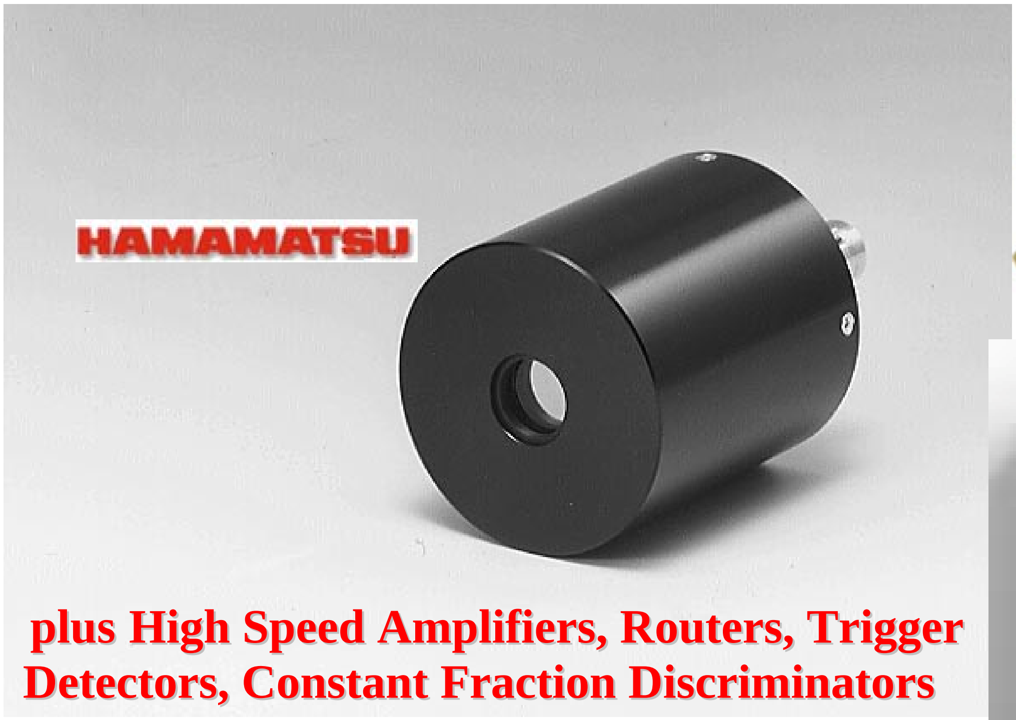
Single Photon Counting APD, MCP & PMT Detectors



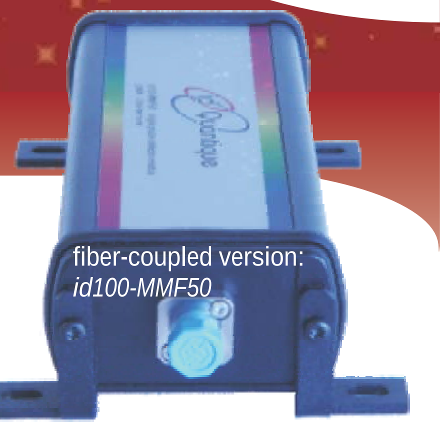
plus High Speed Amplifiers, Routers, Trigger Detectors, Constant Fraction Discriminators

From Becker & Hickl, id Quantique and Hamamatsu

Boston Electronics Corporation

91 Boylston Street, Brookline MA 02445 USA
(800)347-5445 or (617)566-3821 fax (617)731-0935
www.boselec.com tcspc@boselec.com


free-space version:
id100-20 & id100-50


fiber-coupled version:
id100-MMF50

id100

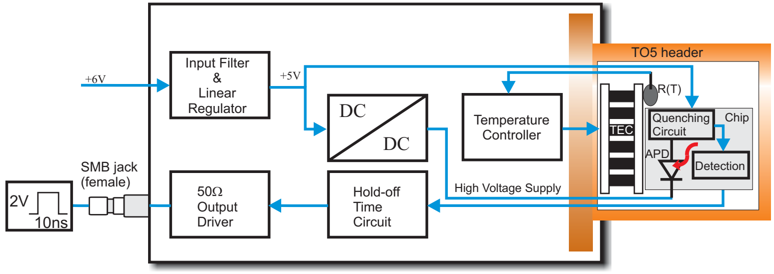
Detect visible photons with high timing accuracy

id Quantique's *id100 series* consists of compact and affordable single-photon counting modules with best-in-class timing resolution and state-of-the-art dark count rate. Based on a reliable silicon avalanche photodiode sensitive in the visible spectral range, these modules are able to detect weak optical signals down to the single photon level. The *id100 series* includes:

- two free-space versions, the *id100-20* and *id100-50* with a 20µm, respectively a 50µm, diameter photosensitive area,
- a fiber-coupled version, the *id100-MMF50*, coming with a standard FC/PC optical input.

The modules are available in two grades depending on the dark count rate specifications. For the Ultra-Low Noise grade, the dark count rate is less than 1Hz for the *id100-20*, less than 20Hz for the *id100-50* and *id100-MMF50*.

The free-space and fiber-coupled modules are easy-to-use, self-contained and can be integrated in every optical set-up. With a timing resolution as low as 40ps and a remarkably short dead time of 45ns, these modules outperform existing commercial detectors in all applications requiring single-photon detection with high timing accuracy. Besides an extremely fast IRF (Instrument Response Function), the modules have an excellent timing stability up to count rates of at least 10MHz.



Block diagram of the id100 (free-space version).

The *id100* consists of an avalanche photodiode (APD) and an active quenching circuit integrated on the same silicon chip. The chip is mounted on a thermo-electric cooler and packaged in a standard TO5 header with a transparent window cap. A thermistor is used to measure temperature. The APD is operated in Geiger mode, i.e. biased above breakdown voltage. A high voltage supply used to bias the diode is provided by a DC/DC converter . The quenching circuit is supplied with +5V. The module output pulse reflects the arrival of a photon with high timing resolution. The pulse is shaped using a hold-off time circuit and sent to a 50Ω output driver. All internal settings are preset for optimal operation at room temperature. No user adjustement is necessary. In the fiber-coupled version, the TO5 header and the optical fiber are included in the housing. The optical input consists of a FC/PC connector on the front side of the module.

Beside the *id100*, the *id101* series includes miniaturized versions intended for large-volume OEM applications (*http://www.idquantique.com/products/files/id101-specs.pdf*). The *id101-20* and *id101-50* have an active area diameter of 20µm and 50µm, respectively. The *id101-MMF50* is fiber-pigtailed with FC/PC connectors.

Ordering information and sales contact

id100-20-XXX: Single photon detection module with 20µm active area .

id100-50-XXX: Single photon detection module with 50µm active area .

id100-MMF50-XXX: Single photon detection module with multimode fiber input (50/125µm, FC/PC connector).

Please insert dark count rate grade code: XXX=STD for standard, XXX=ULN for Ultra-Low Noise .

For further information, please contact id Quantique by phone: +41 (0)22 301 83 71, fax: +41 (0)22 301 83 79, or email: sales@idquantique.com.

New

★ *Ultra-Low Noise Modules Available*

Features

- Best-in-class timing resolution (40ps)
- Small IRF shift at high count rates
- Standard and Ultra-Low Noise grades
- Low afterpulsing probability
- Low dead time (45ns)
- Peak photon detection at λ = 500nm
- Active area diameter of 20µm or 50µm
- Free-space or multimode fiber coupling
- Compact, easy-to-use and reliable
- Standard 50Ω output with BNC connector
- No DC power supply required
- Not damaged by strong illumination
- Highly reliable

Applications

- Photon counting, time correlated photon counting (TCSPC)
- Fluorescence and luminescence detection
- Single molecule detection, DNA sequencing
- Fluorescence correlation spectroscopy
- Decay and multiple decay time measurements
- Flow cytometry, spectrophotometry
- Environment analyses
- LIDAR, optical range finder
- Non contact profilometry
- Laser scanning microscopy
- Adaptive optics, astronomical instrumentation
- Quantum cryptography, quantum optics
- Optical time domain reflectometry
- Educational experiments

id Quantique

id100

Detect visible photons with high timing accuracy

General Specifications at T=25°C

Parameters	Minimum	Typical	Maximum	Units
Spectral range	350		900	nm
Timing resolution [FWHM] 1 2 ①		40	60	ps
Photon detection probability 3				
at 400nm	15	18		%
at 500nm	30	35		%
at 600nm	20	25		%
at 700nm	15	18		%
at 800nm	5	7		%
at 900nm	3	4		%
Afterpulsing probability 4			3	%
Output pulse width 5 ④	9	10	15	ns
Output pulse amplitude 5	1.5	2	2.5	V
Dead time 6		45	50	ns
Maximum count rate (pulsed light) 7		20		MHz
Supply voltage ⑤	5.6	6	6.5	V
Supply current		100	150	mA
Storage temperature	- 40		70	°C
Cooling time			5	s

Dark count rate: id Quantique modules are available in two grades: Standard and Ultra-Low Noise, depending on dark count rate specifications.

	Active Area Diameter	TE cooled	Standard	Ultra-Low Noise
id100-20	20 µm	yes	< 60Hz	< 1Hz
id100-50	50 µm	yes	< 80Hz	< 20Hz
id100-MMF50	③	yes		

① The optimal timing resolution is obtained when the incoming photons are focused on the photosensitive area.

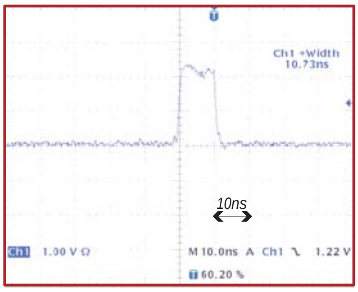
② The *id100* is free of indicating LEDs to maintain complete darkness during measurements.

③ The *id100-MMF50* comes with a 50/125µm multi-mode fiber optimized for the visible spectral range. The numerical aperture is 0.22. The coupling efficiency is larger than 80%.

④ The detector output was designed to avoid distorsion and ringing when driving a 50Ω load. The *id100* is thus compatible with most instruments: correlators, time-to-amplitude converters, time-to-digital converters, counters, oscilloscopes, etc.

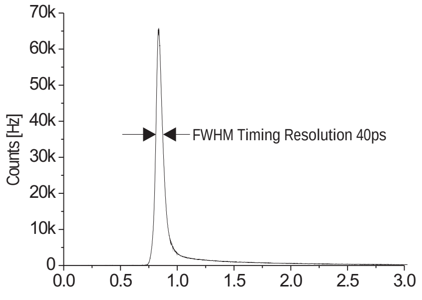
⑤ Universal network adapter provided (110/220V).

5 Output Pulse

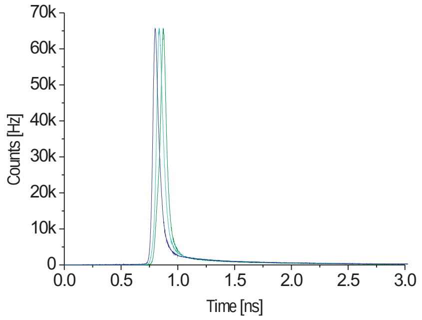


A typical pulse of 2V amplitude and 10ns width is observed at the output of the *id100 series* terminated with a 50Ω load. The recommended trigger level of the measurement device is 1V. For counting applications, the trigger slope can be negative or positive. For timing applications, the trigger slope must be positive in order to take full advantage of the *id100-series* timing resolution.

1 Timing Resolution

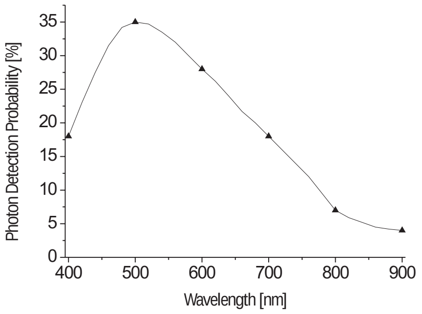


2 IRF Shift with Output Count Rate

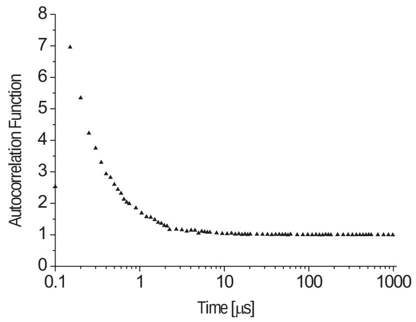


The shift of the instrument response function with the output count rate is small. As shown above, it is less than 70ps from 10kHz to 8MHz count rates (http://www.idquantique.com/products/files/id100-becker.pdf).

3 Photon Detection Probability versus λ



4 Afterpulsing



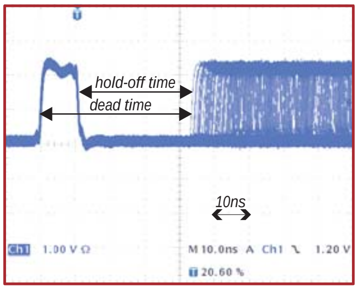
Typical autocorrelation function of a constant laser signal, recorded at a count rate of 10kHz.

id Quantique

id100

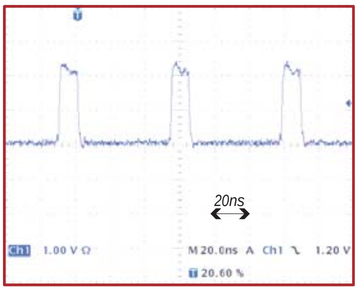
Detect visible photons with high timing accuracy

6 Dead Time



Measurement obtained with an oscilloscope in infinite persistance mode: the dead time includes the output pulse width and the hold-off time during which the *id100* is kept insensitive.

7 Maximum Count Rate - Pulsed Light



The short dead time of the *id100* allows operation at very high repetition frequencies, up to 20MHz.

Mounting options

The *id100 series* comes with different mounting options:

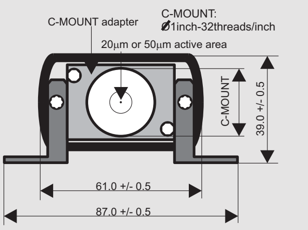
- ☞use four mounting brackets supplied with the module. The brackets accept screws with diameters up to 4mm.
- ☞use a standard optical post holder (not supplied). A M4 mounting hole placed on the bottom side of the *id100-20* & *id100-50* allows its mounting using a standard set screw (not supplied).
- ☞for the free-space version only, a C-MOUNT adapter is added on the module front side.

Accessories supplied

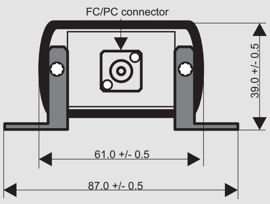
- ☞single photon detection module with four mounting brackets and a C-MOUNT adapter (except for *id100-MMF50*)
- ☞1m coaxial cable with BNC and SMB connectors
- ☞power supply with universal range of input plugs
- ☞operating guide
- ☞angled 2.5 mm hexagon key (except for *id100-MMF50*) supplied in order to remove the C-MOUNT adapter if required
- ☞angled T10 Torx key supplied in order to remove the mounting brackets if required

Dimensional Outline

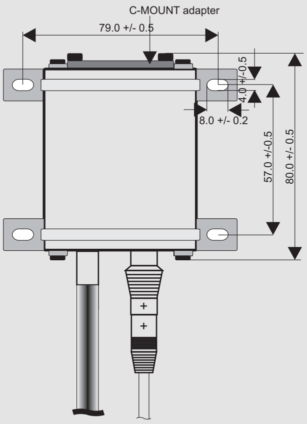
id100-20 / id100-50 Front View



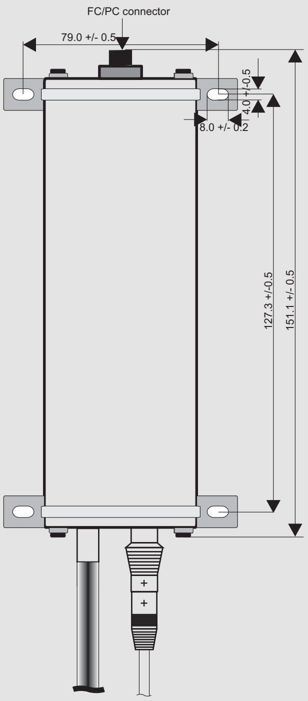
id100-MMF50 Front View



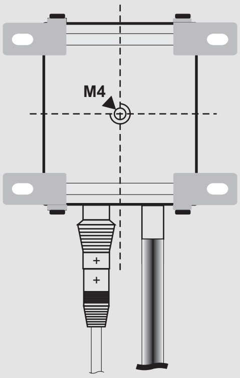
id100-20 / id100-50 Top View



id100-MMF50 Top View



id100-20 / id100-50 Bottom View



UNIT: millimeters


fiber-coupled version:
id100-MMF50

free-space version:
id100-20 & id100-50

The worlds smallest photon counter

id101 series

For large-volume OEM applications, idQuantique offers the *id101 series*. The *id101* consists of a standard TO5 - 8pins optoelectronic package. The CMOS silicon chip combining a single photon avalanche diode and a fast active quenching circuit is mounted on top of a one-stage thermoelectric cooler. A thermistor is placed on the TEC cold side and accessible externally if temperature control is required. The *id101* is sold as an electronic component, free of external printed circuit board. It can be mounted by the customer on a custom printed circuit board. An evaluation board is available upon request. When properly biased, the performance is comparable with that of the *id100-50*. idQuantique's engineering team offers technical support for the proper integration of the *id101* in customer's commercial products. A fiber coupled version, the *id101-MMF50*, is also available. See the *id101* datasheet for more information.

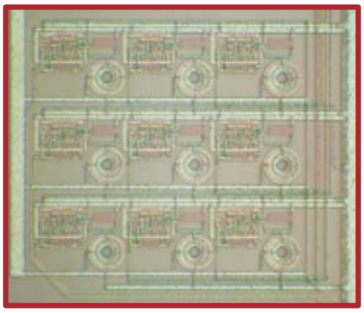
Custom Design Service

id Quantique SA designs and manufactures hardware products serving two main markets: network security and optical instrumentation. In the latter, the company offers innovative solutions for single photon detection. The company’s product portfolio includes the id100 and id150 single-photon detection modules for the visible spectral range. Over the years the company has acquired a broad expertise in the design of silicon photodetectors, operating in linear and Geiger mode.

id Quantique offers a design service to customers with non-standard detector needs. When photomultiplier tubes (PMTs) and silicon-based hybrid solutions (silicon APDs combined with discrete electronic circuits) do not meet your needs, id Quantique provides innovative solutions for industrial, commercial and research applications.

id Quantique's technology offers the possibility to fabricate compact modules, including large 1D and 2D arrays, with superior timing performances. These modules are used in biological/chemical instrumentation, quantum optics, aerospace and defense applications. The company is working with selected CMOS (Complementary Metal Oxide Semiconductor) foundries for the fabrication of its silicon detectors. The CMOS technology is widely recognized in the silicon industry as the most reliable way to fabricate ICs and sensors. Using this technology, detectors and front-end electronics can be integrated on the same silicon chip. Many of the functionalities (e.g. voltage conversion and read-out) are done directly at the chip level, thus almost completely removing the need for discrete electronic components and expensive assembly. Because only a very small number of external components are needed, the size of the module can be greatly reduced.

Our Custom Design Service includes:
- fabrication of 1D or 2D single photon detector arrays,
- design of photon detectors with custom shape and active area diameter,
- integration of dedicated quenching and recharging circuits exhibiting a dead time as short as 10ns,
- on-chip integration of data processing functionalities,
- design optimisation to fit your packaging needs,
- consulting services for the design of custom PIN photodiodes, as well as linear and avalanche-mode photo diodes.



custom design example: 3x3 single photon avalanche diode array

Other Products (please visit our website http://www.idquantique.com)

id101:	miniature single photon counter for the visible spectrum
id150:	1x10 linear array of single photon detectors for the visible spectral range
id201:	single photon counting module for the spectral range between 900 and 1700 nm
id300:	sub-nanosecond laser source at 1310 or 1550 nm
Quantis:	Quantum Random Number Generator
Clavis:	Quantum Key Distribution for secure cryptographic communication
Vectis:	Point-to-point link encryption appliance

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TCSPC Performance of the id100-50 Detector

This report summarizes the results of Becker&Hickel's evaluation of the id100-50, a single photon counting module manufactured by id Quantique (www.idquantique.com).

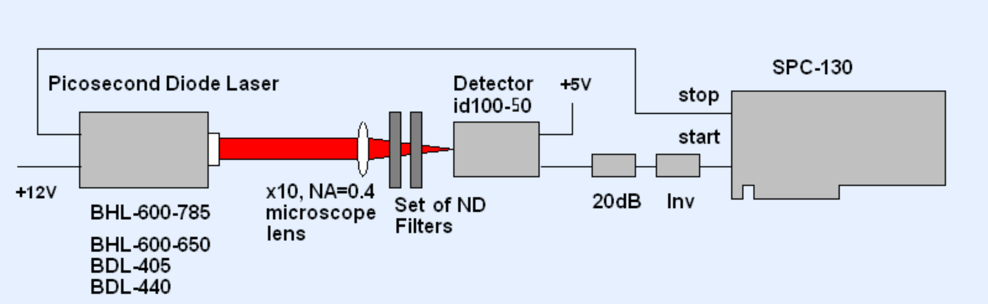
Detector

The id100-50 of id Quantique is an actively quenched single-photon APD (SPAD) module. The quenching circuit is integrated on the diode chip. Compared with the id100-20, the id100-50 has a 6.25 time larger active area. The larger area simplifies optical alignment and focusing while maintaining the low dark count rate and the good time resolution of the id100-20. The key parameters are:

Spectral range	350 to 900 nm
Diameter of the active area	50 µm
Timing resolution (fwhm)	55 ps
Detection probability at 500 nm	35 %
Dark count rate	< 200 s^{-1}
Output pulse amplitude	+ 2 V

Test Setup

The id100-50 was tested in the setup shown below.

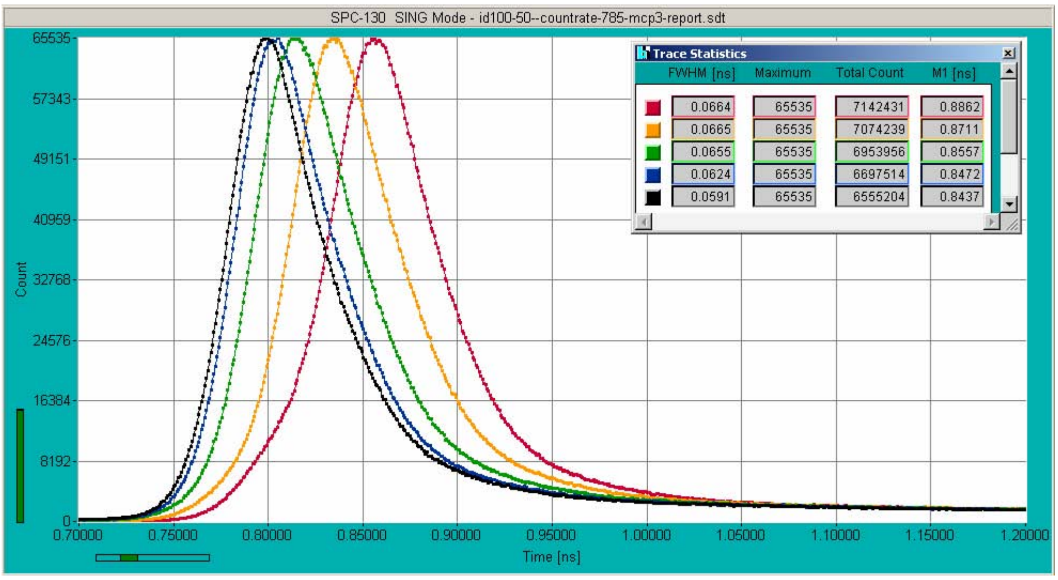


Light pulses of a picosecond diode laser were attenuated by a package of neutral density (ND) filters and focused directly to the SPAD module. The output pulses of the detector were sent to the start input of a TCSPC module. To transform the pulse polarity and the pulse amplitude into the standard input range of the TCSPC module a 20 dB attenuator and a passive pulse inverter were inserted in the signal line. The timing reference pulses at the stop input of the TCSPC module came directly from the laser.

For the measurement of the TCSPC instrument response function we used a BHL-600-785 diode laser. This laser has an exceptionally short pulse width of the order of 24 ps. For the measurement of the diffusion tail at various wavelengths a BHL-600-650 (650 nm), a BDL-440-SM (444 nm), and a BDL-405-SM (405 nm) were used. The measurements of the instrument response functions (IRFs) were performed by an SPC-130 TCSPC module. All lasers and TCSPC modules are Beckel&Hickl products.

Instrument Response Functions (IRFs)

IRF recordings measured at a wavelength of 785 nm are shown in fig. 2. The curves were measured at detector count rates from 214 kHz to 8.1 MHz. The maximum ADC resolution and TAC gain of the SPC-130 was used, resulting in a time channel width of 813 fs.



	FWHM [ns]	Maximum	Total Count	M1 [ns]
🟥	0.0664	65535	7142431	0.8862
🟧	0.0665	65535	7074239	0.8711
🟩	0.0655	65535	6953956	0.8557
🟦	0.0624	65535	6697514	0.8472
⬛	0.0591	65535	6555204	0.8437

Fig. 2: IRF of the id100-50 at 785 nm. Detector count rates 8.1 MHz (red), 5.15 MHz (yellow), 2.1 MHz (green), 0.5 MHz (blue) and 62 kHz (black). Time scale 50 ps per division. The FWHM and the first moment of the IRF curves are shown in the insert.

The measured width of the IRF (Instrument Response Function) varies from 66 ps to 59 ps. Corrected with an estimated width of the laser pulse of 24 ps, these values correspond to 55 ps to 61 ps, in agreement with the id Quantique specifications.

To quantify the shift of the IRF with the count rate, the first moments, M1, of the IRF curves were calculated. The shift of the first moment is

Count Rate (MHz)	0.2	0.5	2.1	5.15	8.1
Shift of M1 (ps)	0	3.5	12	28	42

Compared to other APD modules, these values are exceptionally low. It should also be noted that the IRFs remain free of satellite pulses or other artefacts up to the highest count rates applicable with currently available TCSPC techniques.

The IRFs of all single-photon APDs have a ‘diffusion tail’ caused by carrier generation in the neutral layers below the avalanche region. The amplitude of the tail depends on the wavelength and can reach 10 to 20% of the IRF peak. The diffusion tail of the id-100-50 for different wavelengths is shown in fig. 3.

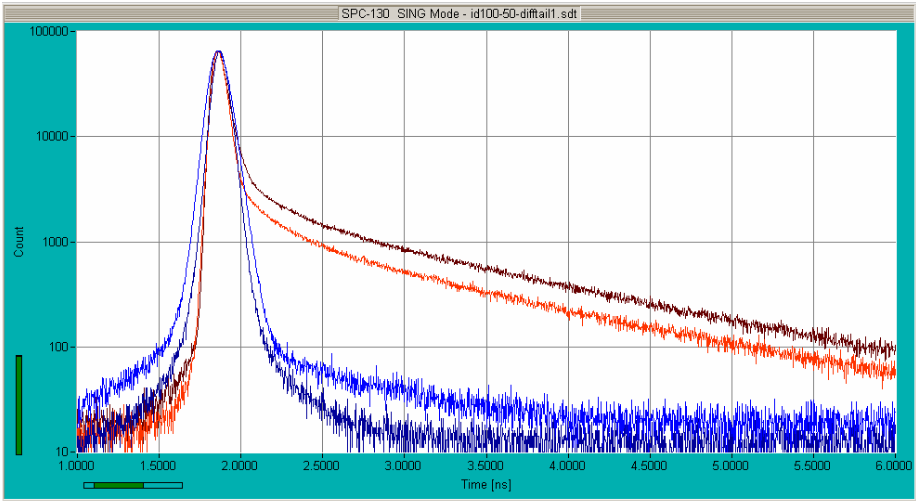


Fig. 3: Diffusion tail in the IRF of the id-100-50. 785nm (dark red), 650 nm (red), 444 nm (light blue), 405 nm (dark blue). The amplitude of the tail is about 5% and 3% at 650 and 785 nm. At 444 nm the tail is at the limit of detection, at 405 nm it is not detectable.

With 5% and 3% at 785 nm and 650 nm, respectively, the amplitude of the tail is relatively low. At 444 nm and 405 nm the diffusion tail is almost not detectable.

Afterpulsing

The afterpulsing of the id100-50 was checked by recording a continuous light signal in the time-tag (FIFO) mode of the TCSPC module. The time-tag data were used to record the autocorrelation function of the photon times. Consequently, the curve resembles the result of a fluorescence correlation (FCS) measurement. The result is shown in fig. 4. The autocorrelation function is normalised to the correlation expected for uncorrelated photon data, i.e. a correlation factor of 1 means that there is no correlation between the events.

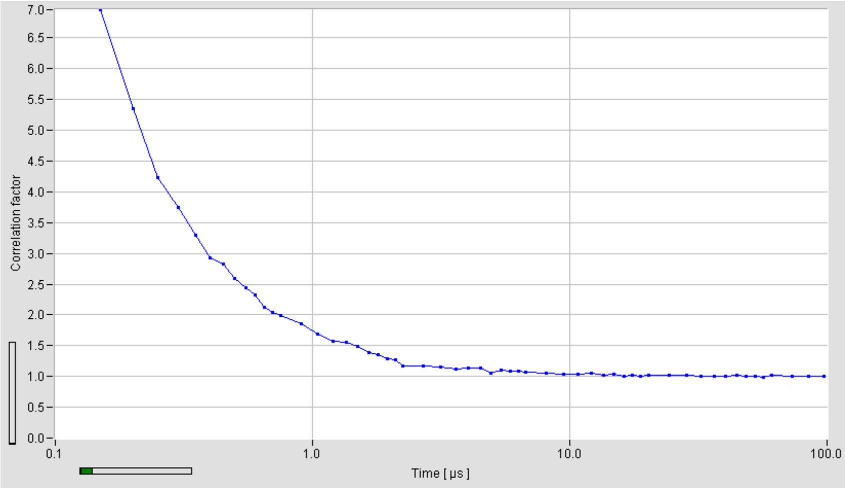


Fig. 4: Autocorrelation function of a light signal of constant intensity, recorded at a count rate of 10 kHz.

When comparing the autocorrelation curves of different detectors, please take into regard that the absolute amplitude of the autocorrelation curve is proportional to the reciprocal count rate.

Quantum Efficiency

We attempted to compare the quantum efficiency of the id100-50 with the quantum efficiency of a Hamamatsu H5773-20 PMT module. The H5773-20 has a ‘high efficiency extended red’ photocathode featuring exceptionally high quantum efficiency in the red and NIR range of the spectrum. At 650 nm, the efficiency of both the id100-20 and the id100-50 detectors were found about 3 times higher than for the PMT module. Based on the spectral sensitivity given for the H5773-20 the quantum efficiency of the id-100 can be estimated to be 25 to 40% at 650 nm. These values are similar or even better than the ‘detection probability’ (22% at 650 nm) specified for the id100-50 and -20.

Conclusions

The id100-50 of id Quantique has an extremely fast IRF and an excellent timing stability up to detector count rates of at least 8 MHz. The IRF is free of bumps and pre-pulses, and drops smoothly at longer times. The timing performance comes close to that of the smaller id100-20 module. The id100-50 is a wonderful detector for all applications in which the light can be concentrated on a small detector area. The good timing stability at high count rates then makes the id100-20 a real alternative to the R3809 MCP PMTs commonly used in TCSPC experiments. Potential applications are single-molecule spectroscopy, time-resolved confocal microscopy, and experiments of quantum-key distribution. Moreover, the detector is particularly suitable for a large number of applications at relatively high light intensity.

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Performance of the id100-20 Detector in B&H TCSPC Systems

This report summarizes the results of Becker&Hickel's evaluation of the id100-20, a single photon counting module manufactured by id Quantique (www.idquantique.com)

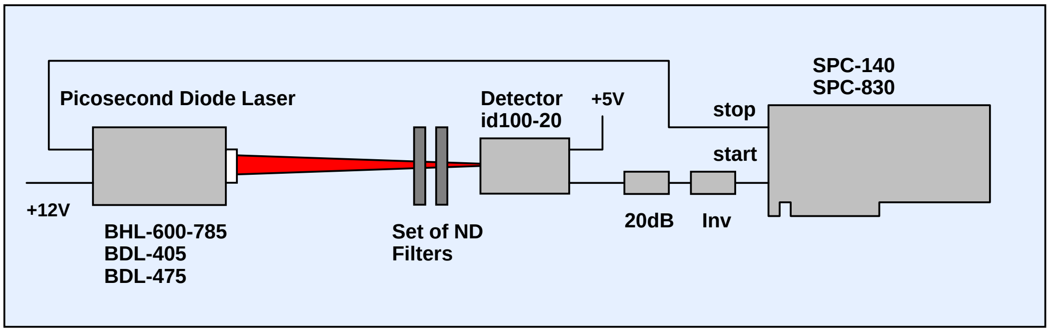
Detector

The id100-20 of id Quantique is an actively quenched single-photon APD (SPAD) module. The quenching circuit is integrated on the diode chip. The key parameters are (typical values):

Spectral range	350 to 900 nm
Diameter of the active area	20 µm
Timing resolution (fwhm)	40 ps
Detection probability at 500 nm	35 %
Dark count rate	200 s^{-1}
Output pulse amplitude	+ 2 V

Test Setup

The id100-20 was tested in the setup shown below.

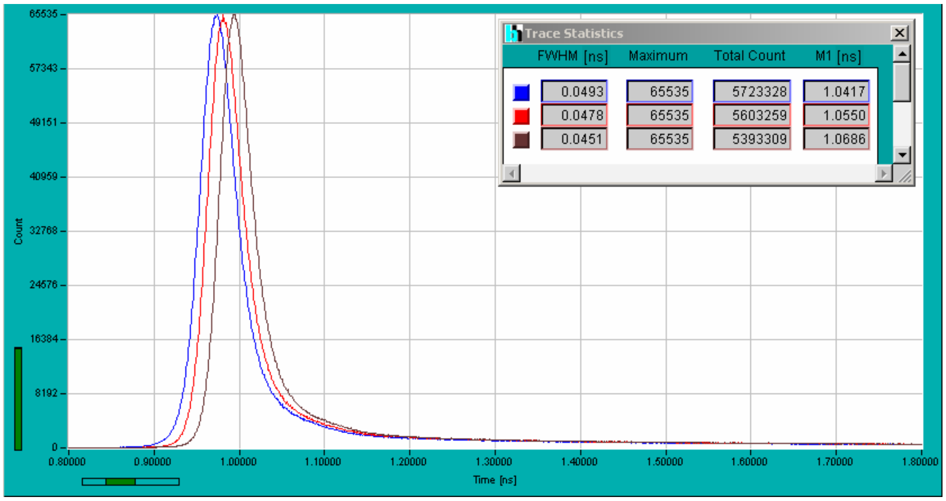


Light pulses of a picosecond diode laser were attenuated by a package of neutral density (ND) filters and sent directly to the SPAD module. The output pulses of the detector are sent to the start input of a TCSPC module. To transform the pulse polarity and the pulse amplitude into the standard input range of the TCSPC module a 20 dB attenuator and a passive pulse inverter were inserted in the signal line. The timing reference pulses at the stop input of the TCSPC module come directly from the laser.

For measurements at various wavelengths we used three different lasers. A BHL-600-785 was used at 785 nm. This laser has an exceptionally short pulse width of the order of 24 ps. The BDL-405 and the BDL-475 were used at 405 nm and 468 nm. The pulse width was about 68 ps and 58 ps, respectively. The measurements of the instrument response functions were performed by an SPC-140 TCSPC module, the correlation measurement by an SPC-830 module. All lasers and TCSPC modules are Beckel&Hickl products.

Instrument Response Functions (IRFs)

Instrument response functions measured at 785 nm are shown in fig. 2. The response was measured at a count rate of 5 MHz, 2.7 MHz, and 62 kHz.



	FWHM [ns]	Maximum	Total Count	M1 [ns]
🟦	0.0493	65535	5723328	1.0417
🟥	0.0478	65535	5603259	1.0550
🟫	0.0451	65535	5393309	1.0686

Fig. 2: IRF at 785 nm. Count rates 5 MHz (blue), 2.7 MHz (red), and 62 kHz (black). Time scale 100 ps per division. The FWHM and the first moment of the IRF curves are shown in the insert.

The measured width of the IRF (Instrument Response Function) varies from 49 ps to 45 ps. Corrected with an estimated width of the laser pulse of 24 ps, these values correspond to 43 ps to 38 ps, in agreement with id Quantique specifications.

To quantify the shift of the IRF with the count rate, the first moments, M1, of the IRF curves were calculated. The shift between 5 MHz and 2.7 MHz and 63 kHz is 13 ps and 26.9 ps. Compared to other APD modules, these values are exceptionally low. They are in fact smaller than for a XP2020 PMT with a standard voltage divider.

Fig. 3 compares the IRF of the id100-20 with the IRF of an R3809U-50 MCP-PMT operated at -3 kV. The measured FWHMs are 47 ps for the SPAD and 37 ps for the MCP-PMT.

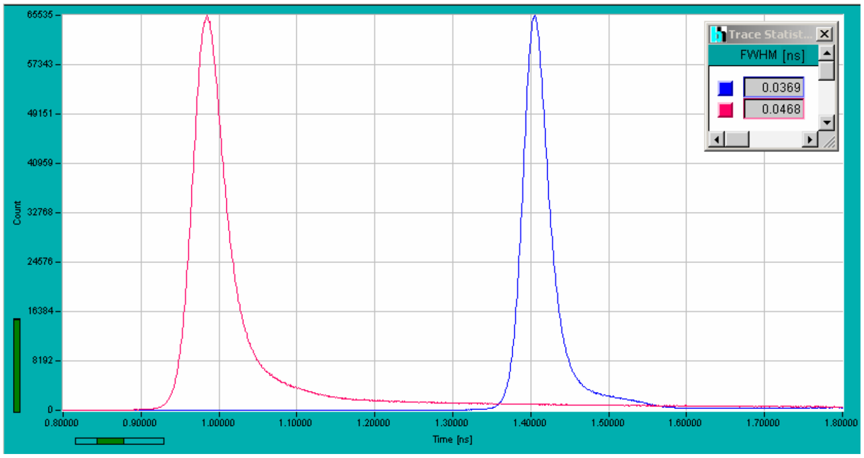


Fig. 3: Comparison of the IRF of the id100-20 (red, left) and the IRF of an R3809U MCP-PMT (blue, right). The measured FWHMs are 47 ps for the id100-20 and 37 ps for the MCP-PMT.

The true IRF width of the MCP-PMT is known to be about 28 ps. With this value, the width of the laser pulse can be estimated to be about 24 ps. The corrected IRF width of the SPAD is then 40 ps.

Fig. 4 shows measurements with the BDL-405 and BDL-475 lasers at the wavelengths of 405 nm and 468 nm.

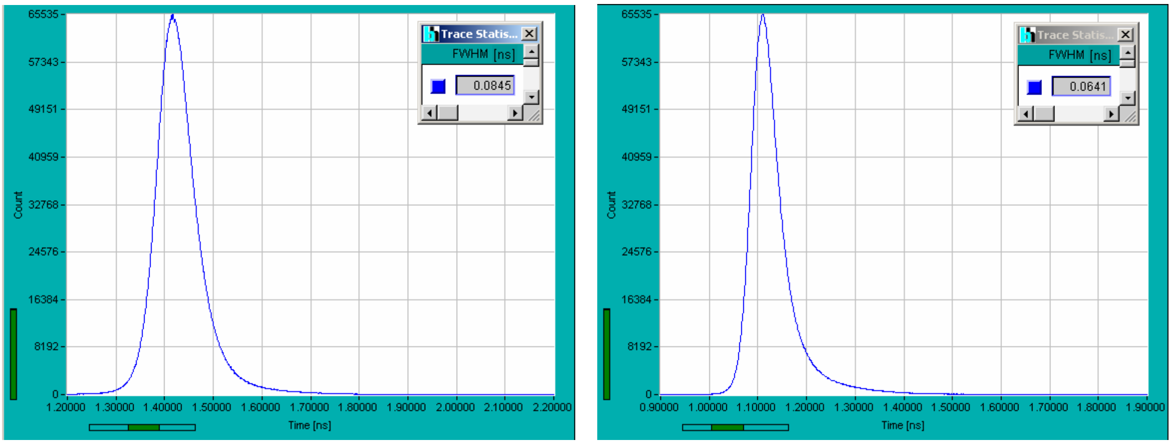


Fig. 4: Laser pulses recorded at 405 nm (left) and 468 nm (right)

The optical pulse width of these lasers is about 68 ps and 58 ps, respectively. Consequently, the recorded pulses are broader than the true IRF of the SPAD.

The comparison of the IRFs of the SPAD and the MCP PMT shows remarkable differences, see fig. 5.

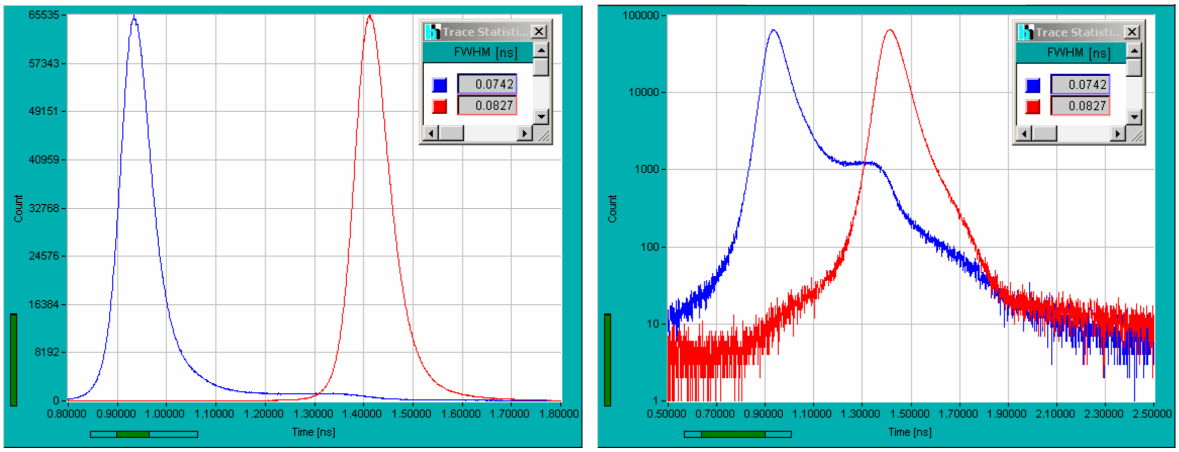


Fig. 5: Laser pulses recorded at 405 nm. Blue MCP PMT, red id100-20. Left linear scale, 100 ps / div, right logarithmic scale, 200 ps / div.

Although the SPAD records the pulse with a larger FWHM than the MCP PMT the response is cleaner and drops faster at longer times. Especially, the bump in the MCP measurement is not present in the SPAD measurement. The measurement shows indeed that the bump - which is usually attributed to the laser - is actually a feature of the MCP response.

With the known response width of the MCP of 28 ps, the true laser pulse width is about 68 ps. The same pulse is recorded with an FWHM of 82.7 ps by the SPAD. The estimated FWHM of the SPAD response is then 47 ps. However, the uncertainty of this result is large. It is therefore not sure whether or not the IRF is longer at 405 nm.

Afterpulsing

The afterpulsing of the id100-20 was checked by recording the laser signal in the time-tag (FIFO) mode of the TCSPC module. The time-tag data were used to record the autocorrelation function of the photon times. Consequently, the curve resembles the result of a fluorescence correlation (FCS) measurement. The result is shown in fig. 6. The autocorrelation function is normalised to the correlation expected for uncorrelated photon data, i.e. a correlation factor of 1 means that there is no correlation between the photons.

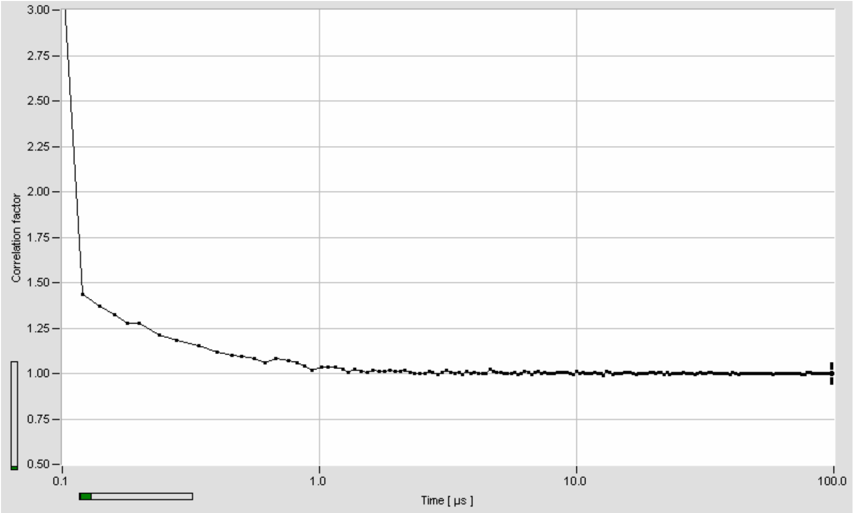


Fig. 6: Autocorrelation function of a constant laser signal, recorded at a count rate of 10 kHz.

Please note that, for a given afterpulsing probability, the amplitude of the autocorrelation curve is proportional to the reciprocal count rate.

The size and the duration of the afterpulsing is comparable to that of a good PMT. In particular, the afterpulsing ceases after about 1 µs. Typical intersystem crossing effects and diffusion times can therefore be measured with a single detector.

Conclusions

The id100-20 of id Quantique has an extremely fast IRF and an excellent timing stability up to count rates of at least 10 MHz. The IRF is free of bumps and prepulses, and drops smoothly at longer times. The IRF at long times is in fact better than that of the Hamamatsu R3809U MCP PMT. The id100-20 is a wonderful detector for all applications in which the light can be concentrated on a small detector area. The good timing stability at high count rates then makes the id100-20 a real alternative to the R3809. Potential applications are single-molecule spectroscopy, time-resolved confocal microscopy, and experiments of quantum-key distribution. Moreover, the detector is particularly suitable for a large number of applications with relatively high light levels. It is then not necessary to focus the light perfectly on the active area. These applications include a large number of standard fluorescence lifetime experiments and laser test setups.

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Detectors for High-Speed Photon Counting

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Detectors for photon counting must have sufficient gain to deliver a useful output pulse for a single detected photon. The output pulse must be short enough to resolve the individual photons at high count rate, and the transit time jitter in the detector should be small to achieve a good time resolution. A wide variety of commercially available photomultipliers and a few avalanche photodiode detectors meet these general requirements. We discuss the applicability of different detectors to time-correlated photon counting (TCSPC), steady-state photon counting, multichannel-scaling, and fluorescence correlation measurements (FCS).

Photon Counting Techniques

In a detector with a gain of the order of 10^6 to 10^8 and a pulse response width of the order of 1 ns each detected photon yields an output current pulse of some mA peak amplitude. The output signal for a low level signal is then a train of random pulses the density of which represents the light intensity. Therefore, counting the detector pulses within defined time intervals - i.e. photon counting - is the most efficient way to record the light intensity with a high gain detector [1].

Steady State Photon Counting

Simple intensity measurement of slow signals can easily be accomplished by a high-gain detector, a discriminator, and a counter that is read in equidistant time intervals. Simple photon counting heads that are connected to a PC via an RS232 interface can be used to collect light signals with photon rates up to a few 10^6 / s within time intervals from a few ms to minutes or hours.

Gated Photon Counting

Gated Photon Counters use a fast gate in front of the counter. The gate is used to count the photons only within defined, usually short time intervals. Gating in conjunction with pulsed light sources can be used to reduce the effective background count rate or to distinguish between different signal components [2,3]. Several parallel counters with different gates can be used to obtain information about the fluorescence lifetime. This technique is used for lifetime imaging in conjunction with laser scanning microscopes [4,5]. The count rate within the short gating interval can be very high, therefore gated photon counters can have maximum count rates of 800 MHz [2].

Multichannel Scalers

Multichannel scalers - or ‘multiscalers’ count the photons within subsequent time intervals and store the results in subsequent memory locations of a fast data memory. The general principle is shown in fig. 1.

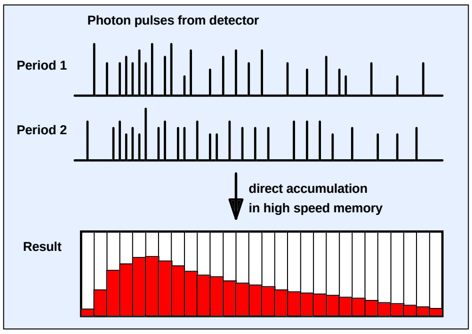


Fig. 1: Multichannel Scaler

Each sequence - or sweep - is started by a trigger pulse. Therefore the waveform of repetitive signals can be accumulated over many signal periods. Two versions of multiscalers with different accumulation technique exist. The photons can either be directly counted and accumulated in a large and fast data memory, or the detection times of the individual photons are stored in a FIFO memory and the waveform is reconstructed when the measurement is finished. The direct accumulation achieves higher continuous count rates and higher sweep rates, with the FIFO principle it is easier to obtain a short time channel width. Multiscalers for direct accumulation are available with 1ns channel width and 1 GHz continuous count rates [6]. Multiscalers with FIFO principle are available for 500 ps channel width [7]. Unfortunately this is not fast enough for the measurements of fluorescence lifetimes of most organic dyes. However, multiscalers can be an excellent solution for phosphorescence, delayed fluorescence, and luminescence lifetime measurements of inorganic samples. Furthermore, multiscalers are used for LIDAR applications.

The benefits of the multiscaler technique are

- Multiscalers have a near-perfect counting efficiency and therefore achieve optimum signal-to-noise ratio for a given number of detected photons
- Multiscalers are able to record several photons per signal period
- Multiscalers can exploit extremely high detector count rates
- Multiscalers cover extremely long time intervals with high resolution in one sweep

Time-Correlated Single Photon Counting

Time-Correlated Single Photon Counting - or TCSPC - is based on the detection of single photons of a periodical light signal, the measurement of the detection times of the individual photons and the reconstruction of the waveform from the individual time measurements [8,9].

The method makes use of the fact that for low level, high repetition rate signals the light intensity is usually so low that the probability to detect one photon in one signal period is much less than one. Therefore, the detection of several photons can be neglected and the principle shown in fig. 2 right be used:

The detector signal consists of a train of randomly distributed pulses due to the detection of the individual photons. There are many signal periods without photons, other signal periods contain one photon pulse. Periods with more than one photons are very unlikely.

When a photon is detected, the time of the corresponding detector pulse is measured. The events are collected in a memory by adding a ‘1’ in a memory location with an address proportional to the detection time. After many photons, in the memory the histogram of the detection times, i.e. the waveform of the optical pulse builds up. Although this principle looks complicated at first glance, it has a number of striking benefits:

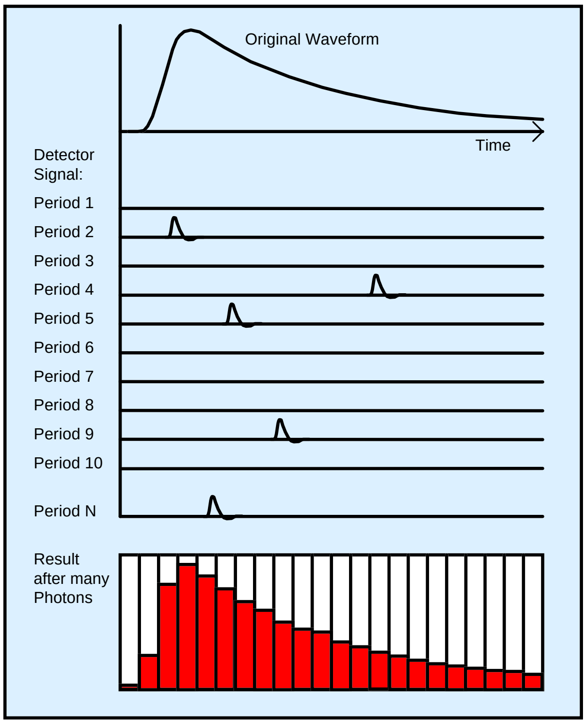


Fig. 2: Principle of the TCSPC technique

- The time resolution of TCSPC is limited by the transit time spread, not by the width of the output pulse of the detector. With fast MCP PMTs an instrument response width of less than 30 ps is achieved [14,27].

- TCSPC has a near-perfect counting efficiency and therefore achieves optimum signal-to-noise ratio for a given number of detected photons [10,11]
- TCSPC is able to record the signals from several detectors simultaneously [9,12-15]
- TCSPC can be combined with a fast scanning technique and therefore be used as a high resolution, high efficiency lifetime imaging (FLIM) technique in confocal and two-photon laser scanning microscopes [9,15,16,18]
- TCSPC is able to acquire fluorescence lifetime and fluorescence correlation data simultaneously [9,17]
- State-of-the-art TCSPC devices achieve count rates in the MHz range and acquisition times down to a few milliseconds [9, 18]

Multi-Detector TCSPC

TCSPC multi-detector operation makes use of the fact that the simultaneous detection of photons in several detector channels is unlikely. Therefore, the single photon pulses from several detector channels - either individual detectors or the anodes of a multi-anode PMT - can be combined in a common timing pulse line. If a photon is detected in one of the channels the pulse is sent through the normal time-measurement circuitry of a single TCSPC channel. In the meantime an array of discriminators connected to the detector outputs generates a data word that indicates in which of the channels the photon was detected. This information is used to store the photons of the individual detector channels in separate blocks of the data memory [9,12-15] (fig. 3).

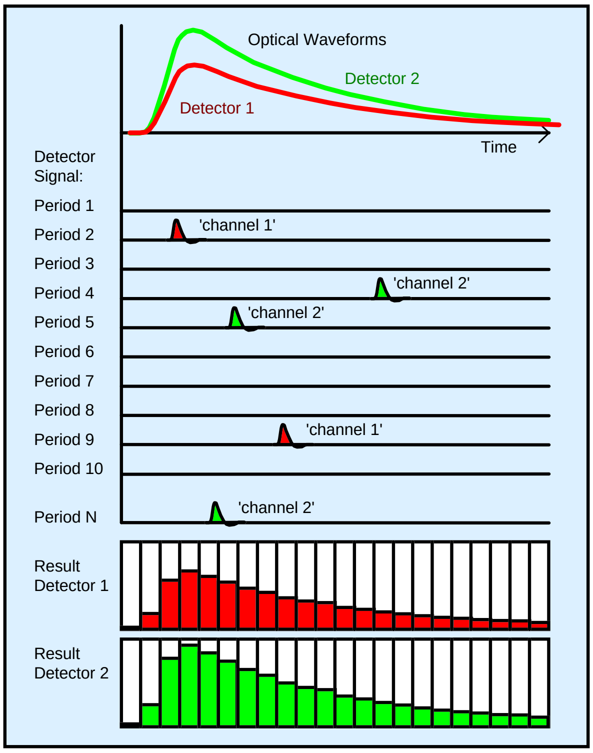


Fig. 3: Multi-detector TCSPC

Multi-detector TCSPC can be used to simultaneously obtain time- and wavelength resolution [15], or to record photons from different locations of a sample [14]. It should be noted that multi-detector TCSPC does not involve any multiplexing or scanning process. Therefore the counting efficiency for each detector channel is still close to one, which means that the efficiency of a multi-detector TCSPC system can be considerably higher of single channel TCSPC device.

Photon Counting for Fluorescence Correlation Spectroscopy

Fluorescence Correlation Spectroscopy (FCS) exploits intensity fluctuations in the emission of a small number of chromophore molecules in a femtoliter sample volume [19,20]. The fluorescence correlation spectrum is the autocorrelation function of the intensity fluctuation. FCS yields information about diffusion processes, conformational changes of chromophore - protein complexes and intramolecular dynamics. Fluorescence correlation spectra can be obtained directly by hardware correlators or by recording the detection times of the individual photons and calculating the FCS curves by software. The second technique can be combined with TCSPC to obtain FCS and lifetime data simultaneously. Moreover, the multidetector capability of TCSPC can be used to detect photons in different wavelength intervals or of different polarisation simultaneously [17,21].

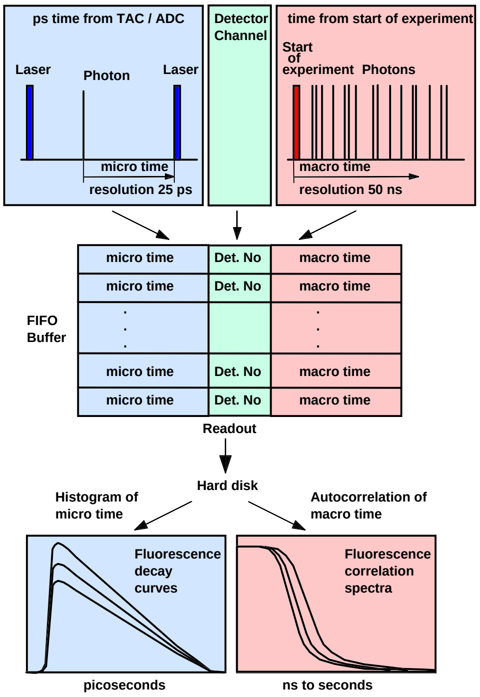


Fig. 4: Simultaneous FCS / lifetime data acquisition

The data structure for combined lifetime / FCS data acquisition in the an SPC-830 module [9] is shown in fig. 4. For each detector an individual correlation spectrum and a fluorescence decay curve can be calculated. If several detectors are used to record the photons from different chromophores, the signals of these chromophores can be cross-correlated. The fluorescence cross-correlation spectrum shows whether the molecules of both chromophores and the associated protein structures are linked or diffuse independently.

Detector Principles

The most common detectors for low level detection of light are photomultiplier tubes. A conventional photomultiplier tube (PMT) is a vacuum device which contains a photocathode, a number of dynodes (amplifying stages) and an anode which delivers the output signal [1,22].

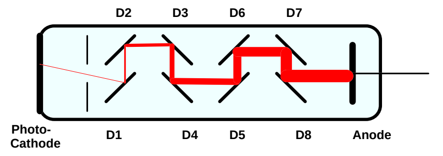


Fig 5: Conventional PMT

The operating voltage builds up an electrical field that accelerates the electrons from the cathode to the first dynode D1, further to the next dynodes, and from D8 to the anode. When a photoelectron emitted by the photocathode hits D1 it releases several secondary electrons. The same happens for the electrons emitted by D1 when they hit D2. The overall gain reaches values of 10^6 to 10^8. The secondary emission at the dynodes is very fast, therefore the secondary electrons resulting from one photoelectron arrive at the anode within a few ns or less. Due to the high gain and the short response a single photoelectron yields a easily detectable current pulse at the anode.

A wide variety of dynode geometries has been developed [1]. Of special interest for photon counting are the ‘linear focused’ type dynodes which yield a fast single electron response, and the ‘fine mesh’ and ‘metal channel’ type which offer position-sensitivity when used with an array of anodes.

A similar gain effect as in the conventional PMTs is achieved in the Channel PMT (fig 6) and in the Microchannel PMT (Fig. 7, MCP). These detectors use channels with a conductive coating the walls of which work as secondary emission targets [1]. Microchannel PMTs are the fastest photon counting detectors currently available. Moreover, the microchannel plate technique allows to build position-sensitive detectors and image intensifiers.

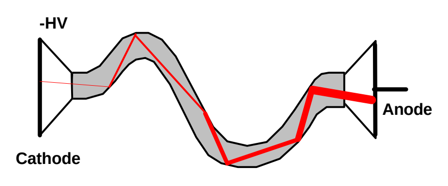


Fig. 6: Channel PMT

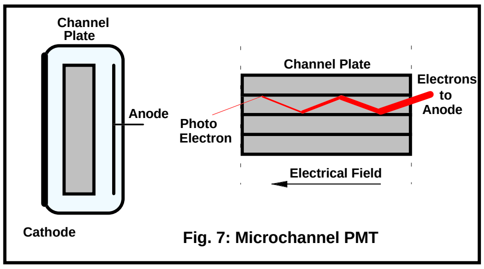


Fig. 7: Microchannel PMT

To obtain position sensitivity, the single anode can be replaced with an array of individual anode elements (fig. 8). By individually detecting the pulses from the anode elements the position of the corresponding photon on the photocathode can be determined. Multi-anode PMTs are particularly interesting in conjunction with time-correlated single photon counting (TCSPC) because this technique is able to process the photon pulses from several detector channels in only one time-measurement channel [9,12-15].

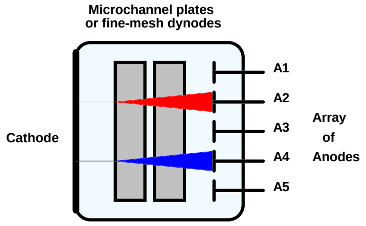


Fig. 8: Multianode PMT

The gain systems used in photomultipliers can also be used to detect electrons or ions. These ‘Electron Multipliers’ are operated in the vacuum, and the particles are fed directly into the dynode system, the multiplier channel or onto the multichannel plate (fig. 9).

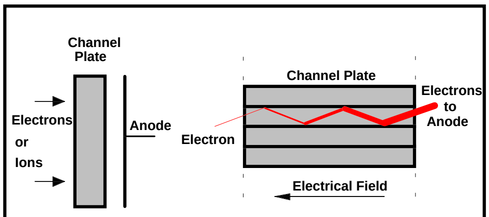


Fig 9: Electron Multiplier with MCP

Cooled avalanche photodiodes can be used to detect single optical photons if they are operated close to or slightly above the breakdown voltage [23-26] (fig. 10). The generated electron-hole pairs initiate an avalanche breakdown in the diode. Active or passive quenching circuits must be used to restore normal operation after each photon. Single-photon avalanche photodiodes (SPADs) have a high quantum efficiency in the visible and near-infrared range.

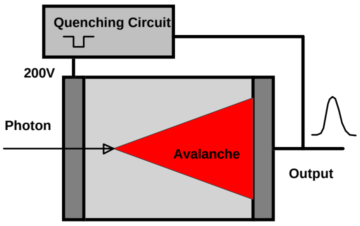


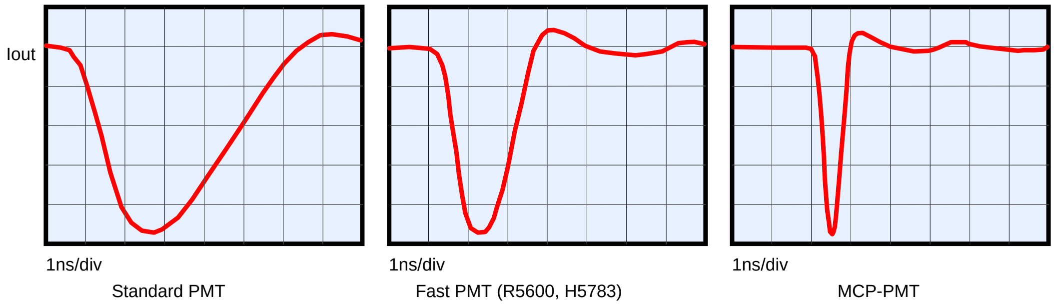
Fig 10: Single Photon Avalanche Photodiode (SPAD)

X ray photons can be detected by PIN diodes. A single high energy X ray photon generates so many electron-hole pairs in the diode so that the resulting charge pulse can be detected by an ultra-sensitive charge amplifier. However, due to the limited speed of the amplifier these detectors have a time resolution in the us range and do not reach high count rates. They can, however, distinguish photons of different energy by the amount of charge generated.

Detector Parameters

Single Electron Response

The output pulse of a detector for a single photoelectron is called the ‘Single Electron Response’ or ‘SER’. Some typical SER shapes for PMTs are shown in fig. 11.



Standard PMT — Fast PMT (R5600, H5783) — MCP-PMT

Fig. 11: Single electron response (SER) of different photomultipliers

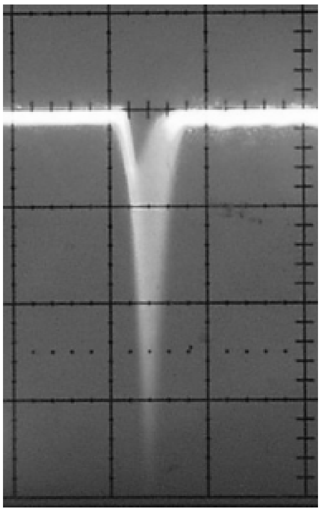


Fig. 12: Amplitude jitter of SER pulses

Due to the random nature of the detector gain, the pulse amplitude varies from pulse to pulse. The pulse height distribution can be very broad, up to 1:5 to 1:10. Fig. 12 shows the SER pulses of an R5600 PMT recorded by a 400 MHz oscilloscope.

The following considerations are made with G being the average gain, and I_{SER} being the average peak current of the SER pulses.

The peak current of the SER is approximately

$$I_{SER} = \frac{G \cdot e}{FWHM}$$

(G = PMT Gain, e=1.6 · 10^{-19} As, FWHM= SER pulse width, full width at half maximum)

The table below shows some typical values. I_{SER} is the average SER peak current and V_{SER} the average SER peak voltage when the output is terminated with 50 Ω. I_{max} is the maximum permitted continuous output current of the PMT.

PMT	PMT Gain	FWHM	I_{SER}	V_{SER} (50 Ω)	I_{max} (cont)
Standard	10^7	5 ns	0.32 mA	16 mV	100uA
Fast PMT	10^7	1.5 ns	1 mA	50 mV	100uA
MCP PMT	10^6	0.36 ns	0.5mA	25 mV	0.1uA

There is one significant conclusion from this table: If the PMT is operated near its full gain the peak current I_{SER} from a single photon is much greater than the maximum continuous output current. Consequently, for steady state operation the PMT delivers a train of random pulses rather than a continuous signal. Because each pulse represents the detection of an individual photon the pulse density - not the pulse amplitude - is a measure of the light intensity at the cathode of the PMT [1,2,3,6].

Obviously, the pulse density is measured best by counting the PMT pulses within subsequent time intervals. Therefore, photon counting is a logical consequence of the high gain and the high speed of photomultipliers.

Transit Time Spread and Timing Jitter

The delay between the absorption of a photon at the photocathode and the output pulse from the anode of a PMT varies from photon to photon. The effect is called ‘transit time spread’, or TTS. There are tree major TTS components in conventional PMTs and MCP PMTs - the emission at the photocathode, the multiplication process in the dynode system or microchannel plate, and the timing jitter of the subsequent electronics.

The time constant of the photoelectron emission at a traditional photocathodes is small compared to the other TTS components and usually does not noticeably contribute to the transit time spread. However, high efficiency semiconductor-type photocathodes (GaAs, GaAsP, InGaAs) are much slower and can introduce a transit time spread of the order of 100 to 150 ps. Moreover, photoelectrons are emitted at the photocathode of a photomultiplier at random locations, with random velocities and in random directions. Therefore, the time they need to reach the first dynode or the channel plate is slightly different for each photoelectron (fig. 13). Since the average initial velocity of a photoelectron increases with decreasing wavelength of the absorbed photon the transit-time spread is wavelength-dependent.

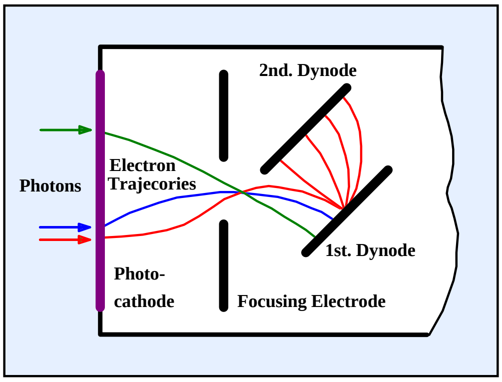


Fig. 13: Different electron trajectories cause different transit times in a PMT

As the photoelectrons at the cathode, the secondary electrons emitted at the first dynodes of a PMT or in the channel plate of and MCP PMT have a wide range of start velocities and start in any direction. The variable time they need to reach the next dynode adds to the transit time spread of the PMT.

Another source of timing uncertainty is the timing jitter in the discriminator at the input of a photon counter. The amplitude of the single electron pulses at the output of a PMT varies, which causes a variable delay in the trigger circuitry. Although timing jitter due to amplitude fluctuations can be minimised by constant fraction discriminators it cannot be absolutely avoided. Electronic timing jitter is not actually a property of the detector, but usually cannot be distinguished from the detector TTS.

TTS does exist also in single-photon avalanche photodiodes. The reason of TTS in SPADs is the different depth in which the photons are absorbed. This results in different conditions for the build-up of the carrier avalanche and in different avalanche transit times. Consequently the TTS depends on the wavelength. Moreover, if a passive quenching circuit is used, the reverse voltage may not have completely recovered from the breakdown of the previous photon. The result is an increase or shift of the TTS with the count rate.

The TTS of a PMT is usually much shorter that the SER pulse width. In linear applications where the time resolution is limited by the SER pulse width the TTS is not important. The resolution of photon counting, however, is not limited by the SER pulse width. Therefore, the TTS is the limiting parameter for the time resolution of photon counting.

Cathode Efficiency

The efficiency, i.e. the probability that a particular photon causes a pulse at the output of the PMT, depends on the efficiency of the photocathode. Unfortunately the sensitivity S of a photocathode is usually not given in units of quantum efficiency but in mA of photocurrent per Watt incident power. The quantum efficiency QE is

$$QE = S \frac{h\,c}{e\,\lambda} = \frac{S}{\lambda} \cdot 1.24 \cdot 10^6 \; \frac{W\,m}{A}$$

The efficiency for the commonly used photocathodes is shown in fig. 14. The QE of the conventional bialkali and multialkali cathodes reaches 20 to 25 % between 400 and 500 nm. The recently developed GaAsP cathode reaches 45 %. The GaAs cathode has an improved red sensitivity and is a good replacement for the multialkali cathode above 600 nm.

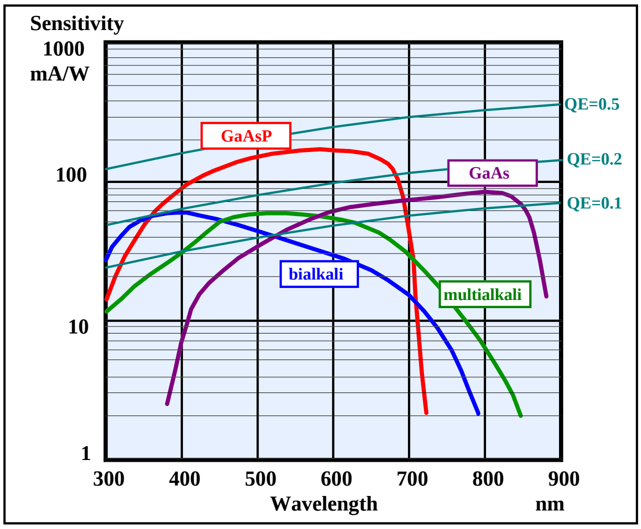


Fig. 14: Sensitivity of different photocathodes [1]

Generally, there is no significant difference between the efficiency of similar photocathodes in different PMTs and from different manufacturers. The differences are of the same order as the variation between different tube of the same type. Reflection type cathodes are a bit more efficient than transmission type photocathodes. However, reflection type photocathodes have non-uniform photoelectron transit times to the dynode system and therefore cannot be used in ultra-fast PMTs. A good overview about the characteristics of PMTs is given in [1].

The typical efficiency of the Perkin Elmer SPCM-AQR single photon avalanche photodiode (SPAD) modules is shown in the figure right (after [24]). The wavelength dependence follows the typical curve of a silicon photodiode and reaches more than 70% at 700nm. However, the active area of the SPCM-AQR is only 0.18 mm wide, and diodes with much smaller areas have been manufactured [23]. Therefore the high efficiency of an SPAPD can only be exploited if the light can be concentrated to such a small area.

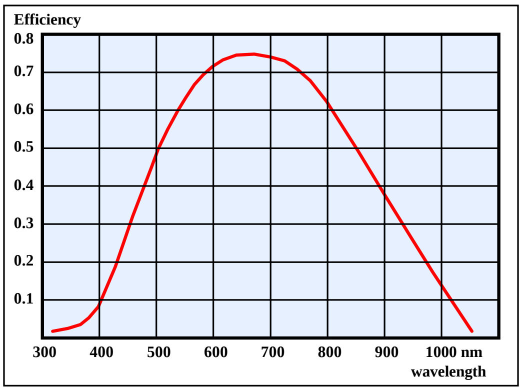


Fig. 15: Quantum efficiency vs. wavelength for SPAD. Perkin-Elmer SPCM-AQR module [24]

Pulse Height Distribution

The single photon pulses obtained from PMTs and MCPs have a considerable amplitude jitter. A typical pulse amplitude distribution of a PMT is shown in fig. 16. The amplitude spectrum shows a more or less pronounced peak for the photon pulses and a continuous increase of the background at low amplitudes. The background originates from thermal emission of electrons in the dynode systems, from noise of preamplifiers, and from noise pickup from the environment. The amplitude of the single photon pulses can vary by a factor of 10 and more.

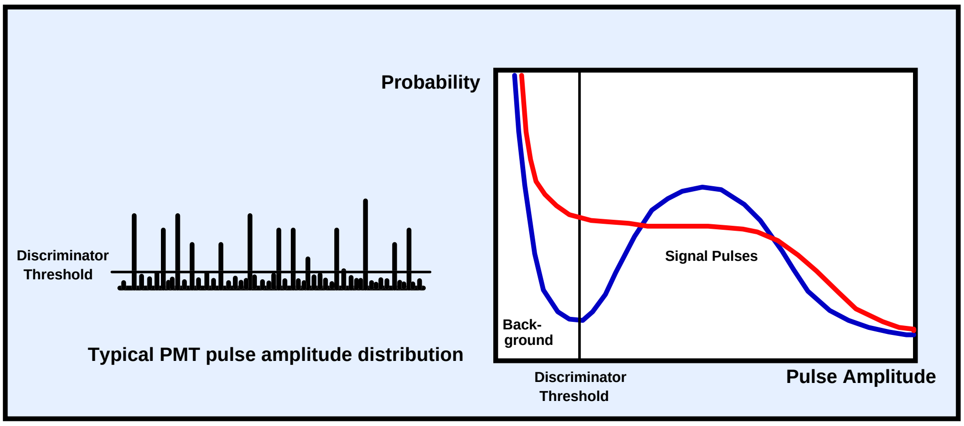


Fig 16: Pulse height distribution of a PMT and discriminator threshold for optimum counting performance

In good PMTs and MCPs the single photon pulse amplitudes should be clearly distinguished from the background noise. Then, by appropriate setting the discriminator threshold of the photon counter, the background can be effectively suppressed. If the photon pulses and the background are not clearly distinguished either the background cannot be efficiently suppresses or a large fraction of the photon pulses is lost. Therefore, next to a high QE of the cathode, a good pulse height distribution is essential to get a high counting efficiency.

The pulse height distribution has also noticeable influence on the time resolution obtained in TCSPC applications. Of course, a low timing jitter can only be achieved if the amplitude of single photon pulses is clearly above the background noise level.

The pulse height distribution of the same PMT type can differ considerably for different cathode versions. The bialkali versions are usually the best, multialkali is mediocre and extended multialkali (S25) can be disastrous. The reason might be that during the cathode formation cathode material is spilled into the dynode system or that the cathode material is also used for coating the dynodes.

Dark Count Rate

The dark count rate of a PMT depends on the cathode type, the cathode area, and the temperature. The dark count rate is highest for cathodes with high sensitivity at long wavelengths. Depending on the cathode type, there is an increase of a factor of 3 to 10 for a 10 °C increase in temperature. Therefore, additional heating, i.e. by the voltage divider resistors, amplifiers connected to the output, or by the coils of shutters should be avoided. The most efficient way to keep the dark count rate low is thermoelectric cooling. Exposing the cathode of a switched-off PMT to daylight increases the dark count rate considerably. For the traditional cathodes the effect is reversible, but full recovery takes several hours, see fig. 17. Semiconductor cathodes should not be exposed to full daylight at all.

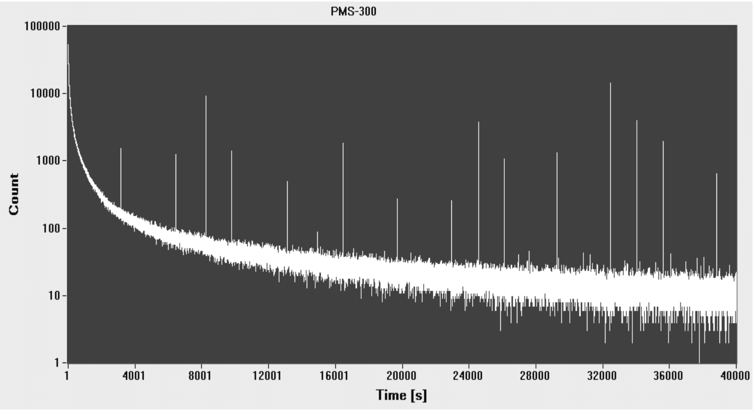


Fig.17: Decrease of dark count rate (counts per second) of a H5773P-01 after exposing the cathode to room light. The device was cooled to 5°C. The peaks are caused by scintillation effects.

After extreme overload, e.g. daylight on the cathode of an operating PMT, the dark count rate is permanently increased by several orders of magnitude. The tube is then damaged and does not recover.

Many PMTs produce random single pulses of extremely high amplitude or bursts of pulses with extremely high count rate. Such bursts are responsible for the peaks in fig. 17. The pulses can originate from scintillation effects by radioactive decay in the vicinity of the tube, in the tube structure itself, by cosmic ray particles or from tiny electrical discharges in the cathode region. Therefore not only the tube, but also the materials in the cathode region must be suspected to be the source of the effect. Generally, there should be some mm clearance around the cathode region of the tube.

Afterpulses

Most detectors have an increased probability to produce a dark count pulse in a time interval of some 100 ns to some µs after the detection of a photon. Afterpulses can be caused by ion feedback, or by luminescence of the dynode material and the glass of the tube. They are detectable in almost any conventional PMT. Afterpulsing of an R5600 tube is shown in fig. 18.

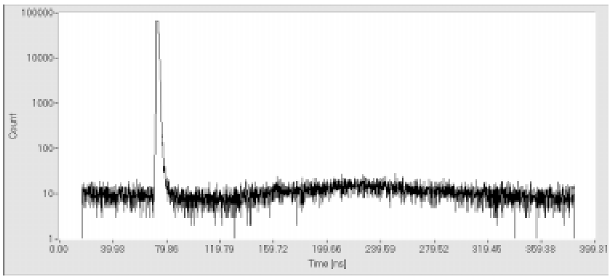


Fig. 18: Afterpulsing in an R5600 PMT tube. TCSPC measurement with Becker & Hickl SPC-630. The peak is the laser pulse, afterpulses cause a bump 200 ns later

Afterpulsing can be a problem in high repetition rate TCSPC applications, particularly with titanium-sapphire lasers or diode lasers, and in fluorescence correlation experiments. At high repetition rate the afterpulses from many signal periods accumulate and cause an appreciable signal-dependent background. Correlation spectra can be severely distorted by afterpulsing.

Afterpulsing shows up most clearly in histograms of the time differences between subsequent photons or in correlation spectra. For classic light, i.e. from an incandescent lamp, the histogram of the time differences drops exponentially with the time difference. Any deviation from the exponential drop indicates correlation between the detection events, i.e. non-ideal behaviour of the detector. Afterpulses show up as a peak centred at the average time difference of primary pulses and afterpulses.

A correlation spectrum is the autocorrelation function of the photon density versus time. Classic light delivers a constant background of random coincidences of the detection events. As in the histogram of time differences, afterpulses show up as a peak centred at the average time difference of primary pulses and afterpulses.

Typical curves for a traditional R932 PMT are shown in fig. 19.

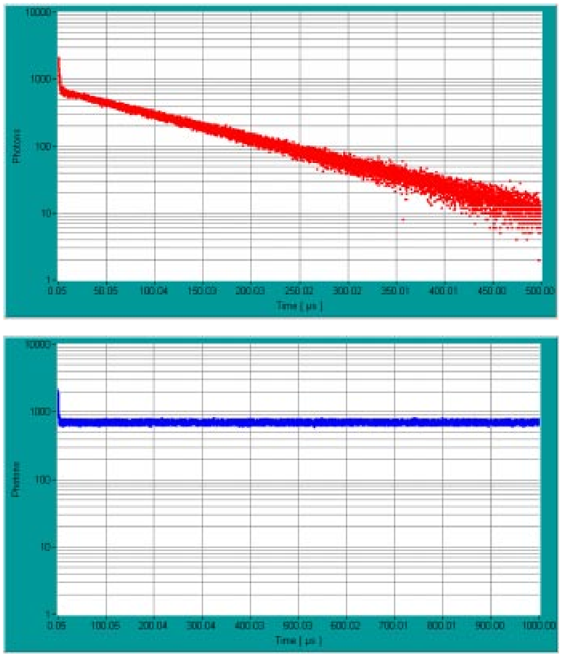


Fig. 19: Histogram of times between photons (top) and correlation spectrum (bottom) for classic light. The peak at short times is due to afterpulsing.

Photon Counting Performance of Selected Detectors

R3809U MCP-PMT

The TCSPC system response for a Hamamatsu R3809U-50 MCP [27] is shown in fig. 20. The MCP was illuminated with a femtosecond Ti:Sa laser, the response was measured with an SPC-630 TCSPC module. A HFAC-26-01 preamplifier was used in front of the SPC-630 CFD input. At an operating voltage of -3 kV the FWHM (full width at half maximum) of the response is 28 ps.

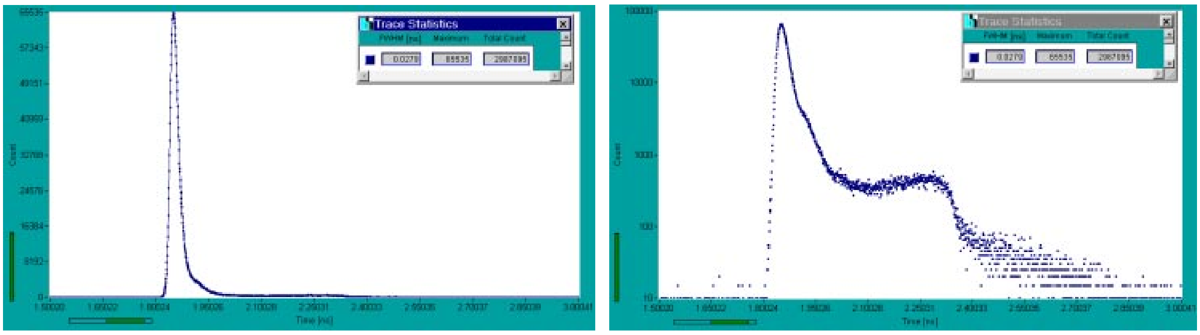


Fig. 20: R38909U, TCSPC instrument response. Operating voltage-3kV, preamplifier gain 20dB, discriminator threshold - 80mV

The response has a shoulder of some 400 ps duration and about 1% of the peak amplitude. This shoulder seems to be a general property of all MCPs and appears in all of these devices.

The width of the response can be reduced to 25 ps by increasing the operating voltage to the maximum permitted value of -3.4 kV. However, for most applications this is not recommended for the following reason:

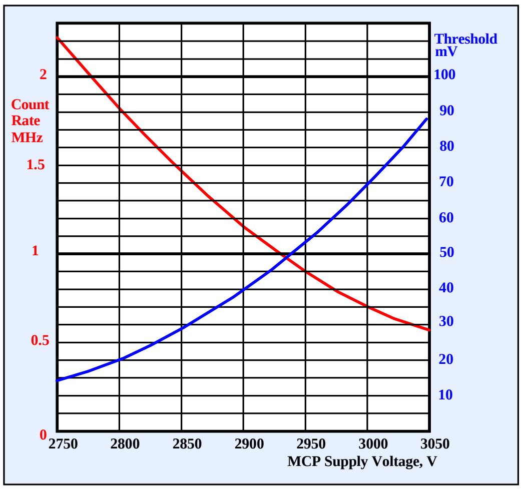


Fig. 21: R3809U, count rate for 100 nA anode current and optimum discriminator threshold vs. supply voltage. HFAC-26-01 (20dB) preamplifier

As all MCP-PMTs, the R3809U allows only a very small maximum output current. This sets a limit to the maximum count rate that can be obtained from the device. The maximum count rate depends on the MCP gain, i.e. of the supply voltage. The count rate for the maximum output current of 100 nA as a function of the supply voltage is shown in fig. 21. To keep the counting efficiency constant the CFD threshold was adjusted to get a constant count rate at a reference intensity that gave 20,000 counts per second. Fig. 21 shows that count rates in excess of 2 MHz can be reached.

The R3809U tubes have a relatively good SER pulse height distribution which seems to be independent of the cathode type - possibly a result of the independent manufacturing of the channel plate and the cathode. Therefore a good counting efficiency can be achieved.

Fig. 22 shows the histogram of the time intervals between the recorded photons. The count rate was about 10,000 photons per second, the data were obtained with an SPC-830 in the 'FIFO' mode. Interestingly, the R3809U is free of afterpulsing.

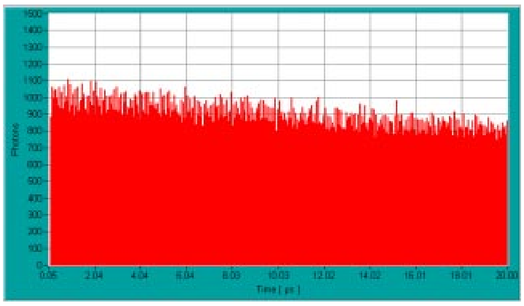


Fig. 22: R3809U, histogram of times between photons. No afterpulses are detected.

Due to the short TCSPC response and the absence of afterpulses the R3809U is an ideal detector for TCSPC fluorescence lifetime measurements, for TCSPC lifetime imaging, and for combined lifetime / FCS or other correlation experiments. Recently Hamamatsu announced the R3809U MCP with GaAs, GaAsP, and infrared cathodes for up to 1700 nm. Although these MCPs are not as fast as the versions with conventional cathodes they might be the ultimate detectors for combined FCS / lifetime experiments.

The flipside is that MCPs are expensive and can easily be damaged by overload. Therefore the R3809U should be operated with a preamplifier that monitors the output current. If overload conditions are to be expected, i.e. by the halogen or mercury lamp of a scanning microscope, electronically driven shutters should be used and high voltage shutdown should be accomplished to protect the detector.

H7422

The H7422 incorporates a GaAs or GaAsP cathode PMT, a thermoelectric cooler, and the high voltage power supply [28]. Hamamatsu delivers a small OEM power supply to drive the cooler. However, we could not use this power supply because it generated so much noise that photon counting with the H7422 was not possible. Furthermore, we found that the H7422 shuts down if the gain control voltage is changed faster that about 0.1V / s. Apparently fast changes activate an internal overload shutdown. Unfortunately the device can only be re-animated by cycling the +12 V power supply.

Therefore we use the Becker & Hickl DCC-100 detector controller. It drives the cooler and supplies the +12 V and a software-controlled gain control voltage to the H7422. Furthermore, the DCC in conjunction with a HFAC-26-1 preamplifier can be connected to shut down the gain of the H7422 on overload. If the H7422 shuts down internally for any reason, cycling the +12 V is only a mouse click into the DCC-100 operating panel.

The TCSPC system response of an H7422-40 is shown in Fig. 23.

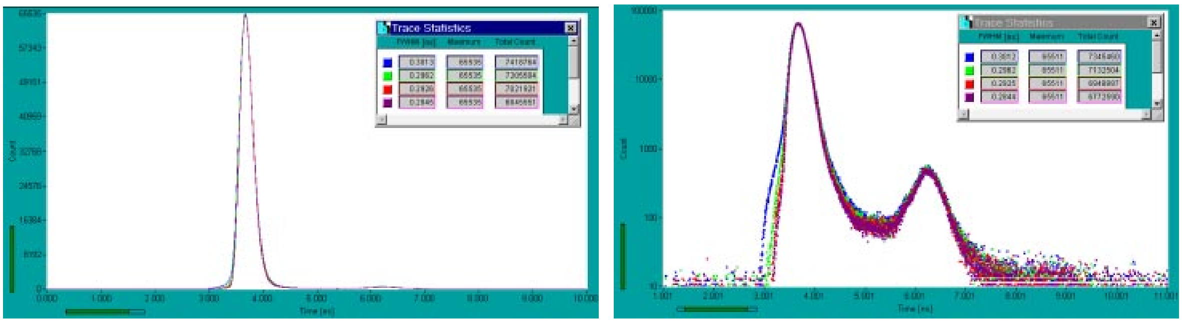


Fig. 23: H7422-40, TCSPC Instrument response function. Gain control voltage 0.9V (maximum gain), preamplifier 20dB, discriminator threshold -200mV, -300mV, -400mV and -500mV

The FWHM of the system response is about 300 ps. There is a weak secondary peak about 2.5 ns after the main peak, and a peak prior to the main peak can appear at low discriminator thresholds. The width of the response does not depend appreciably of the discriminator threshold. This is an indication that the response is limited by the intrinsic speed of the semiconductor photocathode.

The afterpulsing probability of the H7422-40 can be seen from the histogram of the time intervals of the photon (fig. 24). For maximum gain the afterpulse probability in the first 1.5 µs is very high (fig. 24, red curve, control voltage 0.9V). If the gain is reduced the afterpulse probability decreases considerably (fig. 24, blue curve, 0.63V). The timing resolution does not decrease appreciably at the reduced gain, fig. 25.

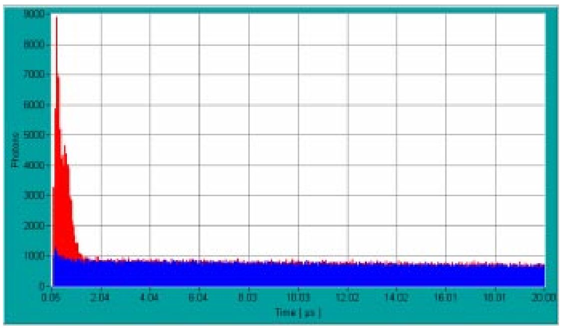


Fig. 24: H7422-40, histogram of times between photons. Gain control voltage 0.9V (red) and 0.63V (blue). Afterpulse probability increases with gain.

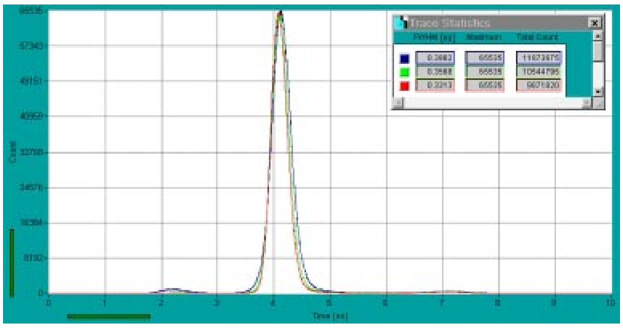


Fig. 25, H7422-40, TCSPC Instrument response function. Gain control voltage 0.63V, preamplifier 20dB, discriminator threshold -30mV, -50mV, -70mV

The H7422 is a good detector for TCSPC applications when sensitivity has a higher priority than time resolution. A typical application is TCSPC imaging with laser scanning microscopes [18,29]. The high quantum efficiency helps to reduce photobleaching which is the biggest enemy of lifetime imaging in scanning microscopes.

The H7422 can also be used to investigate diffusion processes in cells or conformational changes of dye / protein complexes by combined FCS / lifetime spectroscopy. Although the accuracy in the time range below 1.5 µs is impaired by afterpulsing, processes at longer time scales can be efficiently recorded.

Another application of the H7422 is optical tomography with pulses NIR lasers. Because the measurements are run in-vivo it is essential to acquire a large number of photons in a short measurement time. Particularly in the wavelength range above 800 nm the efficiency of H7422-50 and -60 yields a considerable improvement compared to PMTs with conventional cathodes.

H7421

The Hamamatsu H7421 is similar to the H7422 in that it contains a GaAs or GaAsP cathode PMT, a thermoelectric cooler, and the high voltage power supply. However, the output of the PMT is connected to a discriminator that delivers TTL pulses. The output of the PMT is not directly available, and the PMT gain and the discriminator threshold cannot be changed. The module is therefore easy to use. However, because the discriminator is not of the constant fraction type, the TCSPC timing performance is by far not as good as for the H7422, see figure 26.

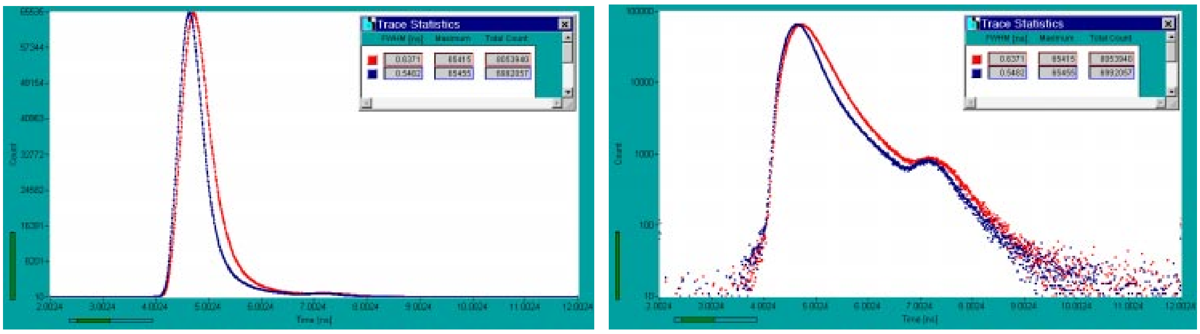


Fig. 26: H7422-50, TCSPC response function for a count rate of 30 kHz (blue) and 600 kHz (red)

The FWHM is only 600 ps. Moreover, it increases for count rates above some 100 kHz. Interestingly no such count rate dependence was found for the H7422. Obviously the H7422 is a better solution if high time resolution and high peak count rate is an issue.

H5783 and H5773 Photosensor Modules, PMH-100

The H5783 and H5773 photosensor modules contain a small (TO9 size) PMT and the high voltage power supply [30]. They come in different cathode and window versions. A ‘P’ version selected for good pulse height distribution is available for the bialkali and multialkali tubes. The typical TCSPC response of a H5773P-0 is shown in fig. 27. The device was tested with a 650 nm diode laser of 80 ps pulse width. A HFAC-26-10 preamplifier was used, and the response was recorded with an SPC-730 TCSPC module.

The response function has a pre-peak about 1 ns before the main peak and an secondary peak 2 ns after. The pre-peak is caused by low amplitude pulses, probably from photoemission at the first dynode. It can be suppressed by properly adjusting the discriminator threshold. The secondary peak is independent of the discriminator threshold.

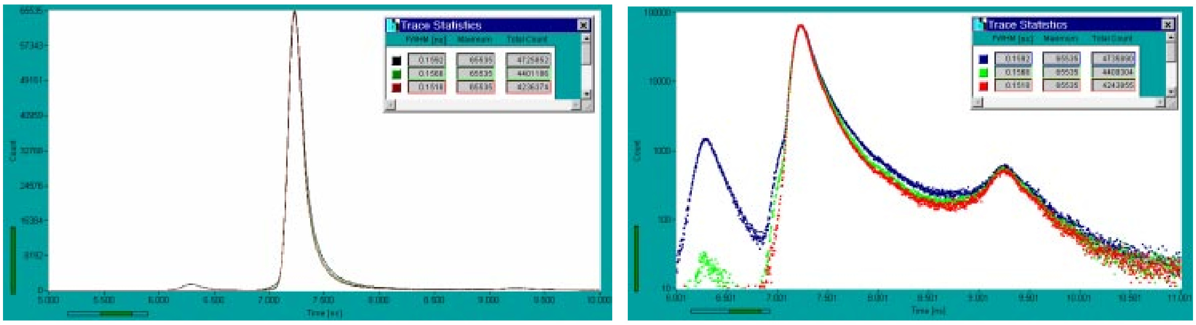


Fig: 27: H5773P-0, TCSPC instrument response. Maximum gain, preamplifier gain 20dB, discriminator threshold -100mV, -300mV and -500mV

The Becker & Hickl PMH-100 module contains a H5773P module, a 20 dB preamplifier, and an overload indicator. The response is the same as for the H5773P and a HFAC-26 amplifier. However, because the PMT and the preamplifier are in the same housing, the PMH-100 has a superior noise immunity. This results in an exceptionally low differential nonlinearity in TCSPC measurements.

A histogram of the times between the photon pulses for the H5773 is shown in fig. 28. The devices show relatively strong afterpulsing, particularly the multialkali (-1) tubes.

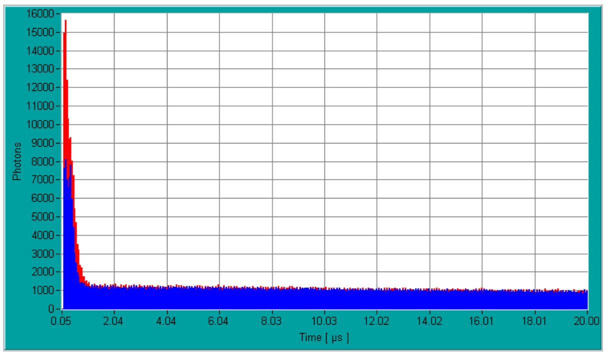


Fig. 28: Histogram of times between photons for H5773P-0 (blue) and H5773P-1 (red). The afterpulse probability is higher for the -1 version

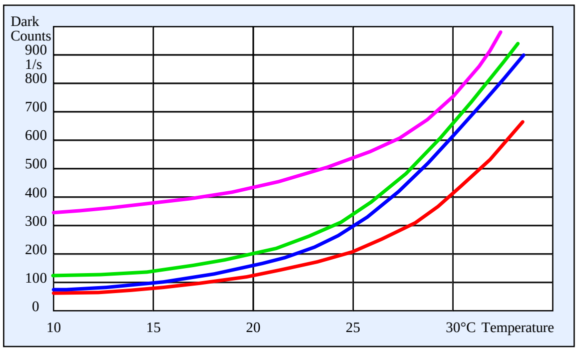


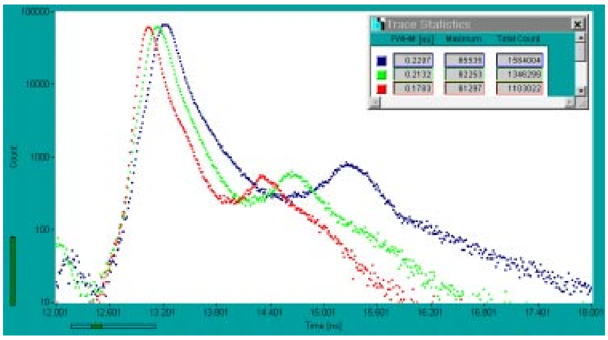
Fig. 29: Dark count rate for different H5773P-01 modules

Fig. 29 shows the dark count rate for different H5773P-1 modules as a function of ambient temperature. Taking into regards the small cathode area of the devices the dark count rates are relatively high. Selected devices with lower dark count rate are available.

The H5783, the H5773 and particularly the PMH-100 are easy to use, rugged and fast detectors that can be used for TCSPC, multiscalers and gated photon counting as well. In multiscaler applications the detectors reach peak count rates of more that 150 MHz for a few 100 ns. The detectors are not suitable for FCS or similar correlation experiments on the time scale below 1 us.

R7400 and R5600 TO-8 PMTs

The R7400 and the older R5600 are bare tubes similar to that used in the H5783 and H5773. There is actually no reason to use the bare tubes instead of the complete photosensor module. However, for the bare tube the voltage divider can be optimised for smaller TTS or improved linearity at high count rate. The TTS width decreases with the square root of the voltage between the cathode and the first dynode. It is unknown how far the voltage can be increased without damage. A test tube worked stable at 1 kV overall voltage with a three-fold increase of the cathode-dynode voltage. The decrease of the response width is shown in fig. 30.



	FWHM [ns]	Maximum	Total Count
🟦	0.2287	65535	1584004
🟩	0.2132	62253	1346299
🟥	0.1783	61287	1103022

Fig. 30: R5900P-1, -1kV supply voltage: TCSPC response for different voltage between cathode and first dynode. Blue, green and red: 1, 2 and 3 times nominal voltage

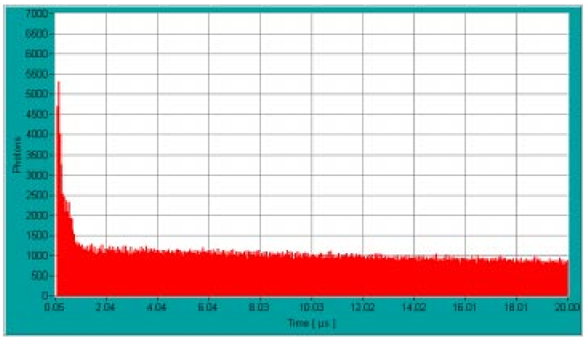


Fig. 31: H5773P-1, -1kV : Histogram of times between photons.

The afterpulse probability is the same as for the H5783 and H5773 photosensor modules (fig. 31).

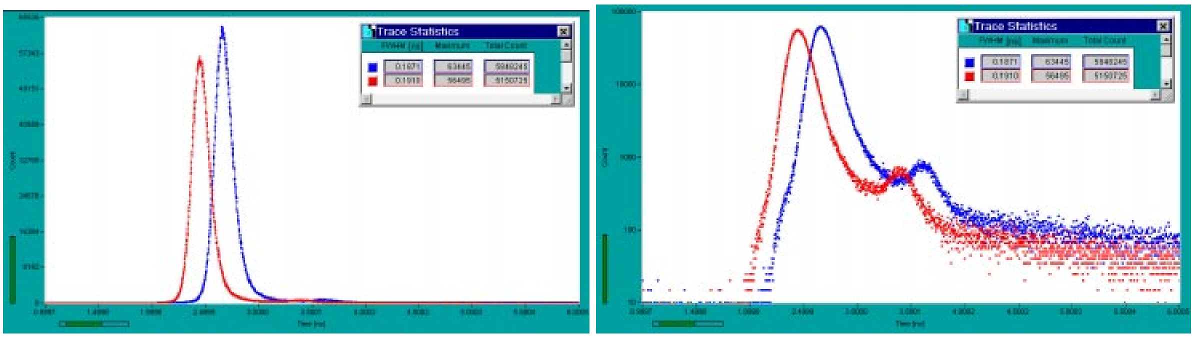
It is questionable whether the benefit of a slightly shorter response compensates for the inconvenience of building a voltage divider and using a high voltage power supply. However, if a large number of tubes has to be used, i.e. in an optical tomography setup, using the R5600 or R7400 can be reasonable.

R5900-L16 Multichannel PMT and PML-16 Multichannel Detector Head

The Hamamatsu R5900-L16 is a multi-anode PMT with 16 channels in a linear arrangement. In conjunction with a polychromator the detector can be used for multi-wavelength detection. If the R5900-L16 is used with steady-state and gated photon counters or with multiscalers 16 parallel recording channels, e.g. two parallel Becker & Hickl PMM-328 modules are required. For TCSPC application the multi-detector technique described in [9] and [12-15] can be used. TCSPC multi-detector operation is achieved by combining the photon pulses of all detector channels into one common timing pulse line and generating a ‘channel’ signal which indicates in which of the PMT channels a photon was detected. The Becker & Hickl PML-16 detector head [13] contains the R5900-L16 tube and all the required electronics.

The R5900-L16 has also been used with a separate routing device [12,31]. However, in a setup like this noise pick-up from the environment and noise from matching resistors and preamplifiers adds up so that the timing performance is sub-optimal.

The TCSPC response of two selected channels of the PML-16 detector head is shown in fig. 32. The response of a single channel of different R5900-L16 is between 150 ps and 220 ps FWHM.



	FWHM [ns]	Maximum	Total Count
🟦	0.1871	63445	5848245
🟥	0.1910	56495	5150725

Fig. 32: System response of two selected channels of the PML-16 detector head

The response is slightly different for the individual channels. Fig. 33 shows the response for the 16 channels as sequence of curves and as a colour-intensity plot. There is a systematic wobble in the delay of response with the channel number. That means, for the analysis of fluorescence lifetime measurements the instrument response function (IRF) must be measured for all channels, and each channel must be de-convoluted with its individual IRF.

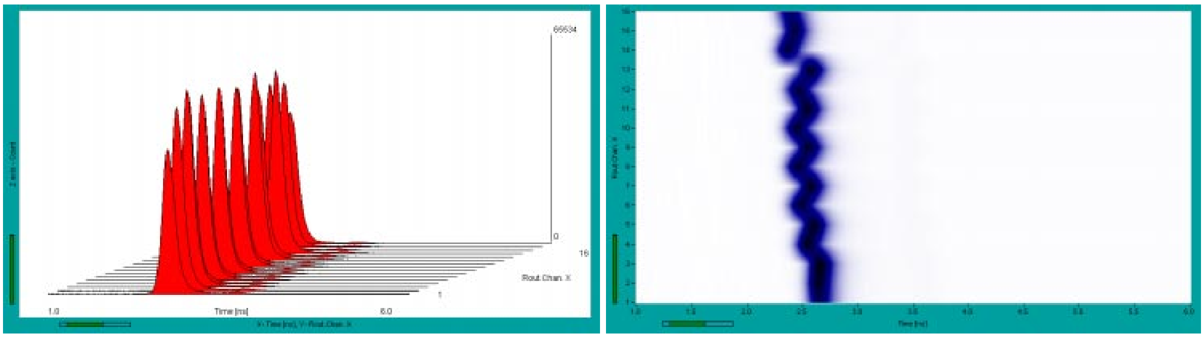


Fig. 33: System response of the PML-16 / R5900-L16 channels. Left curve plot, right colour-intensity plot

The data sheet of the R5900-L16 gives a channel crosstalk of only 3%. There is certainly no reason to doubt about this value. However, in real setup it is almost impossible to reach such a small crosstalk. If crosstalk is an issue the solution is to use only each second channel of the R5900-L16 [31]. If the PML-16 is used with only 8 channels, the data of the unused channels should simply remain unused. If the R5900-L16 is used outside the PML-16 the unused anodes should be terminated into ground with 50 Ω.

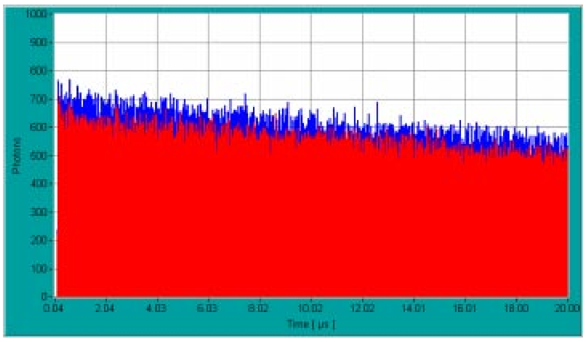


Fig. 34: R5900-L16, histogram of times between photons. No afterpulsing was found.

A histogram of the times between the photon pulses is shown in fig. 34. No afterpulsing was found in the R5900-L16. It appears unlikely that the absence of afterpulses was a special feature of the tested device. The result is surprising because afterpulsing is detectable in all PMTs of conventional design. It seems that the 'metal channel' design of the R5900 is really different from any conventional dynode structure. That means, the R5900-L16 and the PML-16 detector head are exceptionally suitable for combined multi-wavelength fluorescence lifetime and FCS experiments. The absence of afterpulses can be a benefit also in high repetition rate TCSPC measurements in that there is no signal-dependent background. A R5900-L16 with a GaAs or GaAsP cathode - although not announced yet - would be a great detector.

Side Window PMTs

Side window PMTs are rugged, inexpensive, and often have somewhat higher cathode efficiency than front window PMTs. The broad TTS and the long SER pulses make them less useful for TCSPC application or for multiscaling or gated photon counting with high peak count rates. However, side-window PMTs are used in many fluorescence spectrometers, in femtosecond correlators and in laser scanning microscopes. If an instrument like these has to be upgraded with a photon counting device it can be difficult to replace the detector. Therefore, some typical results for side window PMTs are given below.

The width and the shape of the TCSPC system response depend on the size and the location of the illuminated spot on the photocathode. The response for the R931 - a traditional 28 mm diameter PMT - for a spot diameter of 3 mm is shown in Fig. 35.

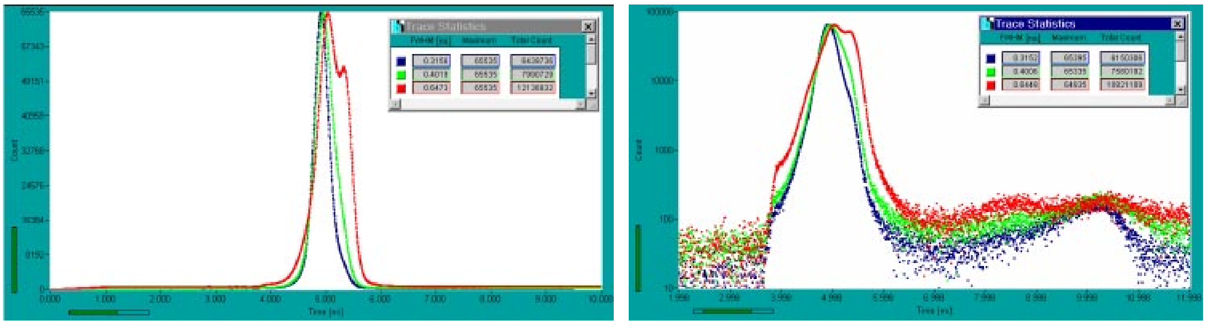


Fig. 35: R931, TCSPC system response for different spots on the photocathode. Spot diameter 3mm

By carefully selecting the spot on the photocathode an acceptable response can be achieved [31,32]. A TCSPC response width down to 112 ps FWHM has been reported [32]. This short value was obtained by using single electron pulses in an extremely narrow amplitude interval and illuminating a small spot near the edge of the cathode.

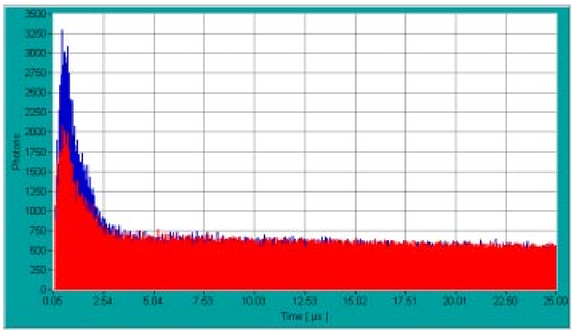


Fig. 36: R931, histogram of times between photons. Red -900V, blue -1000V. The afterpulse probability increases with voltage

The afterpulse probability for an R931 is shown in Fig. 36. The afterpulse probability depends on the operating voltage, and the afterpulses occur within a time interval of about 3 µs. The high afterpulse probability does not only exclude correlation measurements on the time scale below 3 µs, it can also result in a considerable signal-dependent background in high repetition rate TCSPC applications.

Surprisingly, modern 13 mm diameter side window tubes are not faster than the traditional 28 mm tubes. The TCSPC response for a Hamamatsu R6350 is shown in fig. 37.

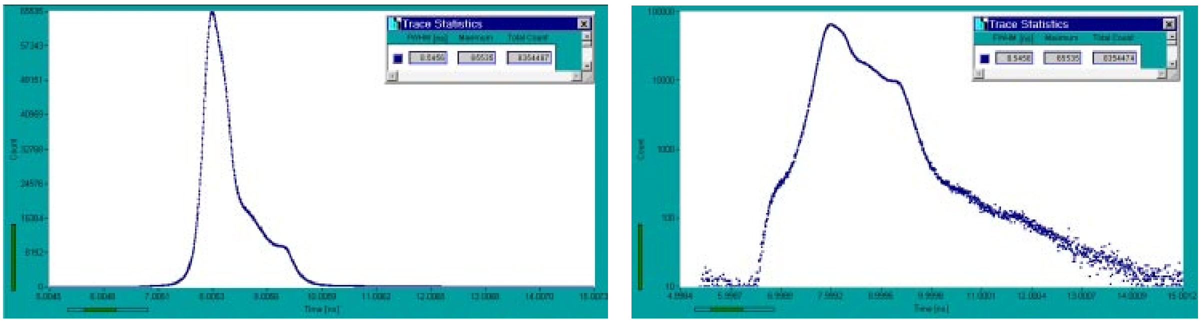


Fig. 37: R6350, TCSPC system response for illumination of full cathode area

13 mm tubes are often used in the scanning heads of laser scanning microscopes. It is difficult, if not impossible to replace the side-window PMTs with faster detectors in these instruments. Therefore it is often unavoidable to use the 13 mm side-on tube for TCSPC lifetime imaging. Depending on the size and the location of the illuminated spot an FWHM of 300 to 600 ps can be expected. Although this is sufficient to determine the lifetimes of typical high quantum yield chromophores, accurate FRET and fluorescence quenching experiments require a higher time resolution.

CP 944 Channel Photomultiplier

The channel photomultipliers of Perkin Elmer offer high gain and low dark count rates at a reasonable cost. Unfortunately the devices have an extremely broad TTS. The TCSPC system response to a 650nm diode laser is shown in fig. 38. The FWHM of the response is of the order of 1.4 to 1.9 ns which is insufficient for typical TCSPC applications.

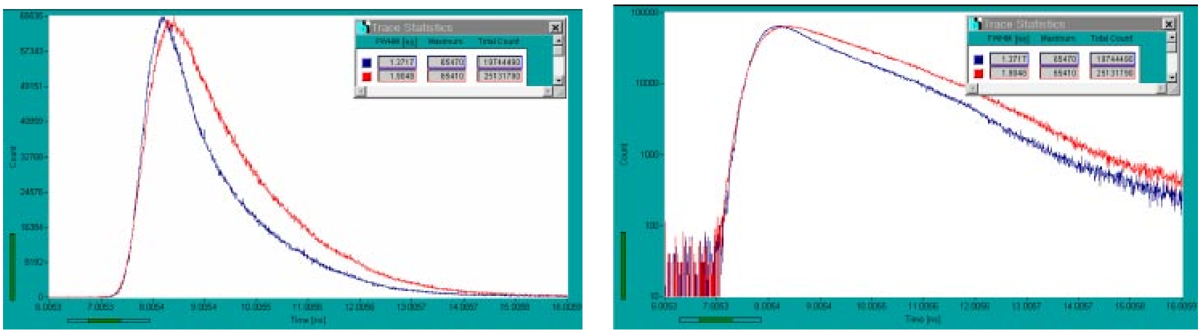


Fig. 38: CP 944 channel photomultiplier, TCSPC response. 650 nm, count rate 1.5.105, high voltage -2.8 kV (red) and -2.9 kV (blue). Full cathode illuminated

However, the Perkin Elmer channel PMTs have high gain, a low dark count rate and a surprisingly narrow pulse height distribution. This makes them exceptionally useful for low intensity steady state photon counting or multichannel scaling.

SPCM-AQR Single Photon Avalanche Photodiode Module

The Perkin Elmer SPCM-AQR single photon avalanche photodiode modules are well-known for their high quantum efficiency in the near-infrared. Unfortunately the modules have a very poor timing performance. The TCSPC response for a SPCM-AQR-12 (dark count class <250 cps) is shown in fig. 39.

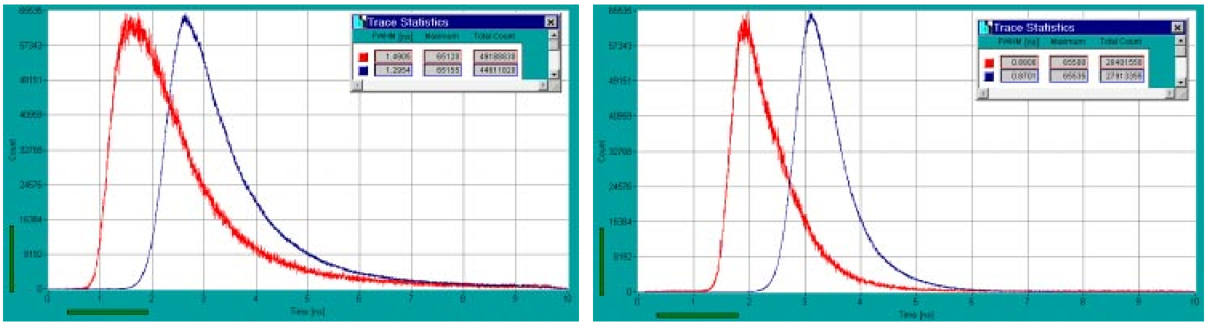


Fig. 39: SPCM-AQR-12, TCSPC response. Left: 405nm, red 50 kHz, blue 500 kHz count rate. Right: 650 nm, red 50 kHz, blue 500 kHz count rate

The response was measured with a 405 nm BDL-405 and a 650 nm ps diode laser of Becker & Hickl. The pulse width of the lasers was 70 to 80 ps, i.e. much shorter that the detector response. The measurements show that the TTS is not only much wider than specified, there is also a considerable change with the wavelength, and, still worse, with the count rate. Therefore the SPCM-AQR cannot be used for fluorescence lifetime measurements.

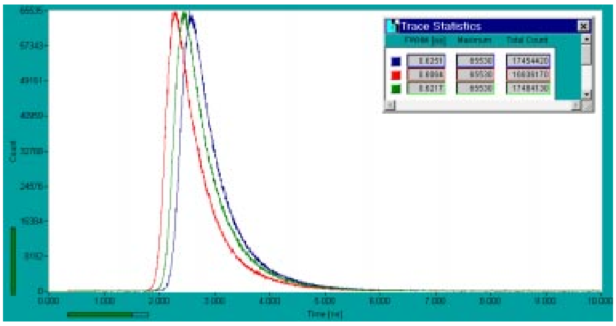


Fig. 40: SPCM-AQR-14, 650 nm, count rates $8 \cdot 10^4$ (green), $5 \cdot 10^5$ (red) and $1 \cdot 10^6$ (blue)

Interestingly, an older SPCM-AQR had a smaller count-rate dependence. Fig. 40 shows the TCSPC response of an SPCM-AQR-14 (dark count class < 40 cps) manufactured in 1999. Although the shift with the count rate is still too large for fluorescence lifetime experiments, it is much smaller than for the new device.

The afterpulse probability of the SPCM-AQR is low enough for correlation experiments down to a few 100 ns, fig. 41.

An inconvenience of the non-fibre version of the SPCM-AQR is that it is almost impossible to attach it to an optical system without getting daylight into the optical path. A standard optical adapter, e.g. a C-mount thread around the photodiode, would simplify the optical setup considerably.

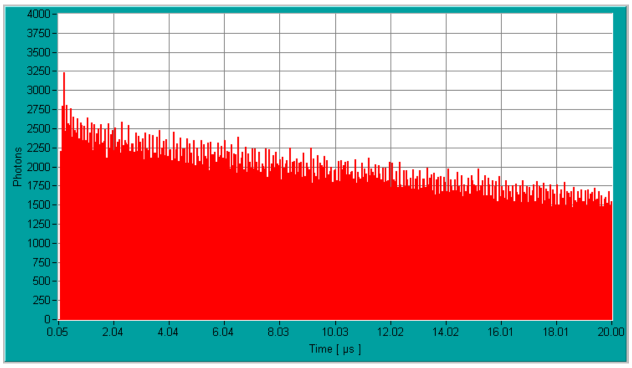


Fig. 419: SPCM-AQR-12, histogram of times between photons

The conclusion is that the SPCM-AQR is an excellent detector for fluorescence correlation spectroscopy and high efficiency steady state photon counting but not applicable to fluorescence lifetime measurements. This is disappointing, particularly because state-of-the-art TCSPC techniques allow for simultaneous FCS / lifetime measurements which are exceptionally useful to investigate conformational changes in protein-dye complexes, single-molecule FRET and diffusion processes in living cells. Currently the only solution for these applications is to use PMT detectors, i.e. the R3809U MCP, the H7422 or the R5900 which, of course, means to sacrifice some efficiency.

Summary

There is no detector that meets all requirements of photon counting - high quantum efficiency, low dark count rate, short transit time spread, narrow pulse height distribution, high peak count rate, high continuous count rate, and low afterpulse probability. The detector with the highest efficiency, the Perkin Elmer SPCM-AQR, has a broad and count-rate dependent transit time spread. The R7400 miniature PMTs and the H5783 and H5773 photosensor modules of Hamamatsu have a short transit-time spread and work well for TCSPC, steady state photon counting, and multiscaler applications. However, they cannot be used for correlation experiments below 1.5 us because of their high afterpulse probability. The H7422 modules offer high efficiency combined with acceptable transit time spread. The afterpulse probability can be kept low if they are operated at reduced gain.

There are two really remarkable detectors - the Hamamatsu R3809U MCP and the R5900 multi-anode PMT. Both tubes are free of afterpulses. The R3809U achieves a TTS, i.e. a TCSPC response below 30 ps FWHM while the R5900-L1 reaches < 200 ps in 16 parallel channels. Only these detectors appear fully applicable for simultaneous fluorescence correlation and lifetime experiments.

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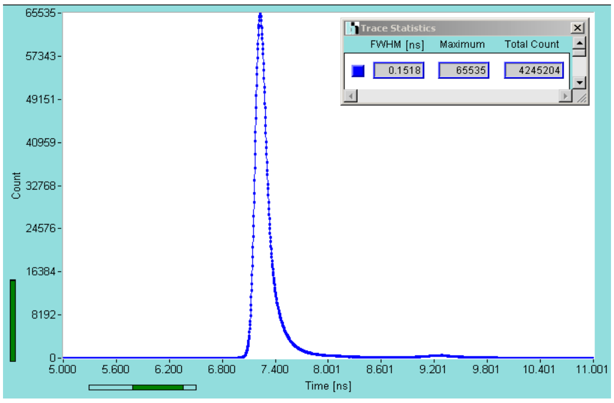
PMC-100

Cooled High Speed PMT Detector Head for Photon Counting

Applicable to Time-Correlated, Steady State and Gated Photon Counting
Non-descanned Detector for TCSPC Imaging
Excellent TCSPC Instrument Response: < 200 ps FWHM
Internal Cooler: Low Dark Count Rate
Internal GHz Preamplifier: High Output Amplitude
No High Voltage Power Supply Required
Excellent Noise Immunity
Overload Indicator and TTL / CMOS Overload Output
Cooling Control and Overload Shutdown via bh DCC-100 module
Direct Interfacing to all bh Photon Counting Devices
Standard C Mount Adapter

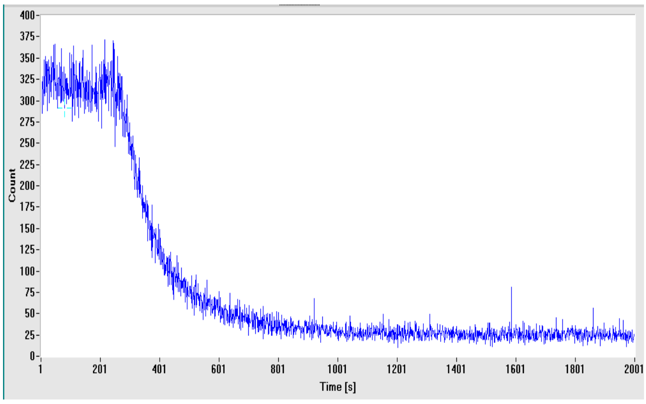
The PMC-100 is a cooled detector head for photon counting applications. It contains a fast miniature PMT along with a Peltier cooler, a high voltage generator, a GHz pulse amplifier and a current sensing circuit. Due to the high gain and bandwidth of the device a single photon yields an output pulse with an amplitude in the range of 50 to 200 mV and a pulse width of 1.5 ns. Due to the high gain and the efficient shielding noise pickup or crosstalk of start and stop signals in time-correlated single photon counting (TCSPC) experiments is minimised. Therefore the PMC-100 yields an excellent time resolution, a high counting efficiency and an exceptionally low differential nonlinearity. The instrument response function in TCSPC applications has a width of less than 200 ps. Overload conditions are detected by sensing the PMT output current and indicated by a LED, an acaustic signal, and a logical overload signal. The PMC-100 is operated by the bh DCC-100 detecor controller card which delivers the current for the Peltier cooler, controls the detector gain, and shuts down the PMT on overload.



Trace Statistics

FWHM [ns]	Maximum	Total Count
0.1518	65535	4245204

TCSPC instrument response function. Gain control voltage 0.9V, PMC-100-0, SPC-630 TCSPC module



Decrease of dark count rate after switch-on of cooler. PMC-100-1with DCC-100 detector controller, cooling current 0.7 A

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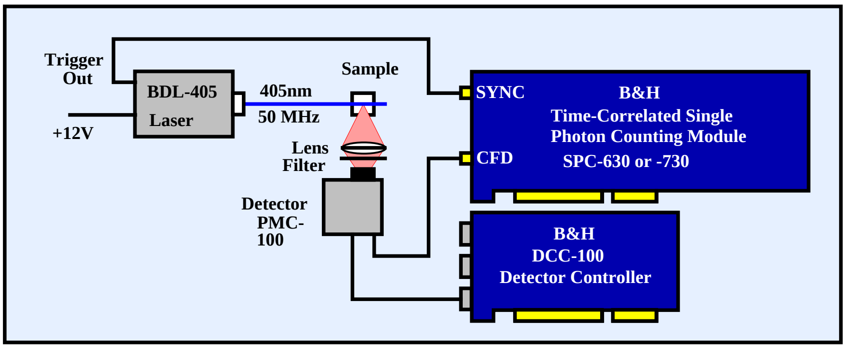
Note:
To avoide restriction of the wavelength range the PMC-100 has no hermetically sealed window. Please make sure that moisture is kept off the photomultiplier cathode by filters, lenses or other window elements inserted directly in front of the device.

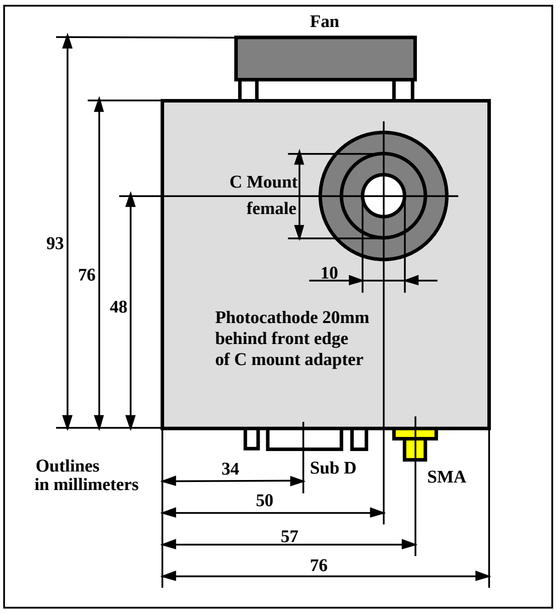
PMC-100

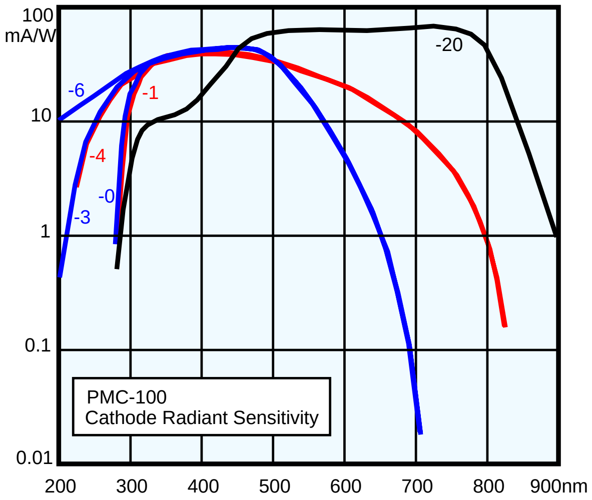
	PMC-100-3	PMC-100-6	PMC-100-0	PMC-100-4	PMC-100-1	PMC-100-20
Wavelength Range (nm)	185 to 650	185 to 650	300 to 650	185 to 820	300 to 820	300 to 900
Dark Counts (Icool=0.7A, Tamb = 22°C, typ. value)	20	20	20	40	40	200 to 500
Cathode Diameter	8 mm					
Transit Time Spread / TCSPC IRF width	180 ps, FWHM, typ. value					
Single Electron Response Width	1.5 ns, FWHM, typ. value					
Single Electron Response Amplitude	50 to 200 mV, Vgain=0.9V					
Output Polarity	negative					
Count Rate (Continuous)	> 5 MHz					
Count Rate (Peak, < 100 ns)	> 100 MHz					
Overload Indicator	LED and acoustic signal					
Overload Signal	TTL / CMOS, active low					
Detector Signal Output Connector	SMA					
Output Impedance	50 Ω					
Power Supply (from DCC-100 Card)	+ 12 V, -12V (fan only), Peltier Current 0.5 to 1A					
Dimensions (width x height x depth)	76 mm x 111 mm x 56 mm					
Optical Adapter	C-Mount female					
Fibre Coupling	SMA 905, on request					

Simple fluorescence lifetime experiment:

The arrangement uses a BDL-405 blue picosecond diode laser, a PMC-100 detector module an SPC-630, -730 or -830 time correlated single photon counting module and a DCC-100 detector controller card. (Please see individual data sheets). The instrument response width is typically <180 ps FWHM. Fluorescence lifetimes down to 20 ps can be determined by deconvolution.







Pin Assignment of 15 pin sub-d-hd connector

1	not used	9	Peltier -
2	Peltier +	10	+12V
3	Peltier +	11	-12 (Fan)
4	Peltier +	12	not used
5	GND	13	Gain Control, 0 to +0.9V
6	not used	14	/OVLD
7	Peltier -	15	GND
8	Peltier -		

A cable is delivered with the PMC-100

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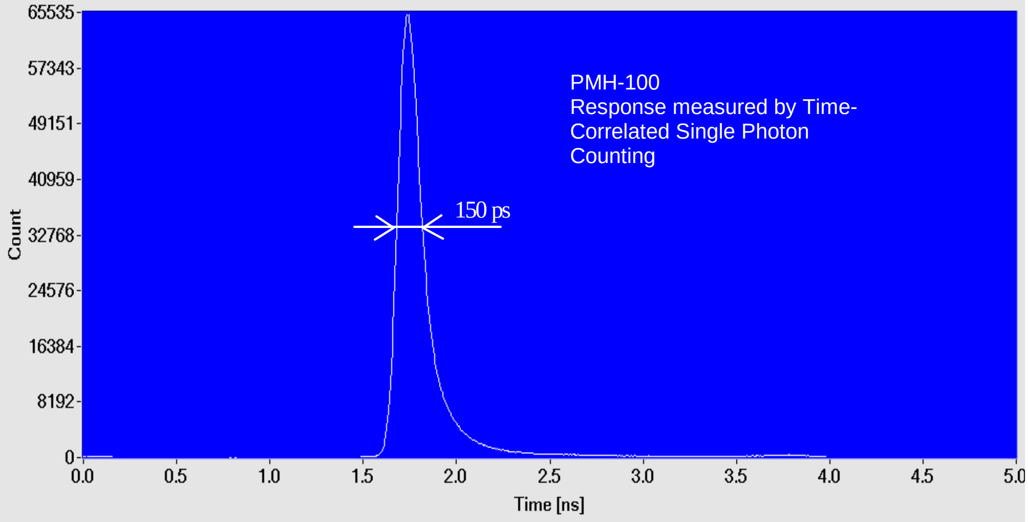
PMH-100

High Speed PMT Detector Head for Photon Counting

Applicable for Time-Correlated, Steady State and Gated Photon Counting
Non-descanned Detector for TCSPC Imaging
Excellent Time Resolution for TCSPC: < 220 ps FWHM
Internal GHz Preamplifier: High Output Amplitude
PMT Overload Indicator
Simple + 12 V Power Supply
Direct Interfacing to all bh Photon Counting Devices

The PMH-100 is a complete detector head for photon counting applications. It contains a fast PMT, a high voltage generator, a GHz pulse amplifier and a current sensing circuit. Due to the high gain and bandwidth of the device a single photon yields an output pulse with an average amplitude up to 300 mV and a pulse width of 1.5 ns. Therefore, noise pickup or crosstalk of start and stop signals in time-correlated single photon counting (TCSPC) are reduced and the PMH-100 yields an excellent time resolution, a high count efficiency and a low differential nonlinearity. Overload conditions are detected by sensing the PMT output current and indicated by a LED.



PMH-100
Response measured by Time-Correlated Single Photon Counting

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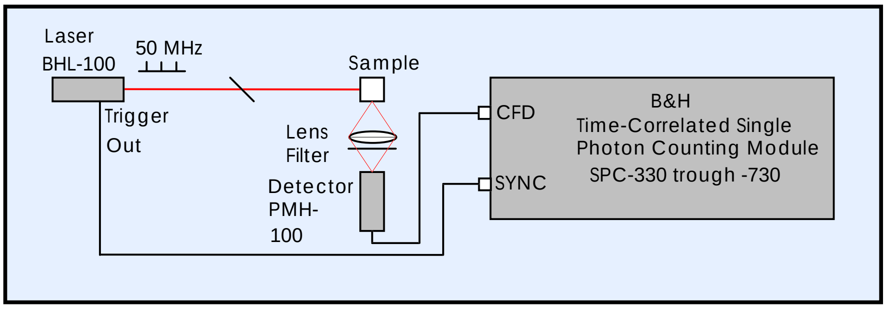
email: info@becker-hickl.com

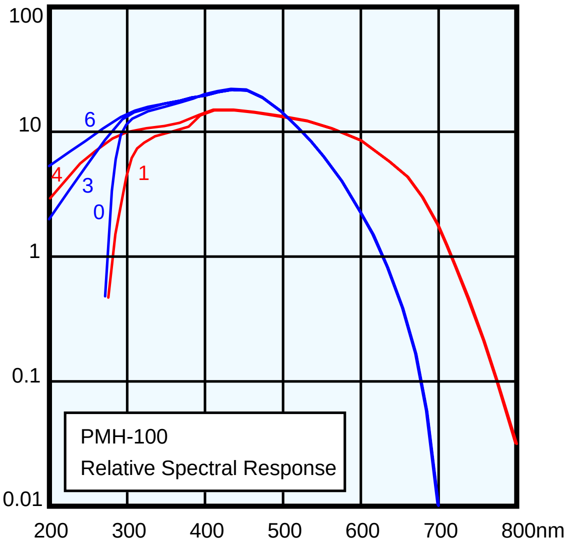
intelligent
measurement
and
control systems

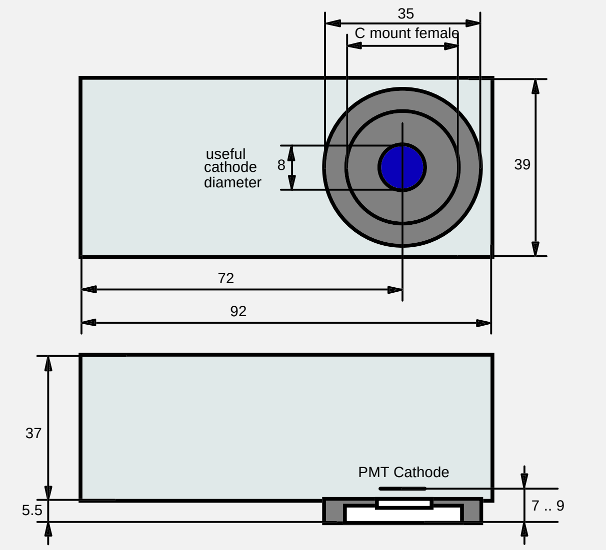
PMH-100

	PMH-100-3	PMH-100-6	PMH-100-0	PMH-100-4	PMH-100-1
Transit Time Spread (FWHM, typ. value)	180 ps				
Wavelength Range (nm)	185 to 650	185 to 650	300 to 650	185 to 820	300 to 820
Dark Counts (20°C, typ value)	80	80	80	400	400
Detector Area Diameter	8 mm				
Single Electron Response Width (FWHM, typ. value)	1.5 ns				
Single Electron Response Amplitude (average)	300 mV				
Output Polarity	negative				
Count Rate (Continuous)	> 5 MHz				
Count Rate (Peak, < 100 ns)	> 100 MHz				
Overload Indicator	LED				
Output Connector	SMA				
Output Impedance	50 Ω				
Power Supply	+ 12 V, 100 mA				
Dimensions	92 mm x 38 mm x 31 mm				
Optical Connection	C-Mount female				

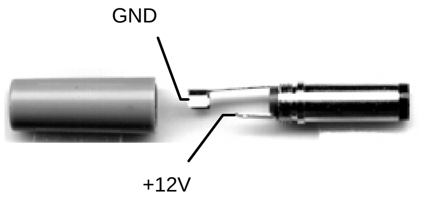
Simple fluorescence lifetime measurement:
The arrangement uses a diode laser (BHL-100), the PMH-100 detector module and the SPC-330 time correlated single photon counting module (please see individual data sheets). The instrument response is <180 ps FWHM. Fluorescence lifetimes down to 20 ps can be determined by deconvolution.







PMH-100 Outline (mm)



Power Supply Connector Pin Assignment

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intelligent
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PML-16-C

16-Channel Photomultiplier Head

16- channel photomultiplier head for bh time-correlated single photon counting modules

1 x 16 arrangement of detector channels

Simultaneous measurement in all 16 channels

Instrument response width 150 ps FWHM

Max. count rate > 5 MHz

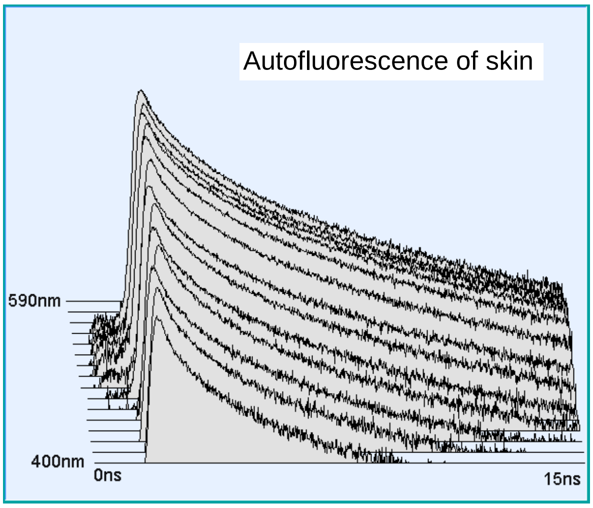
Gain control and overload shutdown via bh DCC-100 card

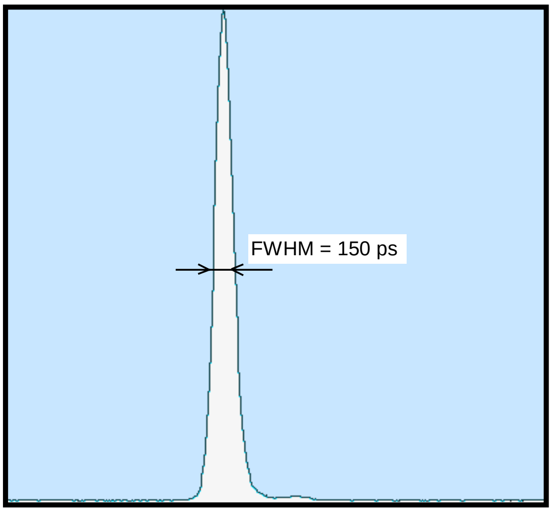
No external high voltage required

The PML-16-C is based on bh's proprietary multi-dimensional time-correlated single photon counting technique. The detector records 16 signals simultaneously into a single TCSPC channel. For each photon, the PML-16-C delivers a timing pulse and the number of the PMT channel in which the photon was detected. These signals are fed into the TCSPC module, which builds up the photon distribution versus the time and the channel number. The technique avoids any time gating or channel multiplexing and thus achieves a near-ideal counting efficiency. The PML-16C detector is part of the bh MW-FLIM multi-wavelength FLIM systems and the PML-SPEC multi-wavelength detection systems. Unlike its predecessor, the PML-16, the PML16-C generates the operating voltage of the PMT internally. Power supply, gain control, and overload shutdown are provided by the bh DCC-100 detector controller card.

Applications:

Autofluorescence of biological tissue
Time-resolved multi-wavelength laser-scanning microscopy
Diffuse optical tomography





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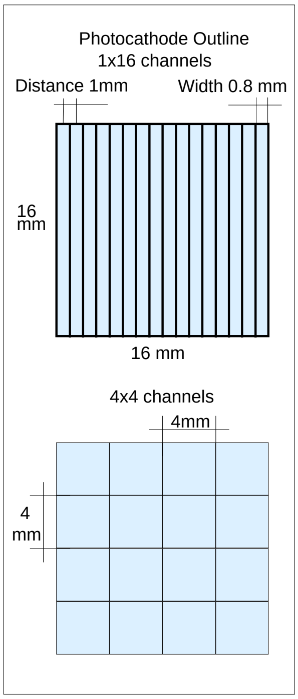
Covered by patent DE 43 39 787

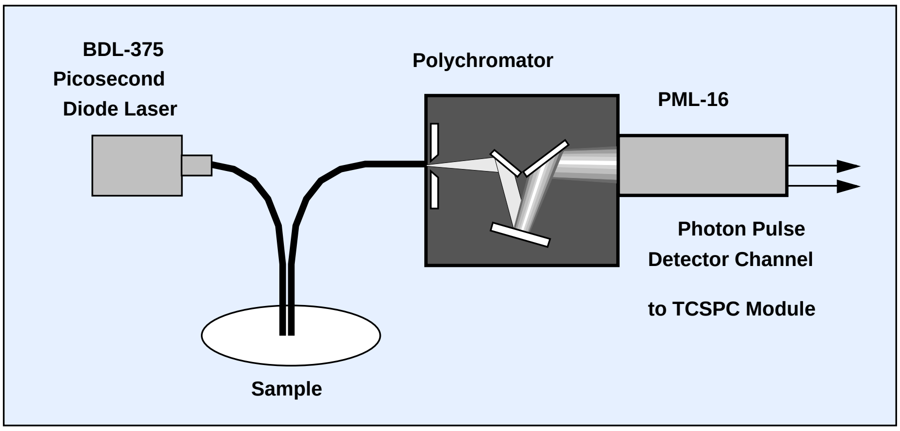
PML-16-C

Specification

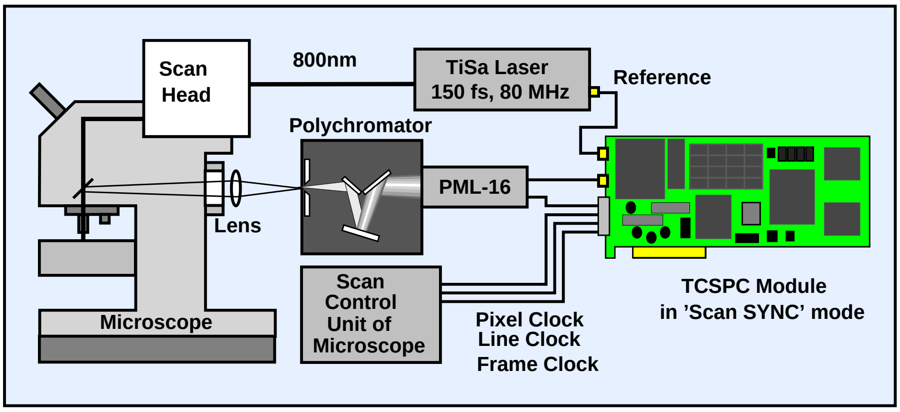
Number of Channels	16
Arrangement	Linear (1 by 16), optional quadratic4x4
Active Area (each channel)	Linear 0.8 × 16 mm, quadratic 4 by 4
Channel Pitch	1 mm
Spectral response	PML-16-C-0: 300 to 600 nm (bi-alkaline) PML-16-C-1:300 to 850 nm (multi-alkaline) Other cathode versions: contact bh
Timing Output Polarity	negative
Average Timing Pulse Amplitude	40 mV
Time Resolution (FWHM)	150 ps (typical value)
Time Skew between Channels	< 40 ps rms
Timing Output Connector	SMA, 50Ω
Routing Signal	4 bit + Error Signal, TTL/CMOS
Routing Signal Connector	15 pin Sub-D / HD
Power Supply	± 5V and +12V from DCC-100 card
Dimensions	52 mm × 52 mm × 145 mm



Applications



Time- and wavelength-resolved tissue fluorescence spectrometer



Multi-spectral time-resolved two-photon laser scanning microscope

Please see also:

SPC-134 through SPC-830 time-correlated single photon counting modules
PML-Spec Multi-spectral fluorescence lifetime detection system
MW-FLIM Multi-spectral FLIM systems
BDL-375-SM, BDL-405-SM, BDL-473-SM picosecond diode lasers

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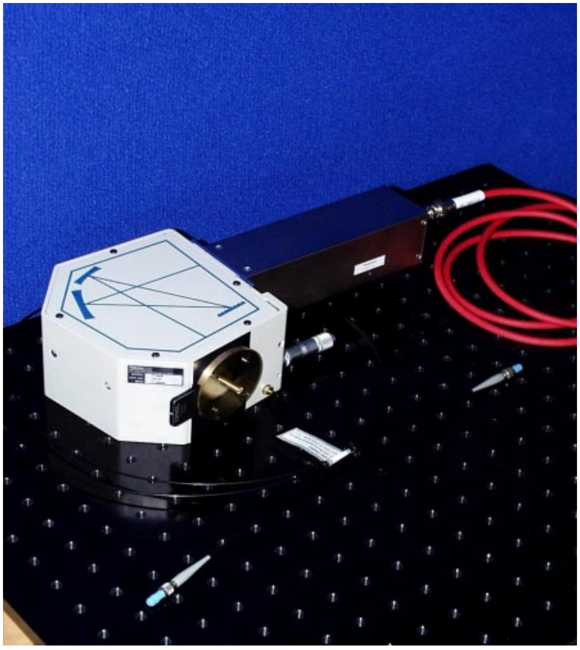
PML-Spec
Multi-Wavelength Lifetime Detection

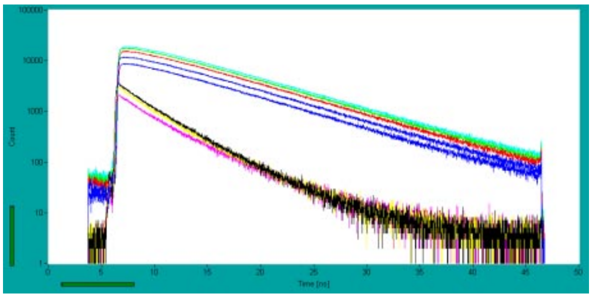
Multi-wavelength detection of fluorescence decay functions

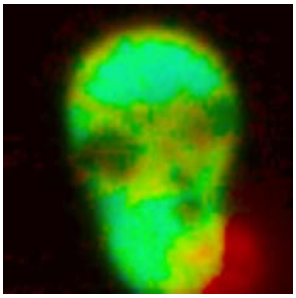


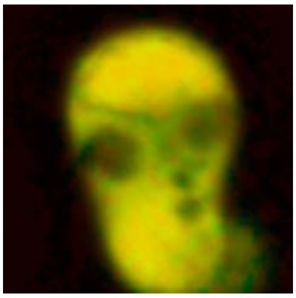
16 wavelength channels recording simultaneously
Spectral range 300-850 nm
High time resolution: 180 ps fwhm IRF width
Useful count rate > 2 MHz
Ultra-high sensitivity
Short acquisition times
Greatly reduced pile-up
Works with any bh TCSPC module

Biomedical fluorescence
Autofluorescence of tissue
Time-resolved laser scanning microscopy
Multi-spectral lifetime imaging
Recording of chlorophyll transients
Stopped flow fluorescence experiments

The PML-SPEC uses bh's proprietary multi-dimensional TCSPC technique. The light is split into its spectrum by a polychromator. The spectrum is detected by a 16-channel multi-anode PMT. The single photons detected in the PMT channels are recorded in a bh TCSPC module. The TCSPC module builds up a photon distribution over the time in the fluorescence decay and the wavelength. The technique does not use any time gating, detector channel multiplexing, or wavelength scanning and therefore reaches a near-ideal counting efficiency.







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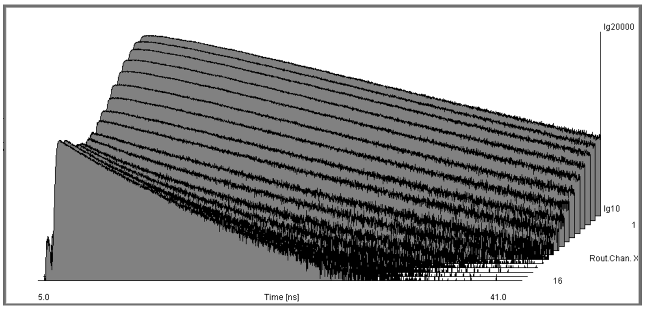
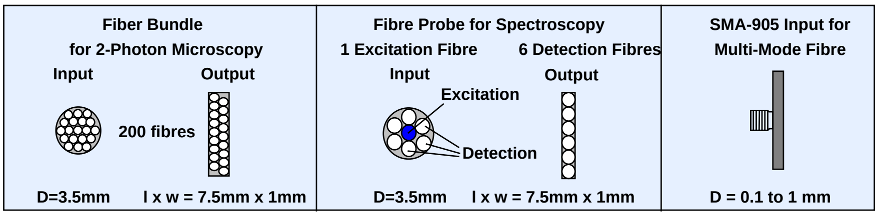


Covered by patent DE 43 39 787

PML-Spec Multi-Wavelength Lifetime Detection

Optical System

Type of grating, lines/mm	400	600	1200
Recorded interval[1], nm	320	208	106
Wavelength channel width, nm	20	13	6.65
Spectral range of grating[2], nm	300-600[2] 300-850[3]	300-600[2] 300-850[3]	300-600[2] 300-850[3]
F number		F / 3.7	
Input slit width, mm		0.6	
Input slit height, mm		7.5	
Optical Input Versions	Fibre bundle, fibre probe with 1 excitation fibre and 6 detection fibres, or SMA-905 connector		



[1] any interval within spectral range of grating

[2] Detector with bi-alkali cathode

[3] Detector with multi-alkali cathode

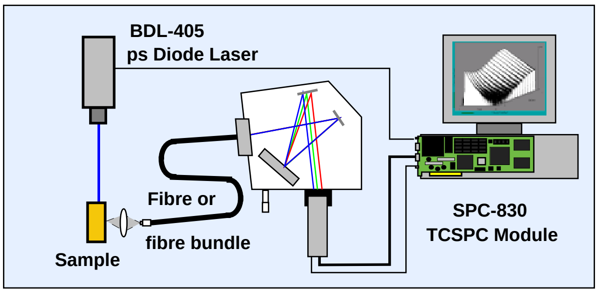
Detector[4]

Cathode spectral response	bi-alkali, 300 to 600 nm	multi-alkali, 300 to 850 nm
Typical dark count rate, s^{-1}	200	800
Number of spectral channels	16	
Timing output polarity of detector	negative	
Average timing pulse amplitude	40 mV	
Time resolution (FWHM)	150 to 200 ps	
Time skew between channels	< 40 ps	
Timing output connector	SMA, 50Ω	
Routing signal	4 bit + Count Disable Signal, TTL/CMOS	
Routing signal connector	15 pin Sub-D / HD	
Power supply (PML-16)	± 5V from SPC module, -800...-900V / 0.35 mA from external HV power supply	
Power supply (PML-16C)	± 5V, +12V from DCC-100 detector controller. Internal HV generator	

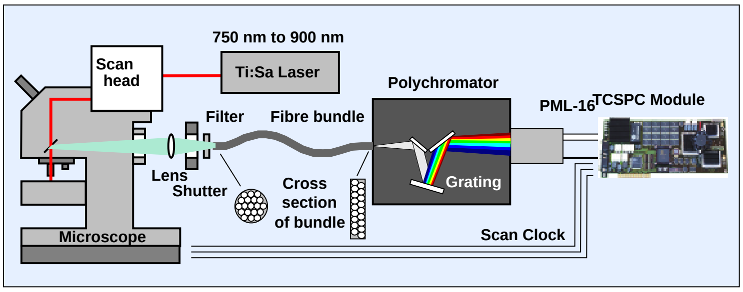
[4] please see data sheet and manual of PML-16 and PML-16C multichannel PMT heads

Applications

Multi-Wavelength Fluorescence Decay Measurement



Multi-Wavelength Picosecond Laser Scanning Microscope



Related Products and Accessories: SPC-134 through SPC-830 TCSPC boards, ps diode lasers, FLIM upgrade kits for scanning microscopes. Please see www.becker-hickl.com or call for individual data sheets.

Supplementary Literature: W. Becker, Advanced time-correlated single-photon counting techniques. Springer, Berlin, Heidelberg, New York, 2005
W. Becker, The bh TCSPC Handbook, Becker & Hickl GmbH, 2005

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91 Boylston Street, Brookline.
Massachusetts 02445 USA
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(617) 731 0935

Metal Package PMT with Cooler

Photosensor Modules H7422 Series

Heatsink with fan (A7423) sold separately

The H7422 series are PMT modules with an internal high-voltage power supply and a cooler installed to the metal package photomultiplier tube. Efficient cooling was achieved by placing the cooler near the photomultiplier tube to reduce thermal noise emitted from the photocathode and a high S/N ratio can be obtained even at extremely low light levels.

The H7422-40 has high sensitivity in the 300 nm to 720 nm wavelength. The H7422-50 is sensitive along a wide spectral range from 380 nm to 890 nm. The H7422-01 and H7422-02 have a maximum rated current value of 100 µA and so are extremely effective when measurements are needed over a wide dynamic range. The photomultiplier tube is maintained at a constant temperature by monitoring the output from a thermistor installed near the photomultiplier and then regulating the current to the cooler.

Product Variations

Type No.	Spectral Response	Max. Rated Output	Features
H7422-40	300 nm to 720 nm	2 µA	GaAsP photocathode, QE 40 % at peak wavelength, high gain (P type)
H7422P-40			
H7422-50	380 nm to 890 nm		GaAs photocathode, QE 12 % at 800 nm, high gain (P type)
H7422P-50			
H7422-01	300 nm to 850 nm	100 µA	Multialkali photocathode
H7422-02	300 nm to 880 nm		Infrared-extended multialkali photocathode

Specifications

Parameter				H7422 Series				Unit
Suffix				-40	-50	-01	-02	—
Input Voltage				+11.5 to +15.5				V
Max. Input Voltage for Main Unit				+18				V
Max. Input Current for Main Unit				30				mA
Max. Input Voltage for Peltier Element				2.6				V
Max. Input Current for Peltier Element				2.2				A
Max. Output Signal Current *1				2		100		µA
Max. Control Voltage				+0.9 (Input impedance 100 kΩ)				V
Recommended Control Voltage Adjustment Range				+0.50 to +0.80		+0.25 to +0.80		V
Effective Photocathode Size				$\phi 5$		$\phi 7$		mm
Sensitivity Adjustment Range				$1: 10^4$ (H7422-01/-02)				—
Peak Sensitivity Wavelength				550	800	400	500	nm
Cathode	Radiant Sensitivity		420 nm	108	15	56	40	mA/W
			550 nm	176	50	36	56	
			800 nm	—	90	1.2	6.4	
Anode	Standard Type	Radiant Sensitivity *1 *4	550 nm	8.8×10^4	2.5×10^4	1.8×10^4	2.8×10^4	A/W
		Dark Current *1 *4	Typ.	0.4	0.5	0.03	0.08	nA
			Max.	1.0	1.3	0.08	0.2	
	P Type	Radiant Sensitivity *1 *4	550 nm	1.8×10^5	5.0×10^4	—	—	A/W
		Dark Count *1 *4	Typ.	100	125	—	—	s^{-1}
			Max.	300	375	—	—	
Rise Time *1 *4				1.00		0.78		ns
Ripple Noise (Max.) *2				0.6				mV
Settling Time *3				0.2				s
Operating Temperature Range				+5 to +35				°C
Storage Temperature Range				-20 to +50				°C
Weight				Approx. 400				g

*1: Control voltage = +0.8 V *2: load resistance = 1 MΩ, load capacitance = 22 pF

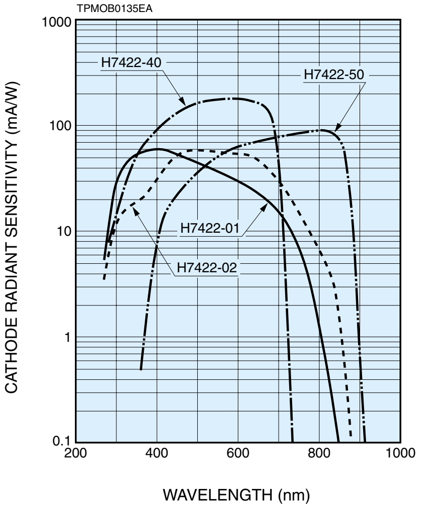
*3: The time required for the output to reach a stable level following a change in the control voltage from +1.0 V to +0.5 V.

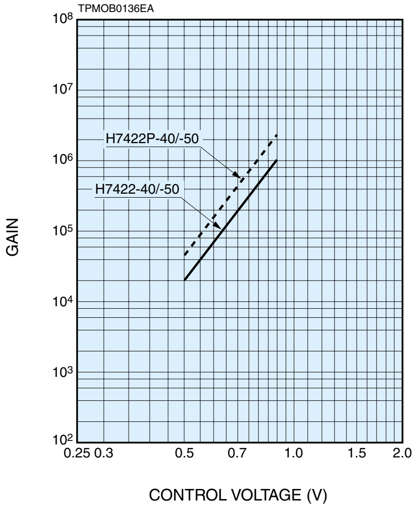
*4: When used with C8137-02 and A7423 Plateau voltage: PMT temperature setting value 0 °C

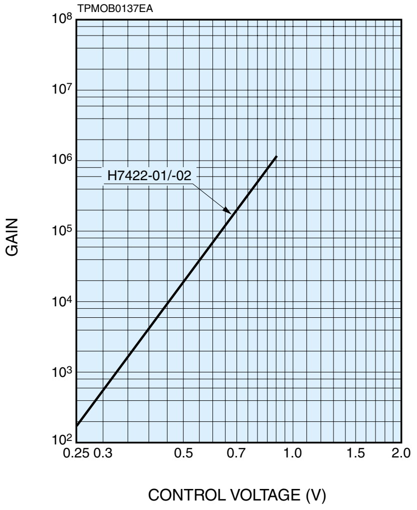
Cooling Specifications

Parameter	H7422/H7422P	Unit
Cooling Method	Thermoelectric cooling	—
Max. Cooling Temperature (ΔT)	35	°C
Cooling Time	Approx. 5	min.
Peltier Element Input Current	2.0	A

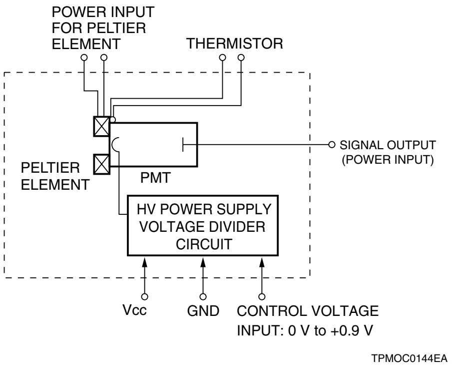
Characteristics (Cathode radiant sensitivity, Gain)



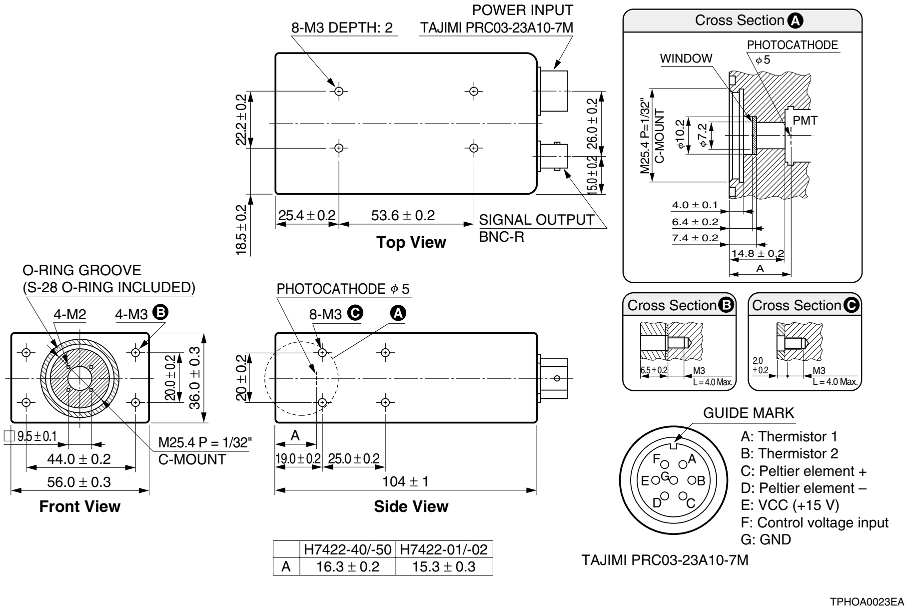




Block Diagram



Dimensional Outlines (Unit: mm)

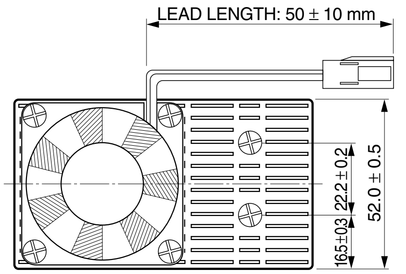


	H7422-40/-50	H7422-01/-02
A	16.3 ± 0.2	15.3 ± 0.3

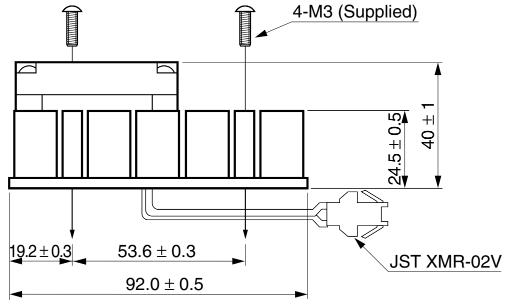
A: Thermistor 1
B: Thermistor 2
C: Peltier element +
D: Peltier element –
E: VCC (+15 V)
F: Control voltage input
G: GND

Options (Unit: mm)

1 Heatsink with fan A7423



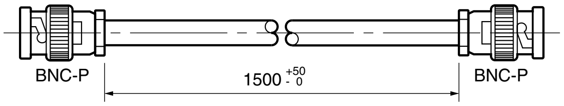
Top View



Side View

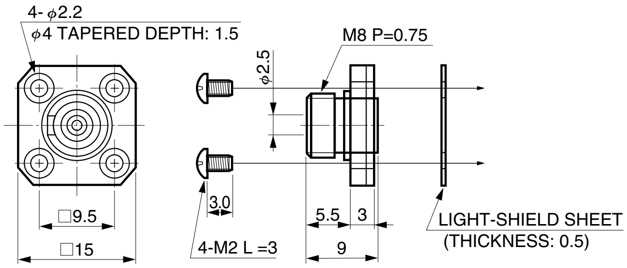
TACCA0188EC

2 Signal cable E1168-05



TACCA0148EA

3 Optical fiber adapter (FC type) A7412

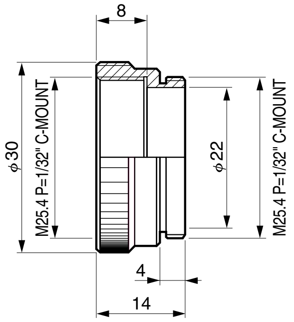


Front View

Side View

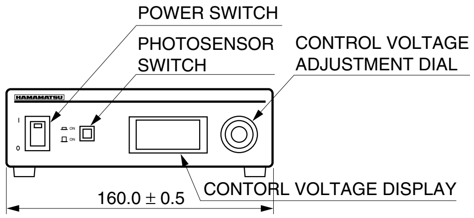
TACCA0190EA

4 C-mount adapter A7413

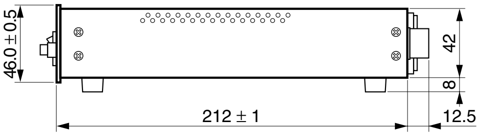


TACCA0191EA

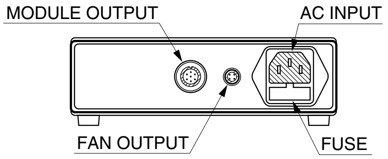
5 Power Supply Unit with Temperature Control C8137-02



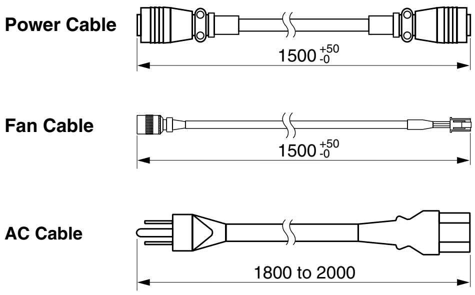
Front View



Side View

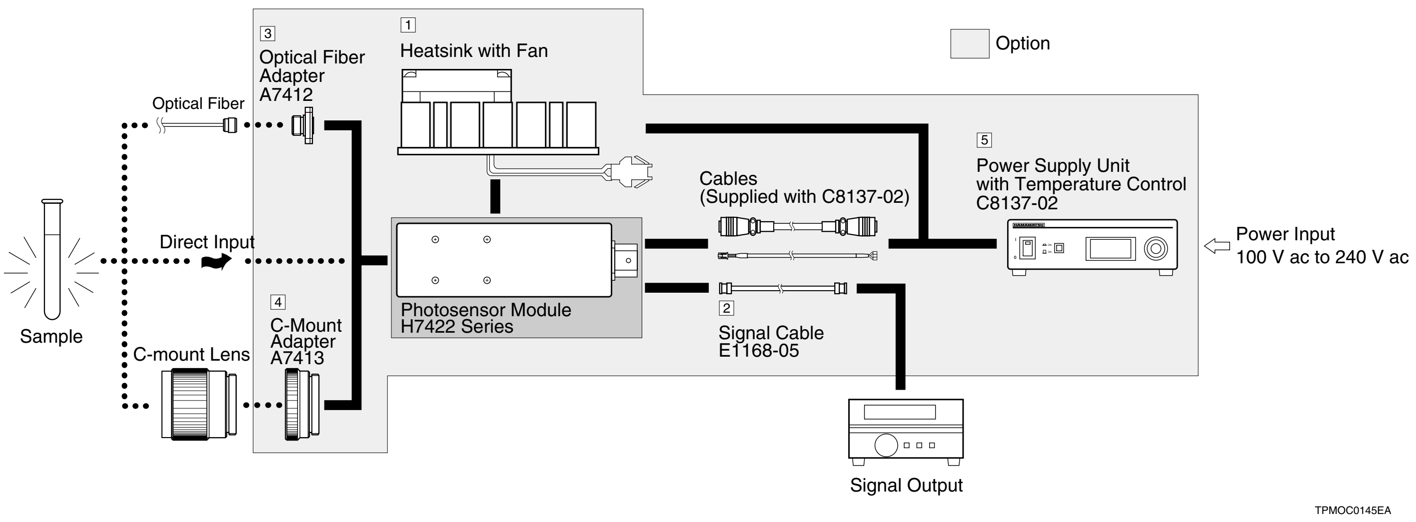


Rear View



TACCA0238EA

H7422 Series option



● Heatsink with Fan A7423

The temperature of the H7422 outer case rises due to the Peltier element housed in the case. The A7423 heatsink efficiently radiates away this heat to maintain the case temperature within 40 °C. The A7423 can be easily installed onto the H7422 with four M3 screws. Apply a coat of heat conductive grease onto the joint surface shared by the H7422 and A7423.

Parameter		Value	Unit
Input Voltage		12	V
Input Current	during lock	140	mA
	during operation	90	mA
Operating Voltage		10.2 to 13.8	V
Weight		120	g

● Signal Cable E1168-05

This signal cable is terminated with a BNC connector for easily connecting the H7422 to external equipment.

● Optical Fiber Adapter (FC type) A7412

The A7412 is an FC type optical fiber connector that attaches to the light input window of the H7422. The A7412 can easily be secured in place with four M2 screws.

● C-Mount Adapter A7413

The A7413 mount adapter is used when a C-mount lens protruding 4 mm or more from the flange-back must be installed onto the H7422.

● Power Supply Unit with Temperature Control C8137-02

The C8137-02 is a power supply unit with a temperature control function. Just connecting to an AC source of 100 to 240 V generates the output voltages for the Peltier element and the A7423 fan, needed for operating the H7422. The photomultiplier tube temperature can be maintained to 0 °C by monitoring the thermistor and regulating the output current from the Peltier element. Control voltage can be varied by a knob on the front panel.

Parameter	Value	Unit
Max. Cooling Temperature	35	°C
Setting Cooling Temperature (preset at factory)	0	°C
Input Voltage	100 to 240	V
Input Voltage Frequency	50/60	Hz
Power Consumption	30	VA
Main Circuit Output Voltage	+15	V
Max. Peltier Element Current	2.2	A
Output Voltage for Fan	12	V
Control Voltage Adjustment Range	0 to +0.9	V
Weight	1.1	kg

HAMAMATSU

MICROCHANNEL PLATE-PHOTOMULTIPLIER TUBE (MCP-PMTs)

R3809U-50 SERIES

Compact MCP-PMT Series Featuring Variety of Spectral Response with Fast Time Response

FEATURES

- **High Speed**
  Rise Time: 150ps
  T.T.S. (Transit Time Spread)1): ≦ 25ps(FWHM)
- **Low Noise**
- **Compact Profile**
  Useful Photocathode: 11mm diameter
  (Overall length: 70.2mm Outer diameter: 45.0mm)

APPLICATIONS

- **Molecular Science**
  Analysis of Molecular Structure
- **Medical Science**
  Optical Computer Tomography
- **Biochemistry**
  Fast Gene Sequencing
- **Material Engineering**
  Semiconductor Analysis
  Crystal Research

Figure 1: **Spectral Response Characteristics**

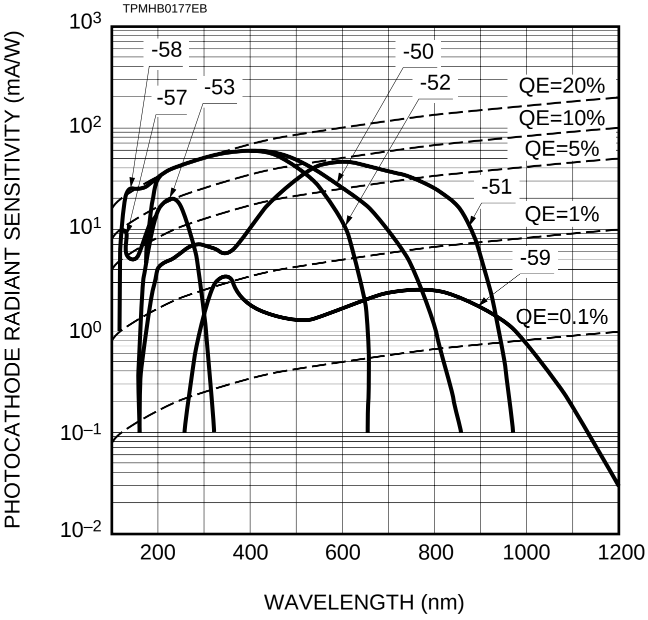


Figure 2: **Transit Time Spread**

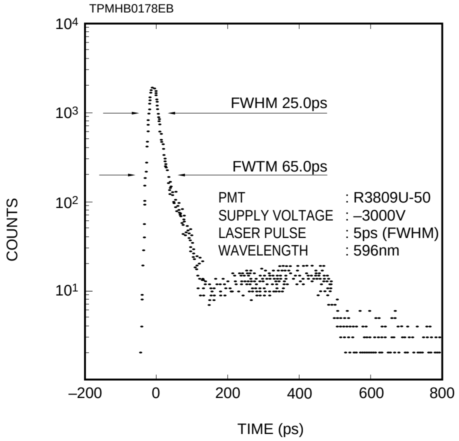
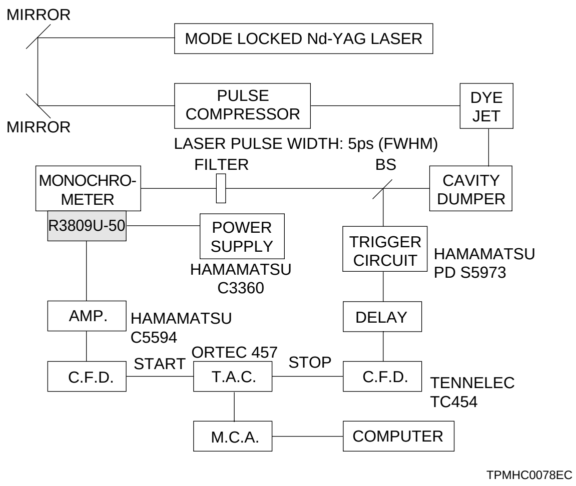


Figure 3: **Block Diagram of T.T.S. Mesuring System**



MCP-PMT R3809U-50 SERIES

SPECIFICATIONS

PHOTOCATHODE SELECTION GUIDE

Suffix Number	Spectral Response(nm)		Photocathode Material	Window Material
	Range	Peek Wavelength		
50	160 to 850	430	Multialkali(S-20)	Synthetic Silica
51	160 to 910	600	Extended Multi. (S-25)	Synthetic Silica
52	160 to 650	400	Bialkali	Synthetic Silica
53	160 to 320	230	Cs-Te	Synthetic Silica
57	115 to 320	230	Cs-Te	MgF_2
58	115 to 850	430	Multialkali (S-20)	MgF_2
59	400 to 1200	800	Ag-O-Cs (S-1)	Borosilicate

GENERAL CHARACTERISTICS

Parameter	Description/Value	Unit
Photocathode Useful Area in Diameter	11	mm
MCP Channel Diameter	6	μm
Dynode Structure 2)	2 - Stage Filmed MCP	–
Capacitance between Anode and MCP out	3	pF
Weight	98	g

ELECTRICAL CHARACTERISTICS (R3809U-50) at 25℃ 3)

Parameter		Min.	Typ.	Max.	Unit
Cathode Sensitivity	Luminous 4)	100	150	—	μA/lm
	Radiant at 430nm	—	50	—	mA/W
Gain at –3000V		1×10^5	2×10^5	—	—
Anode Dark Counts at –3000V		—	200	—	cps
Voltage Divider Current at –3000V		—	—	75	μA
Time Response	Rise Time 5)	—	150	—	ps
	Fall Time 6)	—	360	—	ps
	I.R.F. (FWHM) 7)	—	45 8)	—	ps
	T.T.S. (FWHM)	—	—	25 9)	ps

MAXIMUM RATINGS (Absolute Maximum Values)

Parameter	Value	Unit
Supply Voltage	–3400	Vdc
Average Anode Current	100	nA
Pulsed Peak Current 10)	350	mA
Ambient Temperature 11)	–50 to +50	℃

NOTES

1) Transit-time spread (TTS) is the fluctuation in transit time between individual pulse and specified as an FWHM (full width at half maximum) with the incident light having a single photoelectron state.
2) Two microchannel plates (MCP) are incorporated as a standard but we can provide it with either one or three MCPs as an option depending upon your request.
3) This data is based on R3809U-50. All other types (suffix number 51 through 59) have different characteristics on cathode sensitivity and anode dark counts.
4) The light source used to measure the luminous sensitivity is a tungsten filament lamp operated at a distribution temperature of 2856K. The incident light intensity is 10^{-4} lumen and 100 volts is applied between the photocathode and all other electrodes connected as an anode.
5) This is the mean time difference between the 10 and 90% amplitude points on the output waveform for full cathode illumination.
6) This is the mean time difference between the 90 and 10% amplitude points on the tailing edge of the output waveform for full cathode illumination.
7) I.R.F. stands for Instrument Response Function which is a convolution of the δ pulse function (H(t)) of the measuring system and the excitation function (E(t)) of a laser. The I.R.F. is given by the following formula:

$$\text{I.R.F.} = H(t) \times E(t)$$

8) We specify the I.R.F. as an FWHM of the time distribution taken by using the measuring system in Figure 13 that is Hamamatsu standard I.R.F. measurement. It can be temporary estimated by the following equation:

$$(\text{I.R.F. (FWHM)})^2 = (\text{T.T.S.})^2 + (Tw)^2 + (Tj)^2$$

where Tw is the pulse width of the laser used and Tj is the time jitter of all equipments used. An I.R.F. data is provided with the tube purchased as a standard.

9) T.T.S. stands for Transit Time Spread (see 1) above). Assuming that a laser pulse width (Tw) and time jitter of all equipments (Tj) used in Figure 3 are negligible, I.R.F. can be estimated as equal to T.T.S.(see 8)) above. Therefore, T.T.S. can be estimated to be 25 picoseconds or less.
10) This is specified under the operating conditions that the repetition rate of light input is 100 hertz or below and its pulse width is 70 picoseconds.
11) This is specified under either operation or storage.

TECHNICAL REFERENCE DATA

Figure 4: Typical DC Gain

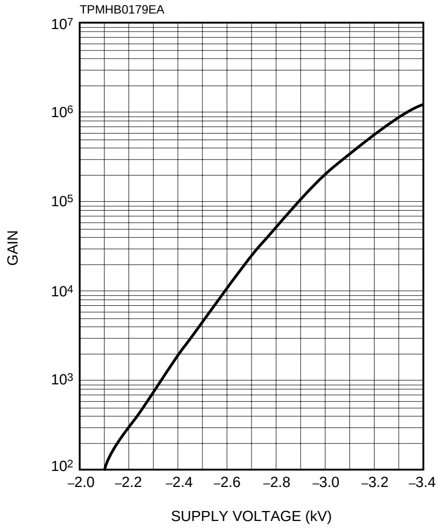


Figure 5: Variation of Dark Counts Depending on Ambient Temperature

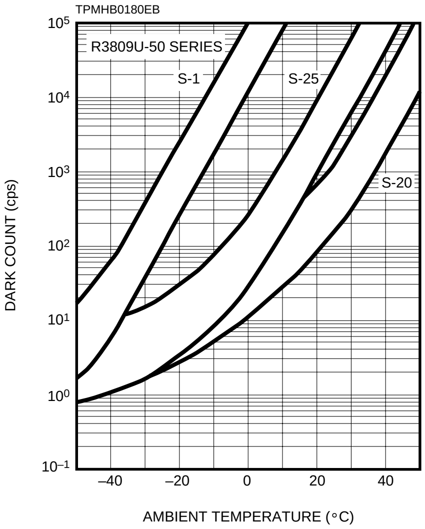


Figure 6: Typical Output Deviation as a Function of Anode DC Current

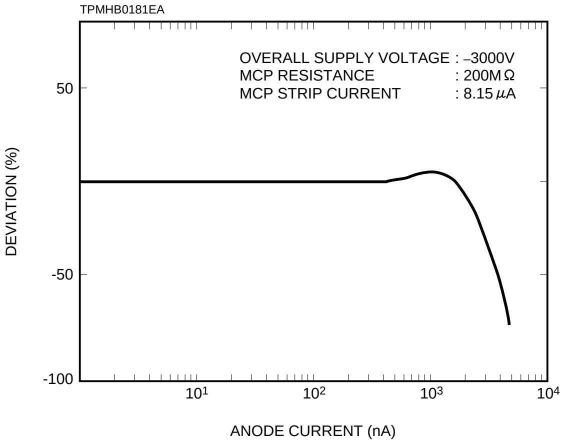


Figure 7: Typical Output Deviation as a Function of Anode Count Rate

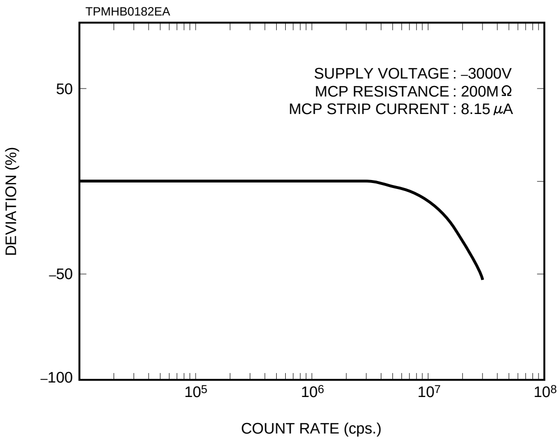


Figure 8: Typical Output Waveform

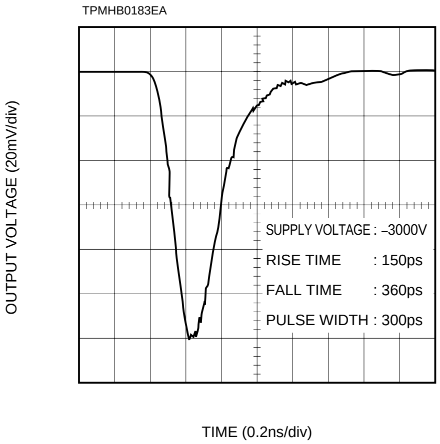


Figure 9: Block Diagram of Output Waveform Measuring System

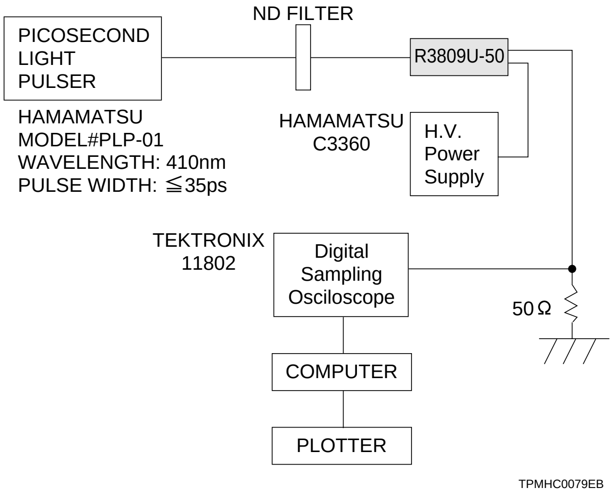


Figure 10: Typical Pulse Height Distribution (PHD)

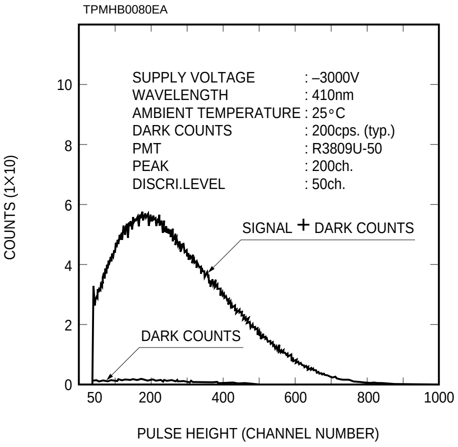


Figure 11: Block Diagram of PHD Measuring System

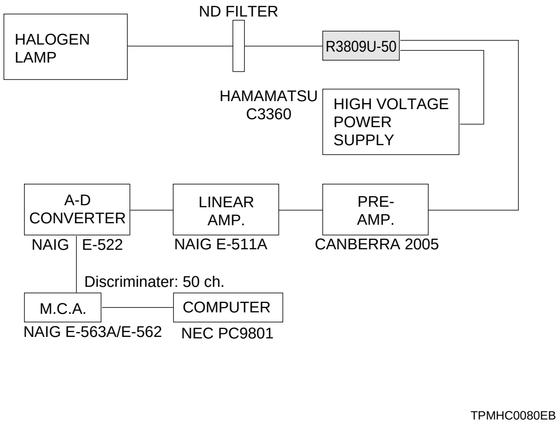


Figure 12: Typical Instrument Response Function (IRF)

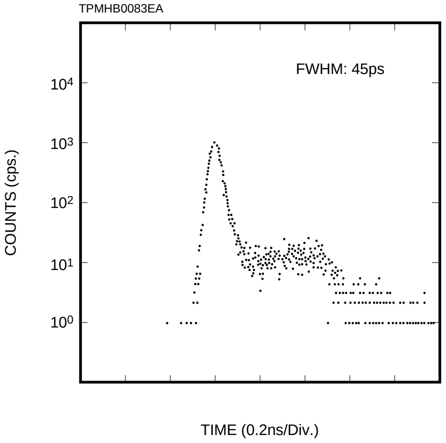


Figure 13: Block Diagram of IRF Measuring System

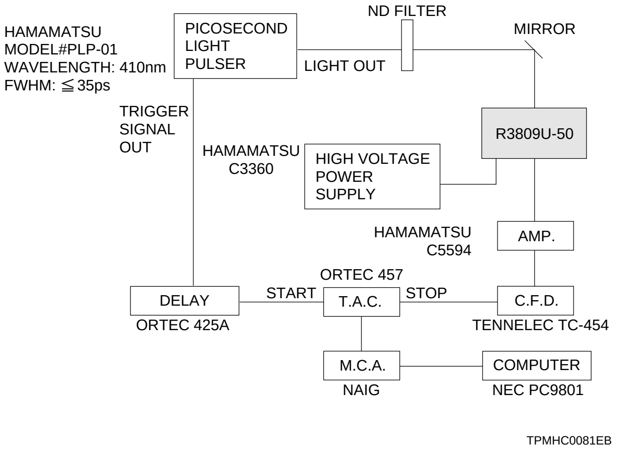
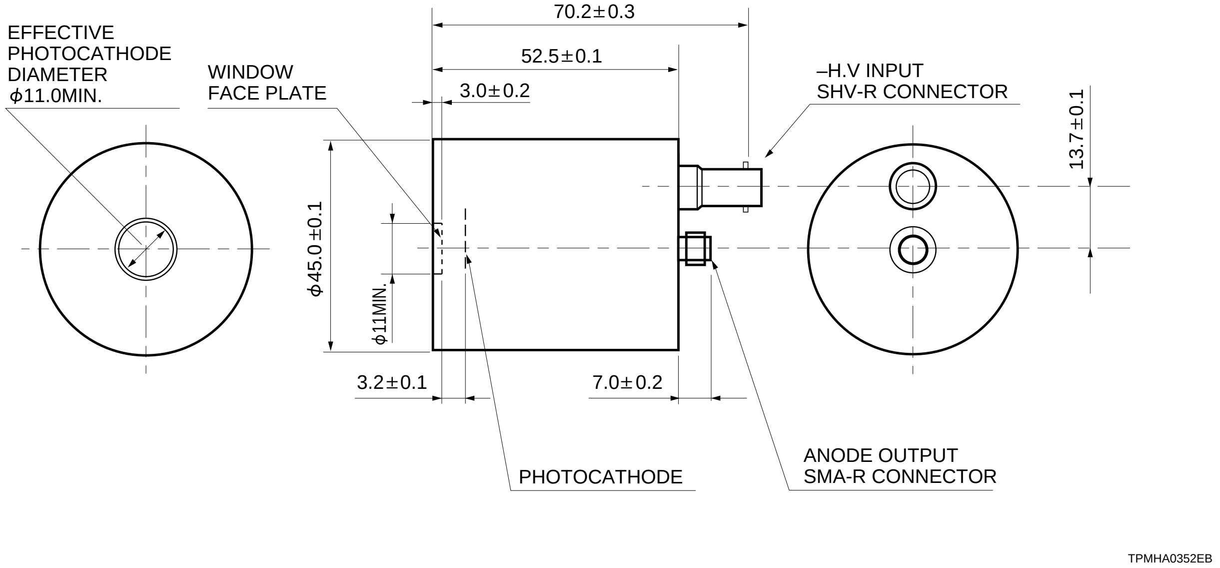


Figure 14: Dimensional Outline (Unit: mm)



PRECAUTIONS FOR PROPER OPERATION

Handling on set-up

1) The photomultiplier tube (PMT) is a glass product under high vacuum. EXCESSIVE PRESSURE, VIBRATIONS OR SHOCKS TO THE TUBE FROM THE SURROUNDING COULD CAUSE A PERMANENT DAMAGE. Please pay special attention on insuring proper handling.
2) DO NOT PLACE ANY OBJECTS OF GROUND POTENTIAL CLOSER THAN 5mm TO THE PHOTOCATHODE WINDOW when negative high voltage is applied to the photocathode. It could generate extra noise and damage the photocathode permanently.
3) DO NOT EXPOSE THE PHOTOCATHODE TO SUNLIGHT DIRECTLY and any light stronger than the room light even during of no operation.
4) NEVER TOUCH THE INPUT WINDOW WITH YOUR BARE HANDS. In case the window contaminated by dust or grease, wipe it off using alcohol and a soft cloth or dust free tissue.
5) DO NOT OPERATE OR STORE IN A PLACE OF UNSPECIFIED TEMPERATURE AND HUMIDITY.

Supplying high voltage

1) DO NOT SUPPLY ANY VOLTAGE HIGHER THAN SPECIFIED. Also make sure the output current does NOT EXCEED THE MAXIMUM CURRENT specified.
2) This device is very sensitive even with weak light input. When applying high voltage to the tube, GRADUALLY (IDEALLY 100 Vdc STEP BUT 500 Vdc STEP IS OK) AND CAREFULLY INCREASE THE VOLTAGE while monitoring the output using an ammeter or oscilloscope. Also make sure before use that the polarity of the applied voltage is correct.
3) DO NOT REMOVE OR CONNECT ANY INPUT OR OUTPUT CABLES WHILE HIGH VOLTAGE IS APPLIED. If a high voltage is applied when its output is opened, DO NOT CONNECT ANY READOUT CIRCUIT TO THE TUBE IMMEDIATELY after turning the high voltage off. Ground the anode of the tube before connecting in order to avoid possible damage to the readout circuit due to an excessive electron charge flowing from its anode.
4) IT IS RECOMMENDED TO TURN HIGH VOLTAGE OFF WHILE NOT BEING USED FOR MEASUREMENTS. This is to avoid shortening its period of life time as well as a risk of damage due to an exposure of excessive incident light.

Incident light amount

1) KEEP THE INCIDENT LIGHT AMOUNT AS LOWS AS POSSIBLE to extend its period of life time.
2) In a case of photon counting application, it is recommended to KEEP THE SIGNAL COUNT RATE LESS THAN 20kcps.
3) ILLUMINATE PHOTOCATHODE EFFECTIVE AREA AS LARGE AS POSSIBLE to keep better linearity characteristics and avoid an excessive stress in partial area, which may result in a reduction of sensitivity partially.

Usage in vacuum

1) KEEP THE TUBE CLEAN. Unless otherwise, it would cause outgassing in a vacuum.
2) DO NOT SUPPLY HIGH VOLTAGE UNLESS THE VACUUM LEVEL REACHES 1×10^{-3} Pa OR HIGHER.
3) DO NOT PROCEED BAKING VACUUM INSTRUMENTS WHILE THE TUBE IS PLACED INSIDE.

OTHERS

1) If the tube won't be used with a cooler, it is recommended to LEAVE THE TUBE IN DARKNESS (YOUR INSTRUMENT WITHOUT ANY INPUT LIGHT) FOR 30 MINUTES OR SO before start any measurements because it occasionally takes a little while until its dark noise settles down.

WARRANTY

The detectors indicated in this data sheet are warranted to the original purchaser for a period of 12 MONTHS following the date of shipment. The warranty is limited to repair or replacement of any defective material due to defects in workmanship or materials used in manufacture.

1) Any claim for damage of shipment must be made directly to the delivering carrier within five days.
2) Customer must inspect and test all detectors within 30 days after shipment. Failure to accomplish said incoming inspection shall limit all claims to 75% of invoice value.
3) No credit will be issued for broken detector unless in the opinion of Hamamatsu the damage is due to a manufacturing defect.
4) No credit will be issued for any detector which in the judgement of Hamamatsu has been damaged, abused, modified or whose serial number or type number have been obliterated or defaced.
5) No detector will be accepted for return unless permission has been obtaind from Hamamatsu in writing, the shipment has been returned repaired and insured, the detector is packed in their original box and accompanied by the original data sheet furnished to the customer with the tube, and a full written explanation of the reason for rejection of detector.

MCP-PMT R3809U-50 SERIES

ACCESSORIES

THERMOELECTRIC COOLING UNIT
C4878

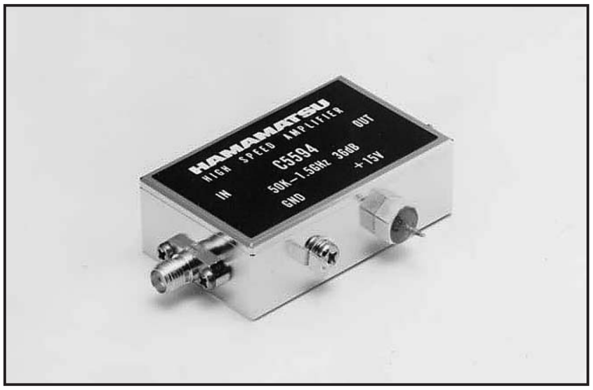
HOLDER
E3059-500

Specifications

Cooling	Thermoelectric Effects
Heat exchange Medium (coolant)	Water (1/3 litters/min. flow rate)
Temperature controllable range	–30℃ to 0℃
Optical window material	Evacuated double-pane fused silica

Note: C4878 reguires a holder (e.g E3059-500 for R3809U-50 series).

HIGH SPEED AMPLIFIER
C5594 Series



HIGH VOLTAGE POWER SUPPLY
C3360

Specifications

Frequency Response Range	50k to 1.5GHz
Gain	36dB(Typ.)
Input/Output Impedance	50Ω
Noise Figure (NF)	7dB(Typ.)
Supply Voltage	+12 to +16V
Recommend Input Voltage	+15V
Supply Current	95mA(Typ.)

Absolute Maximum Ratings

Supply Voltage	+17V
Input Power	10mW

Output Voltage	0 to –5000Vdc
Maximum Output Current	1mA
Output Stabilities	
Input Regulation	±(0.001% + 0.05V)Max. (For ±10% change in input voltage)
Load Regulation	±(0.001% + 0.05V)Max. (For 0 to 100% change in load)
Ripple	20mV p-p Max.
Drift	±0.02%/h Max. (After 1h warm-up)

HAMAMATSU
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314-5, Shimokanzo, Toyooka-village, Iwata-gun, Shizuoka-ken, 438-0193, Japan, Telephone: (81)539/62-5248, Fax: (81)539/62-2205
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Germany: Hamamatsu Photonics Deutschland GmbH: Arzbergerstr. 10, D-82211 Herrsching am Ammersee, Germany, Telephone: (49)8152-375-0, Fax: (49)8152-2658
France: Hamamatsu Photonics France S.A.R.L.: 8, Rue du Saule Trapu, Parc du Moulin de Massy, 91882 Massy Cedex, France, Telephone: (33)1 69 53 71 00, Fax: (33)1 69 53 71 10
United Kingdom: Hamamatsu Photonics UK Limted: Lough Point, 2 Gladbeck Way, Windmill Hill, Enfield, Middlesex EN2 7JA, United Kingdom, Telephone: (44)181-367-3560, Fax: (44)181-367-6384
North Europe: Hamamatsu Photonics Norden AB: Färögatan 7, S-164-40 Kista Sweden, Telephone: (46)8-703-29-50, Fax: (46)8-750-58-95
Italy: Hamamatsu Photonics Italia: S.R.L.: Via Della Moia, 1/E, 20020 Arese, (Milano), Italy, Telephone: (39)2-935 81 733, Fax: (39)2-935 81 741

TPMH1067E05
JUN. 1997

PRELIMINARY

NIR-PMT MODULE

(Thermoelectrically cooled)

H9170-45, -75

Wavelength Range: 950 nm to 1400 nm / 950 nm to 1700 nm, TE cooled, High Speed, Suitable for Photon counting

* Rotary Vacuum Pump is not shown (included)

OVER VIEW

Hamamatsu has developed a highly sensitive semi-transparent NIR photocathode by the novel photocathode technology.

We have adopted this technology to a compact photomultiplier tube (PMT) and have developed a PMT module with the air cooled TE cooler and HV power supply with protection circuit. No liquid nitrogen or cooling water is necessary. The cooling unit is equipped with a condensor lens that allows large input area for easy optical coupling. Adaptors for optical fiber or monochromator are available as an option.

APPLICATIONS

- **Photoluminescence**
- **Singlet Oxygen Measurement**
- **Raman Spectroscopy**
- **Cathodoluminescence**
- **Fluorescence, Fluorescence Life Time**
- **LIDAR**

FEATURES

- **High Sensitivity (Capable of Photon Counting),**
- **Fast Time Response**
  Rise Time: 0.9 ns, TTS: 300 ps
- **Compact**
- **Simple Operation by Air Cooled TE Cooler**
  No Liquid Nitrogen, No Cooling Water in Necessary
- **Operable in 20 min. after Swiched ON**
- **Large Detection Area**
  ϕ19 mm for Collimated Light
- **HV Power Supply with Interlock Function**
- **Mechanical Shutter**
- **Optional Adaptors are Available.**
  For Optical Fiber (FC type)
  For Monochromator

HAMAMATSU

SPECIFICATIONS

GENERAL

Parameter	H9170-45	H9170-75	Unit
Spectral Response	950 to 1400	950 to 1700	nm
Photocathode Material	InP/InGaAsP	InP/InGaAs	—
Detection Area for Collimated Light	ϕ19		mm
Effective Area of PMT	ϕ2		mm
Window Material	Synthetic Silica		—
PMT Operating Temperature	-60		°C
PMT Supply Voltage	-500 to -900		V
Storage Ambient Temperature	-20 to +50		°C
Operating Ambient Temperature	+7 to +30		°C

MAXIMUM RATING

Parameter	H9170-45	H9170-75	Unit
PMT Supply Voltage	-900		V
Average PMT Anode Current	1		μA

CHARACTERISTICS (at -800 V, -60 °C)

Parameter		H9170-45			H9170-75			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	
Cathode Sensitivity ①	Quantum Efficiency	0.48	—	—	0.29	—	—	%
	Radiant	5	—	—	3.5	—	—	mA/W
Anode sensitivity ①	Radiant	1000	—	—	700	—	—	A/W
Gain		2×10^5	1×10^6	—	2×10^5	1×10^6	—	—
Anode Dark Current ②		—	4	10	—	40	100	nA
Anode Dark Count ②		—	2×10^4	—	—	2×10^5	—	s^{-1}
Time Response	Anode Pulse Rise Time	—	0.9	—	—	0.9	—	ns
	Anode Pulse Fall Time	—	1.7	—	—	1.7	—	ns
	Transit Time Spread	—	0.3	—	—	0.3	—	ns

① At 1300 nm (H9170-45), at 1500 nm (H9170-75)   ② At 30 minutes after high voltage is applied with shutter closed

MODULE, CONTROLLER

Parameter		Value / Description	Unit
Cooling Method		Thermoelectric / Air Cooled	—
Condenser Lens Material		Borosilicate glass (BK7)	—
Diameter of the Condenser Lens		20	mm dia.
F Number of the Condenser Lens		1.25	—
Cooling Time to -60 °C PMT Temperature		20	min
Protection Function		High Voltage Interlock for Inappropreate Temperature	—
Input Voltage (AC)		90 to 264 (50 Hz / 60 Hz)	V
Dimensions (W × H × D) *	Module	210 × 205 × 200	mm
	Controller	100 × 205 × 310	
Weight	Module	Approx. 8	kg
	Controller	Approx. 3	

* Excluding projections

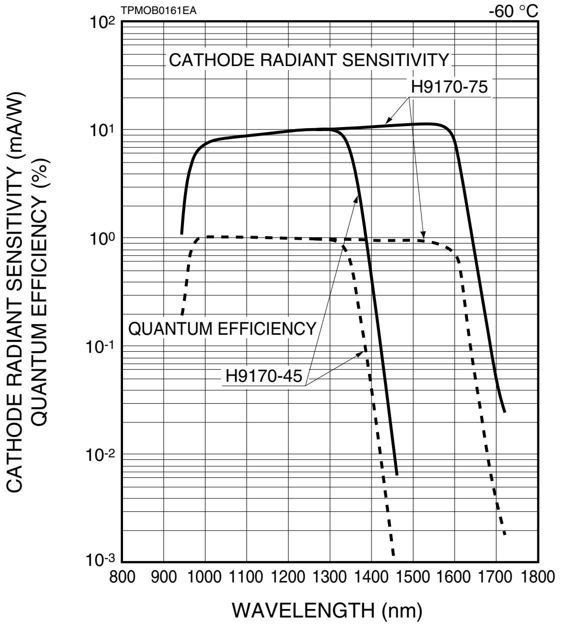
ROTARY VACUUM PUMP

Parameter	Value / Description	Unit
Type	Oil-Sealed Rotary Vacuum Pump	—
Input Voltage (AC)	90 to 126, 180 to 252 (50 Hz / 60 Hz), Single Phase	V
Pumping Speed	50 (50 Hz), 60 (60 Hz)	l/min
Dimensions (W × H × D) *	150 × 427 × 251	mm
Weight	Approx. 16	kg

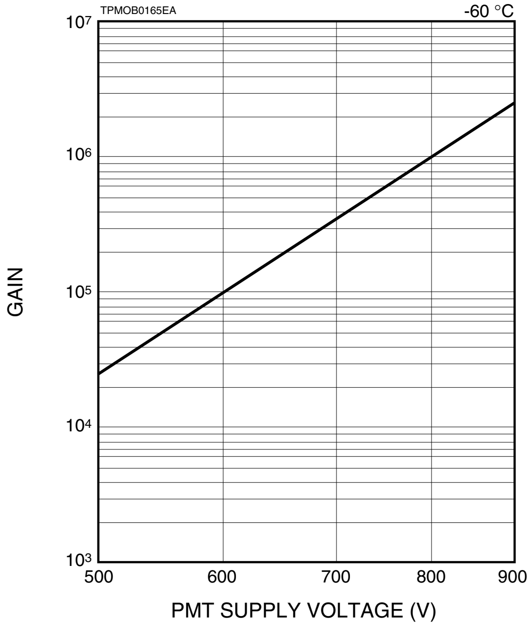
* Excluding projections

CHARACTERISTICS

●Spectral Response

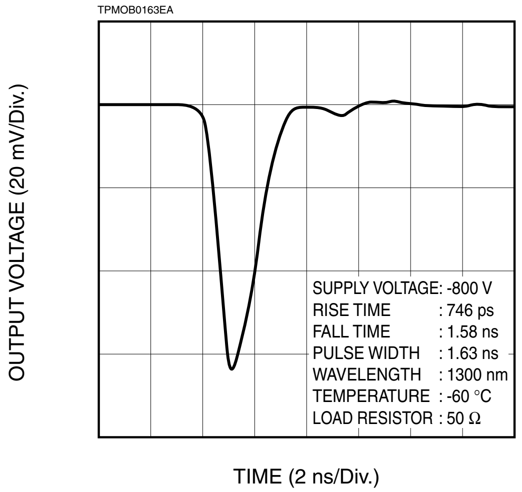


●Typical Gain

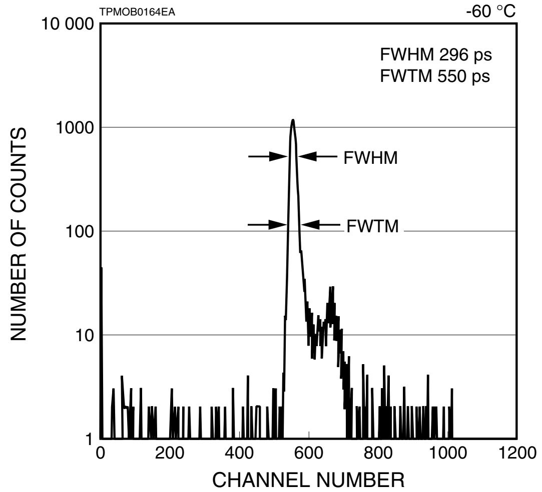


●Timing Properties

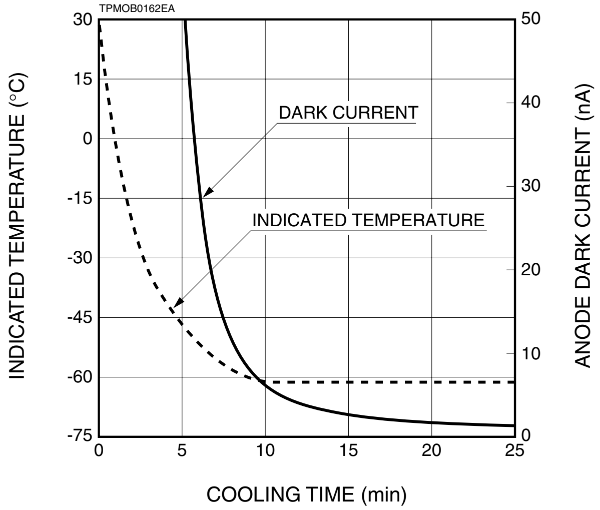
Waveform



Transit Time Spread (T.T.S.)

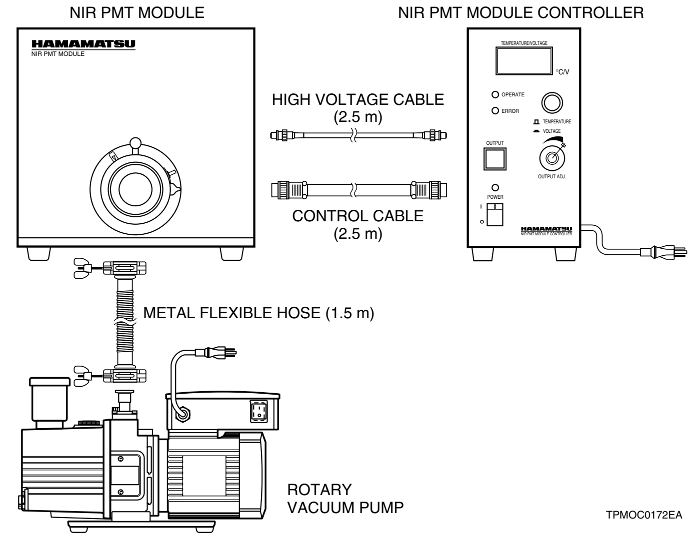


●Temperature / Dark Current vs. Cooling Time (H9170-45)



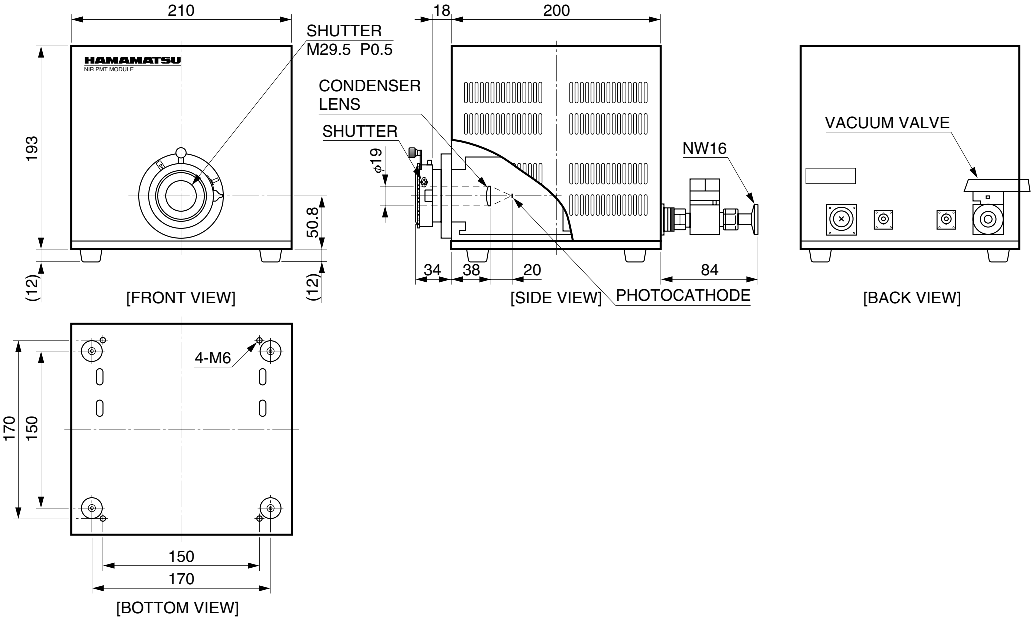
SYSTEM CONFIGURATION

(CONNECTION DIAGRAM)



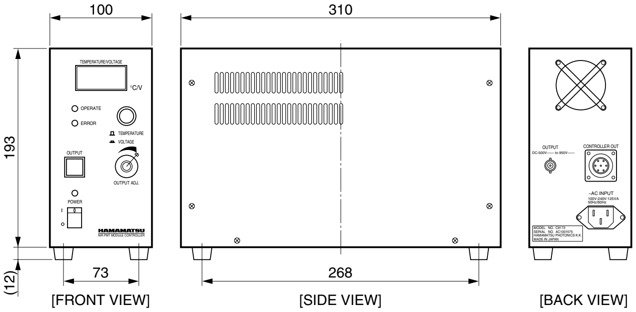
DIMENSIONAL OUTLINES (Unit: mm)

●NIR-PMT Module



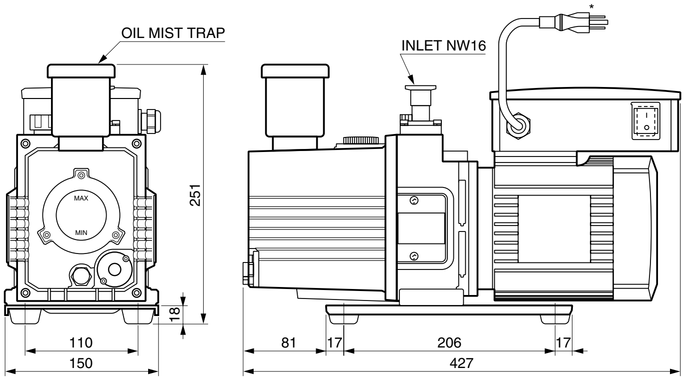
TPMOA0025EA

●NIR-PMT Module Controller



TPMOA0026EA

●Rotary Vacuum Pump



* The drawing of the AC plug shows Japanese / USA types.
European and UK types are also available.

TPMOA0027EA

OPTIONS

Adaptors to match optical fiber connectors or monochromators are available.

●Optical Fiber Adaptor

The adaptor efficiently collects light from the optical fiber with FC connector.

●Monochromator Adaptor

The adaptor collects light from a monochromator efficiently. Please inform us of the type of the monochromator.

*Please contact your local Hamamatsu office for any assistance.

HAMAMATSU WEB SITE http://www.hamamatsu.com
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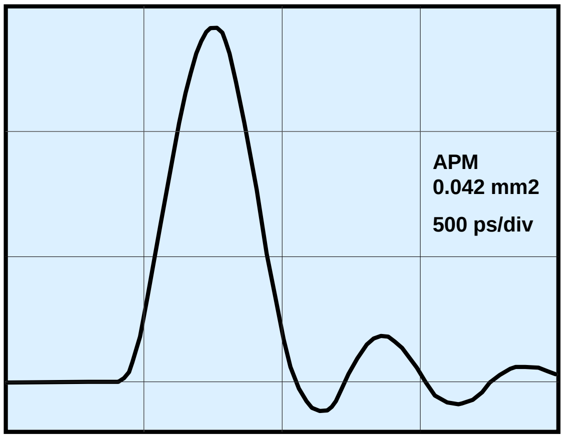
TPMH1026E01
JAN. 2003 IP
Printed in Japan (1000)

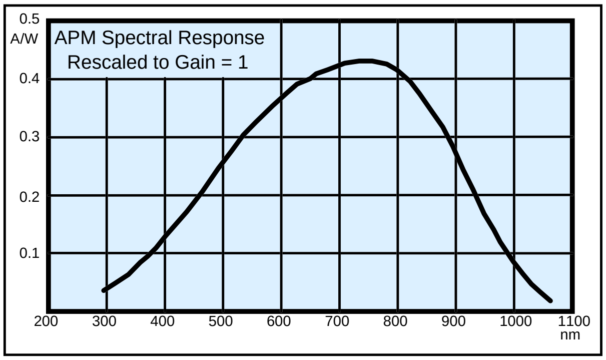
APM - 400

High Speed Avalanche Photodiode Module

- Active Area from 0.03 mm^2 to 7 mm^2
- High Speed: Down to 150 ps Pulse Rise Time / 320 ps FWHM
- Single +12V supply
- Internal Temperature Compensation
- Spectral Range from 330 nm to 1100 nm

The APM-400 is a high speed avalanche photodiode module for the detection of pulsed light signals and for trigger applications. It includes the bias voltage supply for the avalanche photodiode along with a temperature compensation circuit for the diode gain. Due to its single +12V supply the device can be powered directly from the **bh** Sampling / Boxcar Module PCS-150, the **bh** Time-Correlated Single Photon Counting Modules or from a conventional +12V power supply.





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intelligent
measurement
and
control systems

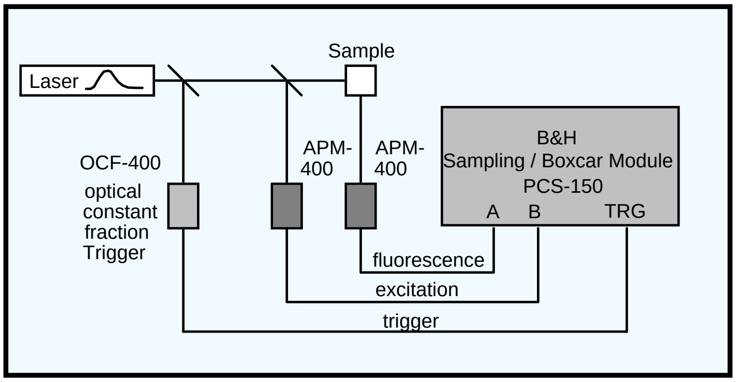
APM - 400

Specification

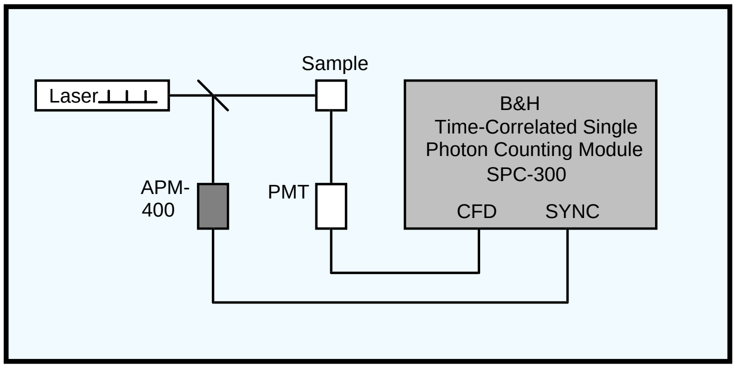
Active Area (please specify)	0.03	0.042	0.19	0.78	1.77	7.0	mm^2
FWHM (630nm, 50 Ohm)	0.45	0.32	0.4	0.5	2.3	3	ns
Pulse Rise Time	0.15	0.16	0.2	0.25	1.1	1.2	ns
Gain (Adjustable by Trimpot)			1 to > 100				
Output Polarity	positive (APM-400 P) or negative (APM-400 N)						
Spectral Range			330 to 1050				nm
Peak Sensitivity Wavelength			750				nm
Quantum Efficiency (630 nm)			75				%
Dimensions		91 mm x 38 mm x 30 mm					
Signal Connector			SMA				

Applications:

Laser induced Fluorescence Excitation with N_2 Laser, Recording of Fluorescence and Excitation Signal by Sampling / Boxcar Technique



Triggering of Time-Correlated Single Photon Counting Experiments



Maximum Ratings

Supply Voltage	-0.3 V ... +13 V
DC Output Current	0.5 mA
Light Pulse Power	100 kW (Duration < 2 ns)
Average Light Power	100 mW
Operating Temperature	0°C ... +70°C

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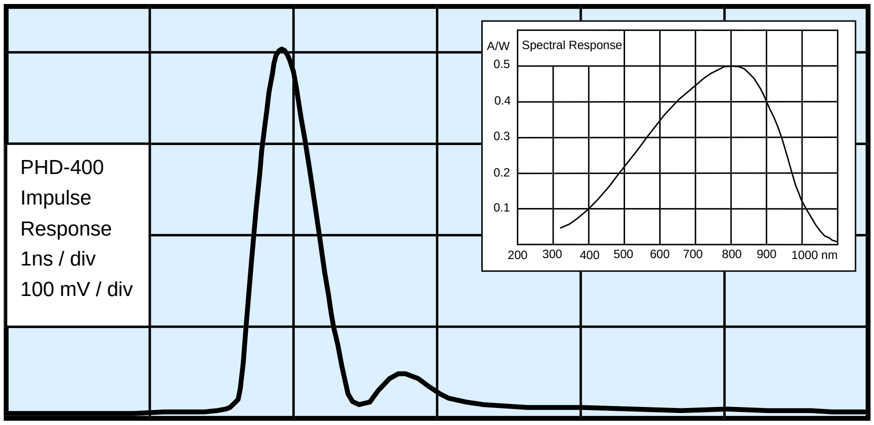
PHD-400

High Speed Photodiode Module

- 200 ps pulse rise time
- 400 ps FWHM
- Detector Area 0.25 mm^2
- Single +5V or +12V supply
- Current indicator



The PHD-400 is used for the detection of light signals and for trigger applications. It contains a Si pin Photodiode with an active area of 0.25 mm^2 - a reasonable compromise between speed and sensitivity. For applications at high repetition rates the built in current indicator provides a convenient means for adjusting and focusing. Due to its single +5V or +12V supply the device can be powered directly from the Sampling / Boxcar Module PCS-150, from the Single Photon Counting Module SPC-300 or from a conventional 5V or12V power supply.

Also available: Detector areas 3.6 mm^2 and 11.9 mm^2, UV versions, modules without current indicator, high sensitivity integrating photodiode modules, avalanche photodiode modules, preamplifiers. Please call for individual data sheets.

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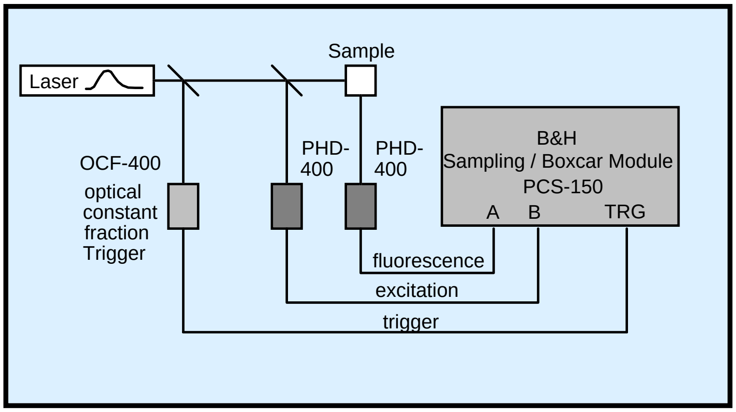
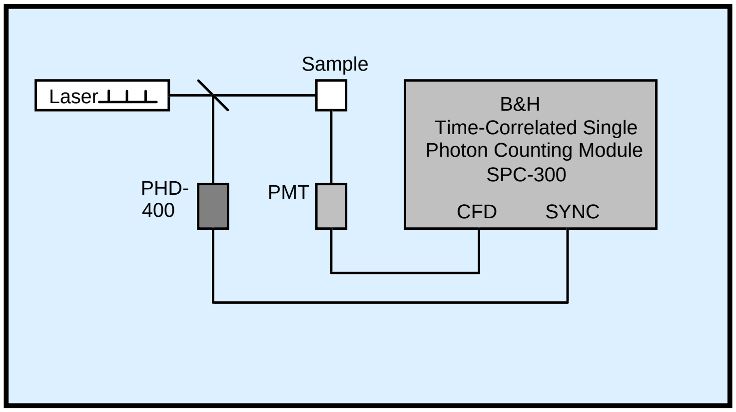
Applications:

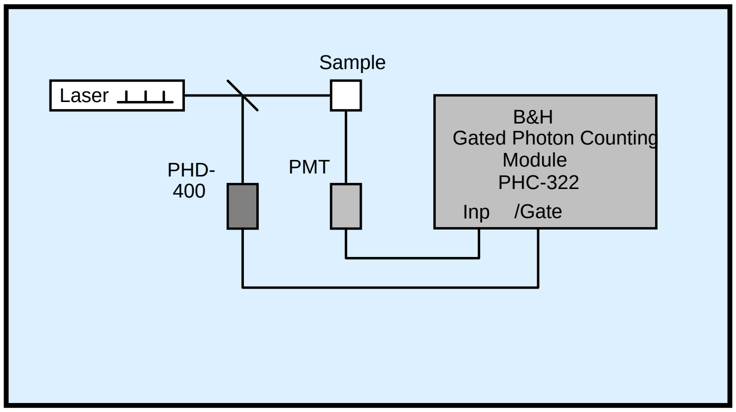
Laser induced Fluorescence Excitation with N_2 Laser, Recording of Fluorescence and Excitation Signal by Sampling / Boxcar Technique



Triggering of Time-Correlated Single Photon Counting Experiments

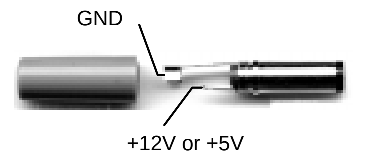


Steady State Fluorescence: Gating off Detector Background Signal



Maximum Ratings

Supply Voltage (5V version)	-0.3 V ... +6.5 V
Supply Voltage (12V version)	-0.3 V ... +13.5V
Light Pulse Power	< 100 kW (Duration < 2 ns)
Average Light Power	< 200 mW
Operating Temperature	0°C ... +70°C



Power Supply Connector Pin Assignment

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intelligent
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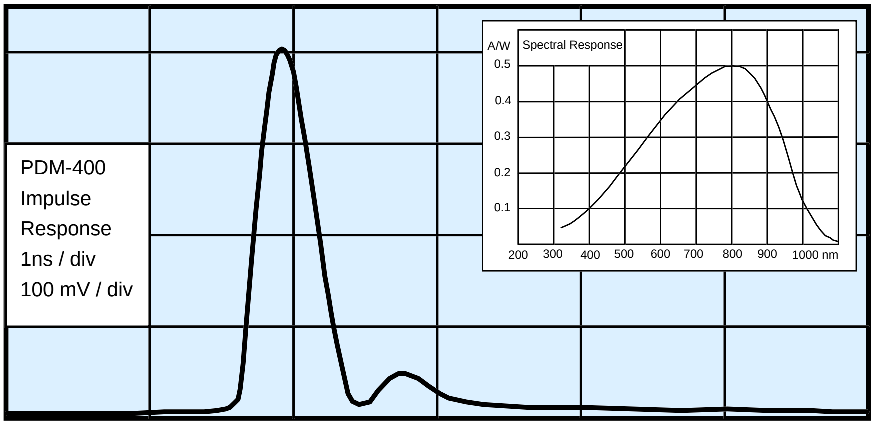
PDM-400

High Speed Photodiode Module

- 200 ps pulse rise time
- 400 ps FWHM
- Detector Area 0.25 mm^2
- Single +5V or +12V supply



The PDM-400 is used for the detection of light signals and for trigger applications. It contains a Si pin Photodiode with an active area of 0.25 mm^2 - a reasonable compromise between speed and sensitivity. Due to its single +5V or +12V supply the device can be powered directly from the Sampling / Boxcar Module PCS-150, from the Single Photon Counting Module SPC-300 or from a conventional 5V or 12V power supply.

Also available: Detector areas 3.6 mm^2 and 11.9 mm^2, UV versions, modules with current indicator, high sensitivity integrating photodiode modules, avalanche photodiode modules. Please call for individual data sheets.

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intelligent
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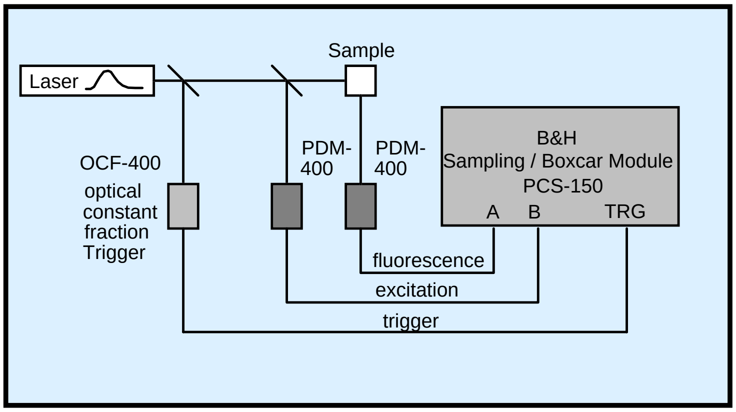
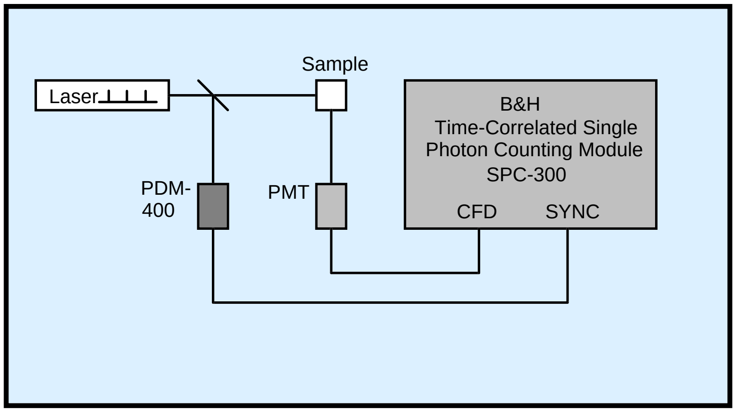
Applications:

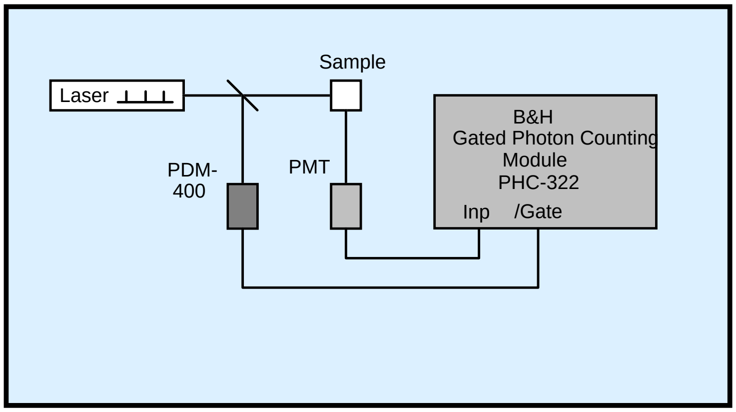
Laser induced Fluorescence Excitation with N_2 Laser, Recording of Fluorescence and Excitation Signal by Sampling / Boxcar Technique



Triggering of Time-Correlated Single Photon Counting Experiments



Steady State Fluorescence: Gating off Detector Background Signal



Maximum Ratings

Supply Voltage (5 V Version)	-0.3 V ... + 6.5 V
Supply Voltage (12 V Version)	-0.3 V ... + 15 V
Light Pulse Power	< 100 kW (Duration < 2 ns)
Average Light Power	< 200 mW
Operating Temperature	0°C ... +70°C

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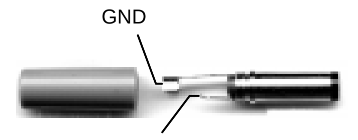

Power Supply Connector Pin Assignment

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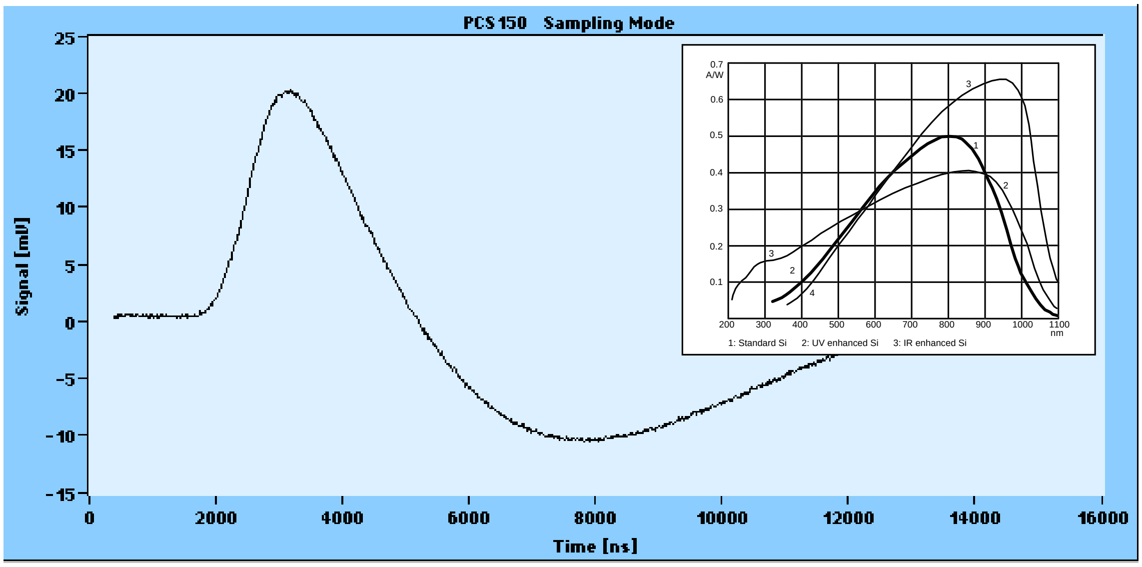
PDI-400

Integrating Photodiode Module

- **Pulse Energy Measurement**
- **Low Noise**
- **High Dynamic Range**
- **Sensitivity in the fJ Range**



The PDI-400 is an integrating detector for pulsed light signals. The PDI-400 includes a high performance photodiode, a low noise charge sensitive amplifier and an active high pass filter. Due to filtering, most of the amplifier noise and low frequency background signals are rejected and the PDI-400 is insensitive to roomlight. Its high sensitivity, low noise and wide dynamic range makes it extremely useful in all applications where accurate and reproducable measurements of light pulse energies are essential. When used in conjunction with our Boxcar devices PCS-150, PCI-200 or BCI-150 the PDI-400 does not require a special power supply.

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PDI-400

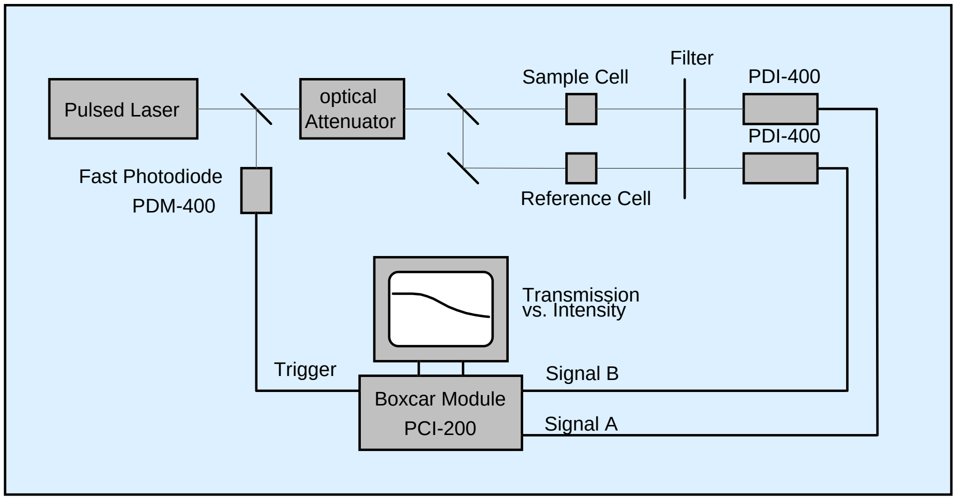
Specification

(typical values, Si standard versions)

	PDI-400/0.25	PDI-400/1.0	PDI-400-7.5	
Active Area	0.25	1.0	7.5	mm^2
Output Voltage Range (R_l=1kΩ, V_{suppl} = ±15V)	10	10	10	V
Output Impedance	50	50	50	Ω
Output Noise (mV, rms, typ.)	0.2	0.5	10	mV
Noise Limited Sensitivity	2	5	100	fJ
Output Voltage at 1pJ, 650nm (typ.)	100	100	100	mV
Supply Voltages		±5 to ±15		V

Also available: Special versions with other detector areas, UV enhanced and IR enhanced versions, UV versions with SiC photodiode, negative output versions. To record the signals of the PDI detectors we recommend our Boxcar devices PCI-200. Please contact Becker & Hickl.

Application: Measurement of Nonlinear Optical Absorption



Maximum Ratings

Power Supply Voltage	Vccmin = -0.3V, Vccmax = +16V Veemin = -16V, Veemax = +0.3V
Light Pulse Power	< 100 kW (Duration < 2 ns)
Average Light Power	< 100 mW
Operating Temperature	0°C ... +70°C

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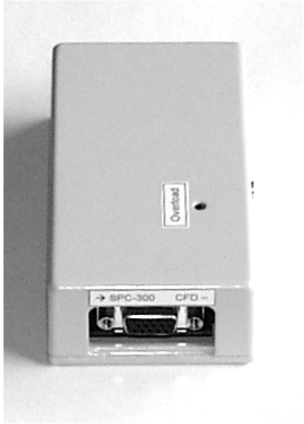
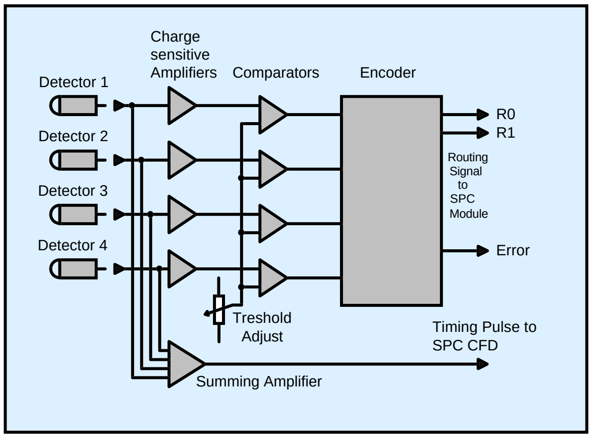
HRT - 41

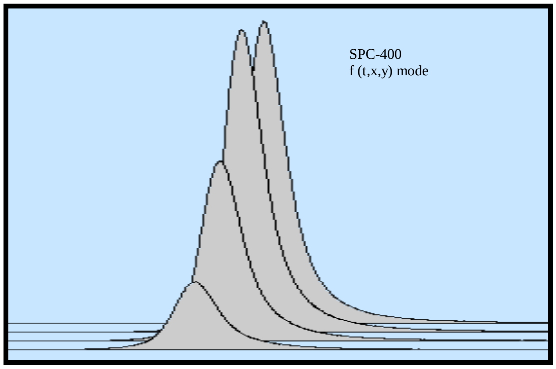
4 Channel TCSPC Router for PMTs

- **Connects up to four separate detectors to one bh time-correlated single photon counting module**
- **Simultaneous measurement in all detector channels**
- **Applicable with most PMTs and MCPs**
- **Time Resolution 30 ps with R3809U MCP**
- **Count Rate > 1 MHz**

The HRT-81 module is used to connect up to four individual detectors to one bh SPC-3, SPC-4, SPC-5, SPC-6 or SPC-7 time-correlated single photon counting module. The photons from the individual detectors are routed into different curves in the SPC memory. Thus the measurement yields a separate decay function for each of the detectors. Typical applications are fluorescence depolarisation measurements or simultaneous decay measurements at different waveleghts.







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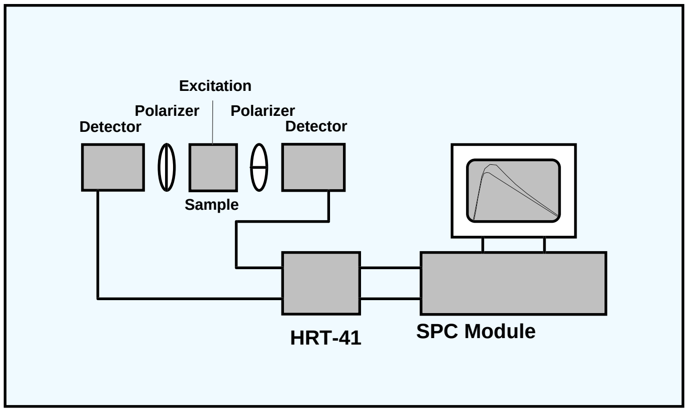
HRT - 41

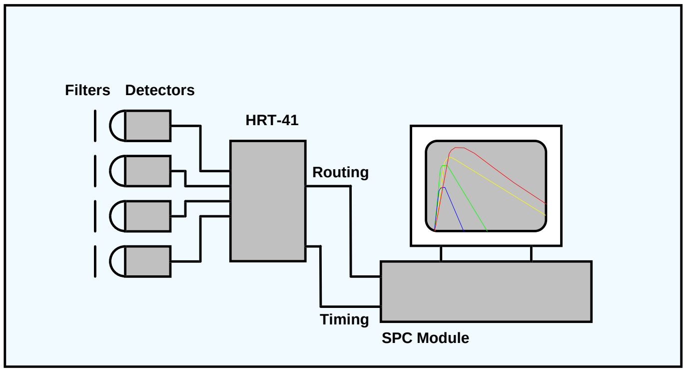
Specification

Input Polarity	negative
Input Connectors	50 Ohm, SMA
Input Pulse Charge for best Routing	0.2 ... 2 pAs
Timing Output Polarity	negative
Delay Difference between Channels	60 ps per Channel
Timing Output Connector	50 Ohm, SMA
Gain of Timing Pulse Output	6
Routing-Signal	TTL 2 bit + Error Signal
Recommended SPC 'Latch Delay'	20 ns
Routing Signal Connector	15 pin Sub-D/HD
Power Supply	+5V, -5V, +12V via Sub-D Connector from SPC Module
Dimensions	110mm × 60mm × 31mm

Applications



Fluorescence Anisotropy Measurement



Multi Wavelength Decay Measurement

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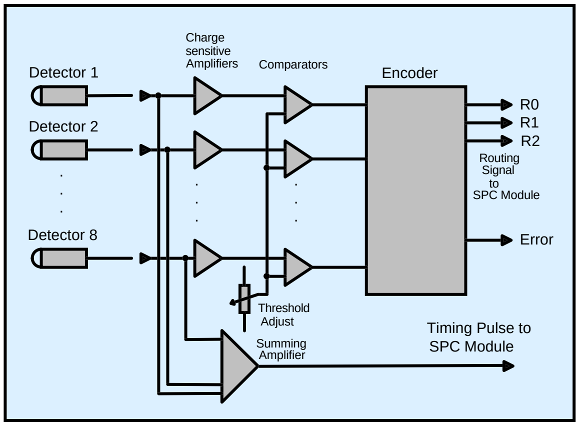
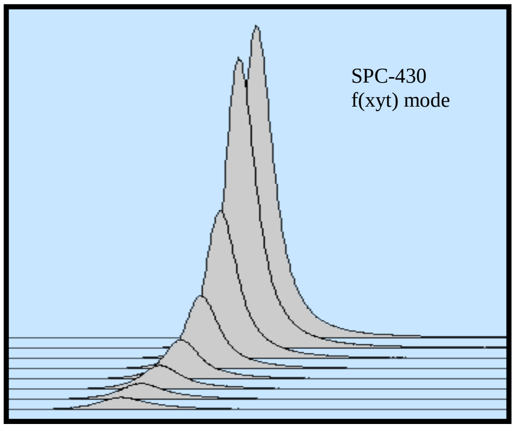
HRT-81

8 Channel TCSPC Router for PMTs

- **Connects up to eight separate detectors to one bh time-correlated single photon counting module**
- **Simultaneous measurement in all detector channels**
- **Applicable with most conventional PMTs and MCPs**
- **Time Resolution 30 ps with R3809U MCP**
- **Count Rate > 1 MHz**

The HRT-81 module is used to connect up to eight individual detectors to one of the bh time-correlated single photon counting modules SPC-xx0. The photons from the individual detectors are routed into different curves in the SPC memory. Thus the measurement yields a separate decay function for each of the detectors. Typical applications are fluorescence depolarisation measurements or simultaneous decay measurements at different waveleghts.





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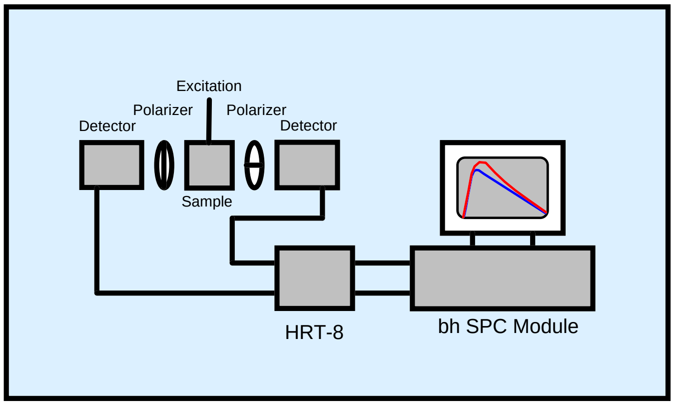
HRT-81

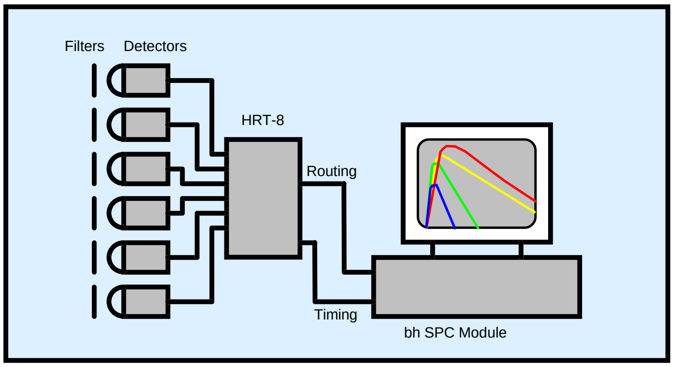
Specification

Input Polarity	negative
Input Connectors	50 Ohm, SMA
Input Pulse Charge for best Routing	0.2 ... 2 pAs
Timing Output Polarity	negative
Delay Difference between Channels	60 ps per Channel
Timing Output Connector	50 Ohm, SMA
Gain of Timing Pulse Output	4
Routing-Signal	TTL 3 bit + Error Signal
Routing Signal Connector	15 pin Sub-D/HD
Power Supply	+5V, -5V, +12V via Sub-D Connector from SPC Module
Dimensions	120mm × 95mm × 34mm

Applications



Fluorescence Anisotropy Measurement



Multi Wavelength Decay Measurement

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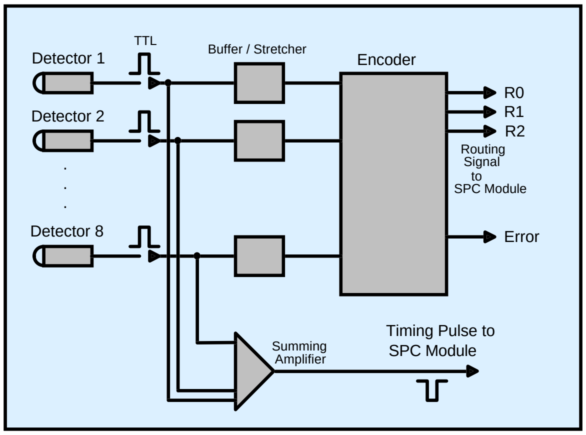
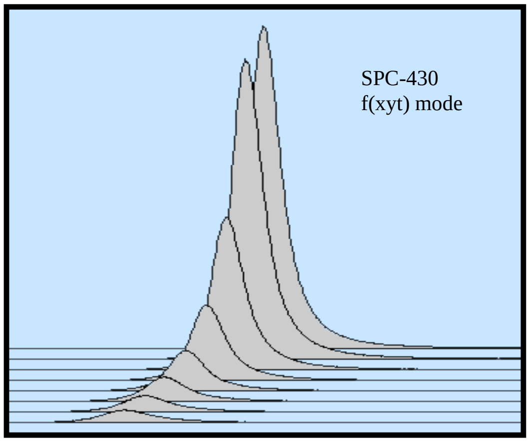
HRT-82

8 Channel TCSPC-Router for APD Modules

- **Connects up to eight separate APD modules to one bh TCSPC module**
- **Simultaneous measurement in all detector channels**
- **Applicable with SPCM-AQR Modules and other TTL Output Detectors**
- **Count Rate > 3 MHz**

The HRT-82 module is used to connect up to eight individual avalanche photodiode (APD) detectors to one of the time-correlated single photon counting modules SPC-xx0. The photons from the individual detectors are routed into different curves in the SPC memory. Thus the measurement yields a separate decay function for each of the detectors. Typical applications are fluorescence depolarisation measurements or simultaneous decay measurements at different waveleghts.





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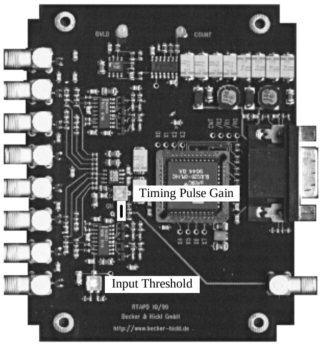
HRT-82

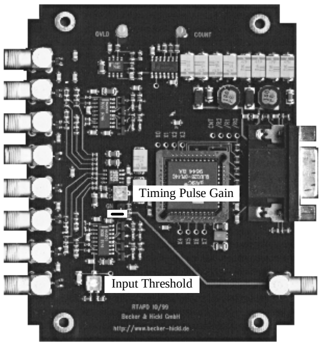
Specification

Input Polarity	positive
Input Voltage	TTL, 1.2 V to 5 V
Input Threshold	adjustable from 0.1 V to 2 V
Input Impedance	50 Ω
Input Pulse Duration	8 ns to 60 ns
Input Connectors	SMA
Timing Output Polarity	negative
Timing Output Voltage (2.5 V Input)	120 mV or 60 mV into 50 Ω (Jumper)
Timing Output Impedance	50 Ω
Timing Output Connector	50 Ohm, SMA
Delay Difference between Channels	max. 60 ps per Channel
Routing-Signal	TTL 3 bit + Error Signal
Routing Signal Connector	15 pin Sub-D/HD
Power Supply	+5V, -5V, via Sub-D Connector from SPC Module
Dimensions	120mm × 95mm × 34mm

Output Voltage Configuration

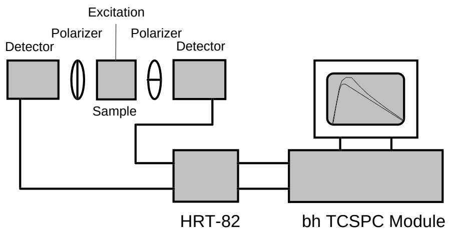


Vout = 120 ... 150 mV mV (SPC-x30)

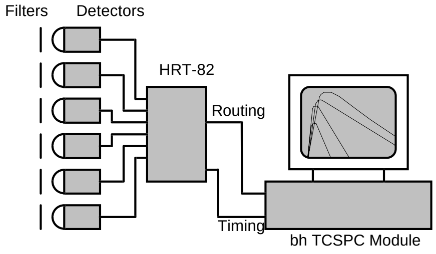


Vout = 50 ... 60 mV (SPC-x00)

Applications



Fluorescence Anisotropy Measurement



Multi Wavelength Fluorescence Decay Measurement

Also available: HRT-41 4 Channel and HRT-81 8 Channel Routers for PMTs and MCPs. Please see individual data sheets.

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OCF - 401

Optical Constant Fraction Discriminator

Accurate triggering to optical pulses

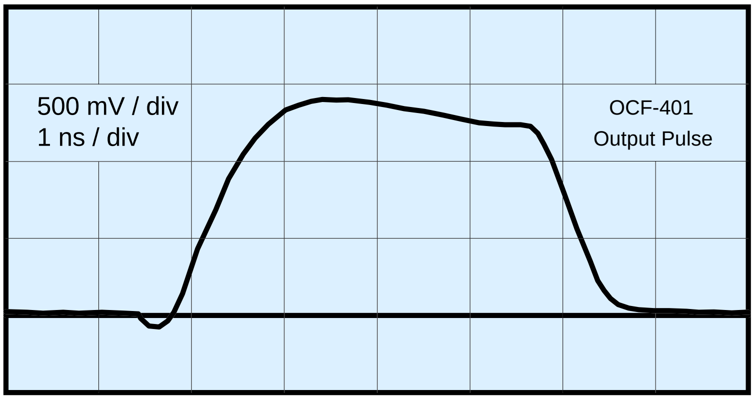
Negligible influence of amplitude fluctuations

Time walk < 30 ps for 1ns pulse with 1:10 amplitude fluctuation

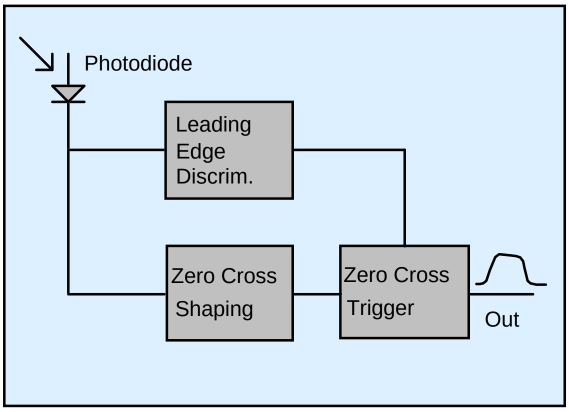
1V output pulse amplitude

Single +5V supply

Trigger indicator LED



The OCF-401 is used to derive electrical trigger pulses from optical pulses with unstable amplitude. Due to the constant fraction trigger technique the trigger delay is widely independent of the pulse amplitude. Typical applications are the triggering of sampling or boxcar measurements, the synchronisation of photon counting experiments or the triggering of streak cameras.



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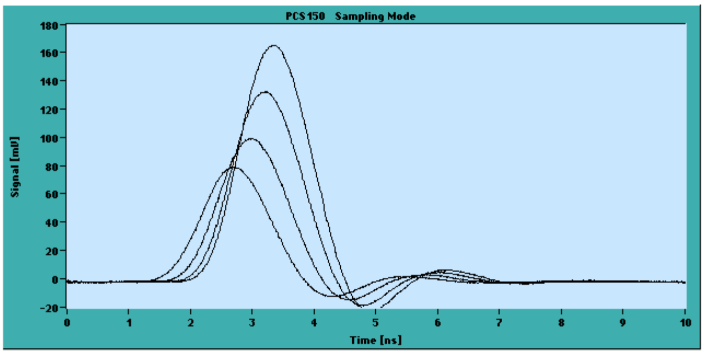
OCF - 401

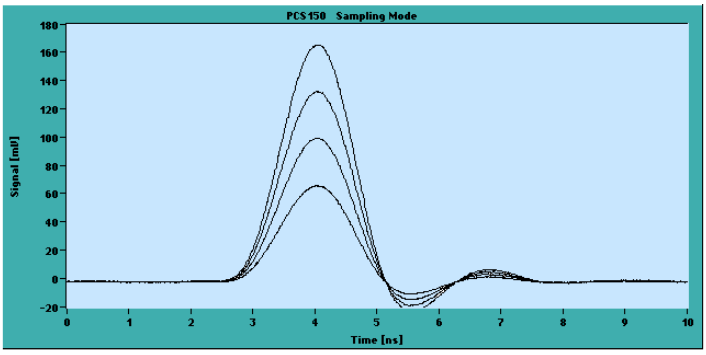
Conventional Triggering:

Trigger point shifts with signal amplitude



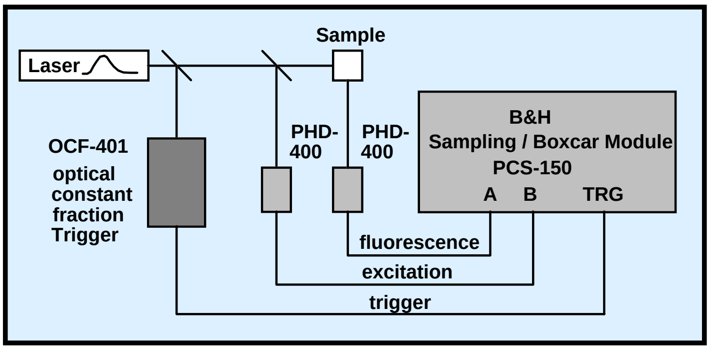
Triggered with OCF-401:

Trigger point independent of signal amplitude



Typical Application:

Triggering of Sampling/Boxcar Measurements



Specification

Supply Voltage	+ 5 V
Output Pulse Voltage (50 Ω)	1 V ... 1.5V
Output Pulse Width	5 ns
Trigger Delay	5 ns
Time Walk (1ns, 1:10)	< 30 ps rms
Sensitivity (600 nm)	10 mW
Spectral Range	300 nm to 1000 nm
Output Connector	SMA, 50 Ω
Power Connector	DC PP3, 1.3 / 3.5 mm

Maximum Ratings

Supply Voltage	-0.3 V ... +6.5 V
Light Pulse Power	< 100 kW (Duration <2ns)
Average Light Power	< 200 mW
Operating Temperature	0°C ... +70°C

Options

OCF-401-1	TTL Output, >2V into 50 Ω

The manual is available under www.becker-hickl.com

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How (and why not) to Amplify PMT Signals

'I have to detect a light signal in the ns range. I use a PMT, but the noise is too high so that I can't see the signal. Which amplifier can I use to improve the signal-to-noise ratio?' The answer to this frequently asked question is usually **'none'**, and the general recommendation for using an amplifier for PMT signals is **'don't'**.

This consideration explains the peculiarities of PMT signals and gives hints to handle these signals.

The PMT

A conventional PMT (Photomultiplier) is a vacuum tube which contains a photocathode, a number of dynodes (amplifying stages) and an anode which delivers the output signal.

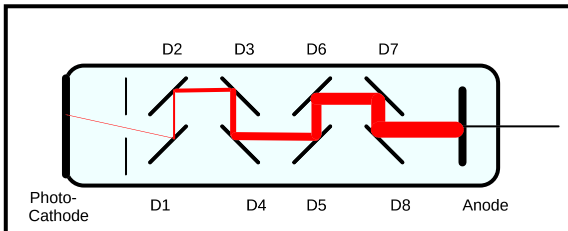


Fig. 1: Conventional PMT

By the operating voltage an electrical field is built up that accelerates the electrons from the cathode to the first dynode D1, from D1 to D2 and to the next dynodes, and from D8 to the anode. When a photoelectron emitted by the photocathode hits D1 it releases several secondary electrons. The same happens for the electrons emitted by D1 when they hit D2. The overall gain can reach values of 10^6 to 10^8. The secondary emission at the dynodes is very fast, therefore the electrons resulting from one photoelectron arrive at the anode within some ns. Due to the high gain and the short response a single photoelectron yields a easily detectable current pulse at the anode.

The operating voltage of a PMT is in the order of 800V to some kV. The gain of the PMT strongly depends on this voltage. Therefore, the gain can be conveniently controlled by changing the operating voltage.

MCP (Micro Channel Plate) PMTs achieve the same effect by a plate with millions of microchannels. The channel walls have a conductive coating. When a high voltage is applied across the plate the channel walls act as a secondary emission target, and an input photon is multiplied by a factor 10^5 to 10^6.

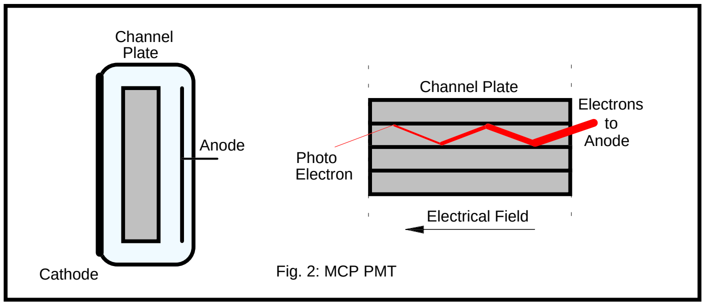
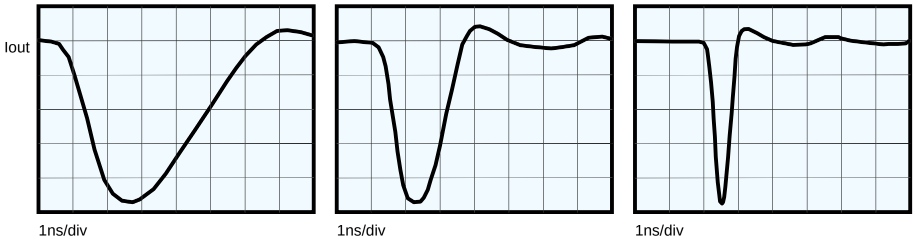


Fig. 2: MCP PMT

Due to their compact design, MCP-PMTs are extremely fast.

The PMT Signal

The output pulse for a single photoelectron is called the ‘Single Electron Response’ or SER of the PMT. Some typical SER shapes are shown in the figure below.



Standard PMT Fast PMT (R5600, H5783) MCP-PMT

Fig. 3: Single Electron Response of Different PMTs

The peak current of the SER is approximately*

$$\text{Iser} = \frac{G \cdot e}{\text{FWHM}}$$

(G = PMT Gain, e=1.6 $\cdot$ 10^{-19} As, FWHM= SER pulse width, full width at half maximum)

Due to the random nature of the PMT gain, Iser is not stable but varies from pulse to pulse. The distribution of Iser can be very broad, up to 1:5 to 1:10. With G being the average gain, the formula delivers the average Iser which is sufficient for the following considerations.

The table below shows some typical values. Iser is the average SER peak current and Vser the average SER peak voltage when the output is terminated with 50 Ω. For comparison, Imax is the maximum useful output pulse current of the PMT.

PMT	PMT Gain	FWHM	Iser	Vout (50 Ω)	Imax (cont)	I max (pulse)
Standard	10^7	5 ns	0.32 mA	16 mV	100uA	50mA
Fast PMT	10^7	1.5 ns	1 mA	50 mV	100uA	100mA
MCP PMT	10^6	0.36 ns	0.5mA	25 mV	0.1uA	10mA

Table 1: Typical PMT parameters

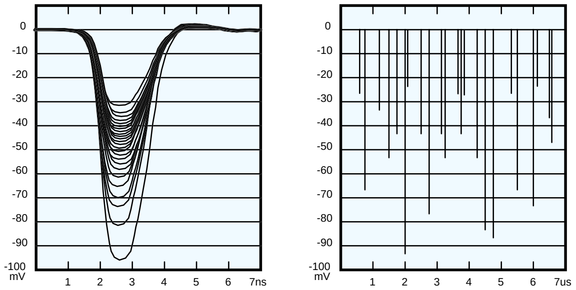
The conclusions from the table above are:

1. The output voltage for a single detected photon is in the order of some 10mV at 50 Ω. This is much more than the noise of any reasonable electronic recording device. Thus, the PMT easily ‘sees’ the individual photons of the light signal. Further amplification cannot increase the number of signal photons and therefore does not improve the SNR.

2. The peak current for a single photon , Iser, is greater than the maximum continuous output current, $I_{max(cont)}$. Therefore, a continuous light signal does not produce a continuous current at the PMT output but a train of random SER pulses.

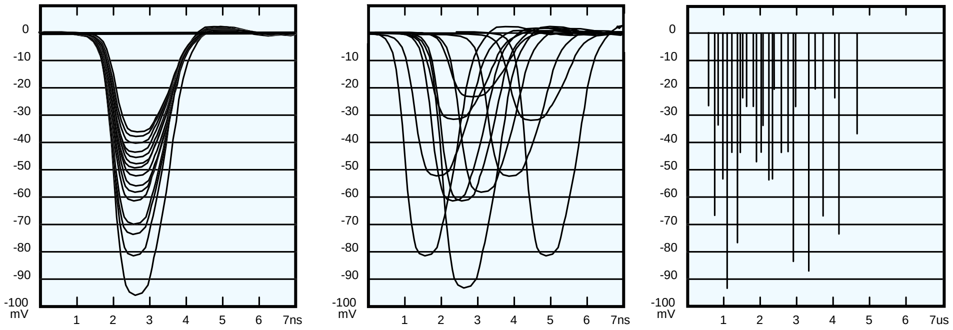
3. The peak current for a single photon , Iser, is only 1/20 to 1/100 of the maximum output pulse current, $I_{max(pulse)}$. Thus, even for light pulses no more than 20 to 100 photons can be detected at the same moment. This limits the SNR of the unprocessed PMT signal to less than 10. Actually the SNR is even worse because of the random nature of the PMT gain. Any additional amplifier can only decrease the ratio Imax / Iser and therefore decrease the SNR.

The typical appearance of the PMT signal for the different cases is shown in the figure below.



a:
Continous Light, ns Scale:
Random SER Pulses

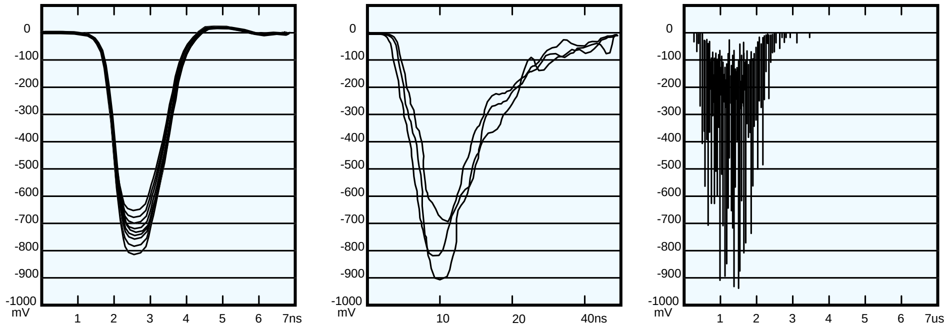
b:
Continous Light, us Scale:
Random SER Pulses



c:
Ultra Short Pulses, Low Intensity:
Random SER pulses at time of light pulse

d:
5ns Pulses, Low Intensity:
Random SER pulses spread over pulse duration

e:
Single us Light Pulse, Low Intensity:
Random SER Pulses spread over pulse duration



f:
Ultra Short Pulses, High Intensity:
SER-like pulses, Amplitude jitters around intensity-proportional value due to random number of photons and random gain

g:
10ns Pulses, High Intensity:
Pulses with noise due to random number of photons and random gain

h:
Single us Light Pulse, High Intensity:
Signal with noise due to random number of photons and random gain

Fig. 4: PMT Signals for different Light Signal

Why NOT to use an Amplifier

Obviously, any additional amplification of the signals shown in fig. 4 does not improve the SNR. The SNR is limited by the number of signal photons which cannot be increased by the amplifier. Actually, an amplifier can only **decrease the useful dynamic range,** because it increases the signal for a single photon while setting additional constraints to the maximum signal level. The situation is shown in the figure below.

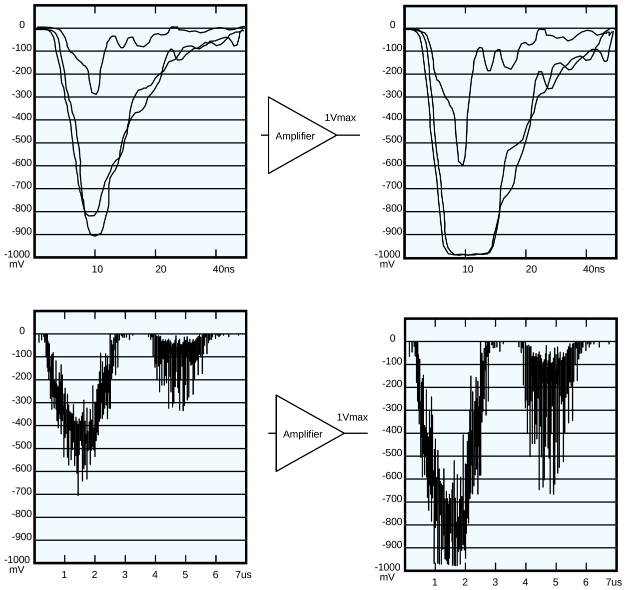


Fig. 5: Effect of an amplifier on a fast PMT signal

The amplifier has a gain of 2, but saturates for input signals above 500mV. Therefore, not the full output signal range of the PMT can be used. The bigger signals with their better SNR are distorted, while the SNR of the smaller signals remains unchanged. For longer signals (lower example) it can happen that only the peaks are clipped. Although this is often not noticed, it makes the signal useless for further processing.

When to use an Amplifier

Low Bandwidth Recording

When a PMT is used as a linear detector its pulse response is given by the SER. Therefore, PMTs are very fast devices. In some applications the high speed is not required, and the signal is recorded with a reduced time resolution. This can be achieved by a passive low pass filter, by a slow amplifier or simply by terminating the PMT output with a resistor much higher than 50 Ω. The slow recording device can be seen as a low pass filter which smoothens the SER pulses.

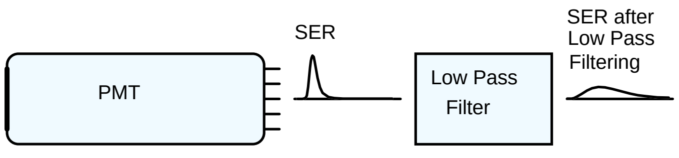


Fig. 6: Effect of Low Pass Filtering on the SER

The virtual peak current of the SER after the low pass filter is approximately

$$\mathrm{Iserf} = \frac{G \cdot e}{\mathrm{Tfil}} \qquad \text{or} \qquad \mathrm{Iserf} = \mathrm{Iser}\ \frac{\mathrm{FWHM}}{\mathrm{Tfil}}$$

(G = PMT Gain, $e=1.6 \cdot 10^{-19}$ As, Tfil= Filter Rise Time, FWHM= SER pulse width, full width at half maximum)

The curves below show the virtual SER peak current and the SER peak voltage for a standard PMT and for different termination resistors.

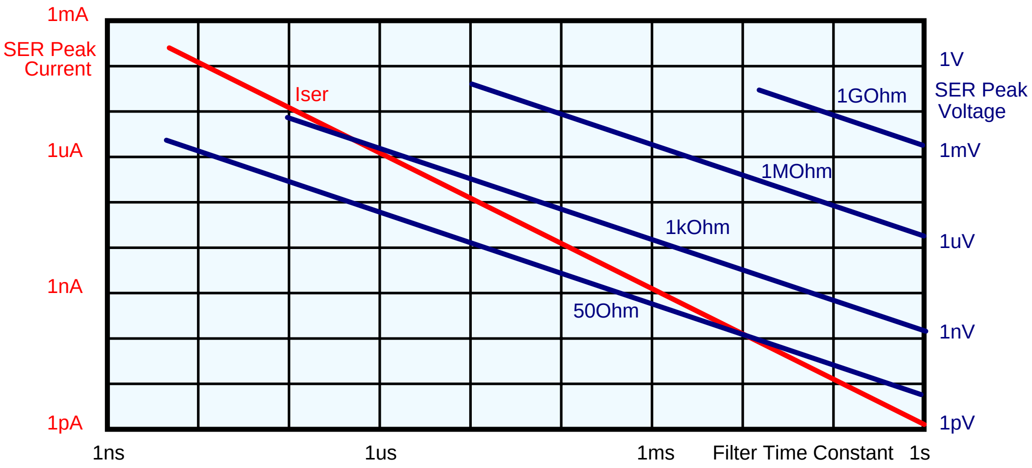


Fig. 7: Virtual SER peak current and SER peak voltage after low pass filtering

Fig. 7 shows that the virtual SER peak current drops to very low values for longer low pass filter times. Additional amplification can be required now. However, for slow measurements the loss of signal amplitude can be compensated by increasing the termination resistor which makes a high amplifier gain unnecessary.

Two basically different amplifier principles are available - the normal ‘Voltage’ amplifier and the ‘Current’ or ‘Transimpedance’ amplifier.

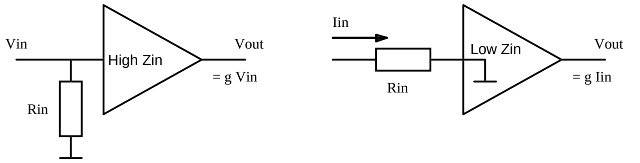


Fig 8 a: Voltage Amplifier
The voltage at the input is transferred
into a voltage at the output
The input has a high impedance

Fig 8 b: Current Amplifier
The current at the input is transferred
into a voltage at the output
The input has a low impedance

A Voltage Amplifier (fig. 8a) transfers a voltage at the input into a higher voltage at the output. The input of the amplifier represents a high impedance. The output current of the PMT is converted into a voltage at the input matching resistor Rin. This voltage appears with the specified gain at the amplifier output.

A Current Amplifier (fig. 8b) transfers a current at the input into a voltage at the output. Thus the gain of a current amplifier is given in V/A. The input of a current amplifier has a low impedance. Ideally, the input should represent a short circuit. Practically an input matching resistor Rin is added (typically 50 Ω) to maintain stability and to avoid reflections at the input cable. Current amplifiers are used to get fast signals from detectors which represent a current source with a high parallel capacitance. In the present case their is neither a high detector capacitance nor a requirement for high speed. Thus, a current amplifier is not the right choice to reduce the bandwidth of a PMT signal. There would be no reasonable and predictable bandwidth reduction, and the strong SER pulses could drive the amplifier into saturation without producing an equivalent output signal. If you really need a fast amplifier for a PMT signal, you should better use a GHz wideband amplifier in 50Ω technique (see ‘Photon Counting’).

High Light Intensities

There are applications where the light intensity is so high that it would saturate the PMT operated at its normal gain. To get an optimum SNR from the PMT for these signals, it is better to reduce the PMT gain than to attenuate the light. However, if the PMT operating voltage is decreased by decreasing the operating voltage, also the speed and the useful output current range of the PMT decreases. To match the decreased signal range to the input range of a recording device a moderate amplification can be reasonable. However, this situation is unlikely because a PMT normally delivers enough output current even if its gain is reduced by some orders of magnitude. If the gain has to be reduced to extremely low values you should consider to use another detector - an avalanche photodiode or even a PIN photodiode.

Photon Counting

Signals as shown in fig. 4b, 4d and 4e are not effectively captured by analog data acquisition methods. They are better recorded by counting the individual SER pulses. This ‘Photon Counting’ method has some striking benefits:

- The amplitude jitter of the SER pulses does not appear in the result.
- The dynamic range of the measurement is limited by the photon statistics only.
- Low frequency pickup and other spurious signals can be suppressed by a discriminator.
- The gain instability of the PMT has little effect on the result.
- The time resolution is limited by the transit time spread of the SER pulses rather than by their width. This fact is exploited for ‘Time-Correlated Single Photon Counting’ to achieve a resolution down to 25ps with MCP PMTs.

Therefore, you should consider to use photon counting for light intensities that deliver well separated single photon pulses.

The discriminators at the input of a photon counter work best at a peak amplitude of some 100mV. Therefore, an amplifier is useful if the SER amplitude is less than 50 mV.

For photon counting with MCP PMTs an amplifier should always be used. Due to degradation of the microchannels by sputtering, these devices have a limited lifetime. Using an amplifier enables the MCP to be operated at reduced gain and reduced output current so that the lifetime is extended.

For photon counting the amplifier gain can be so high that the biggest SER pulses just fit into the amplifier output and the discriminator input voltage range. The amplifier should have sufficient bandwidth not to broaden the SER pulse of the PMT. This requires some 100MHz for standard PMTs and at least 1 GHz for MCPs. The input and output impedance should be

50 Ω for correct cable termination. Such amplifiers are known as ‘GHz wideband amplifiers in 50 Ω technique and are available with a gain of up to 100 and a bandwidth of some GHz.

HFAH-20 HFAH-40

Wide-Band Amplifiers for PMTs and MCPs

Overload indicator

Overload signal for detector shutdown

Gain versions 20 dB and 40 dB

Cutoff frequency 430 MHz and 2.9 GHz

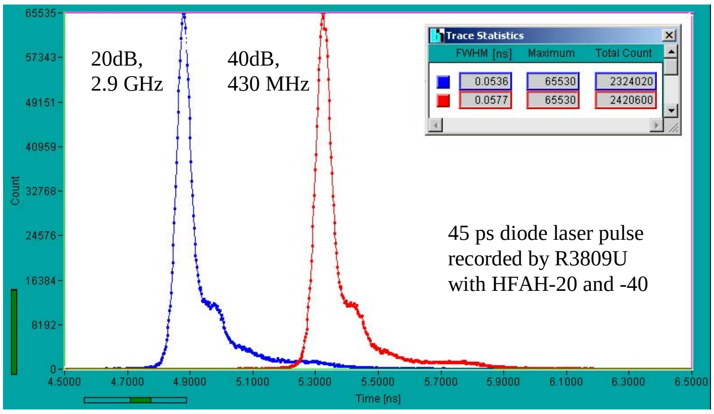
Low noise, high linearity

Input and output impedance 50 Ω

Input protection

The HFAH series amplifiers are used to amplify the output signals of high speed PMTs or MCPs for single photon counting applications. The gain of the amplifier allows the detector to be operated at reduced signal current. This increases the available count rate and extends the lifetime of MCP tubes. Furthermore, the amplifier gain helps to reduce noise pickup in long signal cables. The amplifiers have an input protection circuit preventing damage by overload or by charged signal cables. Exceeding of a specified detector current is indicated by two LEDs and a buzzer. If the detector current exceeds 200% of the specified value a TTL overload signal is activated. This signal can be used to shut down the detector or to close a shutter via the BH DCC-100 detector controller card. The power supply of the HFAH amplifier comes from the BH SPC card or from the DCC-100.

The HFAH comes in two gain / bandwidth and several overload threshold versions. The 20 dB / 2.9 GHz version is used if maximum time resolution is to be obtained from a fast PMT or MCP. The 40dB / 430 MHz is used to obtain MHz count rates from MCP-PMTs within their limited output current capability. The 430 MHz bandwidth filtering maximises the signal-to-noise ratio of the single photon pulses thus providing optimum TCSPC time resolution at reduced detector gain.



	FWHM [ns]	Maximum	Total Count
🟦	0.0536	65530	2324020
🟥	0.0577	65530	2420600

45 ps diode laser pulse
recorded by R3809U
with HFAH-20 and -40

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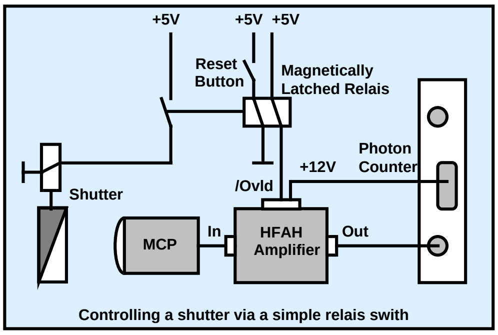
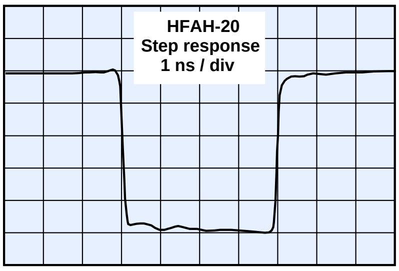
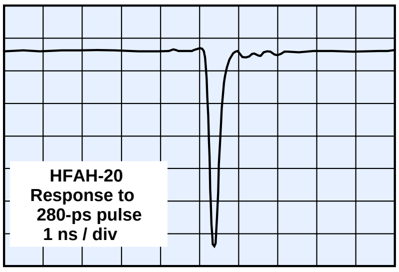


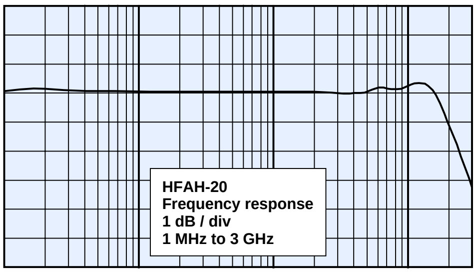
Controlling a shutter via a simple relais swith

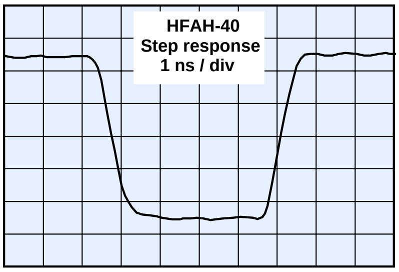
HFAH-20   HFAH-40

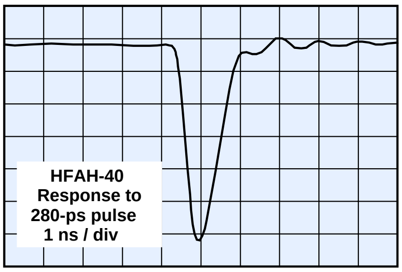
Input / output impedance	50 Ω	50 Ω
Singal Connectors	SMA	SMA
Gain	20 dB, non inverting	40 dB, non inverting
Bandwidth	2.9 GHz	430 MHz
Lower cutoff frequency	500 kHz	500 kHz
Max. linear output voltage	1V	1V
Noise Figure	4 dB	6 dB
Detector overload current threshold, I_{ovl}	0.1 1 2 or 10 µA	0.1 1 2 or 10 µA
Detector overload warning	LEDs and buzzer	LEDs and buzzer
Detector overload signal	TTL, active low, can be or-wired	TTL, active low, can be or-wired
Activation of yellow LED at	0.6 I_{ovl}	0.6 I_{ovl}
Activation of red LED and buzzer at	1.0 I_{ovl}	1.0 I_{ovl}
Activation of overload signal at	2.0 I_{ovl}	2.0 I_{ovl}
Overload signal response time	10 ms	10 ms
Power Supply Voltage	+12 V	+12 V
Maximum safe power supply voltage	+15 V	+15 V
Power Supply Current at +12V	80 mA	45 mA
Dimensions	50 x 60 x 28 mm	50 x 60 x 28 mm
Connector for power and overload out	15 pin HD sub D	15 pin HD sub D
Pin assignment of sub-D connector	1 and 15: GND, 10: +12V 14: /overload	1 and 15: GND, 10: +12V 14: /overload

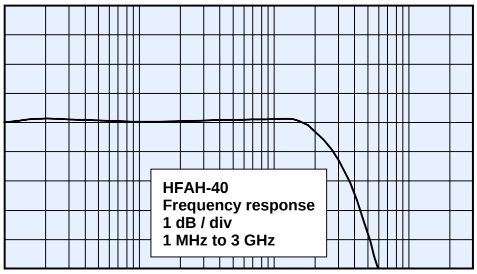


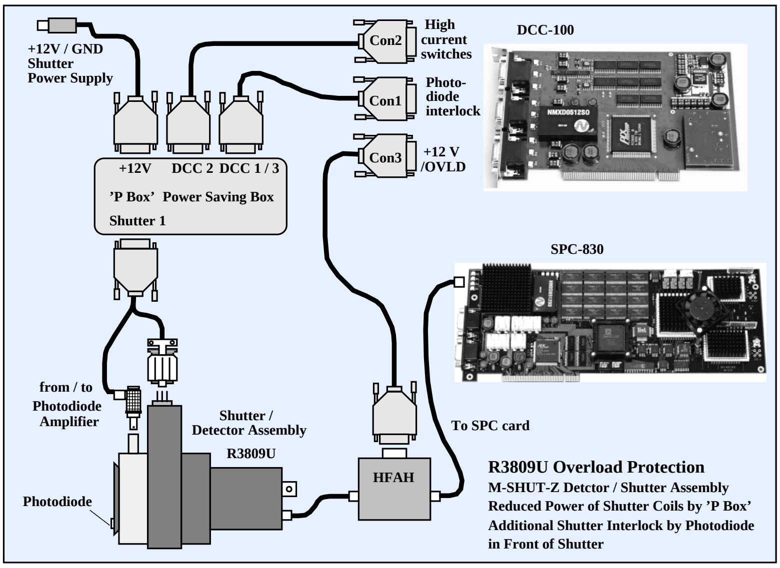












R3809U Overload Protection
M-SHUT-Z Detctor / Shutter Assembly
Reduced Power of Shutter Coils by 'P Box'
Additional Shutter Interlock by Photodiode
in Front of Shutter

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sales@psplc.com
www.psplc.com

HFAC - 26

GHz Wide Band Amplifier with Overload Detection for PMTs or MCPs

- **Cutoff frequency 1.6 GHz**
- **Gain 26 dB**
- **Input and Output Impedance 50 Ω**
- **Low Frequency Limit < 5kHz**
- **Input Protection**
- **Monitoring of Detector Current / Overload Warning**

The HFAC series amplifiers are used to amplify the output signals of high speed PMTs or MCPs, especially in single photon counting applications. The gain of the amplifier allows the detector to be operated at reduced signal current which extends the lifetime of MCP tubes. Furthermore, the amplifier gain helps to reduce noise pickup in long signal cables.The amplifiers have an input protection circuit which avoids damage by overload or by charged signal cables. Furthermore, two LEDs indicate overload conditions in the detector. A TTL signal is provided to switch off the light source or the detector supply voltage if the average detector current exceed the specified value.

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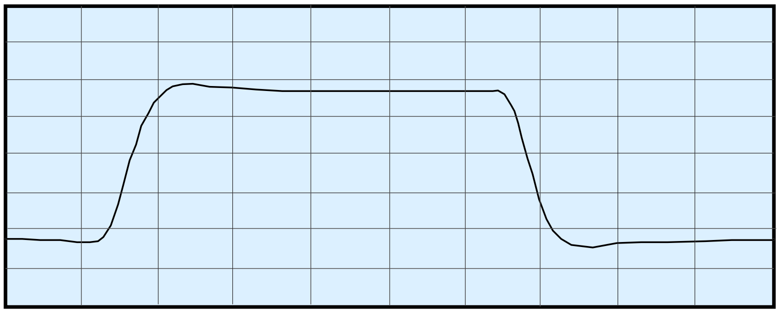
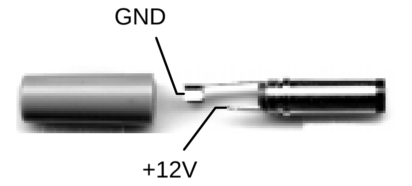
HFAC - 26

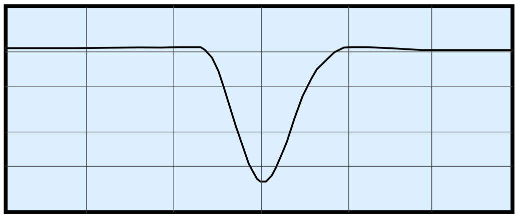
Input / Output Impedance	50 Ω
Connectors	SMA
Gain	26 dB non inverting
Bandwidth	1.6 GHz
Low Cutoff Frequency	5 kHz
Max. Output Voltage	1V
Noise Figure	5 dB
Detector Overload Current	0.1 µA, 1 µA or 10 µA (specified by extension HFAC-26-xx)
Detector Overload Warning	yellow LED at 0.5 I_{max} red LED at I_{max} TTL L-signal at 1.2 I_{max}
Current Warning Response Time	1 ms
Power Supply Voltage	+12 ... +15 V
Power Supply Current	typ. 45 mA
Dimensions	52 x 38 x 31 mm



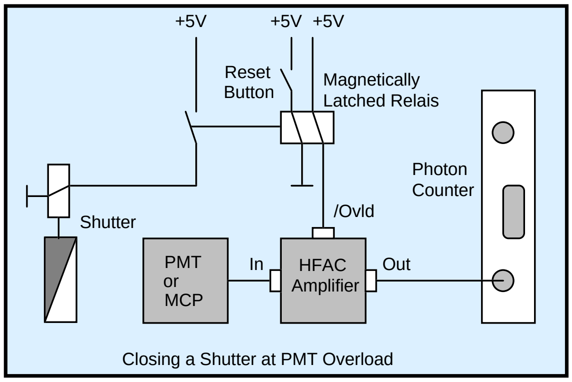
HFAC Step Response



Power Supply Connector Pin Assignment



HFAC Impulse Response



Closing a Shutter at PMT Overload

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HFAM - 26

8 Channel GHz Wide Band Amplifier with Overload Detection for PMTs or MCPs

- **Cutoff frequency 1.6 GHz**
- **Gain 26 dB**
- **Input and Output Impedance 50 Ω**
- **Low Frequency Limit < 5kHz**
- **Input Protection**
- **Monitoring of Detector Current / Overload Warning**

The HFAM series amplifiers are used to amplify the output signals of high speed PMTs or MCPs, especially in single photon counting applications. The gain of the amplifier allows the detector to be operated at reduced signal current which extends the lifetime of MCP tubes. Furthermore, the amplifier gain helps to reduce noise pickup in long signal cables. The amplifiers have an input protection circuit which avoids damage by overload or by charged signal cables. Furthermore, a LED indicates an overload condition if the average detector currents of one or more channels excceed a specified value.

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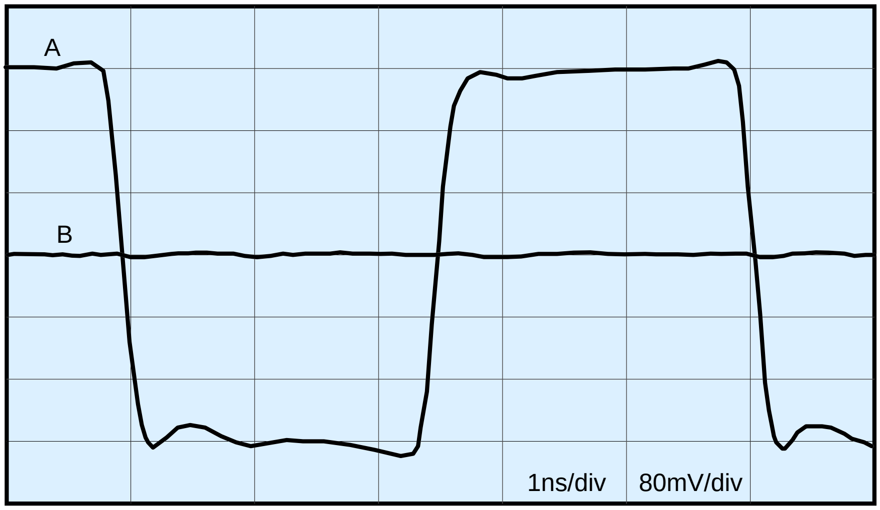
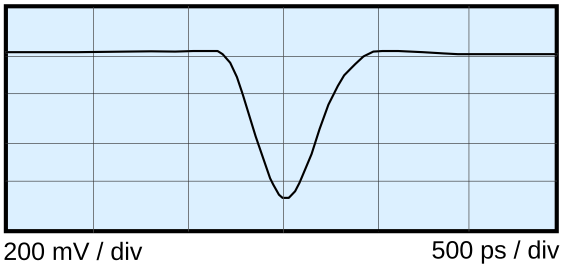
HFAM - 26

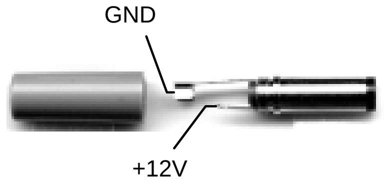
Input / Output Impedance	50 Ω
Connectors	SMA
Gain	26 dB, non inverting
Bandwidth	1.6 GHz
Low Cutoff Frequency	5 kHz
Max. Linear Output Voltage	1V
Noise Figure	5 dB
Detector Overload Current (I_{max}, please specify)	0.1 µA (for MCPs) or 10 µA (for PMTs)
Detector Overload Warning	red LED at I_{max}
Current Warning Response Time	1 ms
Power Supply Voltage	+12 ... +15 V
Power Supply Current	typ. 320 mA
Dimensions	110 x 60 x 30 mm



Step Response (A) and Crosstalk between Adjacent Channels (B)



HFAM Impulse Response



Power Supply Connector Pin Assignment

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ACA - XX

GHz Wide Band Amplifier Family

- **Cutoff Frequency up to 2.2 GHz**
- **Gain from 13 dB to 37 dB**
- **Input and Output Impedance 50 Ω**
- **Low Frequency Limit < 5kHz**
- **Input Protection Available**

	ACA-2 13db	**ACA-2 21dB**	**ACA-2 37db**	**ACA-4 35dB**	
Cutoff Frequency (-3dB)	2.2	1.8	1.6	1.8	GHz
Low Frequency Limit	3	3	3	5	kHz
Gain (dB)	13	21	37	35	dB
Gain (factor)	+4.5	+11	-70	+56	
Noise Figure (50 Ω, 500 MHz)	7	6	5	6	dB
Input / Output Impedance	50				Ω
Connectors	SMA				
Power Supply Voltage	2 to 15				V
Power Supply Current	130	110	160	220	mA
Dimensions	52 x 38 x 31	52 x 38 x 31	52 x 38 x 31	92 x 38 x31	mm

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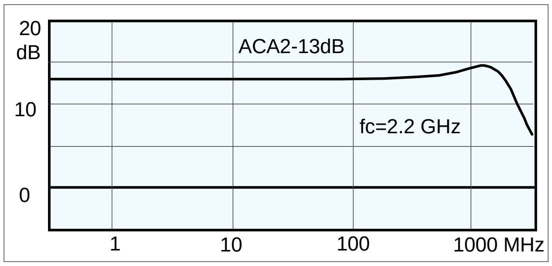
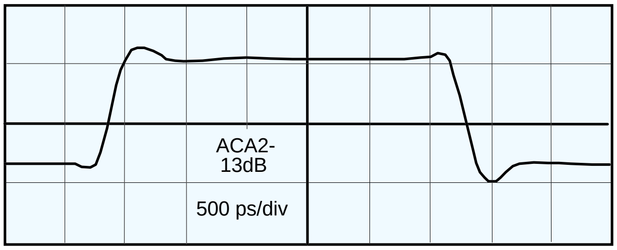
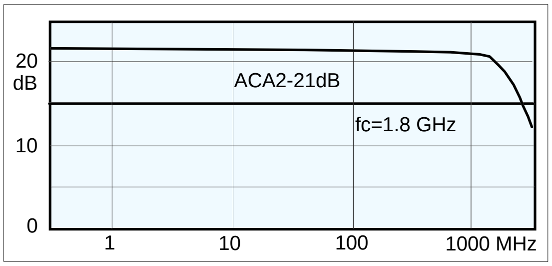
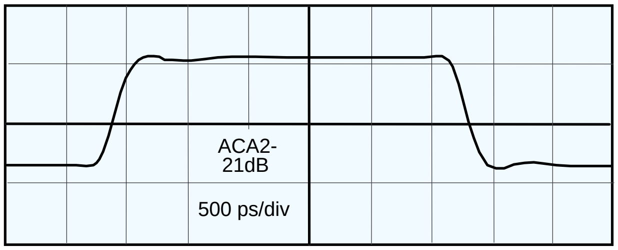
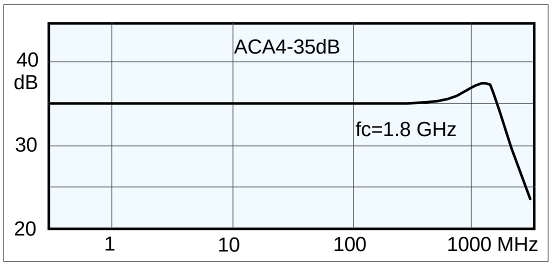
ACA Frequency and Step Response

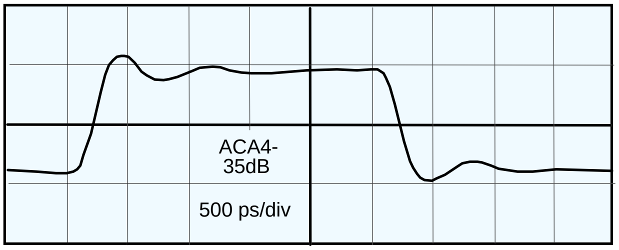


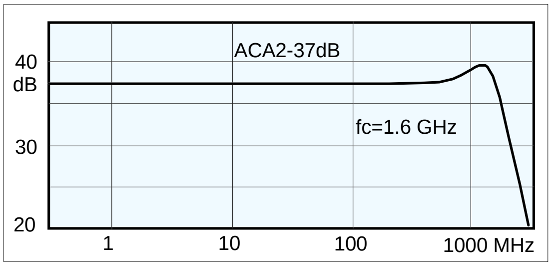


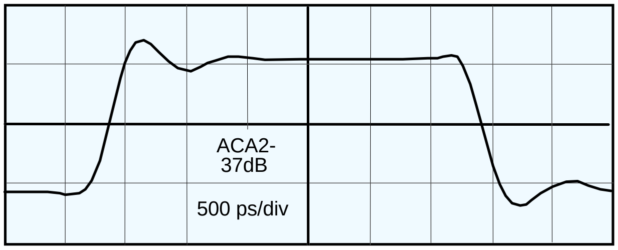












Other amplifier products: HFAC GHz Preamplifiers for PMTs and MCPs, DCA Series Low DC Drift Wideband Amplifiers, HFAM eight Channel GHz Preamplifier for PMTs and MCPs. Please see individual data sheets.

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DCA - XX

Ultra Low Drift Wideband Amplifiers

The DCA series amplifiers use a composite principle to achieve high bandwidth, low drift and high gain stability. They can be used for a wide variety of signal level or signal polarity matching applications and for current-voltage conversion. Due to a flexible design and manufacturing principle the amplifiers can easily be matched to customer specific requirements. Different gain, bandwidth or input and output impedance values are available on request.

	DCA-1-5V	**DCA-2-5V**	**DCA-1-12V**	**DCA-2-12V**
Bandwidth (V_{outpp} < 2V, MHz)	DC to 400	DC to 250	DC to 100	DC to 75
Gain (other values on request)	-1 or -2	+ 4 or +10	-1 or -2	+4 or +10
Input Impedance	50 Ω	50 Ω	50 Ω	50 Ω
Input Offset Voltage	0,5 mV	0,5 mV	0,5 mV	0,5 mV
Offset Drift	10 µV/°C	10 µV/°C	10 µV/°C	10 µV/°C
Input Noise (1kHz...100MHz)	2 nV/Hz$^{1/2}$	2 nV/Hz$^{1/2}$	2 nV/Hz$^{1/2}$	2 nV/Hz$^{1/2}$
Output Impedance	50 Ω	50 Ω	50 Ω	50 Ω
Output Voltage Swing (50 Ω)	± 1,5 V	± 1,5 V	± 4 V	± 4 V
Output Voltage Swing (1 kΩ)	± 3 V	± 3 V	± 10 V	± 10 V
Power Supply	± 5 V	± 5 V	± 12 V	± 12 V
Connectors (other on request)	SMA	SMA	SMA	SMA
Dimensions (mm)	52 x 38 x 31	52 x 38 x 31	52 x 38 x 31	52 x 38 x 31

Power Supply Cable:

red: +5V (+12V)	yellow: -5V (-12V)
white: GND	black (shield): GND

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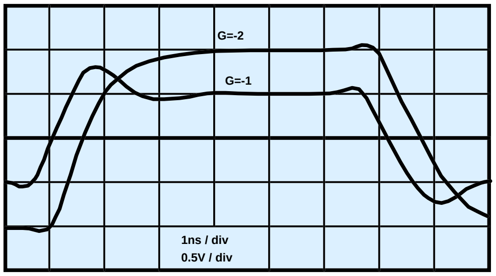
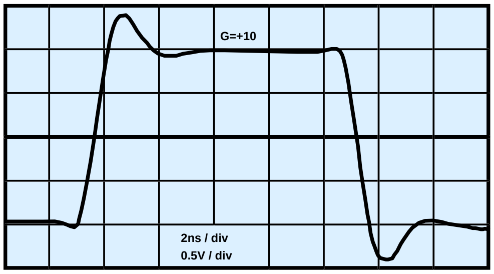
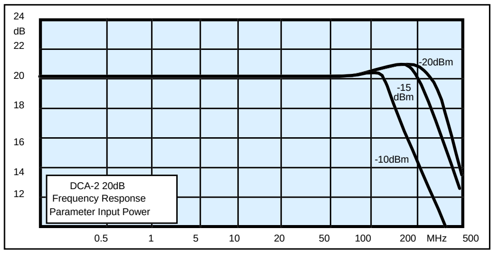
DCA - XX



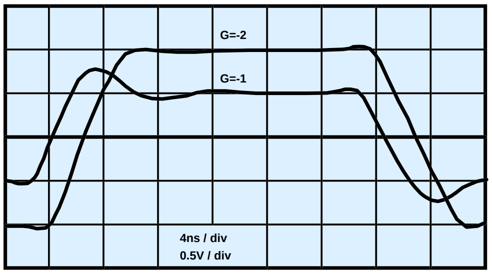
DCA-1-5V
Step Response (Gain = -1 and -2)



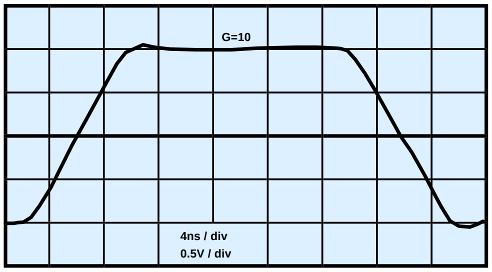
DCA-2-5V
Step Response (Gain = +10)



DCA-2-5V
Gain vs. Frequency at different Input Power



DCA-1-12V
Step Response (Gain = -1 and -2)



DCA-2-12V
Step response (Gain = +10)

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intelligent
measurement
and
control systems

PPA - 100

Precision Preamplifier

Bandwidth (V_{out} < 2V)	DC ... 2 MHz
Gain (Switch Selectable)	100 / 200 / 500 / 1000
Input Impedance (Other Values on Request)	1M Ω / 40 pF
Output Impedance	50 Ω
Input Offset Voltage (unadjusted)	< 0,3 mV
Input Current (25°C)	typ. 2 pA
Offset Voltage Drift	< 2.5 µV/°C
Input Voltage Noise (>1kHz)	5 nV / $Hz^{1/2}$
Input Voltage Noise (100 Hz)	10 nV / $Hz^{1/2}$
Input Current Noise (100 Hz)	4 fA / $Hz^{1/2}$
Output Voltage Swing (Load 1kΩ, Vs ± 12V)	± 10 V
Output Voltage Swing (Load 50 Ω, Vs ± 12V)	± 2 V
Supply Voltages	± 5 V to ±15 V
Input and Output Connectors	SMA
Dimensions	52 x 38 x 31 mm

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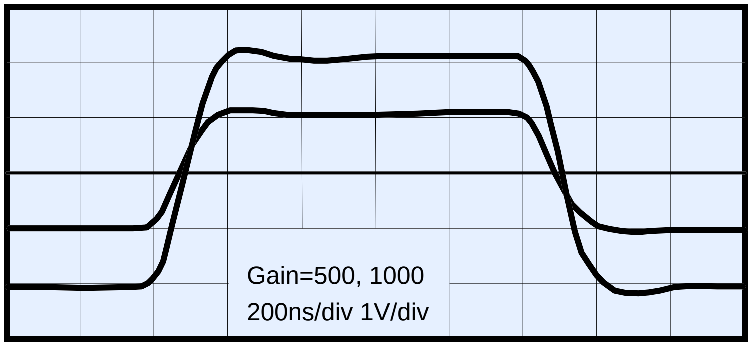
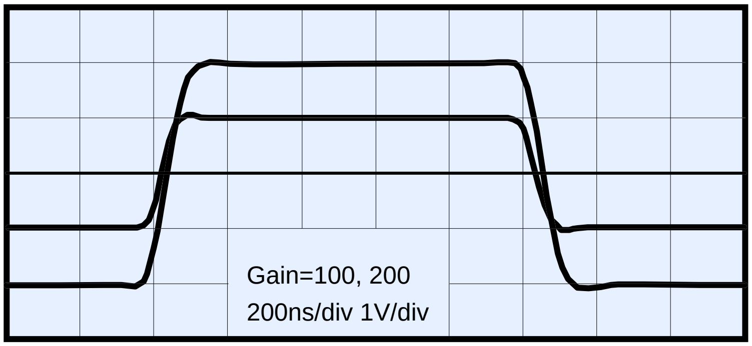
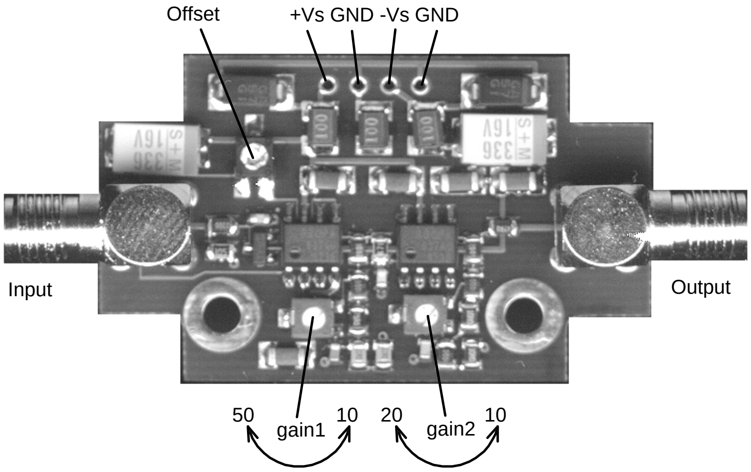
PPA - 100

PPA-100
Step Response
Vs = ± 12V
Vout < ± 5V





PPA-100
Gain Setting Switches
and Offset Adjust



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	SPC-630	**SPC-730**	**SPC-830**	**SPC-134**	**Time Harp 200**
Available multi-detector extension devices for	4 MCPs, 4 PMTs 8 MCPs, 8 PMTs 8 APDs 16 channel pmt head	4 MCPs, 4 PMTs 8 MCPs, 8 PMTs 8 APDs 16 channel pmt head	4 MCPs, 4 PMTs 8 MCPs, 8 PMTs 8 APDs 16 channel pmt head	4 MCPs, 4 PMTs 8 MCPs, 8 PMTs 8 APDs	4 APDs
Operating Modes	Single Oscilloscope 2 dimensional f(xyt) Sequence f(t,T), fi(t,ext) Spectrum fi(T), fi(ext) Continuous Flow (unlimited seq.) Time Tag (FIFO)	Single Oscilloscope 2 dimensional f(xyt) Sequence f(t,T), fi(t,ext) Spectrum fi(T), fi(ext) Imaging (Sync In, Sync Out, XY in, XY out)	Single Oscilloscope 2 dimensional f(xyt) Sequence f(t,T), fi(t,ext) Spectrum fi(T), fi(ext) Imaging (Sync In, Sync Out, XY in) Time Tag (FIFO)	Single Oscilloscope 2 dimensional f(xyt) Sequence f(t,T), fi(t,ext) Spectrum fi(T), fi(ext) Continuous Flow (unlimited seq.) Time Tag (FIFO)	Integration Oscilloscope Sequence f(t,T) Contiuous Time-tag (Option)
Experiment Trigger	Start of measurement Start of sequence Each step of sequence	Start of measurement Start of sequence Each step of sequence Frame Clock, Line Clock, Pxl Clock	Start of measurement Start of sequence Each step of sequence Frame Clock, Line Clock, Pxl Clock	Start of measurement Start of sequence Each step of sequence	Start of measurement Start of sequence
Triggered accumulation of sequences	yes	yes		yes	yes
Detector / Experiment control (Own products only)	Preamplifiers with detector overload protection, PMH-100 Detector modules, PML-16 multichannel detector head, DCC-100 Detector Controller , STP-340 Step Motor Controller, Routers for MCPs, PMTs, APDs, Dual ADC module for XY In operation	Preamplifiers with detector overload protection, PMH-100 Detector modules, PML-16 multichannel detector head, DCC-100 Detector Controller , STP-340 Step Motor Controller, Routers for MCPs, PMTs, APDs, Dual ADC module for XY In operation, Adapters for Zeiss, Leica, Olympus and Biorad laser scanning microscopes	Preamplifiers with detector overload protection, PMH-100 Detector modules, PML-16 multichannel detector head, DCC-100 Detector Controller , STP-340 Step Motor Controller, Routers for MCPs, PMTs, APDs, Dual ADC module for XY In operation, Adapters for Zeiss, Leica, Olympus and Biorad laser scanning microscopes	Preamplifiers with detector overload protection, PMH-100 Detector modules, PML-16 multichannel detector head, DCC-100 Detector Controller , STP-340 Step Motor Controller, Routers for MCPs, PMTs, APDs	Preamplifiers with detector overload protection, Routers for APDs
Free Documentaion available on web site	SPC Manual, 165 pages; TCSPC Introduction, 5 pages; Upgrading laser scanning microscopes for lifetime imaging; Controlling SPC modules; Protecting Photomultipliers; FRET measurements by TCSPC lifetime microscopy; Multi-wavelengthe TCSPC lifetime imaging; High count rate multichannel TCSPC for optical tomography; Optical Tomography: TCSPC Imaging of Female Breast; Setting up High Gain Detector Electronics for TCSPC Applications; Testing SPC Modules; 16 Channel Detector Head for TCSPC Modules; Routing Modules for Time-Correlated Single Photon Counting; Detector Control Module DCC100 Manual; **TCSPC Software is available and FREE**; Manual: Multi - SPC 32 bit Dynamic Link Library				Measurement examples
Related Products (Own products only)	SPC-300, SPC-330 TCSPC; SPC-400, SPC-430 TCSPC; SPC-500, SPC-530 TCSPC; MSA-100 1ns multiscaler; MSA-300 5ns multisclaer; PMS-400 and PMM-328 Gated photon counters / multiscalers; Picosecond Diode Lasers				Time Harp 100 Picosecond Diode Lasers

Boston Electronics Corporation, 91 Boylston St, Brookline MA 02445 USA * (800)3477-5445 or (617)566-3821 * fax (617731-0935 * tcspc@boselec.com

	SPC-630	**SPC-730**	**SPC-830**	**SPC-134**	**Time Harp 200**
Target Application	Standard lifetime experiments Single Molecule Detection Stopped Flow Correlation Experiments FCS Experiments	Standard lifetime experiments, Lifetime imaging, Confocal and two-photon scanning Microscopy Multi parameter experiments Stopped Flow	Standard lifetime experiments, Lifetime imaging, Confocal and two-photon scanning Microscopy Multi parameter experiments Stopped Flow Single Molecule Detection Correlation Experiments FCS Experiments	Optical tomography Single Molecule Stopped Flow Correlation Experiments FCS Experiments	Standard lifetime Single Molecule Microscope with scan stage Correlation Experiments FCS Experiments
No. of TCSPC Channels	1	1	1	4	1
Modules operable in parallel	4 x SPC-630	4 x SPC-730	4 x SPC-830	1 x SPC-134	
Conversion Principle	TAC - ADC with error reduction Patent DE 43 39 784 A1	TAC - ADC with error reduction Patent DE 43 39 784 A1	TAC - ADC with error reduction Patent DE 43 39 784 A1	TAC - ADC with error reduction Patent DE 43 39 784 A1	Time-to-Digital Converter
Detector Channel Sync Channel	Constant Fraction Constant Fraction	Constant Fraction Constant Fraction	Constant Fraction Constant Fraction	Constant Fraction Constant Fraction	Constant Fraction Level Trigger
Time Resolution	820 fs per time channel	820 fs per time channel	820 fs per time channel	820 fs per time channel	40 ps per time channel
Diff. nonlinearity	0.6% to 1% pp, <0.5% rms	0.6% to 1% pp, <0.5% rms	0.6% to 1% pp, <0.5% rms	0.6% to 1% pp, <0.5% rms	<6%pp, <0.5% rms
Detectable Lifetimes	2 ps to 2µs	2 ps to 2µs	2 ps to 2µs	2 ps to 2µs	<100ps to 4.5µs
Histogramming Process	Hardware, on board histogram memory	Hardware, 4-dimensional, on board histogram memory	Hardware, 4-dimensional, on board histogram memory	Hardware, on board histogram memory	Hardware, on board histogram memory
Image size for fast scan modes		max. 256 x 256 pixels	max 4096 x 4096 pixels		
Dead Time	125 ns	180 ns	125 ns	125 ns	<350 ns
Useful continuous count rate, Histogram Modes, 50% loss, per module	4 MHz	2.8 MHz	4 MHz	16 MHz (overall for 4 channels)	1.4 MHz
Peak Count Rate, histogram modes, 50% loss, per moduel	4 MHZ	2.8 MHz	4 MHz	16 MHz (overall for 4 channels)	1.4 MHz
Continuous count rate, time-tag modes	0.4...0.8 MHz, depends on computer speed and background activity		3...4 MHz, depends on computer speed and background activity	0.4...0.8 MHz, depends on computer speed and background activity	Depends on computer speed and background activity
Peak count rate, time-tag modes, 50% loss	4 MHz independent of computer speed		4 MHz independent of computer speed	16 MHz independent of computer speed	Depends on computer speed and background activity
on-board FIFO buffer size, time tag modes	128,000 photons or 256,000 photons		8 Million photons	512,000 photons	128,000 photons
Macro time resolution in time tag (FIFO) modes	50 ns		50 ns from internal clock or 12ns to 100 ns from sync (laser)	50 ns from internal clock or 12ns to 100 ns from sync (laser)	100ns
Scan rate, Scan syn in mode		down to 100ns per pixel independent of computer speed	down to 100ns per pixel independent of computer speed		
Multi-Detector Operation	yes Patent DE 43 39 787 A1	yes Patent DE 43 39 787 A1	yes Patent DE 43 39 787 A1	yes Patent DE 43 39 787 A1	yes
No of curves in memory	2 x 64 to 4096	1024 to 65,536	4096 to 2,000,0000	2 x 32 to 2 x 2048 per TCSPC channel	2 x 32
Min. time per histogram	1µs in continuous flow mode	100ns in scan sync in/out mode	100ns in scan sync in/out mode	1µs in continuous flow mode	1µs in ext sync mode