Development of a Novel Readout Concept for an EIC DIRC

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July 25, 2022

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1 Executive Summary

The objective of this proposal is to pursue opportunities to reduce the material budget and the cost of the DIRC counter for the EIC, without loss of performance. The barrel high-performance DIRC (hpDIRC) has been adopted for the EIC Detector-1 and is an attractive solution for Detector-2. In this program we propose to study the DIRC performance with an innovative optical configuration consisting of narrow, thin radiator bars coupled to wide plates, focusing lenses, and small expansion volume prisms. The outcomes of these studies would be applicable to both Detector-1 and, in particular, to Detector-2. This novel geometry goes well beyond the design established for the project detector and enables opportunities for the application of SiPM for the DIRC readout. This innovative optics is expected to lower the impact of DIRC material on the electromagnetic calorimeters (improving the physics reach of the EIC detector), whereas the use of SiPM readout constitutes an advancement of DIRC technology.

2 Introduction

The DIRC is a crucial subsystem in the barrel region of any EIC detector, providing charged particle identification (PID) over a wide range of momenta and pseudorapidities. The hpDIRC baseline design for Detector-1 is based on a combination of reused bars from the decommissioned and disassembled BaBar DIRC, each connected by a short new bar segment to the spherical focusing lens and the prism expansion volume.

A natural advancement of the DIRC technology is the pursuit of cost reduction by considering alternative geometries, further reducing the size of the bar and prism through a novel design of the optics and readout sections, while maintaining excellent performance. In particular, the new narrow bars in the short section next to the lenses could be replaced by wide plates that would act as an extended expansion volume and allow a smaller prism size and, thus, a smaller sensor area. As the cost of the photodetectors and electronics is a significant part of the DIRC cost, this improvement could have a significant impact on the DIRC budget. The baseline design uses MCP-PMTs as sensors since the lower-cost option of state-of-the-art SiPM suffers from excessively high noise due to high darkcount rates and afterpulsing, even if the DIRC readout were modified to include the infrastructure for cooling and annealing of the SiPMs. A smaller prism and sensor area would increase the signal to background ratio and could make the cooling of the readout box technically more feasible, potentially paving the way for the use of SiPMs as a photodetector for the DIRC.

Thinner radiator bars in the EIC Detector-2 would create a natural synergy with high-resolution EM calorimetry in the barrel, potentially improving the photon energy resolution, which is important for DVCS on nuclei, and the purity in the reconstruction of the scattered electrons, which is essential for parity-violating DIS. Both aspects would create a natural complementarity between the two EIC detectors. While one of the great strengths of the DIRC technology is compactness, further reduction of the material budget is important for experiments in the EIC environment.

3 The "xpDIRC" Concept for the Next-Generation High-Performance DIRC

The proposed innovative readout concept study, referred to as "xpDIRC" below, builds on the high-performance DIRC (hpDIRC) detector developed for the EIC Detector-1. The general idea is similar with synthetic fused silica bars arranged in a barrel shape, segmented in bar boxes. Bars will serve as radiators and light-guide for photons that will be focused before reaching pixelated sensors located at the detector plane behind the expansion volume. The most significant change is a hybrid geometry, where the individual narrow bars are coupled to the expansion volume via a wide plate. This change may enable designs with different focusing systems and smaller expansion volumes. Thinner radiator bars will be considered to mitigate multiple scattering at lower momentum and improve the electron identification performance of the DIRC while simultaneously lowering the impact of the DIRC material on the EM calorimeters.

3.1 "Light-Guide" Options for the hpDIRC

The assembly of the fused silica bar in each bar box in the Detector-1 hpDIRC design is still under study. Three BaBar DIRC bars, glued end-to-end, form a 367.5 cm-long radiator bar. Another section, the so-called "light-guide" section, with a length of about 50 cm, is needed to transport the Cherenkov photons to the lens and the prism. Several options are still being considered for the light-guides.

One option is to cut any available BaBar DIRC bars into two pieces and polish one end to create short bars. The main challenge for this option is that the bar boxes available for disassembly at SLAC cannot produce a sufficient number of bars to cover the entire light-guide section. Even at 100% disassembly yield, the 8 boxes could produce a maximum of 384 bars (with a length of 122.5 cm each). Three bars are needed to form one long radiator bar, for a total of 360 BaBar DIRC bars. This only leaves 24 remaining bars, while at least 60 BaBar DIRC would be needed to build the required 120 light guides. To pursue this option, 1-2 of the GlueX DIRC bar boxes would have to be disassembled, in addition to the bar boxes at SLAC. Furthermore, it is unclear how difficult and expensive cutting, grinding and polishing the cut ends will turn out to be for the optical industry. The main fall-back option is to order the required number of short bars for the light-guide section from industry, adding to the cost and schedule risk. Both of these options, if successful, will be consistent with the Detector-1 hpDIRC baseline bar box design, shown in Fig. 1a and Fig. 2a.

A novel option, shown in Fig. 1b and 1c, is to replace the narrow, short bars in the light-guide section with a wide, short plate. This idea is based on the "small fDIRC design", first proposed in 2017 in Ref. [1], where narrow bars are combined with a wide plate and a fused silica expansion volume with a cylindrical focusing mirror to advance the DIRC performance. Simulation studies in Ref. [1] predicted a significant improvement of the Cherenkov angle resolution. However, this concept did not evolve past the simulation stage and the shape of the described focusing block expansion volume would be challenging to implement

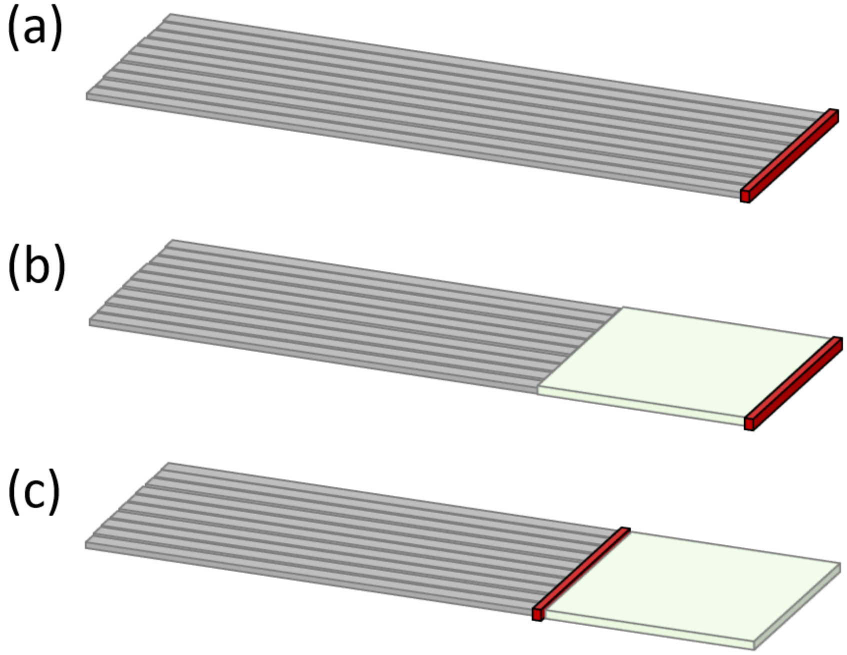

Figure 1: Schematic view of three radiator and light-guide configurations for the EIC DIRC (not to scale). (a) Baseline design for the hpDIRC in the reference detector using only narrow bars; (b) conservative xpDIRC hybrid design with narrow bars coupled to a wide plate and lenses placed at the end of the plate; (c) novel xpDIRC hybrid design with the lens placed between the narrow bars and the wide plate, which couples to a potentially smaller prism. Narrow bars are shown in gray, wide plates in green, focusing lenses in red. (The prism, which would be located on the right side, is not shown.)

in the EIC detector environment. Therefore, the hybrid hpDIRC geometry with a prism expansion volume will first have to be studied in simulation to demonstrate that it meets the performance requirements and that the plate does not make the DIRC more sensitive to the background from multiple particle tracks within one DIRC sector. Furthermore, the reconstruction of the complex hit patterns with spherical or cylindrical lenses attached to a plate needs to be demonstrated with simulation data and, eventually, validated experimentally.

3.2 Readout Section

For the xpDIRC we will study the placement of the focusing system between the bars and the plate, as shown in Fig. 1c and Fig. 2b. The lenses could be either one cylindrical lens for the full width of the plate or an array of spherical lenses, one for each narrow bar. In this configuration, the thickness of the plate may have to increased to retain acceptable levels of the photon transport efficiency through the lenses and the reconstruction and PID algorithms will need to be optimized to deal with the more complicated hit patterns, especially for the array of spherical lenses.

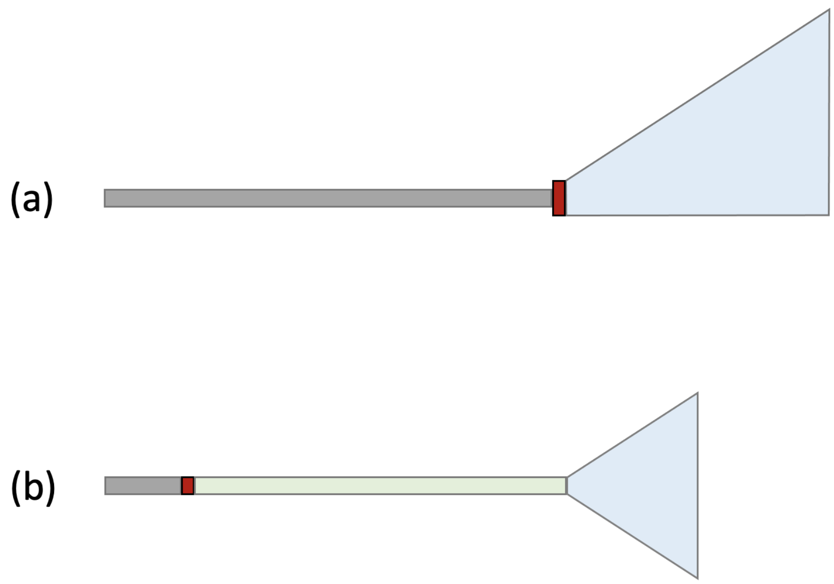

Figure 2: Schematic side view of two readout/prism configurations for the EIC DIRC (not to scale). (a) Baseline design for the hpDIRC in the reference detector with a full-size prism coupled to narrow bars via the focusing lenses; (b) novel xpDIRC hybrid design with the lens placed between the narrow bars and the wide plate, increasing the effective depth of the expansion volume, making a smaller prism size with a smaller sensor area potentially possible. Narrow bars ares shown in gray, wide plates in green, focusing lenses in red, the prism in blue.

The main advantage of this design is that the photon expansion region would start as the photons enter the plate, increasing the effective size of the expansion volume significantly. This could make it possible to decrease the size of the prism from the 30 cm-depth of the hpDIRC, shown schematically in Fig. 2a, to a much smaller size (Fig. 2b). A symmetric shape may aid integration into the main detector and further decrease the amount of DIRC material in front of the EM calorimeters. Since it may be difficult to build the hpDIRC prism, with a width of 35 cm, out of a single fused silica block, we plan to also study a geometry where the single wide plate (35 cm width) is replaced by two plates with a width of 17 cm, separated by a small air gap placed side-by-side. Each plate would be coupled to a narrower, 17.5 cm-wide prism, also separated by a small air gap.

The smaller prism in Fig. 2b would mean a significantly smaller sensor area, and could make a difference in the sensor choice. With the better signal to background ratio and constantly advancing technology, SiPMs could be considered. The more compact design would simplify the integration of the cooling and annealing infrastructure, required for the use of SiPMs in RICH or DIRC counters.

Several simulation studies will be required to evaluate these design changes. The impact of additional reflections in the narrower prism, and of the high dark count rates and afterpulses, on the DIRC reconstruction will have to be studied. The initial feasibility studies would be followed by a detailed mapping of the performance as a function of track polar angle and momentum in second year of the proposed program. The results of this comparison of geometries to the hpDIRC design in terms of performance and cost can also be applied for the Detector-1. The synergy with the hpDIRC prototype program would allow to experimentally validate the new geometry with a relatively small investment. The xpDIRC-related prototype configuration would evaluate the optimized sensor arrangement as well as the potential new focusing approach. While this configuration would very likely offer a significant cost reduction, it has not been experimentally studied so far, requiring experimental validation to decide on the final design.

3.3 Radiator Bar Thickness

The DIRC for the EIC Detector-2 will almost certainly require the purchase of new radiator bars, creating questions about the optimal bar geometry. The hpDIRC bars for Detector-1 are expected to be based on the reused BaBar DIRC bars, each 1225 mm long, 35 mm wide, and 17 mm thick. The maximum length of new bars depends on the size of the available polishing tables, but new processes developed in recent years make bar length between 1500 mm and 2000 mm possible, decreasing the number of required pieces. The width of the bars has to be optimized, together with the lens parameters, as it can impact the performance. The constantly improving photon detection efficiency performance of the photosensors increases the number of detected photons and could make it possible to decrease the thickness of the radiator bar. A very preliminary Geant4 simulation study was performed in which all parameters of the baseline hpDIRC were kept unchanged, except for the bar thickness, which was reduced from 17 mm to 10 mm. The key advantage of the thin hpDIRC is a significant reduction of the multiple scattering at lower momenta, improving the e/π separation performance of the hpDIRC where pion backgrounds are the largest, while maintaining the 3 s.d. performance goal for K/π separation. Furthermore, the 41% reduction in radiator material thickness would provide a significant benefit to the performance of the barrel EM calorimeter and the lower weight of the bar boxes may simplify the design of the mechanical support structure. Although the performance of an hpDIRC with thinner bars would have to be experimentally verified, the feasibility of producing high-quality 10 mm-thick fused silica radiators has already been demonstrated when Nikon Corp. produced a prototype plate for the LHCb TORCH R&D program [2].

4 Activities

The initial xpDIRC development assumes a 3-year program.

The activities in the first year will be focused on feasibility studies of the bar/lens hybrid design with different focusing options and prism geometries, performed with the same Geant4 simulation package used for the hpDIRC. The initial simulation configuration for the hybrid optics was prepared as part of the eRD14 effort. An example of the geometry and expected hit pattern from the standalone DIRC simulation software is shown in Fig. 3.

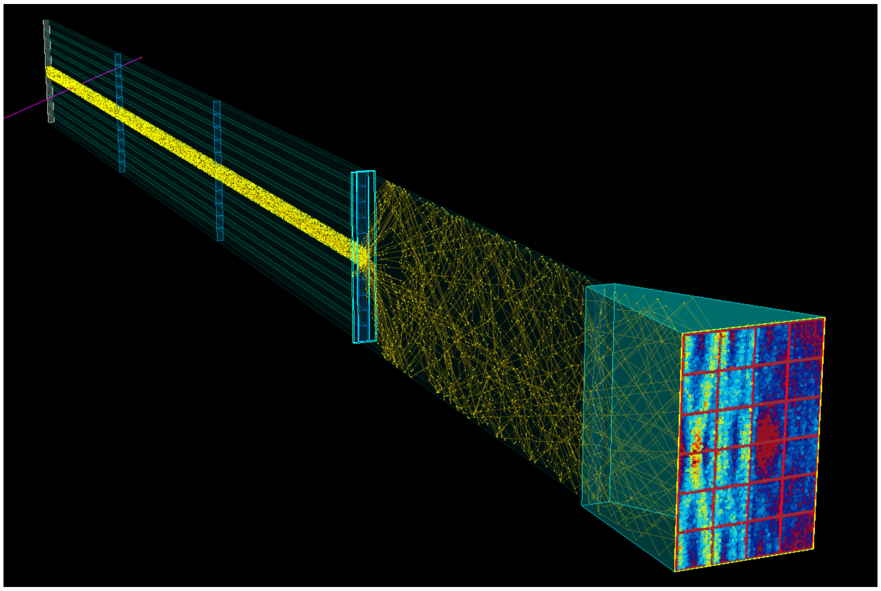

Figure 3: Visualization of the hpDIRC hybrid geometry and an example of the accumulated hit pattern from charged pions, based on the standalone hpDIRC Geant4 simulation package.

The combination of narrow bars with a wide plate and two alternative focusing options will be implemented and the reconstruction will be adjusted to the new type of ring image. For the different prism geometry we plan to study narrow and/or shorter prisms to see if the more complicated image structure will still allow efficient reconstruction with the available reconstruction methods.

In year two we will focus on implementing SiPM readout in the new geometry with the smaller prism. The leading identified geometries will be studied for the optimal bar thickness.

In the final year we plan to quantify the requirements of SiPM performance parameters in terms of maximum allowed dark noise and afterpulsing rates for the xpDIRC design, and corresponding cooling and annealing infrastructures. We hope to be able to take advantage of the synergetic eRD103 hpDIRC prototype test in the cosmic ray setup at SBU and/or with particle beams at Fermilab to validate aspects of the new xpDIRC geometry with the available assembly of bars, plates, prisms, and lenses. However, a new spherical and/or cylindrical lens may have to be procured to test the relevant aspects.

The hpDIRC experts will guide the studies but additional person power, in form of half a Postdoc and an undergraduate student, is crucial to finish the planned tasks on time. In the reduced budget scenario, where the simulation work is performed by a graduate student instead of a Postdoc, some of the initial feasibility studies might shift to year 2. The travel budget will be used to train new members of the group by sending them to GSI to work with the main DIRC simulation expert, or to bring the GSI expert to Jefferson Lab for an extended time to perform the training.

5 Deliverables

5.1 Year 1

- Evaluation of the performance of the hpDIRC hybrid geometry (narrow bars with wide plate, impact on light-guide section decision for Detector-1)
- Evaluation of the performance of the xpDIRC geometry (narrow bars with wide plate and new focusing optics, impact on design of possible DIRC for Detector-2)

5.2 Year 2

- Evaluation of the DIRC performance with thinner bars
- Evaluation of the performance of the xpDIRC geometry with a small and/or narrow expansion volume, with SiPM readout (modeling of SiPM response to radiation damage based on input from experts, cooling annealing requirements)

5.3 Year 3

- Requirements of SiPM performance parameters (dark noise and after-pulsing) for xpDIRC with SiPM readout
- Synergetic test of aspects of new geometry: Testing assembly of spherical lenses (or/and procuring new cylindrical lens)

6 Budget

	100%	80%	60%
Postdoc, CUA, 50%	$70k	$0	$0
Graduate student, CUA, 100%	$0k	$50k	$50k
Undergraduate student, CUA, 100%	$15k	$15k	$15k
Travel, CUA/GSI	$10k	$10k	$0
Total	$95k	$85k	$75k

Table 1: Budget for xpDIRC in first year.

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