HRPPD Inspection and Test Plan

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Abstract

This document describes the Quality Assurance (QA) plan for the high-rate picosecond photodetectors (HRPPDs) which are the baseline photosensors for the pfRICH and hpDIRC particle identification subsystems of the ePIC detector. A three-phase inspection procedure is defined and sensor characteristics to be evaluated are listed. These include gain, quantum efficiency, dark count rate, timing resolution, afterpulsing rate, photon detection efficiency, and collective oscillations. The experimental methods for quantifying these characteristics and necessary equipment are also documented.

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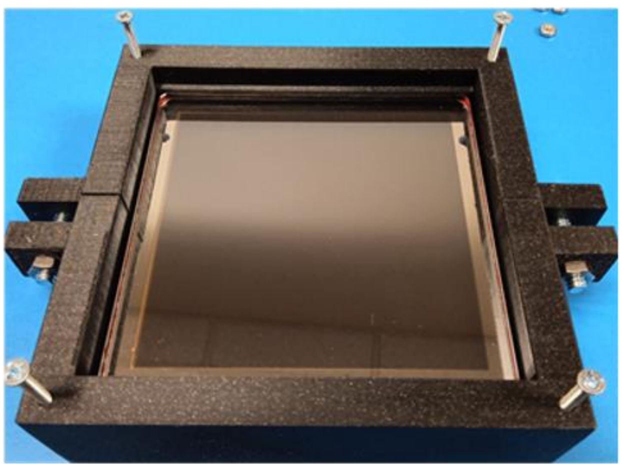
1. HRPPD PROPERTIES

The High-Rate Picosecond Photodetectors (HRPPDs), with a full size of 120 mm x 120 mm and an active photocathode area of 104 mm x 104 mm, are a critical component for the proximity focusing ring-imaging Cherenkov (pfRICH) and high-performance detection of internally reflected Cherenkov light (hpDIRC) particle identification (PID) subsystems in the ePIC detector. On the vacuum side, the anode plate is segmented into a 32x32 pad array with a 3.25 mm pitch. On the air (readout) side, the anode plate is segmented into 4x4 pad groups, each of which is subdivided into 8x8 pads, resulting in a total of 1024 independent readout channels (see Fig 1).

Due to this fine segmentation and large active area, precise characterization and long-term stability studies on a number of properties are required to ensure reliable performance in high luminosity environments such as the Electron-Ion Collider (EIC). A comprehensive Quality Assurance (QA) and Test Plan is therefore essential to validate the HRPPD modules before their integration into the ePIC detector.



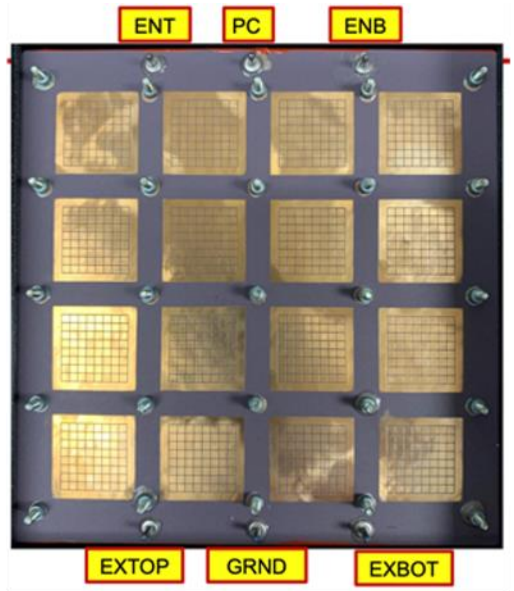


Figure 1. (Left) HRPPD in shipping holder with the photocathode window (internal side) visible. (Right) HRPPD anode plate (readout side) with channel segmentation and HV connectors visible.

The following are the key properties that will be evaluated by these tests and inspections:

- **Physical Characteristics:** This category covers a number of properties including the physical layout of the anode pads, the physical integrity of the unit after shipping, the ability to hold high voltage, and the presence of an output signal on each channel.
- **Gain Uniformity and Rate Dependence:** Gain uniformity describes the consistency of electron multiplication across all 1024 channels of the HRPPD. Variations in gain can distort photon counting efficiency and thus impact reconstruction, so systematic QA and mapping are essential. The gain on a particular channel can depend on the rate of incident photons as each pore in the MCP takes a finite amount of time to recharge after a cascade. Thus, gain will tend to decrease as hit rates increase.
- **Quantum Efficiency Uniformity:** Quantum efficiency (QE) uniformity refers to the consistency of the photocathode's emission of electrons in response to incident photons over the full active area of the

HRPPD. Non-uniform QE can bias photon detection efficiency and degrade Cherenkov ring reconstruction.

- **Dark Current / Count Rate:** The dark count rate (DCR) quantifies spontaneous pulses recorded in the absence of illumination. Excessive DCR can complicate reconstruction of Cherenkov rings.
- **Transit Time Spread:** The transit time spread (TTS) or timing resolution refers to the ability of the HRPPD to precisely register the arrival time of a single photon. A small TTS is important for Cherenkov ring reconstruction and the rejection of background or noise hits.
- **Afterpulsing Rate:** Afterpulsing is the phenomena in which impurities within the HRPPD structure are liberated by the primary electron shower and impact the photocathode – initiating further showers that register as additional hits roughly 10 ns to 100 ns after the primary pulse. Excessive afterpulsing can damage the photocathode over time and reduce the quantum efficiency of the sensor.
- **Photon Detection Efficiency:** The photon detection efficiency (PDE) is the overall rate at which the HRPPD can convert incident photons into detectable signal pulses.
- **Ringing:** It has been observed in some MCP-based photodetectors that illumination with a large flux of photons can cause collective oscillations, or "ringing", across the anode. If these oscillations are large enough, they can exceed the electronics thresholds and be registered as hits.

2. PROCESSES AND PROCEDURES

The HRPPD QA will proceed in three distinct phases: 1) tests performed by the manufacturer, Incom Inc., during the fabrication process, 2) intake QA performed at JLab to ensure basic functionality (e.g. HRPPD holds bias voltage and signals can be seen from each channel) and the physical integrity of the HRPPD after shipping, and 3) detailed evaluation of the gain, quantum efficiency, dark count, timing resolution, afterpulsing, photon detection efficiency, and ringing at BNL or the University of South Carolina (USC). The phase 2 QA is intended to be a short process that should not take more than an hour, while the phase 3 QA will be more involved and could take between 15 and 20 hours depending on the exact parameters of the measurements. The phase 3 QA will be split among several sites both to provide redundancy in case of equipment failure or other unforeseen issues and to ease the burden on any one team. Consistency between phase 3 sites will be ensured by adherence to detailed experimental procedures and communication between the teams. Where appropriate, cross-calibrated equipment such as traceable photodiodes will also be used.

2.1. Physical Characteristics

Key physical parameters of the HRPPD will be measured as part of the manufacturing process to ensure the tiles meet specifications. The integrity of the tiles will also be measured upon delivery to JLab to make sure they are in working order and no damage occurred during shipping.

2.1.1. In Process Testing

The anode plate will be manufactured from multiple layers of high-temperature co-fired ceramic. During the co-firing process, the physical dimensions of the plate can shrink by up to 15%, and the anode manufacturer can only guarantee pad positions to within 1 mm of nominal. Before the anode is integrated into an HRPPD, Incom will take a series of high-resolution photographs of the vacuum side of the anode to document the actual pad positions - this will aid in reconstruction. Incom will perform this measurement because once the anode is integrated into a full HRPPD, the vacuum side pads will be inaccessible.

2.1.2. Incoming Inspections or Acceptance Testing

Upon delivery to Jefferson Lab, each HRPPD will undergo a thorough physical inspection to ensure there was no damage to the unit during shipping. The HRPPD window will be inspected for scratches, cracks, and signs of contamination. The back plate of the HRPPD will also be checked to ensure the high-voltage connectors and mounting screws are securely attached to the unit. Finally, the mechanical dimensions of the HRPPD will be measured to ensure the unit is within specified tolerances.

After the mechanical inspection, the electrical integrity of the unit will be verified by applying the vendor-suggested recommended operational voltages to the photocathode and MCPs. The applied voltages and induced currents will be monitored for stability and for whether they are within expected ranges.

All observations will be recorded in a master spreadsheet for future reference.

2.1.3. Failures and Non-Conformances

Units which show signs of damage, are outside the required mechanical tolerances, or show electrical instability will be sent back to the manufacturer for repair or replacement.

2.2. Gain Uniformity and Rate Dependence

Gain uniformity refers to the consistency of electron multiplication across all 1024 channels of the HRPPD. Variations in gain can distort photon counting efficiency and timing resolution, so systematic QA is required. In addition, single-photon mode measurements allow for an evaluation of the absolute gain, for defining thresholds useful for dark count studies, and provide a data set from which bulk transit time spread measurements can be made. Changes in gain for select channels as a function of the rate of incident photons will also be measured.

2.2.1. In-Process Testing

As part of the phase 1 QA, Incom will perform a gain scan as a function of MCP bias and photocathode voltages on a small number of pixels. This information will provide a basis for selecting voltages to match gains across HRPPDs in subsequent QA tests.

2.2.2. Verification Testing

After the initial physical QA, the unit will undergo additional detailed investigation in the phase 3 QA, including a gain uniformity and rate scan. Using the experimental setup and methods detailed in Sec. 3.2, the gain of each pixel at the ROP will be determined and the rate dependence of selected pixels will be measured. A 2-D gain map will be produced, and the RMS of the pixel-to-pixel gain variation will be determined. In addition, pixels with abnormally high (hot) or low (dead) gains will be flagged.

2.2.3. Failures and Non-Conformances

HRPPDs that exhibit a pixel-to-pixel RMS gain variation of greater than what is indicated in the specification document or which have an excess number of hot or dead pixels will be sent back to the manufacturer for replacement.

2.3. Quantum Efficiency (QE)

Quantum Efficiency (QE) uniformity refers to the consistency of photocathode response across the full active area of the HRPPD. Non-uniform QE can bias photon detection efficiency (PDE) and degrade Cherenkov ring reconstruction. A systematic scan across the active area is required to quantify QE variations.

2.3.1. In-Process Testing

Incom will perform a series of QE uniformity scans at several wavelengths at different points in their internal testing process. These maps will serve as a point of comparison for the more detailed maps obtained during phase 3 QA.

2.3.2. Verification Testing

As part of the phase 3 QA, each HRPPD will undergo a QE uniformity and wavelength dependence scan. Using the experimental setup and methods described in Sec. 3.3, the quantum efficiency at a wavelength of 365 nm will be extracted in a high-density grid over the face of the HRPPD. In addition, QE as a function of wavelength will be determined for a select point on the HRPPD face. The QE map and wavelength scan will be used to assess the suitability of the sensor. The RMS of the point-to-point QE values at 365 nm will be determined, and no localized regions of significantly reduced QE should be present. Also, the absolute QE should be consistent with agreed specifications.

2.3.3. Failures and Non-Conformances

HRPPDs that exhibit QE variations outside the bounds indicated in the specifications, or which have extended regions of significantly lower QE (dead spots) will be sent back to the manufacturer for replacement.

2.4. Dark Current / Dark Counts

The dark count rate (DCR) quantifies spontaneous pulses recorded in the absence of illumination. The DCR is a function of MCP and photocathode voltages with higher voltages tending to increase the DCR.

2.4.1. In Process Testing

Incom will perform scans of the DCR as a function of both MCP and photocathode voltages as part of their determination of the ROP for each individual tile and phase 1 QA.

2.4.2. Verification Testing

As part of the phase 3 QA, each HRPPD will undergo a DCR evaluation at the ROP bias voltages. These measurements can be made directly before or after the Gain scan as they will utilize the same experimental setup (see Sec. 3.4), the light source within the darkbox will be capped and the number of pulses above a threshold of 4 mV will be recorded. The DCR should not deviate significantly from the values obtained by the manufacturer and should not exceed the values in the specifications. The DCR scan results will be recorded in the master QA spreadsheet, and any isolated areas of increased dark count activity will be flagged.

2.4.3. Failures and Non-Conformances

HRPPDs which exhibit DCRs above the limits indicated in the specifications, rates which deviate significantly from the manufacturer's evaluation, or which have extended areas of elevated DCR will be returned to the manufacturer for replacement.

2.5. Transit Time Spread (TTS)

The transit time spread (TTS) or timing resolution refers to the ability of the HRPPD to precisely register the arrival time of single photons. This parameter is critical for Cherenkov-based PID applications, where separation of particles depends on sub-100 ps timing accuracy.

2.5.1. In Process Testing

Incom will perform scans of the TTS at both the ROP and as a function of MCP and photocathode bias voltage as part of their internal testing protocol and phase 1 QA.

2.5.2. Verification Testing

Data taken during the gain uniformity scan can also be used to evaluate the TTS as both the trigger signal and HRPPD pulse will be read out by the digitizers. The variation in the difference in arrival time between the trigger and HRPPD pulses is the TTS. Both the width of the Gaussian core and the full RMS (in a window of -0.5 to 2 ns with respect to the laser pulse) of the time difference distribution will be measured.

For HRPPDs tested at BNL, an additional, more precise, TTS determination can be performed on a small (< 10) number of channels by utilizing the Elmo femtosecond laser and high-performance oscilloscope (see Sec. 3.5). Utilizing the femtosecond laser will remove the jitter inherent in other laser sources (and trigger logic) and the high sampling rate of the oscilloscope will allow for more accurate characterization of the trigger and pulse waveforms leading to TTS resolutions limited by the intrinsic performance of the HRPPD itself.

2.5.3. Failures and Non-Conformances

HRPPDs found to have a significant number of pixels exhibiting timing resolutions greater than what is indicated in the specification documents will be returned to the manufacturer for replacement.

2.6. Afterpulsing Rate

Afterpulsing refers to the presence of additional pulses which come after the primary pulse initiated by an incident photon. The electron avalanche produced by the incoming photon can dislodge impurities present in the MCPs (hydrogen, water, carbonates, nitrogen, etc.) which then accelerate against the electric potential and hit the photocathode, initiating further electron showers. Ions impacting the photocathode in this way will change its chemical composition and degrade its performance over time. The afterpulsing rate tends to increase with increasing MCP and photocathode bias voltage.

2.6.1. In Process Testing

Incom will quantify the afterpulsing probability as part of their internal testing protocol and determination of the appropriate ROP.

2.6.2. Verification Testing

Data taken during the gain uniformity scan can also be used to determine the afterpulsing rate – the digitizers used to record the data simply need to have a wide enough time window set to capture the additional signals (see Sec. 3.6). The manufacturer recommends not running at voltages for which the afterpulse rate is 4% or higher in order to maximize the lifetime of the HRPPD.

2.6.3. Failures and Non-Conformances

HRPPDs which cannot be run at the necessary gains without exceeding the afterpulse rate indicated in the specifications will be returned to the manufacturer for replacement.

2.7. Photon Detection Efficiency

The photon detection efficiency (PDE) is the overall rate at which incident photons are converted into detectable signals by the sensor. The PDE is predominantly given by the product of the photocathode quantum efficiency (probability that an incident photon will produce an electron) and the collection efficiency, which is approximately the active area fraction of the MCP (pore-to-interstitial space fraction of the MCP) which determines the probability that an electron from the photocathode will hit a pore and initiate an electron avalanche. The HRPPD PDE is an essential figure of merit for the overall performance of Cherenkov-based PID detectors.

2.7.1. Verification Testing

As part of the phase 3 QA, the PDE at a given location of each HRPPD will be measured according to the methods detailed in Sec. 3.7. Additionally, a concurrent determination of the quantum efficiency at that location can also be made to extract the collection efficiency. The collection efficiency should closely follow the active area fraction of the MCP which is known from the manufacturing process and will serve as a cross check of the PDE measurement.

2.7.2. Failures and Non-Conformances

HRPPDs which are found to have a PDE less than what is listed in the specification document will be returned to the manufacturer for replacement.

2.8. Ringing

Ringing refers to a phenomenon observed in some MCP-based sensors (A. Lehmann, 2024) in which an oscillation is seen in the readout over an extended time when an area of the sensor is illuminated with a high flux of photons. These oscillations can extend to channels that were not illuminated and, if the magnitude of the oscillations is large enough, can register as additional hits in the sensor. Such phantom signals can greatly complicate Cherenkov ring reconstruction. Ringing can be mitigated by proper readout design, but each HRPPD should be evaluated to ascertain the magnitude of the oscillations. Ultimate procedures for quantifying the ringing still need to be determined. Final checks may not be possible until final ASIC and backplanes are in hand.

3. EXPERIMENTAL/TEST SETUPS

The phase 2 and 3 QA will be performed using dedicated dark box test stands (see **Error! Reference source not found.**) at the participating institutions (except for the mechanical inspection in phase 2, which will proceed on the bench). While the exact specifications and equipment of each test stand will vary depending on what material is available on hand or from vendors at the time of assembly, all will have a pulsed laser system, monochromatic light source, calibrated reference photodiodes, motorized motion stages, digitizer(s), picoammeter(s), high voltage power supply, and various optical components. Note: unless otherwise indicated, the experimental setup and equipment detailed below will be based on the existing BNL test stand.

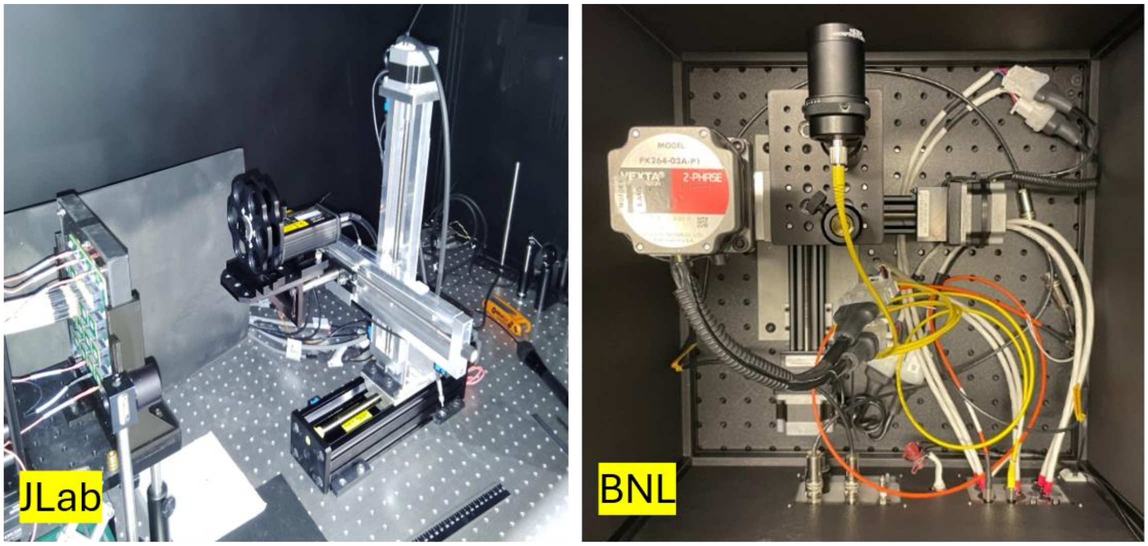


Figure 2. Examples of existing HRPPD dark box test stands at JLab and BNL

3.1. Experimental Method: Physical Characteristics

Several measurements fall under this heading, the procedures for each are listed below:

Anode plate characterization: Before each anode plate is integrated into an HRPPD, the vacuum side surface will be scanned with a high-resolution digital camera and the real coordinates of each pad will be determined. This will necessarily be carried out at Incom.

Physical inspection: After shipment of each HRPPD from Incom to JLab, a detailed physical inspection will be carried out both to ensure that the physical characteristics (sensor dimensions, readout pad placements, HV connector placement, mounting points) are within specs and to make sure there was no damage to the unit during shipping.

Basic operation: Once it is verified that the unit is sound and meets physical specifications, the electrical integrity will be verified by applying the ROP bias voltages and checking their stability. A diffuse light source will then be applied and each channel will be checked to ensure that signals can be seen.

3.1.1. Resource Requirements

No special resources are required to carry out these tests.

3.1.2. Test Conditions

The physical inspections should be carried out in a low humidity environment to prevent possible corrosion to HV connectors and readout pads.

3.1.3. Equipment

Generic equipment needed for these tests include a high-resolution digital camera, HV power supply, linear motion stages, and readout electronics / digitizers.

3.2. Experimental Method: Gain Uniformity and Rate Dependence

The procedure for measuring the gain uniformity is as follows:

1. Apply the ROP voltages to the HRPPD
2. Illuminate the HRPPD using a pulsed laser with a trigger/repetition rate between 100 and 1000 Hz

3. Tune the laser intensity down to the single-photon regime by adjusting the laser properties and/or inserting a neutral density filter(s) into the optical chain
4. Focus the beam using optical components and the movable stages such that the spot size is on the order of 1 mm in diameter at the HRPPD face (beam spot should be smaller than an individual pixel (3.25 mm across)
5. Center the beam on the middle of a pixel and then scan pixel-by-pixel across the face of the HRPPD, digitizing roughly 10^5 events per pixel
6. Fit the single photoelectron peak and extract the absolute gain for each pixel, building up a 2D gain map
7. For a select pixel, take a series of events at increasing laser repetition rate

3.2.1. Resource Requirements

No special resources are required to carry out this test.

3.2.2. Test Conditions

The gain scan should be carried out in a light-tight dark box at standard room temperature and humidity (roughly 72°F and 30-50% humidity).

3.2.3. Equipment

Major equipment used in this measurement is listed below. Note: this is not a detailed parts list and as such various components such as lenses, optical fiber, structural pieces, etc. are omitted.

- Hamamatsu PiLas pulsed laser at 405 nm
- 16ch R8034DN CAEN HV power supply
- 2 32 CH V1742 CAEN DRS4 digitizers – with A3818C CAEN CONET2 PCIe adapter cards
- 3 Velmex motorized linear stages with controllers

3.3. Experimental Method: Quantum Efficiency

The procedure for measuring the Quantum Efficiency is enumerated below. Note that the resource requirements and test conditions for these measurements are identical to those for the gain analysis.

1. Apply 100 V to the photocathode (via a picoammeter)
2. Attach the top side of the MCP closest to the photocathode to a second picoammeter
3. Set up the optical head inside the dark box to include a splitter and a calibrated photodiode to measure photon flux (photodiode should be placed before any neutral density filters)
4. Illuminate the HRPPD with a monochromatic light source at 365 nm
5. Focus the beam using optical components and movable stages such that the spot size is roughly 2 mm in diameter at the HRPPD face
6. Scan across the face of the HRPPD in roughly 2 mm steps
7. For a pre-chosen point on the HRPPD, perform a scan through wavelengths between 250 nm and 600 nm
8. Extinguish the light source and measure the dark current under identical bias conditions and subtract from currents obtained under illumination
9. Calculate QE and build a 2D map at a single wavelength and a QE vs wavelength profile at a single point

3.3.1. Equipment

Major equipment used in this measurement is listed below. Note: this is not a detailed parts list and as such various components such as lenses, optical fiber, structural pieces, etc. are omitted.

- Oriel monochromator with Xenon lamp
- 2 Keithley 6487 picoammeters
- Calibrated reference photodiode (Newport 818-UV/DB)
- Saphire beam splitter
- 3 Velmex motorized linear stages with controllers

3.4. Experimental Method: Dark Count Rate

The procedure for measuring the dark count rate is enumerated below. Note that this measurement can be taken using the same test stand configuration that was used for the gain uniformity scan. Therefore, the resource requirements, test conditions, and equipment are identical to those in Sec. 3.2.

1. Apply the ROP bias voltages to the HRPPD
2. Block or turn off the light source
3. Record the number of pulses above a threshold of 4 mV as a function of real acquisition time
4. Normalize the result to the effective detector area to obtain the DCR per cm^2

3.5. Experimental Method: Transit Time Spread

As stated in Sec. 2.5, the TTS can be obtained from the gain uniformity data set and, if the HRPPD is being tested at BNL, by a high-precision femtosecond laser plus oscilloscope setup. The TTS extraction from the gain uniformity data set requires only a different offline analysis and as such, the method, requirements, conditions, and equipment are the same as outlined in Sec. 3.2. The procedure for extracting the TTS in the femtosecond laser plus oscilloscope configuration is enumerated below.

1. Apply the ROP bias voltages to the HRPPD
2. Illuminate the HRPPD using the femtosecond pulsed laser with a repetition rate between 100 Hz and 1000 Hz
3. Tune the laser intensity down to the single photon regime by introducing ND filters
4. Focus the beam by tuning appropriate optical components and/or repositioning the optical head such that the spot size on the face of the HRPPD is roughly 1 mm in diameter and then center the beam on a particular anode pad
5. Attach the optical trigger output from the laser and the output from the illuminated HRPPD channel to the oscilloscope and record at least 10K triggers at the oscilloscope's maximum sampling rate and bandwidth
6. Repeat for a small sample of anode pads / channels
7. Calculate the trigger vs signal time difference from the digitized waveforms and construct the timing resolution for the selected channels

3.5.1. Equipment

The equipment needed for the scope-based TTS measurement not already covered in Sec. 3.2.3 is listed below:

- Menlo Systems Elmo 780 Erbium Fiber Femtosecond laser
- MSO66B Tektronix oscilloscope (50 GS/s, 8 GHz analogue bandwidth)

3.6. Experimental Method: Afterpulsing Rate

The determination of the afterpulsing rate can be made using the gain uniformity data set meaning the methods, resources, conditions, and equipment are the same as detailed in Sec. 3.2. The only consideration which needs to be taken into account is to ensure the digitizer window extends for a long enough time after the primary signal pulse to capture the afterpulses. The afterpulsing rate is found simply by counting the number of pulses above a set threshold within a time window after the primary pulse and normalizing appropriately.

3.7. Experimental Method: Photon Detection Efficiency

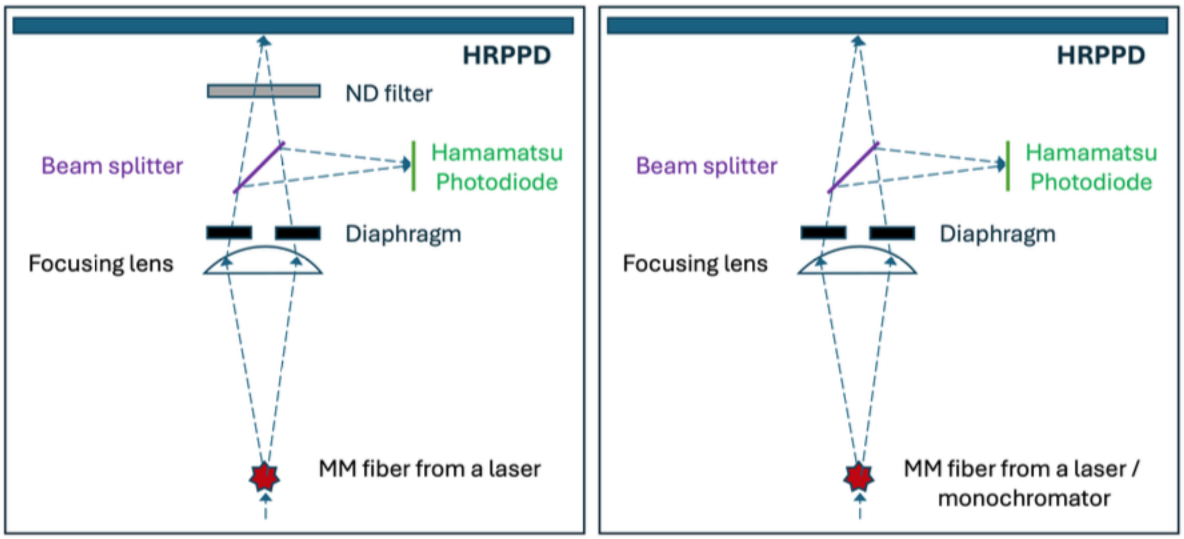


Figure 3. A schematic view of the PDE measurement setup (left) and the QE measurement setup (right).

The procedure for measuring the photon detection efficiency is enumerated below. More detail on the required experimental setup and analysis method, including initial calibrations and characterizations of the photodiode and beam splitter, can be found in (Jin, Kiselev, & Stoll, 2026). Note, in addition to measuring the PDE, the QE can also be measured to allow the calculation of the Collection Efficiency, which is a measure of the active area of the MCP and provides a sanity check of the result.

1. Apply ROP bias voltages to the HRPPD
2. Illuminate the HRPPD using a pulsed picosecond laser with a repetition rate of 1 KHz and insert the appropriate ND filter before the HRPPD to enter single photon mode (see left side of Fig.)
3. Tune the beam spot size to roughly 1 mm at the face of the HRPPD and center on a pixel near the center of the HRPPD
4. Digitize a significant number of events (~100K) and combine the fraction of events with measurable signal and photodiode current information to determine the PDE
5. Optionally, measure the QE by biasing the photocathode using a picoammeter and measuring the current from the first MCP

3.7.1. Equipment

The major equipment needed for the PDE measurement is listed below

- Hamamatsu PiLas pulsed laser at 405 nm
- 16ch R8034DN CAEN HV power supply
- 2 32 CH V1742 CAEN DRS4 digitizers – with A3818C CAEN CONET2 PCIe adapter cards

- Keithley 6485 and 6487 picoammeters
- Hamamatsu S1226-8BQ and Newport 818-UV-DB traceable photodiodes
- MSE Supplies sapphire beam splitter
- 3 Velmex motorized linear stages with controllers

3.8. Experimental Method: Ringing

Note: The exact methods for measuring ringing are still being determined.

4. ENVIRONMENT, SAFETY & HEALTH CONSIDERATIONS

The procedures described above will be implemented in a way consistent with the environment, safety, and health policies of the relevant work areas. Within Jefferson Lab the process is described in the ES&H manual Chapter 3200, Work Planning and Control Program and at BNL within the SBMS: "Work Planning & Control for Experiments and Operations". For work carried out in a university setting, safety protocols will match EIC project standards. Potential exposure to energetic hazards such as high voltage power and laser light will be mitigated via physical barriers around HV leads and interlocked dark boxes. We do not anticipate the need for any personal protection equipment beyond standard laboratory attire (long pants and closed toe shoes), although we do foresee the use of powder free nitrile gloves when handling optical components.

5. RECORDS AND DOCUMENTATION

An integral part of the QA process will be a uniform and centralized documentation system. Detailed records listing all results from all three phases of QA for each HRPPD will be kept and shared with the project. In addition, a common "experimental notebook" will be employed to record conditions, observations, and notes during the QA process.

5.1. Manufacturer/Producer Records

For each HRPPD produced, Incom Inc. will provide a detailed Measurement & Test Report listing all relevant parameters and summarizing the operating characteristics of that particular tile. The manufacturer report will provide the recommended operating point for high voltage bias settings and present the results of Incom's tests of gain, afterpulsing, dark rates, timing resolution, anode geometry, and high voltage stability. The report will also describe the methods used to perform these measurements.

5.2. Deliverable Documentation and Records

The results of each QA investigation, including extracted parameter values and pass/fail determinations, will be recorded in an agreed upon format (database, spreadsheet, etc.) and shared with the project. Detailed parameter tables that may be useful in simulation and/or reconstruction will additionally be stored in a format convenient for use in these applications (ROOT trees or similar).

6. REFERENCES

A. Lehmann, M. B.-J. (2024). Systematic approach to measure the performance of microchannel-plate photomultipliers. *Nuclear Instruments and Methods in Physics Research Section A, 1065*, 169536.

Jin, Y., Kiselev, A., & Stoll, S. (2026). Evaluation of the absolute single-photon detection efficiency of HRPPD. *Nucl. Instrum. Meth. A, 1082*, 171058.