EIC Detector R&D Progress Report

Project ID: eRD14
Project Name: PID Consortium for an integrated program for Particle Identification (PID) at a future Electron-Ion Collider
Period Reported: from 01/01/2020 to 06/26/2020
Contact Persons: Pawel Nadel-Turonski and Yordanka Ilieva
Project Members: The eRD14 Collaboration (See the FY21 eRD14 Proposal for a complete list of collaborators)

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Abstract

Excellent particle identification (PID) is an essential requirement for a future Electron-Ion Collider (EIC) detector. Identification of hadrons in the final state is critical to study how different quark flavors contribute to nucleon properties. Reliable identification of the scattered electron is important for covering kinematics where pion backgrounds are large. The EIC PID consortium (eRD14) was formed to develop an integrated PID program using a suite of complementary technologies covering different ranges in rapidity and momentum, as required by the asymmetric nature of the collisions at the EIC. The PID consortium has been working closely with the relevant groups in the EIC community to ensure that our specific R&D projects are compatible with the detector concepts that are being considered.

Contents

1 Introduction

Identification of hadrons in the final state is essential for key EIC measurements formulated in the EIC White Paper and referenced in the NSAC Long Range Plan. These include 3D imaging of the nucleon in momentum space through semi-inclusive DIS (where flavor tagging can tell us about the transverse momentum distributions and, potentially, the orbital angular momentum of the strange sea), and open charm (with decays of D-mesons into kaons), which is important for probing the distribution of gluons in protons and nuclei.

Satisfying the PID requirements within the very asymmetric kinematics of the EIC (discussed in detail in the eRD14 proposal for FY20) requires a suite of detector technologies that can address the specific challenges (in terms of momentum coverage, available space, *etc.*) encountered in various ranges of rapidity. Thus, the integrated PID program pursued by the eRD14 Consortium includes different detector systems for each endcap and the central barrel, as well as corresponding sensor and readout solutions. While we ensure compatibility with the detector concepts developed for the EIC, all the funded R&D being pursued by the consortium is conceptually novel. The dual-radiator RICH (dRICH) for the hadron endcap is the first such design for a solenoid-based collider detector. The modular aerogel RICH (mRICH), primarily intended for the electron endcap, introduces lens-based focusing, which improves momentum coverage and reduces the required sensor area. The compact, high-performance DIRC (hpDIRC) for the solenoid barrel combines new optics for spatial imaging with good timing (< 100 ps rms) to allow for a significant improvement in momentum coverage compared with the state-of-the-art. The funded work on photosensors in high magnetic fields and on adaptation of LAPPDs to EIC requirements is also aimed at developing a new generation of devices. Starting in FY18, the sensor effort has been extended to include corresponding readout electronics.

At the end of FY19 the consortium was asked to develop a four-year plan to reach readiness to write a technical design report (TDR). The plan was presented during the in-depth review of the eRD14 Collaboration, on September 19, 2019. https://indico.bnl.gov/event/6819/

The first year of the plan coincided with the FY20 proposal, presented to the committee in July 2019, but envisioned an increase in funding for FY21 – 23 as the consortium would transition from generic to targeted R&D. For FY20, the top priorities were to transfer the PANDA DIRC prototype to the U.S., start building the dRICH prototype, and to investigate whether LAPPDs could become a viable photosensor solution for the EIC. We appreciate the positive and constructive feedback from the committee.

The consortium has also been closely following the spending of the approved funds. Since funds do not become available at the beginning of the year, and the handling of invoices can be slow at some institutions, there could be an appearance of unspent funds during a year, but eRD14 does not have a significant actual carryover in FY19, nor is one expected in FY20.

2 Hadron Identification Detectors

2.1 Summary

The funded R&D on the three Cherenkov systems has been proceeding very well, and they all promise significant advances over the fallback options (single-radiator gas RICH for the dRICH, proximity-focusing aerogel RICH for the mRICH, or a DIRC geared only towards spatial imaging or timing).

2.2 Dual-Radiatior RICH (dRICH)

The dual Ring Imaging Čerenkov (dRICH) detector is under design and development to provide full hadron identification (π/K/p separation better than 3σ) from $\sim$3 GeV/c to $\sim$60 GeV/c in the ion-side end cap of the EIC detector. It also offers a remarkable electron and positron identification ($e^{\pm}/\pi$ separation) from a few hundred MeV/c up to about 15 GeV/c. The proposed geometry covers polar angles from $\sim 5°$ up to 25°.

2.2.1 Past

2.2.1.1 What was planned for this reporting period

The main technical goals for 2020 have been: procurement of the prototype components and beginning of construction, continuous improvement of the software tools for further refinement of the baseline design and preparation for the prototype tests. Further co-funding requests for prototyping (both dRICH and mRICH) and critical component tests are being submitted to the Italian National Institute of Nuclear Physics (INFN).

The dRICH activities planned in this period were detailed with the R&D Committee in the September 2019 meeting with the goal of a TDR readiness in 2023: (1) Prototype design, simulation and implementation, (2) Basic mechanics, (3) Electronics adaptation, (4) Component test and selection, (5) Start of INFN funds. The start of the SiPM irradiation program is anticipated to 2020 thanks to the recently broadened INFN expertise. These activities were planned and structured such that the following major objectives, dRICH baseline prototype realization, initial SiPM irradiation campaign, and first beam test, are achieved in FY21.

2.2.1.2 What was achieved?

The discussion within the Yellow Report PID working group has highlighted the importance to have a flexible framework allowing for quick adaptation and performance verification of any proposed detector to changing external constraints and complementary requests arising during integration exercises with other subsystems, such as tracking and calorimetry. The eRD14 dRICH has already developed a complete Geant4 simulation, reconstruction methods for events in the EIC realistic conditions [1], and optimization algorithms based on machine learning techniques.

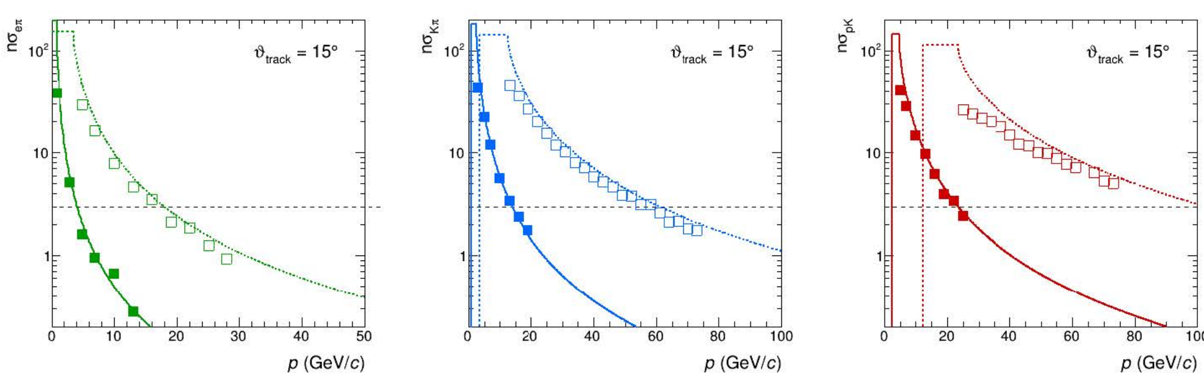

Figure 2.2.1: dRICH performance parameterization (solid and dotted lines) and comparison with full Geant4 simulation (discrete points): electron-pion (left) kaon-pion (center) and proton-kaon (rigth) separation in units of angular resolution as a function of particle momentum.

[1] L. Barion et al., JINST 15 (2020) 02, C02040.

In this reporting period, new tools are being developed for fast performance evaluation and for comparisons with alternative configurations. These include an analytic analysis based on the optical property of each single component and a global performance parameterization based on a full Geant4 simulation, see Fig. 2.2.1. We finalized and published our original approach to detector-design optimization, based on Bayesian optimization and machine learning [2]. This method provides a general optimization framework with parallelized computation associated with automated convergence criteria; it is implemented on python sklearn machine learning libraries, and represents an efficient way to re-optimize relevant design parameters and to consolidate the performances of the dRICH once the prototype test results will be available. The method can be adapted for design optimization of any other detector (with realistic, detailed model) or, even more interesting, to the simultaneous optimization of multiple detectors.

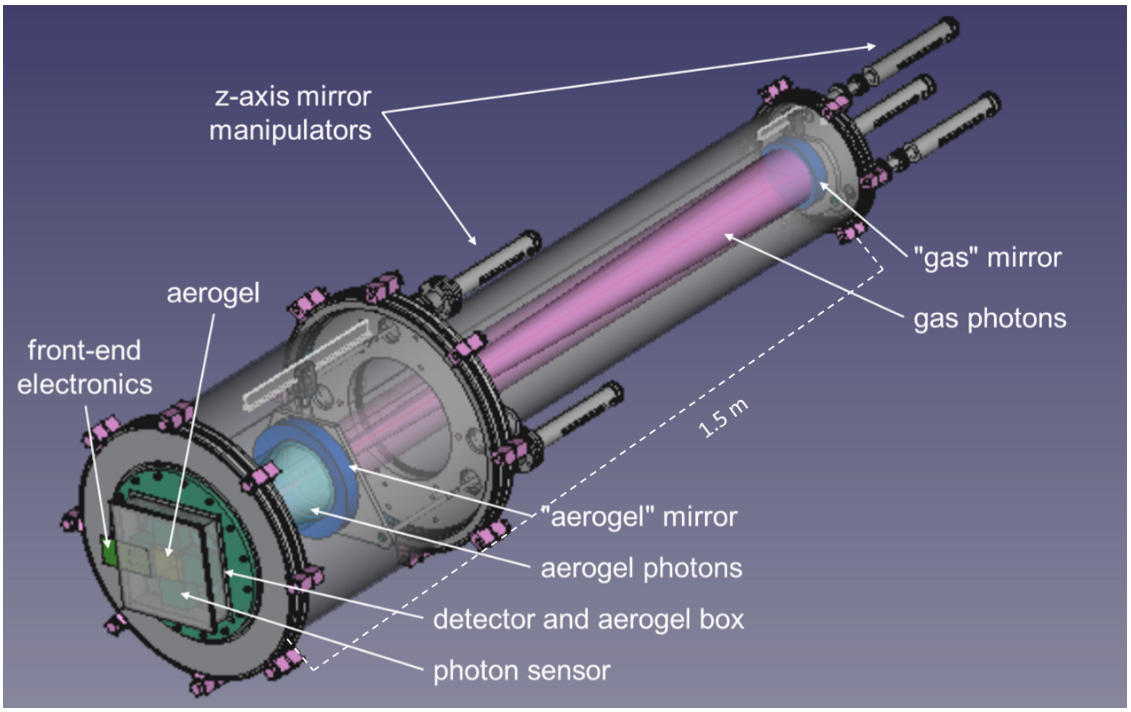

Figure 2.2.2: 3D model of the optimized dRICH prototype.

The prototype design was revisited (activity (1) listed in Section 2.2.1.1) in order to allow for simultaneous imaging of the two radiators. This will simplify the prototype operations during the tests and challenge the photon pattern reconstruction with a realistic occupancy. The prototype (activity (2) listed in Section 2.2.1.1) is a cylinder made of standard vacuum pipes and closing flanges to contain the cost and support pressures different from atmospheric pressure, see Fig. 2.2.2. The system allows for efficient gas exchange and, in principle, also for adjustment of the refractive index and consequent flexibility in the gas choice (in support of the search for alternatives to greenhouse gasses). The mirrors are mounted on the flanges and the alignment system uses three z-axis vacuum manipulators with spherical joints to translate and rotate the mirror support, while the mirror weight load is sustained by a carriage free to run along a z-axis rail. The system allows to align the mirrors and adjust the focal length while the cylinder is pressurized. This opens the possibility to use a mirror with a central hole for the aerogel. Depending on the longitudinal position of the mirror, the Cherenkov cone generated by only the aerogel, only the gas, or both radiators can be imaged. All the access points (*i.e.*, customization) are concentrated onto the vacuum flanges.

[2]E. Cisbani et al., J. Inst., 15 (2020) DOI:10.1088/1748-0221/15/05/P05009.

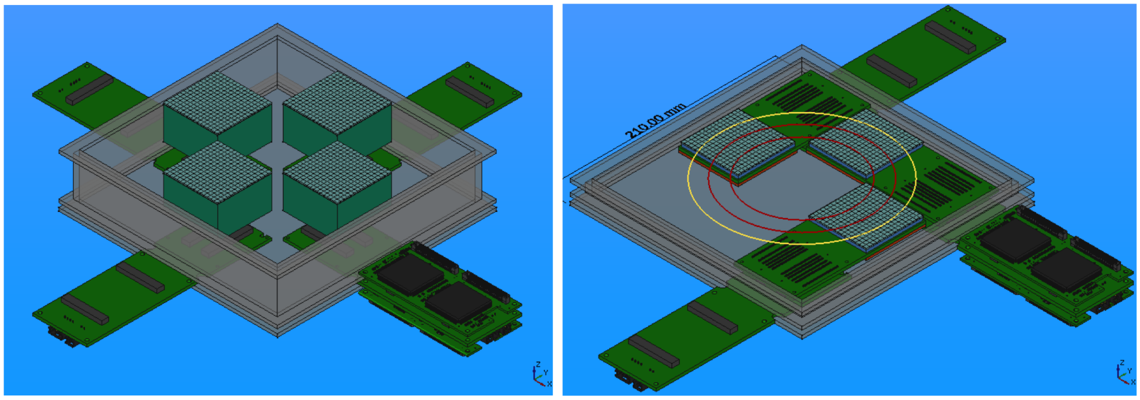

Figure 2.2.3: dRICH photo-sensor box for the already acquired 3 mm-pixel sensor arrays together with the reference MAROC3 readout electronics: multi-anode H13700 MA-PMTs (left) and MPPC matrices (right).

Using INFN funds (activity (5) listed in Section 2.2.1.1), contracts have been awarded for the standard vacuum parts and for the custom flanges. Also, several samples of aerogel have been ordered from the Russian producer. The samples have refractive indices between 1.02 and 1.03 and dimensions suitable to serve both the dRICH and mRICH prototype-test campaigns. New INFN funds have been granted for 2020. These funds will be instrumental for the mirror-system realization. The procurement of the freon gas, mirrors, and manipulators has been initiated.

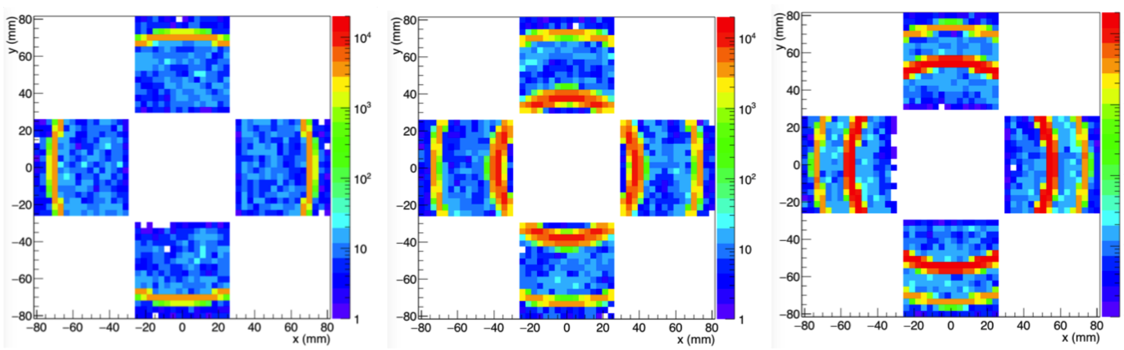

Figure 2.2.4: dRICH prototype imaging of kaons at different momenta spanning the transient region between the two radiators' working intervals. At 10 GeV/c (left) only the almost saturated aerogel ring is visible. At 15 GeV/c (center) the gas ring becomes evident. At 25 GeV/c (right) the gas ring has increased in radius towards saturation.

The photo-sensor box was designed (activity (3) in Section 2.2.1.1) following the same principles that had been applied to the mRICH prototype. The box comprises a frame and a base. The sensors are mounted on the base, while the frame connects the base to the prototype. Gas- and light-tightness is obtained by means of foam rings compressed between the screwed aluminum elements. The base provides thermal contact for the cooling of the internal components and, in particular, the heat exchange with the warm side of the Peltier cells used to bring the SiPMs (when this type of photo-detectors are used) to the working point temperature. The box houses an array of photo-sensors surrounding a central hole where the aerogel radiator can be inserted. The photo-sensor box is mounted on the front flange and is separated from the internal volume by a transparent window. The window isolates the sensor and aerogel radiator from the inner volume of purified gas and can be design to filter UV light in order to suppress Rayleigh scattered photons in the aerogel and to reduce the light chromatic dispersion in the gas, in order to improve the resolution. The box has been designed to work with the reference readout systems already employed for the mRICH prototype, *i.e.*, H13700 multi-anode photo-multipliers (MAPMTs) and S12642-1616PA multi-pixel photon-counter (MPPC) matrices, and the MAROC3 electronics readout [3], see Fig. 2.2.3. These already tested large area instruments are essential to validate the dRICH concept and verify the optical performance of the dRICH prototype shown in Fig. 2.2.4.

The proposed prototype configuration has been modeled and simulated in GEMC/GEANT4. The typical expected number of detected photons is around 6 for the aerogel and 30 for the gas, depending on the prototype configuration details. The prototype resolutions are summarized and compared with the one expected in the EIC detector in the figure shown in Fig. 2.2.5. The uncertainties are similar to the ones expected in the EIC configuration, except for the pixel error with the aerogel radiator that, despite being larger due to the adapted imaging (reduced path of photons), is still comparable to the chromatic error and can be safely controlled by simulations. The prototype allows the study of the Čerenkov yield and resolution as a function of the optical properties of the radiators and wavelength filters. The chromatic dispersion of the aerogel, the expected dominant error in EIC configuration, can be studied with the insertion of optical filters, a method successfully employed in the past [4]. The prototype is instrumental to validate the dual-radiator approach to cover the momentum range of few GeV/c – multi tens of GeV/c. The study of the response with a meson beam at momenta intermediate between the two radiators' working ranges is of particular interest.

1 p.e. error (mrad)		dRICH Aerogel Prototype	dRICH Aerogel EIC	dRICH Gas Prototype	dRICH Gas EIC
Pixel	(3mm pixel)	1.9	(0.6)	0.6	(0.5)
Chromatic	(300 nm filter)	1.8	(2.2)	0.6	(0.5)
Emission	(1 cm out of focus)	0.3	(0.3)	0.4	(0.6)
Tracking	(0.5 mrad)	0.4	(0.3)	0.4	(0.4)
Total		3.0	(2.3)	1.1	(1.0)

Figure 2.2.5: Expected Čerenkov-angle resolution of the dRICH prototype compared to the simulated EIC detector performance.

To pursue a comprehensive investigation of the SiPM usage for RICH detectors at EIC, a collaboration has been initiated among six INFN groups interested in the SiPM application for Čerenkov imaging. In addition to the groups already represented within the eRD14 Consortium, the new INFN units provide complementary resourses and expertise as they have been involved in the readout electronics of the COMPASS RICH and ALICE TOF, and the cryogenic SiPM readout and mass production of the DARKSIDE experiment. These enlarged INFN manpower and expertise are essential for the successful carry-out of a complete program on the assessment of the single-photon detection by post-irradiation SiPMs and their readout electronics.

The collaboration has defined a path towards a possible TDR in the next 2 – 3 years and, in particular, the priority goals to be achieved in FY21, namely the use of irradiated SiPMs at the planned dRICH prototype beam test. A wide-range survey of the available SiPM candidates has been initiated. The development of a dedicated readout electronics compatible with the SiPM

[3] M. Contalbrigo et al., Nucl. Instrum. Meth. A 952 (2020) 162123.

[4] M. Contalbrigo et al., Nucl. Instrum. Meth. A766 (2014) 22

temperature treatment has been planned based on the ALCOR chip, an in-house INFN development. Designed for cryogenic applications, the chip applies a time-over-threshold analysis of the discriminated signals and can be evolved following the dRICH specifications. It can be used in conjunction with a possible signal pre-conditioning (by a high-frequency filter). It offers an alternative to the high-frequency sampling approach already pursued by eRD14 [5]. Units of 4×8 SiPMs will be assembled to be readout by one 32-channel ALCOR chip. Up to 6 units could be readout by a single FPGA test board. This configuration allows to test SiPMs from different producers and at different levels of irradiation, from 10^9 up to 10^{11} $\mathrm{cm}^{-2}\,\mathrm{n}_{\mathrm{eq}}$. Such an active surface is large enough to ensure a reliable statistics for each SiPM selection for the laboratory characterization. At the same time, it allows imaging tests with the prototype, providing a validation of the full readout chain and a proof-of-principle of the post-irradiated SiPM application for single photon detection, see Fig. 2.2.6. The collaboration with the new INFN groups allows to cover all the aspects of the dRICH and SiPM R&D, from the optical customization to the ASIC development. It also opens the possibility to perform preliminary beam tests at the PS facility at CERN and irradiation tests at the proton beam facility operated by INFN TIFPA in Italy. Also, the INFN team is collaborating with JLab to use the pair spectrometer in Hall D, complemented by a tracking system, as a facility for detector tests. In addition to the Fermilab test-beam facility, these options would facilitate the development and optimization of the Čerenkov prototype optics and readout.

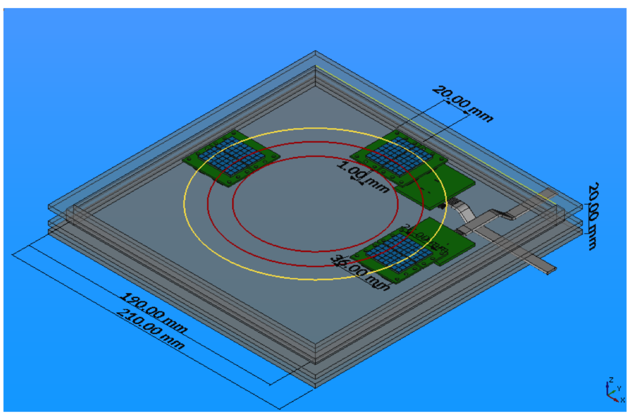

Figure 2.2.6: dRICH detector box instrumented with the irradiated SiPM units readout by the compact ALCOR front-end electronics.

2.2.1.3 What was not achieved?

The prototype assembling activity and activity (4) listed in Section 2.2.1.1 have not started yet. Partially, this is due to the COVID-19 pandemic restrictions. Partially, it is due to the new ideas and developments that suggested to not freeze the design in view of further optimizations. Among these are: the simultaneous imaging (as in the designed EIC dRICH detector), the use of irradiated SiPM sensors, the use of (noble) gas at pressure greater than the atmospheric (as possible to evaluate Freon-based gases), the reduced gap lengths.

2.2.1.4 How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

The COVID-19 pandemic has limited the hardware activity in laboratory and in preparation of the beam tests. Nevertheless, the design and planning activities made important progress so that we do not foresee any delay in achieving in FY21 our main objectives of prototype realization and first beam test.

[5] The consideration of alternative readout electronics was one of the Committee recommendations in their last review report.

2.2.1.5 How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

Travel funds could not be spent due to travel suspensions. However, they cover the cost of only one trip from the E.U. to the U.S. and will be likely spent within this FY.

2.2.1.6 Do you have running costs that are needed even if R&D efforts have paused?

The planned activity for the first part of the year was concentrated on design studies and procurement. Such activity has not paused during the pandemic crisis and, likewise, so has not the running cost for manpower.

2.2.2 Future

2.2.2.1 What is planned for the coming months and beyond? How, if at all, is this planning different from the original plan?

The activity for the coming months is organized as a function of the FY21 goals discussed with the R&D Committee in September 2019: basic prototype realization, first beam test, and SiPM irradiation program. The dRICH prototype design will be finalized. Also, we will continue the components procurement and will initiate the component characterization, testing, and assembling with the goal to be ready for the beam test in summer 2021. The plans for the SiPM irradiation program in FY21 are detailed in the proposal document.

2.2.2.2 What are critical issues?

The increased INFN expertise ensures that the dRICH prototype realization and the SiPM irradiation program can be timely realized if supported by the EIC R&D program. With the new INFN groups, the dRICH in-house experience covers all the technical aspects from RICH realization to SiPM and ASIC chip development. As a consequence, the technical risk is minimized.

2.3 Modular Aerogel RICH (mRICH)

This lens-based, compact, and modular Aerogel RICH detector provides hadron PID capability from 3 to 10 GeV/c (for π/K separation) and electron PID (for e/π separation) below 2 GeV/c. The details of this detector design can be found in the eRD14 FY21 proposal and in our mRICH publication [6]. In this report, we highlight progress made on the mRICH project since January 2020.

2.3.1 Past

2.3.1.1 What was planned for this reporting period

The planned major activities for this period included: (1) continued data analysis of the second mRICH beam-test performed at Fermilab in June of 2018; (2) preparation of the third mRICH beam test with tracking capabilities; (3) implementation of an mRICH array in the sPHENIX experiment in the forward rapidity region using Fun4All simulation framework; and (4) active participation of the EIC Yellow Report activities.

[6] X. He for the EIC PID Consortium (eRD14 Collaboration), https://doi.org/10.1142/S2010194518600807

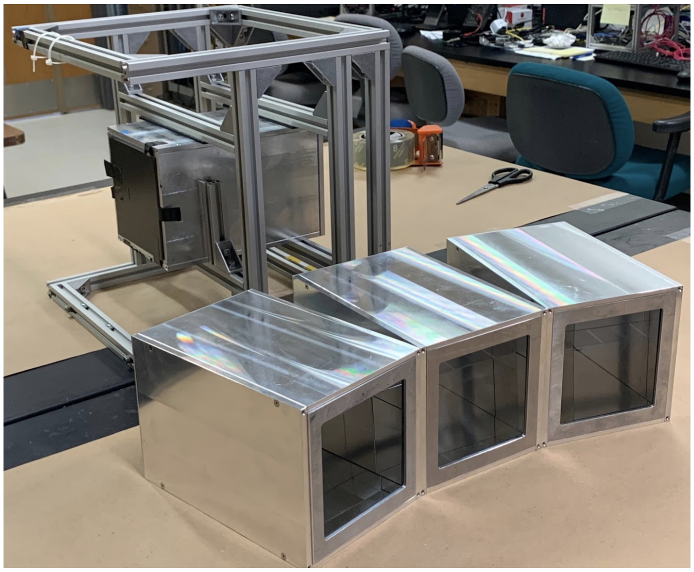

Figure 2.3.7: Newly constructed mRICH modules. The design is an exact copy of the second mRICH prototype, which was used in a beam test at Fermilab in 2018.

2.3.1.2 What was achieved?

Preparation of the next mRICH beam test with tracking capability was one of our major R&D efforts in this report period. Specifically, we worked on planning a beam test in Hall-D at JLab using secondary electron beam with momentum ranging from 1 to 6 GeV/c in early May of 2020. Several meetings among the participants, from JLab (Lubomir Pentchev, Colin Gleason, Benjamin Raydo, Sergei Furletov, Fernando Barbosa), Duke University (Zhiwen Zhao), University of South Caolina (Yordanka Ilieva), INFN/Italy (Marco Contalbrigo and Luca Barion), and Georgia State University (Xiaochun He, Deepali Sharma and Murad Sarsour), established a structured plan for implementation, installation, and running the mRICH setup parasitically in Hall D. Three new mRICH modules (exact copies of the second mRICH prototype) were constructed at GSU as shown in Fig. 2.3.7 in order to support this and other R&D activities (such as optical alignment tests, optical characterization of aerogel tiles, Fresnel lens, and mirror). One of the modules was sent to JLab in early February of 2020 together with the supporting frame as seen in Fig. 2.3.7. The effort on setting up the mRICH photosensor (Hamamatsu H13700) readout for this test was led by INFN, together with a team support from JLab.

A GEANT4-based simulation study of the mRICH performance was expanded to quantify the acceptance and efficiency of an array of mRICH modules in sPHENIX (which could potentially be a Day-One-EIC detector). The GSU group is an active member of the sPHENIX Collaboration and has the expertise in using the sPHENIX software "Fun4All" (which is one of the promoted software options for EIC). We had implemented an array of mRICH modules in the simulation of the forward region of the sPHENIX experiment back in 2017 (see Fig. 2.3.8). However, there were no detailed studies on the mRICH performance because of limited manpower.

Following the recent work on mRICH for the EIC Yellow Report, a revived effort to quantify the performance of an array of mRICH in sPHENIX began in this reporting period. As an example, Fig. 2.3.9 shows simulated photon hits display from a section of the mRICH array implementation (in projective mode) in the sPHENIX experiment. The continued study is one of the proposed activities in FY21, which also include an mRICH PID algorithm development.

As the proponent of one of the three eRD14 PID detector designs (*i.e.*, dRICH, mRICH and hpDIRC), the mRICH group invested efforts in the exercise of evaluating various PID-technology options for EIC by providing a fast parameterization of the mRICH performance in projective mode. The parameterized K/π separation power in the momentum range of 3 to 10 GeV/c and e/π separation for momenta less than 2 GeV/c are shown in Fig. 2.3.10

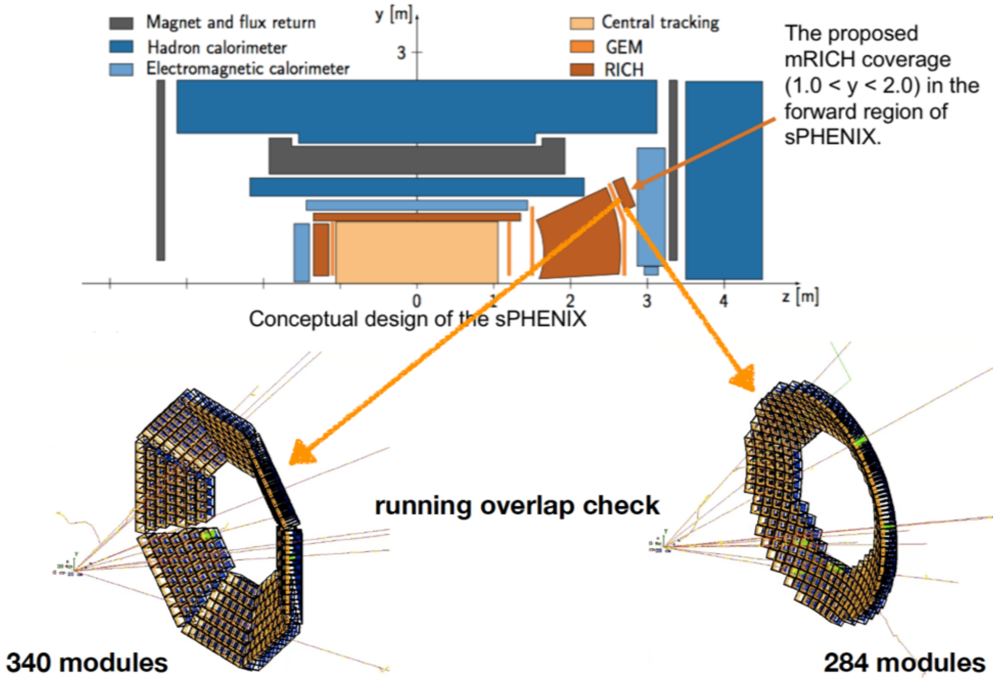

Figure 2.3.8: An array of mRICH modules implemented in the sPHENIX simulation.

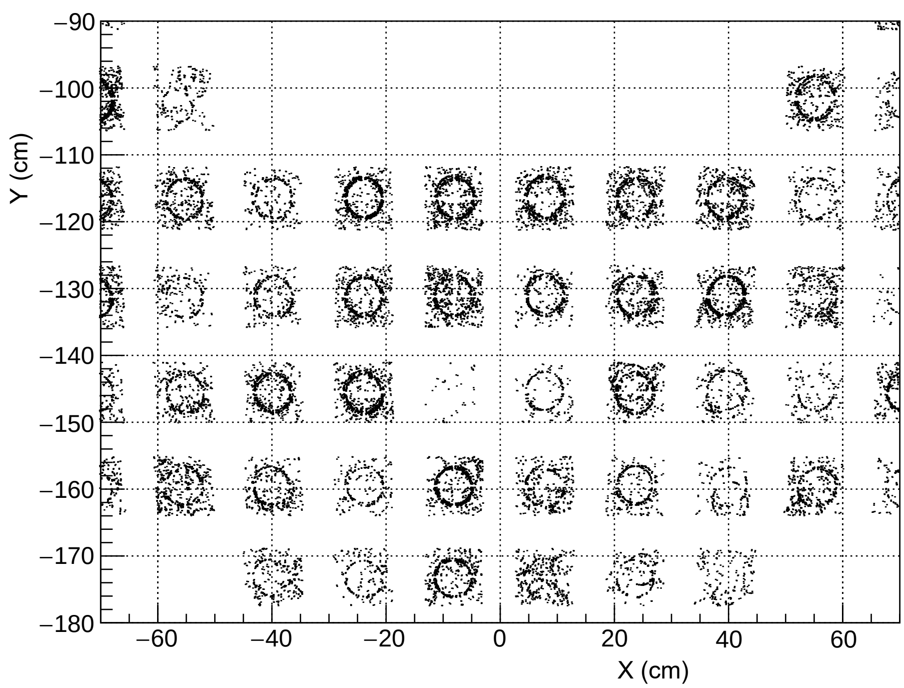

Figure 2.3.9: Simulated photon hits display from a section of the mRICH array implementation in the sPHENIX experiment. These rings are from pions at $p_T = 5$ GeV/c launched at (0,0,0) vertex in a rapidity range of $1 < |y| < 3$.

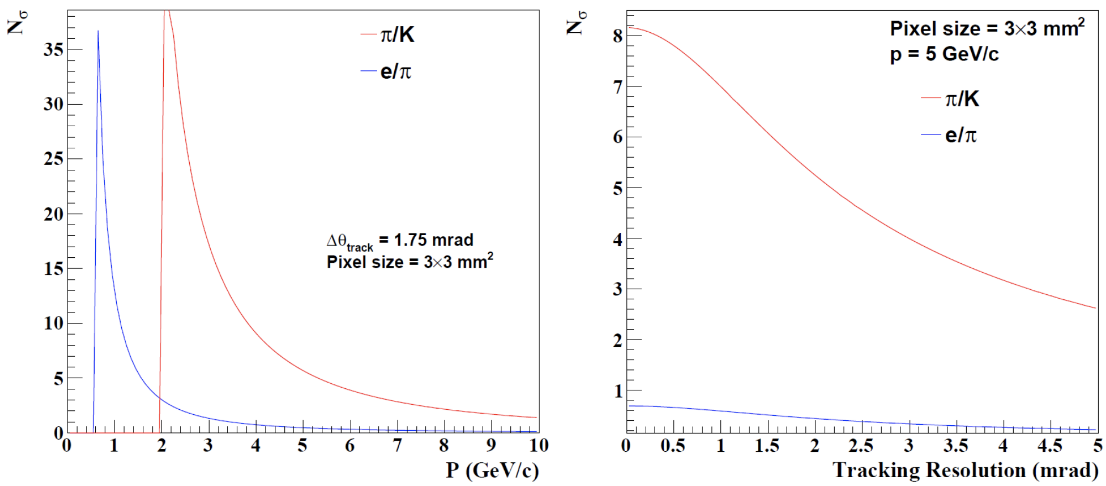

Figure 2.3.10: Fast parameterization of the mRICH PID performance in projective mode.

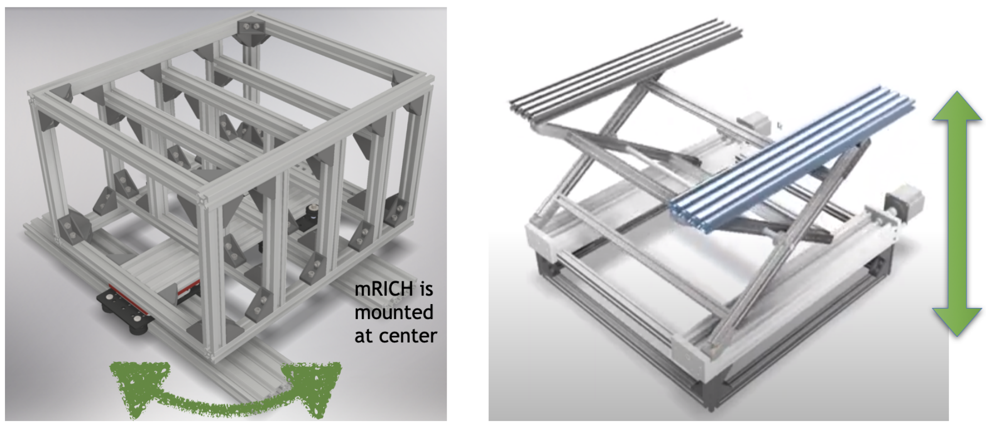

Figure 2.3.11: 3D-model of the support frame of mRICH module for beam test and optical characterization.

2.3.1.3 What was not achieved?

The JLab test planned for May 2020 was not carried out due to the closure of JLab caused by COVID-19. There was also a delay of our effort to improve the design of the support frame of the mRICH for the test with translational and rotational motion capabilities by means of a remote control. A 3D-model of the new frame was made in early March of 2020 (see Fig. 2.3.11), but our plan to complete the hardware assembly and test before the end of April could not be realized. It is hoped that this activity will be completed in the coming months when the lab operation will gradually get back to normal.

2.3.1.4 How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

As described in the previous section, the pandemic caused a delay of six-months in the mRICH R&D efforts, mainly related to hardware work and a beam test.

2.3.1.5 How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

The amount of the FY20 funds that might not be spent according to the original budget allocation for mRICH is $4.2k for travel.

2.3.1.6 Do you have running costs that are needed even if R&D efforts have paused?

The short answer is yes. We need to provide partial salary support both for a postdoc and students.

2.3.2 Future

2.3.2.1 What is planned for the coming months and beyond? How, if at all, is this planning different from the original plan?

Given the uncertainties in how the COVID-19 situation will evolve, the mRICH team will focus of the continuation of the analysis of the second beam-test data and will revisit the loglikelihood PID algorithm which was developed in 2017 following the improved GEANT4 simulation of mRICH. At the same time, the pursuit of a beam test at JLab will remain one of our top priorities.

2.3.2.2 What are critical issues?

There are two critical issues which will affect the success of the third mRICH test: (1) a working tracking system, which is read out together with the mRICH; (2) the acquisition of Aerogel tiles for this test.

2.4 High-Performance DIRC

2.4.1 Summary

The High-Performance DIRC (hpDIRC), a radially-compact RICH detector based on the DIRC (Detection of Internally Reflected Cherenkov light) principle, is a very attractive solution for the EIC, providing clean particle identification (e.g., e/π, π/K, K/p) over a wide range of angles and momenta.

The main activities of this R&D effort during the period of January – July 2020 were the radiation hardness tests at BNL, the upgrade of the laser setup at ODU, the transfer of the prototype to the U.S., and the restart of the simulation work.

2.4.2 Past

2.4.2.1 What was planned for this reporting period

The top priorities for this reporting period were the the hpDIRC system prototype program, the completion of the analysis of the 2019 radiation hardness tests, and the addition of a PostDoc to the hpDIRC team to strengthen the software and hardware effort.

The preparation of the hpDIRC prototype tests consist of both hardware and simulation tasks. As the first step, the core elements of the PANDA Barrel DIRC prototype were to be transferred from GSI to Stony Brook University and the PANDA-based DAQ system was to be validated. In preparation for the first test beam campaign at Fermilab a simulation package was to be developed with the hpDIRC prototype geometry as well as auxiliary instrumentation for the beamline, to define the requirements for tracking, timing, and external PID, as well as the expected prototype resolution and PID performance.

The analysis of the summer 2019 radiation hardness test was supposed to be finalized and the next irradiation run with a focus on the radiation hardness to neutrons, luminescence, and annealing of selected hpDIRC materials was to take place.

The upgrade of the laser setup to evaluate the focusing properties of 3-layer lens prototypes was to be completed and the measurements were supposed to start.

The journal publication about the performance validation of the focusing lens-based optics using the PANDA Barrel DIRC prototype in particle beams was to be completed.

2.4.2.2 What was achieved?

The analysis of of the 2019 radiation hardness run was finalized and we are preparing for the final irradiation runs, planned for August 2020. The upgrade of the laser setup advanced significantly and is almost ready for calibration and initial measurements.

After a break in the detailed EIC DIRC simulation studies in FY19, significant effort during past few months went into setting up the environment for the quantitative studies of three new DIRC geometry options: (1) the system prototype in the Fermilab testbeam environment; (2) the SuperB FDIRC camera as readout for the possible reuse of the BaBar DIRC bar boxes at EIC; (3) the combination of bars and plates in the "ultimate" DIRC configuration[7].

The significantly improved photon detection efficiency of recent commercially available MCP-PMTs was implemented in the hpDIRC simulation and its effect on the performance was studied. An algorithm for the determination of the event time using the hpDIRC "self-triggerd" mode was developed and a first study of the event time precision was performed. We also started the implementation of the hpDIRC in to the ePHENIX full simulation package to study the combined PID.

A first draft of the journal publication about the performance evaluation of the focusing system with the prototype in particle beams was completed and is being discussed within the DIRC group. The goal is to have it ready for submission by the end of this year.

As part of the reaction to rapid developments in the EIC project schedule some of the simulation studies had to be reprioritized. The new hpDIRC fast simulation class, based in the code we created in FY19, was developed for the EIC community to study the physics impact of the hpDIRC and compare it to other detector options. The impact of the angular resolution of the EIC tracking system on the hpDIRC performance was evaluated and a detailed study of the e/π separation power at lower momentum, and the impact of multiple scattering on hpDIRC performance, was started.

Hardware: Radiation Hardness Tests The radiation hardness of materials to be used in the final detector is crucial for the EIC DIRC R&D program. Synthetic fused silica, which is used for most of the optical components in all DIRC systems, was already extensively tested for the BaBar and PANDA DIRC counters and proved to be extremely radiation hard. However, the middle layer of the 3-layer lens was made, in first prototypes, of a high-refractive-index lanthanum crown glass (NLaK33, S-LAH97, and S-YGH51 are equivalent names for the same material from different vendor). Since the beginning our radiation tests strongly suggested that this material may not be suitable for the final EIC design. Several materials were studied as potential alternatives to NLaK33 and, so far, sapphire and PbF_2 are the leading candidates. All potential candidates have to be tested for radiation hardness.

A commonly used source for studies of radiation hardness of optical materials is ^{60}Co. Following the recommendations of the R&D review committee, we prepared a dedicated setup for radiation hardness measurements with the ^{60}Co source at the BNL Gamma facility. In the late summer of 2019 samples of PbF_2, sapphire, S-YGH51, and polycarbonate[8], were exposed to accumulated

[7] B. Dey et al., Nucl. Instr. and Meth. Res. Sect. A876 (2017) 141.

[8] This material is of particular interest to the mRICH activity as material for the Fresnel lens.

doses of up to 2 Mrad. One Fused Silica sample was never irradiated and used as a reference in the transmission measurements. Figure 2.4.12a) shows the monochromator used to quantify the radiation damage. An optical sample is placed in a special fixed holder in front of the integrating sphere used to detect the light. A set of two lamps is used to generate a light beam in wavelength range 200-800 nm that passes through the optical sample to the integrating sphere.

During 2019 we performed first measurements of polycarbonate with two different thickness samples. A visible colour change was observed for the S-YGH51 glass and polycarbonate samples. The color of PbF_2 sample did not change but a minor transmission loss was observed for the lower wavelength range.

Figure 2.4.12b) shows that the transmission of the sapphire sample was immune to the 2 Mrad irradiation, making it an excellent candidate for the hpDIRC lens material. Figure 2.4.12c) shows a dramatic drop of the transmission across the whole wavelength range for the S-YGH51 glass, while for PbF_2 we observed a only a slight drop of the transmission in the 250–400nm range. Figure 2.4.12e) and f) shows only moderate transmission loss for the thin polycarbonate sample while the thicker sample shows more than 50% loss for much of the wavelength spectrum.

The effect of photo-annealing was studied by exposing the PbF_2, polycarbonate, and S-YGH51 samples to direct sunlight for up to 4 hours. Figure 2.4.12c) shows that the Lanthanum crown glass sample showed significant recovery of transmission after 2 hours of sunlight and additional, although weaker, recovery after two more hours. Although the transmission loss of the PbF_2 was smaller, the recovery after exposure to sunlight is nevertheless clearly visible. The two polycarbonate samples showed a clear dependence on the sample thickness. While the thin sample recovered significantly after two hours in the sun, the thicker sample showed almost no transmission recovery, suggesting that the annealing effect of the sunlight is limited to 1–2 mm sample depth.

Due to the sharp cutoff in transmission below 400 nm, polycarbonate is not a good choice for hpDIRC detector.

During the summer-2019 run we performed the initial radio-luminescence tests of the materials. The samples were pressed against a single photomultiplier tube, wrapped in a light-tight cover, and placed into the ^{60}Co chamber. The tube was operated at 1600 V and read out with an oscilloscope. The setup was calibrated with a fluoride sample for two tests: (a) luminescence during irradiation with a low dose rate of 2.2 rad/h and (b) luminescence a few minutes after irradiation with a high dose rate (17 krad/h). None of the materials showed evidence of radio-luminescence after irradiation, as we observed no significant signal in the PMT. We did observe a signal during the irradiation for both sapphire and S-YGH51 glass. However, improved tests have to be performed to quantify this effect.

Hardware: Laser Setup Figure 2.4.13a shows the schematic of the laser setup that was built in the Old Dominion University lab to map the shape of the focal plane of prototype lenses. Different incident photon angles are simulated by rotating the lens through two parallel laser beams. The intersection point of the two laser beams determines the focal length. The lens is placed inside a glass container filled with mineral oil (with a refractive index very close to fused silica) to simulate the focusing behavior of the lens in the DIRC, where it will be placed between the bar and the prism. Each lens is supported in a custom-made 3D-printed holder that makes it possible to map out the focal plane in all three dimensions. As previously reported, the measurements performed for three of the older prototype lenses showed the desired flat shape of the focal plane for beams close to the center of the lens, in good agreement with Geant simulations. This setup was successful in determining the shape of the focal plane, but required several modifications to increase the range of incident angles, improve the precision of the measurement, and limit the systematic uncertainties, in order to have publishable results. The photo in Fig. 2.4.13b shows the advanced state of the construction of the improved setup. The longer oil tank is made of acrylic glass and placed on a scissor lift table that lowers the tank to gain access to the optical elements, suspended above the

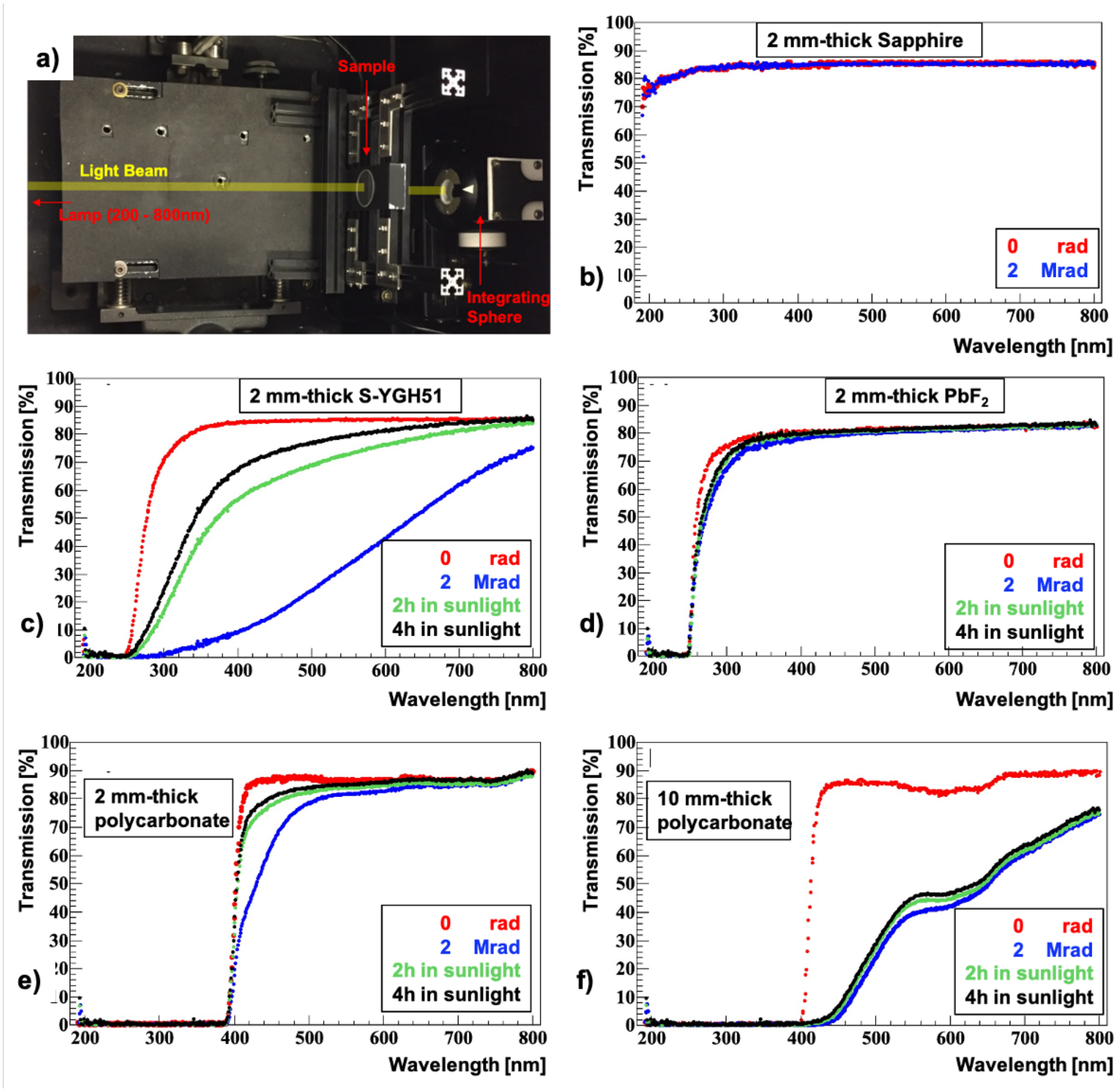

Figure 2.4.12: (a) The monochromator setup at BNL used for the transmission measurements to quantify the radiation damage. Transmission as a function of wavelength (not corrected for Fresnel losses) through the 2 mm-thick samples of sapphire (b), S-YGH51 (c), PbF_2 (d), polycarbonate (e), and the 10 mm-thick polycarbonate sample (f). Figures c, d, e, and f include the transmission after 2 hours and 4 hours of exposure to sunlight.

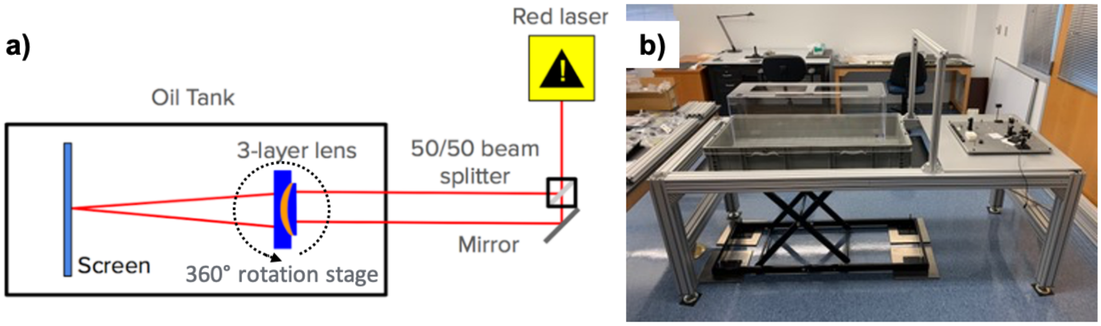

Figure 2.4.13: Schematic of the laser setup for mapping the focal plane of the hpDIRC lens prototype (a) and photograph of the current state after completion of the first steps of the upgrade.

tank, and then lift it up again. This will simplify the calibration of the setup and the changing of the lenses. The rotation stage for the lens and the screen will be redesigned and will be fixed to the stable support structure above the tank. A camera with a special filter will be placed behind the tank to allow for a more precise determination of the focal length and will speed up the measurement significantly.

Simulation: Quantum Efficiency of Sensors The initial hpDIRC implementation in Geant was based on the properties of available commercial MCP-PMT sensors, procured during the early stages of the PANDA Barrel DIRC R&D. However, the latest generation of MCP-PMTs, currently being evaluated for the PANDA experiment, features a significantly higher photon detection efficiency (PDE), defined as the product of the quantum efficiency (QE) and the collection efficiency (CE). Figure 2.4.14a shows the the comparison of different available photocathode options from PHOTONIS. The useful wavelength range is either extended much further into the UV range, which can increase the photon yield significantly compared to a standard bialkali photocathode, or restricted to a narrow range at larger wavelength to reduce the bandwidth of detected photons, thereby limiting the effects of chromatic dispersion. The presented curves are based on data provided by PHOTONIS, which were found to be consistent with measurements performed by the PANDA DIRC group in Erlangen, Germany. Furthermore, recent advances in the fabrication of the MCPs enabled an increase of the average collection efficiency from 65% to 95%. The combination of the two improvements results in an increase of the PDE by a factor 2 or more.

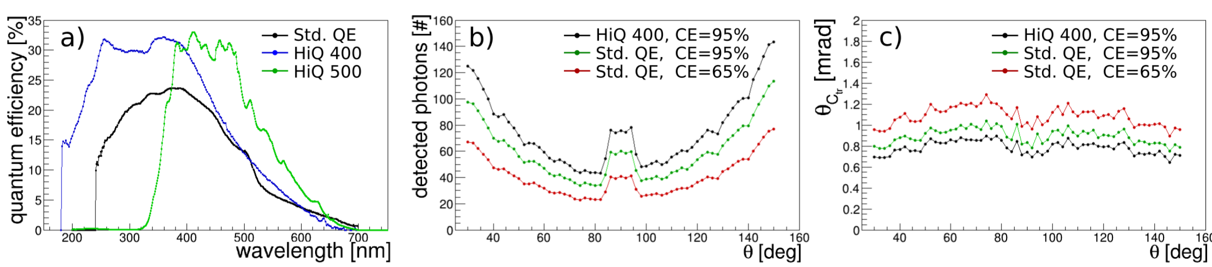

Figure 2.4.14: Comparison of different MCP-PMT PDE options in simulation: (a) Quantum efficiency as a function of wavelength of recent commercial MCP-PMTs (data provided by PHOTONIS). The resulting photon yield (b) and the Cherenkov angle resolution per track (c) are shown as a function of the polar angle for pions with 6 GeV/c momentum.

Figure 2.4.14b,c shows the hpDIRC performance in simulation for three options: the standard photocathode with a standard value of CE=65% (red) and with enhanced CE=95% (green), and the combination of higher QE and enhanced CE (black). We observe the expected clear increase in the number of measured photons per track and see a corresponding improvement in the Cherenkov angle resolution per particle. This initial study did not attempt to optimize the other optical components of the hpDIRC yet. An additional increase of the photon yield is expected if the type of glue used in the assembly of the bars and the lens (Epotek 301-2) can be replaced with one with better UV transmission (e.g., Epotek 305). A simulation study is needed to explore if the increase in the yield is more important for the PID performance than the larger chromatic dispersion term, caused by the larger bandwidth. Similarly, a Geant study using the narrow bandwidth *HiQ 500* photocathode will show if minimizing the chromatic dispersion, at the cost of a loss of photon yield, is preferable.

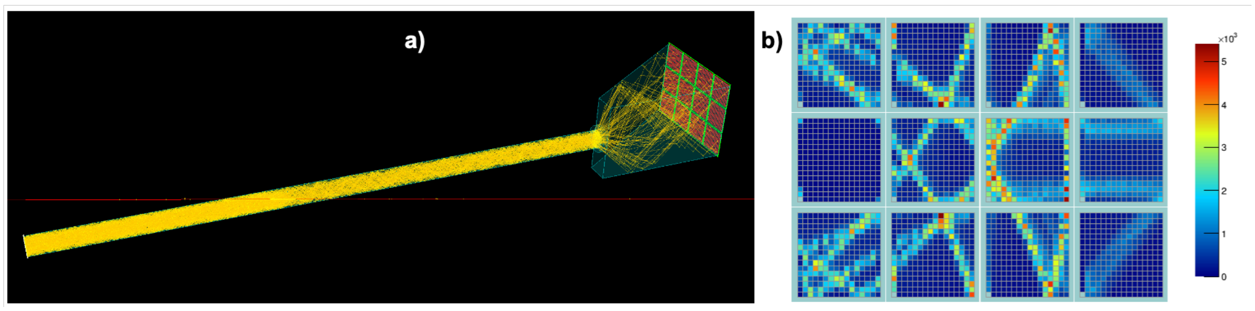

Figure 2.4.15: Simulated hpDIRC prototype: a) Event display of the hpDIRC prototype, b) Distribution of the number of measured hits per MCP-PMT pixel from 30k pions at a polar angle of 20° and a momentum of 6 GeV/c.

Simulation: EIC Prototype Simulation The development of the Geant4 simulation package for the hpDIRC prototype in the beam test environment is in progress. Figure 2.4.15a shows a visualization of a single beam particle traversing the radiator bar of the DIRC prototype in a configuration similar to the PANDA Barrel DIRC beam test at CERN in 2017. The Cherenkov photon tracks are shown in yellow, the array of 12 MCP-PMTs with $3{\times}3$ mm pixels is shown in red. Figure 2.4.15b shows the example occupancy plot for 30k accumulated pions at 6 GeV/c and 20° polar angle.

Simulation: fDIRC Option for EIC The use of legacy detector components could lead to significant cost reduction of the EIC central detector, in particular for a possible second interaction region. One such opportunity could be the reuse of the 12 bar boxes available from the BaBar experiment. A "budget version" of the hpDIRC could be based on these unmodified bar boxes, in combination with a newly designed expansion volume with new sensors and readout electronics. The idea itself is not new, reuse of the BaBar DIRC bar boxes was considered for the SuperB project and the subject of a successful R&D program at SLAC, resulting in the design of the SuperB FDIRC and the study of the performance of a full system prototype with particle beams and cosmic muons[9], predicting 3 s.d. π/K separation power up to 4.5 GeV/c. More recently, four of the BaBar DIRC bar boxes were transported from SLAC to JLab as part of the PID upgrade of the GlueX experiment. The GlueX DIRC uses a simplified lower-cost version of the SuperB FDIRC expansion volume and was commissioned in 2019.

Figure 2.4.16 shows a visualization of the initial implementation of this EIC fDIRC in our stand-alone EIC DIRC Geant4 simulation package. The unmodified reused BaBar DIRC boxes are

[9] B. Dey et al., Nucl. Instr. and Meth. Res. Sect. A775 (2015) 112.

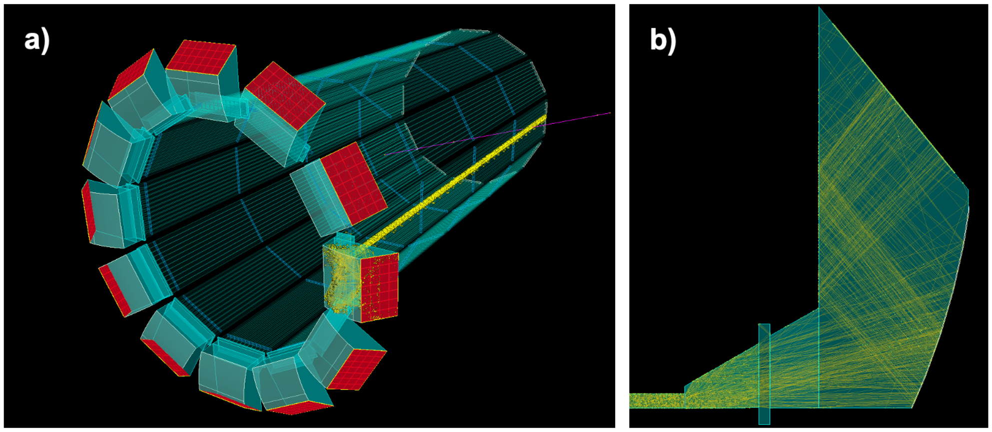

Figure 2.4.16: Visualization of the EIC fDIRC option in Geant4. Overview of the geometry (a) and side view of the expansion volume (b). The tracks from Cherenkov photons are shown in yellow.

coupled via a transition prism to the solid fused silica expansion volume with cylindrical focusing. The dimensions of the focusing block were taken from the SuperB FDIRC design. The next step is to reproduce the results for the photon yield and Cherenkov angle resolution published by the SuperB FDIRC group, followed by optimization of the expansion volume shape and the sensor and electronics resolution for the EIC phase space.

Simulation: DIRC Event Time Resolution The high-precision measurement of the arrival time of many Cherenkov photons by the hpDIRC presents an opportunity to determine the event time with sufficient precision to assign photons to the correct track, even in the absence of high-precision external timing information. This "self-trigger" mode was successfully used by the BaBar DIRC, which achieved an event time resolution limited only by the transit time spread of photons in the PMTs. This information, equivalent to the average time of emission of Cherenkov photons by the particle in the DIRC bar, may be used as "DIRC-stop" time and combined with an external start time to use the hpDIRC for low-momentum time-of-flight.

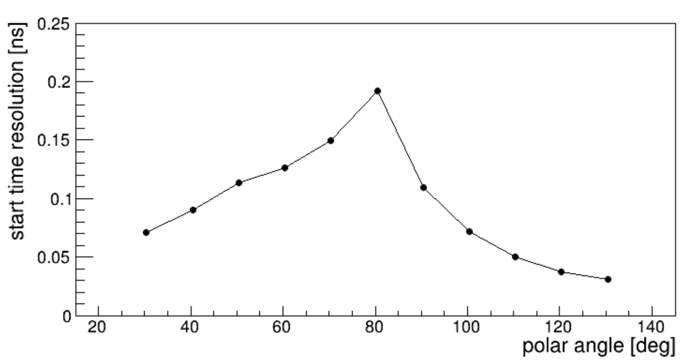

Figure 2.4.17: The resolution of the hpDIRC event time as a function of track polar angle in Geant4 simulation from time-based imaging reconstruction assuming a DIRC-internal timing precision of 100 ps per photon.

The method was studied in the Geant4 stand-alone simulation using both hpDIRC reconstruction algorithms. In the case of the geometrical reconstruction, the start time is determined by finding the average difference between the measured and calculated propagation time of all the Cherenkov photons associated with a particle. A time window with a width of 100 ns was used to assign the photons to the particle, corresponding to a very modest event time requirements. Using time-based imaging, the start time is determined by applying correlated shifts to the time PDFs for all detected photons to obtain the maximum log-likelihood for a given particle hypothesis as a function of the shift value. Initial studies show that the resolution of this DIRC event time can be as good as 50 ps for steep froward and backward angles, as shown by Figure 2.4.17. The resolution gets worse for central polar angles, where Cherenkov photons pass through the lens at steep angles, resulting in larger optical aberrations. In addition, these photons have longer propagation length and are, therefore, more affected by chromatic dispersion effects. A study of aspheric lens surfaces and chromatic dispersion correction using fast photon timing may identify ways to further improve the DIRC event time resolution.

2.4.2.3 What was not achieved?

The wide range of delays and complications connected to the Covid-19 pandemic in 2020 forced us to shift the Fermilab beam test plan from 2021 to 2022, postponing the beam line simulation work to match this new schedule. Administrative delays due to the pandemic delayed the processing of the paperwork for the prototype transfer from GSI to Stony Brook and the hiring the new PostDoc at CUA, resulting in the postponement of some of the simulation studies until the summer of 2020 and FY21.

2.4.2.4 How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

The closure of the CUA University caused delays in many administrative processes, including the selection and hiring of the PostDoc and finalizing the agreement for the prototype transfer from GSI to Stony Brook. We still expect the transfer to take place this summer but the work on the electronics and other prototype activities will shift to FY21. Several of the planned simulation activities were similarly affected and postponed until start date of the PostDoc in June 2020. The production of the PbF_2 lens prototype by the Harbin Institute of Technology in China was delayed and it is still unclear when the normal activity of the institute will be resumed. The laser setup at ODU is close to completion but as of middle of June it is still unclear when we will be able to have access the lab again to finish the construction and calibration. The radiation hardness studies at BNL require outsourced neutron irradiation at the UMass Lowell institute. Assuming that the situation will improve relatively quickly, we expect to be able to finish the studies this FY, as planned.

The shutdown of Fermilab meant that no beams were availabe for detector tests in 2020. This is expected to cause a significant backlog of previously approved beam test proposals in 2021, making it unlikely that conducting our first hpDIRC prototype beam test in FY21 is still a realistic goal. Due to this complication, as well as the delays of the prototype transfer and the beam line simulation, we decided to shift the first beam test to the spring of 2022.

2.4.2.5 How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

As of now, we plan not to have any significant carry over after the end of the FY20 contract. Some items in the FY20 budget got delayed but are still expected to happen in 2020.

2.4.2.6 Do you have running costs that are needed even if R&D efforts have paused?

No.

2.4.3 Future

2.4.3.1 What is planned for the coming months and beyond? How, if at all, is this planning different from the original plan?

The components and plans for the radiation hardness tests of the lens materials to neutrons and for the luminescence measurements are ready and currently scheduled for the late summer at BNL. However, this requires that BNL and the UMass Lowell institute can return to normal operation after the pandemic lock-down soon. If this is not the case, the measurements will be delayed by a few months with the plan to complete them both by the end of 2020.

Two other hardware activities are planned to be finished by the end of the summer 2020: the upgrade of the laser setup at ODU and the transfer of the prototype to Stony Brook. The laser setup will have to be calibrated before the detailed lens measurements can start. The prototype components will be sent disassembled and will require careful checks and reassembly.

The study of the event time resolution from DIRC-only offline reconstruction was started but needs further improvement.

The newly hired PostDoc, Nilanga Wickramaarachchi, started in June 2020. The first priority is getting familiar with the stand-alone Geant4 simulation package. The next step will be to study the effect of different bar sizes and focusing system options on the hpDIRC performance.

The implementation of the hpDIRC in the ePHENIX EIC central detector simulation frameworks is an important step to facilitate the study of the combined PID performance of the eRD14 systems. This activity was already initiated and is expected to be completed by the end of 2020.

2.4.3.2 What are critical issues?

With the TDR schedule in mind, it is crucial to continue the support of the new PostDoc and his work on software as well as the hpDIRC prototype test at Stony Brook. In order to validate the hpDIRC performance in particle beams, a sufficient number of small-pixel sensors with a matching readout systems will be required by late 2021. The procurement of the new sensors should start in FY21 and conclude in FY22 to be ready for first beam at Fermilab in 2022.

The development of the COVID-19 situation and the resulting impact on travel, beam test availability, and the operation of labs and universities, will have a significant impact on the hpDIRC R&D schedule.

2.4.3.3 Additional Information: Contributions to the Yellow Report

Starting in early 2020 the eRD14 DIRC group has made significant contributions to the Yellow Report (YR) Initiative, an effort by the EIC Users Group to document the physics requirements and detector technologies for the EIC. A large amount of effort was required to provide information and documentation to the Yellow Report Detector Working Group on PID, to contribute software tools, and to perform several detailed simulation studies.

A simulation study was performed to determine the tracking angular resolution required by the hpDIRC to perform π/K separation at the 3 s.d. level for the full momentum range. A parameterization of the hpDIRC baseline design performance was developed for the EIC detector fast simulations to study the impact of the PID on various physics analyses.

The status of another YR activity, a new a simulation study of the potential contribution of the hpDIRC to the low-momentum e/π separation in the EIC detector barrel, is described in more detail in the FY21 proposal.

3 Photosensors and Electronics

3.1 Summary

The main objective of this R&D effort during the period January – July 2020 was to continue to identify and assess suitable photosensor solutions for the EIC Cherenkov Detectors and to develop electronics solutions for the readout of the Cherenkov detector prototypes for beam tests. Ultimately, in the long term, this R&D work will allow us to make a recommendation about the best photosensors and electronics solutions for the PID detectors in EIC implementation.

3.2 Sensors in High-B Fields

3.2.1 Past

3.2.1.1 What was planned for this reporting period

During this reporting period we planned to

- Evaluate the gain, ion-feedback, and timing resolution of a multi-anode 10-μm pore-size Planacon XP85122-S as a function of $(B, \theta, \phi, \mathrm{HV})$.
- Carry out a comprehensive study of the gain and timing resolution of XP85122-S with changing $\mathrm{HV}_{Cathode-MCP1}$, $\mathrm{HV}_{MCP1-MCP2}$, $\mathrm{HV}_{MCP2-Anode}$.

3.2.1.2 What was achieved?

The purchase order for Planacon XP85122-S was sent to Photonis and the delivery of the sensor is expected at the end of August 2020. At JLab, the Detector group has started to sample various options to connect to the backplane of the PMT in order to readout several channels for the High-B test. XP85122-S is produced without connector pins on the backplane and such a connectoring solution is a critical aspect of extracting the signals off the PMT. Various backplane connector solutions were tested, such as Samtec and several conductive films from Condalign, before the closure of JLab.

3.2.1.3 What was not achieved?

The evaluation of XP85122-S was not achieved due to the COVID-19 pandemic.

3.2.1.4 How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

The pandemic affected both the delivery and the evaluation of the XP85122-S sensor. Photonis has experienced production delays and the sensor is expected to be delivered at the end of August than in early June. Due to the closure of JLab and the travel suspension at USC for faculty and students, the evaluation of the XP85122-S in High-B field was postponed to December 2020.

3.2.1.5 How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

At the time of submission of this progress report, \$11.3k (including overhead cost) of the USC FY20 travel funding is not spent as the measurements had to be postponed to December 2020. While, formally this means that the funds will be carried over to FY21, they will be spent before the end of the USC FY20 contract with BNL, which is 31 December 2020. These funds will cover the cryogens for the magnet and the travel cost for one USC person to JLab to carry out a 2-week long test. Thus, we do not expect any actual carry over beyond the end of our FY20 activities.

3.2.1.6 Do you have running costs that are needed even if R&D efforts have paused?

No.

3.2.2 Future

3.2.2.1 What is planned for the coming months and beyond? How, if at all, is this planning different from the original plan?

With the staged opening of JLab for research, the work on a connectoring solution for the readout of a few channels of XP85122-S will continue through Summer and early Fall. In October – November, we expect a reference gain measurement of the sensor to be carried out in a test bench in the Detector Lab outside of a magnetic field. The sensor will be evaluated in a magnetic field in December this year. The activity is the same as originally planned, but delayed by six months due to the SARS-Cov2 quarantines and closures.

3.2.2.2 What are critical issues?

The accessibility of JLab for research and of man power at the lab (Detector Group, Cryotarget Group, and Electronics Group) to support the preparation of equipment for the tests is critical.

3.3 MCP-PMT/LAPPD

An important challenge for the EIC particle identification is to provide reliable low-cost highly pixelated photosensors working in high radiation and high magnetic-field environment. The recently commercialized Large Area Picosecond Photo-Detector (LAPPD) provides a promising low-cost photosensor solution for the EIC imaging Cherenkov sub-systems. Optimization of the sensor design for high magnetic-field tolerance, fast time resolution, and the pixelated readout was performed at Argonne National Laboratory with 6×6 cm^2 MCP-PMTs. The effort aims to adapt the LAPPDs to the EIC requirements with optimized design parameters integrated into low-cost LAPPD production.

3.3.1 Past

3.3.1.1 What was planned for this reporting period?

The tasks planned for this reporting period include: (a) Produce 6×6 cm^2 MCP-PMTs with capacitive-coupling pixelated readout through a glass and an integrated magnetic-field tolerant design; (b) Test the glass pixel MCP-PMTs at Fermilab beamline; (c) Test 20×20 cm^2 ceramic LAPPDs, compare advantages and disadvantages of glass pixel vs. ceramic pixel; (d) Further enhance work with the electronics, DIRC, dRICH, and mRICH groups in order to prepare the integration of MCP-PMT/LAPPDs in these sub-systems.

3.3.1.2 What was achieved?

With respect to the 6×6 cm^2 MCP-PMTs, we analyzed the Argonne MCP-PMT component test study for pixelization and in magnetic field, and demonstrated its performance with magnetic field tolerance of 1.5 Tesla, RMS timing resolution of 83 ps and pixel size of 3×3 mm^2 (see Fig. 3.3.18). Based on these results, a fully integrated MCP-PMT with the Argonne low-cost whole glass/fused silica design was prepared for fabrication. The capacitive-coupling anode was redesigned from the

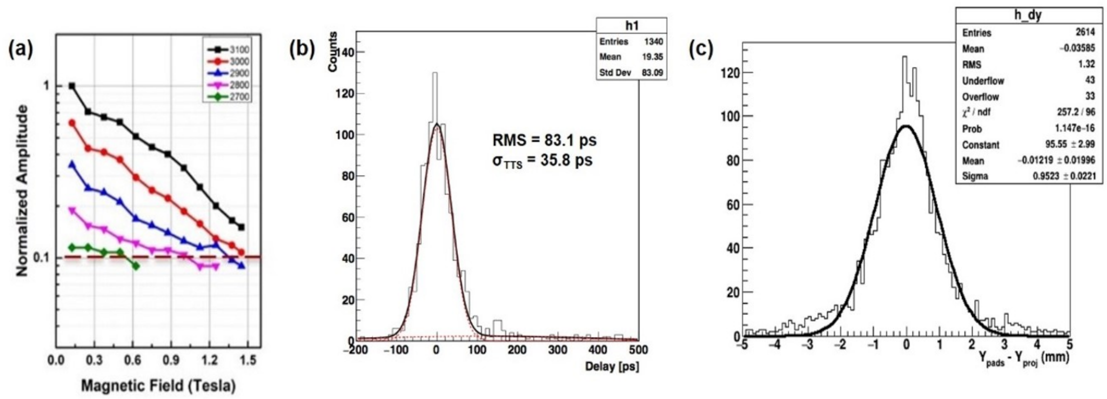

Figure 3.3.18: Performance of Argonne MCP-PMT: (a) Magnetic field tolerance of 1.5 Tesla; (b) RMS timing resolution of 83 ps; and (c) position resolution of 0.9 mm with pixel size of 3×3 mm^2.

Figure 3.3.19: Lower-tile anode with capacitive-coupling pixelated readout through glass ready for pixelated 6cm MCP-PMTs fabrication.

standard Argonne 6cm MCP-PMT anode. The active MCP area was fully coated with a thin resistive film leading out through silk-printed thin layer silver, and 4 high voltage connections leading out by silk-printed silver strips as shown in Fig. 3.3.19. 10 μm pore size MCPs and reduced spacing glass components were also prepared for MCP-PMT fabrication. Due to the COVID-19 closures, the actual fabrication was put on hold.

A major priority for FY20 was to establish effective communication with Incom, Inc. (the commercial manufacturer of LAPPDs) to guide and support their planning for LAPPD fabrication for EIC PID. Multiple communications were conducted between Argonne and Incom, as well as between eRD14 and Incom to clarify the needs of pixelated LAPPD (HRPPD) for EIC PID detectors. Besides bi-weekly meetings between the Argonne group with Incom, we also set up a monthly meeting with eRD14 and Incom to ensure effective communication on the LAPPD progress. The SBIR submitted from Incom to DOE on Gen-III LAPPD (HRPPD) with pixelated co-fire ceramic tile to address the EIC-PID photosensor requirement was awarded in March. The HRPPD work is ongoing, and Argonne shared with Incom the ANL MCP-PMT design parameters for achieving 1.5-T magnetic-field tolerance and 100-ps RMS timing resolution. We are expecting the HRPPD to be delivered, fully characterized on bench in 2021, and ready for hpDIRC beamline testing at 2022.

Given the current availability of 6cm MCP-PMT and Gen-II LAPPD, we planned a beamline test focused on the capacitively coupled Argonne MCP-PMTs and Incom Gen-II LAPPDs in a

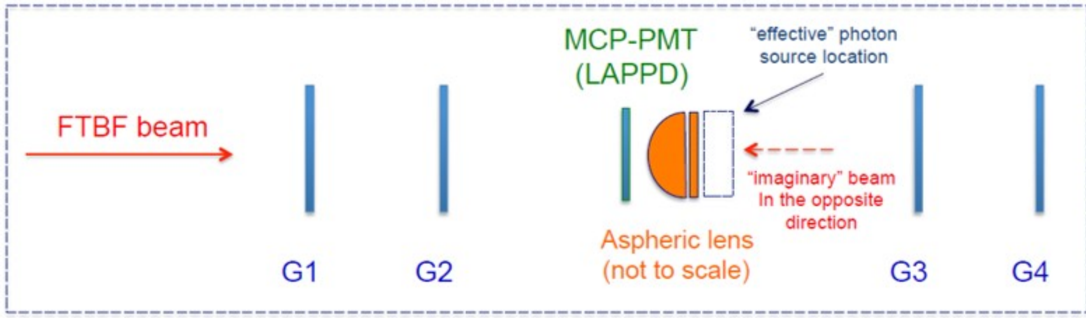

Figure 3.3.20: Beamline configuration for MCP-PMT/LAPPD pixel validation tests.

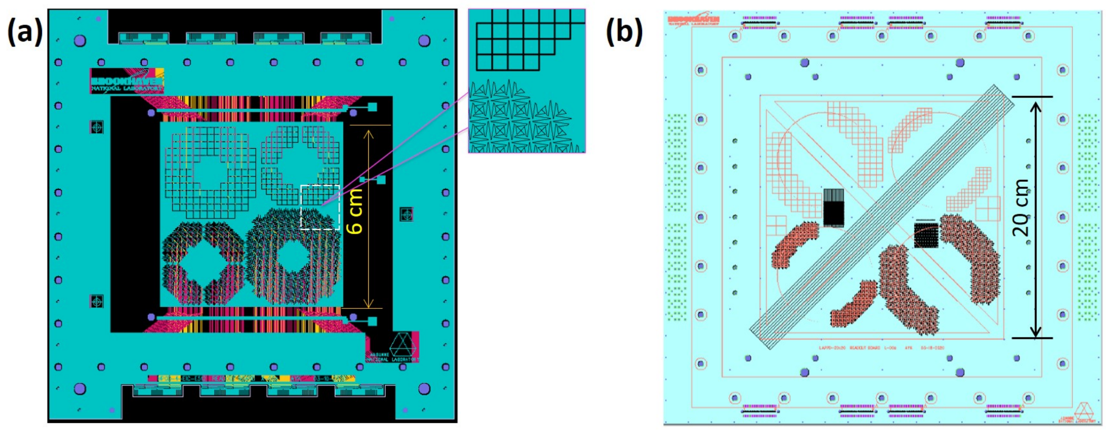

Figure 3.3.21: Design of two PCB boards with pixel pads readout and zigzag readout to accommodate 6cm MCP-PMT and Gen-II LAPPD. Different pixel and zigzag sizes are available for testing.

highly pixelated configuration. In collaboration with the eRD6 group, we designed the Fermilab beamline test setup as shown in Figure 3.3.20. The setup uses existing 128 channels of DRS4 electronics (CAEN VME 1742 digitizers) for signal readout and adapts 4× 2D COMPASS GEM chambers (expected spatial resolution of $20-30$ μm at the LAPPD location) as a tracking system. It takes advantage of the existing RCDAQ implementation and custom PCB design software developed for the MPGD project. This provides a low-cost setup for high tracking for photosensor performance beamline experiments. We designed and fabricated two PCB boards to accommodate the 6cm MCP-PMT and Gen-II LAPPD. Figure 3.3.21 shows the design of these two PCB boards with both pixel pads readout and zigzag readout. Pad pixel with a size of 3mm × 3mm and 5mm × 5mm were chosen based on previous beamline test results. The boards were delivered to us during the pandemic. Due to the COVID-19, the Fermilab beamline test facility was closed and our test was canceled. We have rescheduled our beamline test for Spring 2021. In close communication with Incom, two Gen-II LAPPDs were produced specifically for EIC-PID and will be on-loan to us, free of charge, for the Fermilab beamline photosensor performance validation in Spring 2021.

In collaboration with eRD6 and the mRICH group, we proposed a plan to use the mRICH module as the first detector system for an mRICH-LAPPD-TOF beamline test in Spring 2021. The mRICH-LAPPD-TOF test will use the same GEM tracker as we set up for the MCP-PMT/LAPPD performance test. A combined Spring 2021 beamline experiment campaign is formed to have the maximum results out from one beamline setup installation.

3.3.1.3 What was not achieved?

Due to the COVID-19, the actual fabrication work of 6cm MCP-PMTs with capacitive-coupling pixelated readout through the glass and with magnetic field tolerant design integrated was on pause. With the expected opening of Argonne Lab in July, we expect to complete the fabrication and performance bench test within 2020. The beamline test of MCP-PMT was rescheduled in Spring 2021.

3.3.1.4 How did the COVID-19 pandemic and related closing of labs and facilities affect the progress of your project?

The COVID-19 pandemic and related closing of labs and facilities delayed our 6 cm MCP-PMT fabrication work at Argonne and planned beamline test of MCP-PMT at Fermilab test beam facility. With the reopening of Argonne in July, we expect to catch up on the delay within 2020. Several beamline tests including performance validation of MCP-PMT, Gen-II LAPPD, and mRICH-LAPPD-TOF tests are combined and rescheduled for Spring 2021.

3.3.1.5 How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

The advanced 6cm MCP-PMT fabrication fund has not been spent due to pandemic related lab closing. With the lab reopening now, we expected the fabrication to be completed within FY20.

3.3.2 Future

3.3.2.1 What is planned for the coming months and beyond? How, if at all, is this planning different from the original plan?

With the lab reopening, we plan to catch up with the delayed fabrication and characterization work for 6cm MCP-PMTs. This task is still expected to be completed within 2021. The MCP-PMT beamline test was rescheduled to Spring 2021. Two Gen-II LAPPDs were produced specifically by Incom for EIC-PID.

FY21 tasks will focus on the evaluation of these LAPPDs on bench, in magnetic field, and in beam. The 6cm MCP-PMT beamline performance validation and mRICH-LAPPD-TOF test will be combined within the same beamline test campaign. Using previously produced MCP-PMTs with different ALD coatings, some MCP-PMT principle R&D will be performed.

3.3.2.2 What are critical issues?

Given the accelerated timeline for EIC-PID to demonstrate sub-system readiness by 2023, the emergent for Incom to provide workable HRPPDs and to be characterized in all aspects becomes the most critical issue.

3.4 Readout Sensors and Electronics for Detector Prototypes

A new readout electronics solution is being developed by the Hawaii Group (mainly front-end) and JLab/INFN groups (mainly back-end) to address the requirements and to demonstrate the performance of the advanced, high-performance RICH and DIRC detectors of the EIC. This section highlights the progress made in the development of the readout electronics.

3.4.1 Past

The initial goal of the Readout Sensors and Electronics for Prototyping activities was to instrument a 4-PMT modular RICH prototype. The PMTs are challenging in that these 2" PMTs have a rather dense anode array of 256 signal channels each. The older MAROC-based system developed for the CLAS12 RICH has been used for the early test-beams and adapted for sensors (MAPMTs, SiPMs) with small pixel size of $3 \times 3\,\mathrm{mm}^2$. This readout electronics has since been maintained to provide a reference and fallback solution. Early studies evaluated the existing TARGETX family of 16-channel transient waveform digitizing ASICs. To further speed development, a standard control and readout programmable logic unit, the SCROD, which was developed for the Belle II muon system upgrade was adopted. To reduce cost and further integration, compactness and reliability, the next stage of development upgraded to the SiREAD ASIC on the Daughter Card (DC). The specifications of this SiREAD ASIC are given in Table 3.4.1. In addition to increasing channel density from 16 to 32 channels, most of the state-machine control infrastructure provided by the companion FPGA has been integrated as "system on chip" functionality. This significantly reduces the digital interconnection burden and makes the system more scalable, making better utilization of a reduced number of gigabit fiber optic links used for control and data acquisition. Twenty five DCs, each equipped with two 32-channel SiREAD ASICs, as shown in Fig. 3.4.22 were fabricated. Each DC is capable of processing 64 channels. Four such DCs instrument the readout signals from the 256 anodes of each PMT.

SiREAD Parameter	Specifications
Channels	64
Sampling rate	1-4 GSa/s
Storage samples/ch	4096
Analog Bandwidth	0.7-1.1 GHz
RMS Voltage Noise	<1mV
Dynamic Range	10-11 bits
Signal Voltage range	2.1 V
ADC on Chip	12-bits
Readout	Serial LVDS
Power Consumption	20-40 mW/ch

Table 3.4.1: SiREAD specifications.

The backend development is based on a proper porting of the recent DAQ system developed for the CLAS12/RICH, and based on a powerful optical link to the generic programmable FPGA front-end boards. The development of the DAQ took into account the conflicting requirements of small R&D platforms and full-scale detectors. The initial stand-alone TCP/IP direct link to a desktop has been superseded by a complete CLAS12 DAQ VSX/VME chain, using the JLab SSP protocol, which have been successfully operated with dedicated stand-alone data acquisition software in the second mRICH beam test. A preliminary positive assessment of the SSP DAQ firmware compatibility was performed by the Hawaii group.

3.4.1.1 What was planned for this reporting period

While all of the requisite boards including Transition Board, which connects the SCROD with the DCs and Carrier Board, which themselves connect the DCs to the PMT, have been fabricated, further work is required on the firmware to make the system fully functional. This task was re-initiated with the arrival of postdoc Tripathi, though given the complex nature of this programmable logic and readout system, a significant learning curve was expected.

Being designed to serve a complete detector, the VSX/SSP DAQ system is suitable for EIC, but represents an over-sophisticated and costly solution during the prototyping phase. The INFN and JLab groups planned to work on a simplified version to be distributed among the Consortium groups. The characterization of the readout solutions with standard and innovative sensors requires a benchmark assessment that is most effectively obtained on laboratory test benches. The INFN group has initiated to setup two permanent stations with a pico-second pulsed laser working in a single-photon regime and a complete readout chain, the first in USA (JLab) and the second in Italy.

The major activities planned for this period included:

- Development of SiREAD based readout firmware to operate with the SCROD FPGA.
- Second generation firmware and improved data throughput for front-end to back-end communication.
- Modular and scalable 256-channel building block readout based on the SiREAD ASIC.
- Development of pulsed laser test-benches for the sensor and readout characterization.

3.4.1.2 What was achieved?

The Hawaii team fabricated and populated the boards, and developed a first version of the readout firmware (FW) for the SiREAD based DCs. The FW programming setup is shown in Fig. 3.4.23. These DCs are mounted over the transition board and are controlled by the SCROD master board. The communication between the DC and SCROD is maintained via a custom protocol named Quad Byte Line (QBlink), whereas, the SCROD interfaces with the PC using PCI express optical gigabit transceiver. The SCROD firmware is currently being upgraded in order to incorporate the communication and control of the SiREAD DCs.

Significant progress at improving the test bench environment and learning the tools was achieved. Portions of the firmware pieces are running stand-alone, though need integration. This was slowed by limited access to the lab and personnel with requisite background to assist in troubleshooting.

(a) Top face (b) Bottom face

Figure 3.4.22: Top & bottom photographs of the SiREAD ASIC based Daughter Card.

A 3D drawing of the next generation 4-ASIC solution (256 channels of readout) for instrumenting the volume immediately behind the PMT is shown in Fig. 3.4.24.

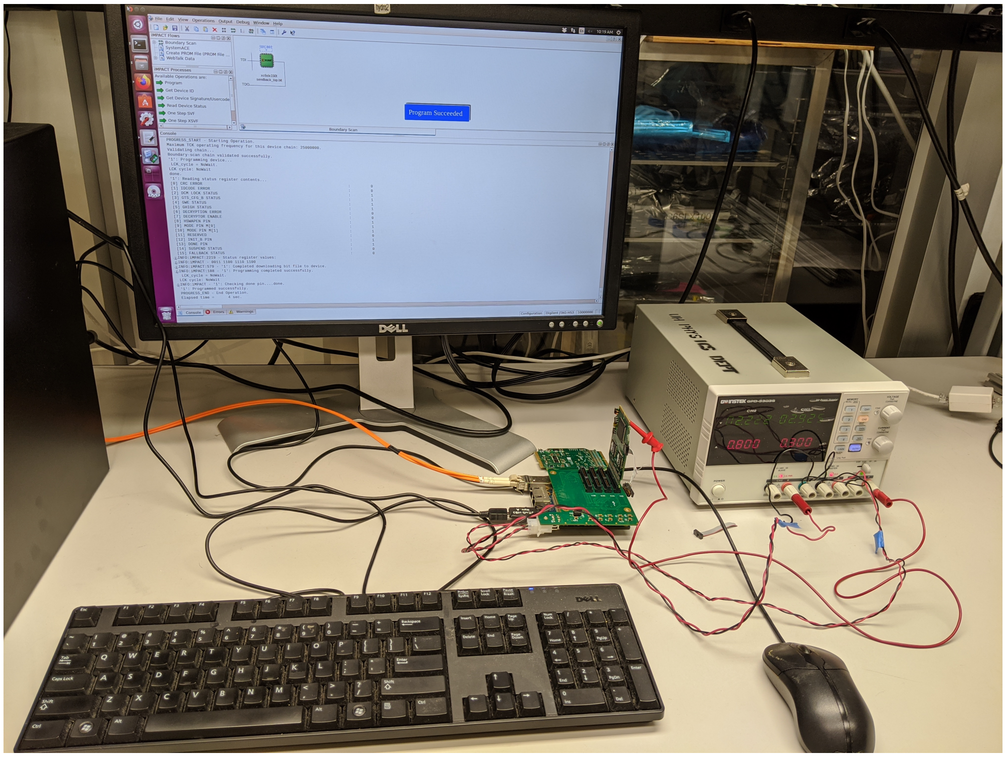

Figure 3.4.23: Our firmware programming setup. The DC is connected to a transition board, which is connected to the SCROD.

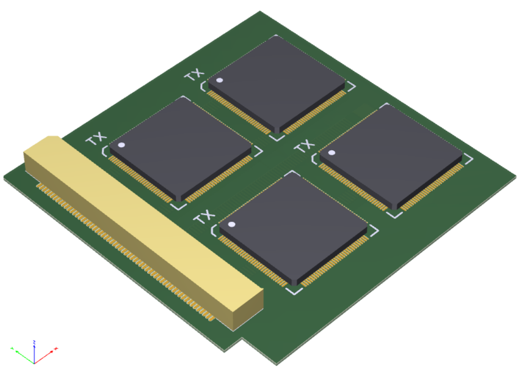

Figure 3.4.24: 3D drawing of the 4 ASIC solution.

Alternative solution for the back-end has been evaluated and a flexible solution has been identified that can serve the Consortium medium-term needs and be the base for future upgrades. As a synergistic evolution of both the CLAS12 TCP/IP development protocol and JLab SSP/VSX large-scale DAQ system, a readout architecture based on the Ethernet Trigger Supervisor (ETS) protocol was evaluated. The ETS, awarded by a U.S. patent [10], has been already successfully used to connect several flash-ADC units with 16 channels of 250 MHz Analog to Digital Converter but can be reprogrammed to link with other front-end units. ETS supports 8 either copper or fiber input lines of up to 5 Gbits serial link. In master mode, ETS is programmed to accommodate coincidence events from any input element and provide the relative information via a 1 Gbit ethernet line to a PC. In slave mode, up to 8 ETS can be connected to a master and only pass data through, in order to connect up to 64 front-end units. This architecture is easily scalable and approaches a streaming concept, supporting self trigger and specific data windows selection for the streams.

The pulsed-laser test station at JLab has been put into operation. The control, acquisition, and analysis software were updated starting from the version used for the CLAS12 sensor characteriza-

[10] https://www.osti.gov/doepatents/biblio/1463908.

tion. Tests have been already performed with one of the H13700 MAPTs and readout electronics employed for the mRICH beam test.

3.4.1.3 What was not achieved?

We had hoped the firmware development would be further along. Delays were incurred in the loss of postdoc fellow Ali, the recruitment of a new postdoc (Tripathi), and getting him up to speed on development work with this very complex system.

3.4.1.4 How did the COVID-19 pandemic and related closing of labs and facilities affect progress of your project?

While University and business facilities in Hawaii and Italy never officially closed, many of us were working from home where possible, and efficiency was subsequently reduced due to inability to interact in the lab, a vital step in troubleshooting many problems. Travel to US was restricted, slowing down the progresses in the common DAQ and laser test station development.

3.4.1.5 How much of your FY20 funding could not be spent due to pandemic related closing of facilities?

We are currently projecting $10k carry over.

3.4.1.6 Do you have running costs that are needed even if R&D efforts have paused?

Manpower. While effort by the Hawaii and INFN groups was not paused, it has not been as efficient as otherwise would be.

3.4.2 Future

3.4.2.1 What is planned for the coming months and beyond? How, if at all, is this planning different from the original plan?

The future activities planned until late Autumn 2020 involve:

- Complete the SCROD FW to implement the communication and control of SiREAD based DCs.
- Testing, Verification & Debugging of the SCROD and DC FWs.
- Characterization of timing, noise and trigger rate performance.
- Study the adaption of SSP and ETS DAQ protocols to the Consortium front-end needs.
- Development of a pulsed-laser test station in Italy.

3.4.2.2 What are critical issues?

Integrating firmware provided by Nalu Scientific, for the ASIC interface, with the SCROD control and communication firmware. Debugging such interactions are a highly non-linear, multi-body process.

4 Manpower

Abilene Christian University
Rusty Towell, Faculty
Argonne National Laboratory
Junqi Xie, Staff Scientist, 30% of time spent on project
Lei Xia, Staff Scientist, 10% of time spent on project
Chao Peng, Postdoctoral Appointee, 30% of time spent on project
Edward May, Argonne Associate, 30% of time spent on project
Tim Cundiff, Electronics Engineer, 5% of time spent on project
Brookhaven National Laboratory
Mickey Chiu, Staff Scientist
Andrey Sukhanov, Electronics Engineer
Rob Pisani, Scientific Associate
Catholic University of America
Grzegorz Kalicy, Faculty, 50% of research time on project
Nilanga Wickramaarachchi, Postdoc, 50% of research time on project
Duke University
Zhiwen Zhao, Research Professor
Erlangen University
Albert Lehmann, Faculty, 10% of time spent on project
Georgia State University
Xiaochun He, Faculty, 20% of time spent on the project
Murad Sarsour, Faculty, 10% of time spent on the project
Deepali Sharma, postdoc, 20% of time on the project
Sawaiz Syed, temp staff, 10% of time on this project
GSI Helmholtzzentrum für Schwerionenforschung
Roman Dzhygadlo, Staff Scientist, 25% of time spent on project
Carsten Schwarz, Staff Scientist, 15% of time spent on project
Jochen Schwiening, Senior Staff Scientist, 15% of time spent on project
Howard University
Marcus Alfred, Faculty, 25% of time spent on project
INFN
Marco Contalbrigo, staff researcher INFN-FE, 10% of time spent on project
Pietro Antonioli, staff researcher INFN-BO, 10 % of time spent on project
Roberto Preghenella, staff researcher INFN-BO, 10 % of time spent on project
Evaristo Cisbani, staff researcher ISS and INFN-RM1, 10% of time spent on project
Michela Chiosso, faculty and staff researcher INFN-TO, 10% of time spent on project
Manuel Dionisio Da Rocha Rolo, staff researcher INFN-TO, 10% of time spent on project
Marco Mirazita, staff researcher INFN-LNF, 10% of time spent on project
Cristina Tuve', faculty and staff researcher INFN-CT, 10% spent on project
Aram Movsisyan, post-doc INFN-FE, 20% of time spent on project
Luca Barion, post-doc INFN-FE, 50% of time spent on project supervised by M. Contalbrigo
Jefferson Lab
Carl Zorn, Staff Scientist
Jack McKisson, Staff Scientist
Los Alamos National Laboratory
Hubert van Hecke, Staff Scientist (ret.)
Joint Institute for Nuclear Research in Dubna
Maria Patsyuk, 10% time on project

Old Dominion University
Charles Hyde, Faculty, 30% of research time on project
Stony Brook University
Pawel Nadel-Turonski, Adjunct Professor, 30% of research time spent on project
University of Hawaii
Gary Varner, Faculty, 10% of time spent on project
Shivang Tripathi, postdoc, 100% of time spent on project
Isar Mostafanezhad, visiting researcher, Nalu Scientific, 5% of time spent on project
University of Illinois at Urbana-Champaign
Matthias Grosse-Perdekamp, Faculty
University of South Carolina
Yordanka Ilieva, Faculty, 30% of time spent on project
Alan Rowland, Undergraduate Student, 17% of time spent on project (8 weeks), located at Jefferson Lab and USC, supervised by Y. Ilieva
Brandon Tumeo, Graduate Student, 5% of time spent on project (2 weeks), located at Jefferson Lab, supervised by Y. Ilieva
Colin Gleason, Postdoctoral Fellow, 5% of time spent on project (2 weeks), located at Jefferson Lab, supervised by Y. Ilieva

5 External Funding

ANL

- ANL-LDRD project: Tomography at an Electron-Ion Collider: Unraveling the Origin of Mass and Spin, Oct 1, 2019 – Sep 30, 2020: $150k
- Staff, post-doctoral salaries, internal match-up covering the funding shortage to complete the proposed tasks.

ODU

- FY16-FY19: 50/50 form DOE Grant funding and University funds for ODU Technician time: $6k per year.
- FY20: 50/50 form DOE Grant funding and University funds for ODU Technician time: $10k.

GSU

- University funds provided the major portion of the support for a graduate student and for the research staff. We also used the university funds for purchasing building materials for construction of the mRICH prototypes and the supporting frames.

GSI

- Replacement for rotating stage and DAQ computer in preparation for PANDA DIRC prototype transfer to the U.S. in FY20: $8k.
- Spherical lens prototype (non-radiation hard) test production: $42k. GSI travel funds for annual DIRC@EIC meeting at JLab and R&D committee meetings at BNL: $12k.

UHawaii

- DOE Detector R&D (Hawaii Grant Task F) support for new detector development and ASIC training stewardship, roughly $100k annually, 25% spent this reporting period.

INFN

- Staffa salary, infrastructure and travel expenses for dRICH prototype and tests, electronics development, SiPM irradiation program;
- MAROC readout electronics;
- mRICH+dRICH: SiPM and cooling system; MAROC readout electronics adaptation €20k;
- dRICH prototype: mechanics, radiators and optical components €30k;
- SiPM irradiation: ALCOR readout electronics with integrated cooling system, climatic temperature and humidity test chamber €20k.

BNL

- Infrastructure and staff salary for the radiation hardness tests of DIRC and mRICH optical materials.

Jefferson Lab

- Salary of staff (detector experts, DAQ, electronics, technicians), facilities, equipment, and infrastructure for the High-B MCP-PMT evaluations.
- Conference space for the annual DIRC collaboration meeting, phone conferencing for the bi-weekly consortium meetings and any other consortium-related remote meetings.

Nalu Scientific

- SBIR grant for developing the SiREAD chip for digitizing SiPM waveforms with applications in EIC PID.

See also the respective sections for more details on TOF, photosensors, *etc.*

6 Publications

6.1 In Preparation

A. Del Dotto et al., *Event based inverse ray-tracing reconstruction for RICH detector*, to be published in NIM.

6.2 Recently Published or Submitted

Junqi Xie et al., *ALD-coated microchannel plate photomultiplier with fast timing and magnetic field immunity*, submitted to NIM A. (under review 2020).

Junqi Xie et al., *MCP-PMT development at Argonne for particle identification*, proceeding of DIRC2019, Journal of Instrumentation 15 (04), C04038 (2020).
https://doi.org/10.1088/1748-0221/15/04/C04038

Junqi Xie, Marcel Demarteau, Edward May, Robert Wagner, and Lei Xia, *Fast-timing microchannel plate photodetectors: design, fabrication and characterization*, Review of Scientific Instruments 90, 043109 (2019). https://doi.org/10.1063/1.5063825

Mohammad Hattawy, Junqi Xie, Mickey Chiu, Marcel Demarteau, Kawtar Hafidi, Edward May, Jose Repond, Robert Wagner, Lei Xia, and Carl Zorn, *Characteristics of fast timing MCP-PMTs in magnetic fields*, Nucl. Instr. and Meth. A 929, 84 (2019).
https://doi.org/10.1016/j.nima.2019.03.045

E. Cisbani, A. Del Dotto, C. Fanelli, M. Williams et al., *AI-optimized detector design for the future Electron-Ion Collider: the dual-radiator RICH case*, J. Inst., vol.15, May 2020.
https://doi.org/10.1088/1748-0221/15/05/P05009

G. Kalicy et al. (EIC PID Collaboration), *Status of the high-performance DIRC detector for the Future Electron Ion Collider Experiment*, Proceedings for DIRC2019, to be published in JINST.

G. Kalicy et al. (EIC PID Collaboration), *Developing high-performance DIRC detector for the Future Electron Ion Collider Experiment*, Proceedings for INSTR20, submitted to JINST.

7 Presentations

X. He and J. Schwiening (EIC PID Collaboration), *Development of Compact, Projective and Modular Ring Imaging Cherenkov Detector for Particle Identification in EIC Experiments*, International Conference "Instrumentation for Collider Beam Physics" (INSTR20), Novosibirsk, Russia, February 24 - 28, 2020.

G. Kalicy and J. Schwiening (EIC PID Collaboration), *hpDIRC: the High-Performance DIRC for the Electron Ion Collider Detector*, International Conference "Instrumentation for Collider Beam Physics" (INSTR20), Novosibirsk, Russia, February 24 - 28, 2020.

J. Xie, *Application of MCP-PMT/LAPPD for EIC Particle Identification*, CPAD Instrumentation Frontier Workshop 2019, 8 – 10 December, Madison, WI, 2019.

A. Rowland (EIC PID Collaboration), *Studies of the Gain of Small-Pore Size Microchannel Plate Photomultipliers in High Magnetic Fields*, poster presentation at Discover USC, April 26th, Columbia, SC, 2019.

A. Rowland (EIC PID Collaboration), *Studies of the Gain of a Small-Pore Size Microchannel Plate Photomultiplier in High Magnetic Fields*, poster presentation at the Conference Experience for Undergraduates at the Fall 2019 Meeting of the APS Division of Nuclear Physics, 14 – 17 October, Crystal City, VA, 2019.

X. He (EIC PID Consortium), *mRICH*, invited talk, Streaming Readout V, RIKEN BNL Research Center Workshop, November 13 – 15, 2019.

E. Cisbani (mRICH and dRICH Groups), *RICH detectors development for hadron identification at EIC: design, prototyping and reconstruction algorithm*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, Castle Rauischholzhausen, Germany, 11 – 13 September 2019.

C. Fanelli, *Machine learning for RICH counters*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, Castle Rauischholzhausen, Germany, 11 – 13 September 2019.

G. Kalicy (EIC PID Collaboration), *High-Performance DIRC Detector for future EIC Detector*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, Castle Rauischholzhausen, Germany, 11 – 13 September 2019.

J. Xie, *MCP-PMT development at Argonne for particle identification*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, Castle Rauischholzhausen, Germany, 11 – 13 September 2019.

G. Varner, *Performance of the imaging Time Of Propagation detector during the first Belle II Physics run*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, Castle Rauischholzhausen, Germany, 11 – 13 September 2019.

G. Varner, *Recent developments in paradise: fast waveform sampling readout electronics for finely pixelated photosensors in Hawaii*, presentation, DIRC2019: Workshop on fast Cherenkov detectors, Castle Rauischholzhausen, Germany, 11 – 13 September 2019.