eRD110 - Photosensors for EIC Detectors

September 30, 2022 - Application for FY23

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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. The proposed R&D effort in FY22 is necessary 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 given 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 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.

1 Photek and Photonis MCP PMTs

The objective of the targeted R&D proposed for the Photonis and Photek MCP PMTs in FY22 was to mitigate technical and schedule risk associated with these sensors, based on our characterization studies performed during the EIC generic R&D program. That proposed R&D was not funded in FY22. Due to man power limitations in FY23, we do not request funding for a characterization campaign in this fiscal year.

We anticipate to put forward a proposal for R&D activities for FY24 to study (a) the cause of significant decrease in collection efficiency we observed in FY21 for Photonis Planacon xp85122-s-HiCE, (b) the gain of Photek MAPMT253 in a 16x16 geometry (as needed for EIC), and (c) cross talk and gain uniformity by means of a full illumination and a complete sensor readout of both Photek and Photonis MCP PMTs. These characterizations will mitigate the associated technical and scheduling risks. In this respect, the manufacturing of a custom readout board for these high-density channel MCP PMTs (using off-the-shelf electronics) done at NALU and Hawaii University within the eRD103 proposal is critical and must be supported.

2 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).

It is relevant to notice that the use of LAPPDs as photon sensors in the backward RICH at the ePIC EIC detector can provide both the detection of the Cherenkov photons produced in the aeregel radiator as well as fine resolution Time-of-Flight (ToF) information. In fact, in the ePIC detector, the backward RICH photon sensors are sitting in the detector acceptance and, therefore, crossed by the backward scattered particles. The detection of the Cherenkov light produced by these particles in the LAPPD quartz window is expected to provide a ToF information with $\sim$10 ps resolution.

2.1 Institution responsibilities

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 Inc. IN FY23, the effort is joined by the JLab and USC groups.

Magnetic field tolerance studies are performed by Argonne group (joined by JLab and USC in FY23) using g-2 calibration magnet equipment, and (starting in FY23) by INFN Trieste using CERN infrastructure.

Pixellation and position-resolution studies are primarily performed by BNL, accommodating the existing equipment and the readout board designs to the LAPPD / HRPPD tiles of different types (10cm and 20cm size, capacitively and directly coupled readout).

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).

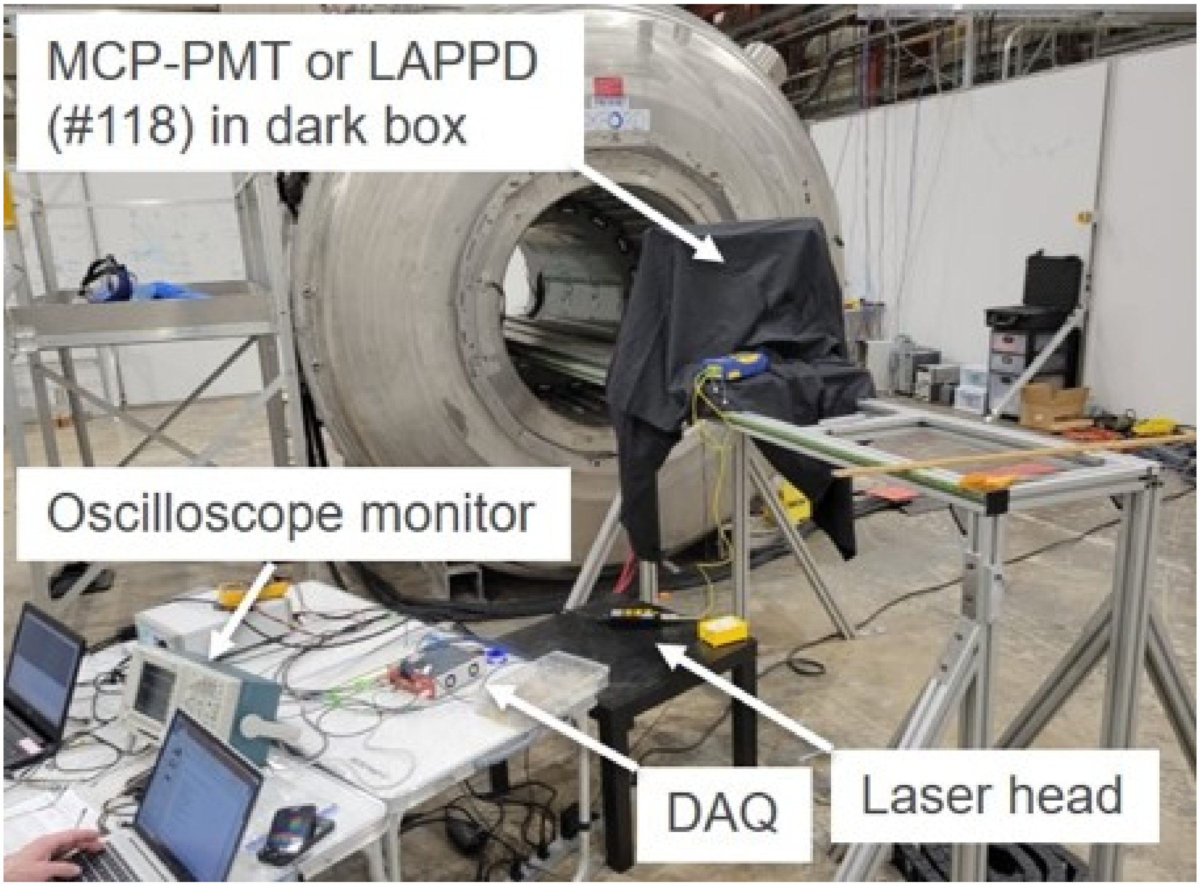

Figure 1: Experiment setup for magnetic field test at ANL.

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 supposed to join the beam tests at FNAL and / or at CERN, to evaluate the sensor behaviour under beam conditions.

2.2 Results of the R&D activity in FY22

FY22 funding for this R&D proposal was only confirmed in Spring 2022, which fact affected both the scope of the FY22 activities and the timelines.

2.2.1 Magnetic field tolerance studies

Magnetic field tolerance test was performed at Argonne National Laboratory with the g-2 magnet, as shown in Fig. 1. Photon sensor was placed in a dark box, movable on a trail into the magnet. Picosecond laser system was used as the photon source, and photons were transported to the photosensor surface with fiber optics. A digital variable attenuator was used to reduce the light intensity. Data were taken with CAEN DT5742b desktop digitizer. LAPPD 118 was used in the magnetic field test. It is a 20cm x 20cm device with 20 μm pore size MCPs and stripline readout. The results are shown in Fig. 2. During the test, the magnetic field orientation is perpendicular to the detector entrance window. The results show that LAPPD gain declined from over 2x10^7 to 7x10^5 as the field strength was increased from 0.02 T to 0.9 T. However, it was recovered at higher field strengths by increasing the MCP voltage. To be specific, at a field strength of 1.39 T, the LAPPD won't work at normal operation MCP voltages, but the

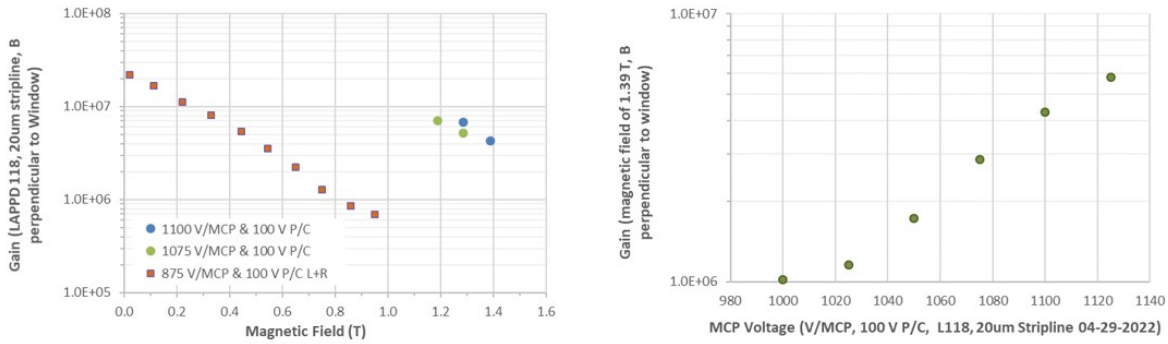

Figure 2: LAPPD 118 test results in magnetic field: (left) Gain decreased with increasing magnetic field; (right) Gain recovered with a higher MCP voltage.

gain could be recovered to 6x10^6 during our test by increasing the MCP voltages far beyond the nominal setting for a zero field.

2.2.2 Beam test at Fermilab in June 2022

Despite the late availability of FY22 funds, a test beam campaign was set up on a very short time scale by a joint BNL-ANL-MSU team and took place in June 2022 at Fermilab. A set of the new readout boards was designed and manufactured in time for this beam test, with a primary goal of simultaneously measuring a single photon spatial resolution and timing performance of a new Incom LAPPD, equipped with the reduced height 10 μm pore MCP stack. Similar to the 2021 design, the readout boards were featuring four 10x10 cm^2 quadrants with circular pad patterns (this time 320 4mm pads each), optimized for detection of $\sim$76 mm diameter Cherenkov rings produced by 120 GeV protons passing through the aspheric quartz lens radiator, see figure 3 left.

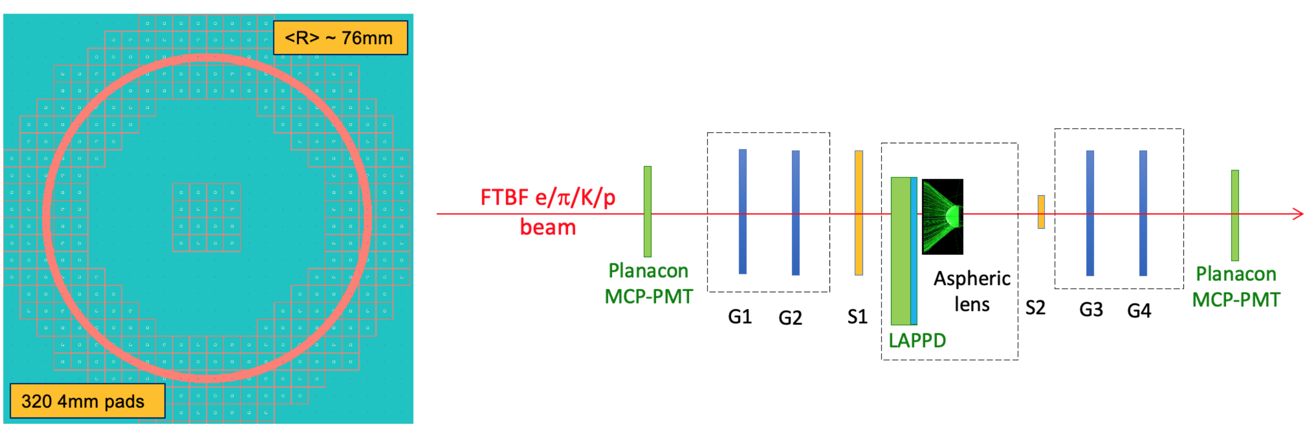

Figure 3: Left: one of the quadrants of the readout board designed for the Fermilab beam test in June 2022. Right: schematics of the beam test setup, shown in a configuration with the aspheric lens radiator (S1..S2 - scintillation counters, G1..G4 - GEM tracker stations).

The outcome of this beam test was hampered by late availability of the provided LAPPD tile 136, as well as a poor performance of the reference Planacon MCP-MPTs and difficulties with precise timing calibration of a complex 320-channel DRS4 readout system. In terms of the *spatial* resolution performance we were not able to improve the already sufficient for EIC application level demonstrated in the 2021 beam test campaign (see figure 4, $\sim$600 μm ring radius resolution).

Data analysis for both single- and multi-photon *timing* performance evaluation is still ongoing. In

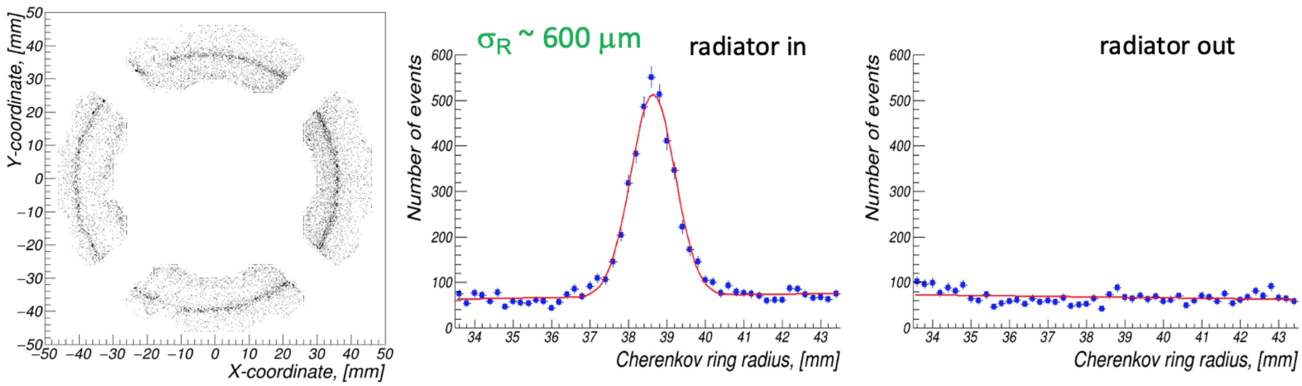

Figure 4: Cherenkov ring radius resolution in a configuration with a 120 GeV proton beam passing through a 14 mm thick aspheric lens radiator with effective focal length of 20 mm. Left: detected single photon cluster positions exhibit a sharp circular pattern with the expected diameter of ∼76 mm. Center: radial width of this circular pattern defines upper limit of the achievable spatial resolution (raw spectrum, none of the instrumental effects unfolded). Right: background spectrum, with the lens radiator taken out of the beam.

the absence of a reliable t_{start} reference we resorted to using relative photon-to-photon timing of the individual Cherenkov photons produced in the aspheric lens radiator (figure 5 left), and to using relative cluster-to-cluster timing of the two-particle events with the Cherenkov photon blobs produced in the 5mm thick LAPPD quartz window itself (figure 5 right), for a single photon and multi-photon timing evaluation, respectively.

2.2.3 Test stand installation at INFN

A complete test bench has been equipped at INFN, partially by existing equipment and partially by novel acquisitions. It includes a dark box equipped with the required through-going connections (HV, LV, analogic and logic signals, Optical fibers, Fig. 6); a novel digital scope (LeCroy oscilloscope WAVERUNNER 9254, 2.5 GHz); a PICOQUANT pulsed laser source, equipped with a new head providing visible light (405 nm); a digital pulser AGILENT 33220A; a complete read-out chain consisting of a 32-channel V1742 digitizer by CAEN based on the front-end ASIC DRS4; basic acquisition/reconstruction software for the read-out chain has been developed; a novel custom amplifier (∼x 10) developed preserving the time characteristics of the LAPPD signal. Concerning the initial LAPPD characterization studies at INFN, the dark count rate has been determined at different voltage/gain (Fig. 7), the LAPPD charge spectrum in response to single photoelectrons has been obtained extracting the gain value and its Polya-type functional behaviour (Fig. 8); the time resolution component related to the signal to noise ratio has been determined; each of the 1024 cells of each of the 32 channels of the V1742 digitizer have been calibrated, both for amplitude and time aspects, in preparation for the October 2022 test beam studies (Fig. 9). The layout for the test beam studies has been optimized with dedicated simulation studies (Fig.s 10 and 11).

2.2.4 Development of a DC-coupled HRPPD interface

As already mentioned earlier, DC-coupled HRPPD photosensors with an active area of ∼10x10 cm^2, predefined pixellation with a 3.2 mm pixel size and minimal charge sharing are of interest for high-occupancy applications, in particular for the ePIC detector barrel DIRC. A substantial effort was invested at BNL in July-September 2022 to design a multi-pattern readout board with spring-loaded pins, and a matching compact light-tight enclosure to perform the initial testing of these new types of Incom

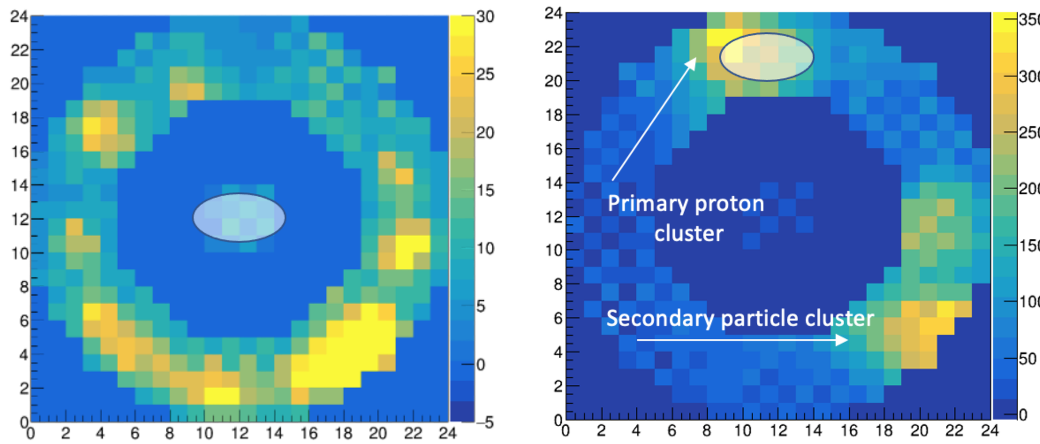

Figure 5: Typical single events as detected by LAPPD 136 equipped with a readout board shown in figure 3. Vertical scale is given in [mV]. Beam spot is indicated by a grey oval. Left: configuration with the aspheric lens radiator and beam passing through the center of the circular pad pattern. Several single photon clusters with amplitudes up to few dozens of mV are seen in the top half of the pad pattern. The bottom half is flooded by photons, indicating that the lens was hit by a beam proton close to its top left side. Right: configuration with the beam centered at the top side of the pad area itself, and LAPPD quartz window used as a radiator. A high energy hadron produces dozens of Cherenkov photons in a 5mm thick UV-grade quartz window, generating pulses of several hundred mV. A small fraction of events contains additional clusters generated by secondary particles originated in the upstream target (bottom right side of the pad pattern in this particular event). Relative timing resolution between such pairs of clusters in the same event can be used as a measure of a possible Time-of-Flight LAPPD performance in the EPIC detector electron-going endcap where secondary particles pass through the sensor window.

photosensors, see figure 12. One of the very first successfully sealed HRPPDs was rented for four months, and delivered to BNL end of September. After a certain delay, the readout boards were ordered and (together with a 3D-printed enclosure) are expected to become available beginning of November 2022.

2.2.5 LAPPD Workshop series

The team dedicated to LAPPD studies for EIC, has identified the need to stimulate world-wide synergies in the field in order to speed-up the progress in LAPPD/HRPPD R&D. A workshop in remote format has been organized by Deb Sankar Bhattacharya (INFN), Silvia Dalla Torre (INFN), Alexander Kiselev (BNL) and Junqi Xie (ANL). The workshop took place on March 21, 2022, and was very well attended (more than 80 participants). A second workshop is being organized now and will take place remotely on October 26, 2022.

2.2.6 Present status of FY22 milestones

The status is provided with respect to the timelines listed in the respective Statements of Work as submitted to the EIC project management in late Spring 2022.

- 20 μm pore Gen II LAPPD magnetic field tolerance measurements at Argonne - Summer 2022; STATUS: accomplished
- Various Gen II LAPPD readout boards designed and delivered to BNL - May-June 2022; STATUS: accomplished

Figure 6: The dark box used for the LAPPD studies at INFN.

- Test stand setup and commissioning at INFN - April 2022; STATUS: accomplished in June 2022
- Fermilab beam test with a new capacitively coupled 10 μm pore LAPPD - June 2022; STATUS: accomplished, data analysis in progress (report due in December 2022)
- Gen II LAPPD single photon position resolution report by BNL (bench tests and beam tests with finely pixelated readout boards) - September 2022; STATUS: to be completed, preliminary results reported at ICHEP in July 2022
- Single and multiple photon timing resolution bench tests report by INFN - September 2022; STATUS: test beam to accomplish this goal is taking place at CERN in October 2022; preparation to the test beam is completed
- Magnetic field tolerance report by Argonne - September 2022; STATUS: to be completed
- Preliminary assessment of the LAPPD / HRPPD feasibility for the EIC detector - by December 2022; STATUS: in preparation

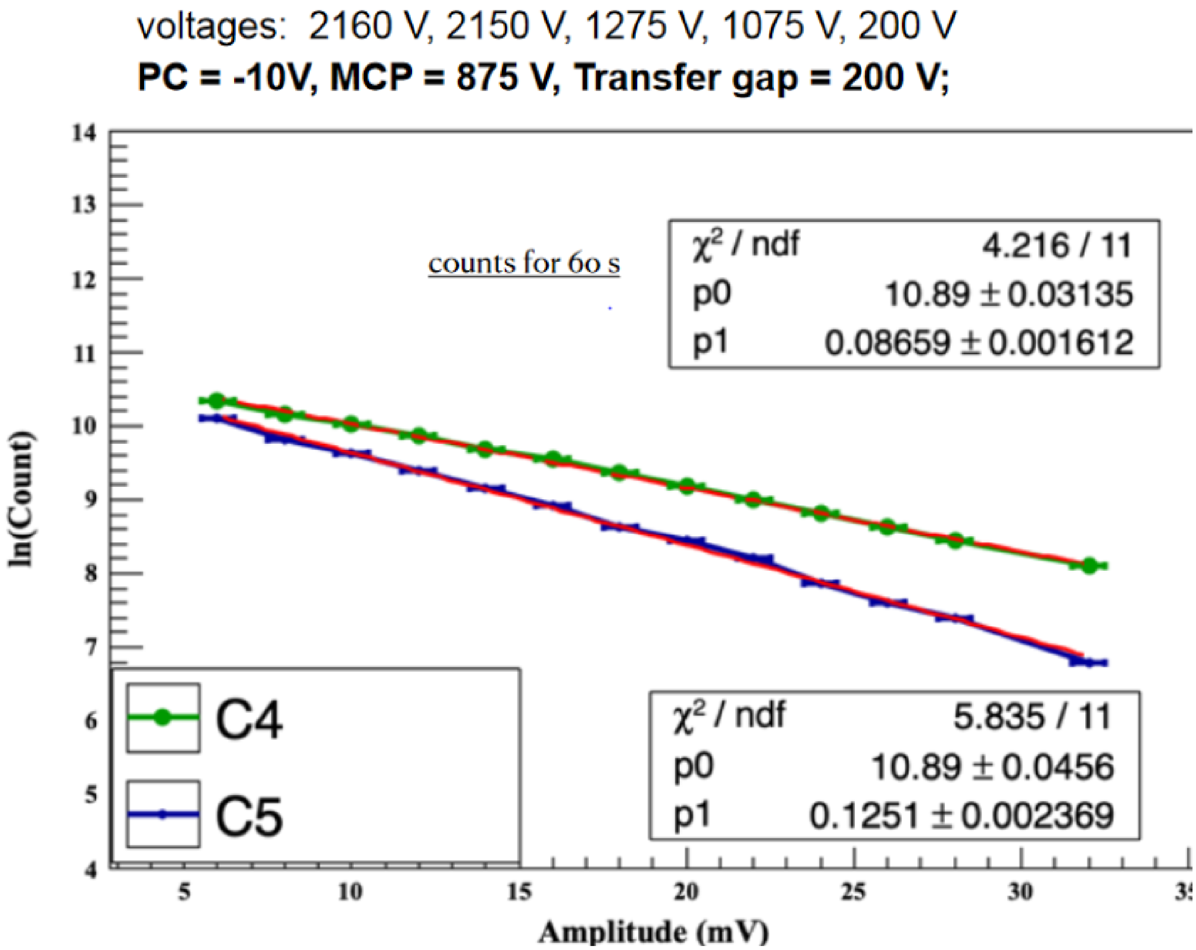

Figure 7: Example of dark rate measurements: rates versus threshold.

2.3 R&D plan for FY23

The work plan foresees activity in four different areas:

- Development of the mechanical and electrical interface to the HRPPD with a direct pixel readout
- Characterization of the more advanced LAPPD and HRPPD prototypes with a goal of obtaining a detailed understanding of the role of several key parameters affecting the sensor performance, such as: the MCP pore diameter, the thickness and material of the anode board (in resistive anode devices), spacing between the stack elements inside the detector, as well as a direct comparison of resistive-anode versus pixelized HRPPD
- Tests of LAPPDs and HRPPDs in a high magnetic field oriented at non-zero angles to the detector plane, specific to the particular anticipated locations of these sensors in the ePIC detector PID subsystems. B-field tests are independently planned at ANL and at CERN of different tiles with direct and capacitively-coupled readout and different pore size. The tests are complementary, given the need to determine and validate the B-field performance across tiles with various characteristics.
- Further LAPPD / HRPPD spatial and timing resolution studies for different pad sizes
- A joint effort with eRD101 to study in a test beam mRICH equipped with LAPPD is a considered option.

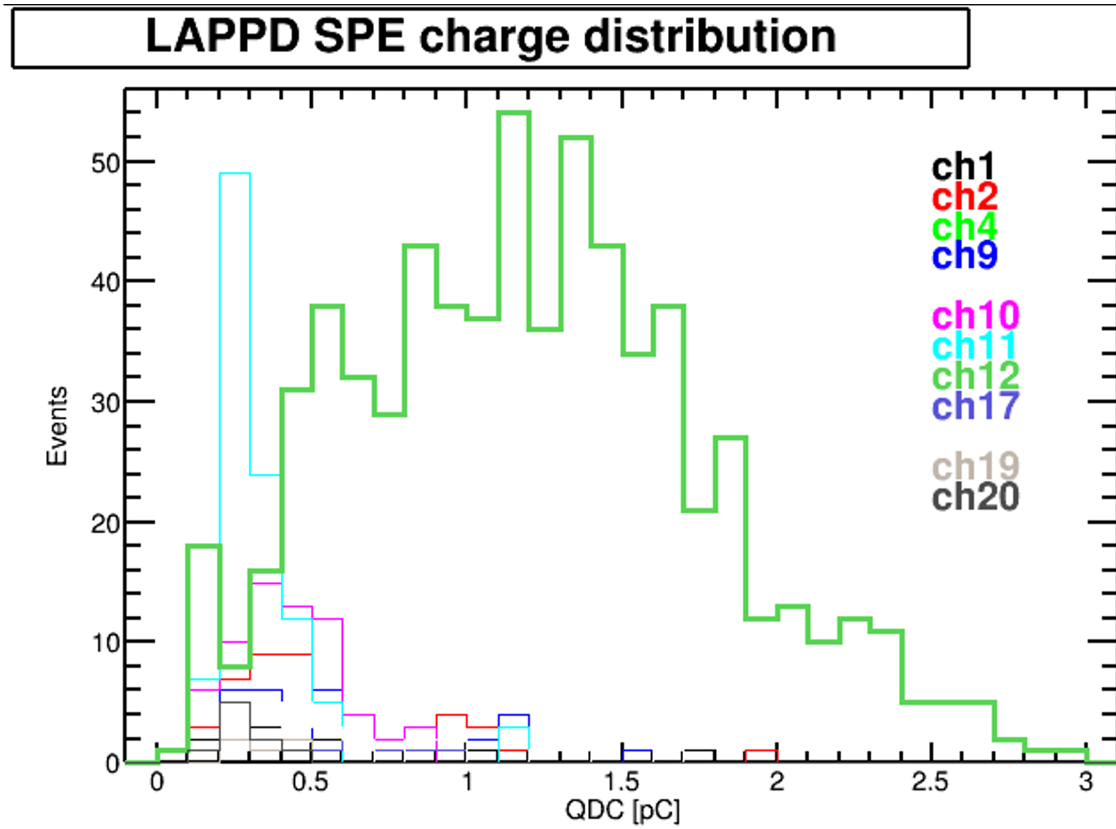

Figure 8: Charge distribution of single photoelectron signal at a mean gain of about 7×10^6.

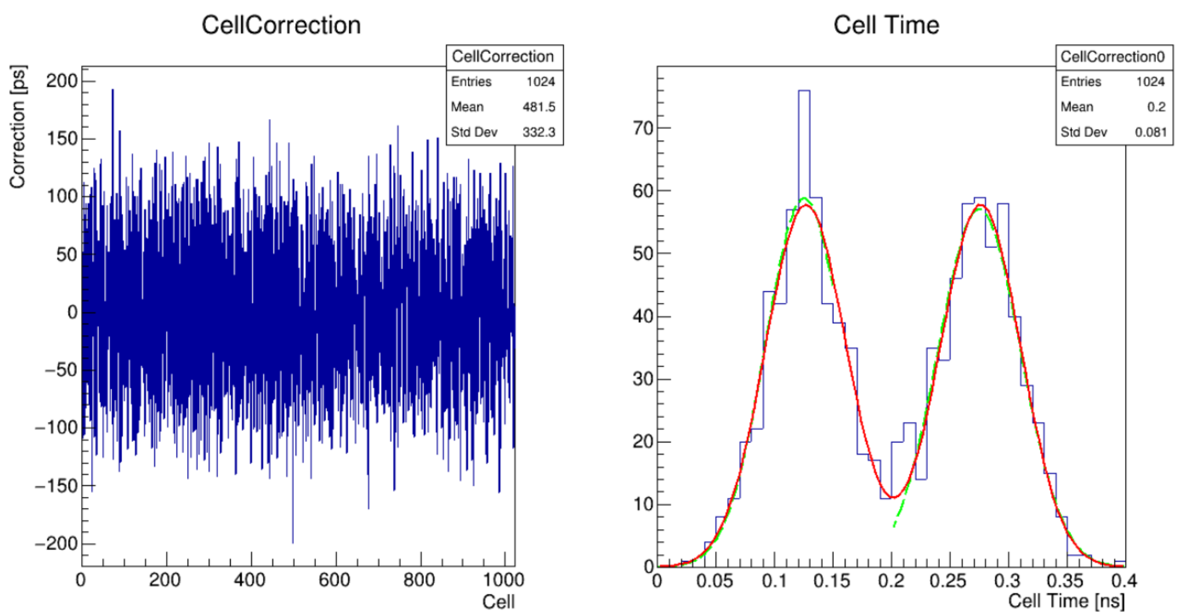

Figure 9: The time calibration of the 1024 cells of one of the 32 channels of the V1742 digitizer. Left: the fractional deviation of the cells from the central value versus the cell number. Right: the distribution of the time response of each cell.

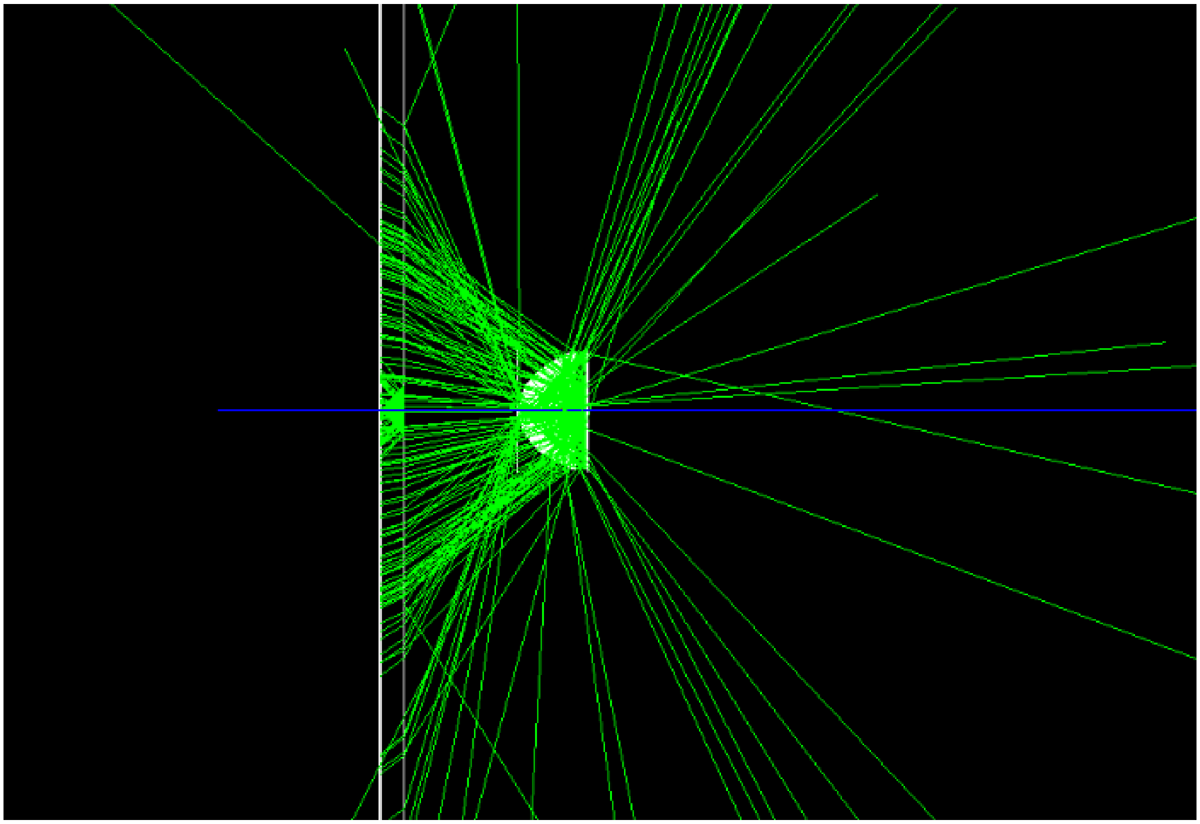

Figure 10: Monte Carlo study of the Cherenkov light generated in the lens-shaped quartz radiator, side view.

2.3.1 Proposed milestones for FY23

- Mechanical and electrical interface to the HRPPD with a direct pixel readout: May 2023.
- Characterization of three different advance LAPPD/HRPPD prototypes, Sep 2023.
- Gain and timing resolution characterization in magnetic field of two different advanced LAPPD/HRPPD prototypes(10 μm vs 20 μm pore size, angle dependence), April 2023. Report results, Sep 2023.
- Further space resolution studies, July 2023.

2.3.2 Complementary test stand equipment at Brookhaven Lab

BNL group is using substantial complementary sources of NIH and DOE funding, as well as the resources remaining from the former EIC Detector R&D program, to upgrade the existing test bench setup. A high-performance Tektronix scope (MSO66B 6-BW-8000, 8 GHz analog bandwidth) was acquired in September 2022. Six more V1742 modules were ordered and will become available by the end of 2022, for a total of 512 DRS4 channels. This set of electronics will be further equipped with the preamplifier boards using requested eRD110 funds. A femtosecond laser and the associated optical equipment will be acquired in the course of FY23.

2.3.3 Manpower required and available in FY23

ANL: staff scientist (Junqi Xie, 5% FTE support requested), engineering and technical support for the B-field test facility operation and maintenance is required (5% FTE requested); **BNL:** staff scientist

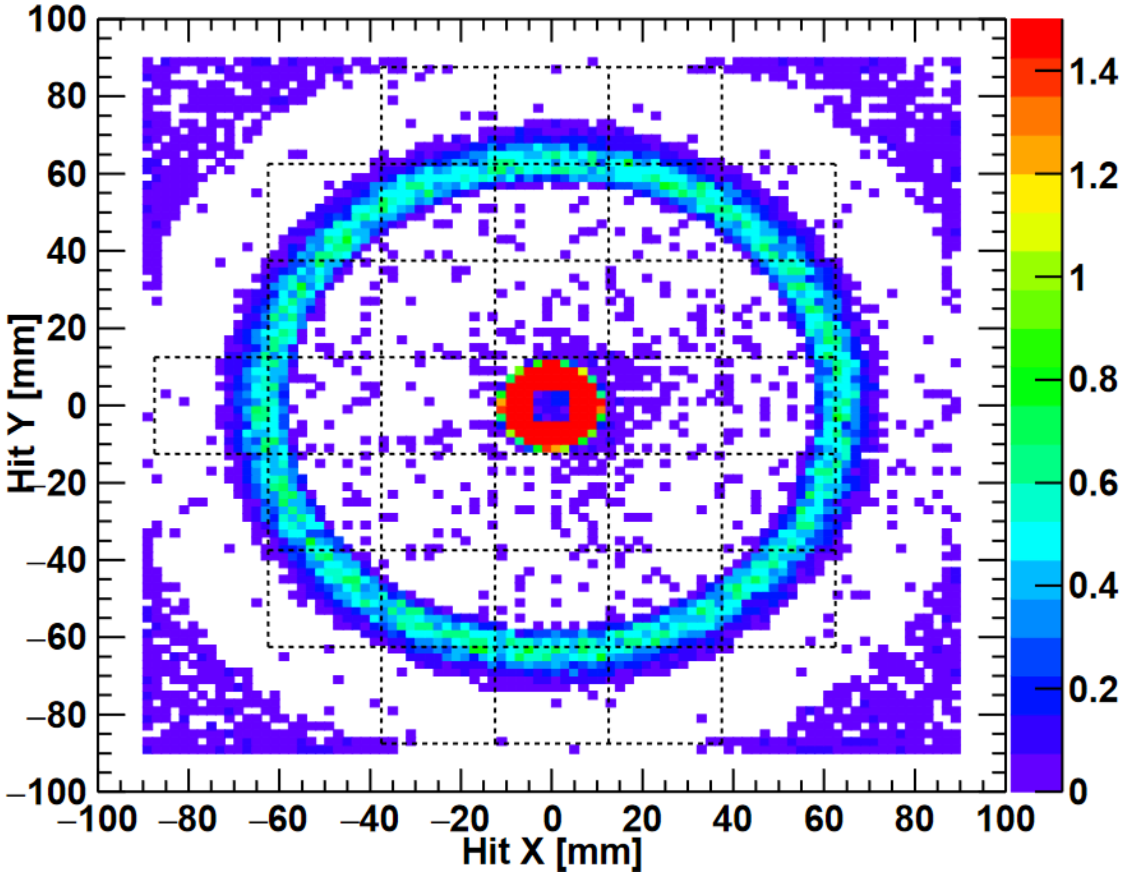

Figure 11: Image of the hits detected in the LAPPD by the Cherenkov light generated in the lens-shaped quartz radiator.

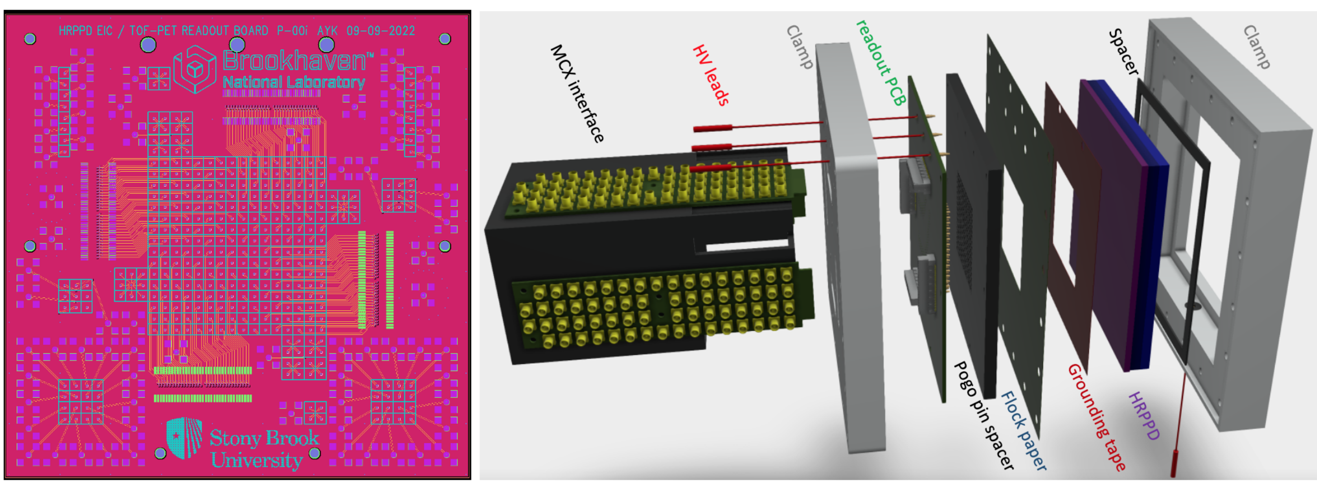

Figure 12: Left: a compact multi-pattern dual purpose readout board, to be used for both EIC-related HRPPD / LAPPD evaluation and in a joint SBU / BNL Time of Flight Positron Emission Tomography project. It will be instrumented by pogo pins and connectors in several different configurations. Right: an expanded view of the HRPPD enclosure, with a readout PCB shown in a configuration with a central 16x16 pixel field instrumented.

(Alexander Kiselev, 15% FTE, 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, available), staff scientist (Michail Osipenko, 30% FTE, available); staff electronics engineer (Saverio Minutoli, 10% FTE, available); **JLab:** staff scientist (Carl Zorn, 5% FTE, available), **MSU:** assistant professor (Sanghwa Park, 10% FTE, available), graduate student (0.5 FTE, 25% support requested), **USC:** faculty (Yordanka Ilieva, 5% FTE, available). We request $20k to complete the partially already available support for the second year contract of Deb Sankar Bhattacharya, whose first year contract ends in October 2022.

2.4 Preview of remaining R&D in FY24

The mechanical and electrical interface to the HRPPD with a direct readout may require further iterations using custom low force spring loaded LGA sockets. Beam test with either the mRICH (together with eRD101) or a simple proximity focusing RICH prototype equipped with a selected LAPPD photosensor type may not happen in FY23 and be postponed till FY24, pending the successful mRICH beam test validation with the MaPMT sensors in FY23. Newest Incom state of the art LAPPD / HRPPD models may require separate evaluation in FY24. A joint with eRD109 effort in building an integrated sensor+ASIC board assembly is foreseen in FY24.

3 SiPMs

3.1 SiPM for RICH applications

In recent years, significant progress has 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 (and for a 3x3 mm sensors it was recently achieved a SPTR of 62 ps (FWHM)).

The moderate radiation level foreseen (up to an expected maximum of 10^{11} 1-MeV$\mathrm{n_{eq}}$/cm^2 fluence at the dRICH location after several years of running at the top luminosity) could make their use possible despite the modest radiation tolerance.

Starting in 2021, INFN groups have initiated a robust R&D program rooted on existing results in literature that 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 initiated a collaboration with ALICE and contacts with LHCb for a synergistic 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 (2021) irradiation campaign were from FBK with designs optimized for better radiation tolerance or for Cherenkov applications (improved single photon resolution).

3.1.1 EIC R&D targeted program context and INFN program

This R&D program application is synergistic and complementary to two other supported eRD programs (eRD102 for the dRICH and eRD109 for the ASIC). Seminal work on streaming readout concepts is also carried out by INFN groups in the context of eRD105 (calorimeters readout) and we expect to move then that know-how to the dRICH throughput challenge. Applications for funds were shared among the projects consistingly their respective main focus. In particular, INFN Torino is no longer part of eRD110 being now responsible in eRD109 for the ALCOR R&D program. Instead, INFN and University of Cosenza (S. Fazio and M. Capua) is joining since 2023 this R&D program.

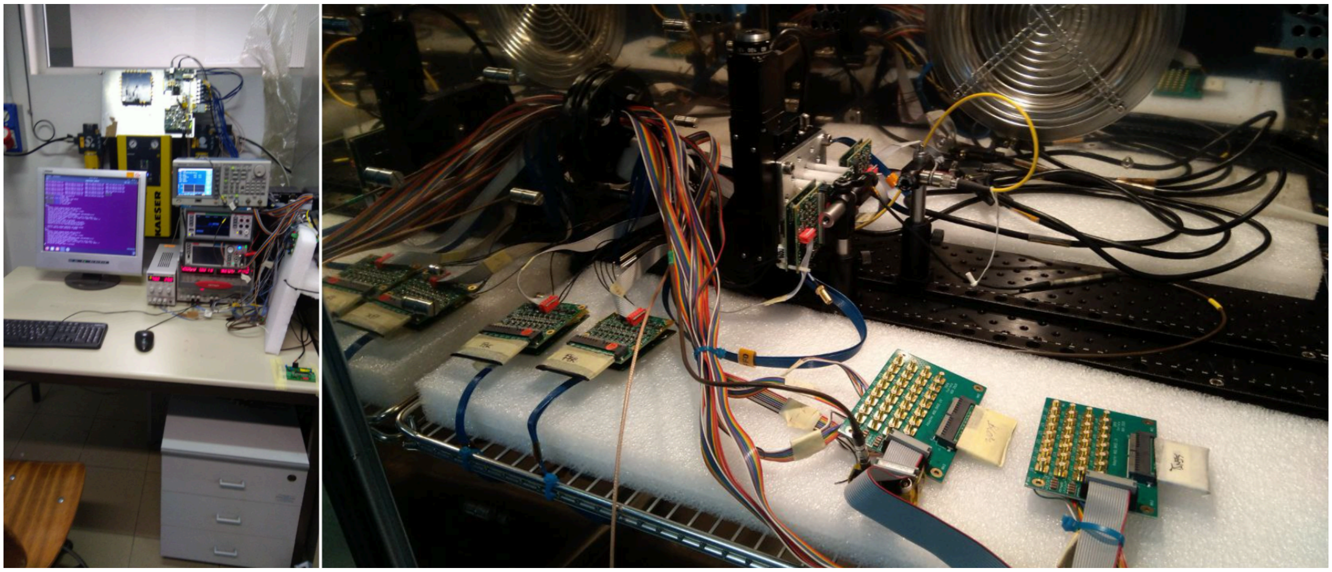

Figure 13: Control, HV and readout electronics (left) and SiPM sensor cards in the climatic chamber (right) in the SiPM Bologna characterization setup. The motor stage with the LED is also visible.

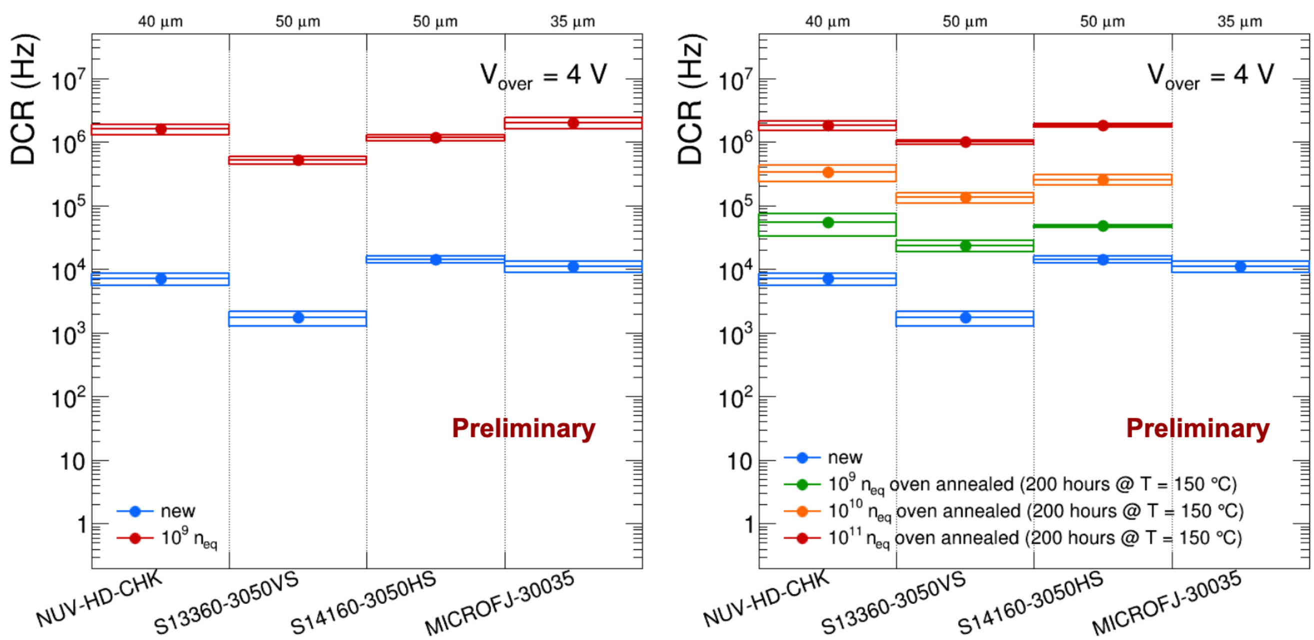

Figure 14: DCR values measured on sensors from Hamamatsu, FBK and OnSemi after irradiation (left) , amd recovery after annealing in oven.

3.1.2 Achieved results in 2021 and 2022 (as of September 2022)

The increase of DCR was characterized for the different sensors under study as well as the obtainable recovery after annealing cycles of 150-200 hours in oven at 150 °C. Results were presented at several international conferences including NDIP, ICHEP and RICH in Summer 2022 and at the AGS RHIC User Group meeting in June 2022 (see Appendix B).

During the first semester 2022, a full-fledged characterization setup for the SiPM was developed in Bologna, allowing automatisation for the measurement of multiple sensors (up to 64) in the climatic chamber of I-V, DCR and relative PDE (using a LED and a motor stage). The readout is made via the

ALCOR chip (INFN TO), with the bias distribution system provided by INFN FE and readout via FPGA from INFN BO. (see FY22 milestone: *automated setup for SiPM characterization in climatic chamber (9/2022))*. The full setup is pictured in Fig. 13.

Within the context of the collaboration with FBK two types of sensors from the "Low Field" development branched from the DarkSide application in the FBK NUV-HD technology have been tested, one being optimised for fast-timing and one optimised for radiation-tolerant calorimetry. Figure 14 reports the measured DCR values on the different sensors when new, after irradiation (using a proton beam with E=140 MeV) and after annealing in oven.

The 2022 campaign, aims to test the reproducibility of repeated irradiation - annealing cycles on the same sensors at increasing radiation load. First irradiations took place at Trento on 4^{th} June and 16^{th} July, with two other irradiation sessions scheduled by the end of the year (November and December) according to the timeline agreed in the Statement of Work (see FY22 milestones: *Comparative assessment of commercial (and prototypes not yet available on the market) of SiPM performance after irradiation (2/2023) (interim results available at 9/2022)* and *Definition of an annealing protocol (2/2023)*).

Very preliminary although promising results were also obtained testing a potential in-situ annealing procedure, applying forward bias voltage to the SiPM heating them via Joule effect. In Fig. 15(left) it is visible the annealing procedure (controlled by a thermal camera) performed over a period of 30 minutes after a fluence of $2 \cdot 10^8$ 1-MeVn_{eq}/cm^2 . The cycle (irradiation and annealing) was repeated five times. The recovered DCR is compared on right panel with the one after the annealing procedure in oven (200 hours) and a equal total fluence ($1 \cdot 10^9$ 1-MeVn_{eq}/cm^2).

All together the results have already made possible to parameterize a rough annealing protocol (duration, temperature and frequency) based on measured data on specific sensors. This now needs to be optimized and demonstrated to a larger scale.

The links to the presentations at the above mentioned conferences, this brief summary and the presentation we will deliver at 19th October meeting constitutes our interim report as per agreed accountability

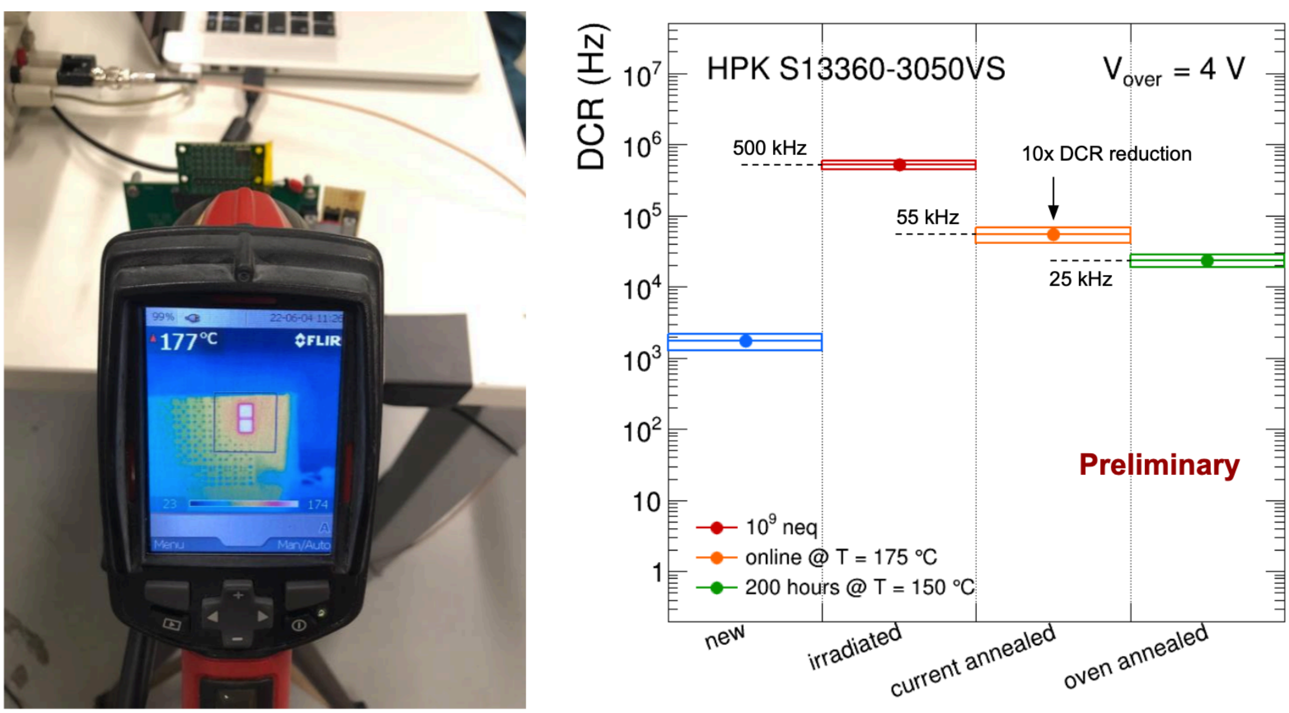

Figure 15: Annealing "in-situ" using reverse bias and Joule effect (left), and comparison of results of the two annealing methods (right).

plan in the Statement of Work.

3.1.3 R&D plan for FY23

INFN is supporting the program since 2021 and the requests made under eRD110 complements and critically integrate the ones funded by INFN. For example the sensors acquired and the electronics produced so far are sufficient only until irradiations foreseen in 2022. The continuation of the activity with the goals discussed in the following requires acquiring new SiPM sensors for irradiation campaigns and corresponding boards, that will be then distributed also to new INFN units involved. These costs will be covered by INFN. We ask support here only for a part of the material needed by the new Cosenza SiPM center, to cover the cost of a Xilinx FPGA Evaluation Board (VC707), to provide the ALCOR readout in that lab **7.5 k$**].

The key research items that will be pursued in 2023 are:

- studies of **recovery from radiation damage** have so far been performed heating up irradiated sensors at high-temperature by means of an industrial oven for long (days) thermal annealing cycles. It is now necessary to explore alternative recovery solutions which can allow one to partially recover the sensors in shorter time-scales and without intervention on the detector. Preliminary studies performed in 2022 show that heating the sensors with direct current exploiting the Joule effect is an effective way to achieve significant recovery factors (10x) in short time-scales (30 minutes). This approach needs to be followed up in a systematic way with a structured R&D program where different heating strategies with direct current and Joule effect are tested (direct forward bias, inverse bias in dark, inverse bias with light, ...) in irradiated sensors.

- studies of radiation damage in irradiated SiPM have been performed so far only with proton beams. The literature shows that at very high doses (much higher than the ones expected at EIC) the damage caused by **neutrons** might be topologically different from the damage caused by protons. Studies at radiation levels expected at the EIC must be performed also with **neutron sources**. It is necessary to establish whether the degree of damage and recovery from annealing observed in the proton irradiation campaigns performed so far is in line with the damage and recovery of the damage induced by neutrons. It is in any case important that data from both types of sources of radiation damage is collected to provide the necessary input to future simulations in support of the work in preparation of the pre-TDR. In the year 2023 more irradiation campaigns with protons will be performed to consolidate the acquired knowledge on SiPM damage and recovery at EIC levels and to support the exploration of alternative annealing recovery strategies and operation cooling modes. A first irradiation campaign with neutrons will be performed to collect also neutron-damage-related data. For the studies discussed in this item and in previous item, the sensors and electronics costs, as well as the travel expenses (to Trento and Pavia) will be covered by INFN. We ask support for the irradiation time cost [**14 k$**] at Centro di Protonterapia in Trento and at LENA in Pavia.

- the excellent SiPM **time resolution for single-photon tagging** is a major ally to counter the high dark count rate of the devices, which degrades with increasing radiation damage. The SiPM-ALCOR readout system is expected to provide photon tagging with very good time resolution (¡ 200 ps RMS), nonetheless there was no capacity within the groups involved in this R&D to perform studies on this topic so far. It is crucial to advance the studies with a preliminary measurement of the time resolution of the system and provide guidance for simulations of the performance. A specialised measurement setup has to be equipped with a low-photon yield high-precision light source (i.e. a picosecond / femto laser and ancillary lab material) and studies to be carried out on sensors before irradiation, after irradiation and after annealing. For this critical study, we ask support in eRD110 for the laser and related laboratory costs [**20 k$**].

- SiPM are operated at **low temperature** to reduce their intrinsic DCR, which reduces by about a factor of 2 every 10 °C of temperature decrease. Studies have been so far performed using climatic chambers where low temperature is achieved in a controlled way. The SiPM readout of the dRICH prototype employs ThermoElectrics Coolers (TEC, Peltier cells) to achieve sub zero (down to -30 °C) operation temperatures, which are an effective but inefficient way to achieve the goal in the experiment. In the year 2023 it will be studied if the use of TEC can provide the same performance as the one measured within the controlled environment provided by the climatic chamber. A direct comparison of the IV characteristics of SiPM and DCR curves measured at -30 °C in the climatic chamber and in an experimental-like environment with TEC will be performed. It is important to stress that while TEC can be an effective way to achieve very low temperatures, it is not clear it is a viable and efficient way in terms of electric power in the experiment. Alternative solutions will be explored like the use of a cooling system with liquid coolant circulating at very low temperature (down to -40 °C) on top of a moderate use of a TEC component. We will report about these studies but we don't ask financial support for them.

- Recent discussions with FBK together with our findings on commercial sensors with different breakdown voltage values paved the way for explorative joint R&D within the INFN-FBK collaboration agreement framework ("convenzione") to develop EIC-application specific sensors. Different values of electric field in the gain region as well as its thickness can studied to eventually obtain the optimal DCR for new sensors and sensors after radiation damage. Furthermore, an aspect that has a large impact on both the DCR of the sensor and of its radiation tolerance is the size of the avalanche multiplication region (both in transverse and longitudinal dimension). While the longitudinal dimension can be optimised with different values of doping profiles and corresponding applied field without significantly affecting the detection efficiency (PDE), the size of the transverse dimension (normally matching the SiPM entrance window area) has direct implications on both the PDE and the DCR, being both directly proportional to the transverse dimension. A significant advance in the SiPM technology might come from devices designed such that a small transverse active area is complemented with a focusing medium that directs onto it the photons impinging on a larger surface. This would effectively give a large acceptance over a small active area, which in turns maintains the PDE approximately constant while effectively reducing the DCR by the ratio of the two areas. Different light concentration approaches can be studied (applying microlenses or nanopothonics material - "metalens" - to the SiPM with focusing capacity). Such approach could be tested in the proposed FBK joint engineering run together with the studies on different field levels. Within the same R&D program we also plan to design monolithic SiPM sensor arrays which will allow the sensor active surface to cover as much silicon as possible while at the same time retain functionality features to efficiently wire-bond the sensors onto PCBs. The large part of costs of this promising and exploratory work will be covered by INFN and FBK. We ask financial support to cover partially that cost **[20 k$]** related to the light concentration process.

3.1.4 Manpower required and available for FY23

The INFN units involved (BO-FE-CS) could count on 4 researchers and several technicians but dedicated personnel can only be co-funded at this stage of the project. Staff scientists: Pietro Antonioli ((10% FTE, available), Marco Contalbrigo (10% FTE, available), Roberto Preghenella (10% FTE, available). Faculty staff: Marcella Capua (10% FTE, available) and Salvatore Fazio (10% FTE, available). In the proposed budget we request as co-funding support [**40 k$**] for two two-year postdoc positions (25% co-fund support, equivalent of a total of 1.0 FTE integrated over two years). Minimum two-year long post-docs contracts are now mandatory by Italian law, with a total cost of approximately 80 k€. We expect to use these funds to be able to open one post-doc position in Bologna and one in Cosenza. The extent of the R&D program critically requires such positions at this juncture.

3.1.5 Other financial requests

The SiPM program benefits from significant INFN in-kind contribution in infrastructures, access to irradiation TIFPA facility (TN, Italy), laboratory equipment (including for cooling), funding for sensors and electronic cards used in the irradiation program, exploratory runs with FBK, etc. As described above, eRD funds are specifically requested for the time resolution measurements equipments, the concentration light process (microlensing) cost for the explorative run with FBK and a FPGA evaluation board to provide readout to the sensors under test.

3.1.6 Milestones for FY23

1. Timing measurement of irradiated (and annealed) sensors [6/23]
2. Comparison of the results achieved with proton and neutron irradiation sources [8/23]
3. Study of annealing in-situ technique with a proposed model selected as baseline for the pre-TDR [9/23]

The deadlines indicated are made in the understanding a decision on funding will be communicated by eRD management for FY23 by 1^{st} November 2022. Delayed decisions will impact on the deadlines. We note their achievement is critical to inform pre-TDR documentation.

3.1.7 Preview after FY23

In FY24 we will continue the optimization of the choice of sensors towards an EIC application as well as the design of the electronics tailored to the chosen sensor. This work is aimed to the finalization of the dRICH design in preparation of TDR and CD-3. In particular we will integrate the last version of the ALCOR in the readout. If fundamental improvements in radiation hardness of the SiPM given modification of the architecture arising from the joint engineering run with FBK will be achieved in time - they will be factorized already in the final design to be presented at the beginning of 2025.

On top of studying the effect of radiation damage caused by hadronic sources we believe it would be wise to foresee already an irradiation campaign with high-energy photon sources (gamma). Literature is not clear about the effect on SiPM of high energy photon radiation, with reports on increase of the leakage current and possible decrease of detection efficiency. It is therefore important to carry out a study with the expected gamma fluxes at the EIC as an initial baseline.

3.2 SiPM for calorimetry applications

In FY23 a complementary effort, targeted at the SiPM application to EIC calorimetry, will be pursued as well. At present, different ePIC groups are using HPK sensors for different calorimeter prototypes. HPK sensors were extensively studied for calorimetry applications during the generic EIC R&D program. HPK sensors were successfully used for two new large calorimetry systems at RHIC (STAR forward calorimeter system in operation since 2022 and sPHENIX barrel ECal starting operation in 2023). As such, HPK sensors will continue to be a baseline sensors for all calorimeter systems of ePIC detector. One drawback of HPK sensors is the lack of SiPMs with large surface area (6 mm x 6 mm) and small pixel size (15 mkm). NDL (Novel Device Laboratory) has been developing a unique SiPM technology (EQR-SiPM) that employs the resistor under each APD cell in the epitaxial layer as the quenching resistor. EQR-SiPM provides large dynamic range (15 mkm pixels size) while retaining high fill factor and high photon detection efficiency (PDE) at 45%. That makes them very attractive for readout of homogenious calorimeters and some areas of forward ECal. Four 6mm x 6mm NDL sensors can potentially replace sixteen 3mm x 3mm HPK sensors needed to readout a single PWO crystal or ScGlass block. For forward ECal, in the region of high rapidity, HPK large area SiPMs do not provide the required dynamic range due to a large pixel size (50 mkm). NDL sensors need to be tested before and after irradiation and compared with the corresponding HPK sensors to understand if they can be used for ePIC calorimetric applications. It is important to measure changes in SiPM characteristics such as noise, gain, PDE as a function of over-voltage. It is also important to understand what is the variation of these changes from one sensor to another. These tests will allow to estimate S/N and the magnitude of degradation of energy resolution with exposure for different types of ePIC calorimeters where NDL sensors may be used. A similar program was carried out by the UCLA group for HPK sensors during the generic EIC R&D program. Members of the UC EIC consortium (UCLA + UCR) who will be leading SiPM testing for forward ECal, are proposing to test a batch of these sensors along with HPK sensors in FY23 to draw a conclusion if they can be used for ePIC calorimeters. This R&D efforts will help to train new UCLA and UCR students and postdocs who will participate in future construction of forward ECal.The budget request for this effort is $10k.

4 Suggested funding for FY23

Core costs only indicated. Institutional overhead is not included.

	ANL	INFN GE/TS	INFN BO/FE/CS	MSU	BNL	JLab	UC EIC	USC
Laser for timing measurement			\$20,000					
Irradiation costs			\$14,000					
SiPM engineering run support			\$20,000					
FPGA eval board for SiPM Readout			\$7,500					
B-field facility maintenance, Helium consumption	\$10,000							
Staff effort support	\$18,000							
Engineering/technical support	\$15,000				\$5,000			
LAPPD, consumables for mag. field studies		\$3,000						
SiPMs							\$5,000	
Postdocs and students		\$20,000	\$40,000				\$5,000	
Travel		\$10,000			\$15,000			\$4,000
LAPPD/HRPPD rentals					\$24,000			
HRPPD interface					\$5,000			
PHOTONIS FT-8 reference MCP-PMT					\$12,000			
LAPPD readout boards and preamp interface					\$5,000			
LAPPD test stand equipment					\$3,000			
TOTAL	\$43,000	\$33,000	\$92,500		\$69,000		10,000	4,000

Supplemental Material

A Generic Photosensor Requirements and Photosensor Specifications

Parameter	hpDIRC	mRICH	dRICH
Gain	$\sim 10^6$	$\sim 10^6$	$\sim 10^6$
Timing Resolution (FWHM)	≤ 100 ps	≤ 800 ps	≤ 200 ps
Pixel Size	2 – 3 mm	≤ 3 mm	≤ 3 mm
Dark Noise	≤ 1 kHz/cm^2	≤ 1 MHz/cm^2	≤ 1 MHz/cm$*2$
Radiation Level	Yes	Yes	Yes
Single-photon mode operation?	Yes	Yes	Yes
Magnetic-field immunity?	Yes (~ 1 T)	Yes (1.5 T)	
Photon Detection Efficiency	$\geq 20\%$	$\geq 20\%$	$\geq 20\%$

Table 1: List of overall performance requirements on the photosensors of EIC Cherenkov detectors. In collaboration with the detector groups, these parameters are beingupdated for each PID detector. An example is the requirement on the magnetic-field tolerance, which has become more precise as the project detector design progressed and the sensor locations, together with a more accurate field map have become available. 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	Photek	SiPM	LAPPD
Area	5×5cm^2	5×5cm^2		20×20cm^2
Pixel	3×3mm available	3×3mm available	3×3mm available	25×25 mm available; 3×3 mm prototypes exist, need further tests
Magnetic Field	Yes	Yes	Yes	0.7 T, needs 10μm MCPs for > 1.5 T
Radiation	Yes	expect good	Needs test	expect good
Availability	In-stock	In-stock	In-stock	In-stock for 20 μm, in 2022 for 10 μm
Price	\$15-20k each, significantly cheaper in large unit	\$15-20k each, reduced cost for large orders	\$1/mm^2?	\$50k each in 2019, \$25k each in 2023 (Incom)
Unit Price	\$17k/25cm^2	\$17k/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	cost, new production	Radiation hardness	Cross talk, integration, availability
Risk	No 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 our characterization effort progresses, such table will be created for each detector and for all considered sensors for that detector. Also, newly available sensors, such as the Photek MAPMT253 and HRPPD are being added and their risks assessed.

B SiPM Supplemental Material

List of communication given at international meetings and conferences on the results arising from funded R&D under eRD101 project reporting results on SiPM studies.

- P. Antonioli,2022 RHIC/AGS Annual Users' Meeting, From RHIC to EIC At the QCD Frontiers, (online), 7-10 June 2022
- L. Rignanese,41st International Conference on High Energy Physics (ICHEP 2022), Bologna (Italy), 6-13 July, 2022.
- R. Preghenella,9th conference on new developments in Photodetection, Troyes (France), 04-08 July 2022
- R. Preghenella,11th International Workshop on Ring Imaging Cherenkov Detectors, Edinburgh (UK), 12-16 September 2022