Prototype of a dual-radiator RICH detector for the Electron-Ion Collider

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Abstract

A dual-radiator Ring Imaging Cherenkov (dRICH) will provide charged hadrons particle identification in the hadronic end-cap of a general-purpose experiment at the future Electron-Ion Collider (EIC). We developed a prototype to test the performance and validate the use of Silicon Photo-Multipliers (SiPM), the baseline photo-sensor candidate for the dRICH. They provide a cheap, highly efficient technology and they are not sensitive to the high magnetic field. The general features of the detector, a detailed view of the prototype and its different configurations, the test beam performed, and the preliminary results we obtained are presented.

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1. Introduction

The Electron-Ion Collider (EIC) [1] will be a new high-luminosity large-scale and high-polarization collider designed to investigate the QCD dynamics in the nucleons with unprecedented precision. It will be built at the Brookhaven National Lab (BNL) in the US. A key element of a general-purpose experiment at EIC is a detector providing particle identification in the hadronic end-cap. It has to allow a 3σ separation of particles in a broad momentum range from a few GeV/c up to 50 GeV/c, while operating in a high magnetic field region. To meet these requirements a dual-radiator RICH (dRICH) is being developed: it exploits Cherenkov light produced by two different mediums to cover the full momentum range without penalty owing to the Cherenkov threshold of the gas. A preview of the detector is visible in figure 1. We developed a prototype and two test beams were performed in the fall of 2021 at CERN PS and SPS.

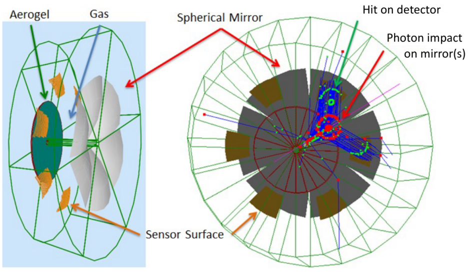

Figure 1: The dRICH at EIC

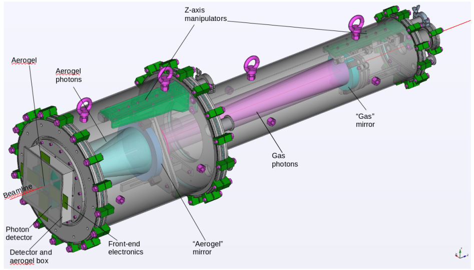

Figure 2: The dRICH prototype

2. The prototype

A scheme of the prototype is represented in figure 2. A charged particle crossing the dRICH initially passes through the aerogel ($n \simeq 1.02$) and produces a Cherenkov-photons cone of about 11 degrees aperture. The photons are reflected back by a first spherical mirror and focused on the photon detector array. Then the particle passes through the gas ($n \simeq 1.00085$), which fills the detector, produces a Cherenkov-photon cone of about 2 degrees aperture. The first mirror has a central hole, to allow the photons produced in the gas at small angles to fly towards a second spherical mirror and be focused back on the same photon detector array. The information of the two imaged Cherenkov rings combined with the beam momentum will allow identificatio of pions, kaons, and protons.

The prototype consists of two main parts: the gas chamber and the detector box. The gas chamber:

- mechanically sustains the dRICH, especially the spherical mirrors;

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- includes the mechanics to regulate the mirrors angle and position along the detector axis;
- bears both under and over pressurization, to evacuate the air and introduce the gas;
- preserves light tightness.

The detector box:

- houses the aerogel box in a N_2 dry atmosphere;
- mounts the photon detector and the front-end electronics;
- supports a cooling system for the silicon photomultipliers (SiPM) matrices.

Three different kinds of photon-sensors were tested in fall 2021, each with its own box. They are Multi-Anode Photo-Multiplier (MAPMT) with MAROC readout (used as reference), Multi-Pixel Photon Counter (MPPC) with MAROC readout (used as magnetic tolerant device prototype), and custom matrices of SiPM with ALCOR readout (developed to study the SiPM post-irradiation and post-annealing [2] performance).

The prototype assembly has been completed in the summer of 2021, in time for the scheduled test beams in the fall. The experimental setup for the test includes a trigger and timing system, based on a 2x1 cm^2 scintillator pair placed in front of the aerogel box, and a tracking system, made by two GEM chambers with 0.4 mm pitch, one upstream and one downstream the prototype. The gas chamber is 1.3 m long, composed of a 50 cm long cylinder (aerogel section) with 50 cm diameter, and a 80 cm long extension (gas section) with 25 cm diameter. The full setup with tracking system is $\sim$ 3 m long. The path length of the gas photons is the same expected for the final detector, while it is reduced to about 1/3 for the aerogel photons to fit within the limited area of the imaging plane, making the pixel contribution to the correspondingly angular resolution more significant. To validate the prototype a simulation has been realized using GEMC (Geant4 Monte Carlo), a C++ framework developed by Jefferson Lab. Currently, the comparison is done with the results of the preliminary and ideal simulation, while a new more realistic version is being completed at the beginning of 2023.

3. Fall 2021 tests

In September 2021 a first test beam was carried out at the H6 SPS beam line at CERN, aimed at commissioning the prototype and its subsystems. Using a proton beam of 120 GeV/c and a mixed hadron beam between 20 GeV/c and 60 GeV/c, the SiPM detector box was tested with aerogel. The prototype and readout were successfully operated, and the focused ring was observed shifting on the SiPM array while the spherical mirror was moved along the cylinder axis.

A second test has been performed in October at the T10 PS beam line at CERN, with the goals to operate the detector in dual-radiator mode, to characterize the optics component, and to study the achievable resolution. In this case the MAPMT and MPPC detector boxes were used. We were the first user of the renewed T10 experimental hall and the beam setup was not fully commissioned yet. As a consequence, we did not have full control of the beam optics and parameters, and access to the complete beam instrumentation. Despite these difficulties, the prototype was successfully operated in the dual-radiator mode, using C_2F_6 gas and two different samples of aerogel, one coming from the Budker Institute of Novosibirsk and the other from Chiba University. Examples of rings obtained with a beam of 12 GeV/c π^- are shown in figure 3. In this test the data were acquired, running the detector in several configurations with a beam of mixed positive or negative hadrons with momenta selected in the range between 4 GeV/c and 12 GeV/c. In the following, the focus is on MAPMTs data because they are being used to characterize the detector.

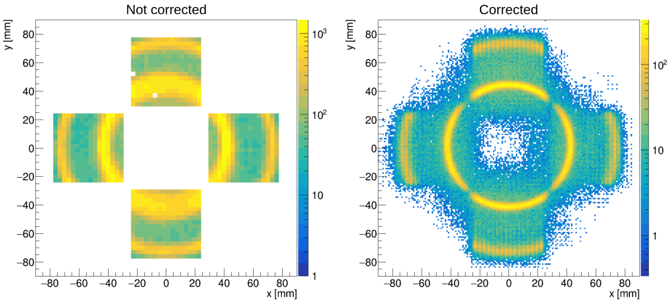

Figure 3: Rings for 12 GeV/c π^- beam, online analysis (left), offline analysis with the tracking corrections (right).

4. Data analysis

The analysis starts with the extraction of the time-coincidence peak of photons, to distinguish the Cherenkov signal from the background. The second step is to divide the aerogel and gas photons based on a geometrical condition. This selection will be improved in the 2022 test-beams when a new trigger readout system will allow the implementation of timing criteria to distinguish the source of the photons, exploiting the different path length of photons produced in aerogel or gas.

The tracking system allowed the observation of a correlation between the ring center (measured as half difference of the mean radius in two opposite MAPMTs) and the polar angle of the particle. A correction has been introduced to redefine the photon position with respect a mean optical center, whose coordinates are taken to be the semi-difference of mean radius in opposite MAPMTs. These values are computed using only the particles with a small polar angle. This correction aims at centering the rings and removing any misalignment of the mirrors. The second is an event-by-event correction, to take account of the incident angle of each single particle with respect to the detector and aims to correct the consequent distortion of the ring. The effect of the corrections is shown in figure 3.

5. Results from the 2021 test campaign

The preliminary simulation results used as reference in the following are obtained by using an ideal beam (point-like with-

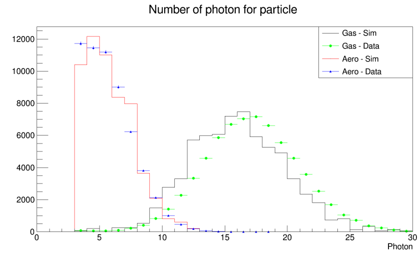

Figure 4: Detected and expected number of photon for particle.

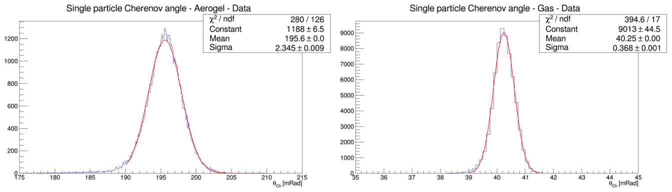

Figure 5: Single particle Cherenkov angle for aerogel (left) and gas (right).

out emittance). In figure 4 is shown the number of photon detected for particle produced in aerogel and gas. The trends are similar, except for a small underestimation for gas in the simulation. Note that the ring coverage provide by the photon detector is about 60% for gas and 40% for aerogel. In figure 5 is shown the single particle Cherenkov angle, obtained by averaging the angles of all the photons detected for the particle. The mean values obtained from data and simulation are similar, while the larger difference concerns the resolution, which is measured to be 4.2 mRad (aerogel) and 1.1 mRad (gas). Simulations show a comparable resolution for gas, but a resolution about a factor 2 better for aerogel. The difference between data and simulations is an indicator that a more refined simulation and a more sophisticated reconstruction algorithm are needed. In figure 6 the angular resolution is shown as function of the number of detected photon, both for data (top) and simulation (bottom), and for aerogel (left) and gas (right). The behavior can be fitted with the function

$$y = \sqrt{\frac{{p_0}^2}{x} + {p_1}^2}$$

where p_0 represents the single photon resolution and p_1 the asymptotic constant term signaling possible systematic effects. The single photon resolution p_0 is consistent between the data and simulations for the gas radiator, but for aerogel radiator is greater than 4 mRad, more than twice the simulation value. The difference could be due to the aerogel model in simulations, that should be refined with laboratory characterization. The asymptotic term might depend on the leverage arm of the fit, but seem different from zero in data for both radiators. This may indicate a possible residual misalignment of the components.

6. Conclusion and outlook

A prototype of the dual-radiator RICH for EIC aiming to identify particles in the momentum range from a few GeV/c up to 50 GeV/c, combining the information provided by two different radiators, aerogel and gas, has been designed, assembled, and tested between 2018 and 2021. During the 2021 test beams, the prototype has been successfully operated in dual mode and a preliminary investigation of the performance was possible. The results obtained from this analysis are encouraging, although they do not fully agree with the simulations; current limitations originate from the simplified modeling in simulations, the approximations in the preliminary reconstruction algorithm, and the need for further improvements like a better timing of the trigger system, and the usage of the beamline Cherenkov detector to tag the particle species.

During 2022, the planned improvements in hardware have been implemented and two new test beams were performed again at PS and SPS in the fall: new data were acquired and the analysis is ongoing. At the same time, the characterization of the optical properties of the prototype components has been performed, in particular the measurement of the aerogel absorption and scattering length, and the lucite window transmittance. These new values are being implemented in a more realistic simulation that will be used to validate the prototype performance.

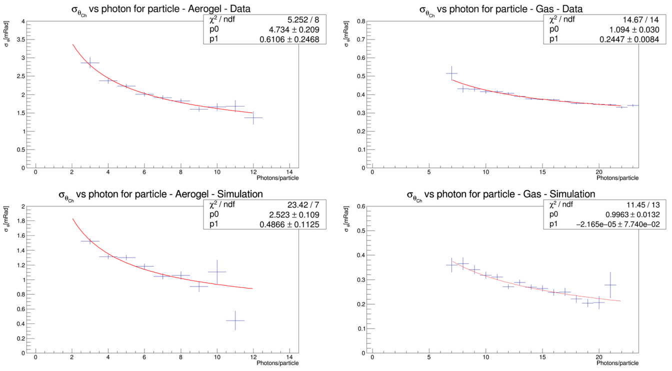

Figure 6: Angular resolution expressed as function of the photon number for particle from data (top) and simulation (bottom), both for aerogel (left) and gas (right). Fitted parameters are given in the top-right box.

Acknowledgments

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References

[1] R. A. Khalek et al., Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report, 2021. doi:10.48550/ARXIV.2103.05419.

[2] M. Calvi et al., Single photon detection with SiPMs irradiated up to 10^{14} cm^{-2} 1-Mev-equivalent neutron fluence, Nucl. Instrum. Methods A 922 (2019) 243. doi:https://doi.org/10.1016/j.nima.2019.01.013.