High-performance DIRC detector for the future Electron Ion Collider experiment

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Abstract: Excellent particle identification (PID) is an essential requirement for a future Electron-Ion Collider (EIC) detector. Identification of the hadrons in the final state is critical to study how different quark flavors contribute to nucleon properties. A detector based on the Detection of Internally Reflected Cherenkov light (DIRC) principle, with a radial size of only a few cm, is a perfect solution for those requirements. The R&D process performed by the EIC PID consortium (eRD14) is focused on designing a high-performance DIRC that would extend the momentum coverage well beyond the state-of-the-art, allowing 3 standard deviations or more separation of $\pi$/$K$ up to 6 GeV/$c$, $e/\pi$ up to 1.8 GeV/$c$, and $p/K$ up to 10 GeV/$c$. A key component to reach such a performance is a special 3-layer compound lens. This article describes the status of the High-Performance DIRC R&D for the EIC detector, with a focus on the detailed Monte Carlo simulation results and performance tests of the 3-layer lens.

Keywords: Cherenkov and transition radiation; Cherenkov detectors
1 Introduction

The Electron Ion Collider (EIC) is the future project for nuclear physics research in the United States that will be build in Thomas Jefferson Lab in Virginia, or Brookhaven National Lab, New York. It will be the world’s first collider with polarized electron and light ion beams, and capable of heavier, unpolarized ion beams up to uranium. The physics program of the EIC, as described in the White Paper [1], the 2010 INT report, the 2015 NSAC Long Range Plan, and elsewhere, is very broad and multifaceted — and so are the corresponding detector requirements.

The ability to identify hadrons in the final state is a key requirement for the physics program of the EIC detector. Being able to tag the flavor of the struck quark in semi-inclusive DIS, for instance, can provide information about the transverse momentum distributions (and potentially orbital angular momentum) of the strange sea, while open charm (with subsequent decays into kaons) is important for probing the distribution of gluons in protons and nuclei. While the distribution of produced particles depends on the specific process, broadly speaking the kinematics for meson production follows the energies of the colliding beams. If the scattering produces a meson traveling in the direction of the proton (ion) beam, this meson can have a momentum which is a significant fraction of that of the original proton (ion) beam. If the meson is produced in the opposite (electron) direction, it cannot acquire more momentum than that carried by the electron beam.

Three alternative model detectors are being developed at BNL and JLab with slightly different layouts of the hadron ID systems. The approach chosen by the PID consortium is to develop an integrated solution that would be suitable for the EIC physics requirements, while maintaining the compatibility with both the accelerator energies proposed at the BNL and JLab, and with the concept detectors developed there. This article will focus on the design of the Jefferson Lab full-acceptance detector, shown in figure 1. A central solenoid provides the magnetic field strength. Particle Identification (PID) detectors include electro-magnetic calorimeters, a fast time-of-flight detector (TOF), and three Cherenkov detectors: modular aerogel and dual radiator Ring Imaging Cherenkov detectors (RICH) and a Detection of Internally Reflected Cherenkov light (DIRC) detector. Selection and arrangement of the sub-detectors were optimized to detect and identify the complete final state...
of a nuclear reaction, including all partonic and nuclear fragments. Excellent hadronic PID in the central detector over a large range of solid angles and particle momenta is essential for studying the current jets, in particular through exclusive and semi-inclusive processes, which allow for imaging of the 3D structure of the nucleon. It is also important for heavy-flavor physics.

Figure 1. Top view of current layout of the full acceptance JLab EIC detector with all subsystems. The detector is divided into three regions, a middle barrel region, an electron side around a left endcup, and an ion side around a right endcup.

On average, hadrons produced in asymmetric \( ep \) collisions and detected on the electron side have momenta up to the electron beam energy, those scattered on the hadron side up to the ion beam energy. In the EIC beam energies will be in the order of 10 GeV for electrons and 100 GeV for ions. The highest energy region is in the hadron part and there a dual radiator RICH, for energies up to 50 GeV, is a good choice. The aerogel RICH is envisioned to cover energies up to 10 GeV on the electron unit side. In the barrel region the lowest energies have to be covered by a system that will be surrounded by the electromagnetic calorimeter that constrains radiation length and has to be able to operate in the fringe field of the solenoid, a non-uniform magnetic field of a magnitude of 3 T or higher. A solution that meets all these requirements is a detector based on the DIRC principle. The High-Performance DIRC, covering momenta up to 6 GeV/c with a separation power of at least 3 standard deviations, would be a perfect match for the EIC detector. This article will focus on the DIRC system. A description of the other PID systems developed for the EIC can be found in ref. [2].

The first DIRC detector [3] used in a large high-energy physics experiment was part of the BaBar experiment. It was successfully operated at SLAC for over 8 years providing hadronic PID and inspired several experiments to include DIRC detectors in their design or upgrade plans. The PANDA experiment at the FAIR facility, now entering the construction phase, designed a lens based
focusing DIRC detector [4] for the barrel region of the target spectrometer. The PANDA Barrel DIRC detector had to be made more compact than the BaBar DIRC. A smaller expansion volume was placed inside the solenoid magnet to fit different environment and geometry than in BaBar. To maintain the resolution, focusing optics as well as small-pixel photosensors and fast electronics, had to be included in the design. The EIC DIRC design is inspired by the PANDA Barrel DIRC detector taking advantage of the geometrical constraint similarities which creates many synergies in the R&D processes of both projects.

2 High-performance DIRC design

The High-Performance DIRC detector is part of all three EIC central detector concepts described in ref. [2]. The implementation of the DIRC into the JLab and both BNL detector concepts differs in its dimensions. The current design of the High-Performance DIRC for the EIC detector and its performance will be described for the JLab version. The Geant4 simulation implementation of the High-Performance DIRC is shown in figure 2. The radiators are synthetic fused silica bars, each 4200 mm long, made by gluing four pieces end-to-end, with a cross-section of $17 \times 35.4$ mm, distributed in 16 modules (called bar boxes). In each box eleven bars are placed side-by-side, separated by a small air gap. The 16 bar boxes are arranged in a barrel with a radius of 1000 mm around the beam line. Mirrors are attached to one end of each bar to reflect photons towards the readout end. On the readout end photons exit the bar through a special 3-layer lens that is described in more detail below. The other side of each 3-layer lens is coupled directly to a synthetic fused silica prism, which serves as an expansion volume. A zoom into the readout end of the bar box, showing details of the lens and prism section is shown on figure 2b. The prism has a $38^\circ$ opening angle and dimensions of $284.3 \times 390 \times 300$ mm. The detector plane of each prism is covered by 27,690 $2 \times 2$ mm pixels giving a total of about 443,040 channels to record the position and arrival time of the Cherenkov photons.

![Figure 2](image)

**Figure 2.** Geant4 simulation of the High-Performance DIRC detector, with the example accumulated hit pattern (a) and the focus on the prism expansion volume, a row of spherical 3-layer lenses and the radiator bars (b). The insert shows the individual lenses and layers of the spherical lens system.
A pixel size of 2 mm was selected as optimal choice for the High-Performance DIRC design based on the Geant4 study [5], which is less than half the size of the standard square microchannel-plate photomultipliers (MCP-PMTs). Reducing the pixel size is not technically challenging for the manufacturers, but it will increase the channel density and cost. The exact sensors used in this simulation are not yet commercially available so some of the parameters, like the quantum efficiency and timing resolution, are taken from data sheets, of PHOTONIS MCP-PMTs [6], as they are closest to the considered sensors for the final High-Performance DIRC detector. The R&D program focused on improving existing sensors to fulfill all the High-Performance DIRC requirements is summarized in ref. [7].

3 Performance in Monte Carlo simulations

To evaluate different design options for the High-Performance DIRC a time-based imaging reconstruction method, based on the approach used by the Belle II time-of-propagation (TOP) counter [8], was developed. In that algorithm the simulation is used to generate a large number of tracks with the observed momentum, location, and charge of the particle. The arrival time of the Cherenkov photons produced by each particle is recorded for every pixel and stored in an array of histograms to produce probability density functions (PDF). For a given track the observed photon arrival time for each hit pixel is compared to the histogram array to calculate the time-based likelihood for the photons to originate from a given particle hypothesis.

![Figure 3](image)

**Figure 3.** Simulated time-based imaging PID performance of the High-Performance DIRC. a) Log-likelihood difference for kaon and pion hypotheses for a sample of 6 GeV/c pions and kaons at 30° polar angle. The π/K separation power extracted from the Gaussian fits is 4.2 s.d. b) π/K separation power as a function of polar angle. Different colors represent the assumption of different time resolutions.

Figure 3a shows an example of the log-likelihood difference for kaon and pion hypotheses for a sample of simulated 6 GeV/c pions and kaons at 30° polar angle. The π/K separation, calculated as the difference of the two mean values of the fitted Gaussians divided by the average width, corresponds to 4.2 standard deviations in this case. The photon timing precision of the sensor plus electronics was set to 100 ps, the realistic assumption of the per-photon timing precision of the sensor and readout electronics in the High-Performance DIRC detector. Figure 3b shows π/K separation as a function of polar angle for the full phase space assuming three different time resolution options. Precision matters most for shorter photon paths (polar angles above 100°). For longer paths the performance is dominated by chromatic dispersion. The optimal use of all observables makes the
time-based imaging algorithm a very attractive reconstruction method for the High-Performance DIRC detector. Applying it to the narrow bar geometry with 100 ps timing precision provides a required 3 s.d. $\pi/K$ separation for the full phase space.

4 Mapping the focal plane of the 3-layer spherical lens

Figure 4. Schematic (a) and photos (b) of the spherical 3-layer lens prototype.

The influence of the bar size on the resolution of the DIRC detector is mitigated by a focusing lens. However, the focal plane of a standard lens is not flat but has a parabolic shape described by the Petzval field curvature. The curved focal plane allows only part of the Cherenkov ring to be properly focused. A special compound lens, with a combination of focusing and defocussing radii can shape the focal plane to better follow the detector plane. A prototype of such a 3-layer spherical lens was designed and build using ZEMAX [11]. Figure 4 shows a schematic and photos of the lens. The two outer layers are made of the synthetic fused silica, with a refractive index of 1.473 at 380 nm wavelength, to match the bar and expansion volume material. The middle layer is made of the Lanthanum crown glass (NLaK33), with a higher refractive index of 1.786 at 380 nm. Using standard lens with air gap at the transition from the lens to the expansion volume would cause dramatic photon loss. The combination of the synthetic fused silica and NLaK33 materials makes the lens work without any air gaps, minimizing the photon loss. The prototype of the lens is 12 mm thick, and has a diameters of 40 mm for the first two layers and 60 mm for the last layer. The two radii of the inner layers are 47.8 mm and 29.1 mm, respectively.

Figure 5a shows the schematic of the setup designed and built at the Old Dominion University laser lab to measure the shape of the focal plane of the spherical 3-layer lens. The lens was mounted on the rotation stage and placed inside a $30\times40\times60$ cm$^3$ glass container filled with mineral oil (with a refractive index very close to fused silica) to simulate the focusing behavior of the lens placed between the bar and the prism. The intersection point of the two parallel laser beams determined the focal length. A special 3D-printed holder, shown in figure 5b, made it possible to map out the focal plane in all three dimensions, which will be particularly important for comparing spherical and cylindrical lens designs. In addition, the lens was shifted in x and y to measure the focal distance
Figure 5. a) Schematic diagram of the optical setup to map out the focal plane of the 3-layer lens as a function of rotation angle of the lens. b) CAD picture of the 3D rotation lens holder. c) Measured shape of the focal plane (points) compared to simulation (solid lines) for two different azimuthal tilts and horizontal shift of the lens. The x coordinate corresponds to the focal length and the y coordinate to the focal point location perpendicular to the incident beams, calculated for different lens rotation polar angles.

when the laser beam is off-center on the lens. Results of that measurement were compared to the prediction from the Geant4 simulation.

Figure 5c shows three example results for different lens rotation angles and laser positions. The measured shape of the focal plane is in very good agreement with the simulation, both for the 3D rotation and for the lasers going off-center through the lens. The spherical lens produces the desired flat shape of the focal plane if the beam passes close to the center of the lens. Due to lens aberrations, the shape starts to slightly bend when the beam is shifted off-center but the simulation still predicts the shape well and it is much more flat than a traditional single-layer lens.

5 Summary

The R&D program of DIRC for the future EIC detector is further improving the High-Performance DIRC detector capability to extend its momentum coverage. A PANDA DIRC-inspired geometry was used as the baseline design, with narrow bars, each coupled to an advanced spherical 3-layer lens and a compact prism expansion volume made of fused silica. A prototype of such a special 3-layer
lens was designed, produced, and validated both in particle beam and on test benches. It provides an excellent performance and significantly decreases aberrations present in regular focusing lenses. The proper combination of focusing and defocussing radii makes the focal plane shape much more flat than a traditional single-layer lens. The new time-based imaging reconstruction method used for the 3-layer lens based High-Performance DIRC design further improves the per track Cherenkov resolution and reaches an excellent charged hadron PID at the future EIC detector.

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