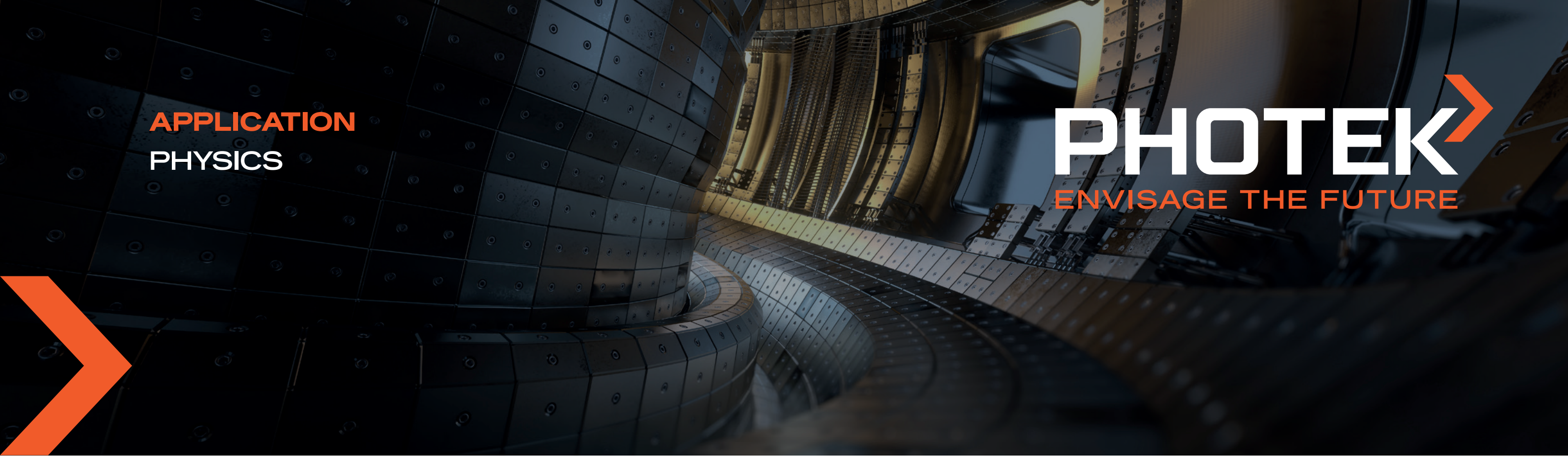

APPLICATION
PHYSICS

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Neutron Time-of-Flight (nToF) Diagnostics for Fusion Research

Physicists have pursued fusion technology for decades as it promises a potential source of near-limitless clean energy using only isotopes of Hydrogen, the most abundant atom on earth.

Photek has a long history providing the fusion community with ultra-fast light detectors critical to diagnostics used in Inertial Confinement Fusion (ICF). In ICF high power lasers, or a combination of lasers and pulsed power, heat a small capsule with varying amounts of Deuterium and Tritium - isotopes of Hydrogen. This causes the confined plasma to implode, generating the enormous sun-like temperatures and densities required for fusion to occur. During the fusion process the Hydrogen isotopes are converted into Helium and neutrons plus excess energy that can be used to generate electricity.

Three US based facilities at the forefront of ICF are the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in California, the Omega facility at the Laboratory for Laser Energetics at the University of Rochester in New York, and the Z Machine at the Sandia National Laboratory in New Mexico. All three of these facilities utilize Photek products in their nuclear diagnostics, including Photomultiplier Tubes (PMT), Pulse Dilation PMTs (PD-PMT), Image Intensifier Tubes and Streak Tubes.

Photek recommends

- **Photomultiplier Tubes** (PMTs)
- **Pulse Dilation PMTs** (PD-PMT)
- **Image Intensifier Tubes**
- **Streak Tubes**

MCP-Photomultiplier Tube

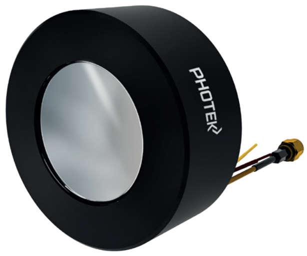
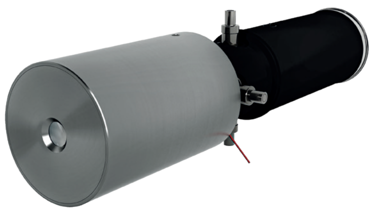


Image Intensifier



Streak Tube

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Instrumentation

The ICF implosion happens extremely fast, as fast as tens of picoseconds where one picosecond is 0.000000000001 seconds. This is an extremely short period of time that is very difficult to measure using traditional techniques. It is a billion times faster than normal video rates.

Our detectors are used to probe what's happening in these implosion experiments to provide scientists insights into fusion reaction dynamics, the efficiency of energy production, and the behaviour of plasma confinement. This information is used to improve the ICF process and to reach ever higher releases of energy.

Each implosion generates many neutrons: neutral particles that normally are confined in atomic nuclei along with protons and gamma-rays. The sheer number of these particles generated creates a severe radiation environment around the implosion chamber and can damage many common types of diagnostic instruments. The vacuum tube technology used in Photek detectors can survive these high levels of radiation, also making them a valuable technology for the harsh radiation environment of space. Photek photodetectors not only survive the harsh radiation environment near the ICF implosions, but they are also among the world's fastest light detectors.

Diagnostic Techniques

An important diagnostic technique used in ICF experiments is neutron time-of-flight (nToF). Since the neutrons are directly generated in the fusion process they contain important information about each implosion event.

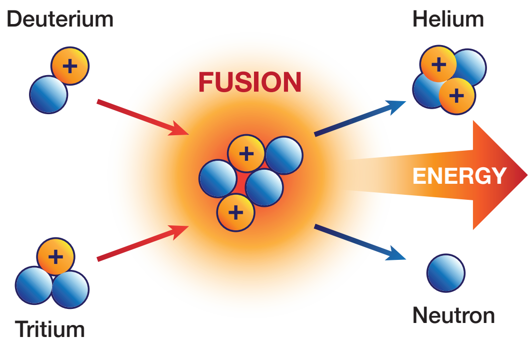
The energy spectrum of the neutrons is particularly useful in diagnosing implosion events. A neutron time-of-flight detector is used to measure the neutron energy spectrum by relating the measured neutron velocity to its energy.

The ICF nToF instruments use very fast organic scintillators, materials that generate light when exposed to ionizing radiation like neutrons and gamma-rays. Photek PMTs view the scintillator and produce a signal that is proportional to the number of particles striking the scintillator.

In an implosion event...

Gamma-rays arrive first since they travel at the speed of light. The neutrons arrive later as they are slower moving. In the experiment the PMTs are typically gated off during the gamma-ray pulse to prevent signal saturation in the PMT, except one PMT which is used to measure the gamma-ray arrival and used as a timing reference.

Prior to the arrival of the highest energy neutrons at the scintillator, hundreds of nanoseconds after the gamma-rays in NIF for example, the PMTs are turned back on and the time history of the neutron signal is recorded for several microseconds, to include the primary fusion neutrons themselves, either Deuterium-Tritium or Deuterium-Deuterium neutrons, and lower energy neutrons created by scattering of the primary neutrons with material in and around the target chamber.



The time to travel a fixed distance provides the neutron velocity, and the energy of the neutron is proportional to the square of the velocity. The signal levels over the full range of neutron energies can span many orders of magnitude, requiring the PMTs to have a very wide dynamic range. Often multiple PMTs are operated at different gains and gated on at different times to enable high precision measurements for the entire neutron signal lasting several microseconds.

Photek PMTs uniquely excel in both their time response which results in excellent precision of the neutron energy spectrum, and in their ability to be gated on and off in a matter of nanoseconds, enabling a wide dynamic range measurement using several PMTs at different gains. Details of nToF instruments at the NIF, Omega and Z can be found in the attached references[1,2,3].

Future developments

Photek is currently working on several new developments with photomultiplier tubes to help address the ever-growing yield or total energy coming out of inertial confinement fusion implosions.

Since scientists continue to run some experiments with low yield to investigate fundamental research into the ICF process they require the PMTs to span an even larger range of signals. Ideally the nToF diagnostics could use the same number of PMTs to cover this larger range to improve calibration of the instruments.

Photek is working with the fusion community on several exciting new developments to extend the PMTs dynamic range, including real-time control of PMT gain and sensitive area. These advances will allow researchers to move closer to their goal of limitless clean fusion energy. Look for more information on these advances in future posts.

References

1. **Moore, A. S., et al.** “The five line-of-sight neutron time-of-flight (nToF) suite on the National Ignition Facility (NIF).” Review of Scientific Instruments 92.2 (2021): 023516. https://pubs.aip.org/aip/rsi/article/92/2/023516/368632/The-five-line-of-sight-neutron-time-of-flight-nToF

2. **Glebov, V. Yu, et al.** “A new neutron time-of-flight detector for yield and ion-temperature measurements at the OMEGA Laser Facility.” Review of Scientific Instruments 93.9 (2022): 093522. https://pubs.aip.org/aip/rsi/article-abstract/93/9/093522/2849086/A-new-neutron-time-of-flight-detector-for-yield?redirectedFrom=fulltext

3. **Chandler, G. A., et al.** “Neutron time-of-flight detectors (nTOF) used at Sandia’s Z-Machine.” Review of Scientific Instruments 93.11 (2022): 113531. https://pubs.aip.org/aip/rsi/article-abstract/93/11/113531/2849251/Neutron-time-of-flight-detectors-nTOF-used-at?redirectedFrom=fulltext

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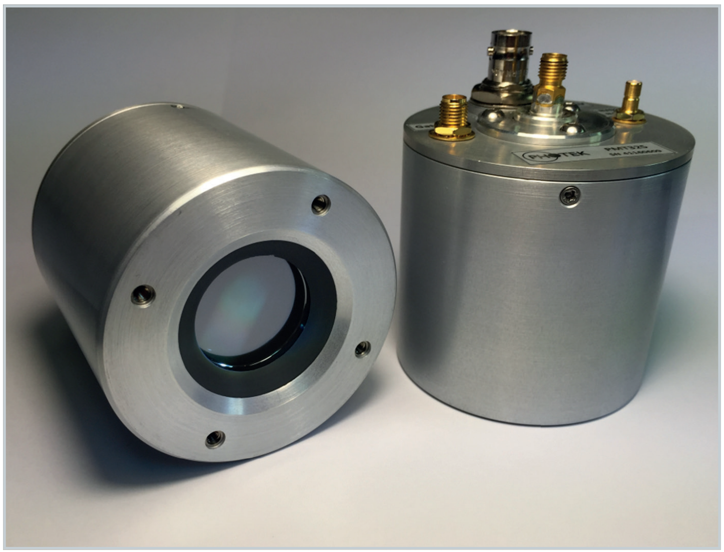
Photomultiplier Tube

Analysis of ultra-fast optical phenomina



Photek's range of photomultiplier tubes (PMTs) provide solutions for analysing ultra fast optical phenomena in a range of applications, including LiDAR, nuclear physics and time correlated photon counting.

Photek manufactures 10, 25, and 40 mm PMTs with a variety of photocathodes having high sensitivity in the UV, visible and NIR spectrum. A number of MCP configurations are available to ensure that Photek's PMTs satisfy all user gain requirements. Photek's PMTs are the fastest in the world with pulse rise times down to 60 ps and pulse FWHM down to 100 ps. For applications where fast gating is required, the Photek photomultipiers can provide gated speeds to 2 ns.

Key Attributes

- 10, 25 and 40 mm areas as standard, other sizes available upon request
- Single, chevron or z-stack MCP options with gain greater than 10^7
- Wide range of photocathodes including UV, solar blind, visible and NIR response
- Rise time to 60 ps (model dependant)
- FWHM to 100 ps (model dependant)
- Single photon jitter to 28 ps field environments
- Multi-photon jitter below 10 ps
- Fast pulse output linear up to 1 A
- Integral 50 ohm output

Applications

- Analysis of fast optical pulses
- Cherenkov light detection
- Fluorescence spectroscopy
- LiDAR
- Particle & Nuclear physics
- Single photon counting fluorescence
- Time correlated photon counting

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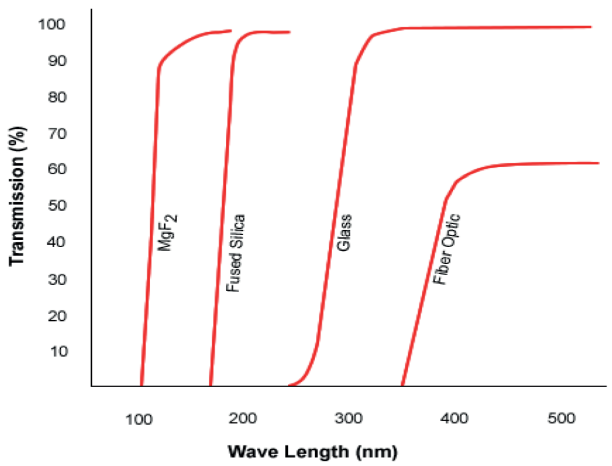
Options Available

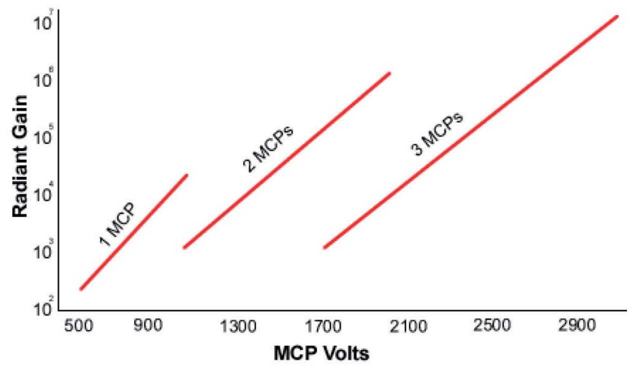
INPUT WINDOW

Photek PMTs are available with a choice of input window materials. These include MgF_2, fused silica, glass and fibre optic, among others.

GAIN

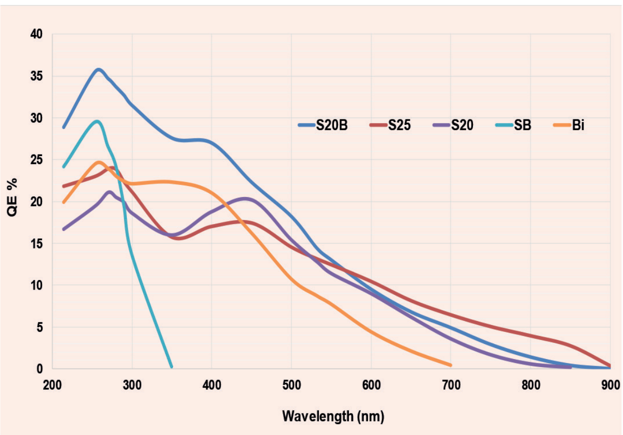
The Photek PMT can be provided with 1,2 or 3 micron channel plates for gain greater than 10^7.





QUANTUM EFFICIENCY CURVES

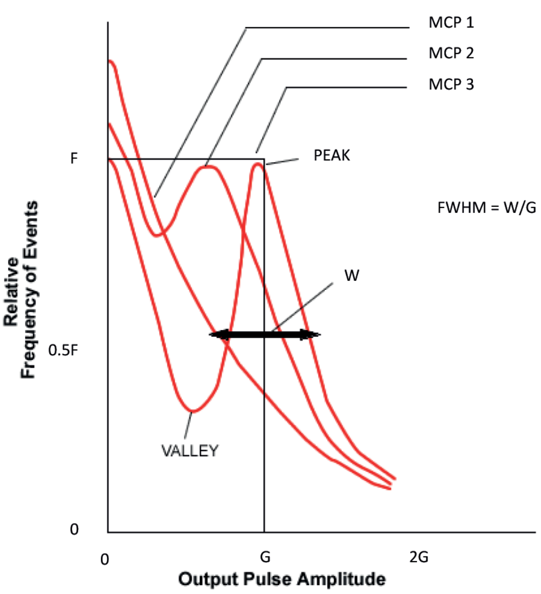
Photek offers a full range of second generation photocathodes. These include CsI, Solar Blind, Bialkali, Low Noise S20, S20 and S25 which demonstrate the broad spectral response that can be achieved, as seen below:



Note: Detectors with fibre optic input windows will have no response below 300 nm. Specific gating requirements may alter the QE. Please contact the Sales Office to discuss your exact requirements

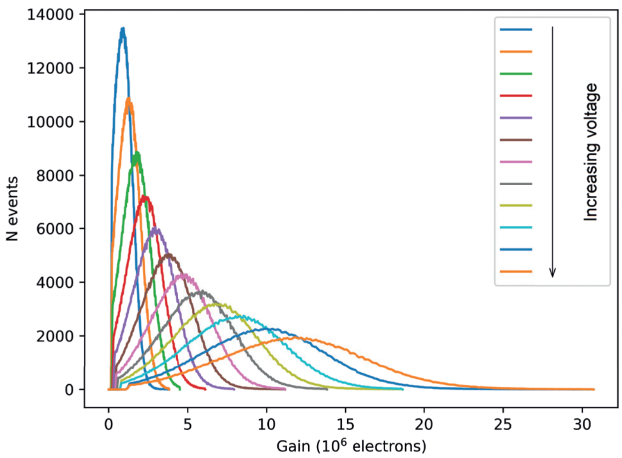
TYPICAL PHD

The diagram below shows how the pulse height distribution (PHD) changes with gain. Both the peak/valley ratio and the full width half maximum (FWHM) of the pulse height distribution are used to characterise photon counting tubes.



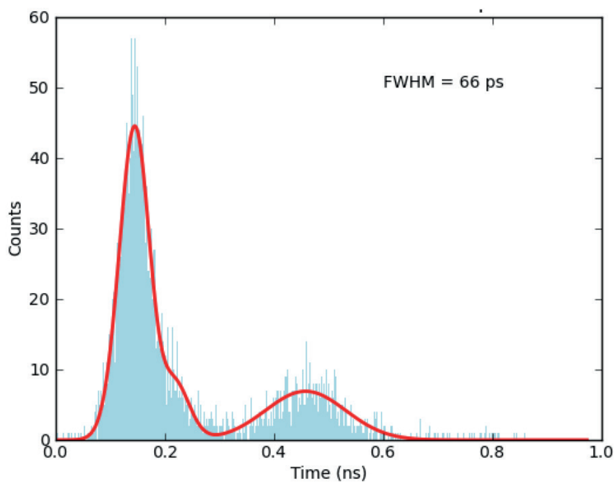
Example PHD for Photon Counting Tube

Below is a graph showing the typical single photon PHD for a 2 MCP PMT for increasing voltages. This is a demonstration of how the FWHM can improve with higher voltage:



Transit Time Spread

Below is a graph showing the typical single photon transit time spread (TTS) for a 10 mm 2 MCP PMT:

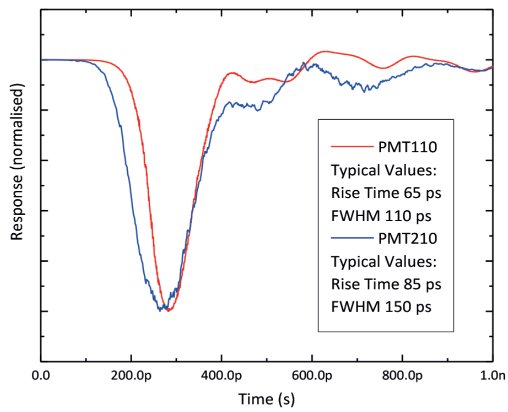


*Results taken from J. Milnes et al., Recent Developments in Ultra-High Speed and Large Area Photomultiplier Tubes, PoS(ECPD2015)005 of a 1 MCP, 10 mm PMT.

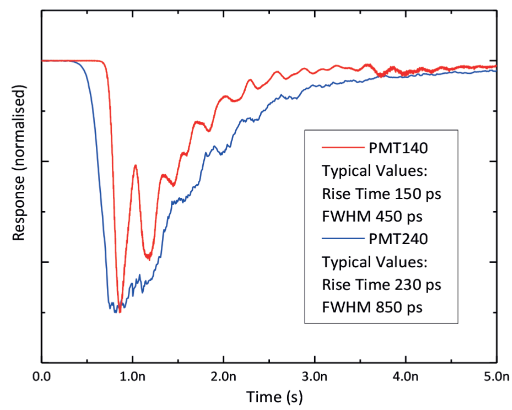
Typical Output Waveform

The graphs below show how the typical output waveform changes with gain and size. The pulse rise time and FWHM are tabulated on the next page.

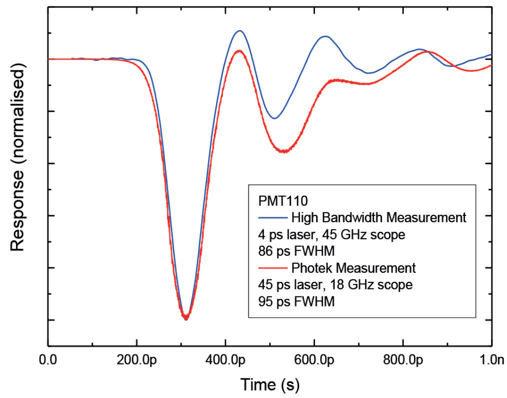
Results for a 10 mm 1 MCP



Results for a 40 mm 1 MCP



The figure below shows the influence of the laser pulse width and measurement bandwidth on the observed result.*



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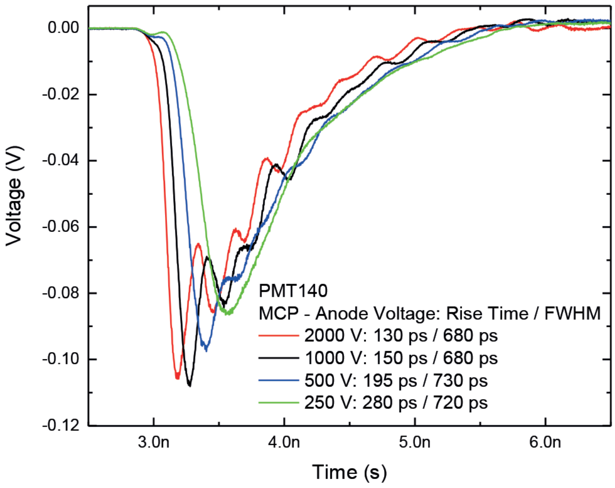
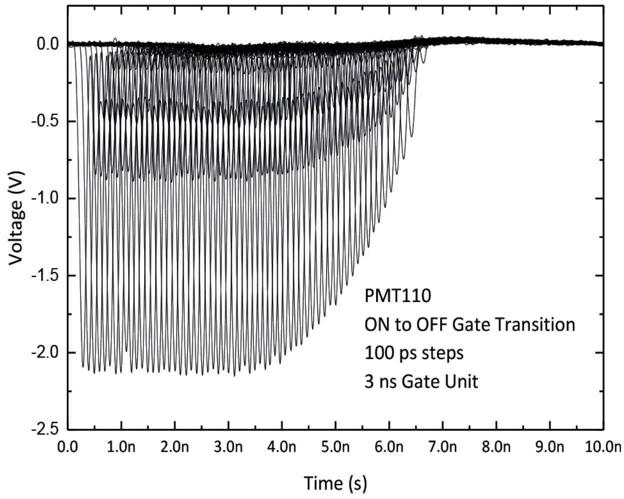
Anode Voltage

The graph below shows the effect that the anode voltage can have on the pulse shape.



Gate Transition

The ON-OFF gate transition for a PMT110 can be seen below using a GM300-3N 3 ns, 300 kHz gate unit.



Time Response - Pulse Rise Time (ps)

MCPs	Detector Diameter								
	10 mm			25 mm			40 mm		
	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max
1	60	65	70		115		100	150	200
2	75	85	95		190		180	230	280
3		105		300	400	500		320	

Pulse FWHMs (ps)

MCPs	Detector Diameter								
	10 mm			25 mm			40 mm		
	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max
1	100	110	120		700		300	450	600
2	130	150	170		840		600	850	1100
3		170		800	1000	1200		920	

Environmental

Operational Limits: -40°C to +45°C shock
Storage: -40°C to +60°C

ENVIRONMENTAL TESTING
For applications where the PMT is exposed to temperature and shock conditions Photek has the appropriate facilities to offer environmental stress screening. Our vibration system offers shock, sine, random, and sine-on-random testing. Our thermal chamber has a temperature range of -75°C to +160°C and can control humidity from 10% to 98%.

Power Supply & Gate Units

Photek designs and manufactures a range of power supplies and gate modules for our PMTs. Our power supplies use the very latest in power supply design and are available in bench and top format.

Our gate modules can gate down to 3 ns with a 300 kHz repetition rate (model dependant) and are used for high brightness or fast optical shutter applications.

Part Numbers

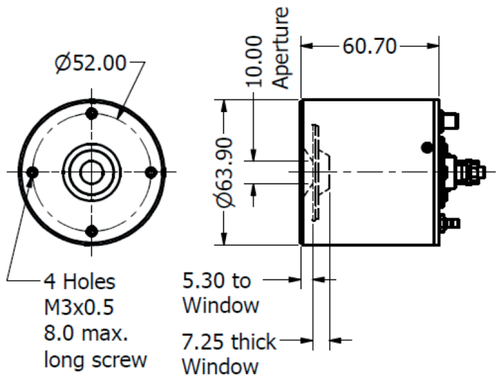
Photomultiplier Tube part numbers start with PMT and are built up as follows:

MCP	Size	Input	Cathode	Gating
1	18	**F** (fibre)	CsI	**G** (fibre optic)
2	25	**Q** (fused silica)	SB	**NG**
3	40	**M** (MgF_2)	BI	**TCU**
		G (glass)	S20B	
			S20	
			S25	

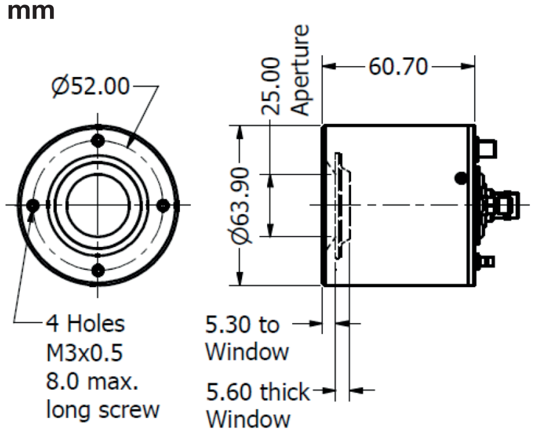
Mechanical

OUTLINE DRAWING

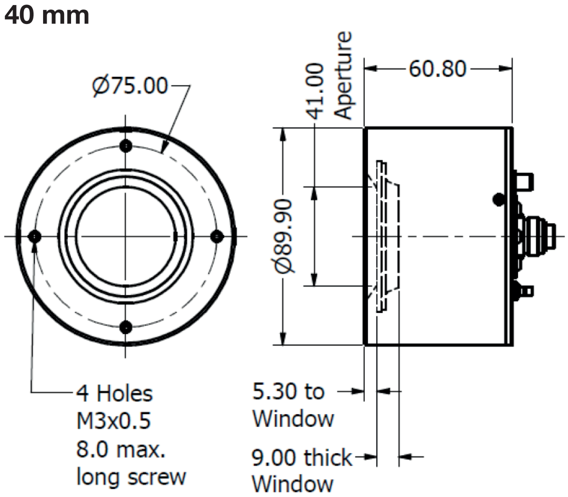
10 mm



25 mm



40 mm



Dimensions are indicative and may vary depending on the optics, number of MCPs and housing required.

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About Photek

Photek is a specialist manufacturer of vacuum based tubes and camera systems for photon detection.

Our product range includes; Camera Systems, Image Intensifiers, Photomultiplier Tubes, Streak Tubes plus a range of associated electronics.

We are experts in large area and ultra-high speed imaging and advanced photon counting camera systems.

Our continuing success is built upon continuous innovation and product development, and by harnessing and applying knowledge to find solutions for all of our customers' applications.

Photek is accredited to ISO 9001 and ISO 14001.

Contact Us

Our team of specialist engineers and scientists are ready to discuss your application requirements in depth.

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