Development of a Novel Readout Concept for an EIC DIRC*

K. Dehmelt[1,2], A. Deshpande[1,2], R. Dzhygadlo[3], T. K. Hemmick[1], Md. I. Hossain[4], C.E. Hyde[5], Y. Ilieva[6], G. Kalicy[4], P. Nadel-Turonski[2], C. Schwarz[3], J. Schwiening[3], N. Shankman[1,2], J. Stevens[7], N. Wickramaarachchi[6], and C. Woody[8]

[1]Department of Physics, Stony Brook University, Stony Brook, NY 11794, USA
[2]Center for Frontiers in Nuclear Science, Stony Brook University, Stony Brook, NY 11794, USA
[3]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[4]Catholic University of America, Washington D.C. 20064, USA
[5]Old Dominion University, Norfolk VA 23529, USA
[6]University of South Carolina, Columbia South Carolina 29208, USA
[7]College of William & Mary, Williamsburg, VA 23185, USA
[8]Brookhaven National Lab, Upton, NY 11973

July 17, 2023

1 Executive Summary

The objective of this program is to pursue opportunities to reduce the material budget and the cost of the DIRC counter for the EIC, without loss of performance, by investigating fundamental DIRC performance limits and new optical configurations. The barrel high-performance DIRC (hpDIRC) has been adopted for the ePIC detector and is an attractive solution for Detector-2. In this program, we 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 ePIC and, in particular, to Detector-2. This novel geometry goes well beyond the design established for ePIC and may enable 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 hybrid optics and SiPM readout constitutes an advancement of DIRC technology.

*Contacts: G. Kalicy (kalicy@cua.edu), J. Schwiening (J.Schwiening@gsi.de)

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 ePIC 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 HRPPD 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 FY23 Progress report

In FY23, the primary objective of our activities was to explore various possibilities for alternative designs of the high-performance DIRC (hpDIRC) detector, which is being developed for the ePIC detector. The fundamental concept entails the use of synthetic fused silica bars as radiators and light guides, enabling photons to be focused before reaching pixelated sensors located in the detector plane beyond the expansion volume. However, several options remain for the configuration of optics in the pre-readout section within each bar box. To tackle this question, two specific deliverables were established for the first year of the program. The first involved evaluating the performance of the hybrid geometry (narrow bars with a wide plate), which has a potential impact on the decision about the light guide section for the ePIC hpDIRC. The second objective aimed at evaluating the performance of the xpDIRC geometry, featuring narrow bars with a wide plate and new focusing optics, with particular relevance for the potential design of a DIRC for Detector-2. Both objectives were effectively accomplished.

In the ePIC hpDIRC baseline design, each bar box comprises 10 long fused silica bars,

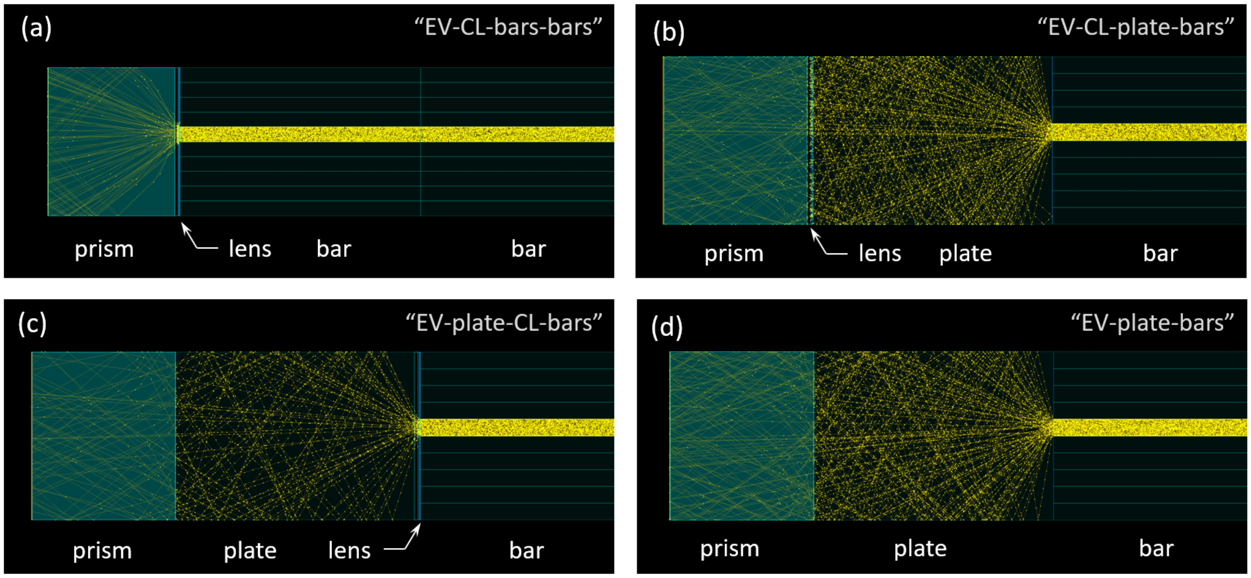

Figure 1: Geant4 visualization (top view) of four radiator–light guide configurations for the EIC DIRC. The paths of Cherenkov photon from a single pion at 6 GeV/c and 30° polar angle are shown in yellow. (a) hpDIRC design using narrow bars for both the active area and the light guide section, in combination with a cylindrical lens (CL), placed between the bars and the prism (EV); (b) conservative xpDIRC hybrid design with narrow bars coupled to a wide plate as light guide via a cylindrical lens; (c) novel xpDIRC hybrid design with the cylindrical lens placed between the narrow bars and the wide plate; (d) simplified design without focusing for comparison, with narrow bars coupled to the wide plate.

with a thickness of 17 mm and a width of 35 mm, placed side-by-side, separated by a small air gap. To achieve the total length of 458 cm, three BaBar DIRC bars are glued end-to-end, forming a 367.5 cm-long bar, which covers the "active area", the angular region in which the hpDIRC is required to deliver its full performance. An additional piece, the so-called "light guide" section, with a length of about 90 cm in ePIC, is glued to the end of the bars to transport the Cherenkov photons to the lens and the prism.

Several options are still being considered for the light guide geometry and were implemented into the standalone Geant4 DIRC simulation package. The baseline arrangement for the ePIC hpDIRC, shown in Fig. 1a, is to use narrow bars with a width of 35 mm for the entire bar length[1]. The required 120 light guide bars could be either newly fabricated by industry or made from extracted BaBar DIRC bars by cutting them to length and polishing one end. The so-called "hybrid geometry" uses one wide plate as a light guide, instead of many narrow bars, to reduce the cost of the light guide fabrication and, possibly, improve the performance. In the conservative xpDIRC design (Fig. 1b) the bars are coupled to the plate and a 3-layer cylindrical lens is placed between the plate and the prism. The novel xpDIRC geometry places the 3-layer cylindrical lens between the bars and the plate, as shown in

[1]Note that the ePIC hpDIRC baseline design uses 3-layer spherical lenses instead of cylindrical lenses, which are used in this study to simplify the comparison of the bar/plate results.

Fig. 1c. In order to facilitate a comprehensive comparison, two alternative options were implemented, which involved a direct connection of narrow bars to the wide plate (Fig. 1d), without any focusing.

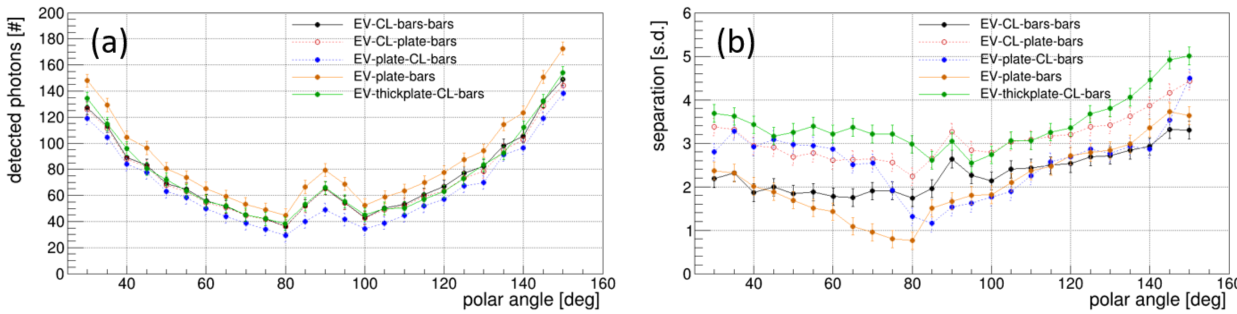

Figure 2: Photon yield (a) and π/K separation power (b) as a function of the polar angle at 6 GeV/c for different DIRC "light guide" and focusing configurations (see Figs. 1,3 for an explanation of the labels).

The performance of the configurations discussed above is shown in Figures 2. The configuration without focusing has the highest photon yield since photon loss due to absorption and reflection from the sides of the lens is avoided. A moderate decrease of 10–20% in photon yield is observed when the lens is located between the light guide (bars or plate) and the expansion volume. For the placement between the bars and the plate, the focal length of the 3-layer cylindrical lens was adjusted for the longer distance to the sensors and the height of the lens was reduced from the original 50 mm to 17 mm, the thickness of the bar and plate, to create a slim bar box of uniform thickness. An additional 10–15% photon loss occurs if the lens is placed instead between the bars and the plate, due to the reduced lens height, which causes additional reflections of the photons on the unpolished sides of the lens.

The corresponding π/K separation results show that, among the various arrangements, only the configuration where the cylindrical lens is positioned between the wide plate and the expansion volume comes close to achieving the desired 3 s.d. separation power at 6 GeV/c across all polar angles[2]. Alternative lens positions clearly demand additional investigations to determine if their performance can be enhanced. As anticipated, the configuration without focusing exhibits inferior separation power and is unable to meet the EIC PID requirements.

To avoid the loss of photons inside of a lens with reduced height, the thickness of the plate was increased to 50 mm, the same as the height of the cylindrical lens, as illustrated in Fig. 3. The configuration featuring the thicker plate, depicted in green in Fig. 2, exhibits an enhanced photon yield and successfully achieves the necessary separation power for almost all polar angles.

While such a thick plate is undesirable from the perspective of mechanical integration and in terms of the material budget for systems behind the DIRC, this xpDIRC geometry

[2]This study does not yet include 3-layer spherical lenses, which are the baseline solution for the ePIC hpDIRC and have been shown to achieve more than 3 s.d. π/K separation at 6 GeV/c for the entire range of polar angles. The main reason is that the reconstruction and PID algorithms first need to be adjusted for the more complicated hit patterns created by spherical lenses placed between the bars and the plate.

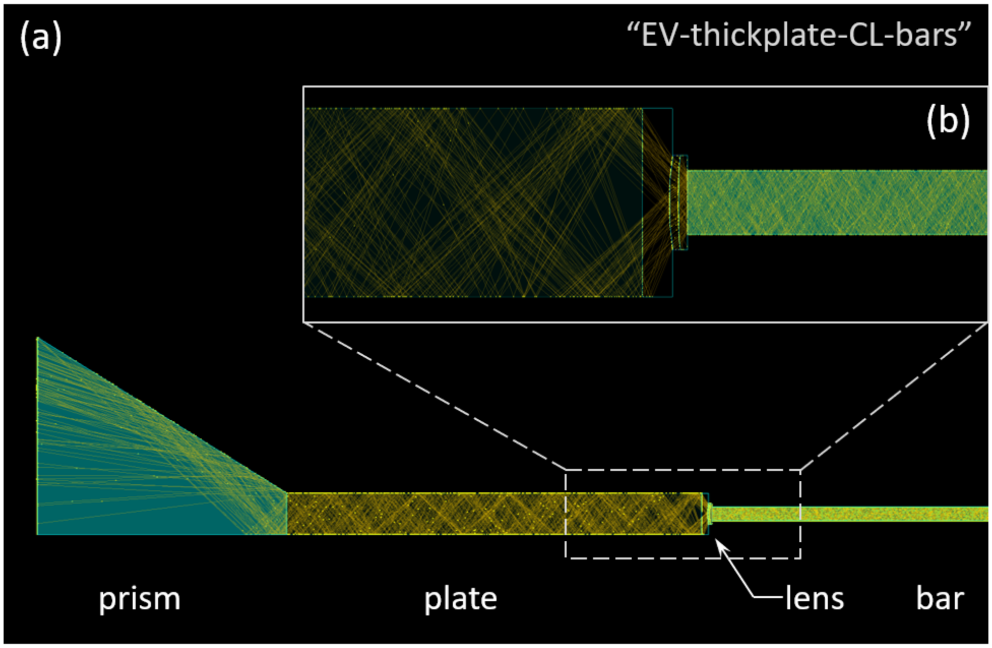

Figure 3: Geant4 visualization of an xpDIRC "thick plate" hybrid design with the cylindrical lens placed between the narrow bars and a wide plate (50 mm thickness). Side view (a) and a close-up of the bar-lens-plate region (b).

will be studied further with thinner bars (10 mm thickness, the topic of our FY24 proposal), which are expected to work with lenses of reduced height, which, in turn, will allow us to reduce the plate thickness without large losses in photon yield.

This encouraging result for the xpDIRC hybrid optics is still significantly worse than the ePIC hpDIRC baseline design with narrow bars and 3-layer spherical lenses, placed in front of the prism. However, additional improvements to the π/K separation power of the novel xpDIRC hybrid design may result from the use of individual 3-layer spherical lenses, placed between each bar and the plate, instead of the cylindrical lens. The performance of this configuration will be studied for the BaBar DIRC bars in the remainder of FY23 and for the thin bars in FY24.

4 R&D plan for FY24

Building on the progress made in FY23, the proposed activities in FY24 focus on further exploring the performance of the bar/plate hybrid design by extending it to thinner bars in the active area, correspondingly thinner plates as light guides, investigating ways to reduce the size of the prism expansion volume, and the possible application of SiPM as photosensors.

4.1 Proposed Activities

The promising results for the geometry with narrow bars coupled to a thick plate via a wide cylindrical lens warrant further investigation. Using an array of 3-layer spherical lenses, with focal lengths optimized for imaging the photons through the plate and prism, could further improve the performance. The resulting changes to the ring image require a tuning of the reconstruction and particle identification algorithms.

The 50 mm thickness of the thick plate geometry, driven by the height of the lens, would triple the material budget of the DIRC radiator for polar angles below 20°, which would have a significant impact on any system after the DIRC. The lens height has not been optimized yet. We plan to perform an optimization of the plate thickness and lens height for different bar thickness values, in order to optimize the PID performance while minimizing the material budget.

A reduced bar thickness would not only benefit the detector systems behind the DIRC, in particular, a high-resolution barrel electromagnetic calorimeter but also reduce the likelihood of multiple scattering inside the radiator bar. Since multiple scattering is known to be one of the main effects limiting the e/π separation power of the DIRC at low momentum, a thinner bar may offer a significant increase in the e/π separation limit of the DIRC.

A simulation study, performed in FY23, demonstrated that multiple scattering in the DIRC bars, as well as optical aberrations of the lenses, have a significant impact on the DIRC performance at high momentum. The ePIC hpDIRC baseline design, with 3-layer spherical lenses placed between narrow bars and the 30 cm-deep expansion volume prism, was compared to a hypothetical configuration in which the lenses were replaced by a mathematical algorithm performing ideal focusing, without any aberrations. Figure 4 shows the resulting DIRC π/K separation as a function of momentum for different physics processes enabled or disabled for the ePIC configuration (a) and the ideal focusing (b).

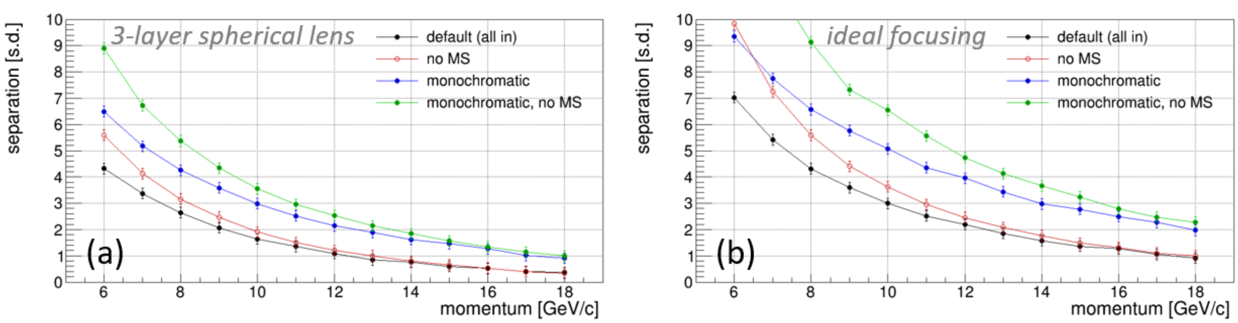

Figure 4: π/K separation power as a function of the particle momentum at 30° polar angle for the ePIC hpDIRC with two focusing scenarios: (a) 3-layer spherical lens and (b) hypothetical ideal focusing without aberrations. The symbol colors correspond to different physics processes being switched on or off. Black markers denote the standard Geant simulation process ("default"); multiple scattering was disabled for the red markers ("no MS"); chromatic effects in the photon emission and propagation were disabled for the blue points ("monochromatic"); both multiple scattering and chromatic effects were disabled for the green symbols.

The smaller bar thickness and the longer focusing distance of the xpDIRC design will result in lenses with larger radius values for the 3-layer spherical lens, which could reduce the optical aberrations and improve the performance. The results also suggest that a performance increase can be achieved by further reducing chromatic effects in the bar. This could be accomplished by reducing the optical bandwidth of the DIRC, for instance by using SiPM or MCP-PMTs with the quantum efficiency shifted to larger wavelengths. We will study lens design options and chromatic dispersion mitigation in FY24.

Another possible advantage of the xpDIRC hybrid, with the lenses placed between the bars and the plate, is that the expansion of the ring image effectively starts at the lens position. This increases the expansion distance by a factor of 3 in the ePIC geometry, reducing the requirements for the depth of the expansion volume. We will study the performance with smaller fused silica prisms, as well as with prisms with different shapes. Figure 5 shows a comparison of the ePIC hpDIRC baseline geometry (a) compared to a novel xpDIRC geometry with a shorter symmetric prism (b).

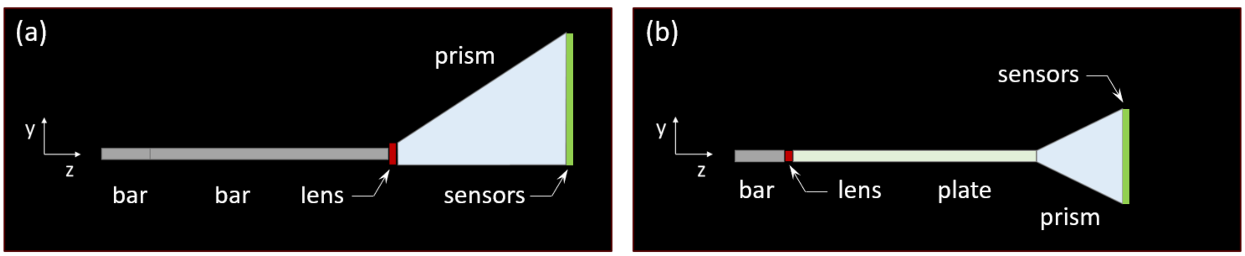

Figure 5: Schematic side view of two readout/prism configurations for the EIC DIRC (not to scale). (a) Baseline design for the ePIC hpDIRC with a full-size prism coupled to narrow bars via the spherical lenses; (b) novel xpDIRC hybrid design with the lenses placed between the narrow bars and the wide plate, increasing the effective depth of the expansion volume, making a smaller prism size with a smaller sensor area potentially possible.

A smaller prism not only reduces the material budget in the endcap region of the detector and simplifies the integration of the DIRC into the experiment, but also shrinks the size of the sensor area, lowering the cost of sensors and electronics and increasing the signal-to-noise ratio (SNR) of the Cherenkov photons relative to readout background. This could be a major advantage in a scenario where SiPMs are used as photodetectors. Their high dark count rate, as well as afterpulsing due to radiation damage, currently prevent the use in the ePIC hpDIRC. A smaller prism is potentially easier to integrate into a cooling and annealing environment, which could further improve the SNR by several orders of magnitude. We will study the possible use of SiPM, and the impact of the associated dark count and afterpulsing rate, in FY24 by implementing the performance parameters of the state-of-the-art SiPMs.

Discussions with the optical industry identified the fabrication of the expansion volume in ePIC, with a width of 35 cm, from a single block of synthetic fused silica, as the main cost driver for the prism. We will investigate a new design in which each light guide plate, with a width of 35 cm, will be replaced by two narrower plates with a width of 17.5 cm, positioned side-by-side with a small air gap in between. Each plate will then be coupled to a narrower prism, measuring 17.5 cm in width, also separated by a small air gap. The cost of two narrow prisms is expected to be substantially below the cost of a wide prism, and the fabrication time is expected to be significantly reduced. The effect of the additional reflections inside the narrower prisms will be studied in simulation.

4.2 Plans beyond FY24

In the third 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 with appropriate cooling and annealing infrastructures. We plan to continue to investigate further improvements of the hpDIRC optics, based on the results of our simulation work in FY23 and FY24.

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 elements.

4.3 Personnel Required and Available for 2024

The proposed R&D program is synergetic with the project R&D hpDIRC proposal eRD103. It will be carried out in a collaborative effort of CUA, GSI, ODU, and SBU, and includes the hpDIRC experts from the former eRD14 consortium.

Significant in-kind workforce contributions from: Dr. Roman Dzhygadlo (GSI), Dr. Charles Hyde (ODU), Dr. Greg Kalicy (CUA), Dr. Carsten Schwartz (GSI), Dr. Jochen Schwiening (GSI), Dr. Pawel-Nadel Turonski (SBU), Nilanga Wickramaarachchi (CUA).

4.4 Deliverables

Year 2

- Evaluation of the DIRC performance with thinner bars, including the xpDIRC hybrid optics option with spherical lenses.
- Evaluation of the performance of the xpDIRC geometry with a small and/or narrow expansion volume.
- Evaluation of the DIRC performance with SiPM readout based on current state-of-the-art sensors.

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).

4.5 Budget

It is essential to continue the support for Md. Imran Hossain, the recently hired graduate student at CUA, who is in the process of becoming an expert in the DIRC simulation and reconstruction software. The addition of a half-time Postdoctoral researcher to this project would be highly beneficial. In a scenario with a reduced budget, where the simulation work is performed by a graduate student without the assistance of a Postdoc, some of the studies may need to be postponed to the third year.

The travel budget will be used to train new team members and maintain crucial collaboration with the GSI group. This will involve sending personnel from CUA to GSI to work with the main DIRC simulation expert there or bringing the GSI expert to CUA/Jefferson Lab to provide necessary training and support.

	100%	80%	60%
Graduate student, CUA, 100%	$50k	$50k	$50k
Postdoc, CUA, 50%	$60k	0	0
Undergraduate student, CUA, 100%	0	$15k	0k
Travel, CUA/GSI	$15k	$15k	$15k
Total	$125k	$80k	$65k

Table 1: Budget for the second year, FY24.