8 eRD14 Summary, March 2021

The EIC PID consortium (eRD14) was established to develop a suite of detector technologies that would satisfy the PID requirements of the EIC, where the asymmetric collision kinematics requires different approaches in the two endcaps and the barrel region. Luminosity constraints on the size of the EIC interaction region translate into space limitations for the detector subsystems and limit the path for time-of-flight (TOF) measurements. This generally favors Čerenkov detectors, the performance of which does not depend on the distance to the collision point. Nevertheless, TOF can cover lower momenta, and high-resolution TOF (on which the consortium performed R&D in the past) is an option for the (outgoing) electron endcap. The consortium is thus currently looking into the possibility of integrating such a capability into the Čerenkov detector developed for this endcap (mRICH).

All R&D pursued by the consortium is novel, but well understood, and does not present a high risk. 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), 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), allowing a significant improvement in momentum coverage compared with state-of-the-art in only 5 cm of radial space. All these subsystems are the primary PID candidates considered in the EIC Yellow Report, and will be an integral part of the detector proposals that will be submitted later in 2021.

An important aspect of the consortium activities has been to seek synergies in key areas such as photosensors and electronics. Work on photosensors in high magnetic fields, adaptation of LAPPDs to EIC requirements, and evaluation of SiPMs has been funded. Since FY18, the consortium has had a dedicated effort on developing readout electronics matching the requirements of the photosensors.

At the end of FY19 the consortium was asked to develop a plan to reach readiness in four years to write a technical design report (TDR), including a cost estimate for the remaining R&D work. The plan was presented during an in-depth review on September 19, 2019. https://indico.bnl.gov/event/6819/ As outlined in this summary (and the full progress report), the consortium is making good progress towards these goals despite complications related to Covid-19, which has limited access to various facilities, including test beams.

8.1 Modular and Compact RICH (mRICH)

The mRICH is designed for providing PID capabilities for EIC experiments for kaon and pion separation in momentum range between 3 to 10 GeV/c and electron and pion separation around 2 GeV/c.

Accomplishments to date: The mRICH detector R&D has been supported within the EIC eRD14 Consortium since 2015. The key components of an mRICH module include a radiator (aerogel, $\sim$10 cm $\times$ 10 cm $\times$ 3 cm, $n = 1.03$), a Fresnel lens (with focal length ranging from 3 to 6 inches), a mirror set, and a photosensor plane. The characteristic longitudinal dimension of an mRICH module is from 15 cm to 25 cm depending on the focal length of the lens. Two rounds of detector prototyping and beam tests were completed with a focus on verifying the detector working principle and performance. The results from the first beam test (in 2016) have been published (NIMA 871, 2017) The second beam test was done in 2018 and the data analysis is still ongoing. A realistic GEANT4-based simulation for mRICH has also been developed and verified with beam-test data.

Two more beam tests with particle tracking capability are under preparation in order to quantify mRICH PID performance and test new photosensors. One is planned at Fermilab in spring of 2021 for testing the mRICH with a LAPPD readout. The groups involved in this test are BNL, ANL, SBU and GSU. The other test is planned in Hall D at JLab in summer of 2021 using secondary electrons in the momentum range $1 < p < 6$ GeV/c. The participating groups for this test include DukeU, INFN, JLab, USC, and GSU.

Assessment of technological readiness: Two key components of an mRICH module are the aerogel block and a photosensor with single-photon detection capability and fine-segmented pixel size (< 3 mm $\times$ 3 mm). The photosensor also needs to be working properly in high magnetic field.

To meet the needs of EIC experiments, a proper photosensor choice is critical. The planned beam test at Fermilab in 2021 will help to evaluate the integration and performance with LAPPD. During the second mRICH beam test in 2018, three SiPM matrices were tested with varying cooling temperatures ranging from $-30°$ C to room temperature. The radiation-damage effects on the SiPM performance are currently under study at INFN. We also pay close attention to the radiation-damage measurements of SiPM sensors from GlueX, STAR, and sPHENIX experiments and any new SiPM sensor technology development.

Besides the two planned mRICH beam tests in year 2021, there is a longer-term R&D effort for mRICH toward engineering design which includes: (a) high-quality mirror and mirror assembly; (b) mRICH holder box engineering for reducing total weight, easy assembling and projective installation; (c) continued testing with available photosensor options. Assessment of these new designs in comparison with engineering assembly of modular components in other major experiments are going to be the next tasks. At the same time, the physics shop staff at Georgia State University has started looking into machining carbon fiber plates for constructing the next generation of mRICH prototype.

Work remaining for a TDR, ballpark cost estimate, and timeline: As stated in the previous section, the choice of a photosensor for mRICH is critical for EIC experiments. This will be the largest uncertainty in estimating the cost of an array installation of mRICH. We have and will continue to fully take advantage of the photosensor and readout development within the consortium. At the same time, supporting a full-time postdoc ($90k per year, which includes institutional indirect cost) will be critical to maintain the steady progress of the mRICH development. R&D funding is also needed for optical hardware (aerogel, Fresnel lens, front-surface mirror characterization) and travel support to carry out planned beam tests. The cumulative cost for these activities is about $50k/year. We expect the mRICH TDR readiness to be achieved by 2024/2025 assuming continued R&D funding support. The total cost of the remaining mRICH R&D work is $140k/year (on top of in-kind machine shop support by GSU).

8.2 Dual radiator RICH

The dual-radiator Ring Imaging Cherenkov (dRICH) detector is designed to provide continuous full hadron identification ($\pi/K/p$ separation better than 3σ apart) from ~ 3 GeV/c to ~ 60 GeV/c in the ion-side end cap of the EIC detector. It also offers a remarkable electron and positron identification from a few hundred MeV/c up to about 15 GeV/c. Currently, dRICH is the reference detector for particle ID in the hadron endcap and by design, the only hadron identification detector in EIC able to provide continuous coverage in RICH mode over the full momentum range required for the forward end-cap.

Accomplishments to date: The dRICH baseline configuration consists of six identical open sectors covering the pseudorapidity range $\approx 1.5 - 3$. Each sector has two radiators (aerogel with refractive index n = 1.02 and gas with n = 1.008) sharing the same outward focusing mirror and instrumented area made of highly segmented photosensors (3×3 mm^2 pixels). The dRICH design and performance have been studied through various means ranging from a full Geant4 simulation (including an event-based particle reconstruction processor) to AI-based learning algorithms with Bayesian optimisation to maximise the hadron separation. The original benchmark configuration assumed ~ 160 cm longitudinal thickness but even a shorter, down to ~ 100 cm, dRICH preliminary version features a performance that fulfills the above mentioned key physics requirements, indicating a remarkable flexibility of possible dRICH configurations. A small-scale prototype is being developed to investigate critical aspects of the proposed dRICH detector, in particular related to the interplay and long-term performance of the two radiators and simultaneous imaging. The prototype vessel is composed of standard vacuum parts to contain the cost and support pressures different from the atmospheric one. This would allow efficient gas exchange and, in principle, adjustment of the refractive index and consequent flexibility in the gas choice. The prototype supports the usage of various type of photosensors, in particular SiPM matrices and MCP-PMTs. Prototype components are under procurement.

Assessment of technological readiness: For most of the components, a commercially available suitable technology already exists as demonstrated by the developments pursued for the CLAS12 RICH: *e.g.*, customized aerogel of large area and high-clarity, use of composite materials for light mirrors of high optical quality, and stiff support structure of low density. The effective interplay between the two radiators while using UV-filtering windows to prevent disruptive interference will be optimized with the prototype. To meet the EIC specifications a critical element, common to other EIC PID detectors, is a proper choice of the photosensor, that should preserve single-photon detection capability inside a strong magnetic field. The dRICH focusing system is designed to keep the detector outside the EIC spectrometer acceptance, in a volume with reduced requests in terms of material budget and radiation levels. This feature makes dRICH a natural candidate for the exploitation of magnetic-field tolerant SiPMs. A program has been initiated to study the use of SiPM at the EIC expected radiation levels in conjunction with the dRICH prototype.

Work remaining for a TDR, ballpark cost estimate, and timeline Dedicated first beam tests with the prototype are scheduled at CERN in Fall 2021, in conjunction with reference photo-sensors and a first selection of irradiated SiPM. In the next 2 – 3 years, cost-effective solutions for the standard components and alternatives to the greenhouse gases or photo-sensors (*e.g.*, LAPPDs) will be investigated, in conjunction with optimized readout solutions. A realistic dRICH configuration will be studied in parallel with the evolving EIC reference detector and optimized with the EIC simulation packages. The planned hardware investment is at the level of $60k/year. A significant INFN in-kind contribution is expected: about 30% of funds, technical and high-experienced personnel, access to EU workshops, laboratories, and irradiation facilities. The investment above does not include dedicated personnel that can only be co-funded by INFN. Continued financial support from the DOE EIC R&D program of the dRICH postdoc and their work on software as well as the dRICH prototype is crucial. If the funding for the continuation of the R&D program is made available, we expect the dRICH TDR readiness to be achievable by 2024/2025.

8.3 High-Performance DIRC

The primary objective of the high-performance DIRC (hpDIRC) activity, which has been part of the EIC Generic Detector R&D program since 2011, is to develop a very compact barrel EIC PID detector with momentum coverage reaching at least 6 GeV/c for clean π/K separation, pushing the performance well beyond the state-of-the-art for current DIRC counters.

Accomplishments to date: Starting from a concept that was inspired by the SuperB fDIRC and the PANDA Barrel DIRC, an initial generic design of the hpDIRC was created and implemented in a detailed Geant4 simulation. This simulation demonstrated the feasibility of the hpDIRC concept to provide 3σ separation of π/K up to 6 GeV/c and e/π up to at least 1 GeV/c.

The key hpDIRC improvements include smaller sensor pixels, faster photon detection, and a radiation-hard spherical focusing system, as well as advanced reconstruction and PID algorithms that make optimum use of the excellent timing precision. The most important elements of the hpDIRC simulation were validated with experimental data obtained in several beam test campaigns of the PANDA Barrel DIRC prototype at the CERN PS/T9 beam line. The simulation was found to be in excellent agreement with all measured key performance parameters.

The development of the radiation-hard 3-layer lens was a a crucial element of the hpDIRC R&D. A number of potential candidate materials were studied using the ^{60}Co source at BNL, with Sapphire and PbF_2 emerging as leading candidates for the middle layer of the lens. Several lens prototypes were fabricated by industry and evaluated in a laser setup at ODU, where the focusing properties are measured in detail and compared to Geant simulation.

Assessment of technological readiness: Pending the successful validation of the radiation-hard spherical lens at ODU, the optical system of the hpDIRC (the bars, prisms, lenses) can be considered technologically ready even though the optimization of the design in terms of cost vs. performance is still ongoing. This leaves the photon detection as the main technological challenge. While a commercial solution exists for fields up to 1.5–2 T, additional studies of the performance of the hpDIRC using MCP-PMTs or SiPMs in stronger fields are required and the design of the prism may need to be modified. Furthermore, matching readout electronics need to be validated. Last but not least, the technological readiness should be confirmed with the hpDIRC system prototype using particle beams or cosmic muons.

Work remaining for a TDR, ballpark cost estimate, and timeline: The feasibility of reusing the BaBar DIRC bars vs. producing new radiator bars, and of using LAPPDs instead of commercially available MCP-PMTs, have to be determined since they have a large impact on the projected cost. R&D will be needed to develop a procedure to transport and safely disassemble the fragile BaBar DIRC bar boxes, extract and separate the radiator bars, and to evaluate the optical quality to ensure that the bars can be used in the hpDIRC. The recently discussed potential increase of the PID momentum coverage, both towards higher momentum π/K and lower momentum e/π separation, required by EIC physics, may motivate additional design improvements and utilizing possible post-DIRC tracking. Since the discussions about higher magnetic-field options for the EIC detector are still ongoing, further investigation of a sensor solution for a possible 3 T field may be needed.

The future hpDIRC prototype, currently in preparation for tests at SBU, will require updates of the photon sensors and readout electronics to achieve the full performance. The largest cost item is the procurement of a sufficient number of MCP-PMTs with small pixels to cover the focal plane on the readout side of the expansion volume. If commercial MCP-PMTs are ordered from Photonis or Photek, the cost is expected to be about $200,000, potentially less if HRPPDs with sufficient quality become available in time for this project. Additional costs, including electronics, lab equipment, supplemental instrumentation, computing, and travel are expected to be about $100,000 in total. This sum does, however, not include personnel. Continued financial support of the hpDIRC postdoc and their work on software as well as the hpDIRC prototype test at Stony Brook is crucial.

If the funding for the continuation of the R&D program is made available, we expect the hpDIRC TDR readiness to be achievable by 2024/2025.

8.4 Photo-sensors

The requirements that the DIRC and RICH detectors must fulfill within the scope of the EIC pose unique constraints on sensor performance different from any previous DIRC and/or RICH implementation. In particular, and beside other important parameters, the sensors must have small pixel size of 2 – 3 mm and single-photon sensitivity in magnetic fields of 1.5 – 3 T, the direction of which could not be always optimized. This unprecedented condition requires innovative solutions. The R&D program pursued within the eRD14 consortium aims to establish the limits of operations of commercially available photo-sensors in a multidimensional space, including magnetic-field magnitude, high voltage, and sensor orientation, and to adapt existing photo-sensor technologies for EIC applications: magnetic-tolerant cost-effective micro-channel plates (LAPPDs) and temperature-conditioned silicon photomultipliers (SiPM).

Accomplishments to date: We brought a High-B test facility into operation at JLab and carried out a series of gain evaluations on Hamamatsu, Photek, and Planacon MCP PMTs. The major findings are that while sensors of smaller pore size retain their single-photon sensitivity to higher B-fields, the performance strongly depends on the relative orientation of the sensor with respect to the B-field and that dependence vary for different manufacturers. The gain loss observed at higher than 1-T fields can be recovered to some extent by increasing the HV. A method of determining the largest operational HV maximizing gain performance, while keeping the ion feedback at low levels, has been established. In order to adapt existing LAPPDs to the requirements of the EIC Čerenkov detectors, at ANL we developed a magnetic-field tolerant MCP PMT with a pixelated readout. Tests of this MCP-PMT design demonstrated 1.5-T magnetic-field tolerance, 100-ps RMS timing resolution as well as less than 1 mm position resolution. The design parameters, as well as the know-how, were transferred to our industrial partner (Incom, Inc.) for fabrication of commercialized low-cost LAPPDs. At INFN, we developed a SiPM characterization protocol, featuring a specific dark count GHz sampling and offline filtering, to evaluate the post-irradiation single-photon counting capability. A selection of most promising 3×3 mm^2 SiPM candidates from Hamamatsu, SenSL, Broadcom, and FBK has been acquired. We designed custom carrier boards to support irradiation and annealing cycles, allow laboratory characterization and Čerenkov imaging tests of SiPM.

Assessment of technological readiness: The optimal sensor choice may depend on the actual EIC configuration and sub-detector location. Commercially-available MCP PMTs of 10-μm pore size are suitable for operations in B-fields up to 1.5 T and at relative orientations to the B-field below $10°$. Our LAPPD industrial partner adopted the ANL R&D MCP-PMT design to develop low-cost pixelated LAPPDs. Meanwhile, a 10×10 cm^2 fabrication facility is under construction to produce larger size, high-performance ANL MCP-PMTs. The moderate radiation level foreseen at EIC (reference value of $10^{11}\,cm^{-2}$ n_{eq}) could make possible the use of the SiPM fast evolving technology that has proven to be robust, magnetic-field insensitive and suitable for mass production. The radiation effects could effectively be mitigated with a proper temperature conditioning (annealing cycles and low-temperature working point) and readout chain as suggested by recent studies available in the literature.

Work remaining for a TDR, ballpark cost estimate, and timeline: Comprehensive gain and timing performance in high B-fields of the latest generation 10-μm Photonis, 6-μm Photek, and the new HRPPD sensors will be completed in the next two years. The total cost of this work is estimated to be \$80k, covering cryogens, travel of USC personnel to JLab, and one Photek 6-μm pore-size MCP PMT. A major milestone of the LAPPD effort is the performance validation of the optimized LAPPD. We plan bench baseline test, magnetic-field test and validation in beamline with sub-detector systems. We expect to achieve the validation milestone within $2 - 3$ years, requiring an investment of $\sim$ \$100k. The SiPM program foresees a 2-3 years effort for the characterization of the state-of-the-art sensors and the development of custom solutions with the manufacturers. Mitigation of radiation effects will be studied and validated with sub-detector prototypes. The planned investment is around \$60k/year with an INFN in-kind contribution of about 30%. This does not include dedicated personnel that can only be co-funded by INFN. Financial support from the DOE EIC R&D program for one postdoc working on the sensor development is crucial.

8.5 Readout Electronics

A synergic effort is ongoing within the eRD14 Consortium to develop readout solutions suitable for the prototyping phase and potentially scalable to the EIC final configuration. The goals are optimization of resources, co-sharing of state-of-the-art electronics and comparative test of complementary approaches.

Accomplishments to date: Much effort has gone into developing the firmware and system-on-chip extensions of the waveform sampling approach that has been the baseline. This has evolved from the 16-channel TARGETX through the 32-channel SiREAD, and will be culminating in the 64-channel HDSoC ASIC. Significant efficiencies are being realized, and the next round of prototypes should provide very good baseline estimates of single-photon processing speed, power and cost. Following a recommendation from the EIC R&D committee, we have started also an initiative to investigate the alternative use of a time-over-threshold (ToT) discriminating readout for the EIC PID detectors. Such a readout architecture can provide excellent time resolution with a moderate use of resources, as it naturally implements a zero suppression with a consequent limited request of data rate. The MAROC electronics employed so far as a reference system is an example of ToT readout. The ALCOR development has been selected as a good candidate for custom EIC adaptations. It is a 32-channel ASIC that features low-power TDCs that provide single-photon tagging with time binning down to 50 ps and is designed to work at cryogenic temperatures. A dedicated design of the front-end shall allow for count rates well exceeding 500 kHz per channel. A complete VME/VSX DAQ chain based on the SSP protocol developed at JLab has been succesfully used during the eRD14 prototype beam tests and proven to be compatible with the

SiREAD/HDSoC front-end. A simplified DAQ solution is under study to be distributed among the eRD14 groups. At JLab, a streaming readout compatible system has been realized where one Ethernet Trigger Supervisor (ETS) connects up to 8 front-end units (or other ETS in chain) located up to hundreds of feet away via either copper or fiber of up to 5-Gbits serial link, and a readout PC via 1-Gbit Ethernet line.

Assessment of technological readiness: HDSoC is based upon heritage from the original IRSX ASIC currently being successfully operated in the Belle II Time Of Propagation detector. Since that development, more advanced versions of the sampling technology have been developed by Nalu Scientific, wherein the feature extraction is done on-chip, and thus reducing the external processing overhead and making triggerless acquisition viable. ALCOR is a ToT readout development for the DARKSIDE experiment that can be customized for EIC sub-detectors. Commercially available chip featuring similar specifications, such as the TOFPET/2, could provide a reference. Previous INFN realizations, as the ALICE TOF readout based on NINO chip and the CLAS12 RICH readout based on MAROC3, can be used as a benchmark for the SiPM post-irradiation performance characterization. The contemporary big data challenges have promoted technological developments that are becoming mature enough to justify the use in the high-energy experiments. This opens the possibility to adopt a streaming readout without the need of a hardware trigger, and the use of commercial standards for the DAQ data-transfer lines.

Work remaining for a TDR, ballpark cost estimate, and timeline: Fabrication and successful operation of a prototype set of readout based upon the HDSoC ASIC will provide a solid basis for the TDR and subsequent WBS costing. To complete this activity will require 2 – 3 years at the current historical level of support of roughly $50k/year for a UH postdoc and a few 10's of k$ for hardware development. With increased funding, this timescale could be reduced. The ALCOR R&D program foresees a 2 – 3 years of effort. In the first year, the prototype chip will be characterized and a readout board realized for imaging tests of irradiated SiPM with the dRICH prototype. In the following years, custom version of the chip will be realized matching the specifications of the EIC PID detectors and validated in beam tests. A cost-effective DAQ solution compatible with streaming readout will be pursued. The planned investment is at the level of $30k/year (on top of a significant INFN in-kind contribution). This does not include dedicated personnel that can only be co-funded by INFN. Continued financial support from the DOE EIC R&D program of the INFN electronics postdoc is crucial.