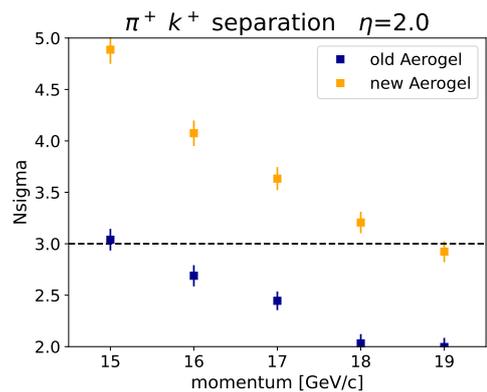

Figure 2: $N\sigma$ $\pi - K$ curve for the two aerogel; $n = 1.019$ is labels as "old" and the current default as "new".

Increasing the number of detected photons improves pattern recognition and leads to better ring resolution. For this reason, we investigated how the $N\sigma$ curve changed when increasing the aerogel thickness up to 6 cm. No self-absorption effects were observed, and performance clearly improved; however, due to

construction complexities, there are currently no plans to increase the radiator thickness.

The simulation is in agreement with the studies performed in laboratory and a series of beam test studies performed at CERN [13].

4. Noise Impact

SiPMs are chosen as baseline photosensor for ePIC, thanks to the several advantages available for using this technology: magnetic field insensitivity, high photo-detection efficiency, high granularity, low cost, high timing performance and the requirement of low bias voltage. At the same time, there is a concerning challenge. The intrinsic Dark Count Rate (DCR) is high and largely increased with high radiation doses. The ePIC dRICH collaboration has demonstrated a mitigation strategy to this problem [14], however up to around 50 DCR hits are expected after 5 years of operation in ePIC at maximum EIC luminosity over 50 K pixels of each sector per events with a 3 ns gating. Therefore, a particular concern is the contamination of DCR hits to the aerogel ring, due to its large Cherenkov angle. To simulate this, white noise counts are added uniformly across the sensor surface before reconstruction. The noise rate is defined per single event for each SiPM. The maximum noise rate expected for the dRICH sensors is 300 kHz, assuming a time window of 1 ns. Calculating the noise under the signal peak allows us to estimate the purity achievable at this noise rate. Signal purity is defined as $Signal/(Signal + Noise)$. To extract the noise contribution in the signal region, a combined fit utilizing a Gaussian for the signal and a first-order polynomial for the noise was applied. The noise was calculated as the integral of the polynomial curve within a 3σ window of the Gaussian peak, while the signal was determined by subtracting this estimated noise from the total counts. The C_2F_6 ring is smaller because its refractive index [15] is lower than that of the aerogel, but the photon count is higher due to the length of the gas volume. This results in a purity of approximately 99% for the C_2F_6 ring, while for the aerogel, it reaches only about 96% as shown in figure 3, which degrades the aerogel ring resolution. As shown in figure 4, the PID performance of the new aerogel with added noise shows that the 3σ $\pi - K$ separation limit decreases by approximately 1.5 GeV/c compared to cases without noise injection.

5. Conclusions

The comprehensive simulation of the dRICH detector demonstrates that the current design meets the PID requirements of EIC and that a substantial overlap between the two radiators is achievable even considering the dark noise of the SiPMs.

Acknowledgments

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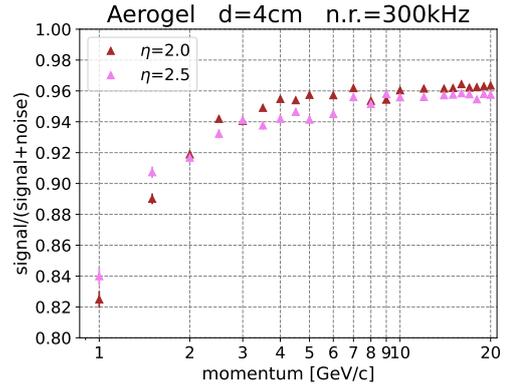

Figure 3: Signal purity as a function of momentum for the aerogel ring. It increase up to saturation resembling the photon yield.
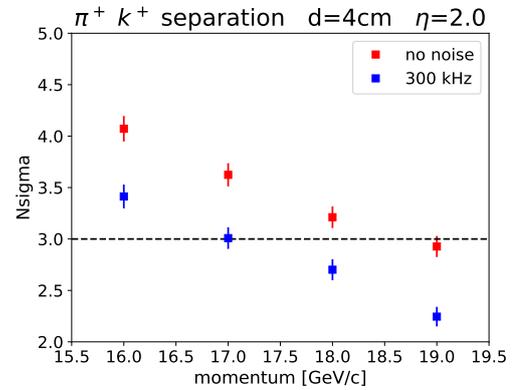

Figure 4: $N\sigma$ curve with and without simulating the noise.

References

[1] R. Abdul Khalek et al. Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report. *BNL-220990-2021-FORE, JLAB-PHY-21-3198, LA-UR-21-20953*, 03 2021. doi: https://doi.org/10.1016/j.nuclphysa.2022.122447. URL https://arxiv.org/pdf/2103.05419.pdf.

[2] Detector Description Toolkit for High Energy Physics. URL https://dd4hep.web.cern.ch/dd4hep/.

[3] S. Agostinelli et al. Geant4—a simulation toolkit. *NIMA*, 506 (3):250–303, 2003. ISSN 0168-9002. doi: https://doi.org/10.1016/S0168-9002(03)01368-8. URL https://www.sciencedirect.com/science/article/pii/S0168900203013688.

[4] DD4hep simulation plugins, front-end, and related utilities. URL https://github.com/eic/npsim.

[5] IRT:Indirect Ray Tracing code for ATHENA event reconstruction. URL https://github.com/eic/irt.

[6] EICrecon: JANA based reconstruction for the EPIC detector. URL https://eicrecon.epic-eic.org/#/.

[7] JANA2:Modern C++ Reconstruction framework in Nuclear and High Energy Physics. URL `https://jeffersonlab.github.io/JANA2/#/?id=jana2`.

[8] EDM4eic - EIC data model. URL `https://eic.github.io/EDM4eic/`.

[9] podio. URL `https://github.com/AIDASoft/podio`.

[10] EDM4hep:A generic event data model for future HEP collider experiments. URL `https://github.com/key4hep/EDM4hep`.

[11] Chandradoy Chatterjee. Particle Identification with the ePIC detector at the EIC. 10 2024. doi: https://doi.org/10.22323/1.469.0266. URL `https://arxiv.org/pdf/2410.20410.pdf`.

[12] M. Contalbrigo et al. Aerogel mass production for the CLAS12 RICH: Novel characterization methods and optical performance. *NIMA*, 876: 168–172, 2017. ISSN 0168-9002. doi: https://doi.org/10.1016/j.nima.2017.02.068. URL `https://www.sciencedirect.com/science/article/pii/S0168900217302644`. The 9th international workshop on Ring Imaging Cherenkov Detectors (RICH2016).

[13] M. Contalbrigo. The ePIC Dual-Radiator RICH Detector; RICH 2025 conference, Mainz. 2025.

[14] Roberto Preghenella et al. A SiPM-based optical readout system for the EIC dual-radiator RICH. *NIMA*, 1046:167661, 2023. ISSN 0168-9002. doi: https://doi.org/10.1016/j.nima.2022.167661. URL `https://www.sciencedirect.com/science/article/pii/S0168900222009536`.

[15] R. Abjean, A. Bideau-Mehu, and Y. Guern. Refractive index of hexafluoroethane (c2f6) in the 300-150 nm wavelength range. *NIMA*, 354 (2):417–418, 1995. ISSN 0168-9002. doi: https://doi.org/10.1016/0168-9002(94)01006-4. URL `https://www.sciencedirect.com/science/article/pii/0168900294010064`.