# Measurement & Test

# Report

# LAPPD 153

# 01/27/2023

## Contents

**LAPPD 153 Specific Performance** .......... 3
Summary .......... 3
LAPPD 153 General Features and Parameters: .......... 3
LAPPD 153 Operational Ratings .......... 3
LAPPD Package / Housing Characteristics .......... 3
LAPPD 153 Microchannel Plate (MCP) Features & Performance .......... 4
LAPPD 153 Operating Performance (ROP = Recommended Operating Point) .......... 4
Gain .......... 5
Dark Rates .......... 8
Transit Time Variation .......... 10
High Voltage Stability vs. Voltage and MCP Resistance vs. Voltage .......... 10
Footnotes .......... 12
**LAPPD Testing Protocols** .......... 13
Introduction .......... 13
Gain .......... 13
Gain vs. MCP voltage .......... 13
Gain vs. repetition rate .......... 13
**Dark rates vs. MCP and photocathode voltage** .......... 13
**Transit Time Variation** .......... 14
Photocathode QE spectrum and map .......... 15
MCP resistance vs. voltage .......... 15
High Voltage Stability vs. Voltage .......... 15
High voltage connection diagram .......... 16
Signal and High Voltage Connectivity .......... 18
Packing .......... 19

# LAPPD 153 Specific Performance

## Summary

LAPPD 153 has single photoelectron gain in the low $10^6$–$10^7$ range. Simultaneously, it has dark rates in the ~0.1-10 kHz/cm$^2$ regime. Gain is sustained at high rates, falling to two-thirds of nominal gain at 100 kHz/mm$^2$. Quantum efficiency is 21.0% at 365 nm, and is spatially uniform to the 0.8% level. This LAPPD can be used in applications requiring external triggering on single photons.

| | |
|---|---|
| Seal Date | 12/22/2022 |
| Pilot Production / Experimental | Experimental Production |
| Version | Gen II |
| Important Features | Mild but long-lasting current and dark rate instability |
| Quality Grade (Production vs. Development) | Development |
| Pass / Fail | Pass |
| Analysis | |
| Disposition | Brookhaven National Laboratory |

### LAPPD 153 General Features and Parameters:

| Feature | Parameter |
|---|---|
| Photodetector Material | Gen II, ceramic lower tile assembly; interior resistive anode |
| Window Material | Fused silica glass, 5.0 mm thick |
| Photocathode Material | Multi-Alkali ($Na_2KSb$) |
| Spectral Response (nm) | 160-650 |
| Wavelength – Maximum Sensitivity (nm) | ≤ 365 nm |
| Photodetector Active Area Dimensions | 195mm X 195mm |
| • Minimum Effective Area | 373cm$^2$ |
| • Active fraction with Edge Frame Rib-Spacers | 97% |
| Anode Configuration | Interior resistive ground plane |
| Voltage Distribution | 5 taps for independent control of voltage to the photocathode and entry and exit of MCP |

### LAPPD 153 Operational Ratings

| Parameter | Rating |
|---|---|
| Supply voltage Photocathode — Anode (Volts) | Typical:<br>50V between MCP and photocathode<br>• 875 V/MCP<br>• 200 V between MCPs<br>• 200 V between MCP and anode<br>• Photocathode voltage is -2200 V<br>Maximum: Photocathode voltage at -2200 V |
| Operating ambient temperature °C | TBD (nominal room temperature) |
| Storage temperature °C | -12 to 50 (Avoid indium seal melt) |

### LAPPD Package / Housing Characteristics

| Parameter | Rating |
|---|---|
| Photodetector Physical Dimensions (L X W X Thickness, mm) | 230 x 220 x 22 |
| Photodetector Mounting Case | ULTEM or equivalent dielectric polymer |
| Photodetector Mounting Case Dimensions | 243 mm X 274 mm X 25.2 mm |
| Connectivity | Passive PC Interface Board, |

| | |
|---|---|
| | (300 mm X 264 mm X 1.6mm) |
| Overall Footprint, with Mounting Case & PC Interface Board | 300 mm X 274 mm X 26.8 mm |
| Shipping Container | Pelican Case + Cardboard Box + G-force indicators |

## LAPPD 153 Microchannel Plate (MCP) Features & Performance

| | |
|---|---|
| MCPs | Two Arranged in a Chevron Pair |
| Dimensions | 203 mm x 203 mm X 1.2 mm |
| MCP Substrate | Incom C5 Glass |
| Capillary Pore Diameter (µm)<br>Center to Center Pitch (µm) | 10<br>13 |
| Channel Length / diameter<br>Substrate Thickness (mm) | 60:1<br>0.6 |
| Bias Angle | 13 |
| Capillary Open Area Ratio | ≥65% |
| Resistive and Emissive Coatings | Chem 1, 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) | CJ19574001-007 / CJ19574001-027 |
| MCP resistance, Entry/Exit (at LAPPD M&T) | 5.5/5.6 MΩ at 900 V |
| MCP Dark Rate in the tile<br>(Obtained by setting the photocathode more positive than the entry MCP) | 5.7 Hz/cm$^2$ at a threshold of 8x10$^5$ gain (134 fC), 900 V/MCP, 10 V positive on photocathode [A] |
| Max Voltage | 900/900 V/MCP (entry/exit), with -2,210 volts on the photocathode; dark rate limited. |

## LAPPD 153 Operating Performance (ROP = Recommended Operating Point)

| **Parameter** | **Performance** |
|---|---|
| Photocathode Quantum efficiency @ 365 nm | Mean QE (@365 nm) = 21.0%, Maximum: 24.8% |
| Photocathode QE Spatial Variability (σ) | 0.8% |
| ROP Voltages | 200V above anode, 200V between MCPs, 875V/MCP, 50V on photocathode |
| LAPPD Gain @ ROP | 7.45x10$^6$ |
| LAPPD Gain @ 10V on Photocathode, 875V MCP | 1.01x10$^7$ |
| LAPPD Dark Count rate @ ROP (threshold = 4mV) | 2.1 kHz/cm$^2$ at a threshold of 8x10$^5$ gain (134 fC), 875 V/MCP, 50 V on photocathode [A] |
| Dark Rate @ 10 V on PC, 900V MCP | 2.72 kHz/cm$^2$ |
| Optimal Transit Time Variation (single P/E) | 64.8 pS |
| Note: INCOM TTS results are “Provisional”. Work recently done at INFN Bologna Italy shows that Incom reported TTS understate the true timing capability of LAPPD. Efforts at Incom are now focused on resolving calibration issues and other factors that can introduce jitter into the TTS result. | |
| Position Resolution Along/Across Pads (mm) (typical, not measured for this tile) | Not measured for this tile |

## Gain

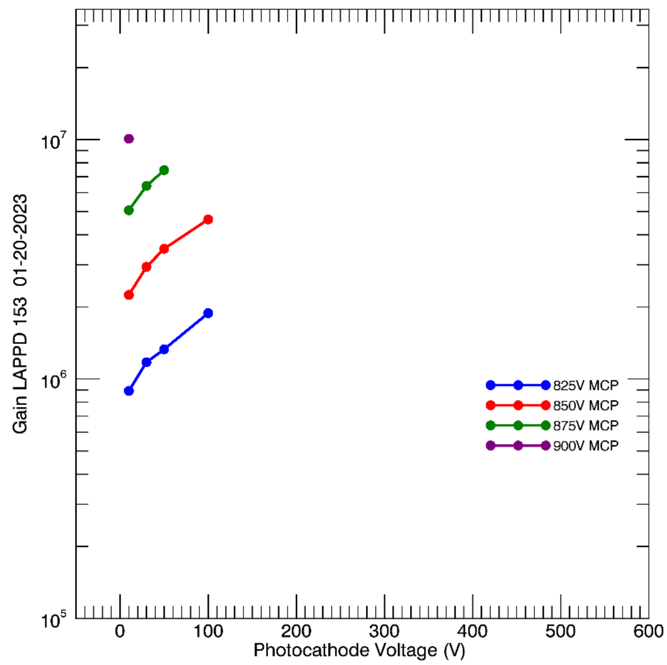



**Figure 1:** Average gain is shown vs. MCP and photocathode voltage, as measured with PSI DRS4 waveform samplers at Pixel D4. [A]

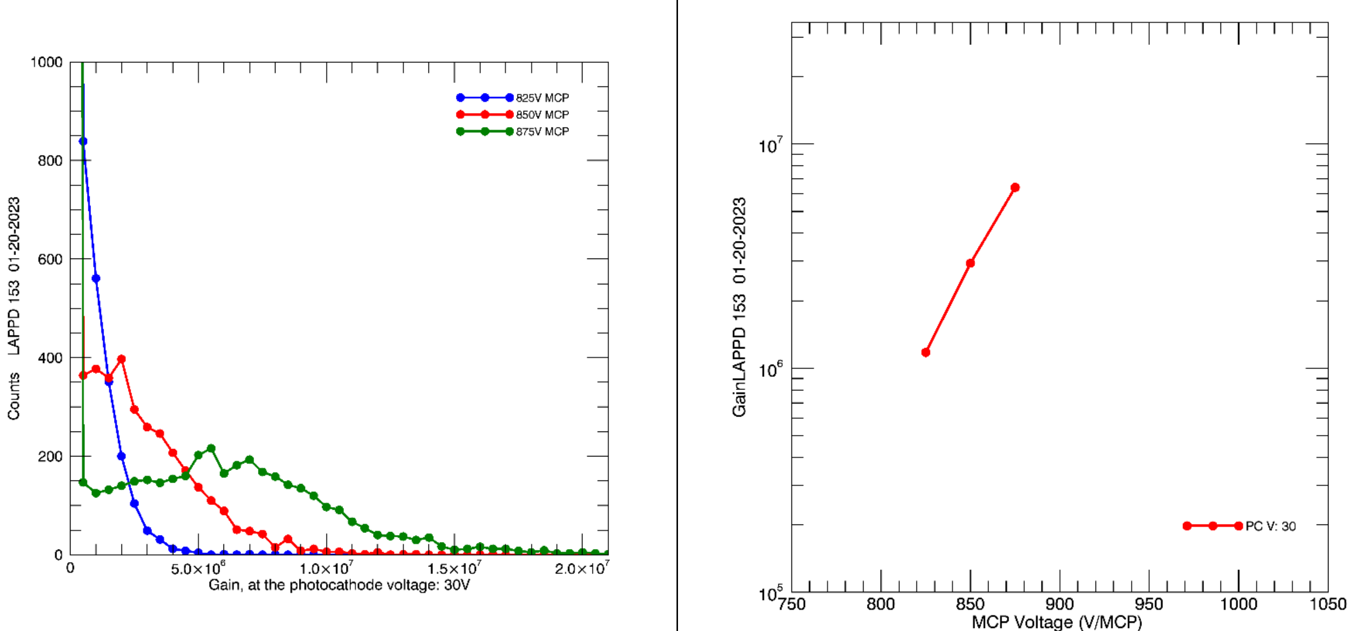



**Figure 2:** Gain is shown as a function of MCP voltage, with 30 V on the photocathode.[A] **Left**: pulse height distributions. **Right**: Average gain vs. MCP voltage.

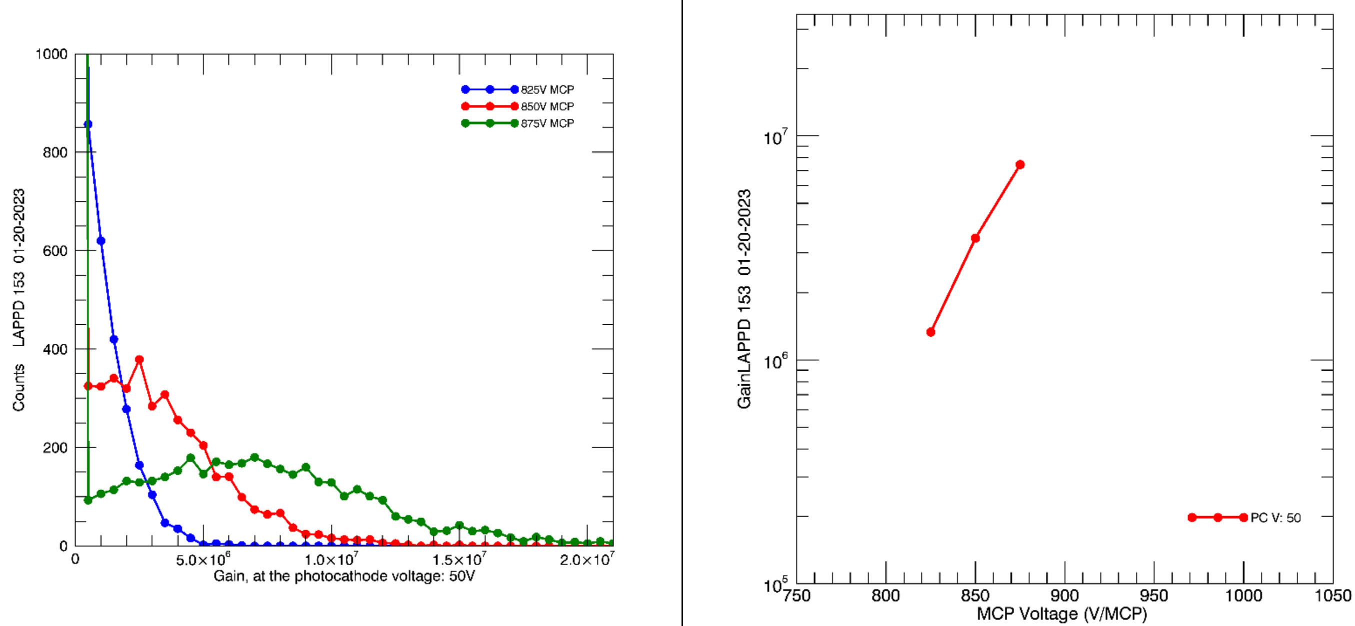



**Figure 3**. Gain is shown as a function of MCP voltage, with 50 V on the photocathode.[A] **Left**: pulse height distributions. **Right**: Average gain vs. MCP voltage.

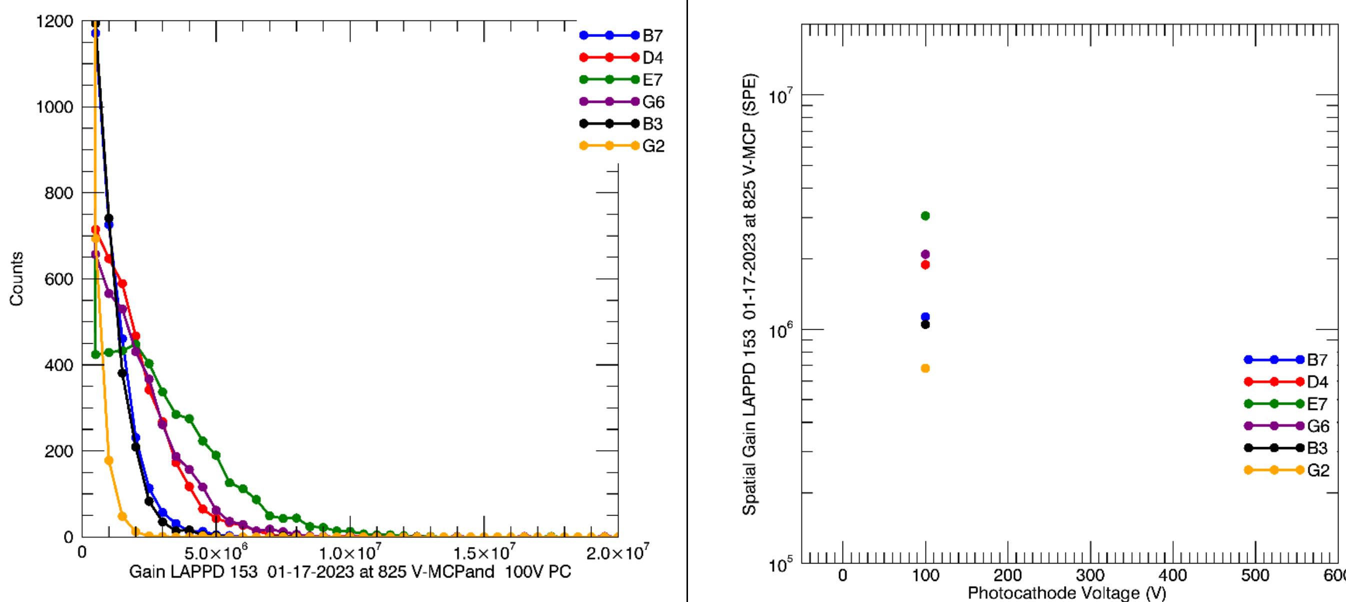



**Figure 4**. Gain is shown as at 825 V/MCP and 100V on the photocathode at six different pixels.[A] **Left**: pulse height distributions. **Right**: Average gain vs. PC voltage.

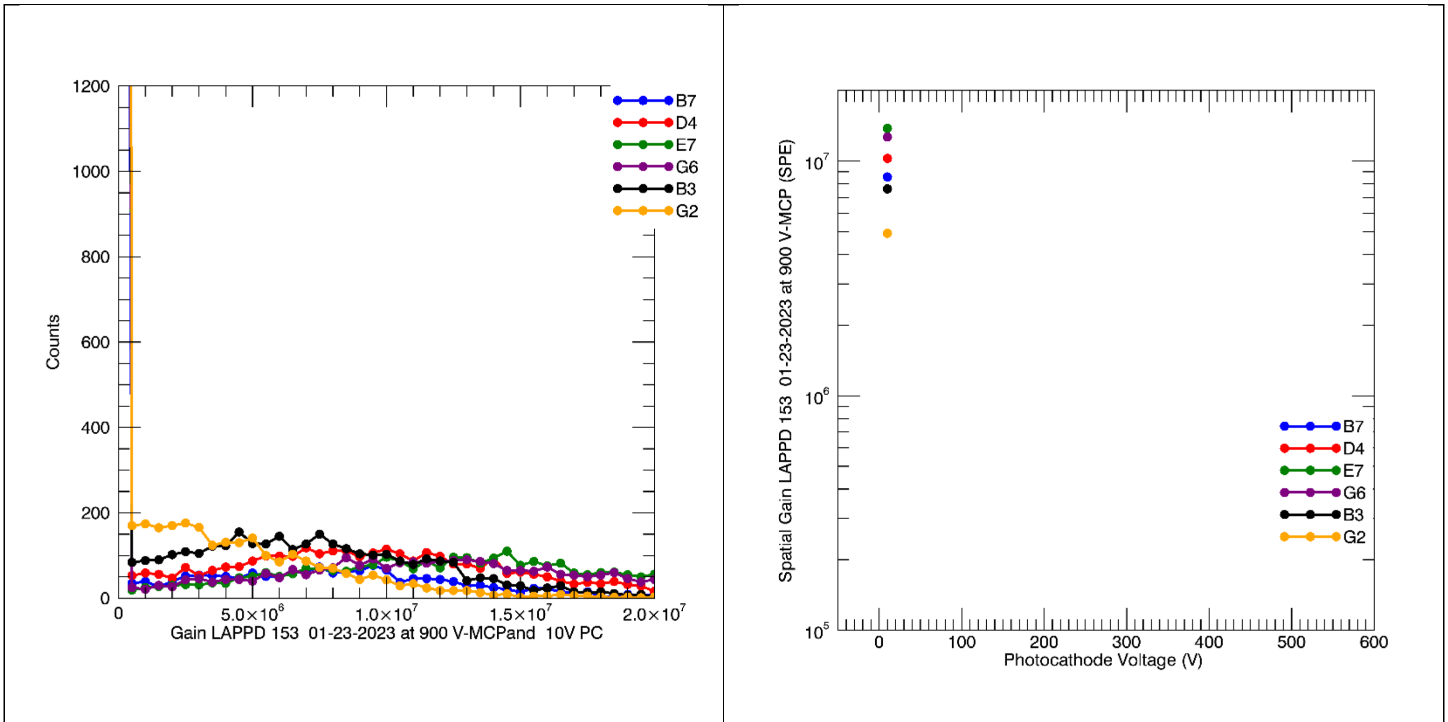



**Figure 5**. Gain is shown as at 900 V/MCP and 10V on the photocathode at six different pixels.[A] **Left**: pulse height distributions. **Right**: Average gain vs. PC voltage.

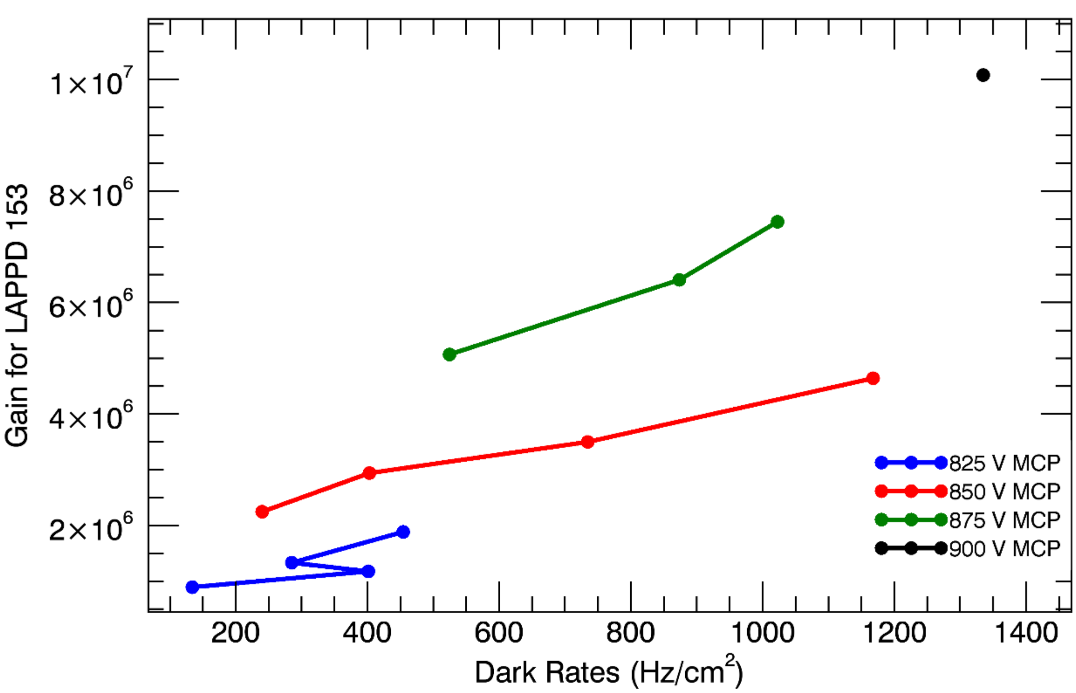



**Figure 6**. Gain at Pixel D4 is shown as a function of dark rates found on the adjacent Pixel D3.[A]

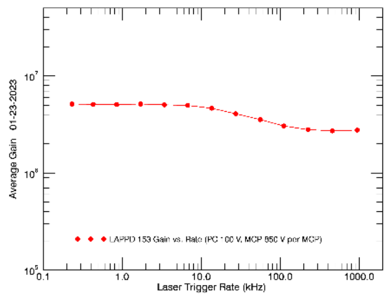



**Figure 7:** Gain is shown vs. laser repetition rate for single photoelectrons. [A]

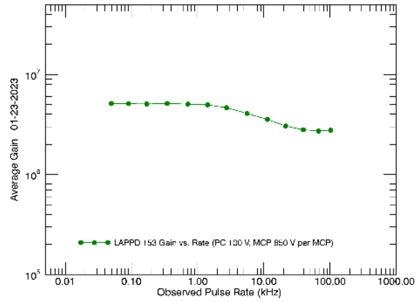



**Figure 8:** Gain is shown vs. observed pulse rate for single photoelectrons.

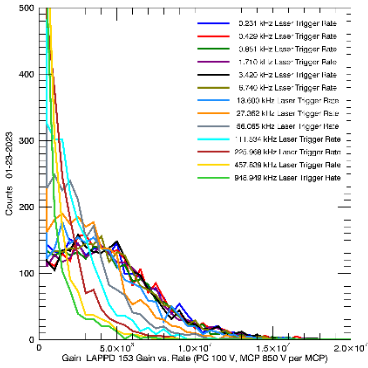



**Figure 9:** The pulse distributions are shown as a function of laser trigger rate.

## Dark Rates

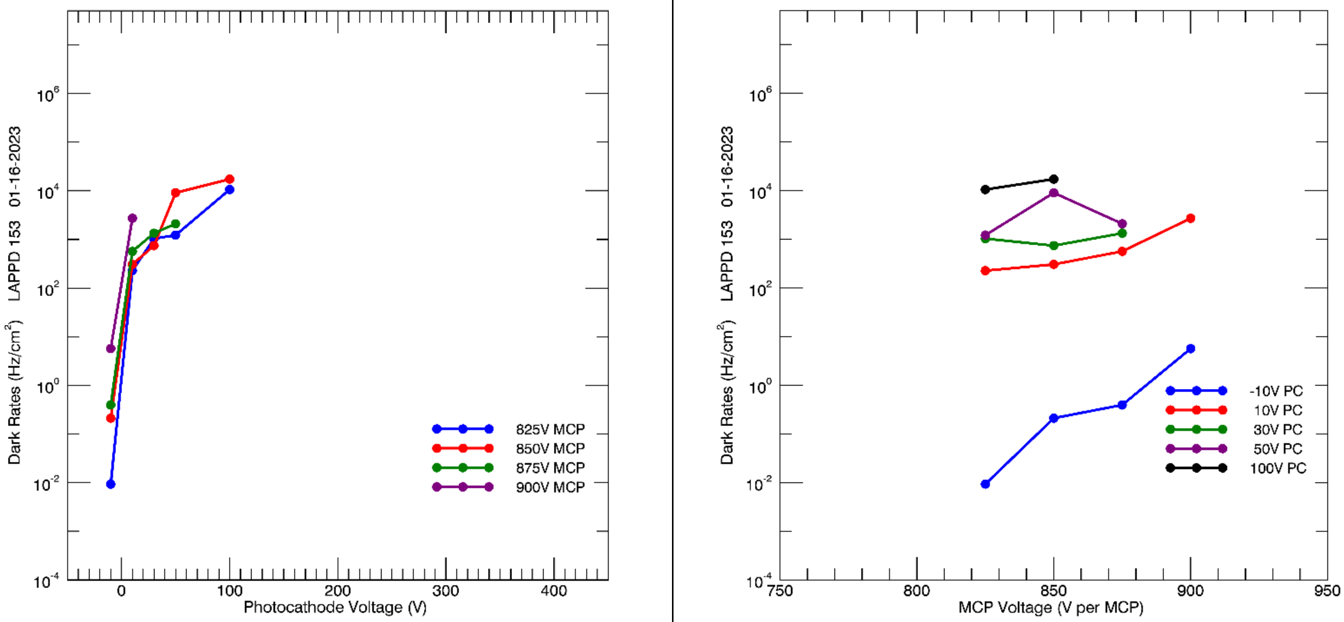



**Figure 10:** Dark rates as a function of photocathode and MCP voltage averaged at four pixels.[A]

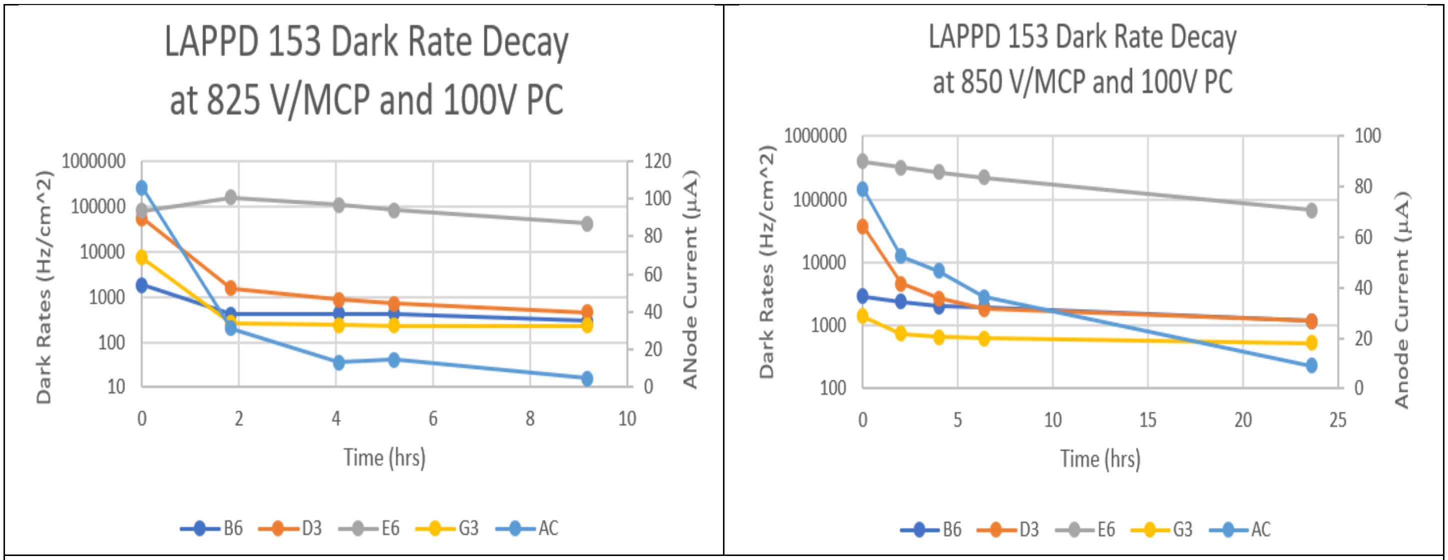



**Figure 11:** Dark Rate and Anode Current (AC) Decay for each of pixels.[A] **Left:** at 825 V/MCP and 100V on the photocathode. **Right:** at 850 V/MCP and 100V on the photocathode.

### Photocathode QE Spectrum

| Date | Mean QE | Max QE |
|---|---|---|
| 01/06/2023 | 21.2 ± 0.91% | 25.8% |
| 01/28/2023 | 21.0 ± 0.8% | 24.8% |

**Table 1**: Quantum efficiency measurements at 365 nm on LAPPD 153 are listed.

### QE Scans

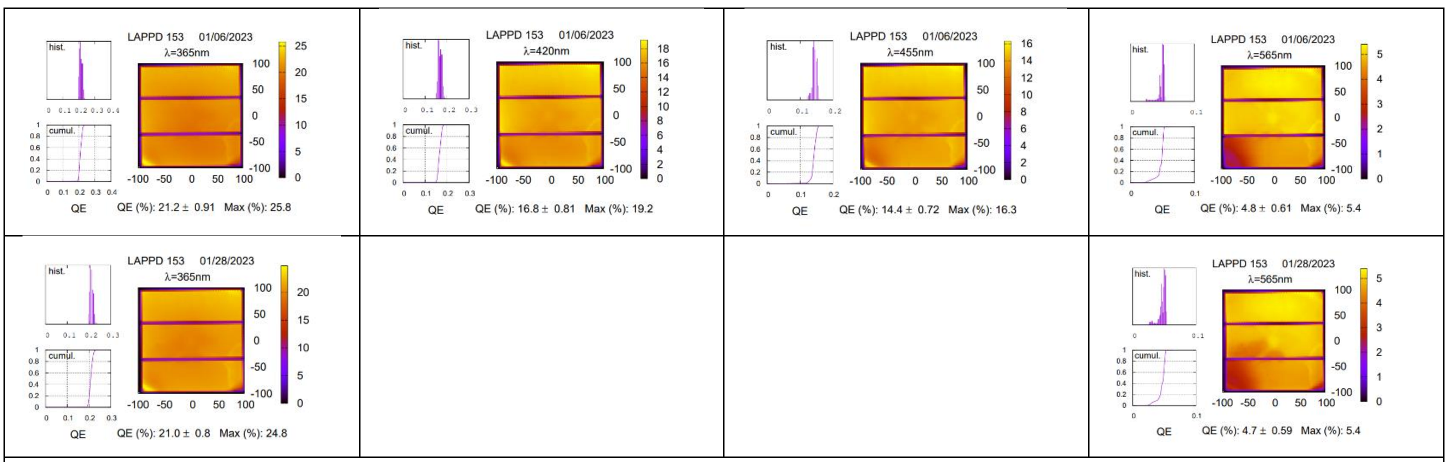



**Figure 12.** QE Scan data. The columns are scans done at different wavelengths. The rows are different test dates.

## Transit Time Variation

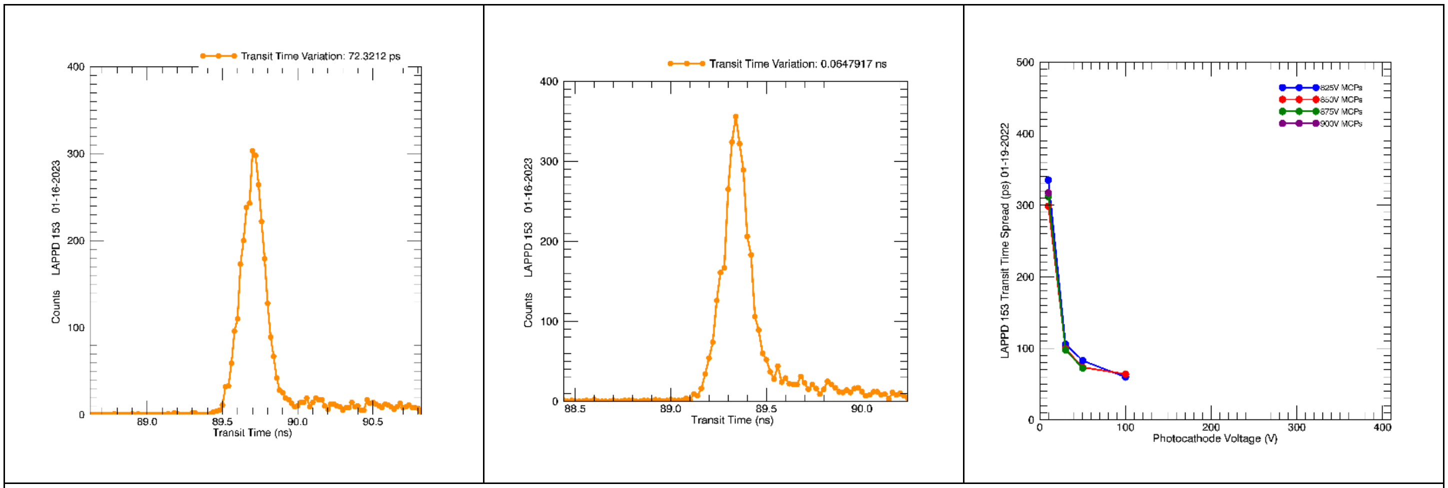



**Figure 13. Left:** The transit time variation is shown for 875 V/MCP and 50 V on the photocathode. This is the time difference between the observed laser firing and the arrival of the MCP pulse at the end of the pixel-transformer chain. **Center:** The transit time variation is shown for 825 V/MCP and 100 V on the photocathode. This is the time difference between the observed laser firing and the arrival of the MCP pulse at the end of the pixel-transformer chain. **Right**: The transit time variation is shown as a function of photocathode voltage for different MCP voltages.

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

The high voltages and currents are shown in Figure 10 for operation of LAPPD 153 over the nominal voltage range. The channel numbers in the figure correspond to labels in the high voltage wiring diagram of Figure 19. The photocathode and MCP voltage combinations shown in Figure 1 may be used without driving the LAPPD into a state of high voltage current instabilities.

In Figure 14, Channel 0 is applied to the photocathode. Channel 1 is applied to the exit of the entry MCP, and Channels 2 and 3 are applied respectively to the top and bottom of the exit MCP. In Figure 15, Channel 3 is applied to the entry of the entry MCP, while the rest are not connected. The left panels of Figures 14 and 15 show the voltages applied. The right panels show the corresponding currents. The green trace in Figure 14 is the strip current in the exit MCP. It is routed to ground through a resistor between the exit MCP and ground. The corresponding yellow trace in Figure 14 is additional current provided to the resistor, to maintain 200 or 300 volts. The yellow current trace is complementary to the green trace – when the exit MCP strip current is low, the yellow current trace goes high enough to maintain 200 volts across the resistor (Figure 14, right).

The sum of the Ch 2 and Ch 3 currents should be 400 microamps when 200 volts are applied to the gap between the MCP and anode, because they are the currents in the 0.5 MΩ resistor between the exit MCP and ground (see Figure 19 “2M” resistor, middle panel). An increase in the green Ch 2 trace into the exit MCP will be matched by a corresponding decrease in the yellow Ch 3 current. If the sum of Ch 2 and Ch 3 currents exceeds 400 microamps, then current supplied to the entry side of the exit MCP is partly going through the MCP as expected, but partly going around the MCP to ground via another path, including directly to the anode.  These increases can be caused by increases in both MCP and photocathode voltage.

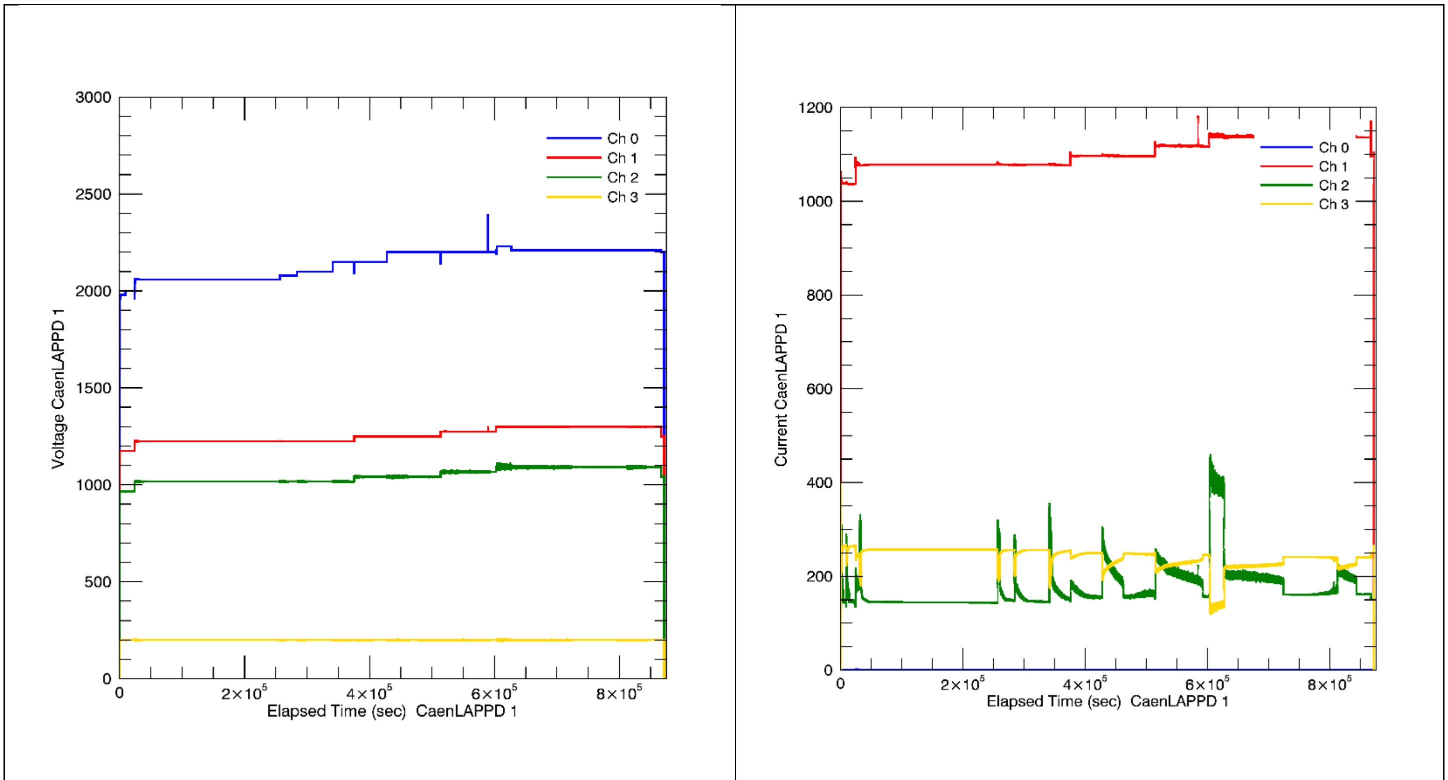



**Figure 14**: The high voltages (left) and currents (right) are shown for LAPPD 153 operation for CAEN0-3. Stability is demonstrated up to 900 V/MCP.

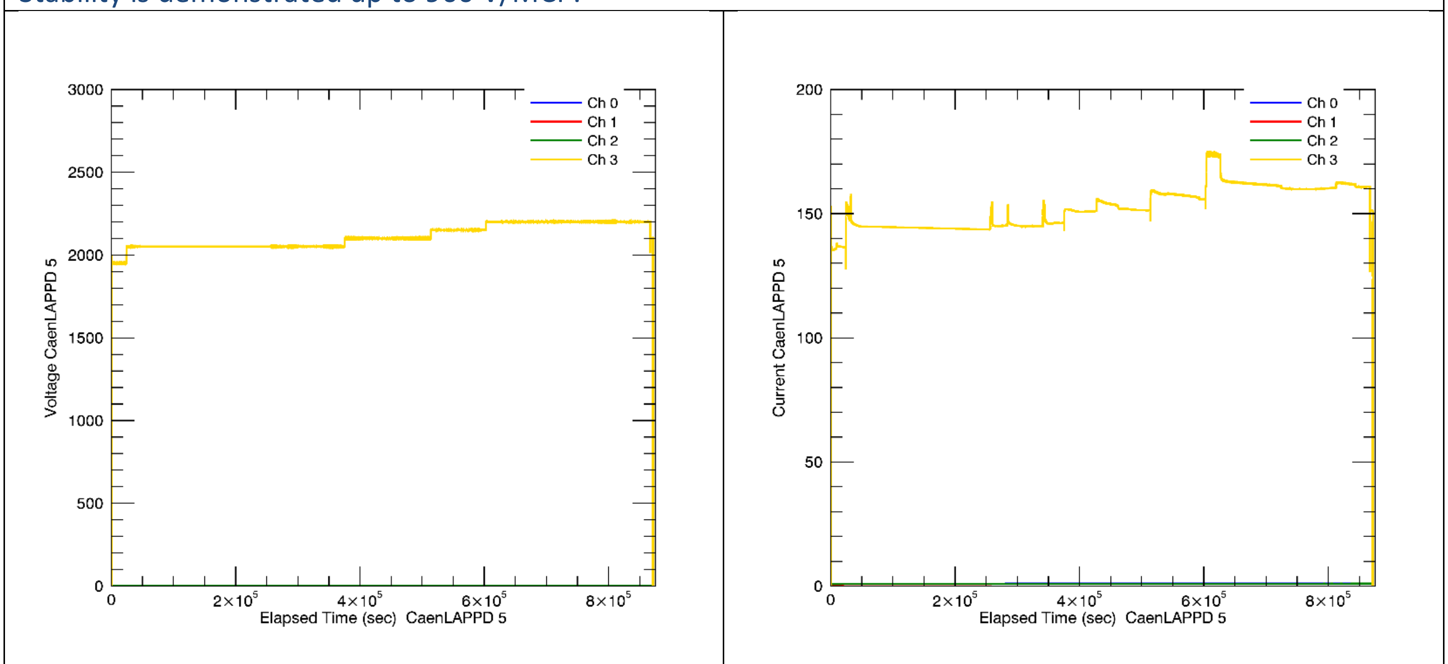



**Figure 15**: The high voltages (left) and currents (right) are shown for LAPPD 153 operation for CAEN5. Stability is demonstrated up to 900 V/MCP.

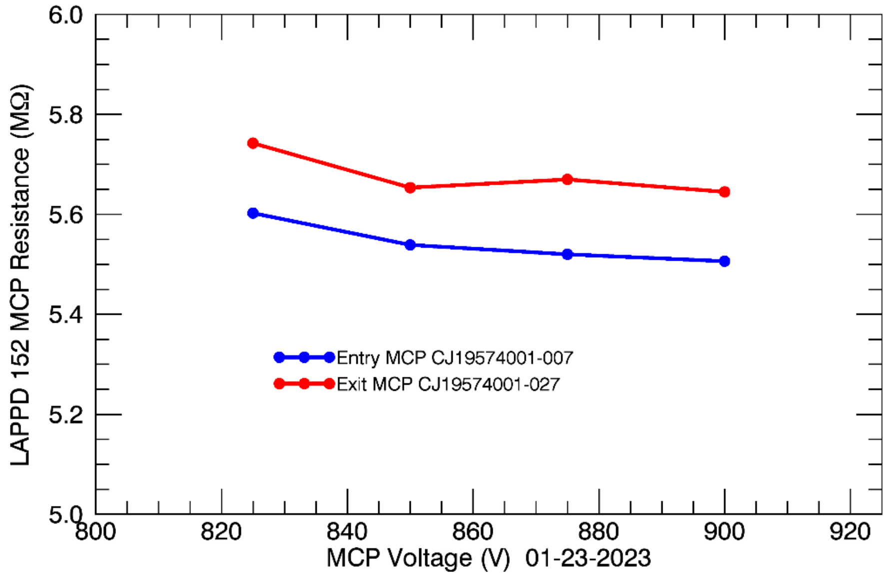



**Figure 16:** MCP resistances are shown for LAPPD 153.[A]

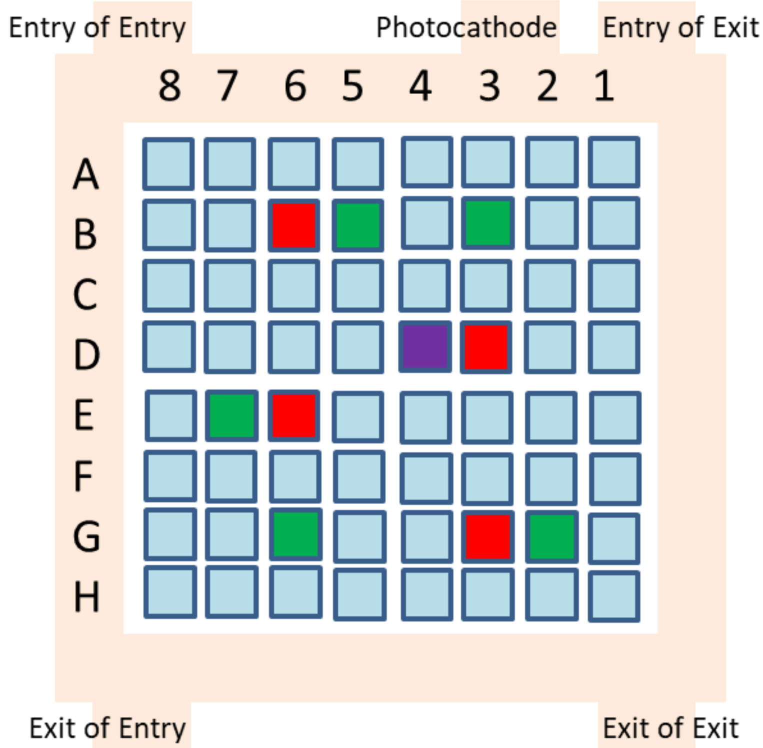



**Figure 17:** Layout for pads used to test LAPPD 153 (as seen looking directly at the front of the detector). The pad highlighted in purple was used to collect waveforms for gain, gain vs rate, and transit time spread. The pads highlighted in green were used to collect data for spatial gain calculations. The pads highlighted in red were used to collect dark rates. Light blue pads were not used. [A]

## Footnotes

A LAPPD 153 01/13/2023 Data.xlsx

# LAPPD Testing Protocols

## Introduction

Functional tests were performed on the LAPPD 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 LAPPD 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 LAPPD responded 15-30% of the laser pulses.

The gain results are a function of both MCP and photocathode voltage. The average LAPPD gain for single photoelectrons is as high at $1.01 \times 10^7$ at 900 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 LAPPD window, of about 1 mm in diameter. The repetition rate was changed, and the corresponding gain was measured. Based on Photocathode QE, the LAPPD 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 $1 \times 10^7$ to $5 \times 10^6$.

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.

### 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 a single 13.5 cm$^2$ strip.

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 LAPPD.

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 LAPPD. 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 LAPPD. 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 LAPPD. 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 LAPPD 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 LAPPD transit time variation may be extracted as a sum of squared variations using the following formula, where $\sigma_{LAPPD}$ is the desired quantity:

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

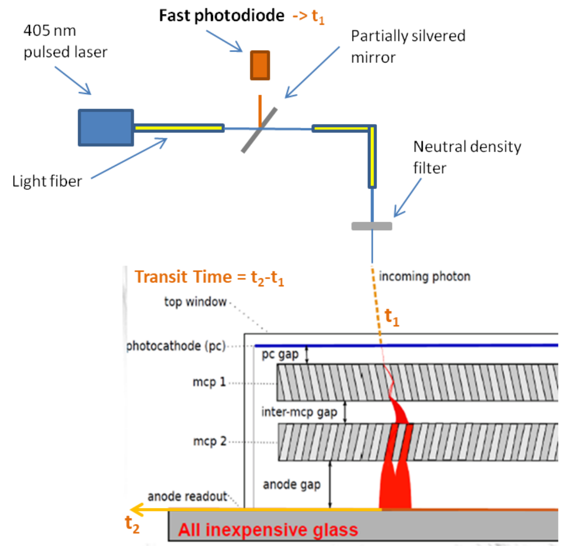



**Figure 18:** The measurement of the Transit Time Variation is shown.

## Photocathode QE spectrum and map

The quantum efficiency of the photocathode was measured across the LAPPD window by scanning a 365 nm UV LED in an XY pattern of 3 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 6485 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 LAPPD window, and at each step, the input light intensity was measured, as well as the resulting photocurrent. The X-spacers are visible in QE maps.

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

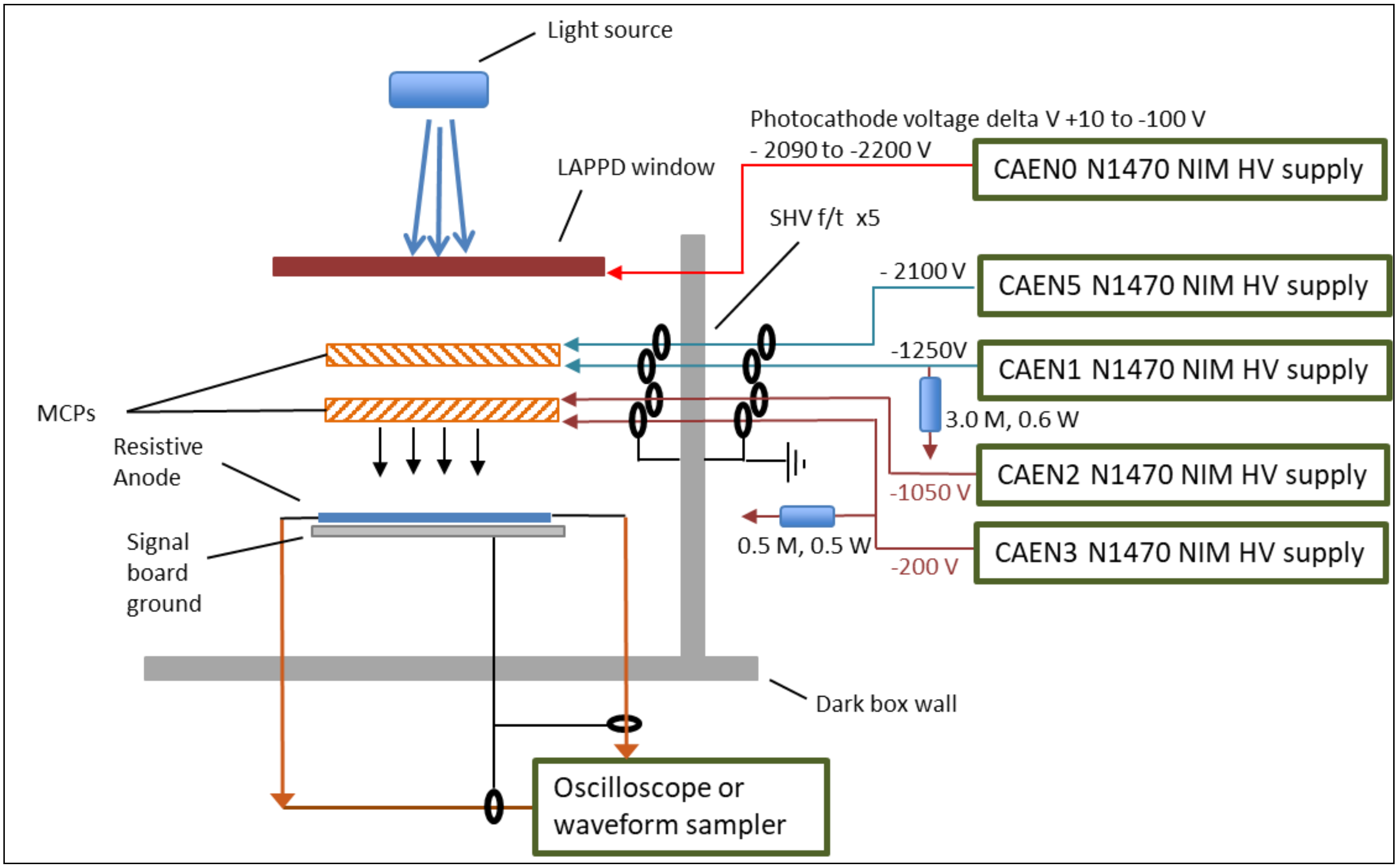
The MCP resistance is measured as a function of voltage. MCPs are non-ohmic, and their resistance decreases somewhat with increasing voltage. Some of this behavior may be attributed to warming, as the MCP resistance decreases with increasing temperature. The variation of resistance with voltage must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

## High Voltage Stability vs. Voltage

The LAPPD is typically electrically stable up to 1000V 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 LAPPD 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 LAPPD to LAPPD, but the ROP for each LAPPD is selected to maximize gain while nullifying the risk of driving the LAPPD into this unstable state. Typically, this unstable state occurs only when increasing voltage, and not when the LAPPD is left running. In fact, sometimes when the LAPPD 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 19 for maximum control of the LAPPD. 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 LAPPD 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 LAPPD to light is anticipated.



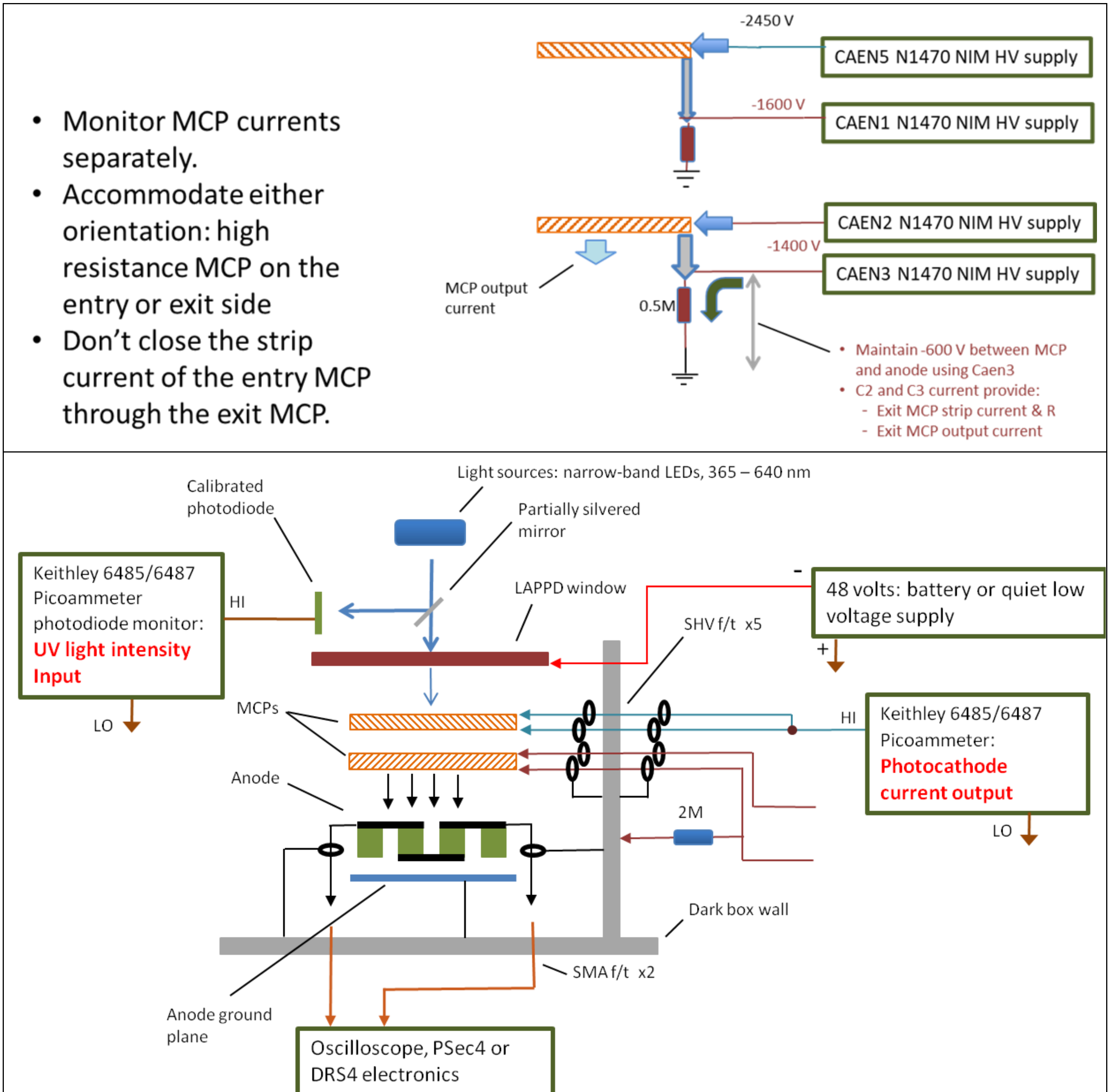



**Figure 19:** Top - The wiring diagram for high voltage and signals is shown for the LAPPD gain and timing testing at Incom.

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 LAPPD (Figure 20). 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 LAPPD 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 LAPPD is wrapped in an antistatic bag and placed in a Pelican case with antistatic foam (Figure 20). 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.

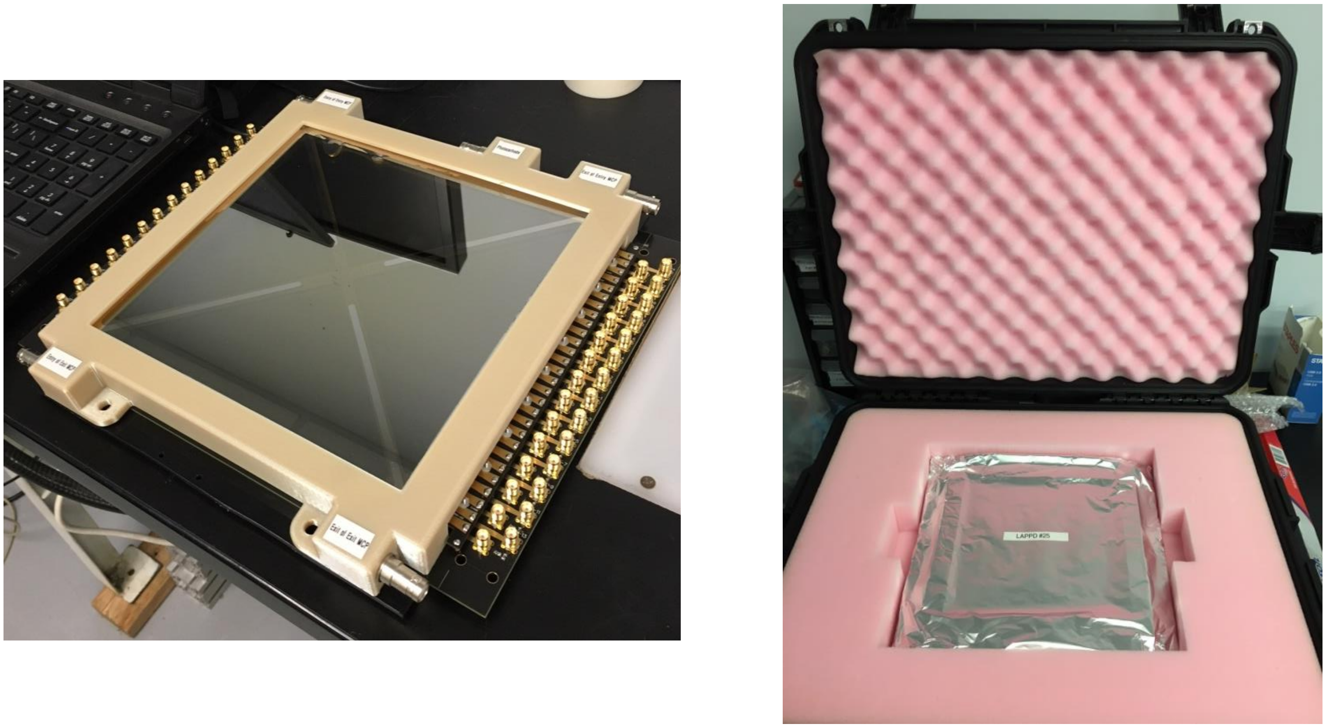


**Figure 20:** Left - the LAPPD is enclosed in an Ultem housing with high voltage connectors, and mounted on a backplane for signal access. Right - The LAPPD is wrapped in foil to manage static charging, and to keep stray light from the photocathode.