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 07/01/2020 to 02/28/2021
Contact Persons: Pawel Nadel-Turonski and Yordanka Ilieva
Project Members: The eRD14 Collaboration (See the FY21 eRD14 Proposal for a complete list of collaborators)

03/05/2021

Abstract

Excellent particle identification (PID) is an essential requirement for the Electron-Ion Collider (EIC) detector. Identification of hadrons in the final state is critical for the study of 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 have been considered.

Contents

1 Introduction

Identification of hadrons in the final state is essential for key EIC measurements formulated in the EIC White Paper and Yellow Report, 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 FY21) 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 ensuring compatibility with the detector concepts developed for the EIC and the Yellow Report detector requirement matrix. 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. From FY18 the sensor effort was extended to include associated 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 funding level for the first year of the plan was at the level of 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. The implicit assumption was that the overall R&D funding level would increase, which did not happen. Nevertheless, despite the budget limitations and the Covid-19 situation, the consortium has made good progress towards the stated R&D goals.

The consortium has also been closely following the spending of the approved funds. Since funds do not become available at the contract period, and the handling of invoices can sometimes be slow, before the end of the year it could appear that some funds are unspent, but in reality eRD14 does not expect to have a significant carryover in FY21.

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 $25°$, corresponding to a pseudorapidity range $\sim 1.5 - 3$.

2.2.1 Past

2.2.1.1 What was planned for this reporting period

The main technical goals for the reporting period have been the preparation of the dRICH prototype beam-test and the SiPM irradiation campaign. Further co-funding requests for dRICH prototyping and SiPM tests were submitted to the Italian National Institute of Nuclear Physics (INFN) and mostly funded.

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 definition and realization, (3) Electronics flexible integration, (4) Components test and selection, (5) Application for INFN funds. The SiPM irradiation program was anticipated in 2020 thanks to the involvement of new INFN expertise. These activities were planned and structured such that the following major objectives are achieved in FY21: dRICH baseline prototype realization, first beam test, and initial SiPM irradiation campaign.

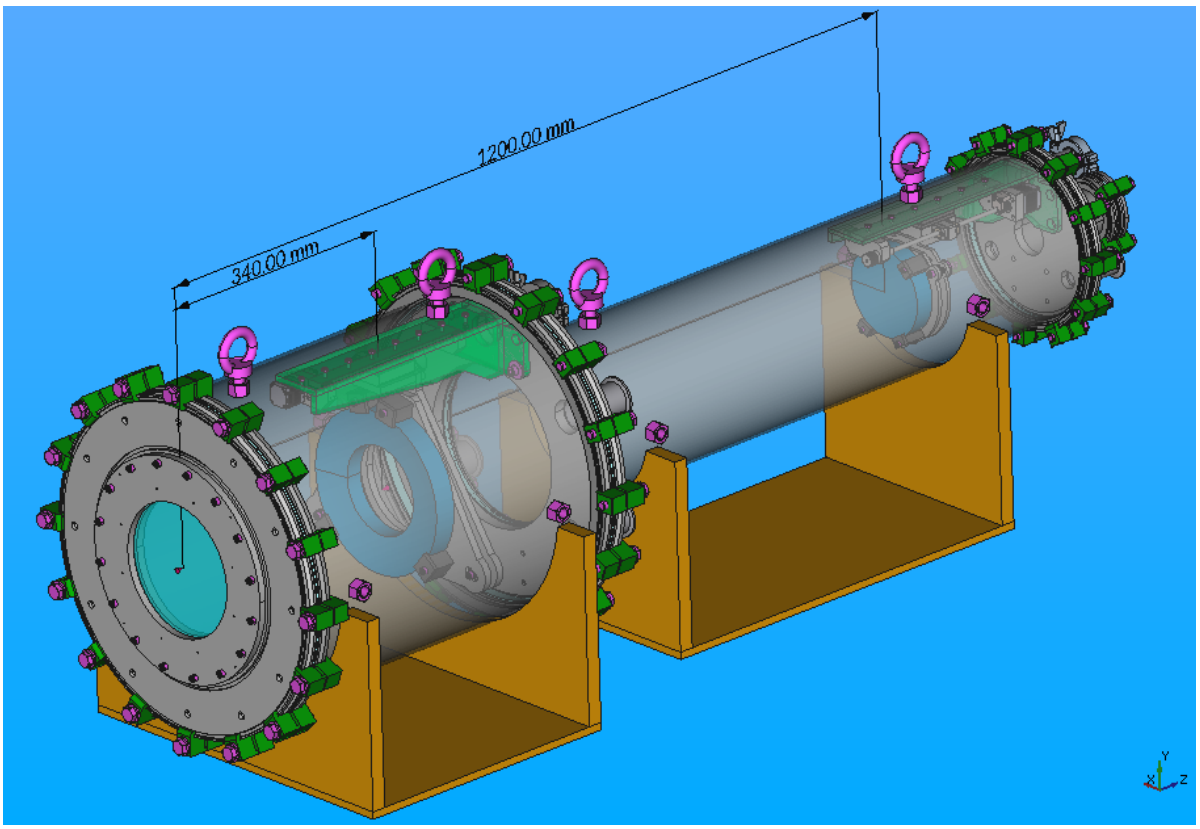


Figure 2.2.1: 3D model of the complete dRICH prototype.

2.2.1.2 What was achieved?

During the Yellow Report initiative, the dRICH has been identified as the reference detector in the EIC hadron endcap. The discussion within the PID working group has highlighted the importance to study the dRICH performance in conjunction with the other EIC detectors and alternatives. In addition to all the stand-alone performance studies pursued so far, an action to import the dRICH model into the current

EIC supported simulation frameworks has been initiated by a team of people at Duke in collaboration with INFN.

Details of the prototype design have been finalized (activity (1) and (2) listed in Section 2.2.1.1) in preparation for production. The vessel is a cylinder made of standard vacuum pipes and closing flanges to contain the cost and support pressures different from atmospheric one, see Fig. 2.2.1. 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 mirror alignment system has been greatly simplified. The expensive and high-pressure incompatible system of three z-axis vacuum manipulators has been replaced with a linear drive and a carriage supporting a plate with three alignment screws, see Fig. 2.2.2. After the first alignment in air, the mirror can be real-time translated along the beam axis (to adjust focalisation or to move the mirror outside acceptance) by means of a remotely-controlled motor while the prototype is pressurized. Depending on the longitudinal position of the mirror, the Čerenkov cones generated by either the aerogel, or the gas, or both radiators can be imaged. This allows to simplify the prototype operations during the tests and to challenge the photon pattern reconstruction with a realistic occupancy. The design of a platform to support and align the prototype has been initiated.

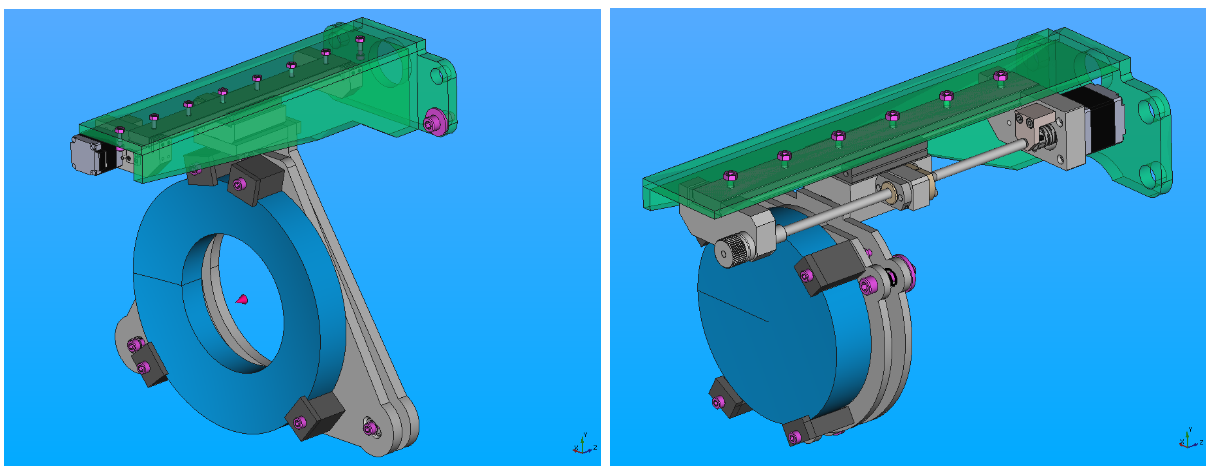


Figure 2.2.2: dRICH mirror support and alignment system for aerogel (left) and gas (right). The central hole in the aerogel mirror allows for the imaging of the gas Čerenkov light.

Using the granted 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 with refractive indices between 1.02 and 1.03 and dimensions suitable to serve both the dRICH and mRICH prototype-test campaigns. With additional INFN funds granted in 2021, the radiator C_2F_6 gas was ordered and the procurement of the mirrors and linear drives has been initiated.

The gas- and light-tight 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 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 to prevent disruptive interaction and can be design to filter UV light to improve resolution, (*i.e.*, to suppress Rayleigh scattered photons in the aerogel and to reduce the light chromatic dispersion in the gas). The box can be adapted to house different arrays of photo-sensors surrounding a central hole where the aerogel radiator can be inserted. In particular, the box can 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, both readout by the MAROC3 electronics [1]. These already tested large area devices are essential to image a sizeable fraction of the ring ($\sim 50\%$), to validate the dRICH concept, and verify the optical performance of the dRICH prototype, see Fig. 2.2.3.

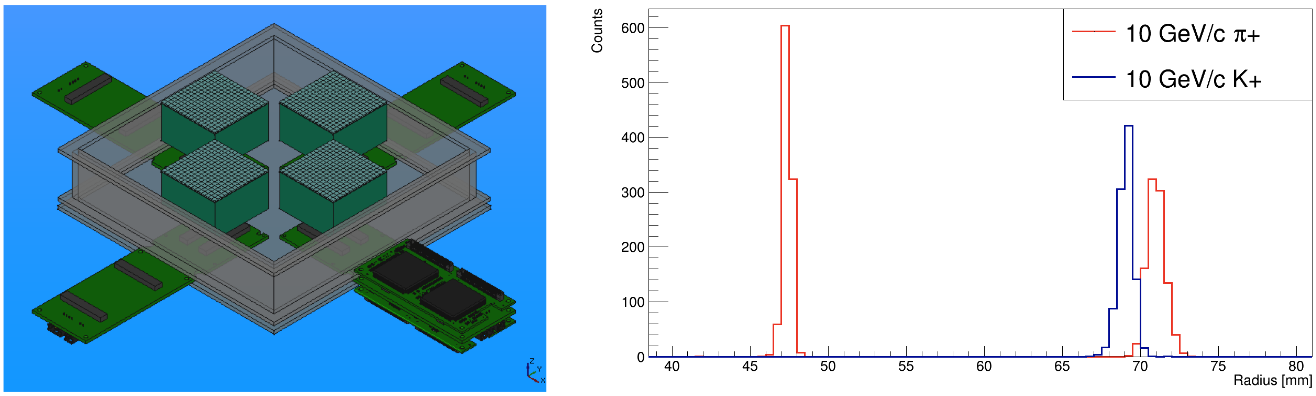


Figure 2.2.3: dRICH detector box instrumented with the reference H13700 MA-PMTs of large area and MAROC readout electronics to study the optical performance of the prototype (left). The reference photo-sensors can image about half of the Čerenkov ring allowing an event-based analysis. Comparison of the imaged radii for pions and kaons at 10 GeV/c, with kaons below the gas Čerenkov threshold (right).

The proposed prototype configuration has been modeled and simulated in GEMC/Geant4. The prototype single-photon resolutions are similar to the ones expected in EIC, except for the pixel error with the aerogel radiator that, despite being larger due to the prototype 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 typical expected number of detected photons depends on the instrumented area and is around 6 for the aerogel and 18 for the gas in the configuration with reference detectors. Even with an incomplete active area, the prototype is instrumental to validate the dual-radiator approach to cover the momentum range from few GeV/c to multi tens of GeV/c, and the interplay of the two radiators at intermediate momenta in between their working ranges, see Fig. 2.2.3.

In 2020 a collaboration has been initiated among seven INFN groups interested in the SiPM application for Čerenkov imaging to pursue a comprehensive investigation of the SiPM use for RICH detectors at EIC. In addition to the groups already represented within the eRD14 Consortium, the new INFN units provide complementary resources 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 capability of irradiated SiPMs with a dedicated 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. After a wide-range survey of the available SiPM candidates, a selection of the most interesting state-of-the-art devices has been acquired from Hamamatsu, Broadcom, OnSemiconductors and Bruno Kessler Fundation. Groups of 4×8 SiPMs will be assembled into a single carrier board designed to support the irradiation and annealing cycles and provide direct access to each sensor for laboratory characterization, see Fig. 2.2.4. This configuration allows to test SiPMs from different producers and at different levels of irradiation, from 10^8 cm^{-2} up to 10^{11} cm^{-2} 1-MeV equivalent neutrons. The instrumented surface is large enough to ensure a reliable statistics for each SiPM selection

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

during the laboratory characterization. At the same time, it allows imaging tests with the dRICH prototype, providing a validation of the full readout chain and a proof-of-principle of the post-irradiated SiPM application for single photon detection.

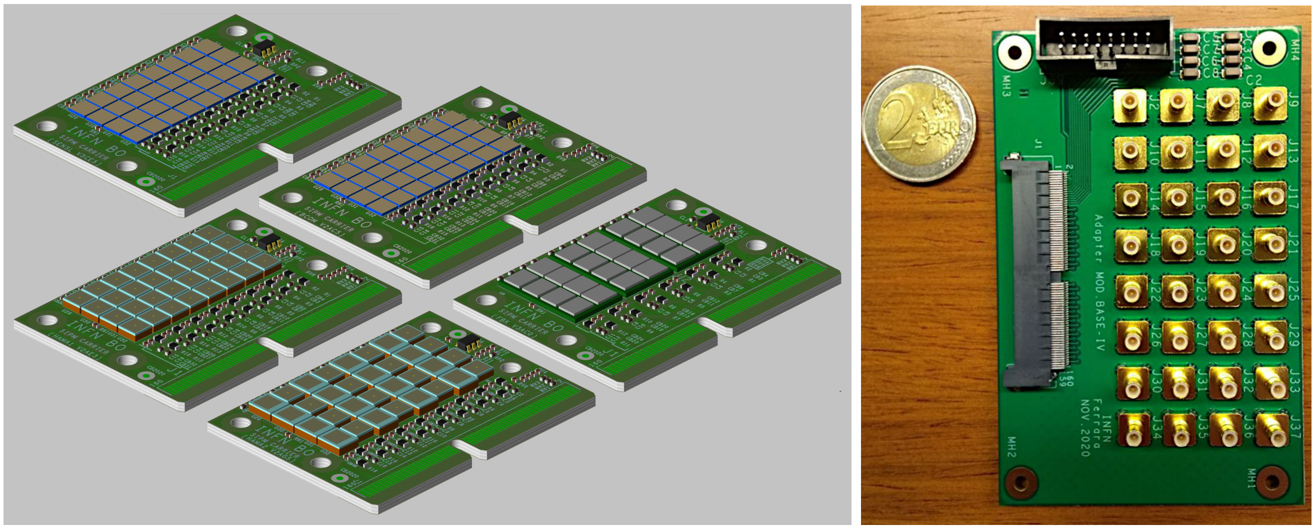


Figure 2.2.4: Carrier boards, each mounting arrays of two selected types of SiPMs from one manufacturer: Hamamatsu (x2), OnSemiconductor, Broadcom, FBK (left). Test board distributing the SiPM bias and temperature control signals, and providing direct connection to each sensor for laboratory characterization (right).

In addition to the use of the MAROC reference readout, the development of a dedicated readout electronics compatible with the SiPM 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 the eRD14 Consortium [2]. The first version of the ALCOR chips has become recently available and is now under study with a dedicated test-board, see Fig. 2.2.5.

An adapter board is being developed to allow readout by a front-end ASICs and imaging tests with the dRICH prototype, see Fig. 2.2.5. The dRICH detector-box 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 to the working point temperature, 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 EU facilities. The SiPM irradiation has been scheduled at the TIFPA INFN facility in Trento, Italy, for May 2021. A dRICH prototype test has been approved for October 2021 at the CERN T10 PS beam line in synergy with ALICE. The test will use mesons with momenta below 10 GeV/c and study the single-photon response of irradiated SiPM in consjunction with Russian and Japanese aerogel. A request for a dRICH dedicated beam test at the CERN H6 SPS beam line has been submitted to reach particle momenta up to 60 GeV/c and study the gas imaging performance. In addition, 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.

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

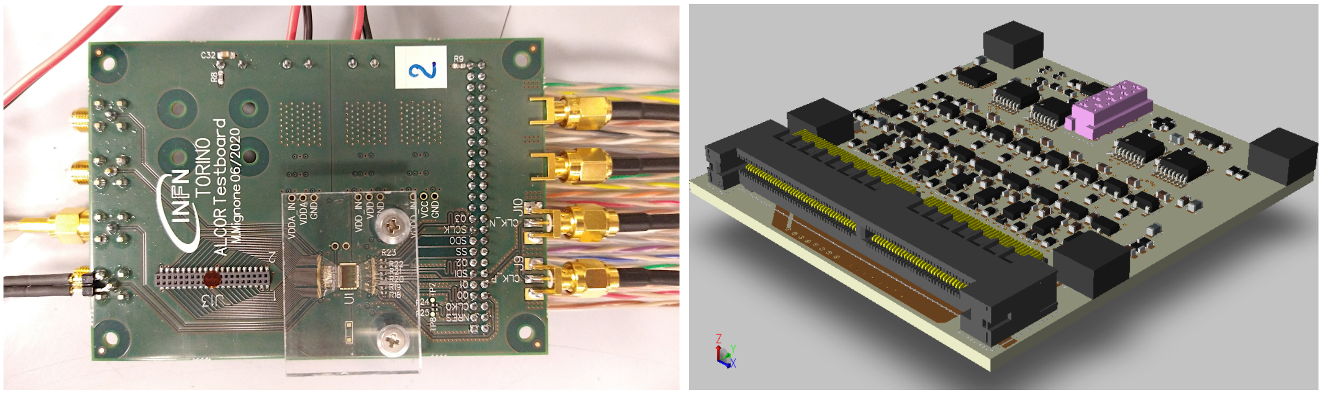


Figure 2.2.5: Test-board in use to validate the performance of the ALCOR front-end chip (left). Adapter board designed to connect the SiPM carrier to the ALCOR (or MAROC) readout (right).

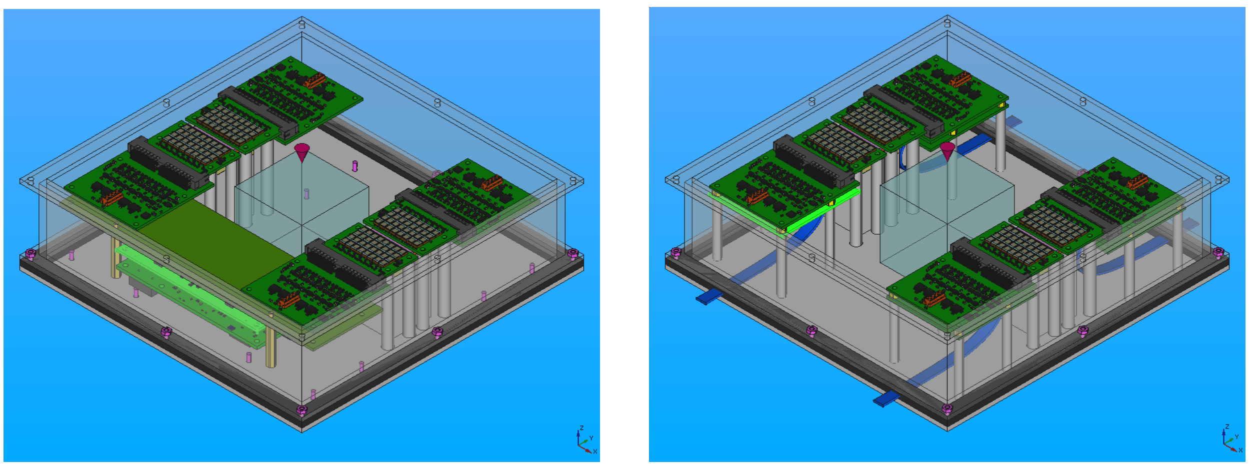


Figure 2.2.6: dRICH photo-sensor box instrumented with the carrier and adapter boards mounting the irradiated 3 mm SiPM arrays together with, highlighted in light green, the reference MAROC3 readout electronics (left) and the new compact ALCOR high-frequency readout (right).

2.2.1.3 What was not achieved?

The component tests and prototype assembling activity have not started yet. This is due to the changes in priorities caused by the pandemic effects and reshuffled in favor of the most urgent SiPM irradiation campaign. All the activities have been rescheduled in preparation of the approved beam tests: SiPM irradiation at TIFPA in May and dRICH prototype at CERN in October.

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 so far limited the hardware activity in laboratory but is not expected to further impact the preparation of the beam tests. The design and procurement activities made important progresses and we are still on track to achieve in FY21 our main objectives of prototype realization and first beam test.

2.2.1.5 How much of your FY21 funding could not be spent due to pandemic related closing of facilities?

The activity is in line with the achievement of the main FY21 objectives. As of now, we plan not to have any significant carry over after the end of the FY21 contract.

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

The planned activity for the reporting period 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 is almost complete and its realization imminent. The aerogel and gas radiators and the SiPM sensors have been acquired. The component characterization, testing, and assembling is being initiated with the goal to be ready for the planned beam tests.

2.2.2.2 What are critical issues?

A deterioration of the COVID-19 situation might still impact travel, beam test availability and operations at the laboratories.

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.

However, it is crucial to continue the support of dedicated personnel (postdocs) that can only be co-funded by INFN.

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 [3]. In this report, we highlight progress made on the mRICH project since July 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 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 in the EIC Yellow Report activities.

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

2.3.1.2 What was achieved?

Preparation of the next mRICH beam tests with tracking capability and new photosensors was one of our major R&D efforts in this report period. Specifically, we worked on planning two beam tests. One was scheduled at Fermilab in March of 2021 and the other in summer of 2021 at JLab.

The test setup at Fermilab is shown in Fig. 2.3.7. The previous two mRICH beam tests were also performed at this beamline. The mRICH team has extensive knowledge of running experiments at this facility. Figure 2.3.8 shows the preparation work at BNL for this test. One of the mRICH prototypes has been shipped to BNL for the test assembly. This will be the first test assessing mRICH performance with an LAPPD readout.

Figure 2.3.7: The planned beam test installation of mRICH with LAPPD readout at MT6 beam line at Fermilab. Two pairs of GEM tracking chambers upstream (G1 and G2) and downstream (G3 and G4) provide a tracking reference with better than 50 μm spatial resolution in X&Y at the LAPPD location. A pair of PHOTONIS Planacon MCP-PMTs (M1 and M2) could be used as a redundant timing reference.

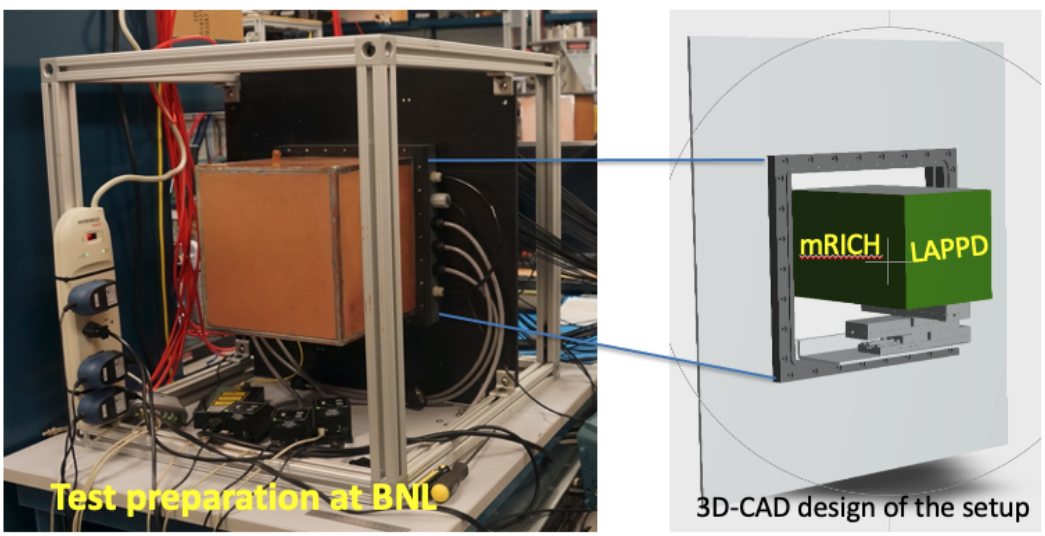


Figure 2.3.8: The preparation of the mRICH and LAPPD test setup at BNL.

The beam test at JLab is planned in Hall D using a secondary electron beam with momentum ranging from 1 to 6 GeV/c, as shown in Fig. 2.3.9. The committed participating institutions include JLab (Lubomir Pentchev, Benjamin Raydo, Sergei Furletov, Fernando Barbosa and Yulia Furletova), 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). The effort of setting up the mRICH photosensor (Hamamatsu H13700) readout for this test was led by INFN, together with a team support from JLab.

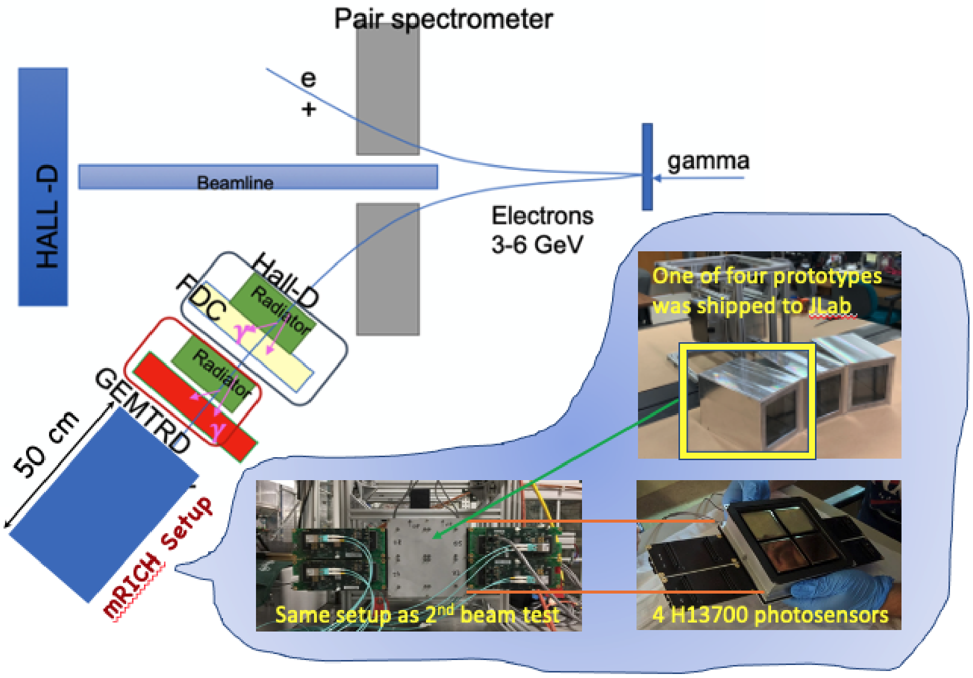


Figure 2.3.9: Planned mRICH test setup in Hall-D at JLab. The mRICH readout will be supported by INFN group. We will use the same tracking system used by the EIC TRD-GEM test team.

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. 2.3.10). 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. 2.3.11 shows a 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. 2.3.12

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. 2.3.13), but our plan to complete the hardware assembly and test before the end of April could not be realized.

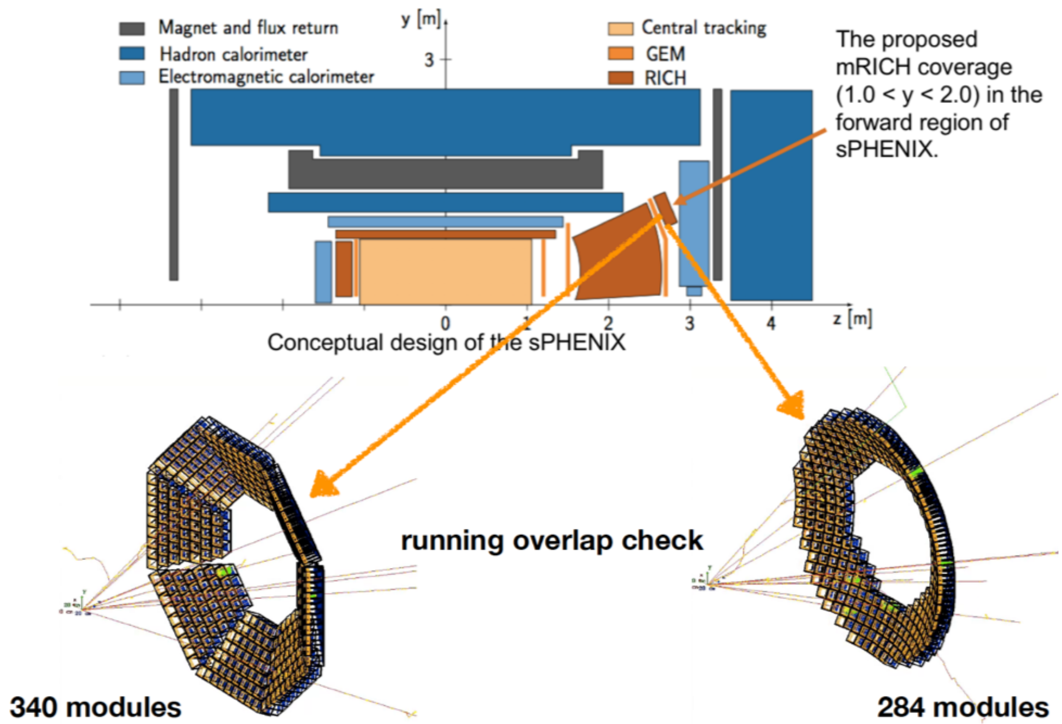


Figure 2.3.10: An array of mRICH modules implemented in the sPHENIX simulation.

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 more than six months in the mRICH R&D efforts, mainly related to hardware work and a beam test. Because of the travel restrictions at BNL, the planned mRICH plus LAPPD test in March of 2021 got delayed. It is not clear at this point if the JLab test will be delayed or not.

2.3.1.5 How much of your FY21 funding could not be spent due to pandemic related closing of facilities?

None. We diverted the unused travel fund to support a postdoc salary in order to speed up the data analysis from the second mRICH beam test and the PID algorithm development.

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 on 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.

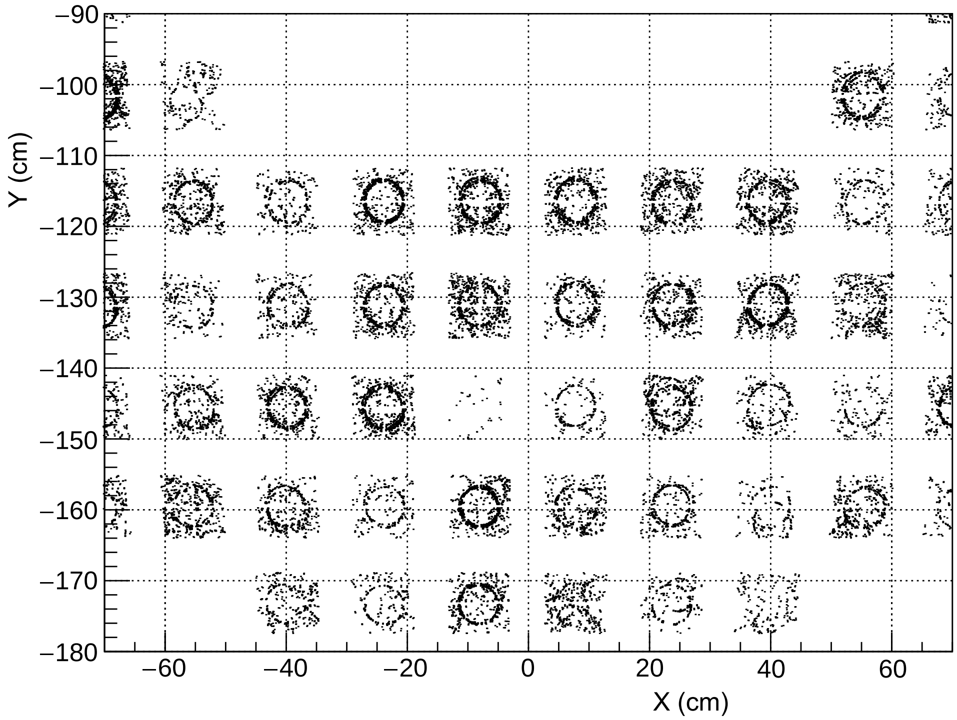


Figure 2.3.11: Simulated photon hits display from a section of the mRICH array implementation in the sPHENIX experiment. These rings are from pions at $p_T = 5$ GeV/c launched at (0,0,0) vertex in a rapidity range of $1 < |y| < 3$.

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 July 2020 – March 2021 were: (1) completion of the upgrade of the laser setup at ODU and commissioning of the new system; (2) initial design of the Cosmic Ray Telescope at Stony Brook University for the hpDIRC prototype tests; (3) improvement of the CERN data analysis and simulation studies of the hpDIRC design and the laser setup.

2.4.2 Past

2.4.2.1 What was planned for this reporting period

The top priorities for this fiscal year were several simulation studies, the preparation for hpDIRC system prototype program, and concluding two component tests: the study of optical component radiation

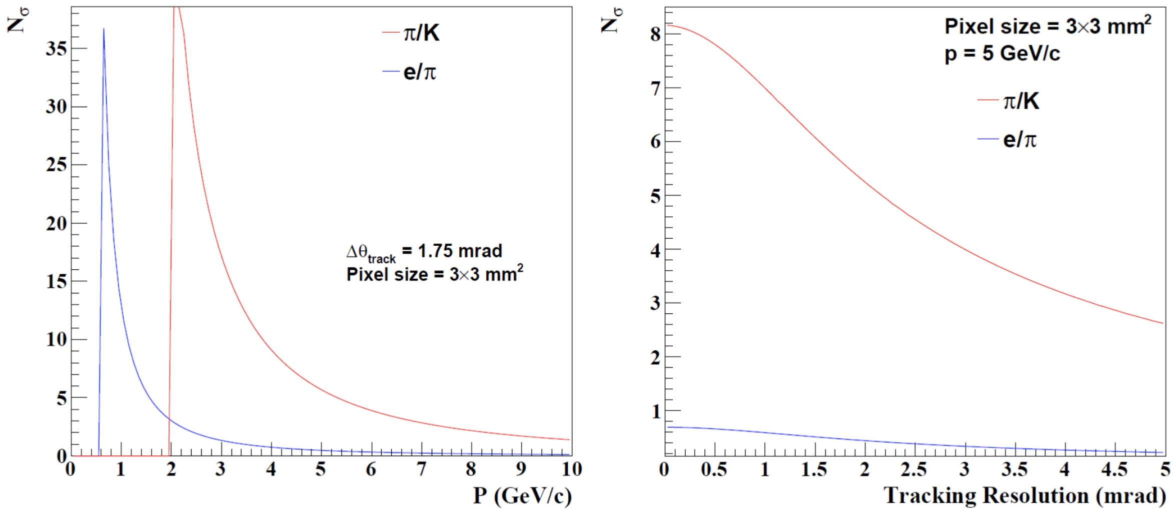


Figure 2.3.12: Fast parameterization of the mRICH PID performance in projective mode.

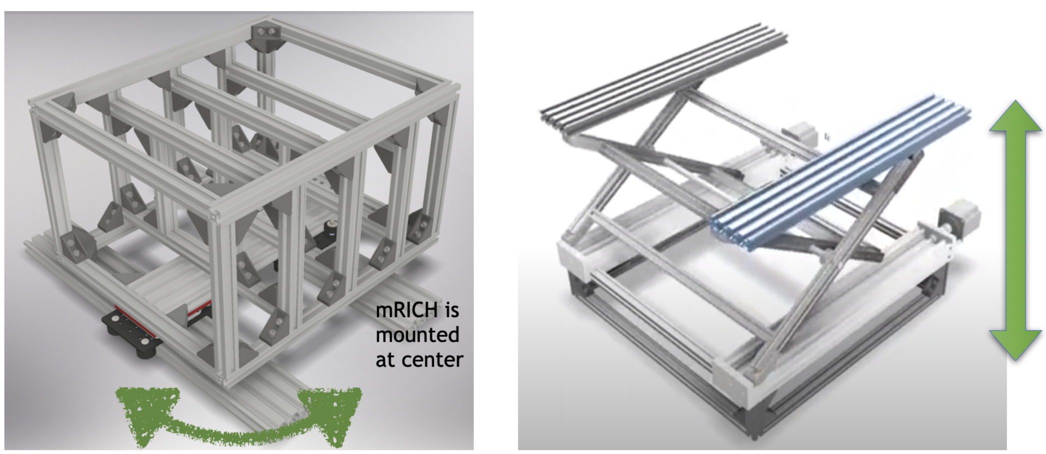


Figure 2.3.13: 3D-model of the support frame of mRICH module for beam test and optical characterization.

hardness to gammas and neutrons and the characterization of the new radiation-hard lens prototypes.

The preparation of the hpDIRC prototype tests consists 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 (SBU) and the PANDA-based DAQ system was to be validated. In preparation for the first beam-test 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. Other planned hpDIRC simulation projects included the optimization of the detector geometry, a study of the performance based on reused BaBar DIRC bars, and an evaluation of the e/π separation at lower momentum.

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 manuscript of 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 upgrade of the laser setup for the lens characterization was completed. The system is currently being commissioned and calibrated. The new prototype lens, made with radiation-hard PbF_2, was delivered and is ready to be tested together with the other prototypes. A Geant simulation of this setup was developed to study in detail how well Geant4 reproduces optical aberrations.

Work on the journal publication about the performance evaluation of the focusing system with the prototype in particle beams is progressing. As part of that process, the analysis of 2017 data was revisited for a better comparison with the 2018 data. The goal is to have the publication ready for submission by the end of this calendar year.

Preparation for the hpDIRC prototype studies at SBU are in progress, including initialization of the Cosmic Ray Telescope setup development by a joint CUA-GSI-ODU-SBU effort.

Additional optical samples were purchased and prepared for the neutron radiation hardness test. Arrangements were made with the Core Research Facilities at UMass Lowell to perform the irradiation and will be scheduled as soon as the pandemic-related restrictions allow.

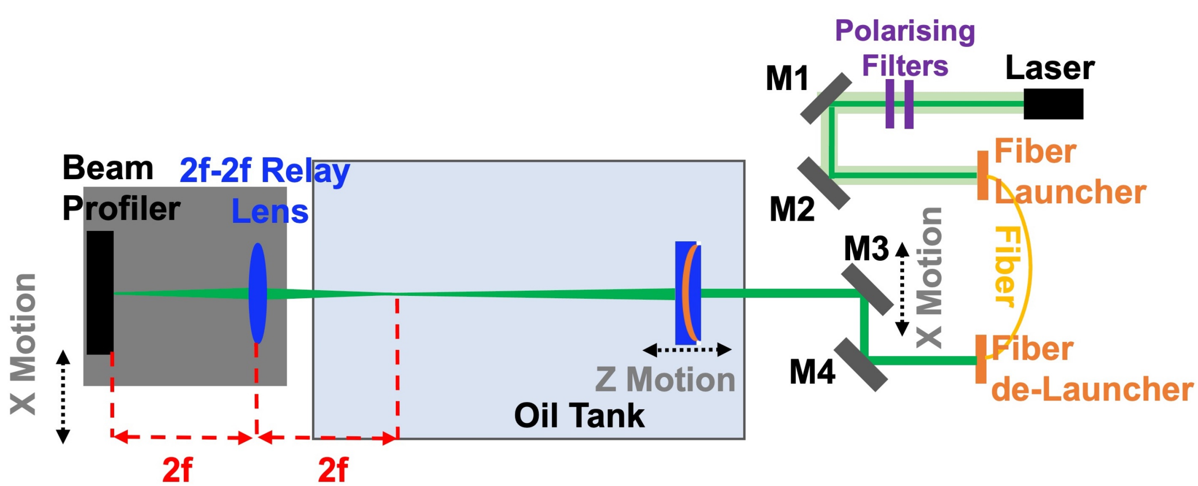


Figure 2.4.14: Schematic of the laser setup for mapping the focal plane of the hpDIRC lens prototype.

Hardware: Laser Setup Figure 2.4.14 shows the schematic of the new laser setup that was built in the Old Dominion University (ODU) lab to map the shape of the focal planes of prototype lenses. In the new method, the width of the laser beam is scanned and recorded at multiple locations after passing through the tested lens. The minimum width determines the focal length. Different incident photon angles are realized by rotating the lens through the laser beam.

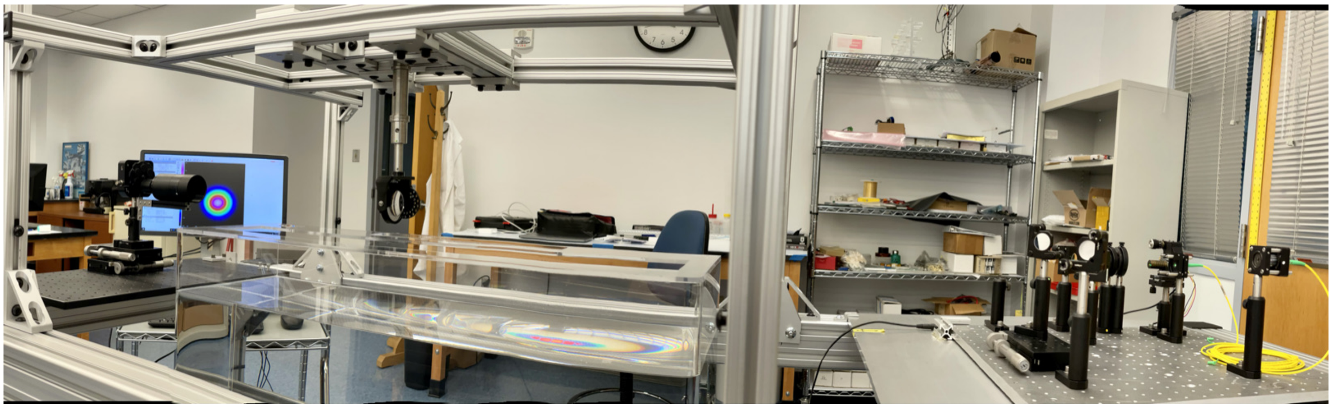


Figure 2.4.15: Photograph of the upgraded laser setup with lowered oil tank.

The photo in Fig. 2.4.15 shows the upgraded setup. The main improvements are a fiber launch system to improve the laser beam quality, an improved mechanical system for easier access to the optical components, and the addition of a CCD camera beam profiler with a commercial software package for determining the position and width of the laser beam.

The 532-nm laser beam passes through an optical fiber to assure a clean Gaussian shape of the laser beam. Two polarizing filters are used to adjust the laser intensity. Mirrors, mounted on micrometer-controlled translation stages, are used to adjust the beam position. The lens is placed inside an acrylic 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 hpDIRC, where it will be placed between the bar and the prism. The oil tank is placed on a scissor lift table that lowers the tank to gain access to the optical elements, suspended above the tank, and then lifted up again. This simplifies the calibration of the setup and the exchange of lenses. The rotation stage for the lens is fixed to a stable support structure above the tank with a motion control system to move it in the z direction, to control the distance to the imaging system. The tested lens is supported in a custom-made 3D-printed holder that makes it possible to map out the focal plane in all three dimensions. The laser beam is recorded with a CCD camera beam profiler connected to a 2f-2f relay lens system to image the laser beam profile inside the oil tank from the profiler position outside of the oil tank.

Figure 2.4.16a shows an example of the beam profile after focusing by a standard commercial air gap lens (without oil in the tank), which is used for calibration of the setup. The width of the beam is defined as the RMS of the beam projections on the x and y axes, provided by the beam profiler software. Both values are saved and the procedure is repeated for the next position of the lens relative to the profiler. A scan of the x-profile beam width as a function of the lens position is shown in Fig. 2.4.16b. The minimum width is found at a distance of 146 mm from the lens. A simulation package was developed in Geant4 for the new laser setup. Figure 2.4.17a shows the event display from the simulation of the 3-layer spherical lens in the oil tank. The red line indicates the location of the imaging plane and the image of the beam profile is shown on Fig. 2.4.17b. The combination of the new setup and the simulation package will allow us to study in detail the optical aberrations of the lens prototypes and how well they are reproduced in Geant4.

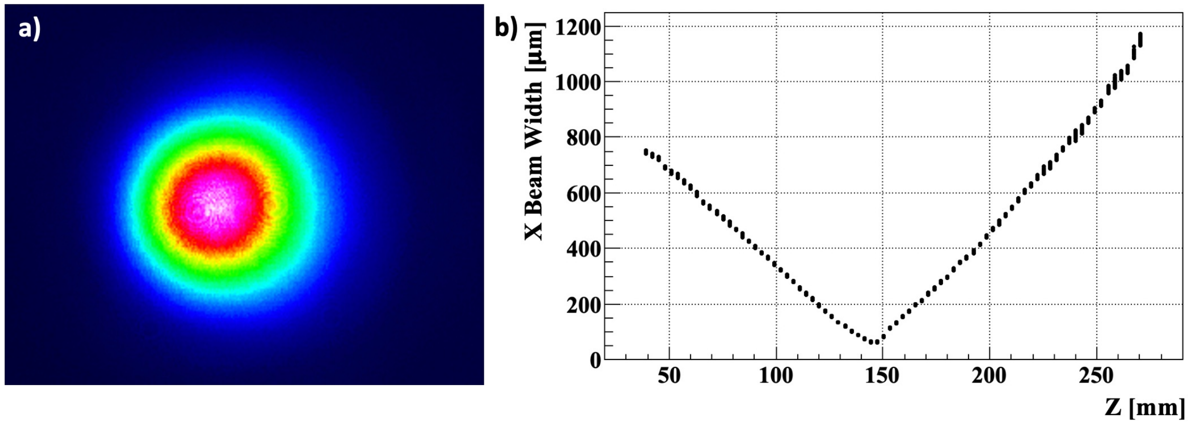


Figure 2.4.16: (a) Example of the imaged laser beam profile after a standard air-gap lens. (b) Measured width of the laser beam projection on the x-axis as a function of the distance from the lens.

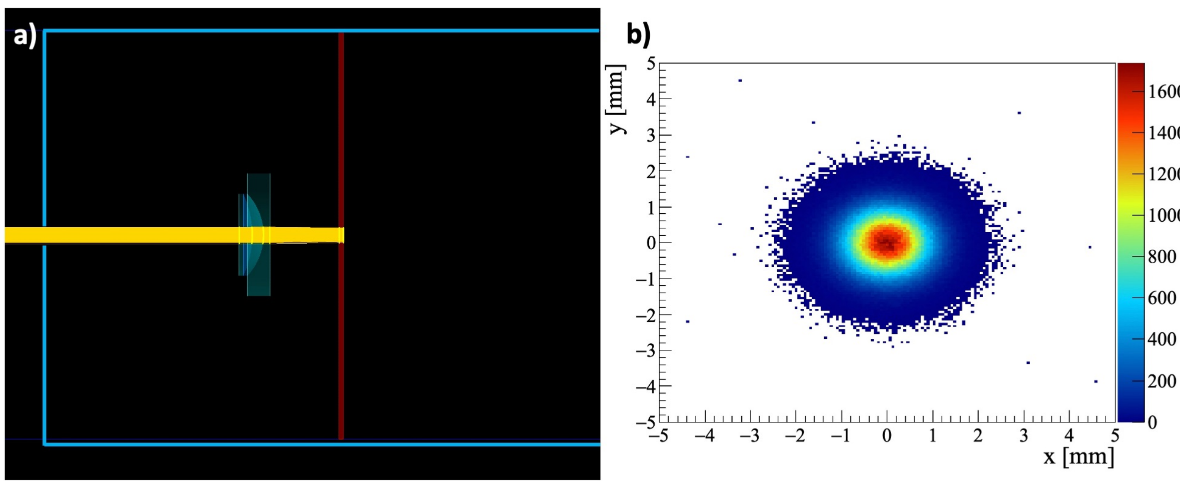


Figure 2.4.17: (a) Event display of the focal-plane mapping simulation. (b) Simulated image of the laser beam profile.

Software: PANDA Barrel DIRC 2018 prototype at CERN As part of the preparation of the NIM paper on the performance of the Barrel DIRC prototype at CERN, the analysis of the 2018 data from the CERN beam-test campaign was improved. The alignment and calibration of the data, as well as the selection cuts, were fine-tuned and the geometric reconstruction results were enhanced using a time-based correction of the chromatic dispersion of the Čerenkov angle. Figure 2.4.18 shows excellent agreement between the measured and simulated data for two main parameters defining DIRC performance, the photon yield and single-photon Čerenkov angle resolution (SPR).

Hardware and Simulation: hpDIRC prototype at SBU The transfer of the PANDA Barrel DIRC prototype from GSI to the U.S. and the preparation for the performance evaluation is making progress. A working group with members from CUA, GSI, ODU, and SBU, was formed to design and build a Cosmic Ray Telescope (CRT) in the future DIRC lab at SBU. Legacy components, such as GEM detectors and a TPC for 3D tracking, and scintillators as triggers and veto counters, will be combined with new detectors, such as a CO_2 threshold Čerenkov counter, which will provide the momentum threshold for the cosmic muons. The initial version of the DIRC prototype will use the optics and electronic

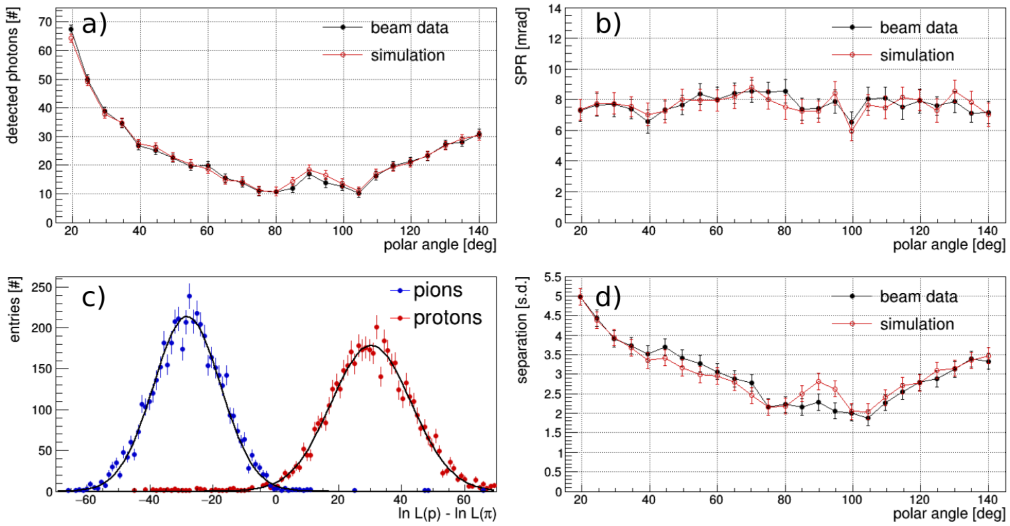


Figure 2.4.18: Performance of the PANDA Barrel DIRC prototype for 7 GeV/c π/p beam during the 2018 beam test at CERN: photon yield (a), SPR (b) and separation power of time imaging reconstruction (d) as a function of polar angle. (c) shows an example of the log-likelihood distributions at a polar angle of 20°.

components from the PANDA DIRC prototype, which will be incrementally upgraded with new sensors and readout electronics, as those become available.

Figure 2.4.19 shows the initial design of the CRT. The CO_2 tagger selects high-momentum muons, whereas the veto counter is used to reject shower tracks. The simulation studies of the hpDIRC showed that in order to reach the desired performance, a tracking resolution at the level of 0.5 mrad is required. This performance can be reached by placing several arrays of GEM trackers with a spatial resolution of about 0.1 mm, available from the sPHENIX effort, above and below the DIRC prototype. The reference time will be provided by the t_0 counter with a timing precision of about 70 ps or better. Several options are under consideration, the leading candidate is a Gen-1 LAPPD sensor, alternatives include an mRPC prototype or a commercial MCP PMT with a thin fused silica radiator glued to the front window of the PMT.

Currently the work is focused on collecting and checking the availability of the desired hardware and preparing the simulation studies to determine the best arrangement of the CRT setup.

Simulation: e/π separation The simulation study of the potential contribution of the hpDIRC to the e/π identification at lower momentum is making progress. In the FY21 proposal we showed that the hpDIRC performance at momenta around 1 GeV/c deteriorates due to the effects of multiple scattering in the DIRC bar. Figure 2.4.20 shows that the hpDIRC nevertheless provides e/π separation at the level of at least 3 s.d. for all polar angles at a momentum of 1.2 GeV/c, which is at the upper limit of the range where supplementary identification of the scattered electrons is most important. It is important to note that this performance is achieved for the generic hpDIRC geometry using the standard time-based imaging reconstruction algorithm, without any adjustments to mitigate the effects of multiple scattering. Additional work is required to investigate the possible use of track information outside the DIRC radius or the modification of the geometric reconstruction method where the track direction is treated as a free parameter in the 2D-fit to the polar and azimuthal Čerenkov angles per photon.

An example of the impact of supplemental e/π separation with the hpDIRC is illustrated in Fig. 2.4.21, which shows the distribution of scattered electrons as a function of momentum in three bins of pseudora-

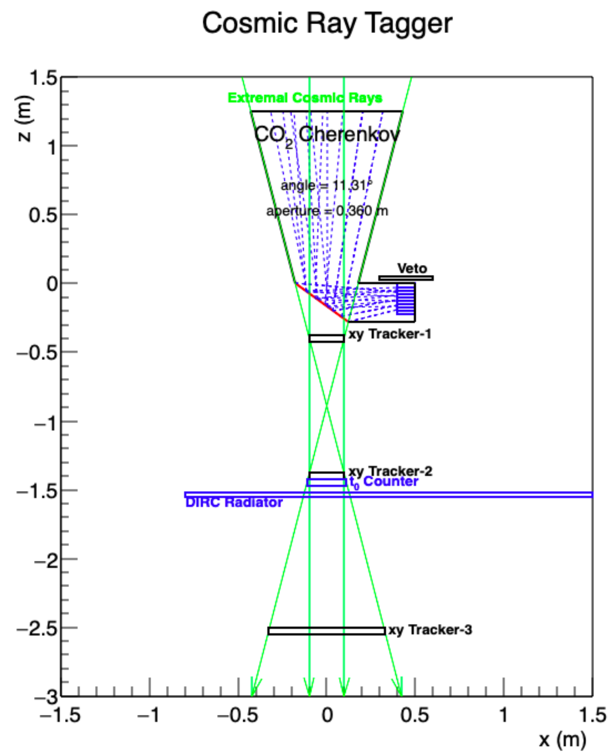


Figure 2.4.19: Preliminary schematic of the Cosmic Ray Telescope. (The hpDIRC prototype is only indicated by the blue radiator bar.) The dashed blue lines are representative Čerenkov photons in the tagger. In the $y - z$ plane, the Čerenkov box flares at $\pm 5.66\,\mathrm{deg}$ from a base that is 18-cm wide in y. This matches the 20 cm (x) by 10 cm (y) profile of the GEM trackers.

pidity (η), where $-1 < \eta < 0$ covers half of the barrel. The scattered electrons, which predominately go into the hemisphere in the outgoing direction of the electron beam, are shown in green and negative pion background is shown in blue. The vertical, dashed yellow line is the kinematic limit for electrons with $Q^2 > 1$ and inelasticity $y < 0.95$. Electrons with momenta below the line can be neglected as they would not be used in data analysis. The magenta line is the blue line scaled by a factor of 10^4. As shown in the figure, the pion background gets more problematic in the barrel ($\eta > -1$), and is also shifted to lower momentum, making it a very good fit for the eID range of the hpDIRC. In the Yellow Report (YR), the pion suppression from the PWO_4 EM cal in the endcap is assumed to be 1,000, while other technologies are assumed to provide a factor of 300. However, only the compact CORE detector concept extends the PWO_4 coverage into the barrel region, where eID is the most challenging. An additional pion suppression factor of 10 or more up to about 1.2 GeV/c would thus greatly improve the overall eID capabilities of any EIC detector, and in particular ones based around larger trackers / solenoids (*e.g.*, the YR "matrix" detector or an sPHENIX upgrade), which make the use of PWO_4 in the barrel not affordable.

Design: hpDIRC integration During the first half of the reporting period the eRD14 DIRC group continued to make significant contributions to the Yellow Report (YR) Initiative. One important outcome was that the hpDIRC was selected as PID system for the barrel of the reference detector. Furthermore, the recently proposed CORE (COmpact detectoR for Eic) concept also includes the hpDIRC as primary hadronic particle ID system in the central barrel. Figure 2.4.22 shows the resulting 2D sketches, which demonstrate the possible integration of the expansion volume prism into the overall central detector design.

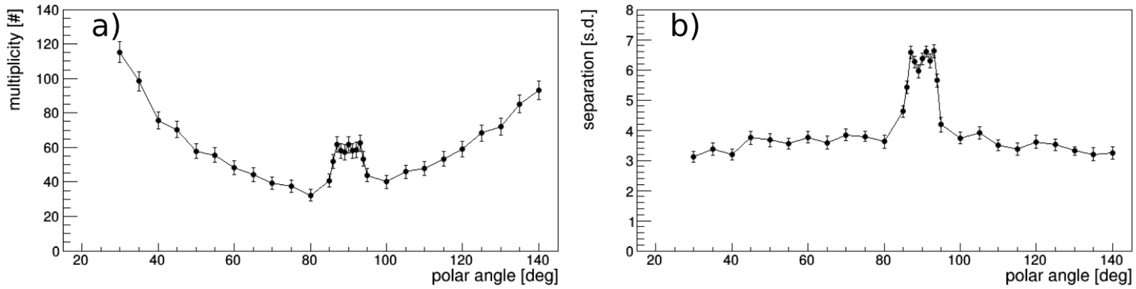


Figure 2.4.20: Photon yield (a) and e/π separation power (b) as a function of the polar angle at 1.2 GeV/c momentum.

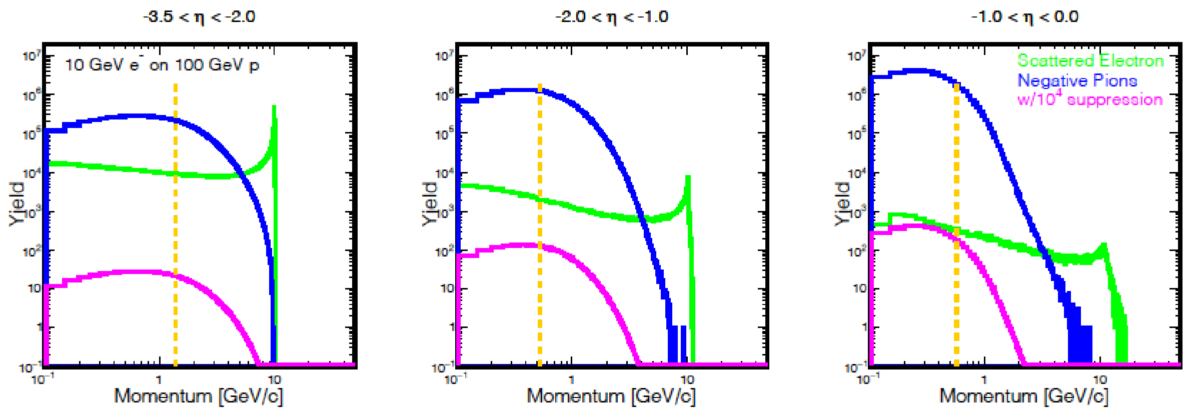


Figure 2.4.21: Simulated momentum distribution of scattered electrons as a function of momentum in three bins of pseudorapidity for different e/π suppression factors (see text).

2.4.2.3 What was not achieved?

The complications connected to the Covid-19 pandemic delayed scheduling the last radiation hardness test and the prototype transfer from GSI to Stony Brook to the second part of the year.

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

The pandemic and closure or reduced availability of labs and facilities affected almost all activities in the hpDIRC project, from the prototype transfer and preparation of the CRT at SBU to the upgrade of the laser setup, the fabrication of lenses, and the irradiation of lens materials.

The closure of the CUA and SBU Universities caused delays in many administrative processes, including legal details of the agreement for the prototype transfer from GSI to CUA and from CUA to SBU. We still expect the transfer to take place this summer and the work on the electronics and other prototype activities is expected to start towards the end of this FY.

The production of the PbF_2 lens prototype by the Harbin Institute of Technology in China was delayed due to the pandemic but both prototype lenses were produced this winter and delivered to CUA.

The laser setup upgrade at ODU was delayed and completed only recently. The planned measurements are now underway.

The next step in the evaluation of the radiation hardness of the lens materials requires access to BNL for measurements in the monochromator and additional irradiation using the ^{60}Co source. The neutron

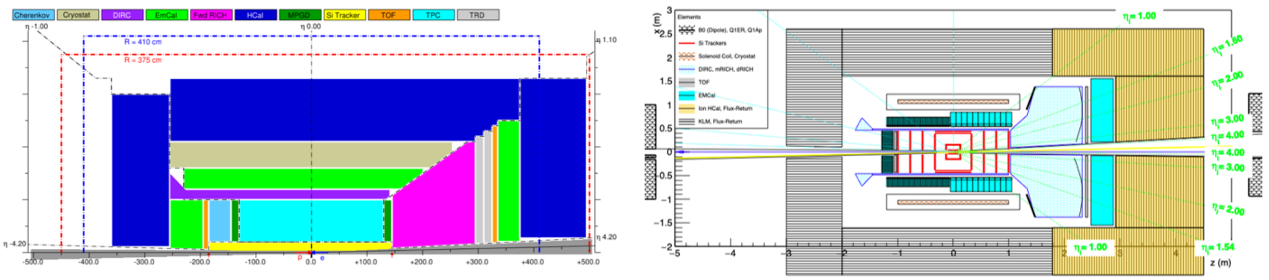


Figure 2.4.22: 2D sketch of potential EIC detector layouts, horizontal cross cut: reference detector from the Yellow Report (left, only upper half shown) and the new CORE (COmpact detectoR for Eic) concept (right). Both layouts include the hpDIRC in the barrel region and show possible solutions for the integration of the expansion volume prism into the detector design.

irradiation will be outsourced and performed at the Core Research Facilities at UMass Lowell. While access to both facilities was limited due to the pandemic, we laid the groundwork for those irradiation tests and expect to be able to finish the studies this FY, as planned, provided the COVID-19 situation does not deteriorate.

2.4.2.5 How much of your FY21 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 FY21 contract. Some items in the FY20/FY21 budget got delayed but are still expected to happen in 2021.

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

The hpDIRC R&D efforts were not paused. The recent focus of the work during the pandemic has been on simulation and data analysis as well as the preparation of the lens evaluation setup and the CRT.

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 for the tests of the radiation hardness of the lens materials with a neutron source and for the luminescence measurements are available and a measurement plan is ready for spring/summer 2021, as soon as BNL and UMass Lowell resume regular operation after the pandemic restrictions are relaxed.

Following the completion of the calibration of the laser setup at ODU, the detailed lens measurements will start shortly.

Once the paperwork for the transfer from Germany to the U.S. is complete, the prototype will be sent to SBU. The design of the CRT and the development simulation of the DIRC performance in the CRT have started. The construction of the mechanical support and the assembly of the supplemental instrumentation is expected to start this summer.

As originally planned, several of the simulation projects, including the optimization of the hpDIRC geometry, the use of the BaBar DIRC bar boxes, and the combination of bars and plates in the "ultimate DIRC" design, and the simulation of the prototype in the FTBF beam line, are scheduled to start this spring/summer.

The manuscript of the beam-test NIM paper should be ready for submission by the end of this fiscal year.

2.4.3.2 What are critical issues?

With the TDR schedule in mind, it is crucial to continue the support of the new CUA postdoc and his work on software as well as the hpDIRC prototype testing at Stony Brook. In order to validate the hpDIRC performance in particle beams, a sufficient number of small-pixel sensors with matching electronic readout will be required, starting as early as late 2021. The procurement of the new sensors should start in FY22 for the initial evaluation of the hpDIRC performance in the CRT at SBU and should conclude with a complete set of sensors by FY23 to stay on track for the TDR-readiness in FY24.

The development of the COVID-19 situation and the resulting impact on travel, beam test availability, and the operation of labs and universities, is expected to continue to have a significant impact on the hpDIRC activity.

3 Photosensors and Electronics

3.1 Summary

The main objective of this R&D effort during the period July 2020 – February 2021 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

- Negotiate a loan agreement with Photek for one tube of their multi-anode $6\mu - m$ pore size MCP PMT.
- Design and test a readout solution for a few channels of the multi-anode 10-μm pore-size Planacon XP85122-S in preparation for the gain and timing resolution measurements in Summer 2021 at JLab.

3.2.1.2 What was achieved?

The Planacon XP85122-S tube, which was purchased in 2020 was delivered at JLab in November 2020. At JLab, the Detector group has continued to work on 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. In addition to the previously sampled conductive films, such as Samtec and Condalign, the use of a Z-conductive mat has also been considered. A PCB board, in contact with the mat/film will be used to translate the signals to the readout electronics.

3.2.1.3 What was not achieved?

The evaluation of XP85122-S (rescheduled from Summer 2020 to December 2020) was not achieved due to the travel restrictions related 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?

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 Summer 2021.

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 by one year. These funds, together with the limited new funds awarded for FY21, will cover partially the cryogens for the magnet and the travel cost for three USC persons to JLab to carry out a 4-week long test. We do not expect unexpended R&D funds beyond the end of the FY21 contracts with USC and JLab.

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 connecting solution for the readout of a few channels of XP85122-S will continue through Spring. In June-July, we expect a complete gain measurement of both, the Planacon and the Photek sensors, to be carried out in and out of magnetic field. The 6-μm pore-size Photek sensor is new on the market and of special interest due to its expected immunity to B-fields above 1.5 T. The activity is the same as originally planned, but delayed by twelve months due to the SARS-Cov2 quarantines and closures. In FY22 and FY23, we will focus on assessing the performance of improved Photek and the new HRPPD sensors, as the manufacturers improve the robustness of the devices and mitigate issues found in the first set of tests.

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 Čerenkov 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 (ANL) with small size MCP PMTs. The effort aims to adapt the LAPPDs to the EIC requirements with optimized design parameters integrated into low-cost LAPPD production.

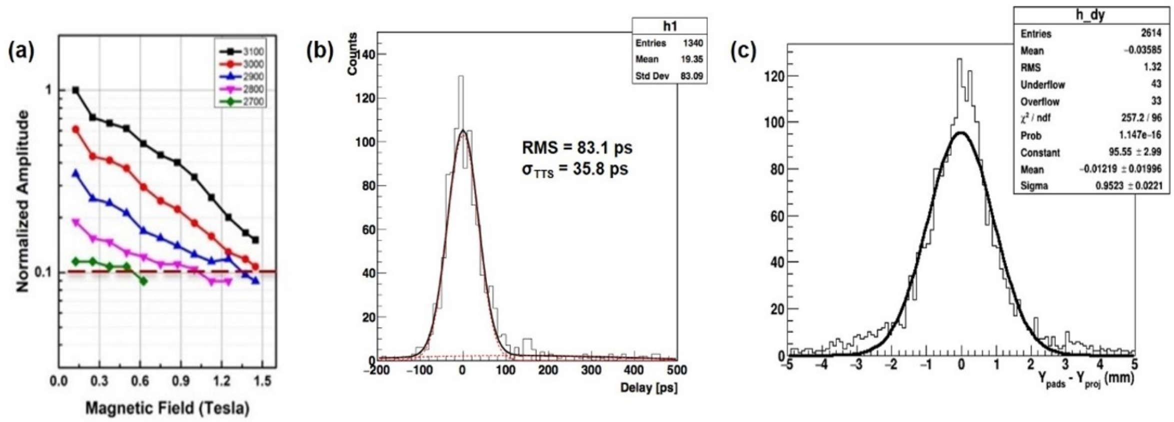


Figure 3.3.23: Performance of the ANL MCP PMT: (a) Magnetic field tolerance of 1.5 Tesla; (b) RMS timing resolution of 83 ps; and (c) position resolution of 0.9 mm with pixel size of 3×3 mm^2.

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) Obtain a loan of 20×20 cm^2 ceramic LAPPDs, prepare for Fermilab beamline test of the LAPPD coupled to mRICH module with the mRICH group; (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?

We have successfully fabricated a 6×6 cm^2 MCP PMT at ANL using 10 μm MCPs through a glass and an integrated magnetic-field tolerant design. This MCP PMT is under bench test now, it is expected to have the required performance for EIC Čerenkov detectors, including magnetic-field tolerance over 1.5 Tesla, 100-ps RMS timing resolution and less than 1 mm position resolution with a pixel size of 3×3 cm^2, as shown in Figure 3.3.23. More characterization results will be reported later while the tests are completed.

A major effort for this period was to prepare for a Fermilab beamline campaign to test both the ANL MCP PMT and commercial LAPPDs. We received a loan of capacitively-coupled LAPPD from Incom, Inc. The bench test results of this LAPPD are shown in Figure 3.3.24. The LAPPD with pixelated and zigzag readout board attached is now installed in experimental dark box enclosure at BNL, ready to be transferred to Fermilab for beamline test. An mRICH module has also been delivered from GSU to BNL, and set up at BNL, ready for beamline test with the on-loan LAPPD as the photo-sensor. However, due to the COVID travel restriction, our planned March-2021 beamline test was postponed to summer 2021. Recently, an SBIR proposal "Application Specific High Fluence Anode Design" led by Incom, Inc. in collaboration with Nalu, BNL, and ANL was approved to further optimize the capacitively-coupled LAPPD and its readout electronics. A kickoff meeting was just held to start the effort.

With the promising results from the bench tests of the ANL MCP PMT, it becomes emergent to expedite the application of MCP PMT in EIC and other projects. Under internal equipment development fund support, a 10×10 cm^2 MCP-PMT fabrication facility is under construction at ANL to produce larger size, high-performance MCP PMTs. Figure 3.3.25 shows the schematic drawing of the 10×10 cm^2 MCP-PMT fabrication facility. We expect the fabrication of larger size ANL MCP-PMTs in summer

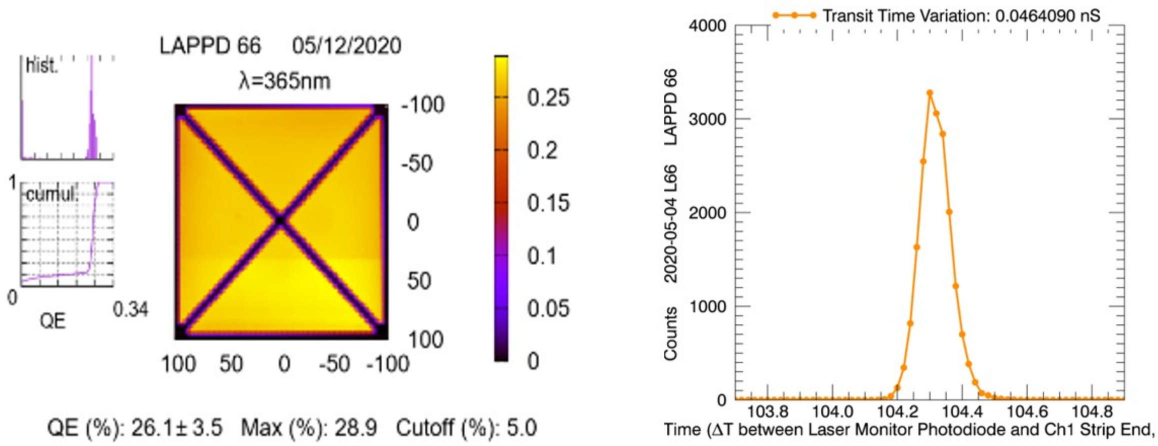


Figure 3.3.24: Performance of the on-loan capacitively-coupled LAPPD: (left) uniform QE with an average of 26.1%; (right) transit time resolution of 46 ps.

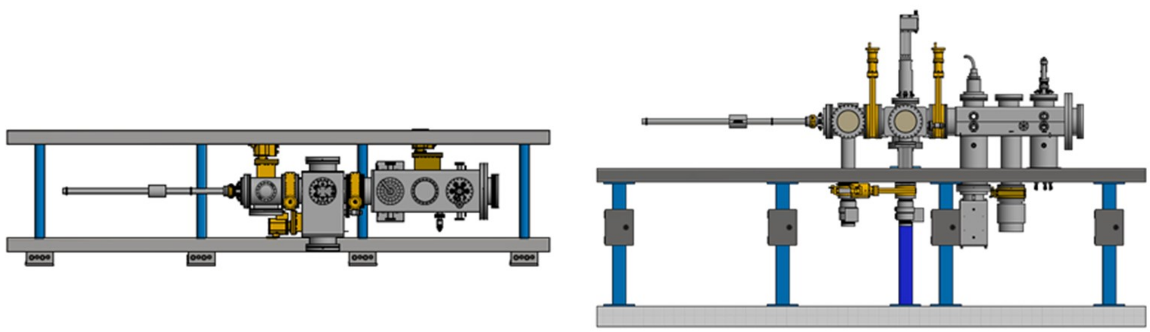


Figure 3.3.25: Schematic drawing of the 10×10 cm^2 MCP-PMT fabrication facility under construction at ANL: top view and side view.

2021 for future sub-system validation.

3.3.1.3 What was not achieved?

Due to the COVID-19 concern and travel restrictions, the Fermilab beamline experiment was postponed from March to summer 2021. We expect to complete the performance test of both, the ANL MCP PMT and the on-loan LAPPD, with beam, and the sub-system test of mRICH using LAPPD as the photo-sensor.

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 planned beamline test of ANL MCP PMT and LAPPD at the Fermilab test beam facility.

3.3.1.5 How much of your FY21 funding could not be spent due to pandemic related closing of facilities?

The Fermilab-beamline-test funds have not been spent due to a pandemic-related schedule change. With the re-planned experimental schedule, we expect to spend the funds in summer 2021.

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?

The coming months' tasks will focus on the continued evaluation of the ANL MCP PMT and on-loan LAPPDs on bench and in beam. The planning is the same as in the original plan with a time delay of about 3 months.

3.3.2.2 What are critical issues?

Given the accelerated timeline for EIC-PID to demonstrate sub-system readiness by 2023, the most critical issues are for Incom, Inc. to provide operational HRPPDs and their comprehensive characterization in full parameter space. Incom, Inc. is currently producing an HRPPD specifically meant for EIC applications.

3.4 Readout Sensors and Electronics for Detector Prototypes

Novel readout electronics solutions are being developed by the Hawaii group and JLab/INFN groups to address the requirements and to demonstrate the performance of the advanced, high-performance RICH and DIRC detectors of the EIC. The goals of this synergic effort are optimization of resources, co-sharing of status-of-the-art electronics and comparative test of complementary approaches. 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. Earlier studies of the TARGETX family of 16-channel transient waveform digitizing ASICs, led to evaluation of the 32-channel SiREAD ASIC on dedicated readout Daughter Card (DCs). To further speed development, a standard control and readout programmable logic unit, the SCROD, which was developed for the Belle II muon system upgrade has been used. To reduce cost and further integration, compactness and reliability, lessons learned from the SiREAD ASIC are being applied to a next-generation HDSoC ASIC, whose specifications are given in Table 3.4.1. An initial 32-channel prototype (funding limited due to HDSoC being funded as a DOE Phase I SBIR project) is in fabrication and after successful demonstration, will move to a 64 channel form factor. To significantly reduce implementation overhead, most of the state-machine control infrastructure provided by a 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. In the first phase, twenty five DCs, each equipped with two 32-channel SiREAD ASICs, were fabricated and permit readout of a prototype mRICH module as illustrated in Fig. 3.4.26. Four such DCs instrument the readout signals from the 256 anodes of each PMT. When available, these will be upgraded with HDSoC as shown in Fig. 3.4.27.

HDSoC Parameter	Specifications
Channels	64 (32 proto)
Sampling rate	1-2 GSa/s
Storage samples/ch	2048
Analog Bandwidth	∼0.5 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: HDSoC 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, had been fabricated, further work was required on the firmware to make the system fully functional. This task has been the prime task of postdoc Tripathi. Given the complex nature of this programmable logic and readout system, a significant learning curve was expected.

Following a recommendation from the EIC R&D committee, an initiative has started to investigate the alternative use of a time-over-threshold (ToT) discriminating readout for the PID detectors at EIC. As this readout architecture naturally implements a zero suppression with a consequent limited requests of data rate, it is expected to provide excellent time resolution with a moderate use of resources. The study has been focused on the ALCOR development, that has been selected as a good candidate for custom EIC adaptations.

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. To support the ALCOR development and the SiPM irradiation and imaging program, a new flexible high-data rate DAQ protocol has been adopted based on the ARCDIA INFN development.

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:

- Debug 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.
- Initial study of the alternative ToT readout architecture based on ALCOR ASIC.
- Study the adaption of DAQ protocols to the consortium front-end needs.
- Development of a pulsed-laser test station in Italy.

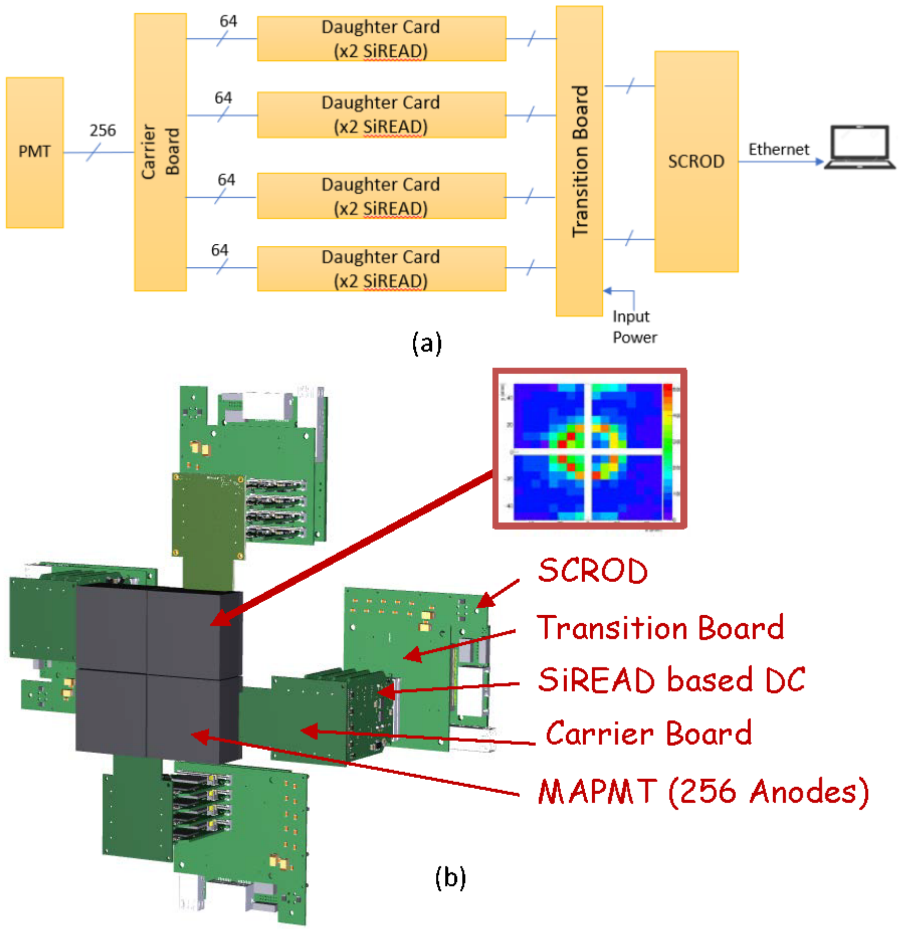


Figure 3.4.26: (a) Block diagram of a single 256-anode PMT readout. (b) Overview of a complete mRICH detector image plane readout for initial prototypes. Future developments will locate the readout in the envelope directly behind the photosensors.

3.4.1.2 What was achieved?

The Hawaii team devoted enormous effort to debugging the firmware for the populated the boards based on the SiREAD DCs. The FW is depicted in Fig. 3.4.28, where the communication between the DC and SCROD is maintained via a custom protocol named Quad Byte Line (QBlink), and the SCROD interfaces with the PC using an optical gigabit transceiver, is quite complex. Due to vexing communication errors, a deep dive was required into all of the details of each interface, and providing extensive hardware and firmware emulation environments. In the process, significant progress at improving the test bench environment and learning the tools was achieved. Portions of the firmware pieces are running stand-alone, though still need integration. This was slowed by limited access to the lab and personnel with requisite background to assist in troubleshooting.

The prototype ALCOR chip and the relative test-board were produced. Functionality tests have been initiated and so far provided positive indications. The design of a complete readout chain based on the ALCOR chip is in progress. As the initial target is to support the SiPM irradiation campaign and dRICH prototype tests, the relative details are provided in the dRICH section.

A spare VSX/SSP system has been acquired to support the labortory and beam test activity in EU. A new high-data transfer protocol based on the ARCADIA development at INFN is in preparation to be used in conjunction with the ALCOR front-end and serve during the SiPM test-beam campaign in EU.

The pulsed-laser test station at JLab has been put into operation and is daily in use for sensor char-

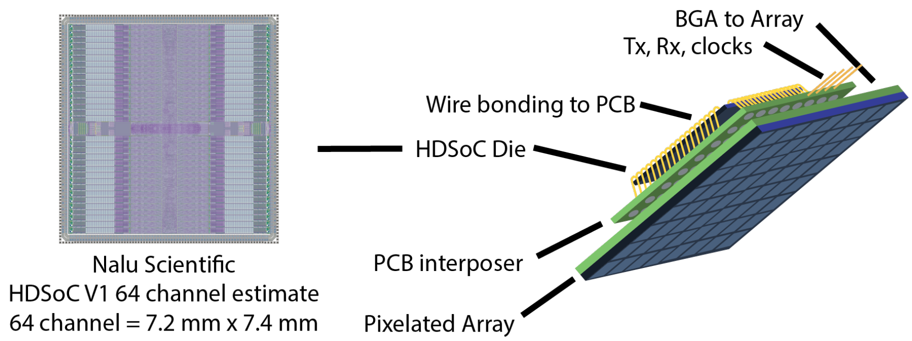
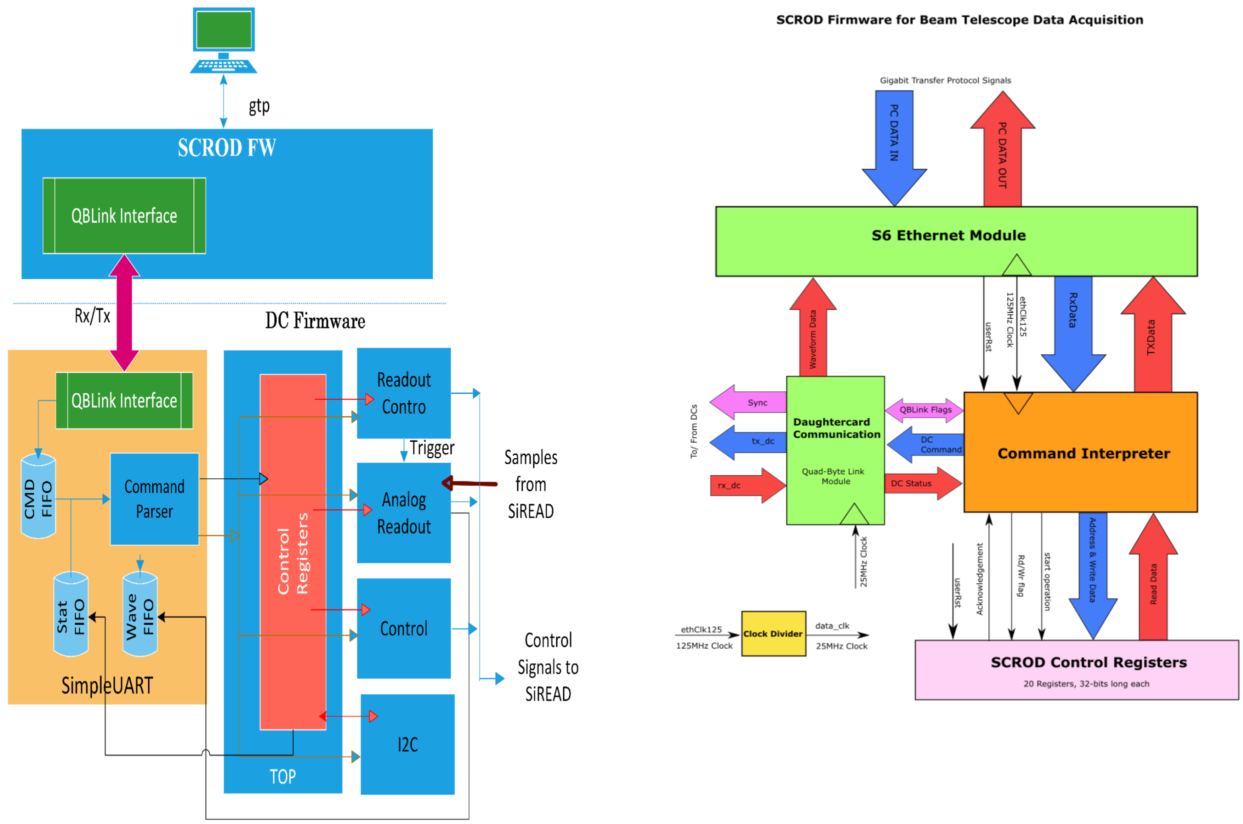


Figure 3.4.27: 3D drawing of the 4 ASIC solution.

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



(a) Readout system Flow Control

(b) Firmware interconnection details

Figure 3.4.28: Details of the SiREAD ASIC based Daughter Card interconnect and firmware infrastructure.

3.4.1.3 What was not achieved?

We had hoped the firmware development would be further along, though the process of developing detailed firmware test benches and understanding of the QuadByteLink protocol by postdoc Tripathi lead to a discovery (not at all trivial to sort out) that there was in fact a hardware problem with the impedance of the differential transmission lines between the DCs and SCROD, via the transition board. This was exacerbated by the fact that there were power problems due to a subtle power-pin mismapping on the transition board. All of these took much time and effort to debug, which were slowed by trying to do much of this remotely. Therefore additional commissioning work is still needed.

Due to the limited access to the laboratory, the setup of the laser station in Italy has been postponed. It will be now pursued with high priority to serve the characterization tests of the SiPM during the irradiation campaign and in preparation of the dRICH test-beam scheduled in fall 2021.

Due to the impossibility to travel, the new DAQ developments in collaboration with JLab has been slowed down. The DAQ activity is anyway on track to support the 2021 dRICH and SiPM test-beam campaign with the existing hardware (VSX/SSP) and new optimized solutions (ARCADIA).

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 2021 involve:

- Testing, Verification & Debugging of the SCROD and DC FWs.
- Characterization of timing, noise and trigger rate performance of the SiREAD readout.
- Prepare for receipt of upgrade HDSoC ASICs.
- Realize a complete SiPM readout chain based on ALCOR and ARCADIA developments.
- Commissioning of a pulsed-laser test station in Italy.

3.4.2.2 What are critical issues?

Integrating the ASIC control and readout 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, 20% of time spent on project
Tim Cundiff, Electronics Engineer, 5% of time spent on project
Whit Armstrong, Staff Scientist
Sylvester Joosten, Staff Scientist
Jihee Kim, Postdoctoral Appointee
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
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, 15% of time spent on project

5 External Funding

ANL

- ANL-LDRD project: Tomography at an Electron-Ion Collider: Unraveling the Origin of Mass and Spin, Oct 1, 2020 – Sep 30, 2021: $900k (ANL investment on EIC project)
- Staff, post-doctoral salaries, internal base fund 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

- Laboratory power supplies to be included in PANDA DIRC prototype transfer to the U.S.: $2k.

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

- Staff 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 HDSoC 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, 2020 JINST 15 C04038,
https://doi.org/10.1088/1748-0221/15/04/C04038

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*, 2020 JINST 15 C02040,
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*, 2020 JINST 15 C06060,
https://doi.org/10.1088/1748-0221/15/06/C06060

G. Kalicy et al. (EIC PID Collaboration), *Developing high-performance DIRC detector for the Future Electron Ion Collider Experiment*, 2020 JINST 15 C11006,
https://doi.org/10.1088/1748-0221/15/11/C11006

X. He et al. (EIC PID Collaboration), *Development of Compact, Projective and Modular Ring Imaging Cherenkov Detector for Particle Identification in EIC Experiments*, JINST 15 C09049,
https://doi.org/10.1088/1748-0221/15/09/C09049

7 Presentations

M. Contalbrigo, *Physics opportunities at the future Electron Ion Collider*, IWHSS 2020 - Workshops on Hadron Structure and Spectroscopy, ECSC Trieste, Italy, 16-18 November 2020 (virtual meeting).

G. Kalicy (EIC PID Collaboration), *The DIRC Detector for the Future Electron Ion Collider Experiment*, 2020 IEEE Nuclear Science Symposium (NSS) and Medical Imaging Conference (MIC), Oct 31 - Nov7, 2020 (virtual meeting).

G. Kalicy, N. Wickramaarachchi (EIC PID Collaboration), *Developing the high-performance DIRC detector for the future Electron-Ion Collider*, 2020 Fall Meeting of the APS Division of Nuclear Physics, Oct 29 – Nov 1, 2020 (virtual meeting).

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.

E. Cisbani and M. Contalbrigo (dRICH group), *Dual Ring Imaging Cherenkov Status*, talk at the first EIC TR Meeting, Temple University, Philadelphia, USA, March 19-21 2020 (virtual meeting).

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.

M. Contalbrigo, *Hadron Identification for Flavor Separation at EIC*, QCD with Electron-Ion Collider Workshop, IIT Bombay, India, January 4-7 2020.

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, 2019, Crystal City, VA.

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.