eRD110 - Photosensors for EIC Detectors

July 7th, 2023 - Application for FY24[*]

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Executive Summary

The objective of the R&D effort presented here is to mitigate a remaining technical risk related to the baseline readout sensors of the EIC electron-side and barrel Cherenkov detectors, the Incom HRPPDs. The proposed R&D effort in FY24 continues to be needed in order to demonstrate that the HRPPDs satisfy all the technical requirements for each of the above detectors and to assess a backup solution (Planacon HiCE and Photek MAPMT253, neither of which have been previously used on a large scale as Cherenkov readouts in another experiment). The proposed R&D activities related to Incom HRPPDs are linked to the execution of the EIC-Incom Project Engineering & Design (PED) contract and involve primarily characterization of the first batch of five EIC HRPPD photosensors. These studies will also partially assess if Incom can deliver larger quantities of HRPPDs within agreed timelines and with consistent performance quality across the sensor units. We also provide a report with the results achieved during FY23 under activities funded through eRD110.

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1 HRPPDs by Incom Inc.

A Project Engineering & Design (PED) contract between EIC and Incom Inc. [1] was signed in June 2023. The first phase of this contract is aimed at finalizing the design of DC-coupled ”EIC HRPPD” sensors (see Section 1.2) and their interface to the readout electronics, and will continue through September 2023. The second phase will consist of building five HRPPD sensors according to this design within a period of time between October 2023 and March 2024.

All of the eRD110 HRPPD-related activities in FY24 will therefore be aimed at evaluation of these first five tiles, providing feedback to the manufacturer, and arriving at a definitive conclusion of their applicability in the EIC ePIC detector subsystems where they are presently considered as a baseline photosensor solution: a proximity focusing Ring Imaging Cherenkov detector (pfRICH) in the electron-going endcap, and a Detection of Internally Reflected Cherenkov light detector (hpDIRC) in the barrel.

Rental of either the currently designed DC-coupled HRPPDs or capacitively coupled LAPPDs in FY24 is not being planned, unless production of the first five fully functional HRPPDs by Incom gets substantially delayed. However, assuming the decision is taken to procure the remaining necessary devices for the ePIC detector, and the production of these devices is for any reason delayed, the collaboration would continue the development of the ePIC detectors with other alternative HRPPD or LAPPDs (assuming they would be available) in order to keep the project on schedule.

1.1 FY23 results

See section A in the Appendix.

1.2 EIC HRPPD photosensor design

Several features of the present HRPPD design will be adjusted to ePIC Cherenkov detector needs during the first phase of the EIC-Incom PED contract [2]. Open area ratio will be increased to 75% within the same footprint of 120 mm x 120 mm. Micro-Channel Plates (MCPs) with the same 10 μm pore size will receive individual bias voltage connections, implemented via brazed leads instead of spring loaded plates. A 3.8 mm thick sapphire window will be used instead of a 5.0 mm thick fused silica window.

1.2.1 Readout backplane interface

A 3.3 mm thick Low Temperature Co-fired Ceramic (LTCC) anode base plate with a non-trivial routing inside of the stack was designed in FY23 to provide a better means for sensor electrical and mechanical integration in the experiment (see Section A.3.2 and Fig. 1 for the first prototype built in May 2023).

Custom floating double-sided Samtec compression interposers [3] with 2 mm pitch ([**$16.0k**], including $7.5k NRE costs), matching the improved layout of the HRPPD rear plate pixellation, will be used for production of the first five tiles.

1.2.2 HRPPD integration package with a passive readout backplane

A 3D printed enclosure, a custom passive readout board with sixteen 64-channel high-density Samtec ERF8 DV connectors identical to the ones we will use on Photek Auratek MCP-PMTs (see section 2.1), and a 64-channel ERM8-to-MCX adapter card will be designed by BNL. Five sets of the new EIC HRPPD sensors, enclosures [**$3k**], readout boards [**$5k**], adapter cards [**$4k**] and Samtec interposer sets will be procured and distributed for basic performance studies among the five research groups (Argonne, BNL, University of Glasgow, INFN Trieste and Genova, Yale), starting from late Fall 2023.

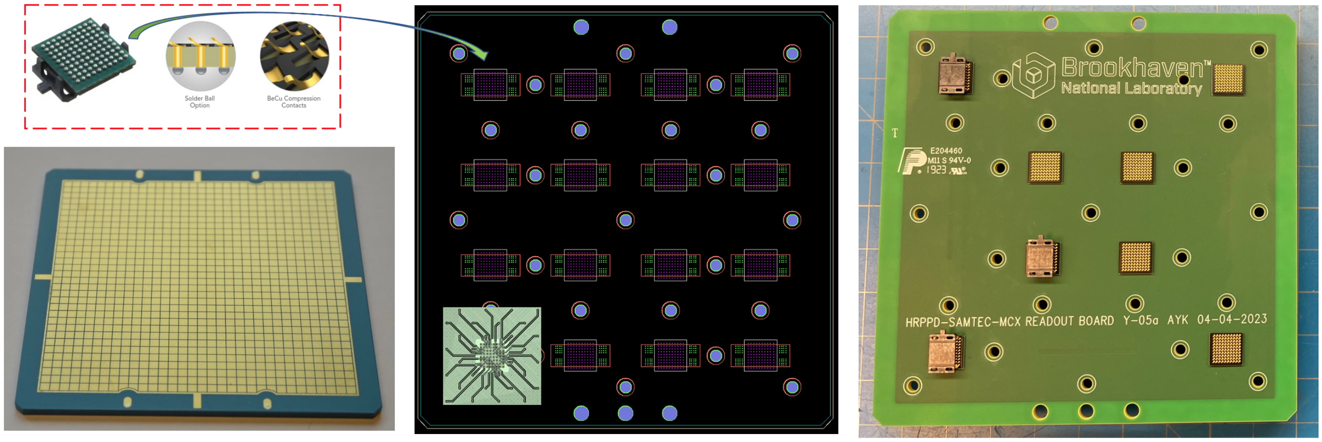

Figure 1: Left: first EIC HRPPD anode base plate prototype, with a regular pixellation of the inner (vacuum) side. Center: proposed layout of a matching ASIC readout backplane with smaller pitch interposer footprints on one PCB side shown in magenta, high-density HGCROC3 ASIC footprints on the other PCB side shown in green, and LTCC routing snapshot of one of the 8x8 pixel areas in the bottom left corner. Mechanical holes are shown in blue. Right: a passive readout backplane with soldered single-sided stock Samtec interposers with a 800 μm pitch used for evaluation of the concept.

1.2.3 HRPPD integration package with an ASIC readout backplane

A rigorous evaluation of a 1024-pad HRPPD sensor, including timing resolution, Photon Detection Efficiency (PDE) and gain uniformity scans requires an integrated high performance ASIC backplane with a matching number of channels. Research groups at CNRS/IN2P3-Ecole Polytechnique, Oak Ridge and Debrecen University will design such a board [**in-kind**] equipped with sixteen HGCROC3 [4] ASIC chips [**$3k**, assuming two iterations], in a collaboration with eRD109 and Jefferson Lab electronics engineers. They will also assist in establishing an FPGA interface using an AMD KCU105 evaluation kit [**$4k**]. We will benefit enormously from the ongoing R&D effort at Oak Ridge, which requires interfacing of the same HGCROC3 ASIC for the ePIC forward hadronic calorimeter (LFHCAL) prototype. Manufacturing and assembly costs of a 512-channel pilot version and a full-size 1024-channel backplane are estimated at [**$7k**]. A single set in a matching 3D printed enclosure with a pair of Twinax cables [**$1k**] will be built and made operational at BNL, and later on sent to either Glasgow or Yale (see also Section 1.6.2).

1.3 R&D activities in FY24

1.3.1 Quantum Efficiency (QE) absolute measurement and uniformity scans

These measurements will be first performed at Argonne for all five new HRPPDs, after a minor upgrade of the available equipment [**$2k**], using a well established technique of measuring a photocathode current against a calibrated photosensor, to quickly confirm that the tiles meet the requirements and the parameter spread is within the defined limits. No readout backplane is needed for this evaluation.

1.3.2 Photon Detection Efficiency (PDE) and gain uniformity scans

These studies will be started at Brookhaven, applying necessary mechanical modifications to the existing HRPPD dark box setup [**$5k**] and making use of the HRPPD ASIC integration package (see section 1.2.3). The PDE measurement technique yet needs to be developed, following the experience gained by A. Lehmann at Erlangen evaluating other types of MCP-PMTs for PANDA experiment at GSI [5]. Routine PDE scans for all HRPPD sensors will later be performed at Yale University on a QA station setup to be built in 2023/2024, see Section 1.6.2.

1.3.3 Timing resolution studies in the lab environment

All five research groups mentioned earlier will have a combination of a picosecond laser with a pulse RMS <20 ps, high analog bandwidth scopes and at least 32 channels of DRS4 electronics. Such a setup is sufficient to quantify HRPPD single photoelectron timing resolution performance expected to be on the level of $\sigma \sim$ 35-50 ps, as a function of photocathode voltage, gain and other operating parameters.

A compact femtosecond Menlo Systems laser, recently acquired at Brookhaven, will be used to provide an ultimate timing reference for laboratory measurements where unfolding the laser pulse width will not be required. We request [**$3k**] for a laser dark box and various other mechanical and optical components in order to finalize and test this setup.

1.3.4 Magnetic field tolerance studies

Magnetic field tolerance studies will be independently performed by Argonne (joined by JLab and USC, adding [**$8k**] for travel) using g-2 calibration magnet equipment ([**$8k**] M&S), and by INFN groups using 0.5 T and 1.5 T MRI solenoids in Italy ([**$16k**] travel money request), see Fig. 2.

The main objective of these studies will be to confirm the first observations made in FY23 at Argonne, using a current design HRPPD #6 with MCPs in a ”stacked” configuration (no gap and no individual MCP bias voltage), see Section A.1. Namely, the facts that in a strong magnetic field (i) these sensors exhibit only a marginal degree of charge sharing, and (ii) that their gain can be restored by just a few hundred volts increase of the MCP bias voltage. In addition, a first direct confirmation that such a tuning allows one to also recover a single photon timing resolution on the level <50 ps will be provided, for the field strength and orientation expected at the ePIC pfRICH and hpDIRC sensor plane locations with a newly designed MARCO solenoid at a full 2 T central field.

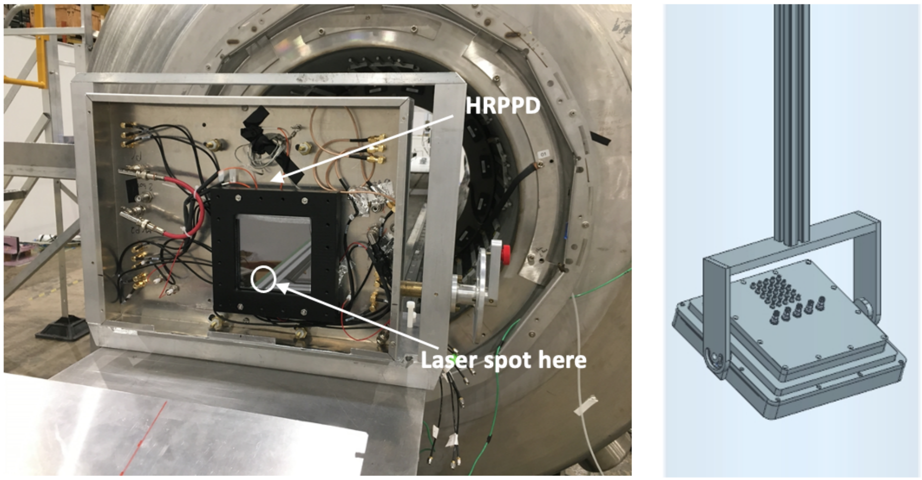

Figure 2: Left: HRPPD #6 ready to be installed inside of the Argonne g-2 test solenoid bore in February 2023. Right: mechanical design of a compact dark box to study LAPPD #153 performance in an MRI solenoid magnetic field in September 2023.

1.3.5 Preliminary ageing studies

Ageing tests in terms of QE degradation and gain reduction versus the integrated extracted charge will be performed by INFN Trieste [**$6k** M&S request] using a subset of techniques developed earlier at INFN Bologna [6] and the University of Texas, Arlington [7]. A spot on one of the five HRPPDs will be illuminated using a sufficiently powerful light source. Periodically, typically every couple of days, the intense illumination will be paused, and a single photoelectron illumination mode will be used to measure both the gain and the detection rate. These periodic measurements, performed after increased integrated illumination, will allow us to disentangle a possible HRPPD degradation in two essential parameters: photocathode QE and MCP gain. A required integrated photon flux will be estimated using the ePIC Monte-Carlo, assuming realistic luminosity, DIS cross section and electron-beam-gas interaction rates, number of Cherenkov photons from the aerogel radiator and HRPPD window per charged particle track, as well as an expected conservative HRPPD gain of up to $\sim 10^6$ to be used in the experiment.

1.3.6 Performance optimization specific to hpDIRC

While many of the sensor requirements for the pfRICH and the hpDIRC are quite similar, and the required studies are synergistic, a few requirements are more challenging for the hpDIRC, and need to be confirmed separately to validate HRPPDs for this application.

The hpDIRC requires a single photon timing precision of ~100 ps or better, but the meaning of this requirement is different as compared to pfRICH. To properly consider the impact of tails in the photon timing spectrum, the relevant quantity is not the transit time spread (TTS) but the RMS of the measured photon arrival time in a window of [-0.5 .. 2.0] ns around the expected time.

Besides this, studies performed in the past have shown that earlier MCP-PMT models suffered from "coherent oscillations" when more than 5–10 photons were detected on a 2-inch sensor. ePIC simulations of the hpDIRC predict that the average photon yield will, for some polar angles, be more than 120 detected photons per particle. This corresponds to an average of up to 40 photoelectrons per event on a single HRPPD. Therefore, coherent oscillations need to be investigated, and the excellent RMS timing precision needs to be demonstrated, not only for single photons hitting the sensor, but also in a high-occupancy environment with up to ~100 detected photons per trigger per HRPPD. These properties will be studied during MCP PMT tests at the University of Glasgow. See Section 2 for more details on the proposed MCP PMT tests and the related costs for test stand upgrades.

1.3.7 Beam test at Fermilab

A short test beam campaign at the Fermilab Test Beam Facility [8] in early 2024 will be aimed at establishing the timing performance of the first produced EIC HRPPDs in a multi-photon mode. A timing difference between the HRPPD signal from dozens of Cherenkov photons in a flash generated by a 120 GeV proton passing through a 3.8 mm thick sapphire window, and a pair of fast reference MCP-PMTs (see Fig. 3) will be measured to evaluate the expected pfRICH HRPPD performance to provide a reference timing signal for other ePIC TOF subsystems. A configuration with an aspheric lens is optional. It may be used to assess how much small amplitude single photon pulses hitting the periphery of the sensor are disturbed by a large pulse from a photon flash generated in the center of the sensor window.

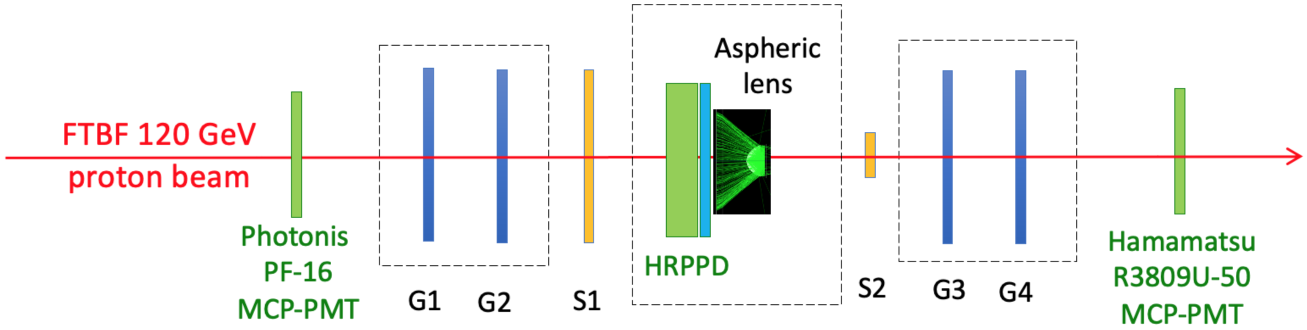

Figure 3: Schematic of the beam test setupin FTBF area MT6.2, shown in a configuration with an aspheric lens radiator (S1..S2 - scintillation counters, G1..G4 - GEM tracker stations).

Assuming one full week of beam time, a team of up to seven people, and shipment costs we request [**$30k**] to support this campaign.

1.4 Proposed milestones for FY24

The following milestones are proposed, following the described R&D activities in FY24, and under the assumption that the new EIC HRPPDs will become available from Incom starting from no later than November 2023, and at a production rate of at least one per month.

- Design and production of five HRPPD integration packages with a passive backplane and 64-channel ERM8-to-MCX adapters: November 2023
- Beam test at Fermilab: February 2024, with a data analysis report by Summer 2024;
- Design and production of either a 512- or 1024-channel version of the HGCROC3-based HRPPD backplane and a customized 3D printed enclosure: March 2024
- QE uniformity scans at Argonne: a report for all five HRPPDs by May 2024
- Gain and PDE uniformity scans at BNL: July 2024 (after a pfRICH beam test in June 2024)
- Magnetic field studies at Argonne and at medical facilities in Italy: reports by September 2024
- A consolidated HRPPD performance evaluation report: September 2024

1.5 Manpower required and available in FY24

ANL: staff scientist (Junqi Xie, 8% FTE support requested [**$18k**]), engineering and technical support for the B-field test facility operation and maintenance is required (8% FTE requested [**$15k**]); **BNL:** staff scientists (Alexander Kiselev at 15% FTE, Craig Woody at 10% FTE, Babak Azmoun at 10% FTE, Martin Purschke at 5% FTE, Sean Stoll at 10% FTE, all available); **INFN:** staff scientist (Silvia Dalla Torre, 10% FTE, available), post-doctoral fellow (Deb Sankar Bhattacharya, 75% FTE, available), post-doctoral fellow (Chandradoy Chatterjee, 20% FTE requested [**$20k**]), staff scientist (Fulvio Tessarotto, 10% FTE, available), staff scientist (Mikhail Osipenko, 30% FTE, available); staff electronics engineer (Saverio Minutoli, 10% FTE, available); **JLab:** staff scientists (Carl Zorn at 5% FTE, Sanghwa Park at 10% FTE, both available); **University of Glasgow:** faculty (Rachel Montgomery, 10% FTE, available); **USC:** faculty (Yordanka Ilieva, 5% FTE, available).

1.6 Complementary R&D and PED activities in FY24

1.6.1 pfRICH prototype beam test at Fermilab

A pilot version of the HRPPD ASIC integration package (see 1.2.3) will be replicated by the pfRICH Detector Subsystem Collaboration as part of their FY24 R&D prototyping proposal. As part of the pfRICH proposed prototyping the newly produced five EIC HRPPD tiles will be used in a separate beam test at Fermilab in early Summer of 2024, in a full chain detector prototype test funded via a separate PED request. Such a test performed outside of the scope of eRD110 FY24 activities, will provide an ultimate evaluation of HRPPD photosensor performance in a real life physics detector setup.

1.6.2 HRPPD / MCP-PMT QA station setup at Yale University

A replica of Incom's own QA station, with the necessary modifications following the layout of a similar MCP-PMT setup in Erlangen [5], will be built at Yale University in 2023/2024, to perform a routine evaluation of HRPPD (or other MCP-PMT) sensors produced for the EIC. It is expected that an in-kind contribution towards equipment procurement by Yale will be used in a combination with the PED money provided by the EIC Project as part of the ePIC pfRICH FY24 funding request.

1.7 Preview of remaining R&D in FY25 / FY26

It is anticipated that further (incremental) modifications to the EIC HRPPD photosensors may be required from Incom before a mass scale production for the EIC starts after DOE CD-2/3 approval, which is expected in Spring 2025. One of the tasks of the eRD110 consortium will then be evaluation of this new batch of sensors in the same way as the first five tiles will be examined in FY24.

Both the pfRICH and the hpDIRC are planning to use the EICROC ASIC by the OMEGA group [9] to read out the HRPPDs in their full scale detector configurations. A high channel count version of this ASIC (64 and more channels) will likely not become available before 2025. That's why we are going to use HGCROC3 chip from the same family in the first version of HRPPD ASIC backplane (see Section 1.2.3). A final validation of the HRPPDs and a suitable version of EICROC ASIC as a fully integrated large area photosensor, with a specified timing resolution, may therefore become required in FY26, including lab measurements and beam test campaigns.

2 Photek and Photonis MCP PMTs

Addressing a technology risk associated with the HRPPDs, we propose to resume characterization studies of the 2” Photonis and Photek MCP PMTs, in a 16 x 16 pad configuration, as a viable fallback solution for the ePIC pfRICH and hpDIRC detectors.

Studies will be performed at the University of Glasgow, and will focus on sensor interfacing and a basic performance evaluation in a configuration without a magnetic field: gain and QE scans, degree of charge sharing and cross-talk, and timing resolution. We request an additional [**$25k**] to upgrade the existing test stand equipment (a VME waveform digitizer with a PCI card, LED switcher box including UV optical path components, calibrated photodiode, MCX cabling, etc) and make it more consistent with EIC test stand needs. As indicated in the budget breakdown (see Table 1), part of this equipment, as well as the MCP PMTs themselves, will be ordered via the University of South Carolina.

2.1 Photek Auratek

We propose to order an MAPMT253/M MCP PMT [10] in a native 16 x 16 pad configuration [**$25k**] with a readily available Samtec ERF8 high density connector interface [**$2k**], and make use of the custom 64-channel HRPPD ERM8-to-MCX adapter cards (see section 1.2.2) to provide connectivity to the existing DRS4 electronics in their V1742 CAEN VME implementation.

2.2 Photonis Planacon

We also propose to order a bare Photonis Planacon XP85122-S-HiCE photosensor [11] (32 x 32 pads) with a Hi-QE Blue photocathode [**$25k**] and make use of our experience with HRPPDs to build a custom readout board interface to this sensor [**$2k**], using off-the-shelf Samtec Z-Ray compression interposers with a 0.8 mm pitch. The electrical and mechanical design of the proposed solution must be sufficient to convert 10 x 10 pixel pads with a pitch of 1.6 mm on the exterior of the Planacon anode base plate into 5 x 5 pad fields with a pitch of 3.2 mm and ERF8 connectivity, to make use of the custom ERM8-to-MCX adapter cards mentioned in section 1.2.2.

2.3 Proposed milestones for FY24

The expected outcome of the FY24 R&D activities is (i) making a preliminary choice between the Planacon or Auratek MCP PMTs in case the HRPPD program path does not show a clear success in FY24, (ii) setting the stage for the remaining FY24 (/ FY25 / FY26) R&D for a selected choice of 2” MCP PMT in this case, and being able to launch this R&D without incurring an additional delay if needed.

The following milestones are proposed:

- Test stand modifications required for HRPPD and MCP-PMT gain and QE scans: May 2024
- Report on the Planacon and Auratek MCP-PMT performance evaluation: by September 2024

2.4 Preview of remaining R&D in FY25 / FY26

The ePIC pfRICH and hpDIRC detectors both have Incom HRPPDs as their baseline configuration photosensors. Assuming that the proposed evaluation of the first five produced EIC HRPPDs in FY24 shows that they demonstrate expected level of performance and robustness to meet the detector needs for both the pfRICH and the hpDIRC, the MCP PMT part of the eRD110 R&D program for FY25 / FY26 will be put on hold. Otherwise it will be formulated according to the outcome of FY24 HRPPD R&D, up to the necessity to interface EICROC ASICs to Photonis and / or Photek MCP PMTs, ordering them in more representative quantities, conducting extensive lab studies, performing beam tests, etc. See also section 1.7.

3 SiPMs

3.1 SiPMs for RICH applications

In previous applications for eRD110 (FY22, FY23) the rationale of exploring the SiPM as sensor of choice for RICH detectors was explained and it is not repeated here. In short, the immunity to magnetic fields makes the SiPM the baseline option for the dRICH detector, and a robust R&D program was run by INFN groups to evaluate the radiation damage and its mitigation, through repeated annealing cycles, as well as studies of time resolution.

The results of the FY23 studies, funded as a PED activity, will be consistently reported in a separate PED application for FY24.

Several key steps and advancements are still needed on SiPM-related studies toward the optimization and engineering of the details towards the preparation and delivery of an ePIC TDR (October 2024) for FY24. A corresponding funding application will be submitted for PED funds.

3.1.1 EIC R&D targeted program context, INFN program and roles of institutions

The R&D program applications for SiPM for FY22 and FY23 were synergistic and complementary to two other supported eRD programs (eRD102 for the dRICH and eRD109 for the ASIC). The INFN groups directly involved were Bologna, Ferrara, Torino (for FY22) and Cosenza (for FY23). Note the FY23 application was supported only partially via PED funds.

3.1.2 R&D plan for FY24

No application for R&D activities is presented for FY24.

3.2 SiPMs for calorimetry applications

In a communication with various ePIC Detector Subsystem Collaborations, responsible for electromagnetic and hadronic calorimetry design and construction, it was determined that the remaining activities towards a Final Design stage do not address risks to the EIC Project. As such they do not qualify to be included in this R&D proposal, but will rather be funded via PED requests of either the particular DSCs or eRD110 or other eRD1** Consortia.

4 Suggested funding for FY24

The summary of funding requests is reported in Table 1.

	ANL	INFN	Glasgow	BNL	JLab	USC
B-field maintenance, He consumption	\$8.0k					
B-field studies, QE scans (staff effort support)	\$18.0k					
B-field studies, QE scans (engineering support)	\$15.0k					
B-field studies (travel)		\$16.0k			\$4.0k	\$4.0k
Consumables for ageing studies		\$6.0k				
Postdocs and students		\$20.0k				
Beam test travel and freight		\$4.0k	\$10.0k	\$12.0k	\$4.0k	
Five HRPPD passive integration packages				\$12.0k		
HRPPD ASIC integration package				\$15.0k		
Samtec compression interposers				\$16.0k		
Photek / Photonis MCP-PMT procurement						\$50.0k
Photek / Photonis MCP-PMT interface				\$4.0k		
Test stand M&S and technical support	\$2.0k		\$9.0k	\$8.0k		\$16.0k
TOTAL	**\$43.0k**	**\$46.0k**	**\$19.0k**	**\$67.0k**	**\$8.0k**	**\$70.0k**

Table 1: Suggested eRD110 funding in FY24. *Institutional overhead is included wherever applicable.*

A Results of the LAPPD / HRPPD R&D activity in FY23

A.1 Magnetic field tolerance studies at Argonne

A magnetic field tolerance test was performed at Argonne National Laboratory with the g-2 magnet in February 2023. Photon sensors were placed in a dark box, movable on a trail into the magnet, see Fig. 2. A picosecond laser system was used, with photons transported to the photosensor surface using an optical fiber. A digital variable attenuator was used to reduce the light intensity to a single photon level. Data was taken with a CAEN DT5742b desktop digitizer.

Two photosensors were delivered to Argonne from Incom for this test campaign: LAPPD #144 and HRPPD #6. LAPPD #144 is a 20cm × 20cm device, with 20 μm pore size MCPs and capacitively coupled readout. HRPPD #6 is a current design DC-coupled 10cm × 10cm device, with 10 μm pore size MCPs in a ”stacked” configuration (no gap and no individual bias voltage).

During the test, the magnetic field orientation was perpendicular to the detector entrance window, except when doing angle dependence tests, for a field magnitude and orientation matching sensor locations in pfRICH and hpDIRC detectors. The results show that in the presence of a strong magnetic field pulses from both LAPPD #144 and HRPPD #6 are localized on the readout pattern (Fig. 4), with minimal cross talk and signal spread observed.

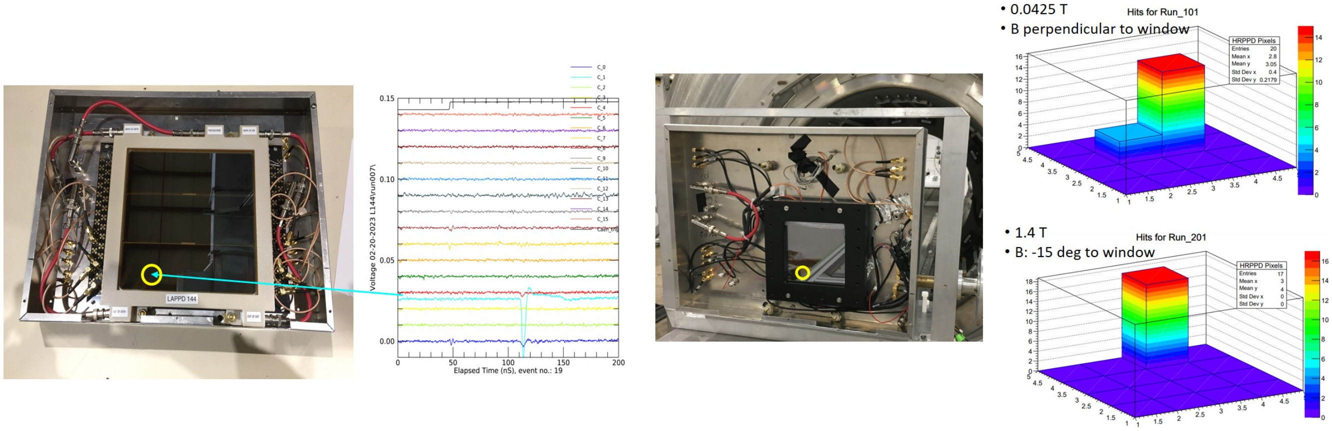

Figure 4: Pulses from LAPPD #144 (left) and HRPPD #6 (right) are confined on the readout plane.

LAPPD #144, with 20 μm pore size MCPs, exhibits a magnetic field tolerance up to ∼0.9 T. Whereas HRPPD #6, with 10 μm pore size MCPs, exhibits a magnetic field tolerance up to ∼1.8 T (Fig. 5).

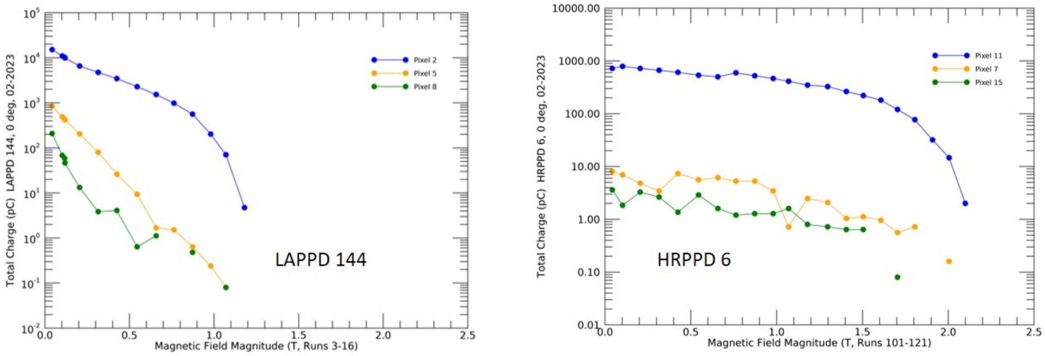

Figure 5: Gain vs magnetic field strength: LAPPD #144 (with 20 μm pore sizes) does well up to a field of ∼0.9 T (left), whilst HRPPD #6 (with 10 μm pore sizes) can operate up to ∼1.8 T (right).

When operating in a high magnetic field environment, the gain of both the LAPPD #144 and the HRPPD #6 can be recovered by increasing the photocahtode bias voltage (Fig. 6).

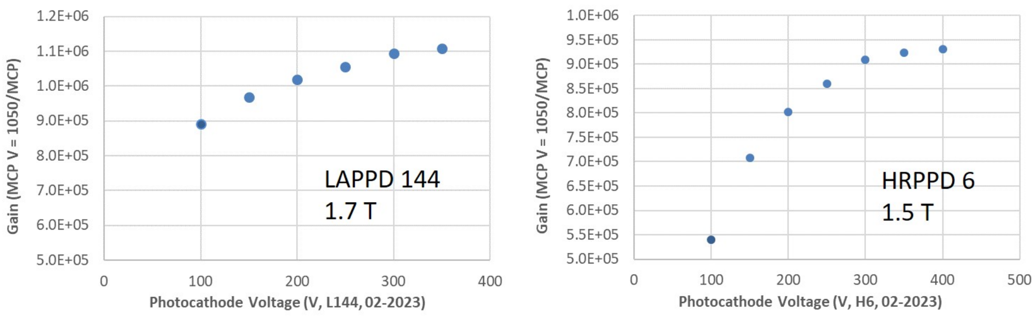

Figure 6: Gain recovery in a high magnetic field: by increasing the photocathode bias voltages, both LAPPD #144 (left) and HRPPD #6 (right) show recovered gains in 1.7 T and 1.5 T fields respectively.

The test results also demonstrated that the dark rates of LAPPD #144 and HRPPD #6 decrease with increasing magnetic field strength (Fig. 7).

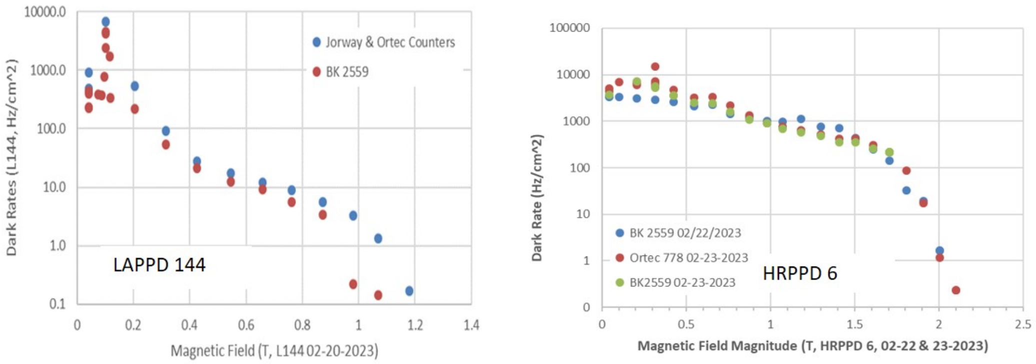

Figure 7: Dark rate vs magnetic field strength: dark rates for the LAPPD #144 (left) / HRPPD #6 (right) are low in strong magnetic fields.

A.2 LAPPD beam test at CERN PS in October 2022

This test beam campaign was led by INFN Trieste and Genova. In the campaign, the timing response of a Gen II LAPPD #126, with 20 μm pore MCPs, has been studied by detecting Cherenkov light produced by a hadron beam in a fused silica lens. The setup also included a scintillation counter, which was read out by an SiPM and which acted as a trigger, as well as a fast Hamamatsu R3809U-50 MCP PMT, exhibiting ∼6 ps timing resolution, which was used as a timing reference. The layout is presented schematically in Fig. 8. See also Fig. 9 (top left).

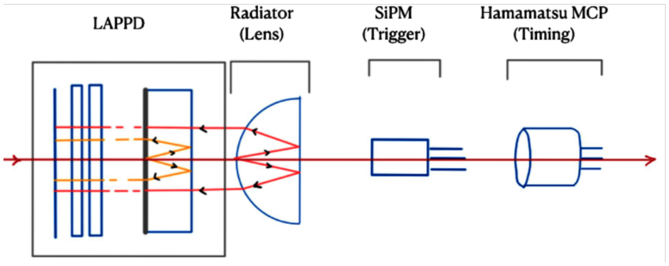

Figure 8: Schematic of the CERN PS beam test in October 2022 (not shown to scale). The LAPPD assembly was placed in a dark box, together with the aspheric lens.

The LAPPD signals were amplified by custom-made inverting amplifiers based on Microwave Monolithic Integrated Circuit (MMIC) Darlington amplifiers, with a high dynamic range, analog bandwidth of 2 GHz, gain of 20 dB, and input and output impedance internally matched to 50 Ohm. Waveforms from the LAPPD, the trigger SiPM and the Hamamatsu MCP PMT were recorded by a CAEN V1742 digitizer, which featured four DRS4 ASICs.

Fig. 9 (bottom left) provides examples of the online signal monitor plots from the different detectors. The preparation of the beam test included dedicated simulations to optimize the geometrical layout and laboratory characterization of the LAPPD and the trigger counter.

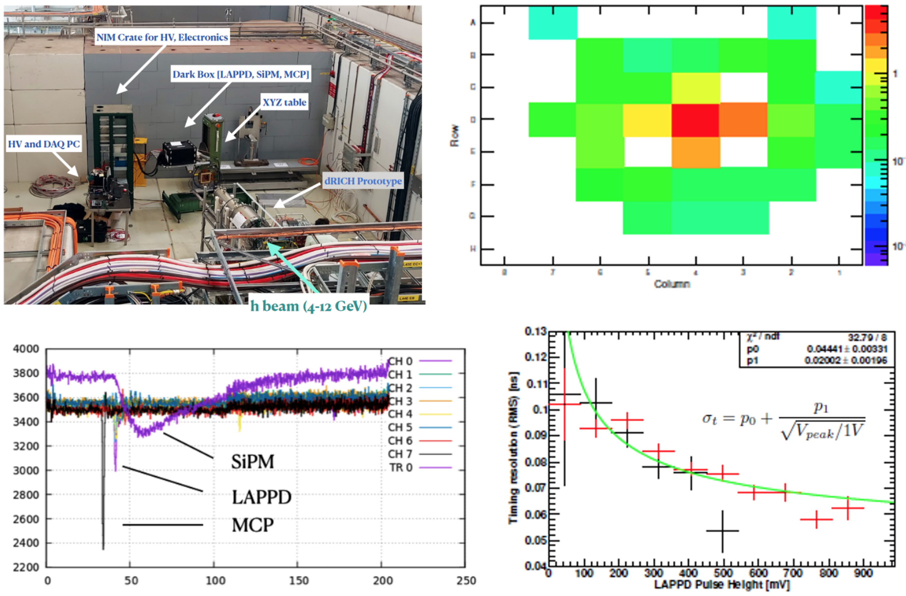

Figure 9: Bottom left: Example waveforms from a slow SiPM signal compared with the fast LAPPD and MCP PMT signals. Top left: photo of the test beam setup. Bottom right: RMS of the LAPPD time resolution versus signal amplitude. Cherenkov ring readout pad (black) and a beam spot pad (red) are superimposed for comparison. Green solid line shows a fit to the data points. Top right: Averaged signal amplitude collected in the LAPPD readout pads. The beam spot in the center corresponds to high signal amplitudes caused by multiple Cherenkov photons produced by a charged beam particle in the HRPPD quartz window. Empty pads were not read out, due to the availability of only 32 out of the 8x8 readout board channels.

The available LAPPD had performance limitations, which prevented us from applying the ideal voltage setting and limited the gain to about 3×10^6, and also limited the voltage bias between the photocathode and the first MCP to only 50 V. Since the capacitively coupled LAPPD readout board had large 1” x 1” square pads, this resulted in rather coarse Cherenkov “ring” images, as shown in Fig. 9 (top right). The main result was the time resolution measurement (Fig. 9, bottom right), showing that, even with the limitations affecting this particular LAPPD tile, a single photon time resolution better than 100 ps can be obtained.

The test beam also offered an opportunity to understand important issues in operating the LAPPD. Two major ones are mentioned below.

- LAPPD High Voltage stability can only be obtained using a power supply in a stacking connection scheme (daisy chain) for all electrodes of the LAPPD. This requires power supplies which are compatible, by design, with the needed stacking connection scheme. At the test beam we used a CAEN power supply of this type (DT1415ET).

- Gen II LAPPDs suffer from important crosstalk, affecting also non-adjacent pads. We believe this cross-talk is generated by signal propagation through the resistive anode surface. This effect has been confirmed via a dedicated campaign of subsequent lab measurements using a pulsed light source and a pad plane PCB designed to avoid a trace-to-trace cross talk induced in the electrical lines. This type of cross-talk can be particularly problematic when a MIP particle passes through the LAPPD window, producing very large signals comprising dozens of coherent Cherenkov photons generated in the dense fused silica medium. This is a clear indication that the usage of LAPPDs / HRPPDs with a resistive anode may be problematic in such a setup, and that devices with directly coupled readout are better suited for applications like the EIC backward RICH.

A.3 Development of a DC-coupled HRPPD interface

Bearing in mind that one can probably use a permanently mounted passive backplane glued to the HRPPDs by conductive epoxy as a fallback solution, other ”less invasive” approaches have been tried out in FY23.

A.3.1 Pogo pin based interface

A substantial effort was invested at BNL, in the end of FY22, to design a multi-pattern readout board with spring-loaded pins, and a matching compact light-tight enclosure to perform the initial testing of the newly available Incom HRPPD photosensors, see Fig. 10.

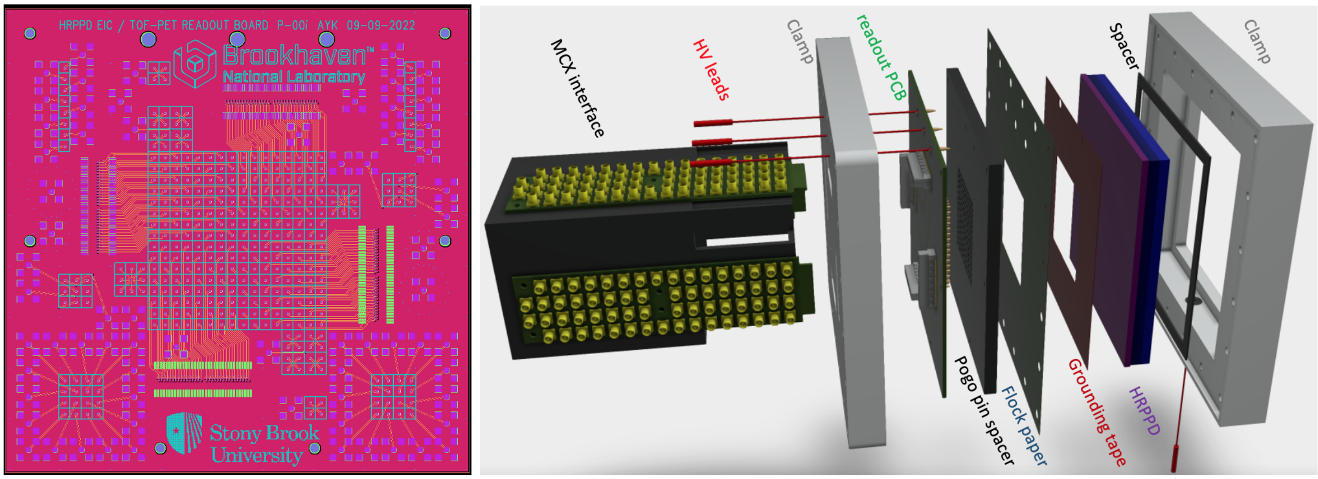

Figure 10: Left: a compact multi-pattern dual purpose readout board, usable for both the EIC-related HRPPD evaluations and in a joint SBU / BNL Time of Flight Positron Emission Tomography project. It can be instrumented with pogo pins and connectors in several different configurations. Right: an expanded view of the HRPPD enclosure, with a readout PCB instrumenting in a central 16x16 pixel field.

This type of a readout backplane and a respective 3D printed enclosure were realized in hardware in the beginning of FY23, and used for both the HRPPD #6 magnetic field resilience studies at Argonne in February 2023 (see Section A.1) and lab evaluations at Brookhaven in May 2023 (see Section A.4).

A.3.2 Compression interposer based interface

The pogo pin implementation described in Section A.3.1 provided means for evaluation of the first available HRPPDs on a short time scale. However, it was clear from the very beginning that it cannot be considered as a final solution in the experiment, because of the necessity to manually solder dozens of thousands of pogo pins, as well as a substantial force (at least 50 g per pin) applied to the sensor rear surface, and concerns about reliability of the provided electrical contact.

A more advanced approach, making use of the commercial multi-pad compression interposers [3], was tried out in FY23. The HRPPD multi-layer ceramic anode base plate was re-designed in a way to provide non-trivial routing between the inner (vacuum) side and the outer (air) side, compressing the inner side pixel pitch of $\sim$3.3 mm to 4x4 fields of 8x8 pads, with a pitch of either 800 μm in a first iteration or 2 mm in the final EIC HRPPD design, and providing free space for brazing mechanical fixtures (screws) on the rear side of the sensor, see Fig. 1. In this approach either single- or double-sided compression interposers by Samtec can be sandwiched between the anode base plate and a readout backplane (see Fig. 11). The backplane itself is bolted to the sensor in a way such that (1) the force produced by the conductive springs gets locally compensated by a group of neighboring screws, and (2) the backplane can be replaced later if needed.

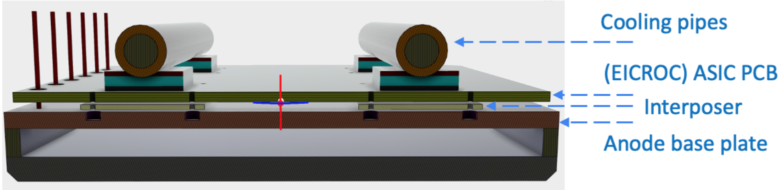

Figure 11: A cross-cut of an HRPPD assembly CAD model, with Samtec interposers and an ASIC PCB.

The respective R&D was conducted by BNL, Incom and a Polish LTCC manufacturer named Techtra. It started in early 2023 from producing a small 3" size prototype with various types of traces in a five layer stack, and under the assumption that in this iteration high density connectors can be either soldered or glued onto the rear side, see Fig. 12.

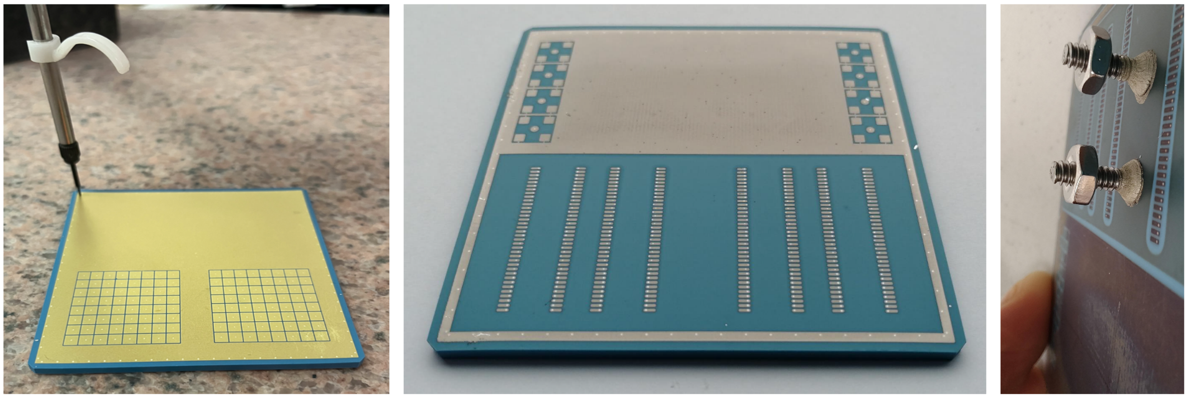

Figure 12: A first 3" LTCC prototype manufactured by Techtra. Left: examination of a pad side flatness on a granite plate. Center: connector side of the plate, providing MCX and MEC8 DV connectivity to a pair of 8x8 pad fields seen on the left picture. Right: a pair of screws brazed onto the connector side of the plate.

This prototype was proven to be vacuum tight, and mechanically flat within a few dozens of microns. Traces connecting 3.2 mm pads on one side and Samtec MEC8 DV connector pads on the other side were isolated from each other via extensive grounding inside the ceramic stack (a 50 Ohm co-planar waveguide configuration, similar to the one used by BNL in the capacitively coupled Gen II LAPPD readout boards). The traces did not exhibit any noticeable cross-talk to each other, as verified by Incom. There were no shorts observed either. A group of four 6 cm long traces with MCX connectivity, various widths and spacing to ground is seen in Fig. 12 (center) and was used to prove that: (1) the trace capacitance is less than 2 pF/cm, matching the design values, (2) there is no substantial signal degradation even for such long traces, and (3) there are no substantial reflections on the trace-to-connector boundaries.

A full size (120 mm) seven layer HRPPD anode base plate was then designed by BNL and built by Techtra in May 2023, see Fig. 1 (left). A uniform inner side pixellation with a pitch of 3.25 mm was reduced to sixteen groups of 64 pads with 800 μm pitch on the outer side. The prototype was proven to be flat within 100 μm across the whole surface, as well as vacuum tight. However, around 10% of traces were either shortened to ground or showed discontinuity between the inner and the outer sides of the stack. X-ray examination conducted by Techtra showed that this was caused by a mismatch between high density pad pattern on the outer side of the plate, the quality of the screen printing equipment used in the manufacturing process and the limitations of the LTCC technology, per se. Despite a partial failure of this iteration, Incom is planning to build a functional HRPPD prototype out of this full size anode plate, and verify its integration using a passive backplane produced by BNL, see Fig. 1 (right). As a result of this iteration, we increased the pad pitch on the outer side of the LTCC plates, from 800 μm to 2 mm in the design of the first five EIC HRPPD sensors. The production order was placed to Kyocera (Japan).

A.4 HRPPD #6 performance evaluation at Brookhaven

A preliminary evaluation of HRPPD #6 was conducted in May 2023 at BNL. The HRPPD was mounted in a pogo pin based enclosure, and examined in the same test stand used to evaluate the capacitively coupled Gen II LAPPDs in 2021-2022, see Fig. 13. A small 4x4 pad area was used, see Fig. 13 (right). Pads were connected to a single V1742 module via 6" MCX-to-MCX cables. A PiLas laser with a wavelength of 420 nm was used at full intensity. A focusing assembly with an ND 3.0 absorptive neutral density filter was used to suppress the laser light to a level where around 95% of events did not produce a visible signal (to imitate a single photon mode), and focus the laser light into a few hundred micron size spot. The bias voltage across the pair of MCPs was kept at 1850 V, to maintain a stable operation. Under these conditions the HRPPD produced pulses with an average amplitude of around 60 mV. The photocathode voltage was varied between 20 V and 160 V. The HRPPD exhibited a reasonably small degree of charge sharing between neighboring pixels, when the laser spot was moved across a chain of pads, see Fig. 14.

Single photon timing resolution was evaluated by centering the laser spot on one of the pixels, digitizing a PiLas laser synchro pulse on the same DRS4 chip as the HRPPD single pulse, and measuring time difference between the two. A custom DRS4 calibration was used. An upper limit on the timing resolution was estimated by fitting the leading edge of the signal across the time bins between 20% and 80% of the full amplitude, and taking the fit value at 50% amplitude, essentially implementing a constant fraction discriminator in software. Preliminary results are shown in Fig. 15. Instrumental effects (in particular the width of the laser pulse, which has an expected FWHM of ∼ 35 ps) were not unfolded.

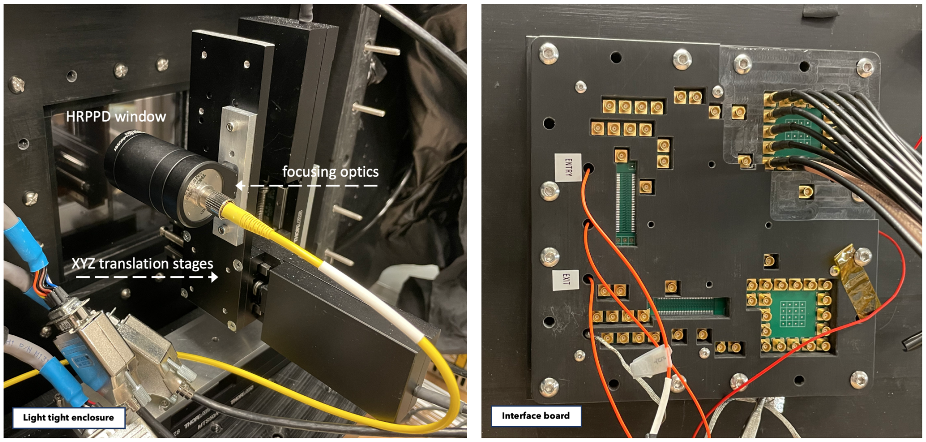

Figure 13: HRPPD test stand setup at BNL. Left: inner part of the light tight enclosure with XYZ-translation stages, focusing optics and the HRPPD window seen in the rear. Right: outer side of the enclosure, where a readout PCB, signal and HV connections are seen.

The core of the timing distribution shrinks to about 35 ps once the photocathode voltage is increased to 80 V. The tail structure, which is a convolution of the late signals produced by photo-electrons hitting first the interstitial space between the pores of the top MCP plate, and then bouncing back, and possible signal reflections in the electronics chain, requires further investigation.

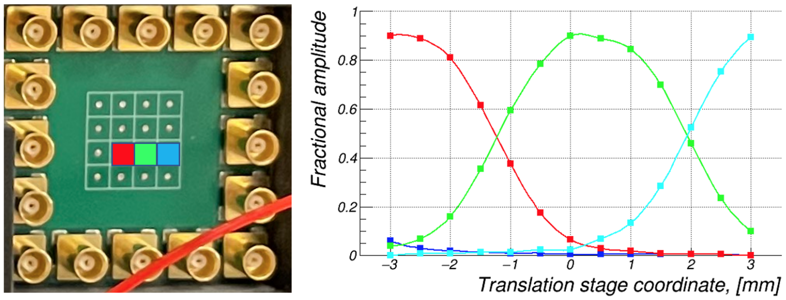

Figure 14: Left: a 4x4 pad area connected via MCX cables to the DRS4 electronics seen in Fig. 13 (right), with three consecutive pixels color coded the same way as in the right picture of this figure. Right: a fraction of charge deposited on the three pads (which are highlighted in the left picture) when the laser spot was moved across them in a horizontal direction.

A.5 LAPPD Workshop series

Realizing the need to stimulate world-wide interest and information exchange in LAPPD/HRPPD R&D, Deb Sankar Bhattacharya (INFN), Silvia Dalla Torre (INFN), Alexander Kiselev (BNL), Simona Malace (JLAB) and Junqi Xie (ANL) organized two more LAPPD workshops in FY23, one in October 2022

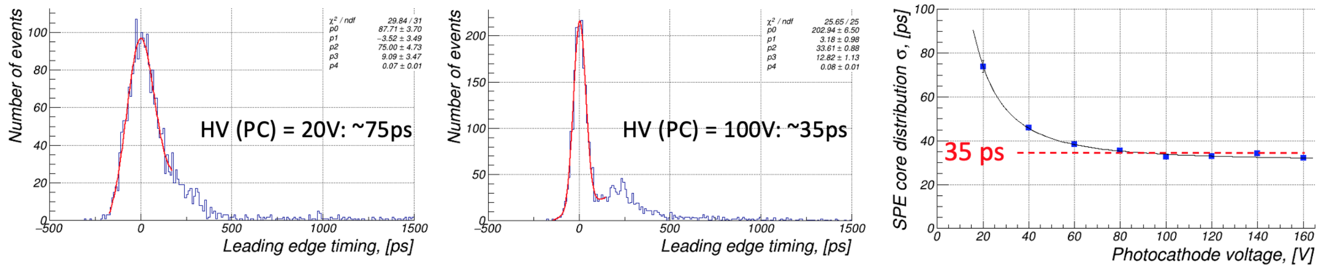

Figure 15: Timing resolution plots for HRPPD #6 in a single photon mode. Left: wide central core distribution at a low photocathode voltage. Center: the central core shrinks down to ∼35 ps at a high enough photocathode voltage. Right: the timing distribution core Gaussian width vs photocathode voltage.

and another one in April 2023. The workshops attracted quite some attention, and were attended by all leading groups participating in the LAPPD research.

A.6 Present status of FY23 milestones

Below the status is provided with respect to the timelines listed in the FY23 proposal as submitted to the EIC project management in October 2022.

- Mechanical and electrical interface to the HRPPD with a direct pixel readout: May 2023.
  - STATUS: a pogo pin based interface was implemented in late 2022 (see Section A.3.1) and used for HRPPD #6 characterization at Argonne and BNL in 2023, see Sections A.1 and A.4, respectively. A more advanced option based on Samtec compression interposers (see Section A.3.2) was developed in early 2023 and is now under test at Incom.
- Characterization of three different state-of-the-art LAPPD/HRPPD prototypes, in particular gain and QE uniformity: Sep 2023.
  - STATUS: in progress. Only one LAPPD and one HRPPD are being studied due to the limited availability of LAPPDs/HRPPDs from Incom.
- Gain and timing resolution characterization in magnetic fields of two different advanced LAPPD / HRPPD prototypes (10 μm vs 20 μm pore size, and angle dependence): April 2023. Report: Sep 2023.
  - STATUS: a first measurement campaign at Argonne with two different LAPPDs and one HRPPD was accomplished in February 2023, see Section A.1. The second campaign, using a state of the art LAPPD with individually biased 10 micron pore MCPs and a thin ceramic base plate is in preparation for September 2023 by INFN groups in Italy.
- Report on the simultaneous spatial and timing resolution optimization: Sep 2023.
  - STATUS: in progress. Preliminary results reported at various conferences, see Section A.7.

A.7 Presentations at workshops and conferences

- Deb Sankar Bhattacharya, INFN beam test of LAPPD at CERN PS: The setup, 2nd LAPPD Workshop, virtual format, October 26, 2022
- Silvia Dalla Torre, INFN beam test of LAPPD at CERN PS: Observed issues, 2nd LAPPD Workshop, virtual format, October 26, 2022

- Mikhail Osipenko, INFN beam test of LAPPD at CERN PS: First hints about the data, 2nd LAPPD Workshop, virtual format, October 26, 2022
- Junqi Xie, Magnetic field testing of LAPPD at Argonne National Laboratory, 2nd LAPPD Workshop, virtual format, October 26, 2022
- Alexander Kiselev, LAPPD R&D @ Brookhaven Lab status update, 2nd LAPPD Workshop, virtual format, October 26, 2022
- Sanghwa Park, ”Pixelated Capacitively Coupled LAPPDs as photosensors for Ring Imaging Cherenkov Detectors with a High-Resolution Timing Capability”, 2022 IEEE NSS MIC RTSD, November 9, 2022
- Alexander Kiselev, 2D Pixelated LAPPDs for Ring Imaging Cherenkov Detectors in High Energy and Nuclear Physics Experiments, CPAD 2022, Stony Brook (USA) November 29 - December 2, 2022
- Alexander Kiselev, HRPPDs for ePIC Cherenkov detectors, 3rd LAPPD Workshop, virtual format, April 20, 2023
- Mikhail Osipenko, CERN October 2022 LAPPD beam test results, 3rd LAPPD Workshop, virtual format, April 20, 2023
- Alexander Kiselev, 2D pixelated LAPPDs for RICH detectors with a high resolution timing capability, FAST 2023, La Biodola (Italy) May 28 - June 1, 2023
- Deb Sankar Bhattacharya, “High Rate Picosecond Photon Detector for EIC/ePIC”, First European Summer School on the Physics of the Electron-Ion Collider, Corigliano-Rossano (Italy), June 18-22, 2023

References

[1] https://incomusa.com/

[2] A. Lyashenko, ”Incom LAPPDs: status and plans”, LAPPD Workshop, April 20, 2023

[3] Samtec Z-Ray compression interposer design

[4] S. Extier, ”HGCROC: the front-end readout ASIC for the CMS High Granularity Calorimeter”

[5] A. Lehmann, ”Readout of PANDA MCP-PMTs”, EICROC ASIC evaluation for EIC HRPPD/MCP-PMT photosensors (zoom meeting), March 6, 2023

[6] V. Vagnoni, ”LAPPD R&D effort at INFN Bologna”, virtual LAPPD Workshop, March 21, 2022

[7] V. Chirayath, ”Pixel-based accelerated aging of Large Area Picosecond Photodetectors (LAPPDs) at UTA”, virtual LAPPD Workshop, October 26, 2022

[8] https://ftbf.fnal.gov/mtest-beam-areas

[9] Christophe de La Taille, ”EICROC ASIC: architecture, status, applications and plans”, EICROC ASIC evaluation for EIC HRPPD/MCP-PMT photosensors (zoom meeting), March 6, 2023

[10] J. Milnes, ”High timing accuracy from a microchannel plate PMT with 256 ASIC readout channels”, FAST 2023, La Bioloda, Italy, May 2023

[11] https://www.photonis.com/products/planacon