Measurement & Test

Report

HRPPD #25

04/30/2024

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HRPPD #25 Specific Performance

Summary

HRPPD #25 has single photoelectron gain in the high 10^5-10^7 range. Simultaneously, it has dark rates in the ~10 Hz -10 kHz/cm^2 regime. Gain is sustained at high rates, falling to half of nominal gain at 200 kHz/mm^2. Quantum efficiency is 26.5% at 365 nm, and is spatially uniform to the 1.3% level. Tile lifetime is also expected to be maximized, given that most operating points, including the recommended operating point, is measured to have an afterpulse rate of ≤4%. This HRPPD can be used in applications requiring external triggering on single photons.

Seal Date	04/11/2024
Pilot Production / Experimental	Experimental Production
Version	Cofired Direct Readout
Important Features	
Quality Grade (Production vs. Development)	Production
Pass / Fail	Pass
Analysis	
Disposition	Jefferson Lab (On Behalf of the EIC)

HRPPD #25 General Features and Parameters:

Feature	Parameter
Photodetector Material	Cofired Direct Readout, ceramic lower tile assembly; interior pixel anode
Window Material	Fused silica glass, 5.0 mm thick
Photocathode Material	Multi-Alkali (K_2NaSb)
Spectral Response (nm)	160-650
Wavelength – Maximum Sensitivity (nm)	≤ 365 nm
Photodetector Active Area Dimensions (inside of detector sidewalls)	103.92 mm X 103.92 mm
• Minimum Effective Area	107.99 cm^2
• Active fraction with Edge Frame Spacers	75%
Anode Configuration	1024 gold pads, Width = 3 mm, pitch 3.25 mm, nominal 50 Ω Impedance
Voltage Distribution	5 taps for independent control of voltage to the photocathode and entry and exit of MCP

HRPPD Package / Housing Characteristics

Parameter	Rating
Photodetector Physical Dimensions (L X W X Thickness, mm)	119.6 x 119.6 x 21
Photodetector Mounting Case	ULTEM or equivalent dielectric polymer
Photodetector Mounting Case Dimensions	213.8 mm X 190 mm X 23.2 mm
Connectivity	Passive PC Interface Board, (119.6 x 119.6 x 5)
Overall Footprint, with Mounting Case & PC Interface Board	213.8 mm X 190 mm X 23.2 mm
Shipping Container	Pelican Case + Cardboard Box + G-force indicators

HRPPD #25 Microchannel Plate (MCP) Features & Performance

MCPs	Two Arranged in a Chevron Pair
Dimensions	108 mm x 108 mm X 0.6 mm

MCP Substrate	Incom C14 Glass
Capillary Pore Diameter (µm) Center to Center Pitch (µm)	10 13
Channel Length / diameter Substrate Thickness (mm)	60:1 0.6
Bias Angle	13
Capillary Open Area Ratio	≥70%
Resistive and Emissive Coatings	Chem 5, Applied via Atomic Layer Deposition (ALD)
Secondary Emission (SEE) Layer Material	MgO
Electrode Penetration – Input & Output (Pore Diameter)	0.5-1.0
MCP ID (Entry / Exit)	CJ24147-031/ CJ24147-029
MCP resistance, Entry/Exit (at HRPPD M&T)	7.2/6.0 MΩ at 800 V
MCP Dark Rate in the tile (Obtained by setting the photocathode more positive than the entry MCP)	24.4 Hz/cm^2 at a threshold of 8x10^5 gain (134 fC), 800 V/MCP, 10 V positive on photocathode [A]
Max Voltage	800/800 V/MCP (entry/exit), with -2,010 volts on the photocathode; dark rate limited.

HRPPD #25 Operating Performance (ROP = Recommended Operating Point)

Parameter	Performance
Photocathode Quantum efficiency @ 365 nm	Mean QE (@365 nm) = 26.5%, Maximum: 29.2%
Photocathode QE Spatial Variability (σ)	1.3%
ROP Voltages	200V above anode, 200V between MCPs, 700V/MCP, 200V on photocathode
Example Voltage Configuration at ROP See Table 2 for all HVs used in Standard Testing	Photocathode: -2000V Entry of Entry MCP: -1800V Exit of Entry MCP: -1100V Entry of Exit MCP: -900V Exit of Exit MCP: -200V
HRPPD Gain @ ROP	1.90x10^7
HRPPD Gain @ 10V on Photocathode, 800V MCP	6.52x10^7
HRPPD Dark Count rate @ ROP (threshold = 4mV)	2.58 kHz/cm^2 at a threshold of 8x10^5 gain (134 fC), 700 V/MCP, 200 V on photocathode [A]
Dark Rate @ 10 V on PC, 800V MCP	172.1 kHz/cm^2
Optimal Transit Time Variation (single P/E) (Lowest/ROP)	71.9 ps/ 77.0 ps
Note: INCOM TTS results are presented as the core sigma result with laser uncertainty subtracted out.	
Position Resolution Along/Across Pixels (mm) (typical, not measured for this tile)	~0.14

Gain

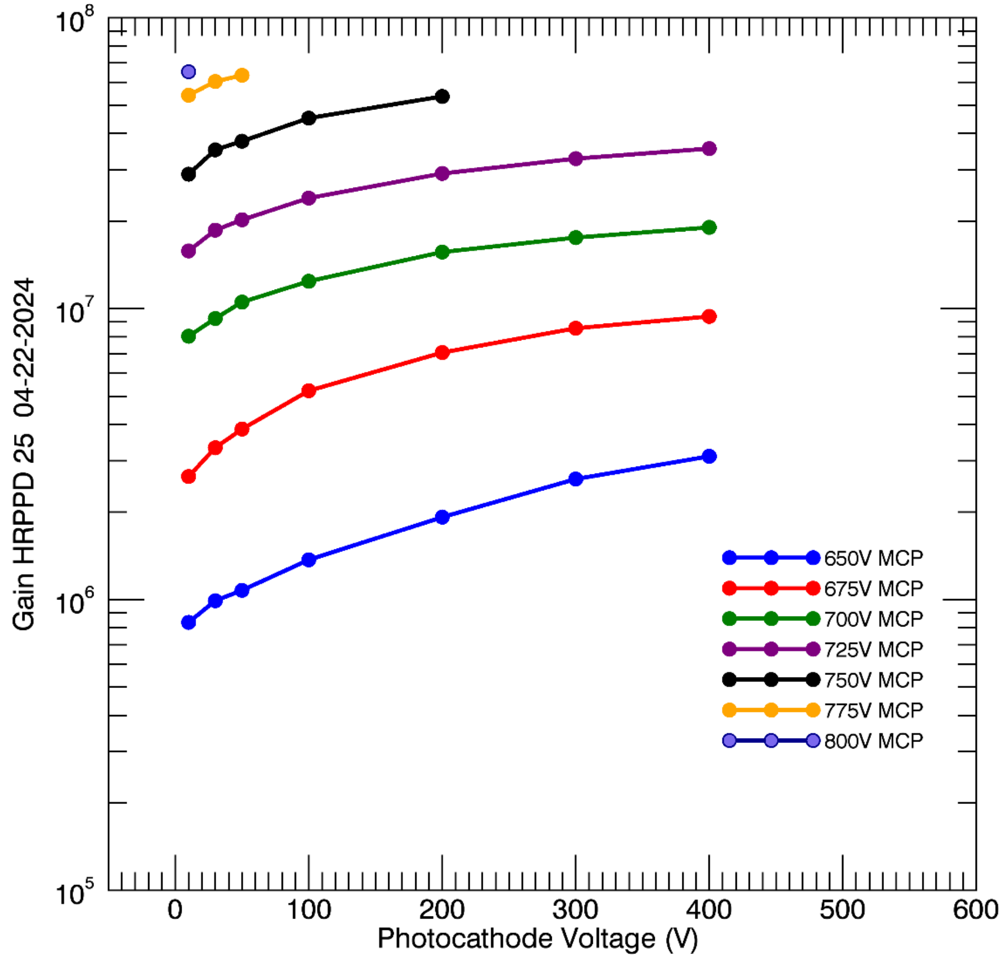
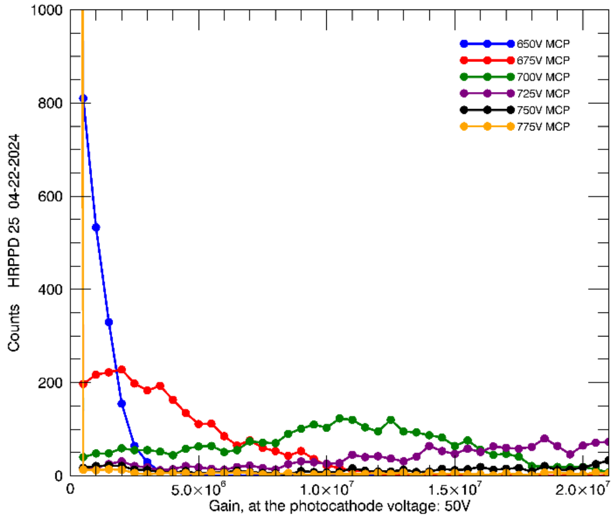


Figure 1: Average gain is shown vs. MCP and photocathode voltage, as measured with PSI DRS4 waveform samplers. [A]



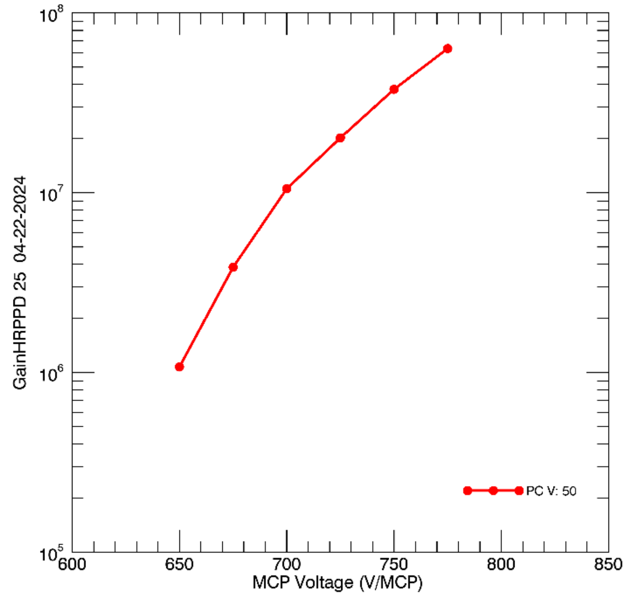
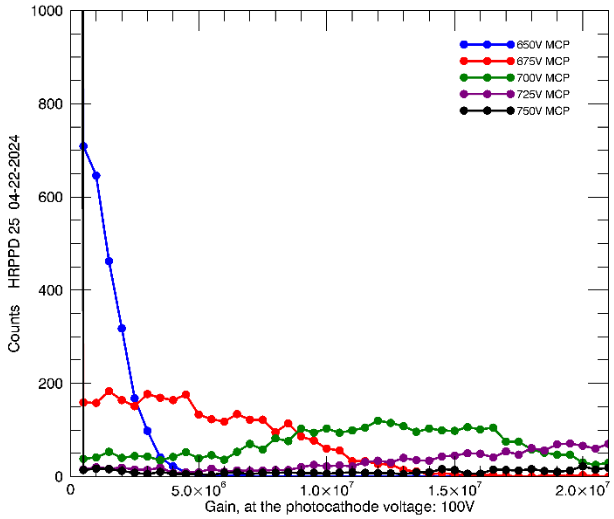


Figure 2: Gain is shown as a function of MCP voltage, with 50 V on the photocathode.[A] **Left**: pulse height distributions. **Right**: Average gain vs. MCP voltage.



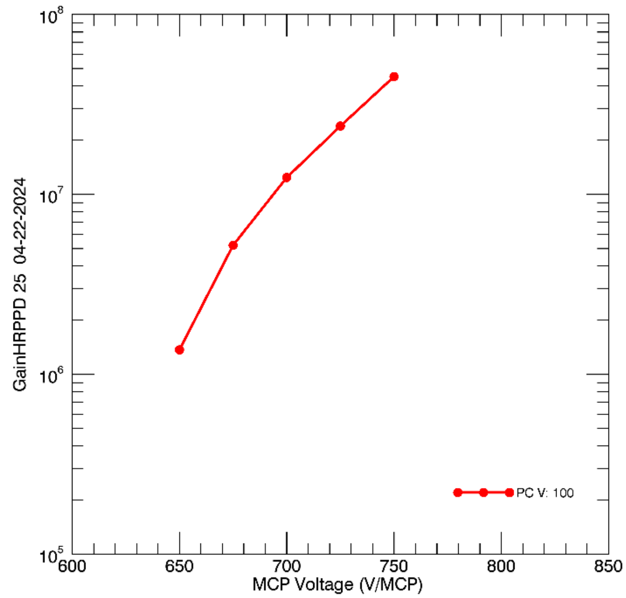


Figure 3. Gain is shown as a function of MCP voltage, with 100 V on the photocathode.[A] **Left**: pulse height distributions. **Right**: Average gain vs. MCP voltage.

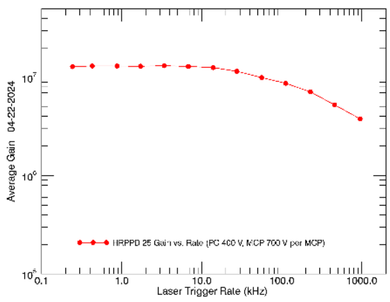


Figure 4: Gain is shown vs. laser repetition rate for single photoelectrons. A

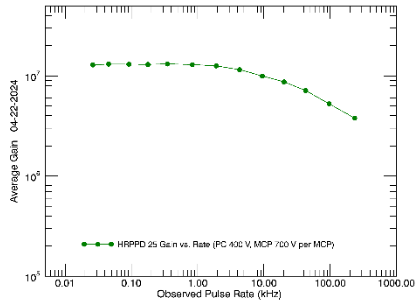


Figure 5: Gain is shown vs. observed pulse rate for single photoelectrons.

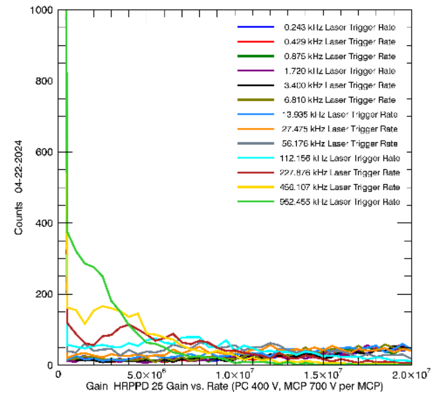


Figure 6: The pulse distributions are shown as a function of laser trigger rate.

Afterpulsing and Tile Lifetime

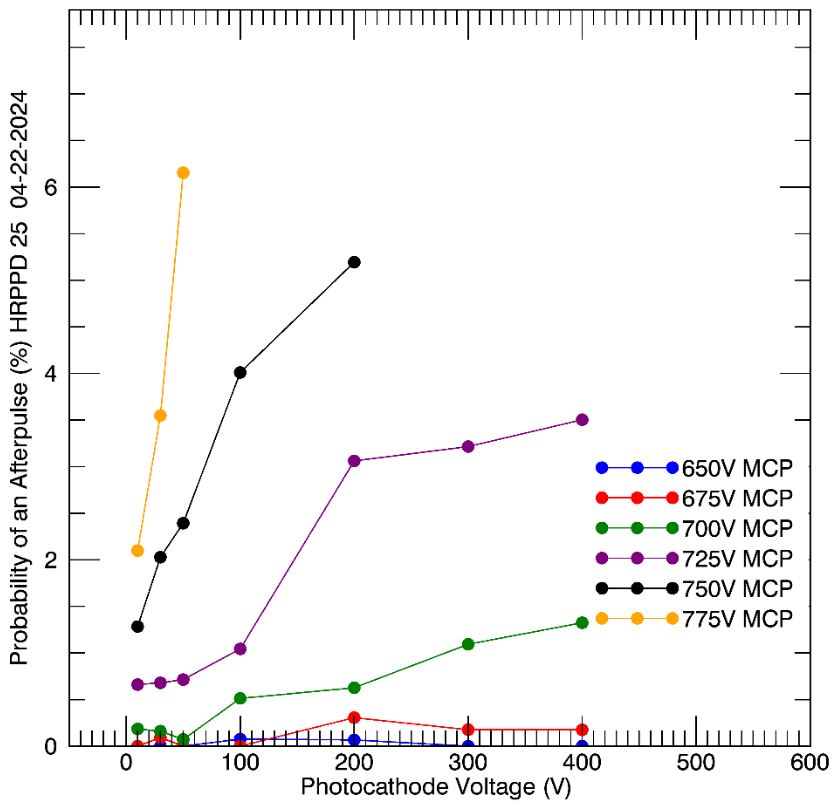


Figure 7: Percentage of Afterpulsing found for HRPPD 25 as a function of photocathode voltage and MCP voltages.

Dark Rates

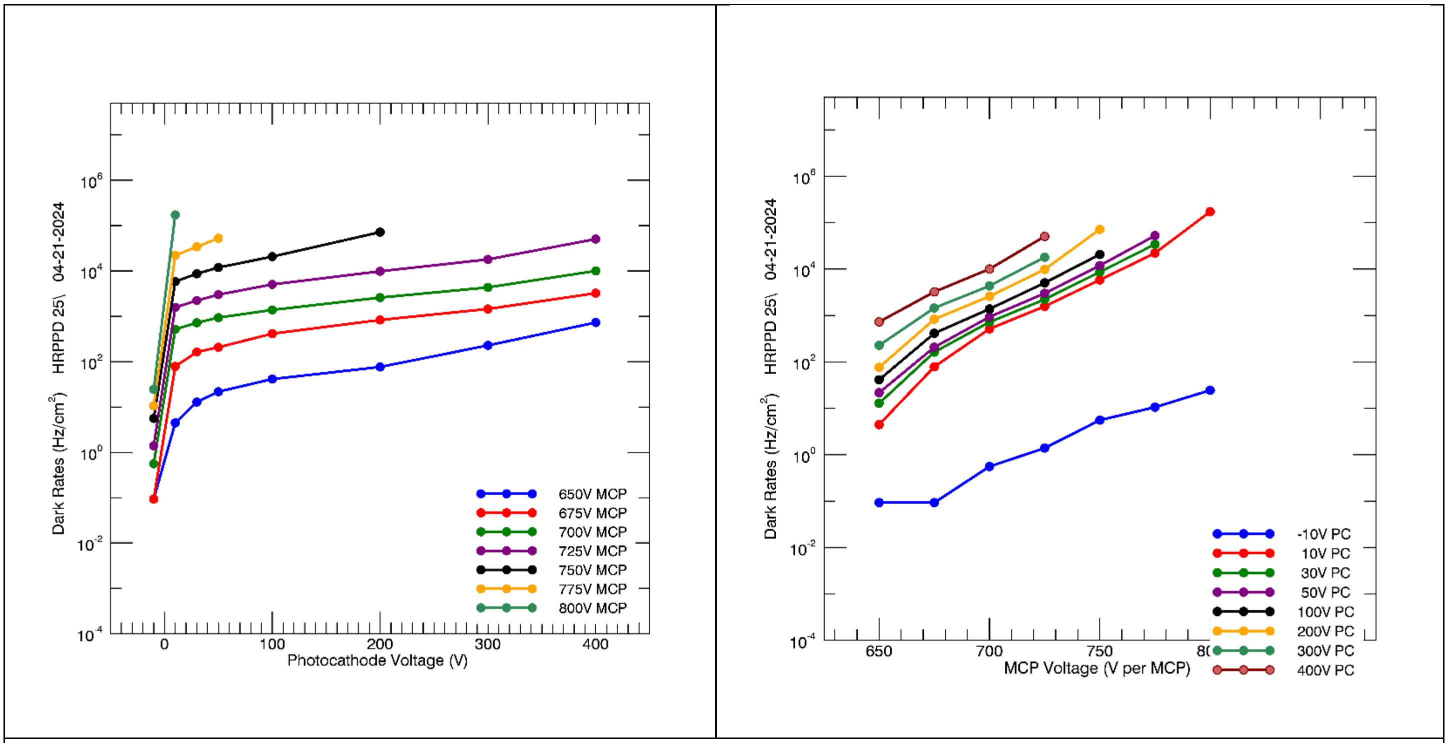


Figure 8: Dark rates as a function of photocathode and MCP voltage.[A]

Photocathode QE Spectrum

Date	Mean QE	Max QE	QE Variability
04/17/2024	26.3 ± 1.2%	28.8%	4.2%
04/29/2024	26.5 ± 1.3%	29.2%	4.4%

Table 1: Quantum efficiency measurements at 365 nm on HRPPD #25 are listed.

QE Scans

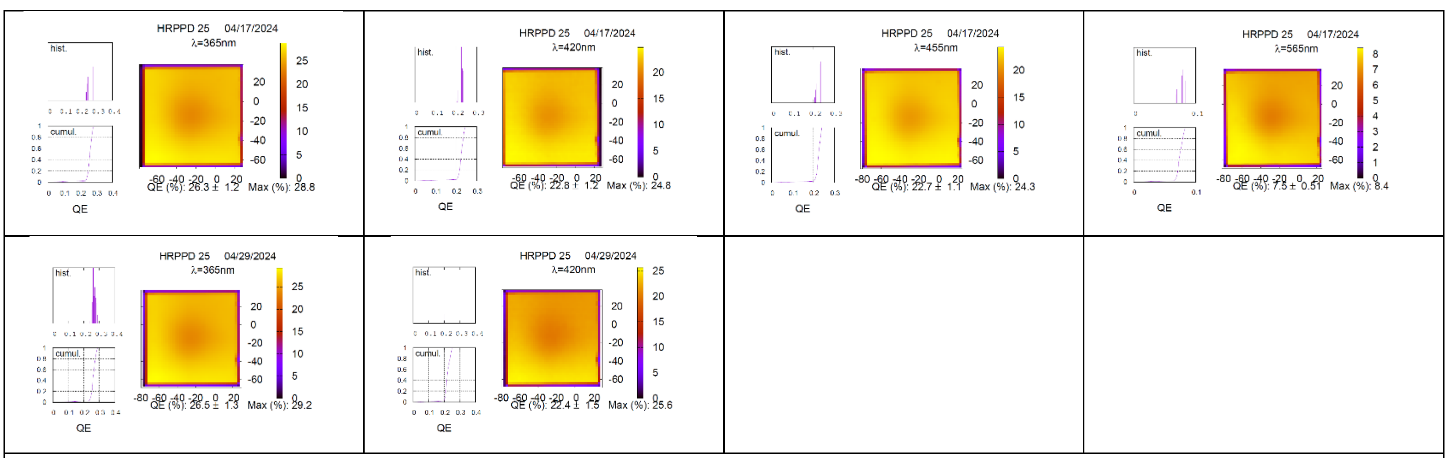


Figure 9. QE Scan data. The columns are scans done at different wavelengths. The rows are different test dates.

Please Note: Outer border on second row QE scans (corresponding to HRPPD sidewall) are not included in calculations.

Transit Time Variation

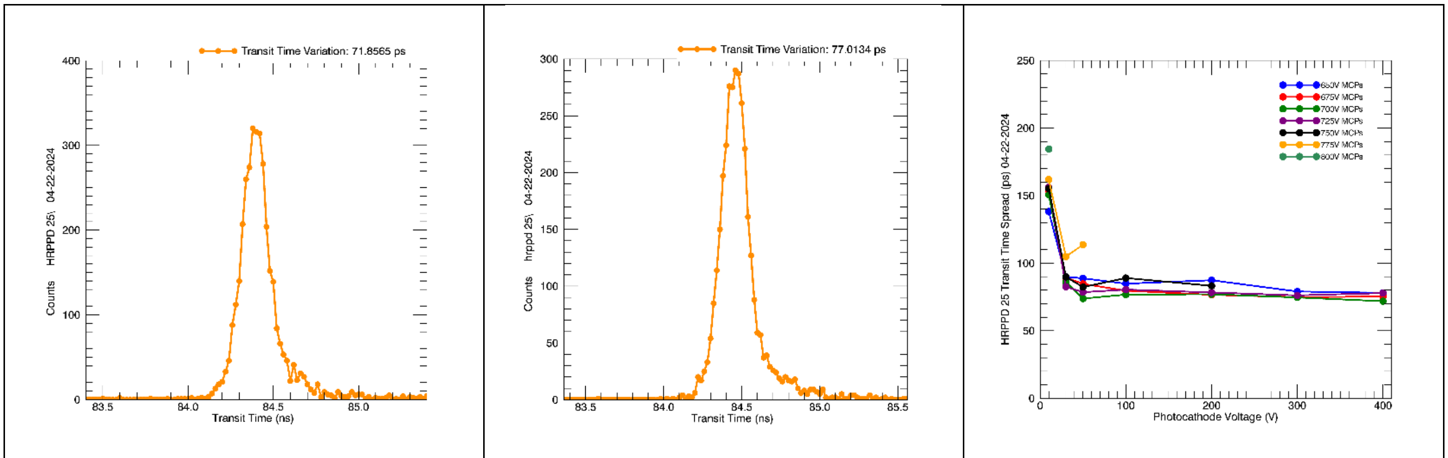


Figure 10. Left: The transit time variation is shown for 700 V/MCP and 400 V on the photocathode. This is the time difference between the observed laser firing and the arrival of the MCP pulse at the readout electronics. **Center:** The transit time variation is shown for 700 V/MCP and 200 V on the photocathode. This is the time difference between the observed laser firing and the arrival of the MCP pulse at the readout electronics. **Right**: The transit time variation is shown as a function of photocathode voltage for different MCP voltages.

Please Note: Data shown above has laser trigger uncertainty subtracted out only. Timing Uncertainty is predicted to be ~5 ps, but is not included in subtraction. Sub-60 ps timing will be confirmed by EIC.

High Voltage Stability vs. Voltage and MCP Resistance vs. Voltage

MCP Voltage Bias (V)	Photocathode Bias (V, relative to Entry of Entry MCP High Voltage)
650	+10 to -400
675	+10 to -400
700	+10 to -400
725	+10 to -400
750	+10 to -200
775	+10 to -50
800	+10 to -10

Table 2: High Voltage Settings used for HRPPD 23 Standard Testing. Both the bias between MCPs and between the Exit MCP and the anode are both set at 200V.

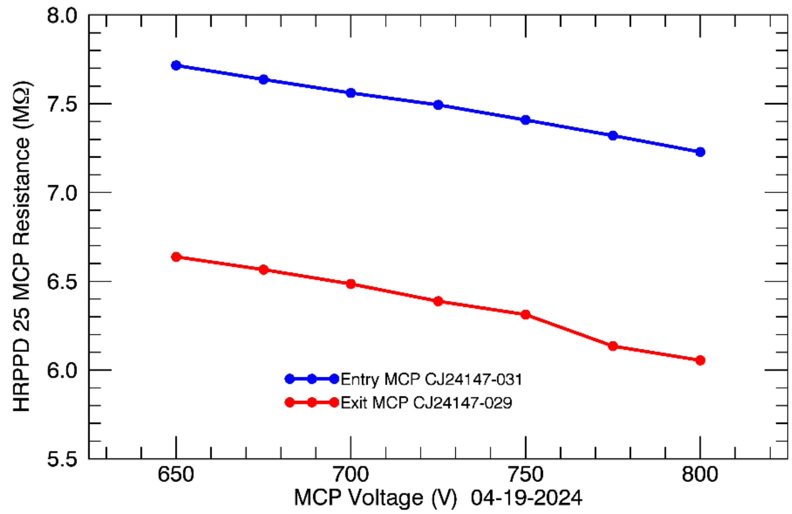


Figure 11: MCP resistances are shown for HRPPD #25.[A]

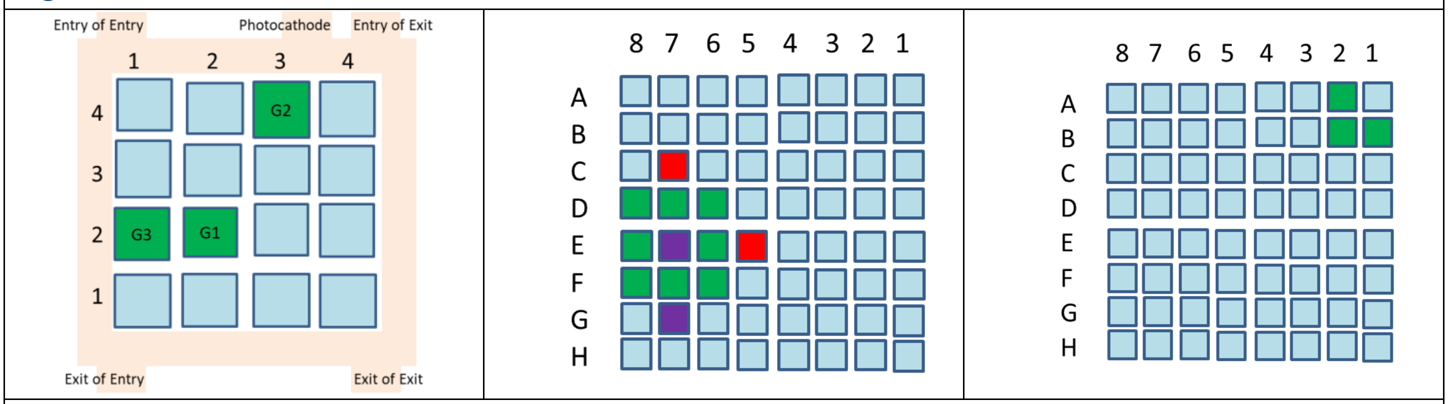


Figure 12 Left: Layout for groups of pads used to test HRPPD #25 (as seen looking directly at the front of the detector). The pads highlighted in green were used to collect waveforms for gain, gain vs rate, transit time spread, and dark rates. Light blue pads were not used. **Center:** Layout of pads used by HRPPD 24 in Groups 1 and 3 (as seen looking directly at the front of the detector). The pads highlighted in purple were used to collect waveforms for gain, gain vs rate, and transit time spread. The pad highlighted in green were used to collect data for spatial gain calculations via the CAEN DRS4s. The pad highlighted in red were used to collect dark rates. Light blue pads were not used. **Right:** Layout of pads used to HRPPD 24 in Group 2 (as seen looking directly at the front of the detector). The pads highlighted in green were used to collect data for spatial gain calculations via the CAEN DRS4s. Light blue pads were not used.[A]

HRPPD Testing Protocols

Introduction

Functional tests were performed on the HRPPD in a dark box that was fitted with a UV light source and signal acquisition hardware. A summary of the results is shown below. The measurements include:

1. **Gain**
   - Gain vs. MCP and Photocathode voltage
   - Gain vs. repetition rate
2. **Dark rates** vs. MCP and photocathode voltage
3. **Transit Time Variation**
4. **Photocathode QE spectrum and map**
5. **MCP resistance vs. voltage**
6. **High voltages and currents vs. time**
7. **High voltage connection diagram**

Gain

Gain vs. MCP voltage

Gain was measured as a function of MCP voltage, using PSI DRS4 waveform samplers. MCP pulses were produced by directing a 405 nm Pilas 19-63 pS UV pulsed laser to a selected point on the HRPPD window. The laser was triggered externally at 3.0 kHz.

A neutral density filter (NE530B from Thorlabs) and a polarization filter were used on the laser to reduce the intensity to the single photon level. At this level, the HRPPD responded 15-30% of the laser pulses.

The gain results are a function of both MCP and photocathode voltage. The average HRPPD gain for single photoelectrons is as high at 6.52×10^7 at 800 V/MCP and 10 V on the photocathode. The gain tends to increase with increasing photocathode voltages. This is consistent with the expected increase in the number of secondary electrons from the MgO film as incident electron energy rises (Jokela et al., 2012).

Typically, pulse height distributions are well-separated from threshold at 900 V/MCP and above.

Gain vs. repetition rate

When a microchannel produces a charge pulse, it needs time to recharge. Otherwise, subsequent pulses will be smaller than the first. The microchannel plates are suitable for high rate conditions because the channels are nearly independent of each other, and unless the same one is struck twice, they will have time to recover.

The reduction of gain as a function of rate was tested by applying the 405 nm laser to a spot on the HRPPD window, of about 1 mm in diameter. The repetition rate was changed, and the corresponding gain was measured. Based on Photocathode QE, the HRPPD typically respond to 3-6 out of 20 laser pulses. The gain is therefore also analyzed as a function of observed pulse rate, rather than the laser trigger rate. The gain typically declines by a factor of approximately two as the observed rate is increased from ~0.2 kHz/mm^2 to ~50 kHz/mm^2), a gain decrease typically from 1×10^7 to 5×10^6.

This rate is somewhat threshold-dependent, so at higher rates, some pulses fall below threshold and therefore the pulse height distributions shift to the left, corresponding to reduced gain.

Afterpulsing and Tile Lifetime

A mechanism that can adversely affect Photomultiplier Tube (PMT) lifetime is afterpulsing. During normal operation, trapped molecules in the pores of the MCPs left over from MCP fabrication (such as water, carbonates, nitrogen, etc.) can become ionized from the incoming electron cascade. These ions, being positively charged, move up through the MCP against the negative potential applied to the MCP. If this occurs in the entry MCP, this can cause the resulting ions to shoot up into and embed in the photocathode in a process called ion feedback. This will begin to change the composition of the photocathode and thereby decreasing the QE of the device. We are able to detect this phenomenon by studying afterpulses. These pulses occur most commonly 20-100 ns after the initial pulse and result when the energy from the incoming ion is enough to emit a photoelectron from the photocathode, producing another pulse. In Figure 7, the afterpulsing rate for HRPPD 25 is shown. In order to maximize lifetime of the device, it is generally recommended that customers not operate at voltages that are reported to have an afterpulse rate of 4% or higher.

SPE Calculations

As mentioned in the "Gain vs. MCP Voltage" Section, we utilize a 405 nm Pilas 19-63 pS pulsed laser when calculating gain for the HRPPD. Furthermore, in addition to physically attuning the laser, we utilized a Thorlabs NE530B neutral density filter to control the output of the laser such that we are in the single photoelectron regime. This, as mentioned before, typically has the HRPPD produce pulses 15-30% compared to laser pulses.

We utilize Poisson Statistics based on the average number of responses and nonresponses from the HRPPD at that MCP Voltage level (Figure 13). From this, we find that we mostly get single photoelectrons at 78%, with an occasional set of two photoelectrons.

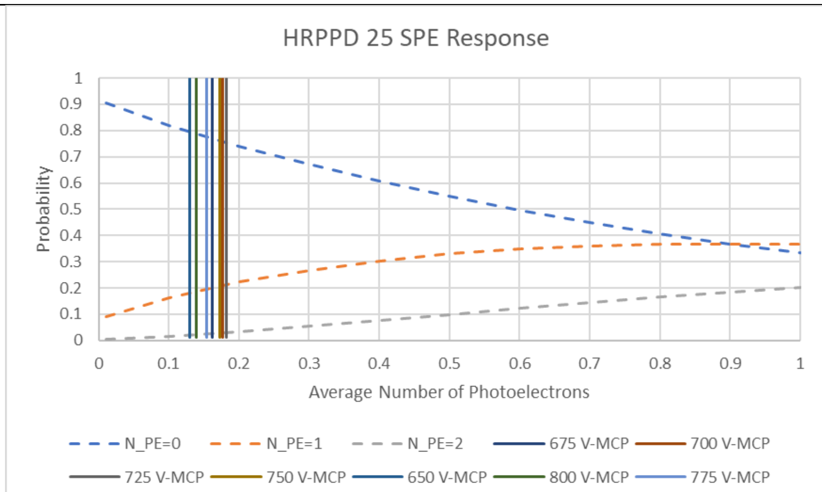


Figure 13: HRPPD 25's response to laser set to 78% tune, producing photons in the SPE regime. Dashed lines represent the Poisson Statistic probabilities for a certain number of photoelectrons and the solid lines represent the average number of photoelectrons calculated for each MCP voltage tested based on the response from HRPPD 25.

Dark rates vs. MCP and photocathode voltage

Dark rates are a function of MCP voltage and photocathode voltage. The higher photocathode voltages tend to increase the gain, but they also increase the dark rates. Rates were acquired from one 0.09 cm^2 pixel. Some combinations of MCP and photocathode voltages can sharply increase the dark rates, simultaneously create high voltage current instabilities, and produce excess currents to ground within the HRPPD.

The Recommended Operating Point (ROP) voltages are selected by examination of the gain and dark rates as a function of MCP and photocathode voltage. The voltages are high enough to provide a gain in the mid-10^6 range, good transit time spread, and yet avoid high dark rates and high voltage current instabilities.

Transit Time Variation

The time variation between the initiation of a photoelectron and the arrival of the MCP pulse at the end of a strip is of interest for timing applications. This variation represents the timing uncertainty of the HRPPD. The time variation was measured by using a fast photodiode to directly monitor the 405 nm laser pulse. The time difference between the monitor pulse and the corresponding pulse from a single strip was measured using the DRS4 waveform samplers. The variation in this time is the transit time variation of the HRPPD. Variations may come from phenomena such as the depth to which the photoelectron advances into the microchannel before striking the walls of the channel. Additional variations arise from electronic noise superimposed on the strip measurement, and on the photodiode waveform. There is also a ~±25 pS jitter in the width of the DRS4 timesteps, which is not corrected here. Hence, the quality of the measurement is somewhat environment-dependent, and the result here may not be the best achievable with the HRPPD. Typically, the best transit time variation is found at an MCP voltage setting with a high gain before excess dark rates are observed, and with at least 100V on the photocathode.

The transit time variation was also measured as a function of photocathode voltage, at a fixed MCP voltage. Typically, the transit time variation improves rapidly with increasing photocathode voltage, up to about 50 volts. Above that, the variation continues to improve, but at a slower pace.

The 405 nm laser that is used for the HRPPD tests has a 19 pS FWHM firing window at the laser intensity used for the measurement. The intensity is further reduced by a neutral density filter to produce single photoelectrons. Therefore, the laser photon that produces the single electron may arrive at any time within the 19 pS window. The standard deviation of the distribution is measured. The variation of the laser photon is believed to have a standard deviation of (19/2.35) pS. Therefore, the HRPPD transit time variation may be extracted as a sum of squared variations using the following formula, where σ_{HRPPD} is the desired quantity:

$$\sigma_{\mathrm{Meas}}^2 = \sigma_{\mathrm{HRPPD}}^2 + \sigma_{\mathrm{LaserWidth}}^2.$$

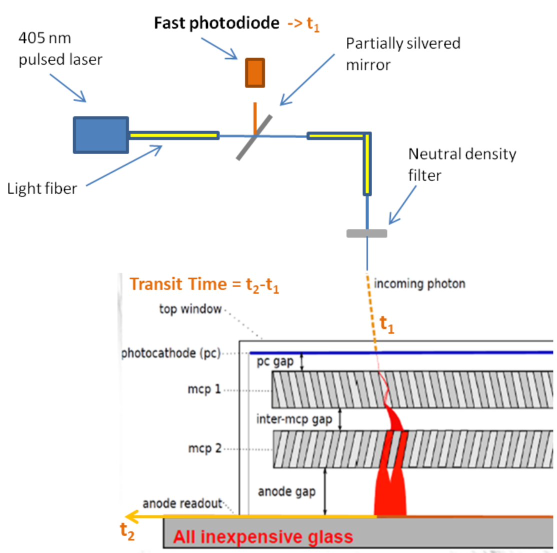


Figure 14: The measurement of the Transit Time Variation is shown.

Photocathode QE spectrum and map

The quantum efficiency of the photocathode was measured across the HRPPD window by scanning a 365 nm UV LED in an XY pattern of 2.5 mm steps. The illumination on the window had a circular pattern with a ~2.5 mm diameter. The intensity of the input light was measured with a Thorlabs SM1PD2A photodiode, and a Keithley 6485 picoammeter. The photocurrent was collected and measured by connecting both sides of the entry MCP to a Keithley 2400 picoammeter, with a 42 V bias voltage between the MCP and the photocathode. The quantum efficiency is calculated from the ratio of these two quantities, less the dark current in each.

The UV LED source was stepped across the HRPPD window, and at each step, the input light intensity was measured, as well as the resulting photocurrent.

A series of QE maps are made throughout testing, beginning at the fabrication chamber and the initial installation in the darkbox, and then after characterization in the darkbox. Before and after characterization, the average QE is measured at 365nm, 420nm, 455nm, and 565nm. Typically, the QE will not change during testing within the uncertainties of the QE measurement. Changes in QE that occur with operation would normally suggest that the photocathode degraded as a result of ion implantation of feedback ions, while changes that occur with elapsed time would suggest leakage. Variation of the average QE in the plots may be symptomatic of the uncertainty of the QE measurement.

A reduction in QE might occur if ions are ejected from the entry MCP through an ion feedback during operation. The electric field imposed on the MCPs to make the electron cascade move down to the anode will also drive loosely bound ions upward. If the ions implant in the photocathode, the composition of the photocathode, and therefore the ionization energy, could change.

MCP resistance vs. voltage

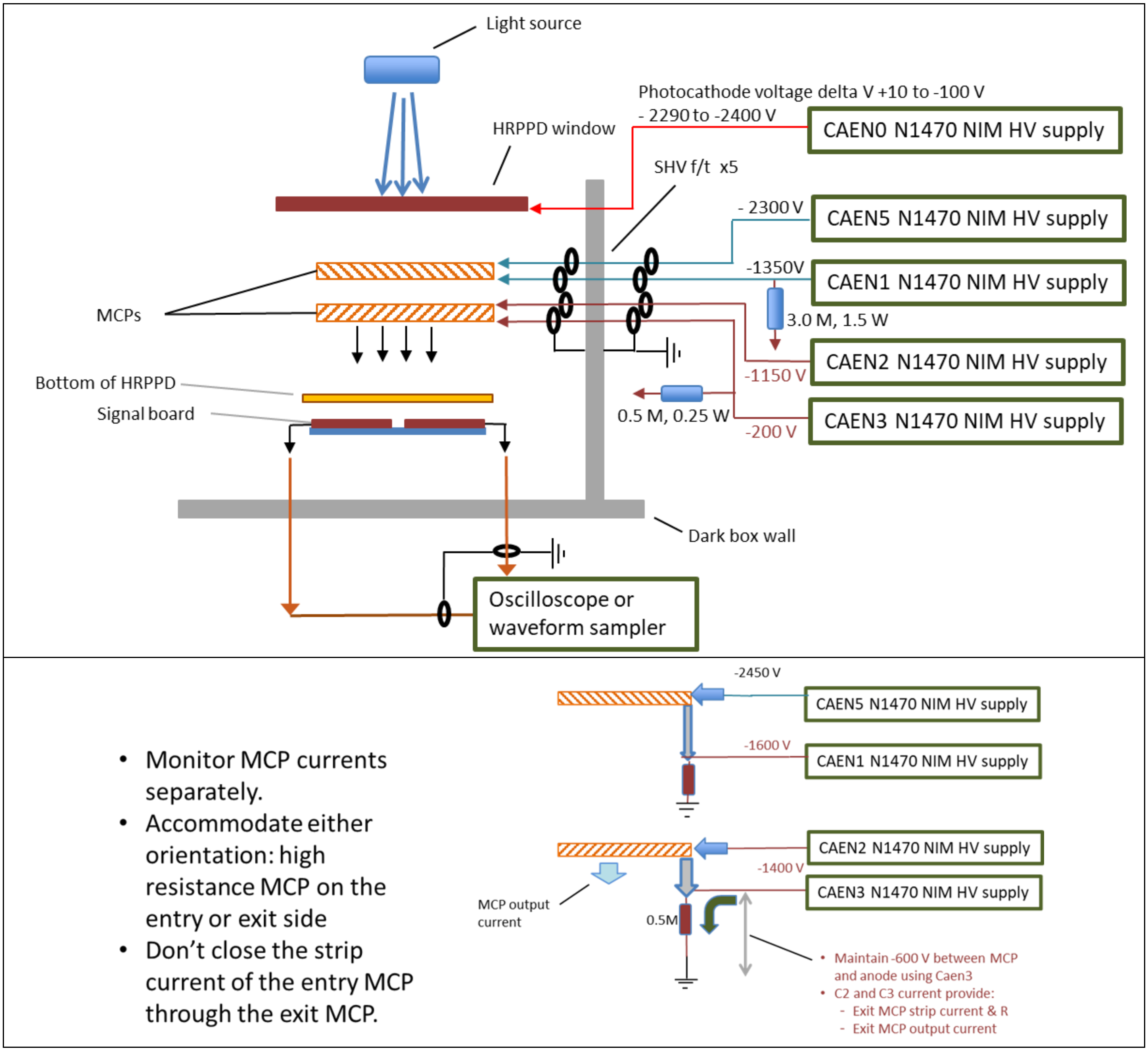
The MCP resistance is measured as a function of voltage. MCPs are non-ohmic, and their resistance decreases somewhat with increasing voltage. Some of this behavior may be attributed to warming, as the MCP resistance decreases with increasing temperature. The variation of resistance with voltage must be considered if a resistor divider network will be used to distribute high voltages.

High Voltage Stability vs. Voltage

The HRPPD is typically electrically stable up to 725V per MCP and up to 400V bias between the entry MCP and the photocathode. However, as the voltages across each MCP and the photocathode bias are increased, eventually the HRPPD will be driven into an unstable state where the currents start fluctuating by several to a few dozen µA and the dark rates sharply increase. The voltage settings at which this phenomenon occurs vary from HRPPD to HRPPD, but the ROP for each HRPPD is selected to maximize gain while nullifying the risk of driving the HRPPD into this unstable state. Typically, this unstable state occurs only when increasing voltage, and not when the HRPPD is left running. In fact, sometimes when the HRPPD is driven into this unstable state, the device will stabilize over time if left running.

High voltage connection diagram

The high voltages may be connected as shown in Figure 15 for maximum control of the HRPPD. This arrangement is used for all measurements at Incom. This approach separates the current paths of the entry and exit MCPs, so anomalies in either may be detected. Additionally, the photocathode voltage may be controlled independently of the MCPs. Without changing the MCP gain, the photocathode voltage may be increased, which will increase the HRPPD gain somewhat as the photoelectrons acquire more energy before impacting the microchannel. Alternatively, the photocathode voltage may be decreased so it is more positive than the entry side of the entry MCP. In this case, the photoelectrons will remain at the photocathode, and the MCP dark pulses may be observed. This state may also be used if an accidental exposure of the HRPPD to light is anticipated.



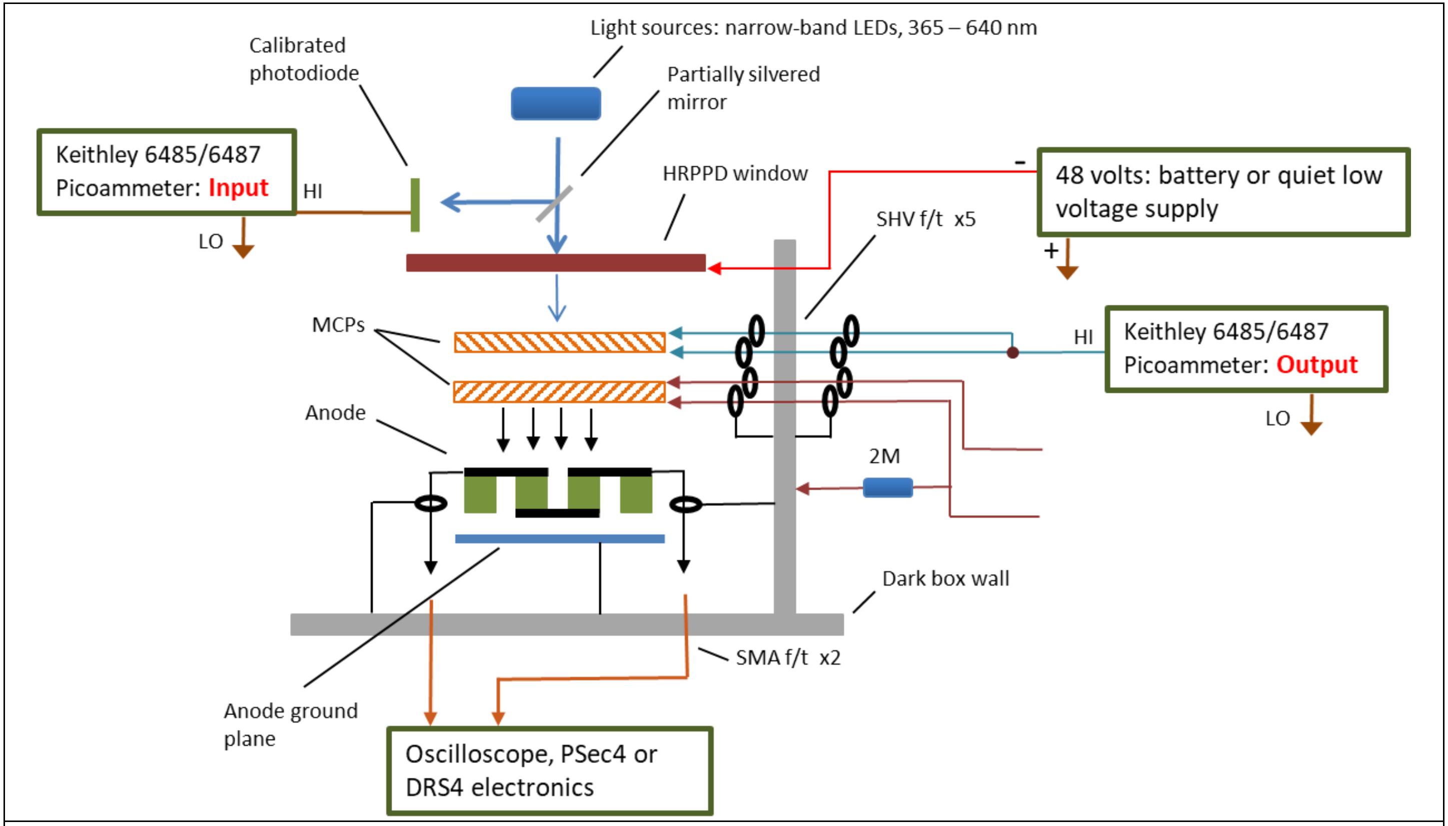


Figure 15: Top - The wiring diagram for high voltage and signals is shown for the HRPPD gain and timing testing at Incom.

Please Note: Voltages shown are for generic operation of standard Incom detectors. Please consult Table 2 and the ROP for voltages used during standard testing.

Middle - A schematic shows the separation of the two MCP current paths, and the techniques used to separately measure the output current to the anode and the strip current through the exit MCP.

Bottom - The wiring diagram for the QE measurement is shown. The exit MCP and the anode are not involved in this measurement. Instead, the entry MCP serves as the anode for the photocurrent.

Signal and High Voltage Connectivity

An ultem housing and a backplane are provided with each HRPPD (Figure 16). The backplane connects the strips to SMA connectors with near-50 Ω impedance. The ultem housing provides the high voltage connections. They consist of SHV panel mount connectors on the outside, and Mill-Max spring-loaded ball tip pins on the inside. The pins touch the high voltage pads on the HRPPD envelope. The 5 high voltage connectors are labeled according to their function. The shields on the SHV connectors simply terminate the high voltage cable shield, and minimize unwanted signal pickup in the detector. They do not close any high voltage current paths.

Packing

The HRPPD is wrapped in an antistatic bag and placed in a Pelican case with foam (Figure 16). The bag helps manage static charging, which could be harmful to charge-sensitive electronics that will be attached to it. It also keeps unnecessary stray light from exciting the photocathode, and charging the entry MCP.

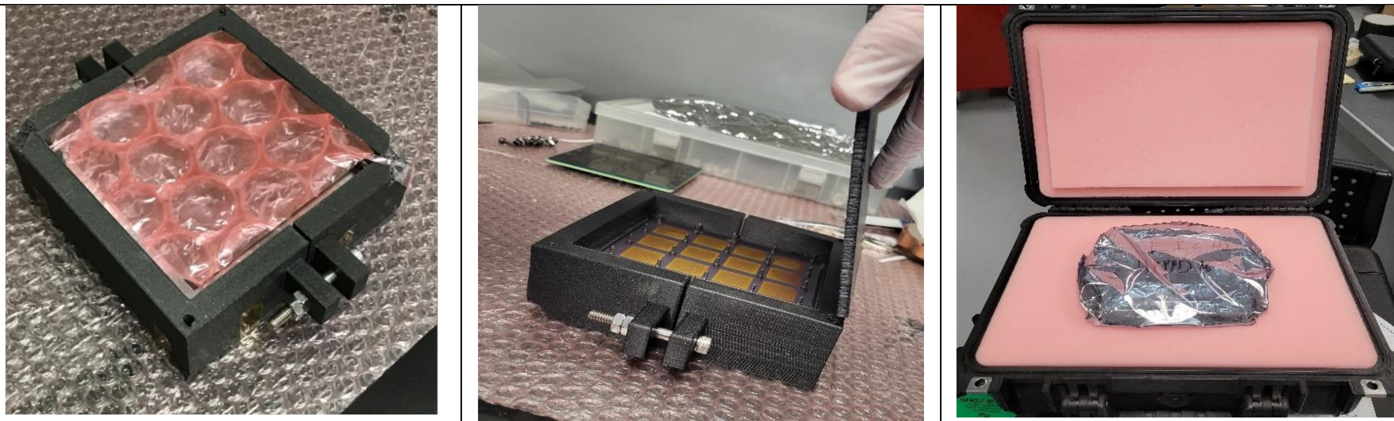


Figure 16. Left: The bare HRPPD is enclosed in an Ultem housing. **Center:** The bottom of the detector is covered to protect the pins, screws, and interposer contact points. **Right:** The HRPPD is wrapped in foil to manage static charging, and to keep stray light from the photocathode. It is additionally covered in antistatic bubble wrap and a Mylar bag.