eRD110 - Photosensors for EIC Detectors

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Executive Summary The objective of the R&D effort presented here is to mitigate technical, cost, and schedule risk related to readout sensors of EIC Cherenkov detectors and Calorimeters. The call for this proposal requests that this R&D effort comes to a clear and well-informed decision for a baseline sensor solution for each PID detector in FY22. Our common consensus is that R&D effort beyond FY22 is absolutely necessary in order to be able to form a decision that capitalizes on all state-of-the-art technologies to mitigate all of the risks specified above. The decision about a low-risk photosensor baseline solution will be based on the assessment whether each sensor under consideration (1) satisfies the technical requirements of each PID detector, (2) has an acceptable cost, and (3) can be delivered by the manufacturer in the required quantities within the timelines of the project, and with consistent performance quality across the sensor units. Tables 1 and 2 are representative of the specification requirements of a detector, the sensors that are being considered for that detector, and their risk analysis. One of the main objectives of the consortium is, in collaboration with the detector consortia, to establish more precise limits on the performance requirements for the readout sensor of each specific detector. For example, Table 1 is populated with values that were used as guidelines during the generic R&D program. As the work on detector design advances, some of these values, such as the combination of B-field strength and relative sensor orientation with respect to the B-field direction, or the expected radiation levels, become more precise. The proposed R&D activities related to Photek/Photonis MCP PMTs and Incom LAPPD/HRPPDs involve primarily characterization campaigns to address (1) and some aspects of (3). The effort on SiPMs will additionally involve development, in collaboration with the manufacturers, to optimize the sustainability of the proper temperature treatment.

Photek and Photonis MCP PMTs

The objective of this targeted R&D is to mitigate technical and schedule risk associated with commercially established MCP PMTs, namely Photonis Planacon xp85122-s-HiCE and Photek MAPMT253. To a large extent, the classification of the technical risks associated with these PMTs is based on characterizations done within the PANDA DIRC R&D and the generic EIC R&D program. In FY21, we have verified that gain performance is within the requirements up to 2 T for relative angles with respect to the B-field direction up to 10°. A strong decrease in collection efficiency (CE) at larger angles made it unpractical to continue with the gain evaluation. The origin of the CE drop needs to be understood in FY22 and the B-field performance limitations fully established. The B-field scans were done by illuminating and reading out only a few pixels. Some performance parameters, such as cross talk and gain uniformity can only be assessed reliably with a full illumination and a complete readout. The Photek MAPMT253 is relatively new on the market and needs to be studied in a 16x16 geometry (as needed for EIC). The situation with the Photonis sensor is similar; moreover, that PMT is delivered to users with 32x32 conductive contacts on the back, and out-of-the-box readout does not exist. Full characterization over the full B-field range of both PMTs in a 16x16 geometry, while the full photocathode is illuminated, must be done to understand the B-field evolution of collection efficiency observed during the 2021 B-field scans, and to assess cross talk and gain uniformity. This characterization will mitigate the associated technical and scheduling risks. In this respect, the adaptation of the NALU ASICs (done at the Hawaii University within the eRD103 proposal) into a custom readout solution is critical and must be supported.

R&D plan for FY22: Collection efficiency, timing resolution, cross talk, and gain uniformity of Photonis Planacon xp85122-s-HiCE and Photek MAPMT253 in B-fields over the full range of PMT response (full photocathode illuminated).

Manpower required and available for FY22 The B-field measurements will be performed at JLab in the High-B test facility established within the generic EIC R&D program. Manpower required, includes up to six shift takers per day. Of these, three are USC students, and three are faculty (USC, CUA, and SBU). JLab provides manpower for operations of the superconducting magnet, detector and DAQ support. This R&D will support travel cost to and from JLab of all USC personnel and a summer stipend of one USC undergraduate student. The cross-talk characterization of the tubes at 0 T will be performed by a postdoc at Hawaii University (HU) as a natural extension of their work on adapting the existing NALU HDSoC ASIC into a custom readout board. Funding for the postdoc is requested in the eRD103 (DIRC) proposal. The HU readout will bypass the use of magnetic signal cables, which we suspect may have been the reason for the observed efficiency drop in the FY21 gain evaluation.

Milestones for FY22: Risk classification of collection efficiency, timing resolution, cross talk, and gain uniformity of Photonis Planacon xp85122-s-HiCE and Photek MAPMT253 in B-fields over the full range of PMT response (full photocathode illuminated).

Timeline: The cross-talk characterization will be performed in Spring 2022, whereas, the B-field characterizations will be completed in Summer 2022.

Funding profile for FY22: See Appendix. The budget covers 2-months travel of USC personel to JLab, cryogens for a 1-month-long characterization data taking, rental cost of a fast scope, budget for small components (such as connectors, adapters, holders, etc.), summer salary of one undergraduate student, and the cost of one Photek MAPMT253 MCP PMT.

Preview of remaining R&D after FY22 and until FY24: We envision that this R&D activity will mostly be concluded in FY22. Any risk-mitigation characterization that needs to be performed beyond FY22 will be shifted to FY23–24.

LAPPD / HRPPD

The recently commercialized Large Area Picosecond Photo-Detector (LAPPD) by Incom provides a promising low-cost photosensor solution for the EIC imaging Cherenkov sub-systems. Both Gen II (capacitively coupled) and direct readout modifications are of interest for EIC. The latter one is associated with the small (10cm) formfactor High Resolution Picosecond Photo-Detector implementation (HRPPD). Special emphasis should be made on the modifications with improved tolerance to the magnetic field (10 micron pore size, reduced stack height). Capacitively coupled models are equipped with a user-defined external readout PCB, allow for much higher versatility of the readout plane pixellation, and were shown to provide a higher spatial resolution due to charge sharing properties (mRICH, dRICH). Direct readout models are better suited for high occupancy applications (DIRC).

R&D plan for FY22: The LAPPD / HRPPD evaluation process for EIC is seen as a coordinated effort between Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Istituto Nazionale di Fisica Nucleare (INFN) Trieste and Genova, and Mississippi State University (MSU) in a close contact with Incom (see Appendix for details of the institutional commitments). In the first half of 2022 we expect to receive from Incom 1) full size GEN II (20cm) with 20 micron pores as a baseline model, 2) the same 20cm GEN II, with 10 micron pores and potentially an MCP stack with reduced gaps, 3) 10cm size HRPPD, with 10 micron pores, reduced height MCP stack and capacitively coupled readout (GEN II style), 4) the same HRPPD, with a co-fired ceramic base and 1024 Direct Readout pads. The R&D in FY22 will include both bench tests and beamline evaluation of these tiles. The duration of a single rental period is four months, which gives one enough time to pass each tile through the full evaluation chain, as well as to have few of them available at the same time for the beam test at Fermilab.

Manpower required and available for FY22:
ANL: staff scientist (Junqi Xie, 20% FTE support requested), engineering and technical support for the B-field test facility upgrade and maintenance is required (10% FTE requested); **BNL:** staff scientist (Alexander Kiselev, 15% FTE, available); **INFN:** staff scientist (Silvia Dalla Torre, 10% FTE, available), post-doctoral fellow (Deb Sankar Bhattacharya, 75% FTE, available as of Nov 2021), staff scientist (Michail Osipenko, 10% FTE, available); **MSU:** assistant professor (Sanghwa Park, 10% FTE, available), graduate student (0.5 FTE, 25% support requested). We request $20k for 100% FTE support of a new postdoc over 6 months. The postdoc will have an overlap with Deb Sankar Bhattacharya and will replace him at the end of Dr. Bhattacharya's contract in October 2022.

Milestones for FY22: The deliverables in FY22 include full evaluation of up to four different LAPPD and HRPPD tiles in the lab and under beam conditions: quantum efficiency (QE) and gain uniformity scans, operation under high rate, timing and position resolution measurements in a finely pixelated configuration. More details are provided in the Appendix, including tentative timelines.

Preview of remaining R&D after FY22 and until FY24: We envision that the testing schedule will be tight for a full test of the four LAPPDs, especially if the funding for this program starts later than anticipated. The mechanical and electrical interface to the HRPPD with a direct readout will not be ready by the first beam test in May 2022. This work will most likely be continued in FY23. Beam test with either the mRICH or a simple proximity focusing RICH prototype equipped with a selected LAPPD photo-sensor type is planned for FY23 together with eRD101, pending the successful mRICH validation with the MaPMT sensors in FY22. Newest Incom state of the art LAPPD / HRPPD models may require separate evaluation in FY23/24. A joint with eRD109 effort in building an integrated sensor+ASIC board assembly is foreseen in FY23/24.

SiPM In recent years, significant progresses have been made in reducing SiPM after-pulse and optical cross-talk effects, resulting in a typical dark count rate of about 50 kHz/mm^2 at 20 C. Temperature control is needed to ensure linearity (calorimetry) and limiting the dark count rate (Cherenkov applications). To further suppress dark noise, single photon sensitivity requires in addition an excellent timing, approaching the intrinsic resolution of the sensor ($\approx$ 150 ps for a 3 mm device). The moderate radiation level foreseen at EIC, i.e. a reference of $10^{11}\,\mathrm{cm}^{-2}$ 1-MeV neutron equivalent (neq) dose at dRICH location, could make their use possible despite the modest radiation tolerance. Preliminary results indicate that proper low-temperature working point and high-temperature annealing cycles could mitigate the adverse effect, to the level that SiPMs are being considered for LHC upgrades, at much higher expected doses than EIC. INFN has already initiate a collaboration with ALICE and contacts with LHCb for a synergic long-term study toward radiation hardness. A formal collaboration and an agreement exists between INFN and FBK (Fondazione Bruno Keller) for development and production of prototypes of SiPM, facilitating custom realizations. Some of the SiPM under test in the first irradiation campaign are from FBK with designs optimized for better radiation tolerance or for Cherenkov applications (improved single photon resolution).

R&D plan for FY22: In FY21, a selection of most promising 3×3 mm^2 SiPM candidates has been acquired and assembled onto custom carrier boards. A first irradiation campaign has been conducted on a sub-sample of devices up to 10^{11} neq/cm^2. Annealing cycles are ongoing and seems to confirm that temperature is more efficient than time in curing lattice effects and a photon counting capability could be restore after several days above 150 C. The main goal of the FY22 program is to demonstrate that a proper choice of the SiPM layout and temperature treatment, in conjunction with a precise timing readout, could mitigate the technological risk on photo-sensors at EIC. It is planned to complete the study on the acquired SiPM and extend to other SiPM candidates, with particular attention to micro-cell size, protective window material and bonding. Initial R&D will be pursued with the manufacturers to optimize the temperature treatment sustainability. The sensor response will be characterized with laboratory instruments, but also with a realistic readout chain based on the ALCOR ToT chip, an INFN development that could be initially adapted to EIC needs as in-kind contribution.

Manpower required and available for FY22 INFN could count on 10 researchers (about 0.1 FTE each) and several technicians but dedicated personnel can only be co-funded at this stage of the project. In the proposed budget we request 30k$ for 100% FTE support of a postdoc over nine months as part of a two year position.

Milestones for FY22:

1. Comparative assessment of commercial (and prototypes not yet available on the market) of SiPM performance after irradiation. Prototypes were made already available to INFN.

2. Definition of an annealing protocol

Timeline: We plan a new irradiation campaign by end of June 2022 and the start of custom developments during summer 2022.

Funding profile: See Appendix. FY22 is representative of the following years. The SiPM program benefits from significant INFN in-kind contribution in infrastructures, e.g. irradiation TIFPA facility (TN, Italy) and laboratory equipment. EIC funds are request to support part of the SiPM procurement, custom developments with the companies and manpower.

Preview after FY22: The realization of a benchmark $5 \times 5\,\mathrm{cm}^2$ unit with optimized SiPM and integrated cooling will be pursued towards EIC needs. This effort will aim to the definition of the technical specifications of the SiPM optical performance, temperature treatment and consequent layout optimized for EIC. Fundamental improvements in radiation hardness of the SiPM substrate are not excluded, but will likely require a longer time scale, and could be pursued in collaboration with LHC.

In FY23 a complementary effort, targeted at the SiPM application to EIC calorimetry, will be pursued as well. Homogeneous calorimeters (PWO and SciGlass) require state of the art resolution and for that will have to use a large number of SiPMs to readout a single channel. Hadron calorimeters have a low-light yield in general, and will be affected by the increased noise of exposed SiPMs. SiPMs will be exposed to the neutron and charged hadron background produced by the RHIC collider during the run. Their dark current increase will be monitored as a function of exposure and location, in a way similar to what was done for the STAR FCAL R&D program. The estimated budget request for this effort is \$10k.

Supplemental Material

A Generic Photosensor Requirements and Photosensor Specifications

Parameter	hpDIRC	mRICH, dRICH
Gain	$\sim 10^6$	$\sim 10^6$
Timing Resolution	≤ 100 ps	≤ 800 ps
Pixel Size	$2-3$ mm	≤ 3 mm
Dark Noise	≤ 1 kHz/cm^2	≤ 1 MHz/cm^2
Radiation Hardness	Yes (depends on the sensor location)	Yes (depends on the sensor location)
Single-photon mode operation?	Yes	Yes
Magnetic-field immunity?	Yes ($1.5-3$ T)	Yes ($1.5-3$ T)
Photon Detection Efficiency	$\geq 20\%$	$\geq 20\%$

Table 1: List of overall performance requirements on the photosensors of EIC Cherenkov detectors as considered during the generic R&D program. In collaboration with the detector groups, we aim to update these parameters for each PID detector. An example is the requirement on the magnetic-field tolerance, which will be updated in regard to the sensor location in an actual EIC detector and a realistic field map that also includes the relative orientation of the photosensors and the B-field. The possibility to mitigate large relative angles by adapting the orientation of the readout plane, will be taken into account for these detectors where this is possible. The photosensors capabilities and cost, as well as the classification of the corresponding risks to the project, will be benchmarked against the spec requirements.

	Planacon	SiPM	LAPPD
Area	5×5cm^2		20×20cm^2
Pixel	3×3mm available	3×3mm available	25×25 mm available; 3×3 mm prototypes exist, need further tests
Magnetic Field	Yes	Yes	0.7 T, needs 10μm MCPs for > 1.5 T
Radiation	Yes	Needs test	expect good
Availability	In-stock	In-stock	In-stock for 20 μm, in 2022 for 10 μm
Price	\$15-20k each, significantly cheaper in large unit	\$1/mm^2?	\$50k each in 2019, \$25k each in 2023 (Incom)
Unit Price	\$15k/25cm^2	\$2.5k/25cm^2	\$3.125k/25cm^2 in 2019 or \$3.125k/25cm^2 in future, HRPPD in 2022
Concerns	No, except cost	Radiation hardness	Cross talk, integration, availability
Risk	No risk	No risk if radiation is ok	Achievable with risk, Gen-II, HRPPD design

Table 2: A representative table of an overall assessment of considered sensors for EIC Cherenkov detectors as submitted to the generic R&D Program in 2019. As our characterization effort has progressed and progresses, such table will be created for each detector and all considered sensors for that detector. Also, newly available sensors, such as the Photek MAPMT253 and HRPPD will be added and their risks assessed.

B LAPPD Supplemental material

Commitments of the participating institutions: Primary bench tests of the QE, gain uniformity and operation under high rate conditions will be performed at ANL, using to a large extent the equipment developed for the 6cm MCP-PMT program. The existing B-field test facility will be modified to accommodate for the large (20cm) size devices.

Pixellation and position-resolution studies will be primarily performed at BNL, accommodating the existing equipment and the readout board designs to the LAPPD tiles of a different formfactor (10cm size, directly coupled readout). Mechanical and electrical interface of the directly coupled HRPPDs has to be developed from scratch, using technical feedback from Incom.

The single and multi-photon timing resolution measurements are the primary focus of INFN Trieste and Genova (essential for the imaging Cherenkov detectors and Time-of-Flight application, respectively). This effort requires tedious calibration of the existing DRS4 electronics, and will be performed in collaboration with INFN Bologna, using a substantial base funding via the EIC_NET Collaboration in Italy.

INFN and MSU will provide the most part of the manpower for the bench and beam test data analysis.

All groups are planning to join the beam test at FNAL in May 2022, to evaluate the sensor behaviour under beam conditions, as well as the performance of a representative detector (either mRICH mock-up or a proximity-focusing RICH) equipped with an LAPPD readout.

Milestones for FY22: In the tentative list below it is assumed that funding starts in the beginning of 2022, and Incom provides the four LAPPD / HRPPD tiles between March and June 2022 as expected.

- Magnetic field test facility at Argonne ready for 20cm tiles - February 2022
- Various Gen II readout boards designed and delivered to BNL - March-April 2022
- Test stand setup and commissioning at INFN - April 2022
- Fermilab beam test with the capacitively coupled LAPPDs / HRPPD - May 2022
- Single photon position resolution report (bench tests with pixelated boards) by BNL - July 2022
- Single and multiple photon timing resolution bench tests report by INFN - September 2022
- Magnetic field tolerance report by Argonne - September 2022
- Beam test data analysis and report - by October 2022
- Preliminary assessment of the LAPPD / HRPPD feasibility for the EIC detector - by October 2022

C Suggested funding profile for FY22

Core costs only indicated. Institutional overhead is not included.

	ANL	BNL	INFN	MSU	USC	JLab
LAPPD rental		$48,000				
SiPMs and related equipment			$30,000			
ANL B-field facility upgrade, Helium consumption	$18,000					
Gen II readout boards		$10,000				
HRPPD readout interface		$7,000				
Staff effort support	$50,000					
Engineering/technical support	$12,000	$7,000				
LAPPD test stand equipment		$5,000	$15,000			
Postdocs and students			$50,000	$2,500	$5,000	
Travel	$3,000	$7,000		$5,000	$14,000	
Photek 16x16 MAPMT253					$16,000	
Cryogens for High-B at JLab						$11,000
Small components for High-B at JLab						$3,000
Fast Oscilloscope Rental (JLab)					$5,000	
TOTAL	$83,000	$84,000	$95,000	$7,500	$40,000	$14,000