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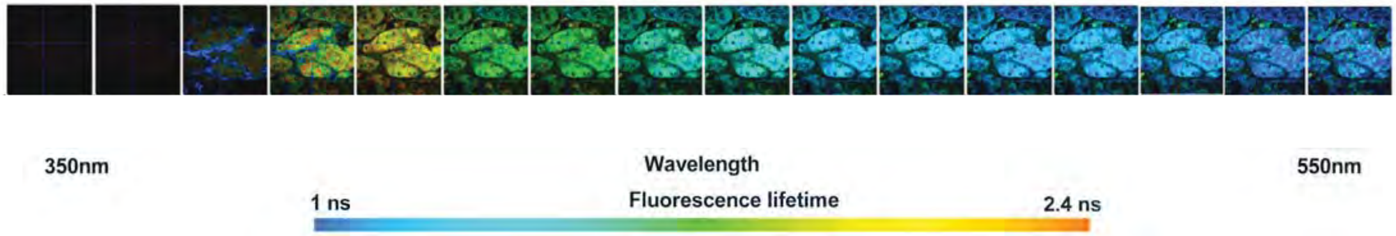
Single Photon Counting Detectors for TCSPC

From
Becker & Hickl



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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.

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

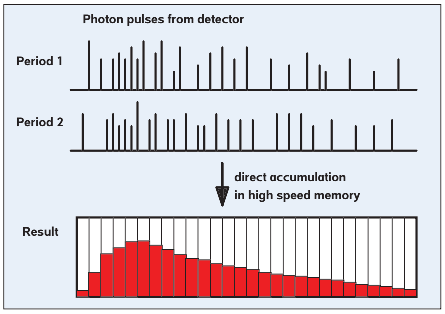


Fig. 1: Multichannel Scaler

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.

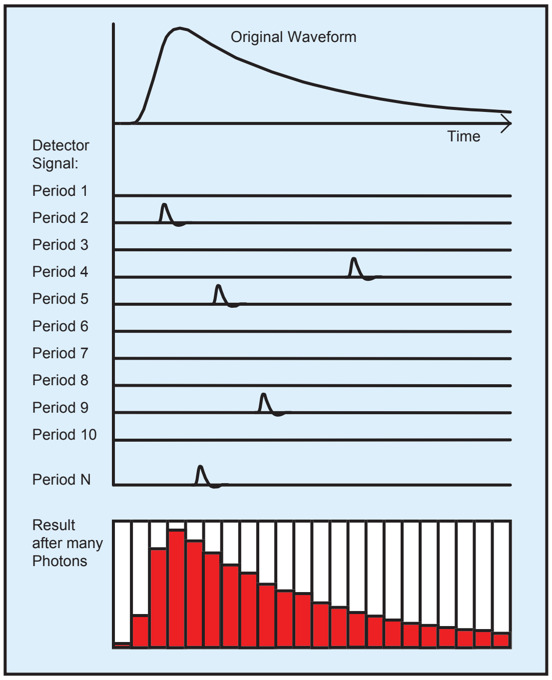


Fig. 2: Principle of the TCSPC technique

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:

- 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).

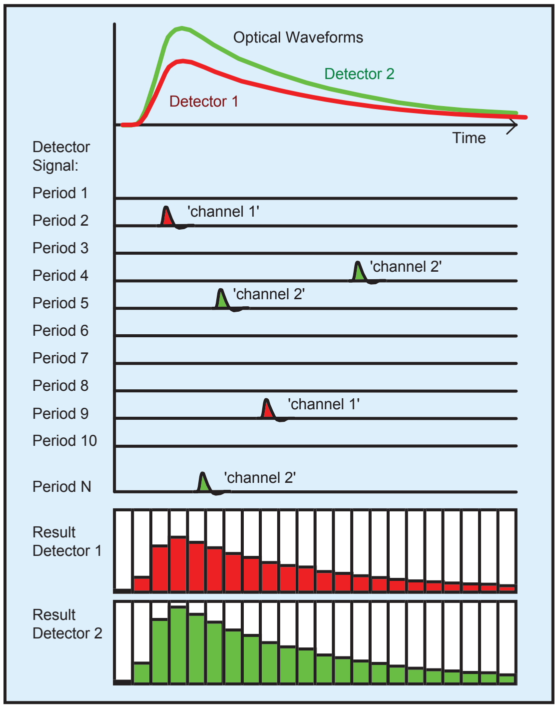


Fig. 3: Multi-detector TCSPC

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

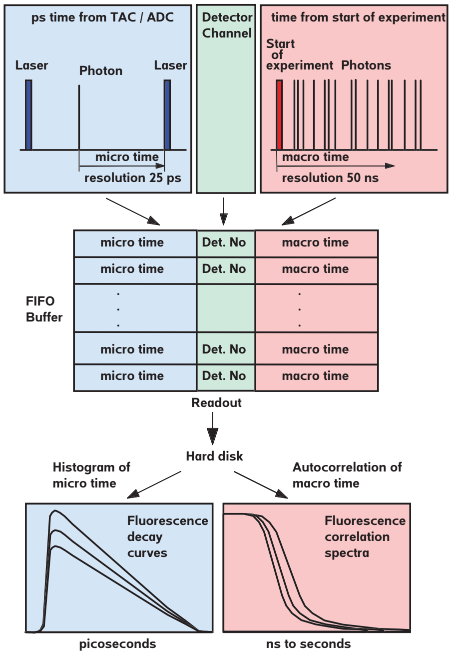


Fig. 4: Simultaneous FCS / lifetime data acquisition

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].

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].

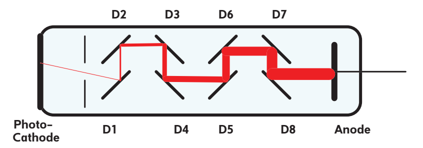


Fig 5 Conventional PMT

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.

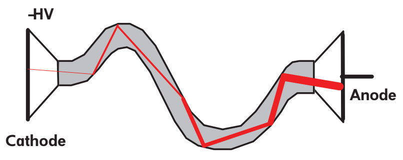


Fig. 6 Channel PMT

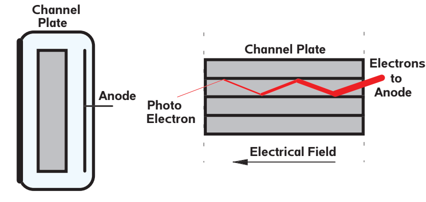


Fig. 7 Microchannel PMT

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].

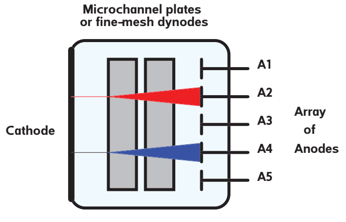


Fig. 8 Multianode PMT

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).

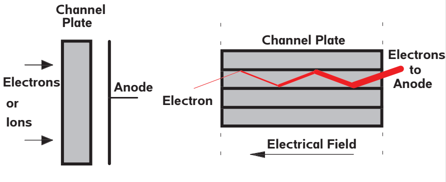


Fig 9 Electron Multiplier with MCP

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.

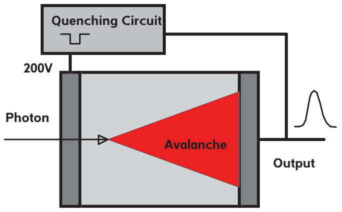


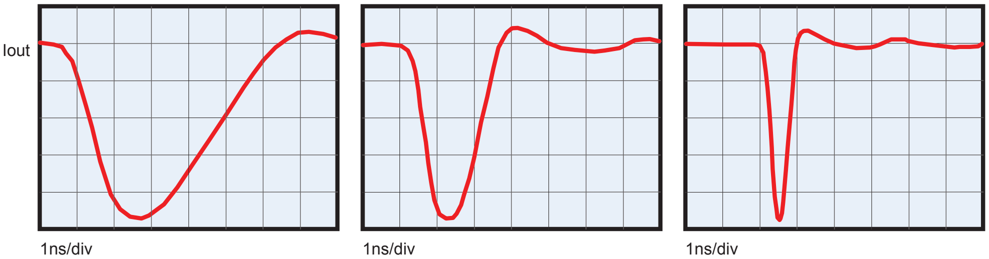
Fig 10: Single Photon Avalanche Photodiode (SPAD)

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

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.

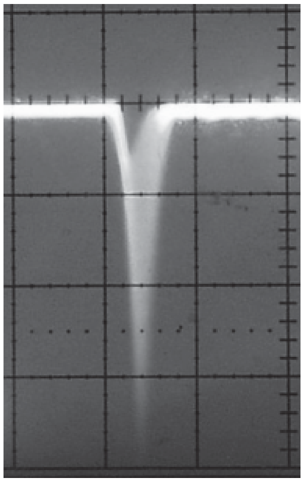


Fig. 12: Amplitude jitter of SER pulses

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, $e=1.6 \cdot 10^{-19}$ 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.

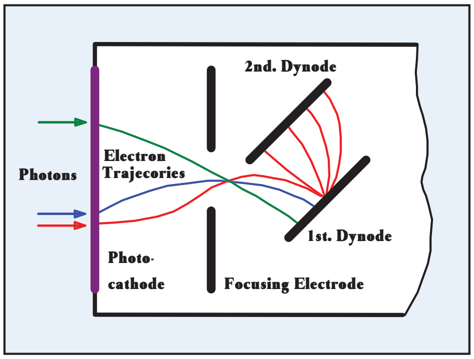


Fig. 13: Different electron trajectories cause different transit times in a PMT

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.

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

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

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.

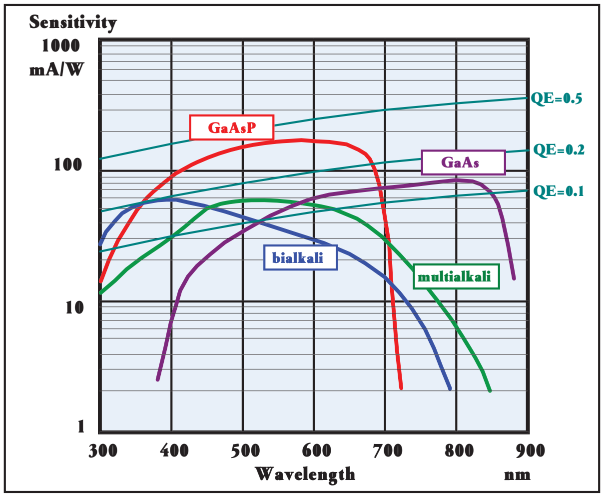


Fig. 14: Sensitivity of different photocathodes [1]

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.

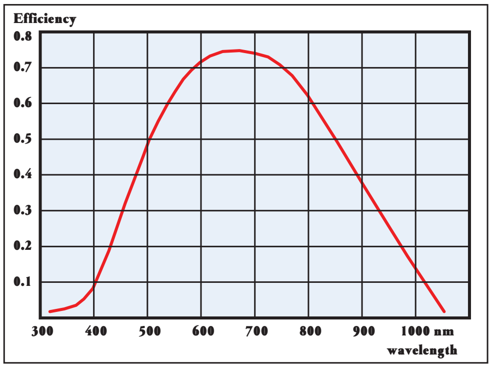


Fig. 15: Quantum efficiency vs. wavelength for SPAD. Perkin-Elmer SPCM-AQR module [24]

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.

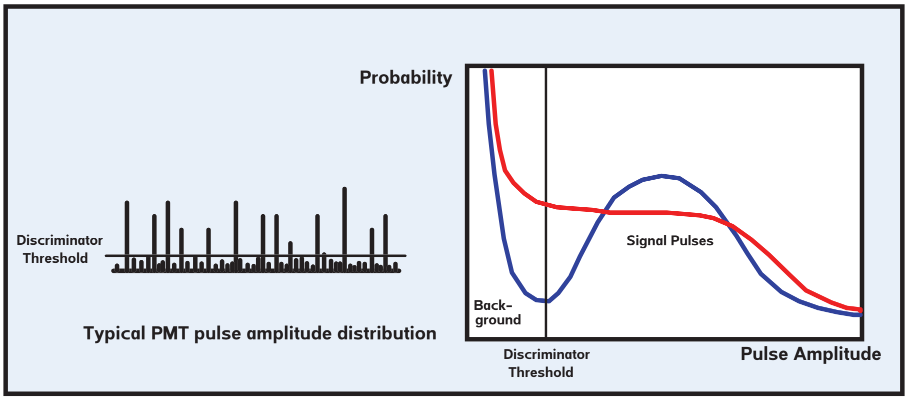


Fig 16: Pulse height distribution of a PMT and discriminator threshold for optimum counting performance

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

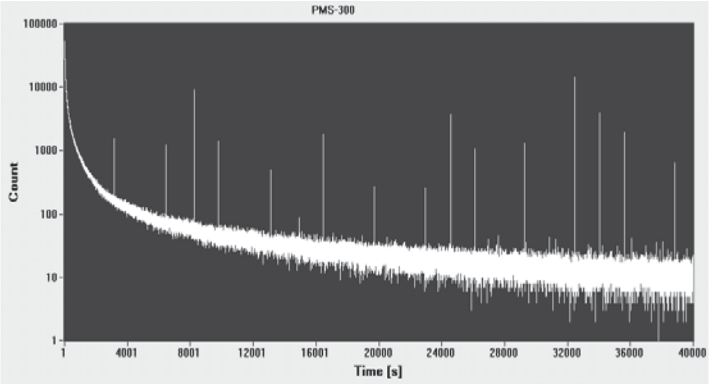


Fig.17: Decrease of dark count rate (counts per second) of a H5773P-01 after exposing the cathode to room light. The device was cooled to 5°C. The peaks are caused by scintillation effects.

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.

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.

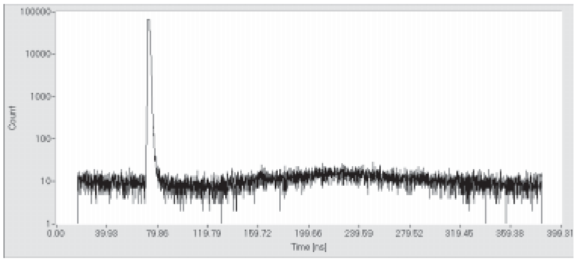


Fig. 18: Afterpulsing in an R5600 PMT tube. TCSPC measurement with Becker & Hickl SPC-630. The peak is the laser pulse, afterpulses cause a bump 200 ns later

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.

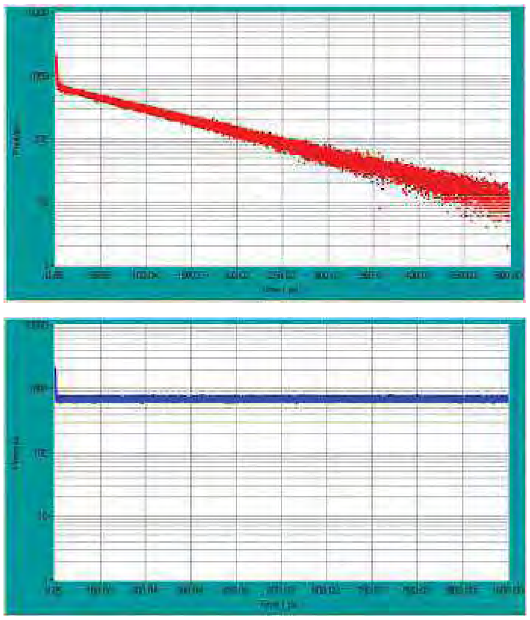


Fig. 19: Histogram of times between photons (top) and correlation spectrum (bottom) for classic light. The peak at short times is due to afterpulsing.

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.

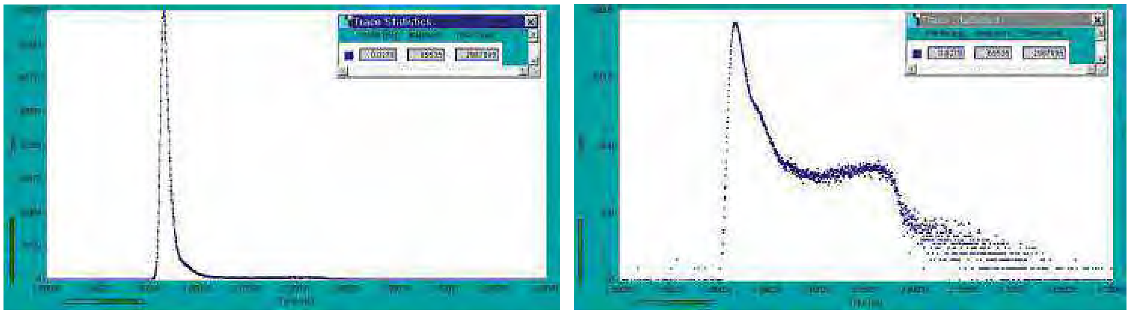


Fig. 20: R38909U, TCSPC instrument response. Operating voltage-3kV, preamplifier gain 20dB, discriminator threshold - 80mV

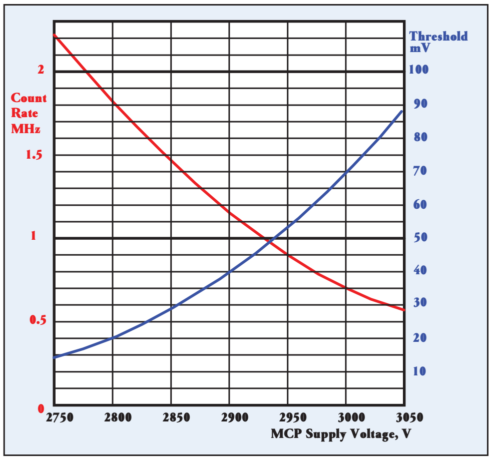


Fig. 21: R3809U, count rate for 100 nA anode current and optimum discriminator threshold vs. supply voltage. HFAC-26-01 (20dB) preamplifier

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:

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.

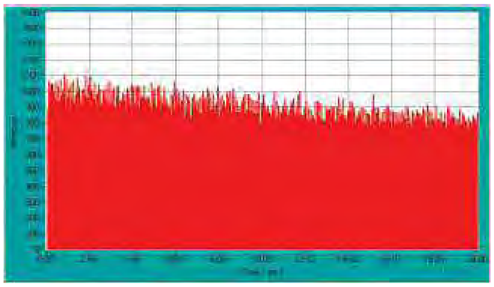


Fig. 22: R3809U, histogram of times between photons. No afterpulses are detected.

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.

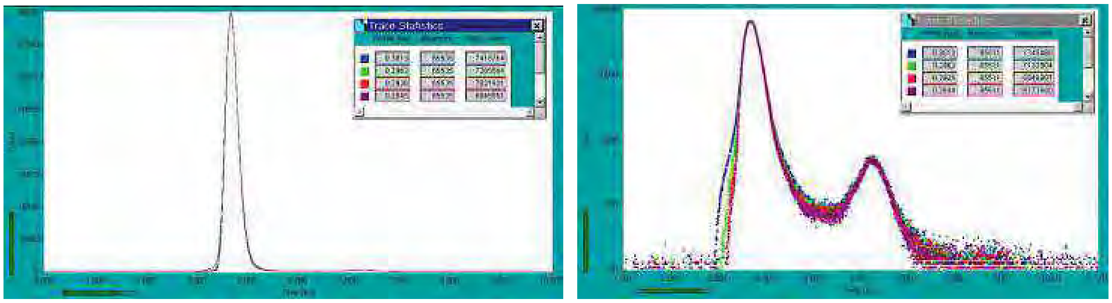


Fig. 23: H7422-40, TCSPC Instrument response function. Gain control voltage 0.9V (maximum gain), preamplifier 20dB, discriminator threshold -200mV, -300mV, -400mV and -500mV

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.

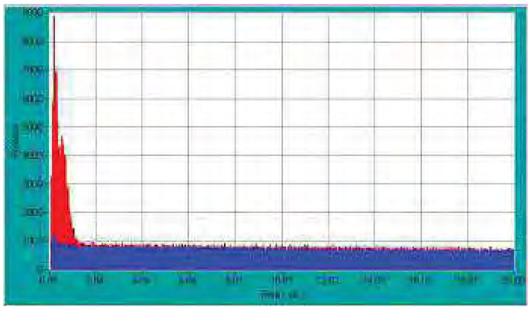


Fig. 24: H7422-40, histogram of times between photons. Gain control voltage 0.9V (red) and 0.63V (blue). Afterpulse probability increases with gain.

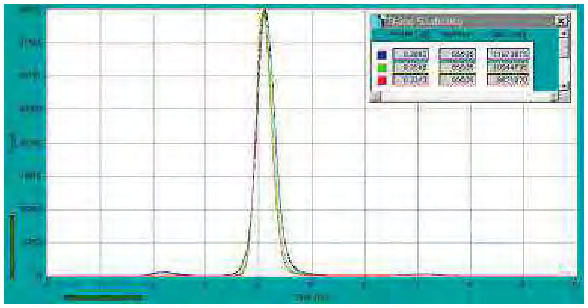


Fig. 25, H7422-40, TCSPC Instrument response function. Gain control voltage 0.63V, preamplifier 20dB, discriminator threshold -30mV, -50mV, -70mV

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.

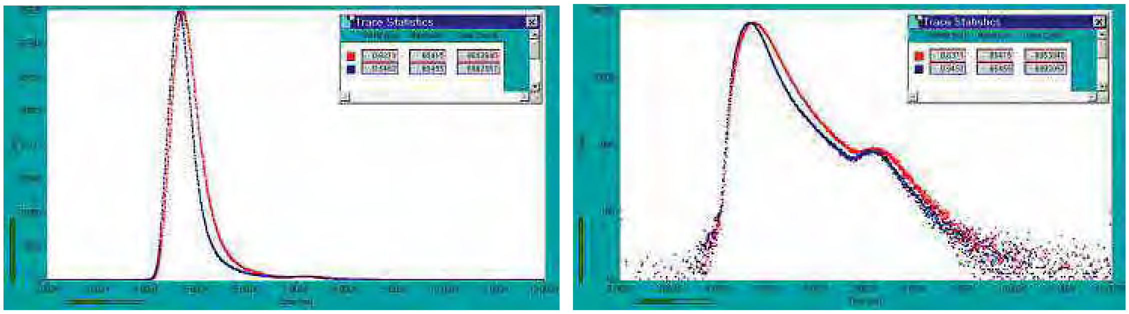


Fig. 26: H7422-50, TCSPC response function for a count rate of 30 kHz (blue) and 600 kHz (red)

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.

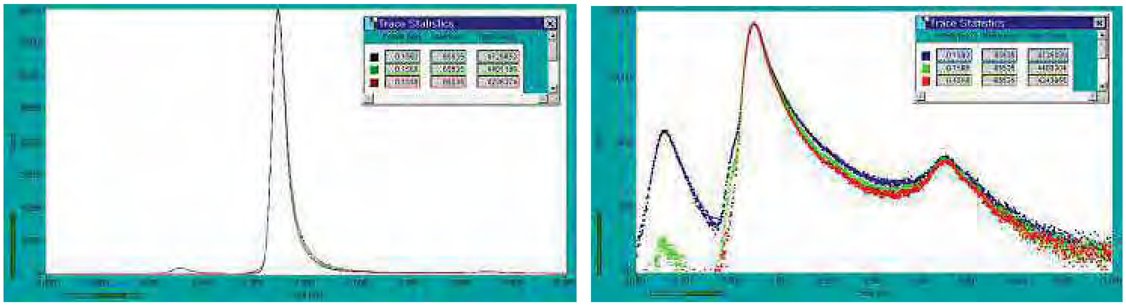


Fig: 27: H5773P-0, TCSPC instrument response. Maximum gain, preamplifier gain 20dB, discriminator threshold -100mV, -300mV and -500mV

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.

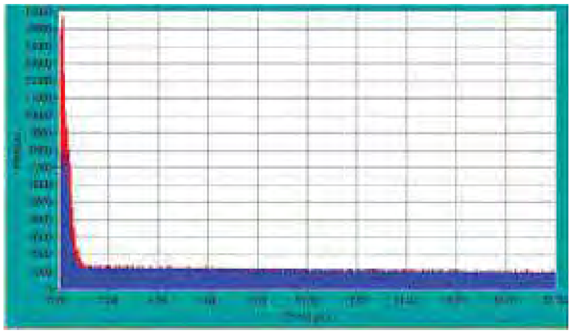


Fig. 28: Histogram of times between photons for H5773P-0 (blue) and H5773P-1 (red). The afterpulse probability is higher for the -1 version

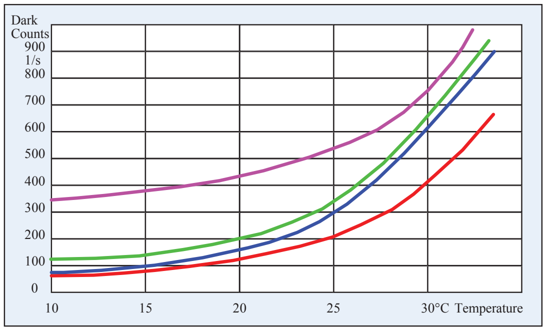


Fig. 29: Dark count rate for different H5773P-01 modules

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.

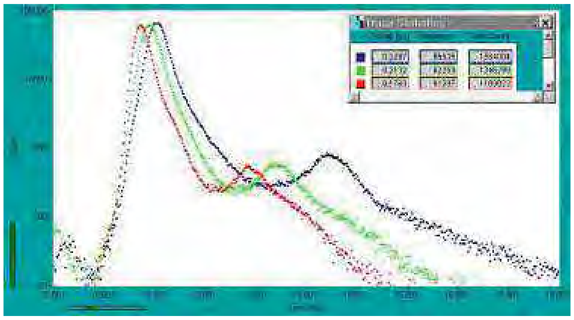


Fig. 30: R5900P-1, -1kV supply voltage: TCSPC response for different voltage between cathode and first dynode. Blue, green and red: 1, 2 and 3 times nominal voltage

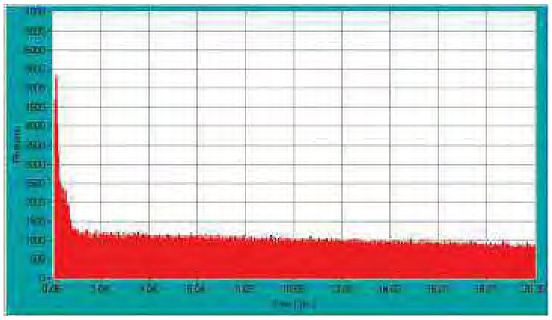


Fig. 31: H5773P-1, -1kV : Histogram of times between photons.

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.

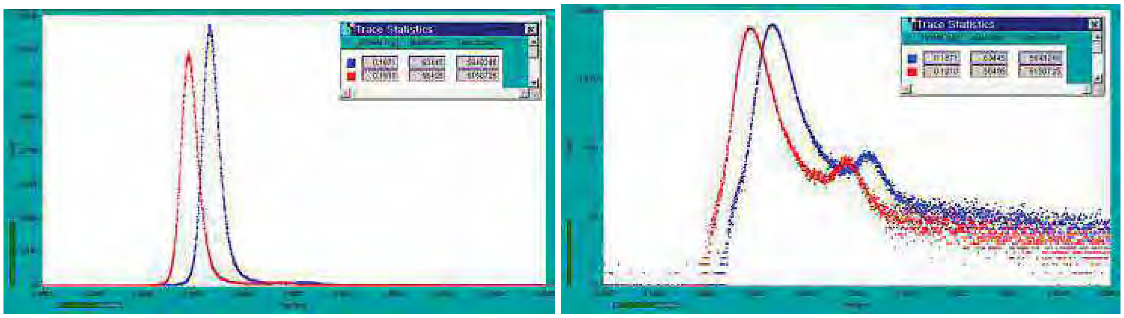


Fig. 32: System response of two selected channels of the PML-16 detector head

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.

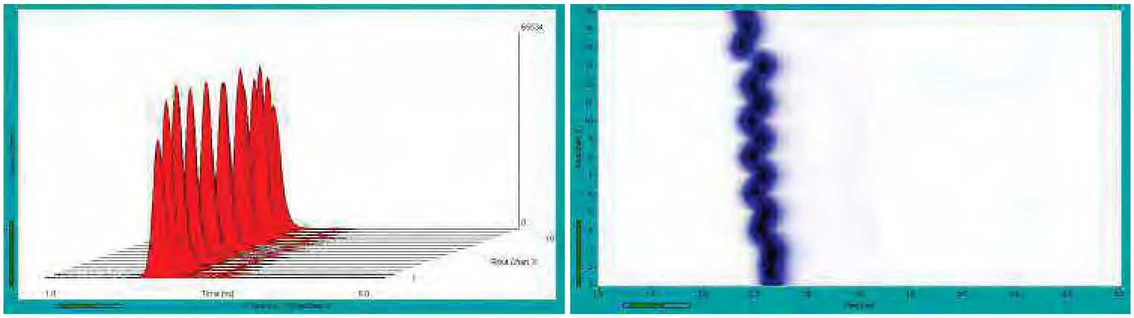


Fig. 33: System response of the PML-16 / R5900-L16 channels. Left curve plot, right colour-intensity plot

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.

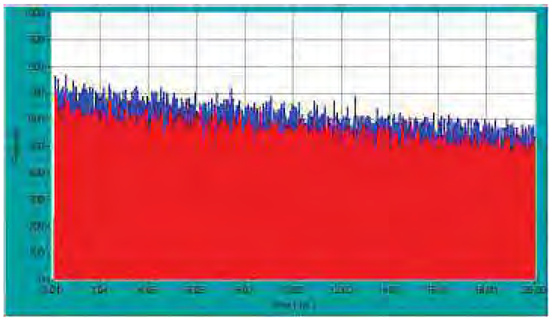


Fig. 34: R5900-L16, histogram of times between photons. No afterpulsing was found.

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.

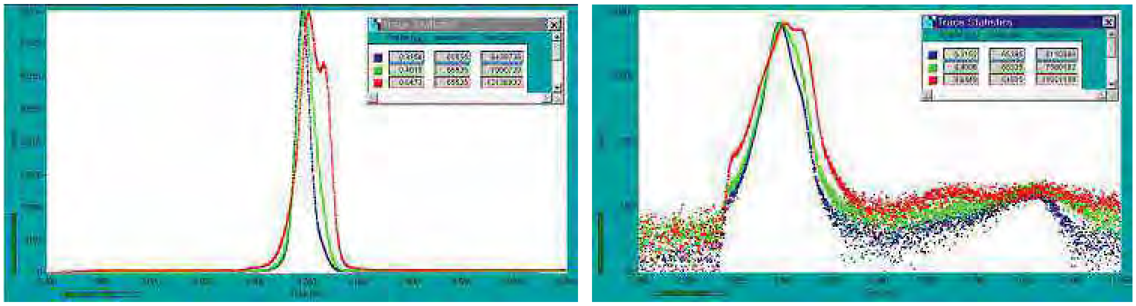


Fig. 35: R931, TCSPC system response for different spots on the photocathode. Spot diameter 3mm

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.

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.

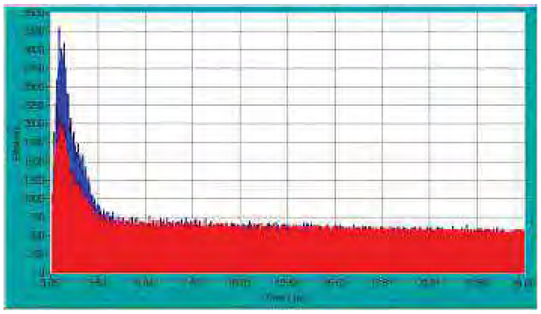


Fig. 36: R931, histogram of times between photons. Red -900V, blue -1000V. The afterpulse probability increases with voltage

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.

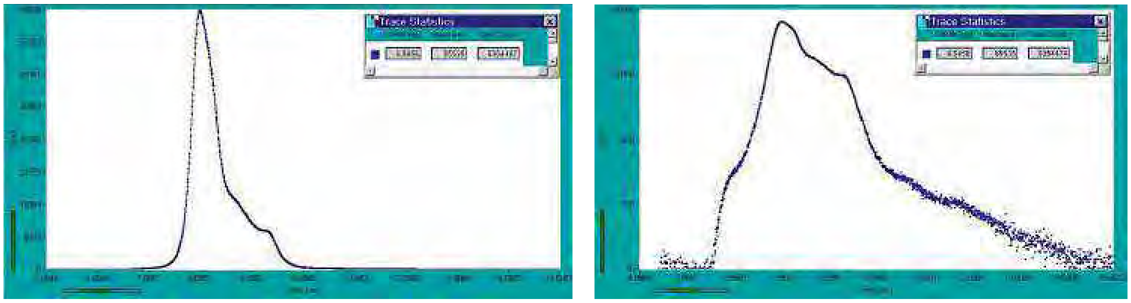


Fig. 37: R6350, TCSPC system response for illumination of full cathode area

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.

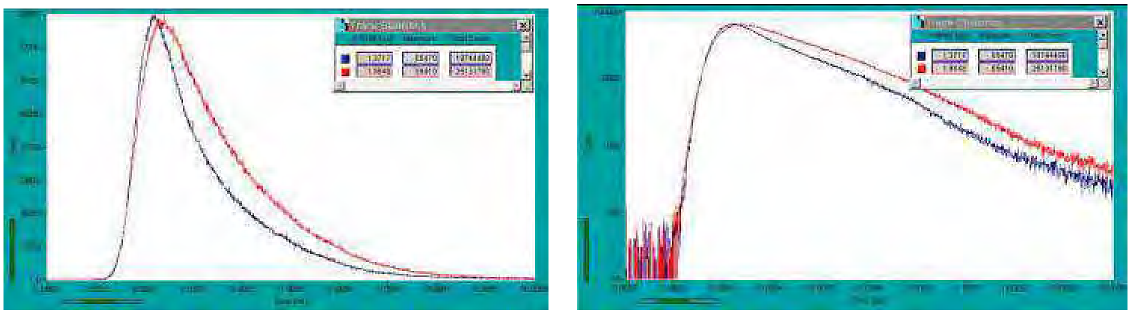


Fig. 38: CP 944 channel photomultiplier, TCSPC response. 650 nm, count rate 1.5.105, high voltage -2.8 kV (red) and -2.9 kV (blue). Full cathode illuminated

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.

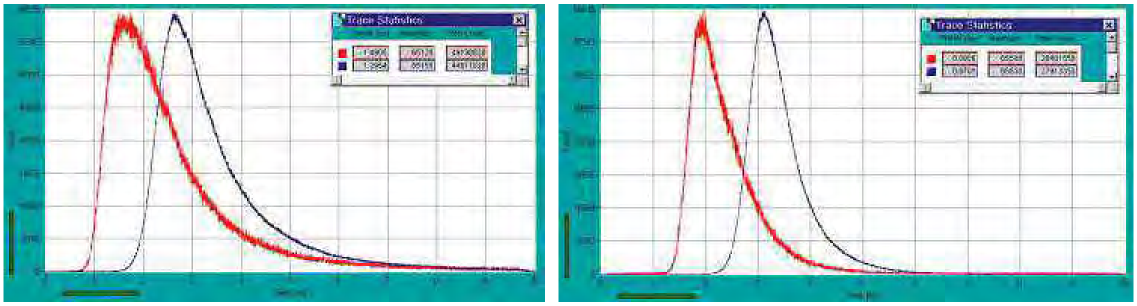


Fig. 39: SPCM-AQR-12, TCSPC response. Left: 405nm, red 50 kHz, blue 500 kHz count rate. Right: 650 nm, red 50 kHz, blue 500 kHz count rate

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.

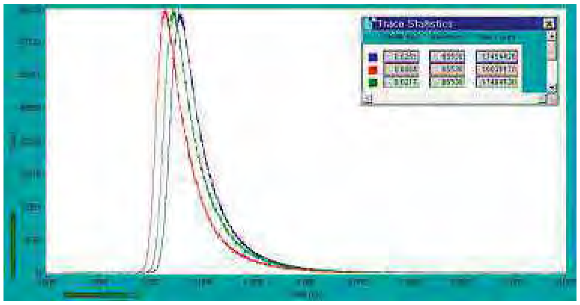


Fig. 40: SPCM-AQR-14, 650 nm, count rates 8 10^4 (green), 5 10^5 (red) and 1 10^6 (blue)

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.

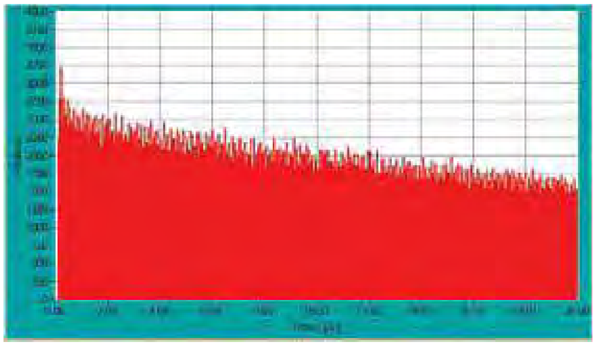


Fig. 419: SPCM-AQR-12, histogram of times between photons

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.

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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HPM-100-06

Ultra-High Speed Hybrid Detector for TCSPC

Instrument response function <35 ps FWHM

Clean response, no tails or secondary peaks

No afterpulsing background

Excellent dynamic range of TCSPC measurements

Internal generators for PMT operating voltages

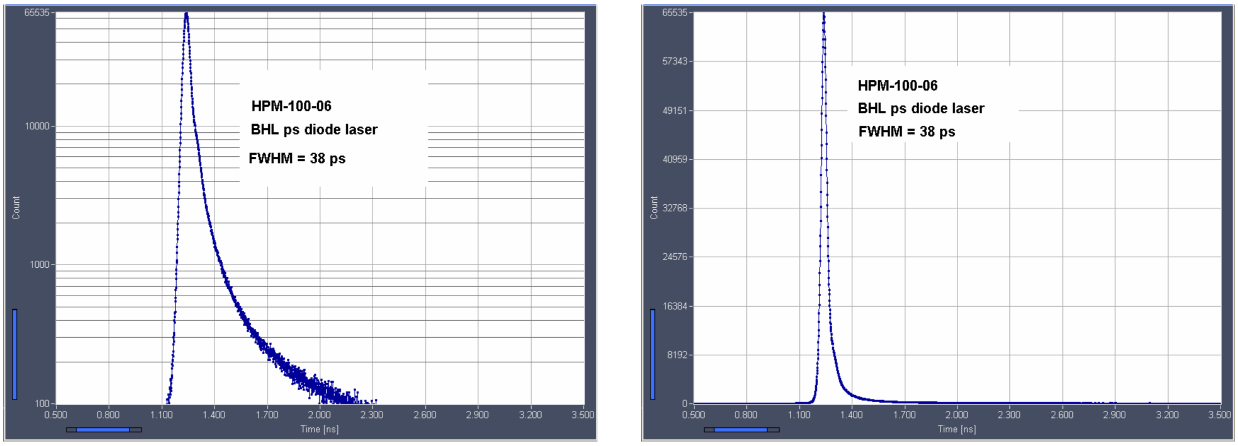
Power supply and control via bh DCC-100 card

Overload shutdown

Direct interfacing to all bh TCSPC systems

The HPM-100-06 module combines a Hamamatsu R10467-06 hybrid detector tube with a preamplifier and the generators for the tube operating voltages in one compact housing. The principle of the hybrid detector yields excellent timing resolution, a clean TCSPC instrument response function, high detection quantum efficiency, and extremely low afterpulsing probability. The absence of afterpulsing results in a substantially increased dynamic range of TCSPC measurements.

The HPM-100-06 module is operated via the bh DCC-100 detector controller of the bh TCSPC systems. The DCC-100 provides for power supply, gain control, and overload shutdown. The HPM-100 interfaces directly to all bh SPC or Simple Tau TCSPC systems. It is available with standard C-mount adapters, adapters for the bh DCS-120 confocal scanning FLIM system, and adapters for the NDD ports of the Zeiss LSM 710 NLO multiphoton laser scanning microscopes.

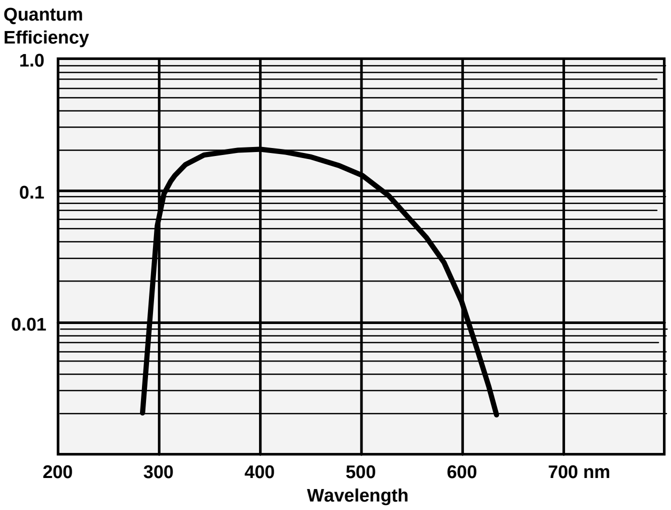


Instrument response function. Left linear scale, right logarithmic scale. Light pulse from BHL-150 picosecond diode laser recorded with SPC-150 TCSPC module. FWHM of recorded pulse shape is 38 ps. With a pulse width of the laser of 25 ps the estimated IRF width is 29 ps.

Technology Leader in TCSPC

HPM-100-06

Detection quantum efficiency vs. wavelength



Specifications, typical values

Wavelength Range	300 nm to 600 nm
Detection Quantum efficiency, at 400 nm	20 %
Dark Count rate, Tcase = 22°C, 3mm version	100 to 400 s^{-1}
Cathode Diameter	3 mm or 5 mm
TCSPC IRF width (Transit Time Spread)	<40 ps, FWHM
Single Electron Response Width	850 ps, FWHM
Single Electron Response Amplitude	50 to 80 mV, V_{apd} 95% of V_{max}
Output Polarity	negative
Output Impedance	50 Ω
Max. Count Rate (Continuous)	> 10 MHz
Overload shutdown at	>15 MHz
Detector Signal Output Connector	SMA
Power Supply (from DCC-100 Card)	+ 12 V, +5 V, -12V
Dimensions (width x height x depth)	60 mm x 90 mm x 170 mm
Optical Adapters	C-Mount, DCS-120, LSM 710 NDD port

Related products: HPM-100-40 GaAsP and HPM-100-50 GaAs hybrid detector modules
Literature: The bh TCSPC Handbook, 5th edition, Becker & Hickl GmbH, 2013

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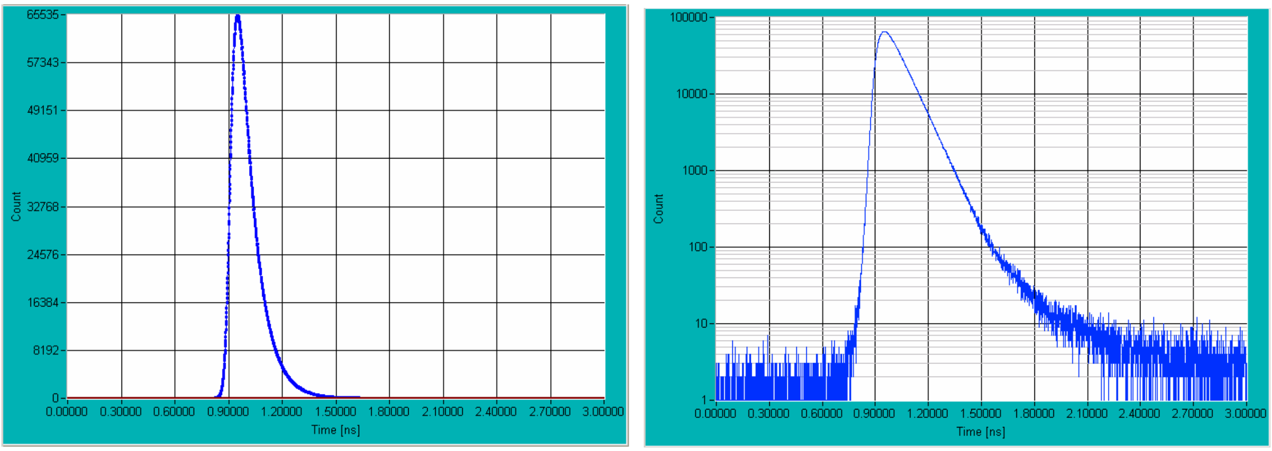
HPM-100-40

High Speed Hybrid Detector for TCSPC

GaAsP cathode: Excellent detection efficiency
Instrument response function 120 ps FWHM
Clean response, no tails or secondary peaks
No afterpulsing
Excellent dynamic range of fluorescence decay measurement
No afterpulsing peak in FCS measurements
Internal generators for PMT operating voltages
Power supply and control via bh DCC-100 card
Overload shutdown
Direct interfacing to all bh TCSPC systems
Adapters to bh DCS-120 FLIM system and Zeiss LSM 710 NLO NDD port

The HPM-100 module combines a Hamamatsu R10467-40 GaAsP hybrid PMT tube with the preamplifier and the generators for the PMT operating voltages in one compact housing. The principle of the hybrid PMT in combination with the GaAsP cathode yields excellent timing resolution, a clean TCSPC instrument response function, high detection quantum efficiency, and extremely low afterpulsing probability. The virtual absence of afterpulsing results in a substantially increased dynamic range for fluorescence decay recordings. Moreover, FCS curves obtained with the HPM-100 are free of the typical afterpulsing peak. FCS is thus obtained from a single detector, without the need of cross-correlation. The HPM-100 module is operated via the bh DCC-100 detector controller of the bh TCSPC systems. The DCC-100 provides for power supply, gain control, and overload shutdown. The HPM-100 interfaces directly to all bh SPC or Simple Tau TCSPC systems. It is available with standard C-mount adapters, adapters for the bh DCS-120 confocal scanning FLIM system, and adapters for the NDD ports of the Zeiss LSM 710 NLO multiphoton laser scanning microscopes.



Instrument response function. Left linear scale, right logarithmic scale. FWHM is 120 ps.

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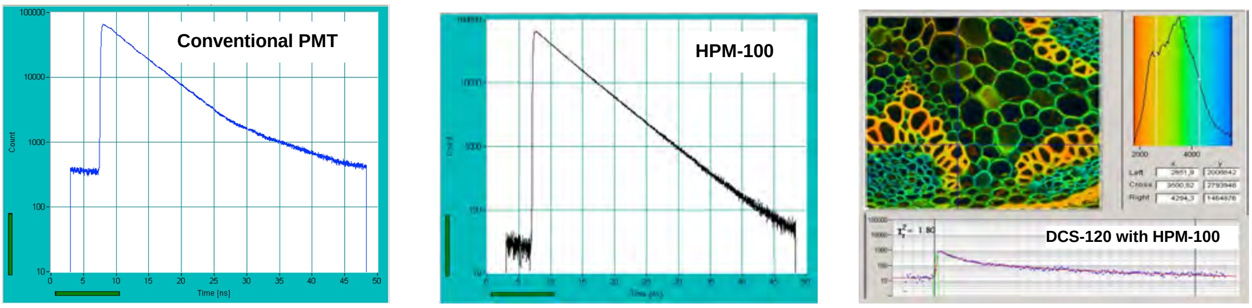
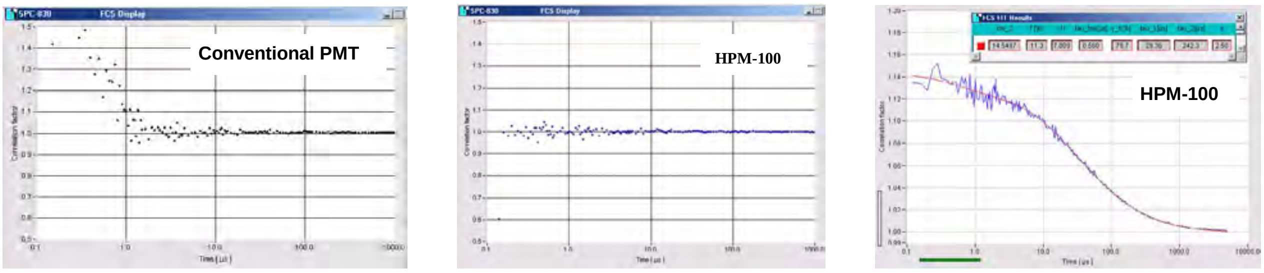
HPM-100-40

Absence of afterpulsing improves dynamic range of fluorescence decay measurements



Left: Fluorescence decay recorded with conventional PMT. The background is dominated by afterpulsing. Middle: The only source of background in the HPM is thermal emission of the photocathode. The dynamic range is substantially increased. Right: The lower background yields improved lifetime accuracy and lifetime contrast in FLIM measurements.

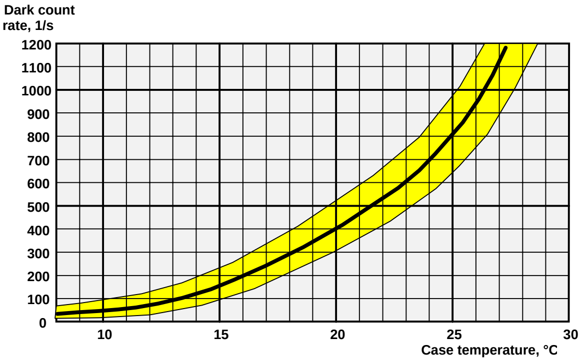
Fluorescence correlation measurements are free of afterpulsing peak



Left: Autocorrelation of continuous light signal of 10 kHz count rate, conventional GaAsP PMT. Middle: Autocorrelation of continuous light signal of 10 kHz count rate, HPM-100 module. The curve is flat down to the dead time of the TCSPC module. Right: FCS curve of fluorescein solution, HPM-100 module. The red curve is a fit with one triplet time and one diffusion time. bh DCS-120 confocal FLIM system, laser 473 nm.

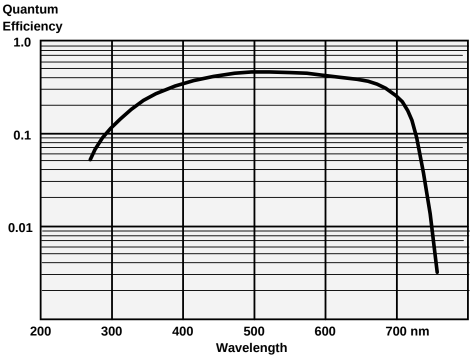
Dark count rate vs. temperature

Typical values and range of variation



Detection quantum efficiency vs. wavelength

APD voltage 95% of maximum

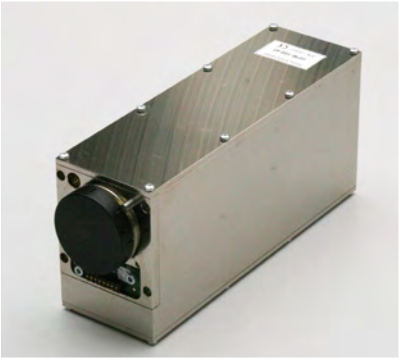


Specifications, typical values

Wavelength Range	300 nm to 730 nm
Detector Quantum efficiency, at 500 nm	45%
Dark Count rate, Tcase = 22°C	560 s^{-1}
Cathode Diameter	3 mm
TCSPC IRF width (Transit Time Spread)	120 ps, FWHM
Single Electron Response Width	850 ps, FWHM
Single Electron Response Amplitude	50 mV, V_{apd} 95% of V_{max}
Output Polarity	negative
Output Impedance	50 Ω
Max. Count Rate (Continuous)	> 10 MHz
Overload shutdown at	>15 MHz
Detector Signal Output Connector	SMA
Power Supply (from DCC-100 Card)	+ 12 V, +5 V, -12V
Dimensions (width x height x depth)	60 mm x 90 mm x 170 mm
Optical Adapters	C-Mount, DCS-120, LSM 710 NDD port

HPM-100-50

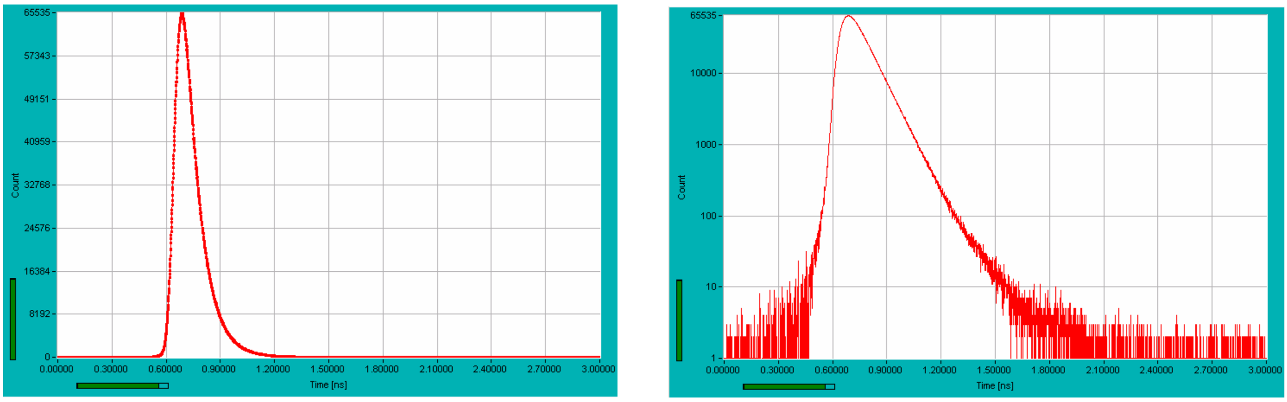
High Speed Hybrid Detector for TCSPC



GaAs cathode: Excellent detection efficiency
Sensitive up to 900 nm
Instrument response function 130 ps FWHM
Clean response, no tails or secondary peaks
No afterpulsing background
Excellent dynamic range of TCSPC measurements
Internal generators for PMT operating voltages
Power supply and control via bh DCC-100 card
Overload shutdown
Direct interfacing to all bh TCSPC systems

The HPM-100-50 module combines a Hamamatsu R10467-50 GaAs hybrid detector tube with the preamplifier and the generators for the tube operating voltages in one compact housing. The principle of the hybrid detector in combination with the GaAs cathode yields excellent timing resolution, a clean TCSPC instrument response function, high detection quantum efficiency up to NIR wavelengths, and extremely low afterpulsing probability. The absence of afterpulsing results in a substantially increased dynamic range of TCSPC measurements. The HPM-100-50 is therefore an excellent detector for NIR fluorescence decay measurements and time-domain diffuse optical tompgraphy.

The HPM-100-50 module is operated via the bh DCC-100 detector controller of the bh TCSPC systems. The DCC-100 provides for power supply, gain control, and overload shutdown. The HPM-100 interfaces directly to all bh SPC or Simple Tau TCSPC systems. It is available with standard C-mount adapters, adapters for the bh DCS-120 confocal scanning FLIM system, and adapters for the NDD ports of the Zeiss LSM 710 NLO multiphoton laser scanning microscopes.



Instrument response function. Left linear scale, right logarithmic scale. FWHM is 130 ps.

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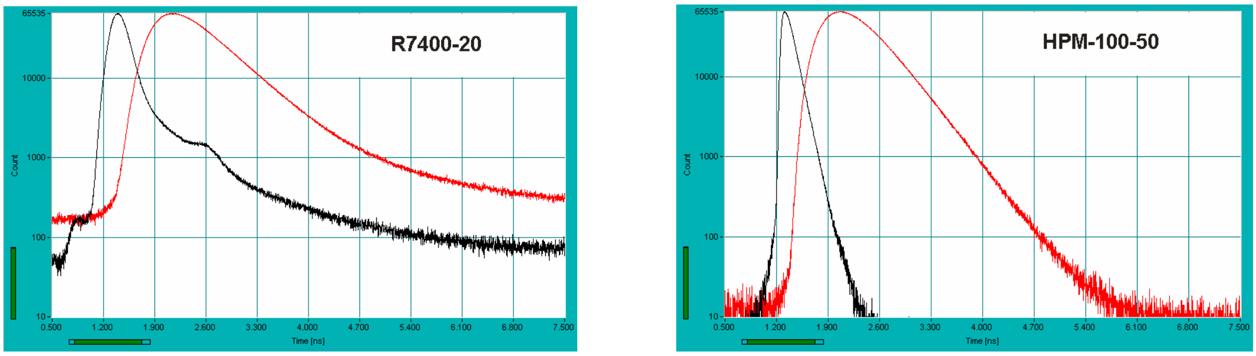
dbhpm-50-04.doc March 2010

HPM-100-50

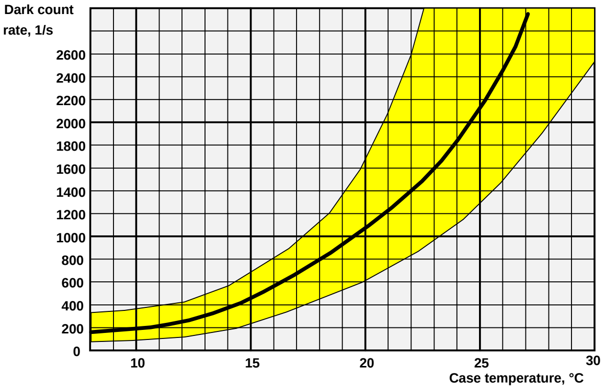
Absence of afterpulsing improves dynamic range of TCSPC measurement



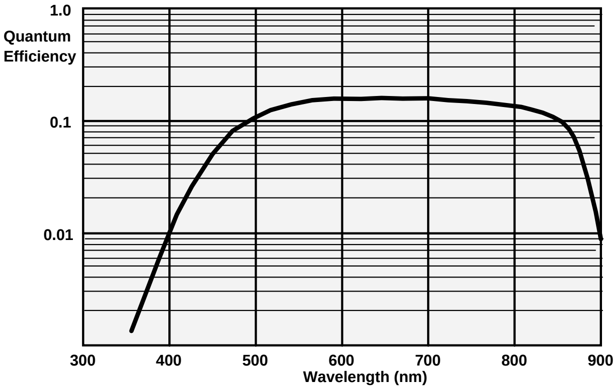
Photon migration curves (red) and IRF (black) recorded with conventional PMT (left) and HPM-100-50 (right). The background signal of the conventional NIR PMT is dominated by afterpulsing. Late photons are lost in the background. Right: The HPM-100-50 is free of afterpulsing. The only background is the thermal emission of the photocathode. The dynamic range is substantially higher than for the conventional PMT.

Dark count rate vs. temperature

Typical values and range of variation



Detection quantum efficiency vs. wavelength



Specifications, typical values

Wavelength Range	400 nm to 900 nm
Detector Quantum efficiency, at 600 nm	15 %
Dark Count rate, Tcase = 22°C	500 to 3000 s^{-1}
Cathode Diameter	3 mm
TCSPC IRF width (Transit Time Spread)	130 ps, FWHM
Single Electron Response Width	850 ps, FWHM
Single Electron Response Amplitude	50 mV, V_{apd} 95% of V_{max}
Output Polarity	negative
Output Impedance	50 Ω
Max. Count Rate (Continuous)	> 10 MHz
Overload shutdown at	>15 MHz
Detector Signal Output Connector	SMA
Power Supply (from DCC-100 Card)	+ 12 V, +5 V, -12V
Dimensions (width x height x depth)	60 mm x 90 mm x 170 mm
Optical Adapters	C-Mount, DCS-120, LSM 710 NDD port

Related products: HPM-100-40 hybrid detector module, 300 to 700 nm, 45% quantum efficiency

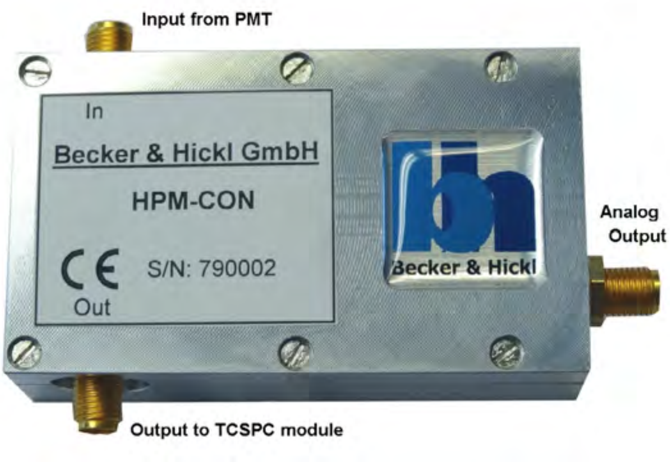
Literature: [1] The HPM-100-50 hybrid detector module: Increased dynamic range for DOT. Application note, www.becker-hickl.com
[2] The HPM-100-40 hybrid detector. Application note, www.becker-hickl.com

HPMCON-02

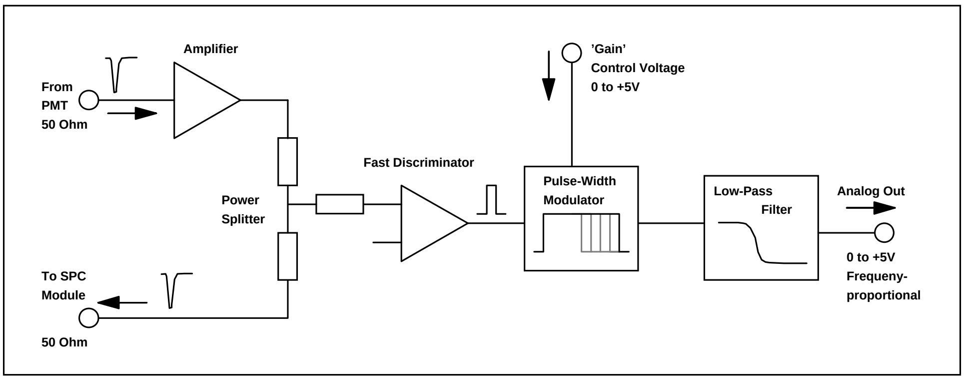
Frequency-to-Analog Converter for PMT Pulses

The HPMCON module converts the single-photon-pulse sequence of a photon-counting detector into an intensity-proportional analog signal.

Input pulse amplitude -30 mV to -200 mV
Input pulse width down to 500 ps
Inserts directly in detector output pulse line
Compatible with bh PMT modules and hybrid detectors
Input pulse rate up to 10^7 pulses per second
Output voltage range 0 to +4.9 V
Power supply ± 5V from bh SPC or DCC module



Principle



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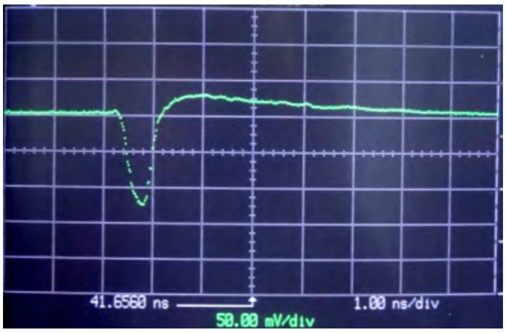
dbhpmcon-01 Aug. 2013

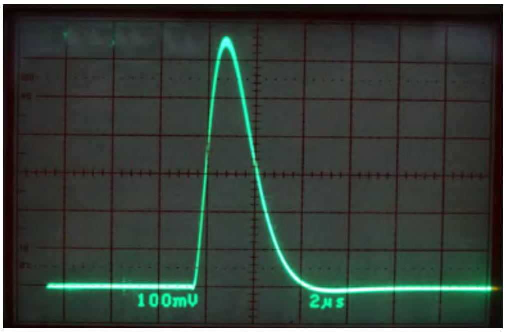
HPMCON-02

Specifications

Input pulse amplitude		-30 to -200 mV
Input pulse width		600 ps to 10 ns
Gain from PMT In to OUT		1 to 1.5
PMT In an OUT connectors		SMA
PMT in and PMT out impedance		50 Ω
Output amplitude for single photon	V_{gain}=1V	650 mV
	V_{gain}=5V	180 mV
Output pulse width for single photon		2 µs
Output voltage, F_{in}=100kHz	V_{gain}=1V	0.13 V
	V_{gain}=5V	0.03 V
Output voltage, F_{in}=1MHz	V_{gain}=1V	1.35 V
	V_{gain}=5V	0.34 V
Output filter response time		2 µs
Maximum load at output		1 kΩ
Output connector		SMA
Gain control voltage		0 to +5V, or potentiometer 250kΩ from +5V into V_{gain}
Gain control characteristic		Gain = 1/Vgain
Impedance of gain control input		2 kΩ
Power supply	+5V	90 mA
	-5V	152 mA
Power supply connector		Mini-USB



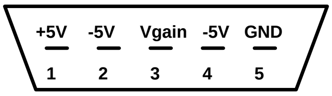
Output to SPC, Input pulse with 500 ps,
Input pulse amplitude 100 mV



Output signal for a single photon. Gain vontrol voltage
Vgain = 1V

Pin assignment of Mini-USB Connector

Power supply is provided at SUB-D connectors of SPC and DCC modules



Related Products:

HPM-100 hybrid detectors, PMC-100 PMT modules
SPC-130, SPC-130EM, SPC-150, SPC-830 TCSPC modules
Simple-Tau TCSPC systems
DCS-120 confocal scanning FLIM systems

bh International Sales Representative

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The HPM-100-40 Hybrid Detector

The bh HPM-100 module combines a Hamamatsu R10467-40 GaAsP hybrid PMT tube with the preamplifier and the generators for the PMT operating voltages in one compact housing. The principle of the hybrid PMT in combination with the GaAsP cathode of the R10467-40 yields excellent timing resolution, a clean TCSPC instrument response function, high detection quantum efficiency, and extremely low afterpulsing probability. The virtual absence of afterpulsing results in a substantially increased dynamic range for fluorescence decay recordings. FCS curves down to 100 ns correlation time can be obtained from a single detector, without the need of cross-correlation. The HPM-100 module is operated via the bh DCC-100 detector controller of the bh TCSPC systems.

Principle

The basic principle of a hybrid PMT is shown in Fig. 1. The photoelectrons emitted by a photocathode are accelerated by a strong electrical field and injected directly into a silicon avalanche diode [4, 8].

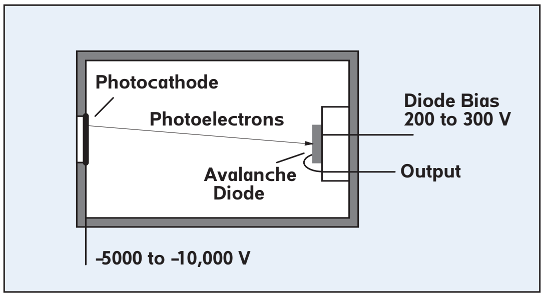

Fig. 1: Principle of a hybrid PMT

When an accelerated photoelectron hits the avalanche diode it generates a large number of electron-hole pairs in the silicon. These carriers are further amplified by the linear gain of the avalanche diode. The principle of the hybrid PMT has a number of advantages over other detector principles.

An obvious advantage of the hybrid PMT is that a large part of the gain is obtained in a single step. Hybrid PMTs therefore deliver single-photon pulses with a narrow amplitude distribution. The devices can thus be used to distinguish between one, two, or even more photons detected simultaneously [8]. In TCSPC applications the low amplitude fluctuation virtually eliminates the influence of the CFD circuitry on the timing jitter.

More important for TCSPC, the high acceleration voltage between the photocathode and the APD results in low transit time spread [4]. With an acceleration voltage of 8 kV the transit-time spread of the electron time-of-flight is only 50 ps [4, 5]. Moreover, the TCSPC instrument response of a hybrid PMP is very clean, without significant tails, bumps, or secondary peaks.

Compared to a conventional PMT, the hybrid PMT has also an advantage in terms of counting efficiency. In a conventional PMT, a fraction of the photoelectrons is lost on the first dynode of the electron multiplication system [1]. Instead of being multiplied electrons may also get absorbed or reflected. There are no such losses in the hybrid PMT: A photoelectron accelerated to an energy of 8 keV is almost certain to generate a signal in the avalanche diode. With a high-efficiency GaAsP cathode a hybrid photomultiplier reaches the efficiency of a single-photon APD (SPAD), but with a cathode area several orders of magnitude larger.

The perhaps most significant advantage of the hybrid PMT has been recognised only recently: The hybrid PMT is virtually free of afterpulsing [2]. Afterpulsing is the major source of counting background in high-repetition-rate TCSPC applications, and a known problem in fluorescence correlation measurements. Background has a detrimental effect on the accuracy of fluorescence lifetime determination [6]. Afterpulsing in FCS results in a false peak at correlation times shorter than a few µs. So far, the afterpulsing peak could only be suppressed by splitting the light and recording cross-correlation between two detectors.

The absence of afterpulsing in a hybrid PMT is inherent to its design principle. In conventional PMTs afterpulsing is caused by ionisation of residual gas molecules by the electron cloud in the dynode system. In single-photon avalanche photodiodes afterpulsing results from trapped carriers of the previous avalanche breakdown. Both effects do not exist in the hybrid PMT: Ionisation is negligible because only single electrons are travelling in the vacuum, and there is no avalanche breakdown in the APD.

On the downside, there are also a few disadvantages of the hybrid PMT. The extremely high cathode voltage is difficult to handle. It can be a problem especially in clinical biomedical applications. The APD reverse voltage must be very stable, and be correctly adjusted. The most significant problem is the low gain of the hybrid PMTs. Earlier devices reached a gain on the order of only 10^4. At a gain this low, the single-photon pulse amplitude is in the µV range. Therefore electronic noise from the termination resistor and from the preamplifier impaired the time resolution of single photon detection. Until recently, hybrid PMTs were therefore not routinely used for TCSPC experiments. The situation changed with the introduction of the R10467 hybrid PMTs of Hamamatsu [5]. The devices reach a total gain on the order of 10^5. The single-photon pulse amplitude is on the order of several 100 µV, the pulse width about 800 ps. A high bandwidth, low-noise preamplifier is able to amplify the pulses into an amplitude range where they are detected by the constant-fraction discriminator of a bh TCSPC module. Initial tests have shown the superior performance of the R10467 compared to previously existing detectors [2]. However, in practice RF noise pickup from the environment, noise from the high voltage power supplies, and low-frequency currents flowing through ground loops make the bare R10467 tube difficult to use in TCSPC experiments.

The bh HPM-100 Hybrid Detector Module

To make the R10467 applicable to standard TCSPC experiments bh have integrated the R10467 tube, the power supply for the cathode voltage, the power supply for the APD voltage, and the preamplifier in a compact, carefully shielded detector module. The device is shown in Fig. 2.

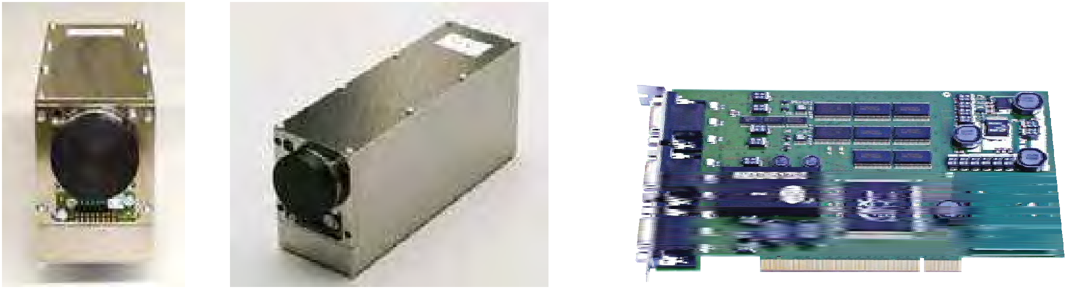

Fig. 2: bh HPM-100 hybrid PMT module. The module contains the Hamamatsu R10467 hybrid PMT tube, the generators for the cathode voltage and the APD reverse voltage, and the preamplifier. The module is operated via the DCC-100 card of the bh TCSPC systems (right)

The housing has separate compartments for the voltage generators, the R10467 tube, and the preamplifier. These are shielded and decoupled against each other and the environment. The complete module is operated via the bh DCC-100 detector controller card. The DCC-100 provides for power supply, control of the APD reverse voltage, and overload shutdown. One DCC-100 card can control two HPM-100 hybrid PMT modules.

Instrument response function

The instrument response function of an HPM-100-40 with an R10467-40 tube is shown in Fig. 3.

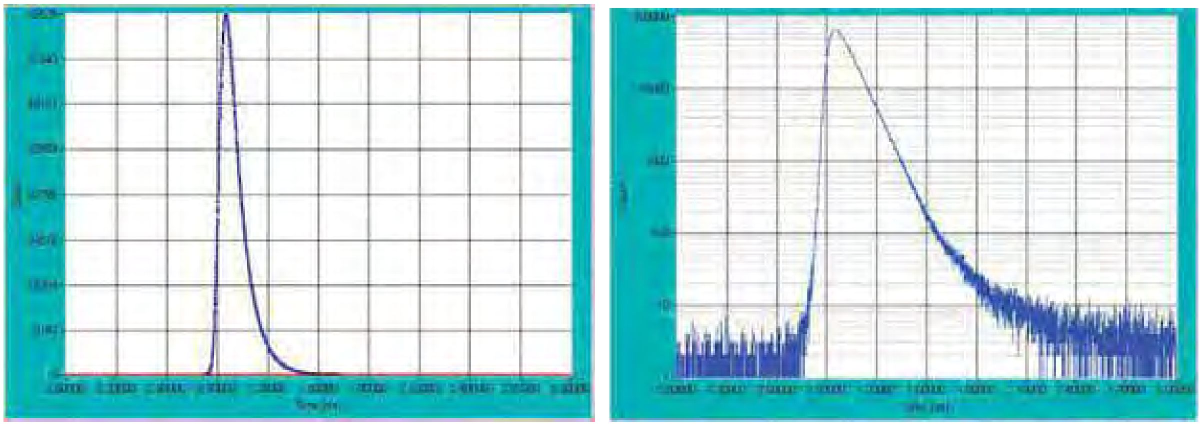

Fig. 3: Instrument response function of the HPM-100-40. Left: linear scale. Right: Logarithmic scale. BDL-445 SMC picosecond diode laser, bh SPC-830 TCSPC module.

The recorded instrument response function (IRF) width is 130 ps. Corrected for the laser pulse width of 60 ps the IRF width is about 120 ps. The response function is remarkably clean, as can be seen in the logarithmic plot on the right. It should be noted that the transit time spread and thus the IRF width of the R10467-40 is dominated by the internal time constants of its GaAsP cathode. The R10467-06 tube (with a conventional bialkali cathode) is faster, with an IRF width of about 50 ps.

Afterpulsing

The afterpulsing is characterised best by the autocorrelation function of the photons of a continuous light signal detected at a known count rate [1, 2]. Fig. 4 compares the autocorrelation function of an HPM-100-40 at 10 kHz count rate with that obtained by a Hamamatsu H5773-1 photosensor module. The autocorrelation for the HPM is flat down to the dead time of the SPC-830 module used. Comparable performance has been achieved so far only for NbN superconducting detectors. These detectors have active areas with µm extensions and need to be operated in a liquid-He cryostat [9].

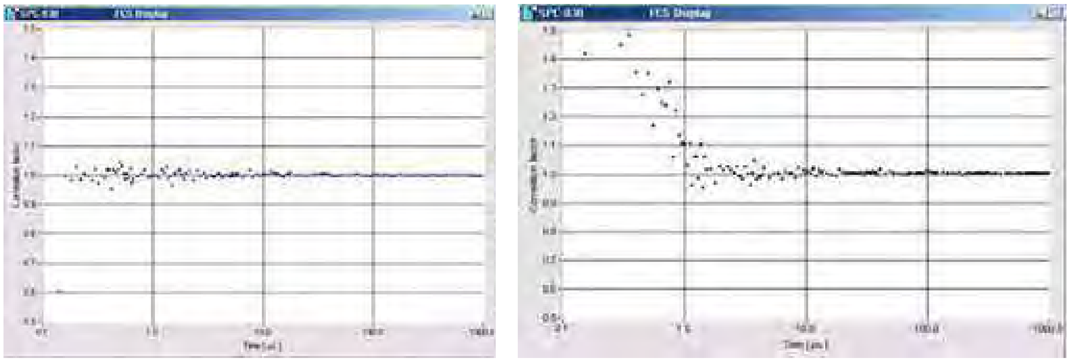

Fig. 4: Autocorrelation function of a continuous light signal of 10 kHz count rate. Left: HPM-100-40. Right: H5773-1. The autocorrelation function measured with the HPM is flat down to 125 ns, indicating that no afterpulses are detected.

Fig. 5 shows an FCS curve measured for a solution of fluorescein in water. The data were recorded by an HPM-100-40 connected to the bh DCS-120 confocal scanning FLIM system [3]. Because there is no afterpulsing peak diffusion and triplet times are obtained by autocorrelation of the photons detected in a single detector.

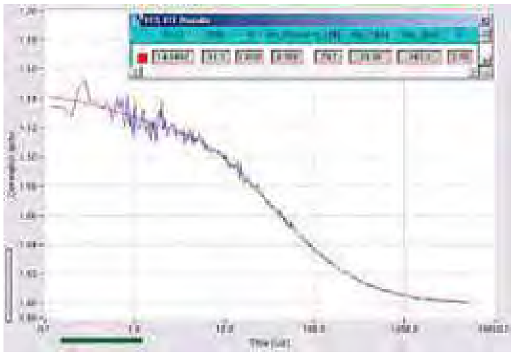

Fig. 5: Fluorescence correlation function of fluorescein molecules in water. Recorded with HPM-100-40, connected to bh DCS-120 confocal scanning FLIM system

The low afterpulsing results in a significantly improved dynamic range of fluorescence decay measurements. An example is shown in Fig. 6. It shows the fluorescence decay of fluorescein recorded at a laser repetition rate of 20 MHz. The signal was detected by a HPM-100-40 (left) and a H5773-1 photosensor module (right). Both detectors have approximately the same dark count rates.

For the HPM-100, the dark count rate is the only source of background. Because the dark count rate is only a few 100 counts per second an extraordinarily high dynamic range is obtained. For the H5773-1 the background is dominated by afterpulsing. The background is substantially higher, and the dynamic range is far smaller than for the HPM-100.

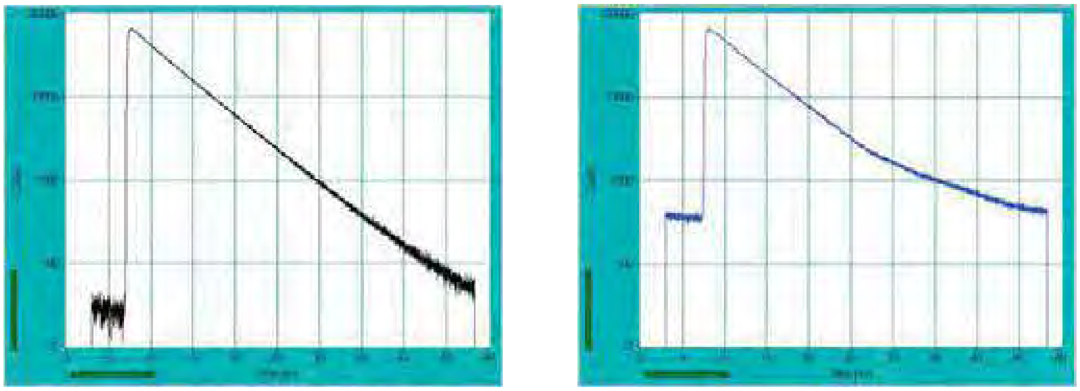

Fig. 6: Fluorescence decay curves for fluorescein recorded at a laser repetition rate of 20 MHz. Left: HPM-100-40. Right: H5773-01

Sensitivity

We had no possibility to verify the detection quantum efficiency of the R10467-40 quantitatively. The curve of cathode quantum efficiency versus wavelength shown in Fig. 7, left, was therefore copied from the specifications of Hamamatsu [5]. What we could verify, however, is that the detection efficiency surpasses the efficiency for the Hamamatsu H7422P-40. The H7422P-40 has the same cathode type but uses a conventional PMT design. Until now, the H7422P-40 was the ultimate in sensitivity for visible-range PMTs. The HPM reaches at least the same efficiency, but at a far better time resolution and without any afterpulsing.

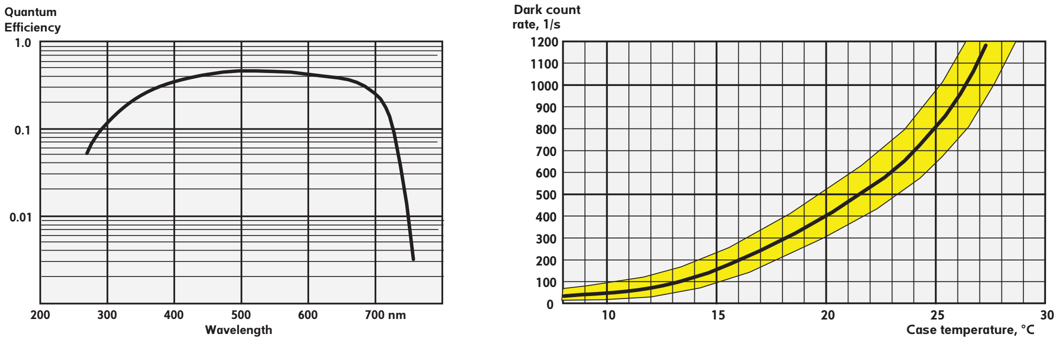

Fig. 7: Left: Detection quantum efficiency according to Hamamatsu specification. Right: Dark count rate. Black curve average of 4 detectors. Yellow area: Range of variation for 7 detectors, measured over several days.

For low-level light detection the limiting parameter is often not only the efficiency but also the dark count rate. Typical curves of the dark count rate versus temperature are shown in Fig. 7, right. The values we found are a bit lower than the numbers in the Hamamatsu test sheets, and significantly lower that the numbers given in [7]. The reasons are not clear. It should be noted that low dark count rates are only obtained if (a) the reverse voltage of the avalanche diode is selected below the breakdown level and (b) the tube has been kept in darkness for several hours after any exposure to daylight.

The advantage of large active area

In most applications it is difficult or even impossible to concentrate the light to be detected on an extremely small area. A typical case is multiphoton microscopy. Multiphoton microscopy is used to obtain images from image planes deep in a sample. The fluorescence photons from these layers are scattered on the way out of the sample and emerge from a large area of the sample surface. Although these photons can be transferred to a detector by 'non-descanned detection' they cannot be concentrated on an area smaller than a few mm in diameter [1, 2].

A similar situation can exist even in a confocal microscope. Confocal detection uses a pinhole in a plane conjugate with the image plane in the sample [3]. One would expect that the light from the pinhole is easy to focus an a small detector, such as a single-photon avalanche diode (SPAD). Unfortunately, in practice this is often not the case. Normally scan heads of laser scanning microscopes have additional magnification built in so that the physical pinhole size in on the order of millimeters. Demagnifying the pinhole to the size of a SPAD by a single lens can be impossible. This is especially the case when larger pinholes, on the order of tens of Airy Units, are used.

An example is shown in Fig. 8. Both lifetime images were recorded at a pinhole size of 3 Airy Units. Data recorded with the HPM-100 are shown left, data recorded with an id-100-50 SPAD right. Despite of the fact that the quantum efficiencies of the detectors do not differ substantially the image recorded with the HPM contains about twice the number of photons as the image recorded with the SPAD.

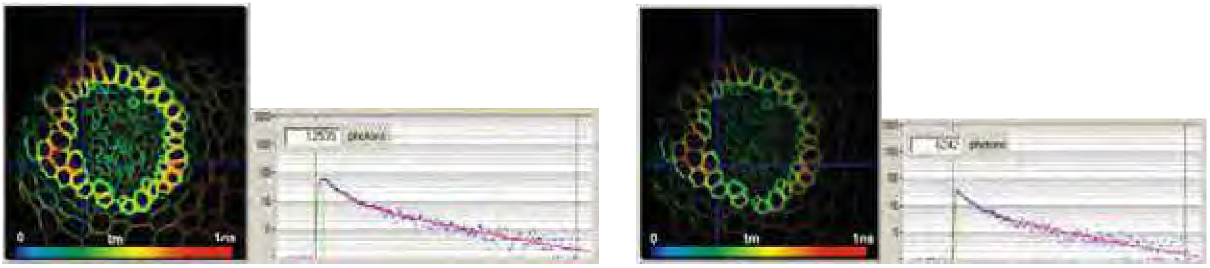

Fig. 8: Fluorescence lifetime images recorded with an HPM-100 (left) and with an id-100-50 SPAD (right). Images and decay functions at selected cursor position.

Controlling the HPM-100-40

The HPM-100 is operated and controlled via the DCC-100 card of the bh TCSPC systems [2]. The DCC control panel is shown in Fig. 9.

For safety reasons, the DCC-100 comes up with all outputs disabled, see Fig. 9, left. Both the acceleration voltage and the reverse voltage of the avalanche diode (AD) are turned off. The panel is shown for one detector and for two detectors.

Once the outputs are enabled ('Enable' button) and the +12V operating voltage is turned on (+12V button) the internal high-voltage generator applies the 8 kV acceleration voltage to the R10467 tube and turns on the reverse voltage of the avalanche diode. The +5V and the -5V must also be turned on, they are used in the preamplifier. The AD reverse voltage is controlled via the 'Gain' sliders.

Fig. 9: DCC-100 control panel, for one detector and for two detectors. Left: After software start, the detectors are disabled. Right: Detectors enabled. The ‘Gain’ sliders control the AD voltages.

The correct selection of the operating parameters is critical to the operation of the HPM. The recommended CFD threshold of the SPC module is -30 mV. The AD reverse voltage must be selected to operate the AD close to the maximum stable gain, but not in the breakdown region.

The selection of the AD voltage is demonstrated in Fig. 10. The gain of the AD increases steeply with the voltage, see Fig. 10, left. Consequently, photon counting is obtained in a relatively narrow interval of the reverse voltage, or DCC ‘Gain’. The gain-voltage characteristics vary for different detectors. Different detectors therefore need different values of the DCC gain. The correct DCC gain can easily be found by slowly increasing the DCC gain and observing the count rate displayed by the TCSPC module. Typical curves of the count rate versus DCC Gain are shown in Fig. 10, right. At low DCC gain no counts are obtained. At a specific DCC gain the count rate rises steeply. Then it remains almost constant over an interval of 5 to 10 % of DCC Gain. Beyound this interval the count rate rises steeply. The APD is driven in the breakdown region, the APD current becomes unstable, and eventually the DCC-100 shuts the HPM-100 down. The correct operating point is in the middle of the flat part of the curve, as indicated in Fig. 10, right.

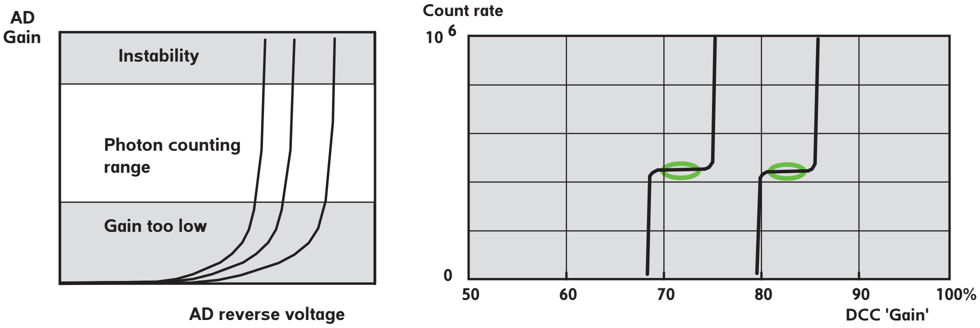

Fig. 10: Left: General dependence of the AD gain on the AD reverse voltage. Right: Dependence of the count rate on the DCC Gain for different detectors. The correct operating point is in the flat part of the curve.

If the AD current becomes too high, either because the ‘Gain’ was pulled too far up or the light intensity is too high, the DCC-100 shuts down the HPM-100. The acceleration voltage is turned off, and the APD reverse voltage is reduced down to zero. This brings the detector in a safe state. After the reason of the overload has been removed, the detector can be brought back to operation by clicking on the ‘Reset’ button. The DCC-100 panel in the overload state is shown in Fig. 11.

Fig. 11: DCC-100 panel after overload shutdown. Left one detector. Right: Two detectors, both detectors shut down.

Summary

With the bh HPM-100 module, there is, for the first time, a detector that combines high speed, clean response, high efficiency, large active area, absence of afterpulsing, and ease of use. Combined with the bh TCSPC systems, it detects fluorescence decay functions with unprecedented dynamic range, has the sensitivity to efficiently acquire FCS data, and delivers FCS without the need of cross-correlation. The main area of application of the HPM-100 is time-resolved microscopy which demands for exactly the combination of parameters the HPM-100 provides. However, the HPM-100 may be used for any TCSPC experiments that require high precision, high sensitivity, and wide dynamic range.

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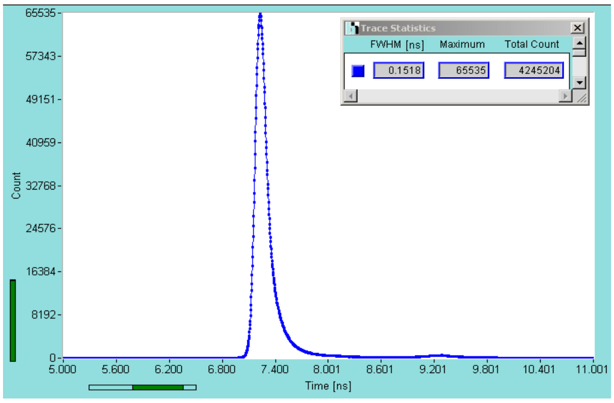
PMC-100

Cooled High Speed PMT Detector Head for Photon Counting

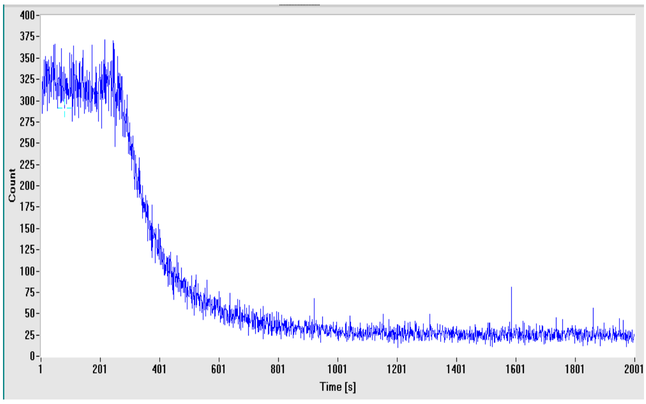
Applicable to Time-Correlated, Steady State and Gated Photon Counting
Non-descanned Detector for TCSPC Imaging
Excellent TCSPC Instrument Response: < 200 ps FWHM
Internal Cooler: Low Dark Count Rate
Internal GHz Preamplifier: High Output Amplitude
No High Voltage Power Supply Required
Excellent Noise 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.



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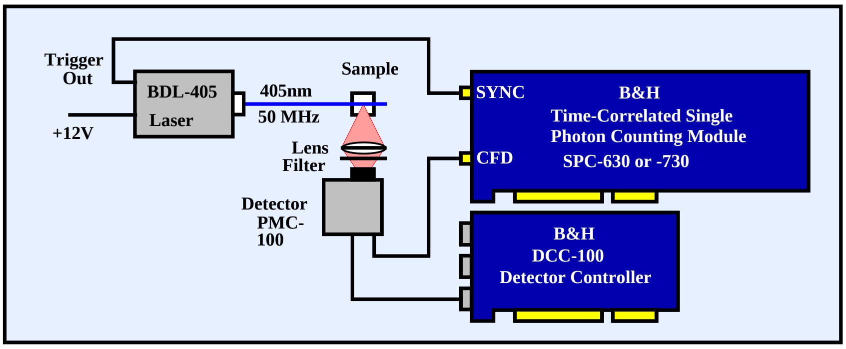
Note:
To avoide restriction of the wavelength range the PMC-100 has no hermetically sealed window. Please make sure that moisture is kept off the photomultiplier cathode by filters, lenses or other window elements inserted directly in front of the device.

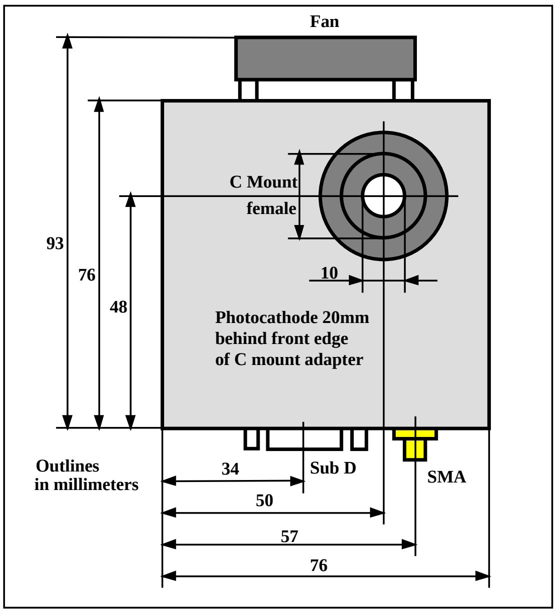
PMC-100

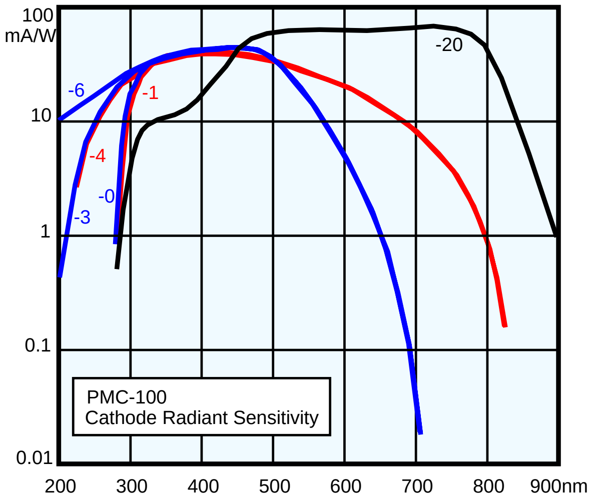
	PMC-100-3	PMC-100-6	PMC-100-0	PMC-100-4	PMC-100-1	PMC-100-20
Wavelength Range (nm)	185 to 650	185 to 650	300 to 650	185 to 820	300 to 820	300 to 900
Dark Counts (Icool=0.7A, Tamb = 22°C, typ. value)	20	20	20	40	40	200 to 500
Cathode Diameter	8 mm					
Transit Time Spread / TCSPC IRF width	180 ps, FWHM, 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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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

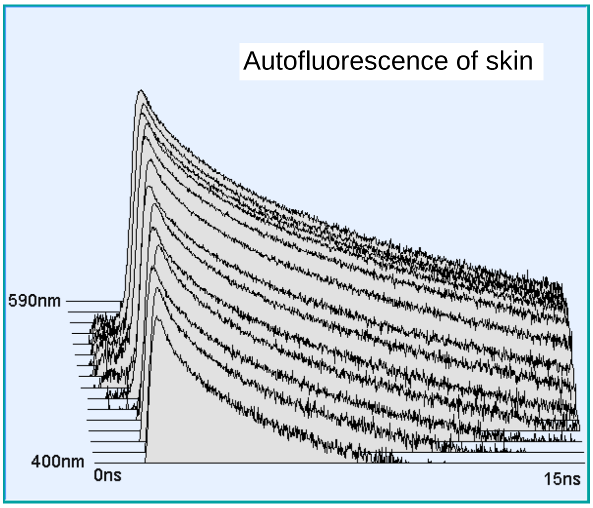
Gain control and overload shutdown via bh DCC-100 card

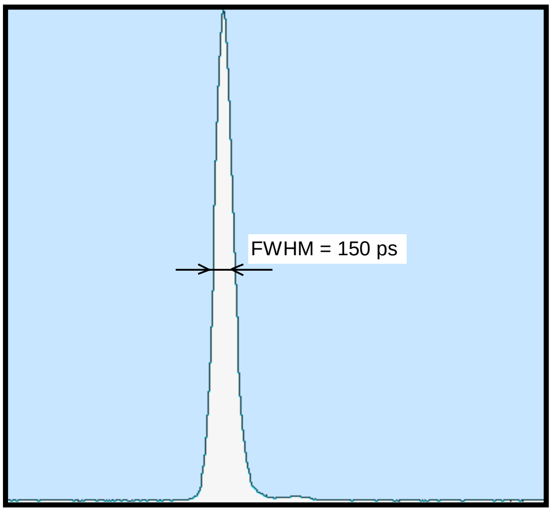
No external high voltage required

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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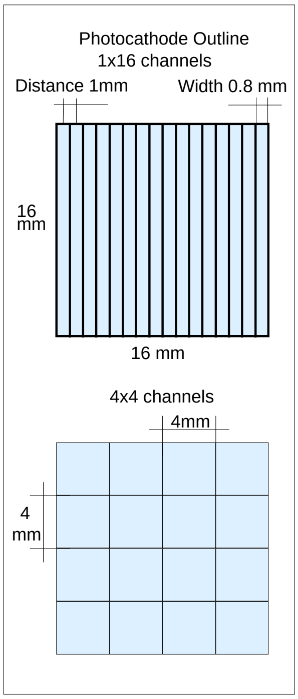
Covered by patent DE 43 39 787

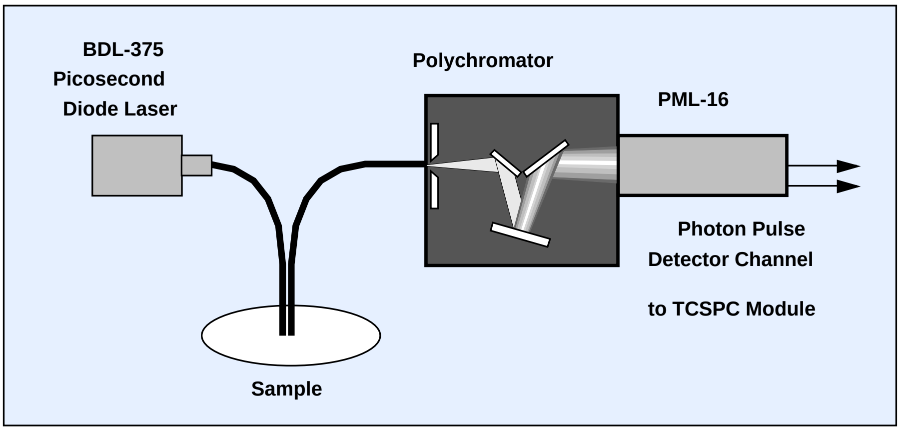
PML-16-C

Specification

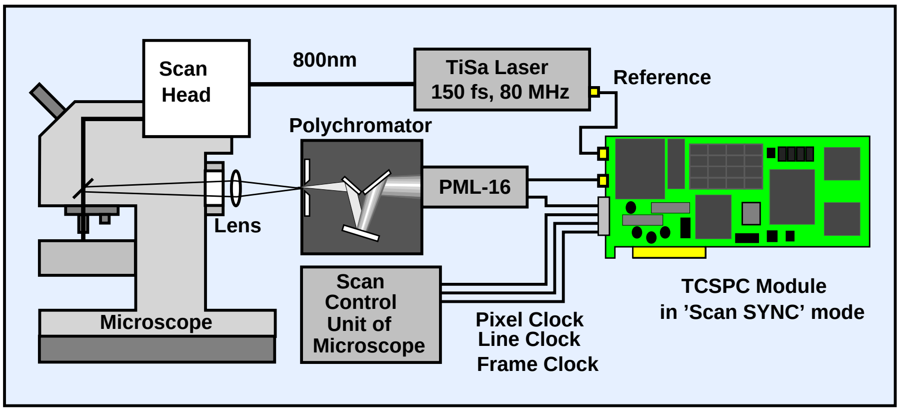
Number of Channels	16
Arrangement	Linear (1 by 16), optional quadratic4x4
Active Area (each channel)	Linear 0.8 × 16 mm, quadratic 4 by 4
Channel Pitch	1 mm
Spectral response	PML-16-C-0: 300 to 600 nm (bi-alkaline) PML-16-C-1:300 to 850 nm (multi-alkaline) Other cathode versions: contact bh
Timing Output 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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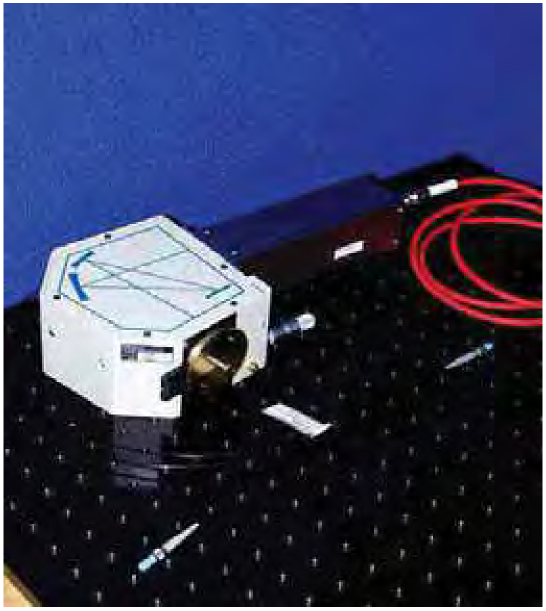
PML-Spec
Multi-Wavelength Lifetime Detection

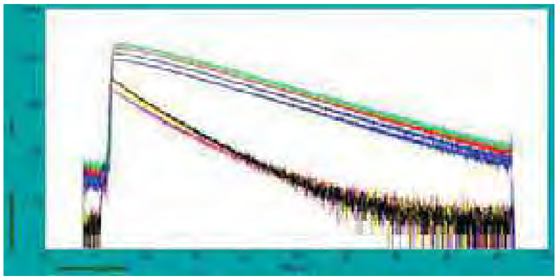
Multi-wavelength detection of fluorescence decay functions

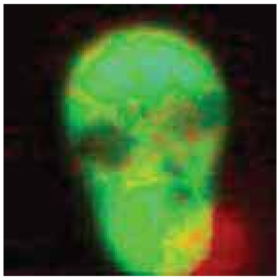
16 wavelength channels recording simultaneously
Spectral range 300-850 nm
High time resolution: 180 ps fwhm IRF width
Useful count rate > 2 MHz
Ultra-high sensitivity
Short acquisition times
Greatly reduced pile-up
Works with any bh TCSPC module

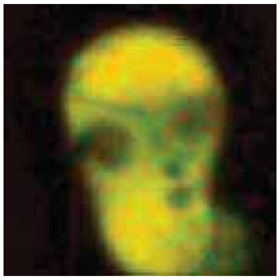


Biomedical fluorescence
Autofluorescence of tissue
Time-resolved laser scanning microscopy
Multi-spectral lifetime imaging
Recording of chlorophyll transients
Stopped flow fluorescence experiments

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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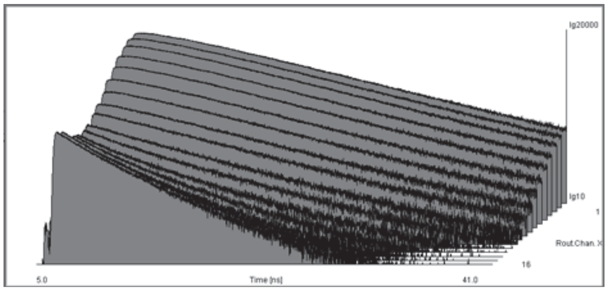


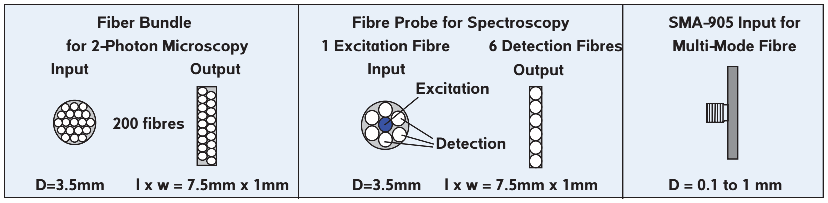
Covered by patent DE 43 39 787

dbpmlspec1 Dec. 2005

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

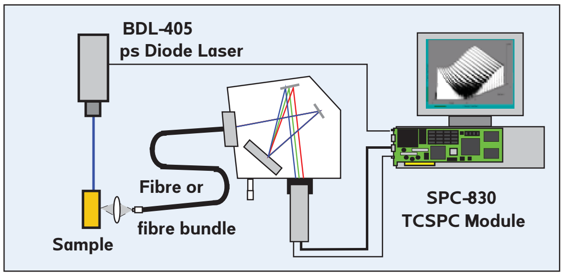
Detector[4]

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	

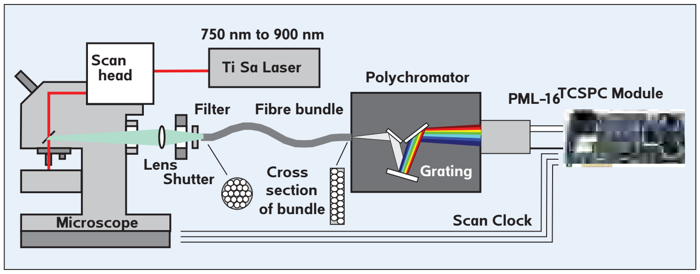
[4] please see data sheet and manual of PML-16 and PML-16C multichannel PMT heads

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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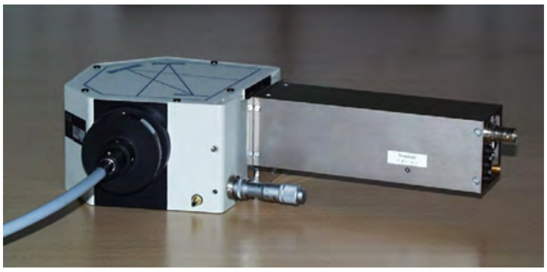
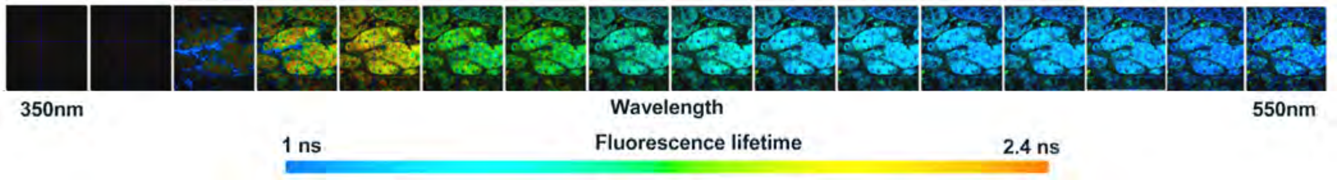
(617) 731 0935

MW FLIM Multi-Wavelength FLIM Detector

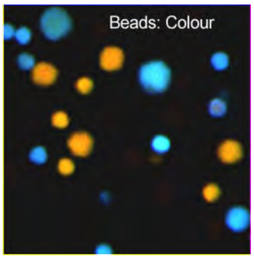
Fluorescence lifetime imaging with spectral resolution
Picosecond time resolution
Simultaneous detection in all time and wavelength channels
Based on BH's multi-dimensional TCSPC technique
Connects directly to all bh SPC modules
Adapters for non-descanned outputs of multiphoton microscopes
Adapters for confocal microscopes
Upgrade for existing bh FLIM systems

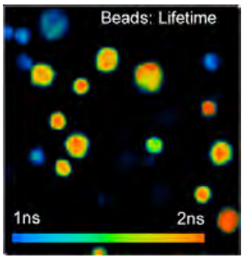


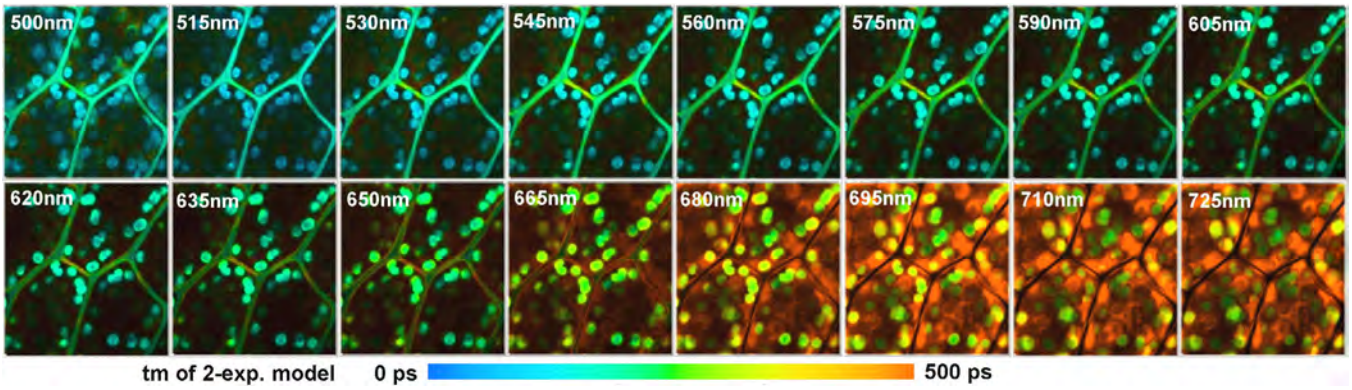


Mouse kidney tissue, autofluorescence. Zeiss LSM 510 NLO multiphoton microscope, non-descanned detection

The bh MW-FLIM system is based on a 16-channel multi-anode PMT detector module, routing electronics, spectral dispersion optics, and BH's multi-dimensional TCSPC technique. A fibre bundle is used to transfer the light from the microscope into the entrance slit of the polychromator. Due to the large light collection area a high efficiency is obtained both for confocal detection and for non-descanned (direct) detection in multiphoton microscopes. Typical applications are multi-spectral autofluorescence imaging of biological tissue, combined FLIM and SHG imaging, plant physiology, and investigation of protein interaction by FRET.







Plant tissue, autofluorescence. Zeiss LSM 710 NLO multiphoton microscope, 2-photon excitation, non-descanned detection

More than 19 years experience in multi-dimensional TCSPC. More than 1300 TCSPC systems worldwide.

MW FLIM Multi-Wavelength FLIM Detector

Part List of Detector Assembly

M-SHUT field lens and shutter assembly [1]
MW-FLIM fibre bundle
MW-FLIM fibre adapter to spectrograph
LOT MS125 spectrograph
PML-16-0-C (300 to 600 nm) or PML-16-1-C (300 to 800 nm) 16 channel PMT module, with MS125 adapter

TCSPC components required

SPC-830 or SPC-150 TCSPC module [2]
DCC-100 detector controller [2]
SPCImage FLIM data analysis software

or

Simple-Tau 830 or 150 stand-alone TCSPC system [3]

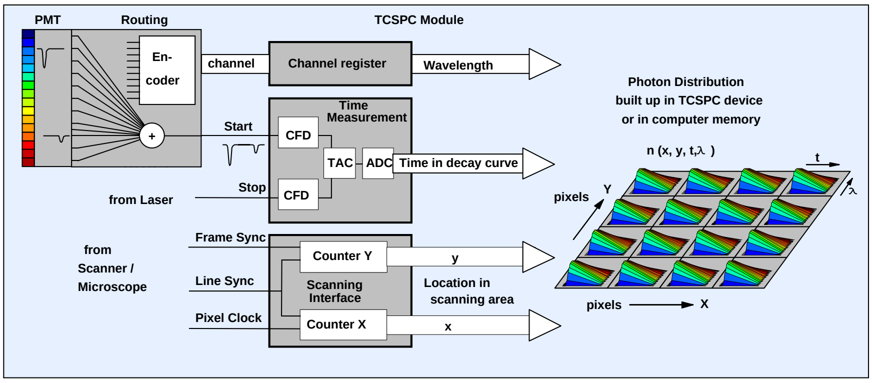
1) please specify microscope type and configuration in your order
2) PC cards, to be inserted in a Pentium PC
3) Laptop based stand-alone system, contains SPC-830 or SPC-150 and DCC-100

Wavelength range and resolution

Grating Part No.	Primary wavelength region adjustable by set screw[4]	Width of recorded wavelength interval, channel 1 to 16	Blaze Wavelength
77417	340-820 nm	300 nm	500 nm
77414 (standard)	340-820 nm	200 nm	400 nm
77411	340-820 nm	100 nm	350 nm

4) for PML-16-1, may vary due to transmission range of microscope optics

The setup employs BH's multi-dimensional TCSPC technique featuring multi-wavelength capability, high count rate, near-ideal counting efficiency, low differential nonlinearity, and ultra-high time-resolution. It contains the usual building blocks (CFDs, TAC, ADC) in the 'reversed start-stop' configuration together with a scanning interface and a large histogram memory integrated on a single PC board. For each photon the TCSPC module determines the time within the fluorescence decay function, t, the wavelength, λ, and the location within the scanning area, x and y. These values are used to address a memory in which the events are accumulated. Thus, in the memory the distribution of the photon density over X, Y, λ, and t builds up. With a 16-channel detector, the result contains 16 data sets for different wavelength, each containing a large number of images for different time in the fluorescence decay curve. The recording process runs at any scan rate, including ultra-high rates of resonance scanners.



For more information please download or request

W. Becker, The bh TCSPC Handbook, 5th edition, Becker & Hickl GmbH (2012), www.becker-hickl.com
Becker & Hickl GmbH, PML-16-C User Handbook, www.becker-hickl.com
Becker & Hickl GmbH, FLIM systems for Zeiss LSM 510 and LSM 710 family microscopes, www.becker-hickl.com
Becker & Hickl GmbH. DCS-120 confocal scanning FLIM systems, www.becker-hickl.com
W. Becker, A. Bergmann, C. Biskup, Multi-Spectral Fluorescence Lifetime Imaging by TCSPC. Micr. Res. Tech. 70, 403-409 (2007)
P. A. A. De Beule, C. Dunsby, N. P. Galletly, G. W. Stamp, A. C. Chu, U. Anand, P. Anand, C. D. Benham A. Naylor, P. M. W. French, A hyperspectral fluorescence lifetime probe for skin cancer diagnosis. Rev. Sci. Instrum. 78, 123101 (2007)
A. Rück, Ch. Hülshoff, I. Kinzler, W. Becker, R. Steiner, SLIM: A New Method for Molecular Imaging. Micr. Res. Tech. 70, 403-409 (2007)
D. Chorvat, A. Chorvatova, Multi-wavelength fluorescence lifetime spectroscopy: a new approach to the study of endogenous fluorescence in living cells and tissues. Laser Phys. Lett. 6 175-193 (2009)
E. Dimitrow, I. Riemann, A. Ehlers, M. J. Koehler, J. Norgauer, P. Elsner, K. König, M. Kaatz, Spectral fluorescence lifetime detection and selective melanin imaging by multiphoton laser tomography for melanoma diagnosis. Experimental Dermatology 18, 509-515 (2009)

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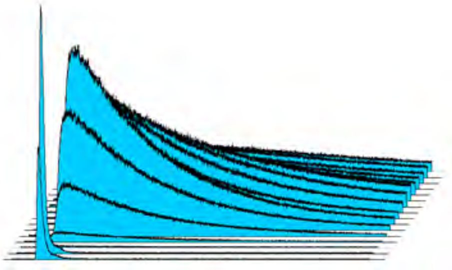
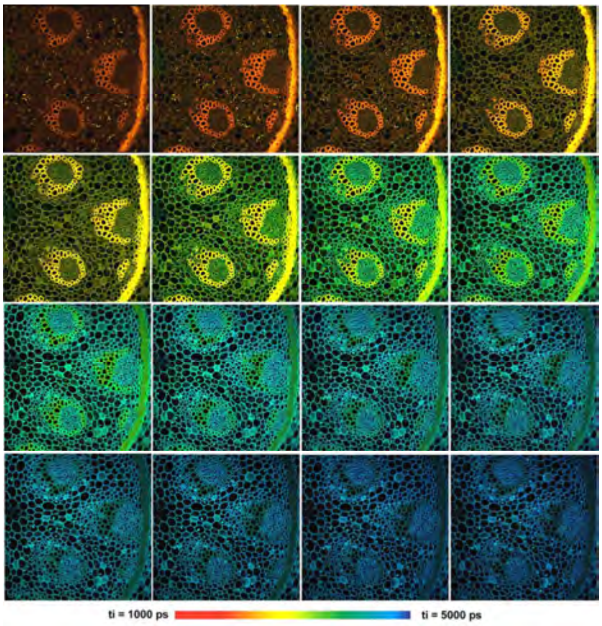
MWFLIM-GaAsP

16-Channel Multi-Wavelength FLIM Detector with GaAsP Cathode

Fluorescence lifetime imaging and single point decay recording with spectral resolution
Simultaneous detection in 16 wavelength channels
Based on BH's multi-dimensional TCSPC technique
High efficieny GaAsP cathode
Picosecond time resolution
Confocal laser scanning microscopes
Multiphoton microscopes
Upgrade for existing bh FLIM systems
Compatible with SPC-130EM, SPC-150, SPC-150N, SPC-160, SPC-830 TCSPC modules and Simple-Tau systems

The MWFLIM GaAsP module detects fluorescence decay data in 16 spectral channels simultaneously. It uses an input fibre bundle for light collection, a grating polychromator for spectral dispersion, a Hamamatsu 16-channel multi-anode GaAsP PMT, and routing electronics for bh's multi-dimensional TCSPC technique. The detector can be used for multi-wavelength FLIM in combination with confocal or multiphoton laser scanning microscopes and for single-point multi-wavelength fluorescence decay measurements. The MWFLIM-GaAsP detector is controlled by a bh DCC-100 detector controller. It is connects directly to the bh SPC-130EM, SPC-150, SPC-150N, SPC-160 and SPC-830 TCSPC / FLIM modules, and to the bh Simple-Tau 130EM, 150, 150N, 160, and 830 table-top TCSPC systems.





Convallaria sample, 16 wavelength channels, 490 to 690 nm
bh DSC-120 confocal FLIM system. Each channel 512x512 pixels

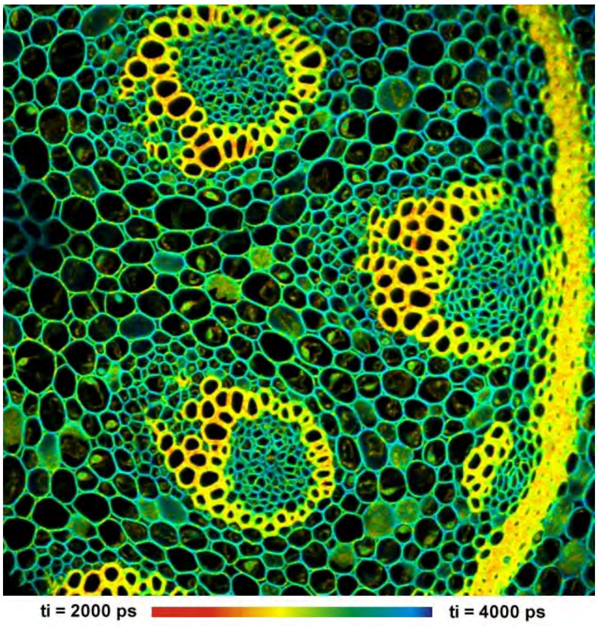
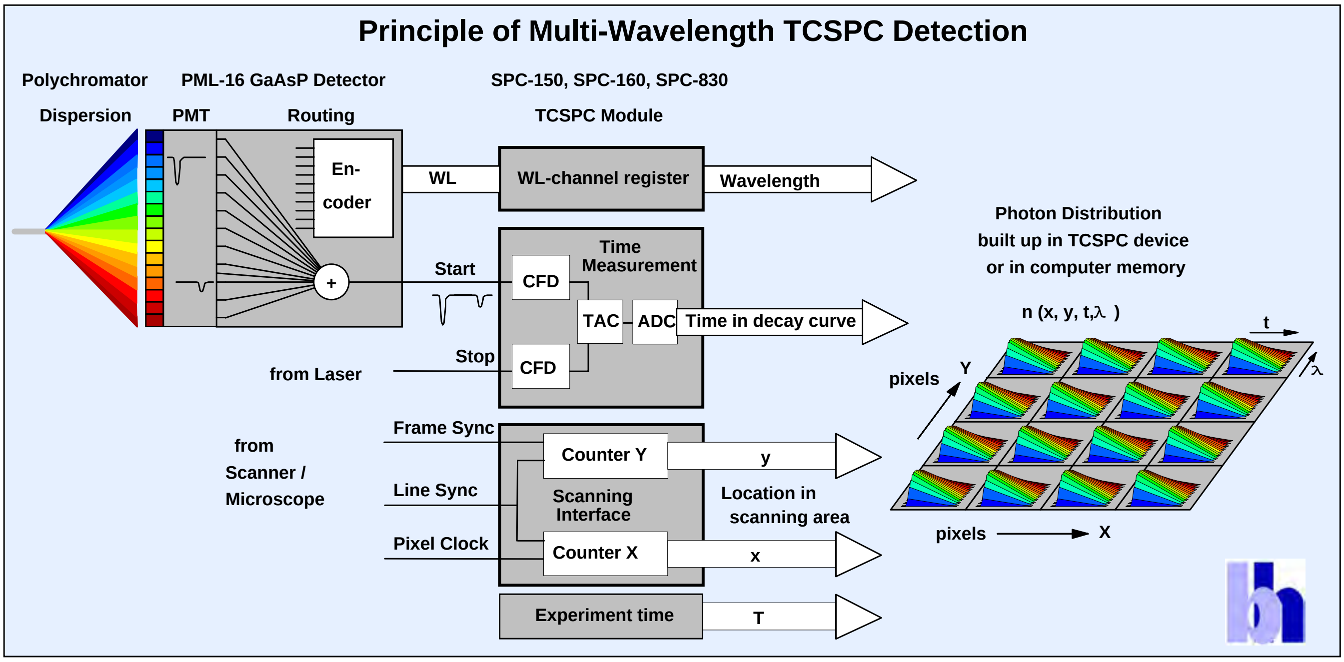


Image in 565 nm channel of data shown left. 512x512 pixels

Technology Leader in TCSPC

MWFLIM-GaAsP Multi-Wavelength FLIM Detector

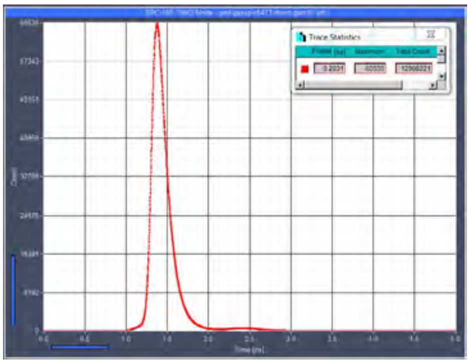

Principle of Multi-Wavelength TCSPC Detection

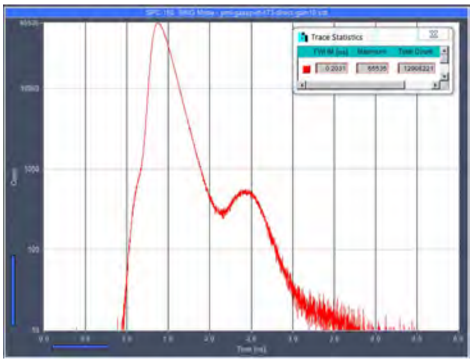
Wavelength range and resolution

Grating Part No.	Primary wavelength region adjustable by set screw	Wavelength channel width	Width of recorded wavelength interval, channel 1 to 16	Blaze wavelength
77417	340-820 nm	18.75 nm	300 nm	500 nm
77414 (standard)	340-820 nm	12.5 nm	200 nm	400 nm
77411	340-820 nm	6.25 nm	100 nm	350 nm

TCSPC instrument response function (IRF, single channel)

IRF width 200 to 250 ps FWHM





International Sales Representative

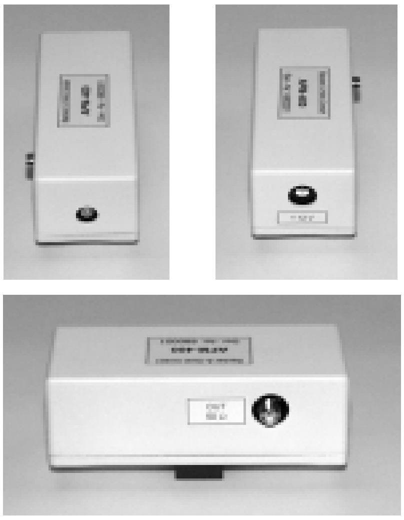
US:
Boston Electronics Corp
Tel: 617-566-3821
tcspc@boselec.com
www.boselec.com

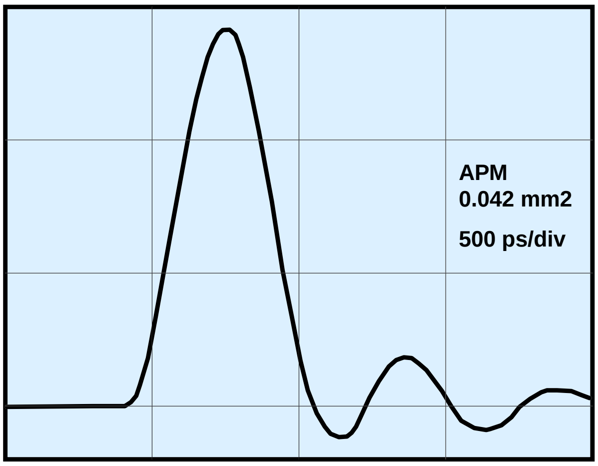
APM - 400

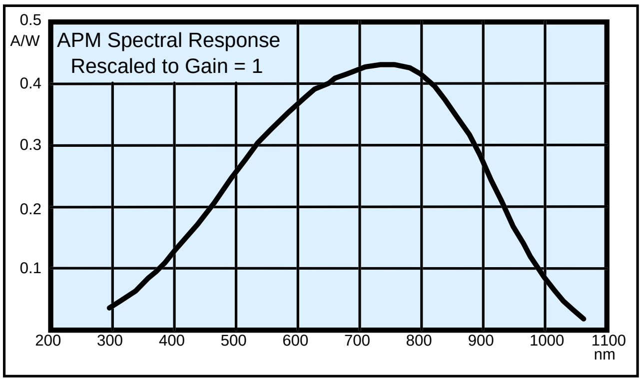
High Speed Avalanche Photodiode Module

- 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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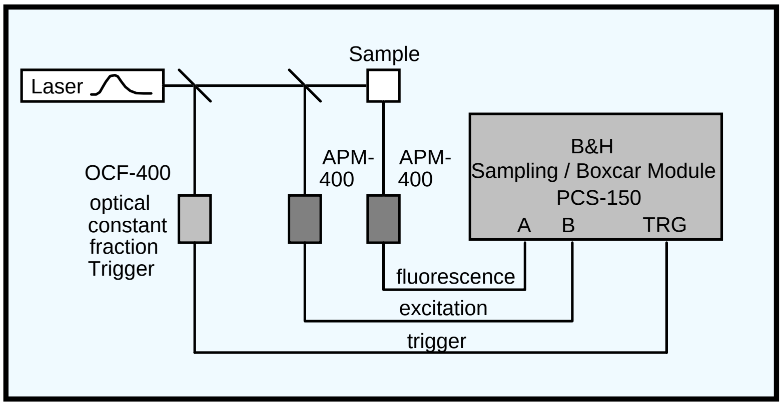
APM - 400

Specification

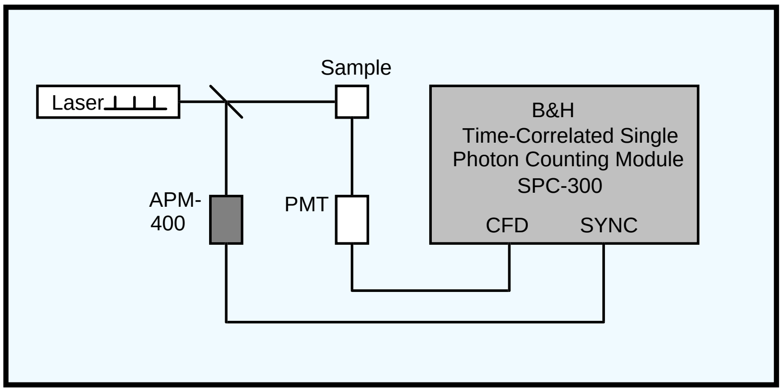
Active Area (please specify)	0.03	0.042	0.19	0.78	1.77	7.0	mm^2
FWHM (630nm, 50 Ohm)	0.45	0.32	0.4	0.5	2.3	3	ns
Pulse Rise Time	0.15	0.16	0.2	0.25	1.1	1.2	ns
Gain (Adjustable by Trimpot)			1 to > 100				
Output Polarity	positive (APM-400 P) or negative (APM-400 N)						
Spectral Range			330 to 1050				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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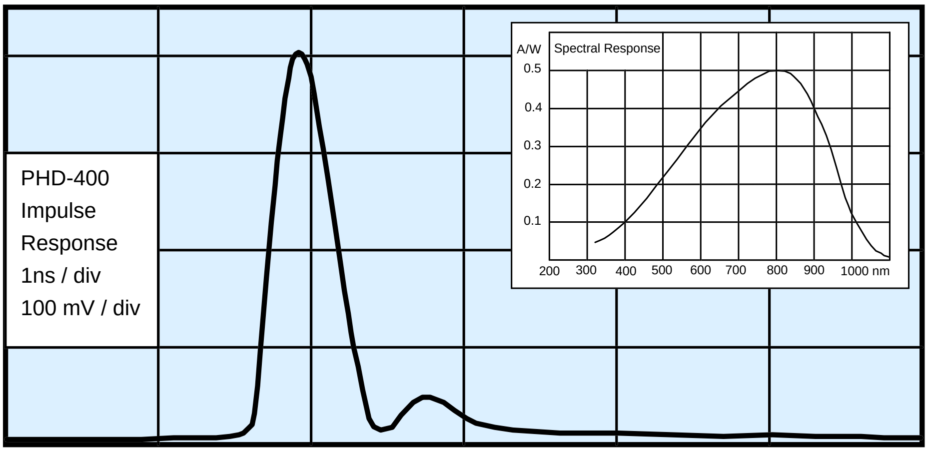
PHD-400

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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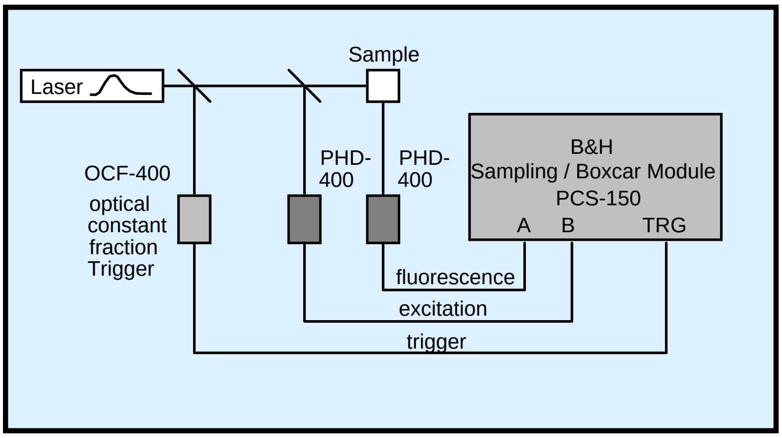
Applications:

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



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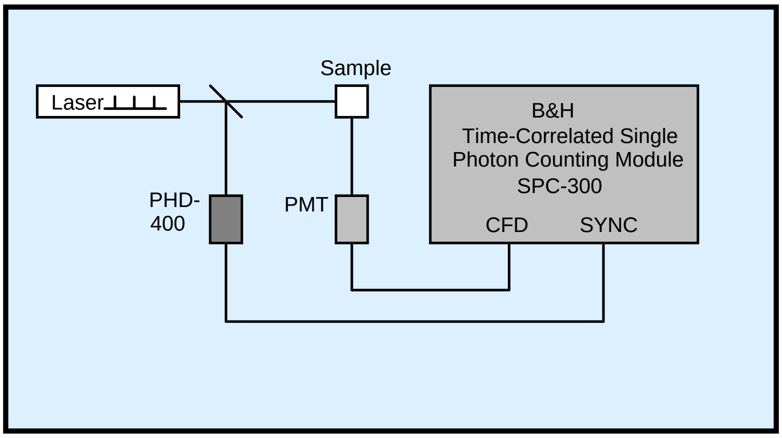
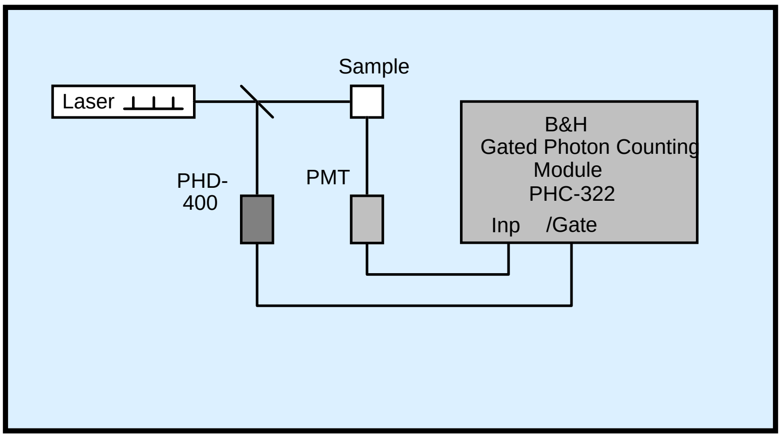
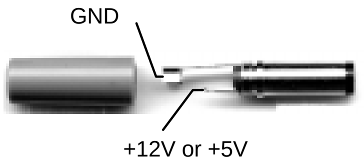


Steady State Fluorescence: Gating off Detector Background Signal



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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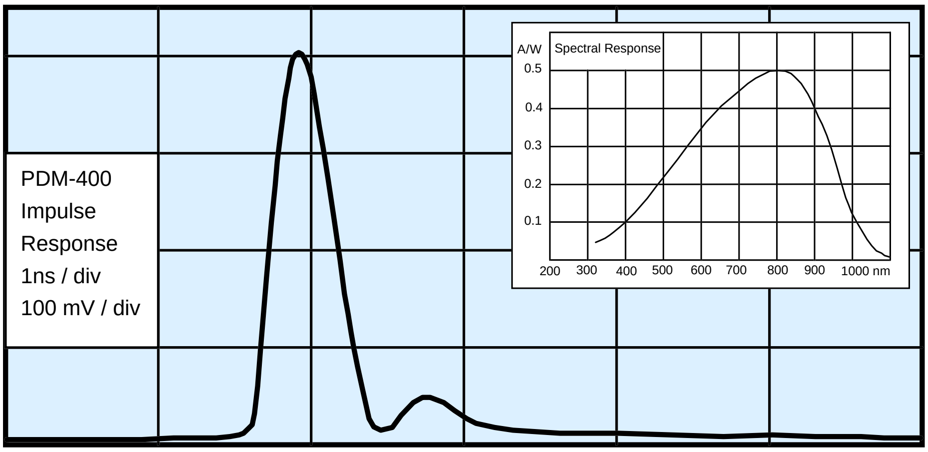
PDM-400

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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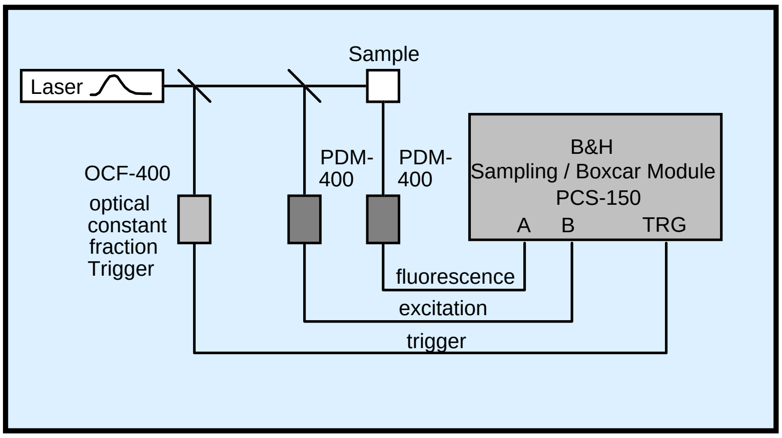
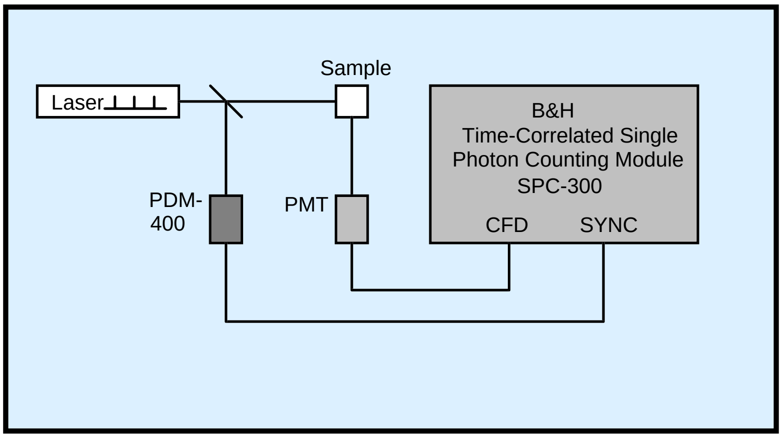
Applications:

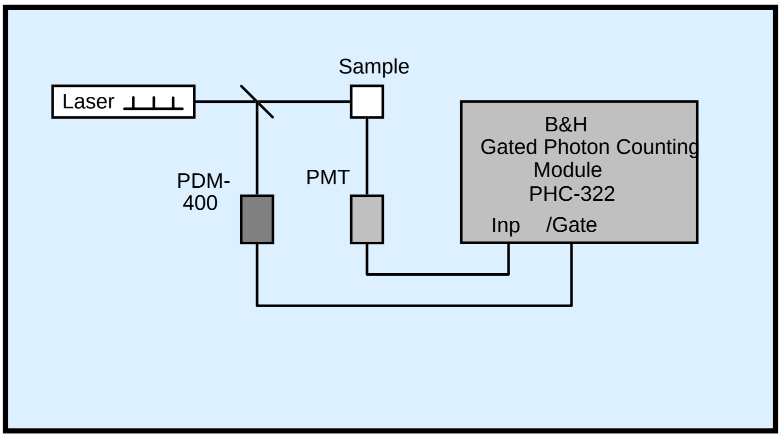
Laser induced Fluorescence Excitation with N_2 Laser, Recording of Fluorescence and Excitation Signal by Sampling / Boxcar Technique



Triggering of Time-Correlated Single Photon Counting Experiments

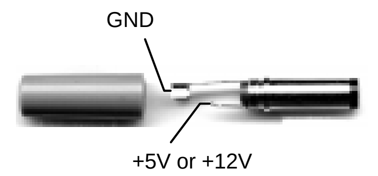


Steady State Fluorescence: Gating off Detector Background Signal



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



Power Supply Connector Pin Assignment

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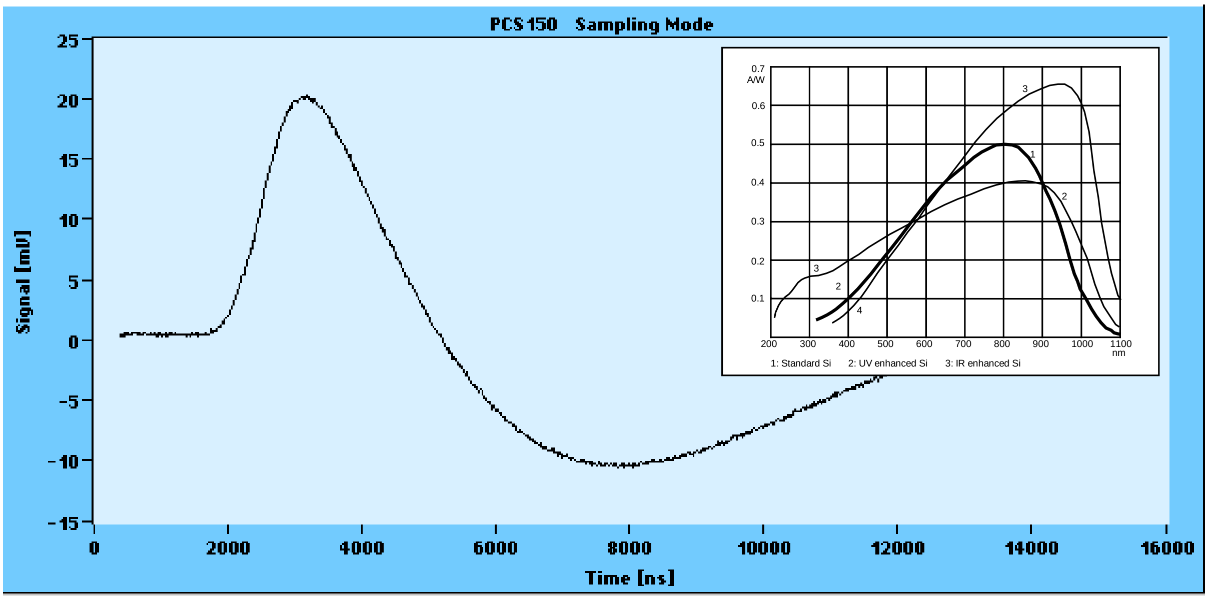
PDI-400

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

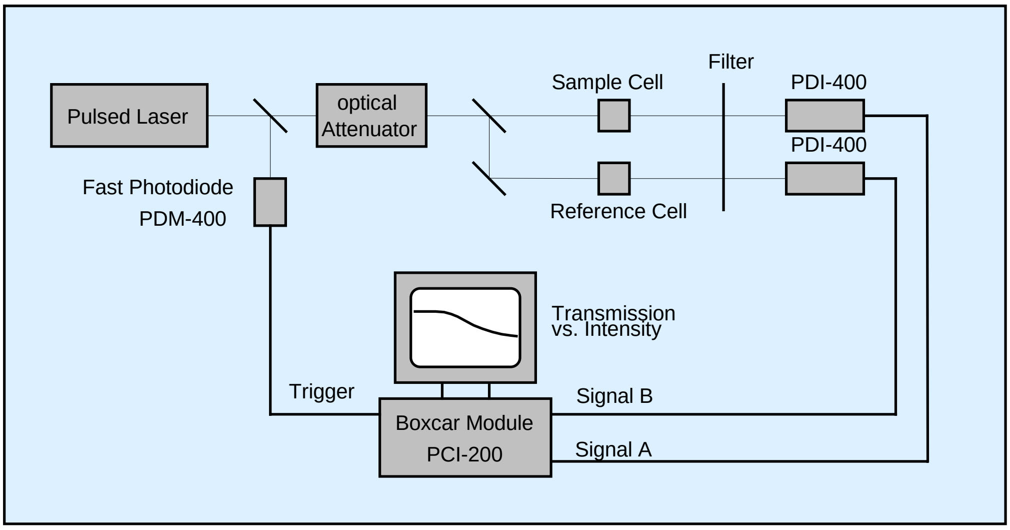
Specification

(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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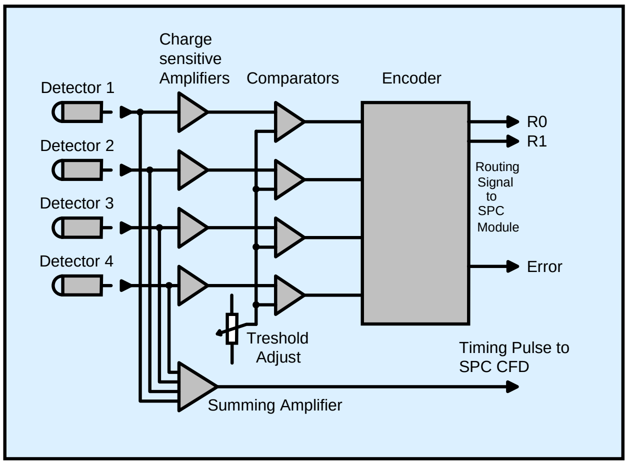
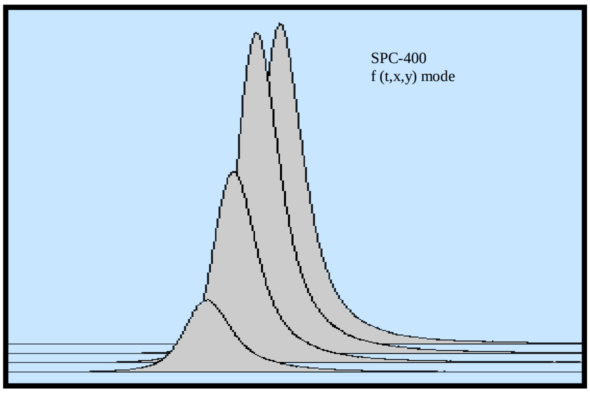
HRT - 41

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-41 module is used to connect up to four individual detectors to one bh SPC 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.





Covered by patent DE 43 39 787

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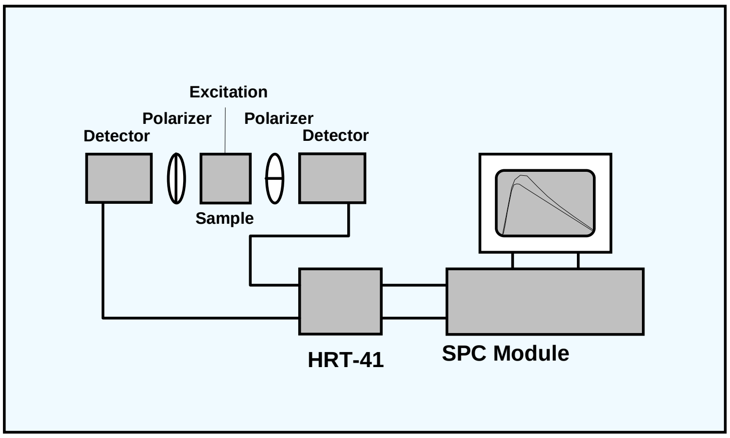
HRT - 41

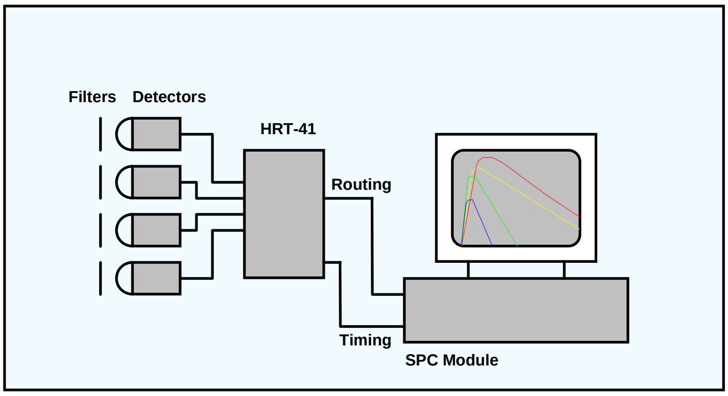
Specification

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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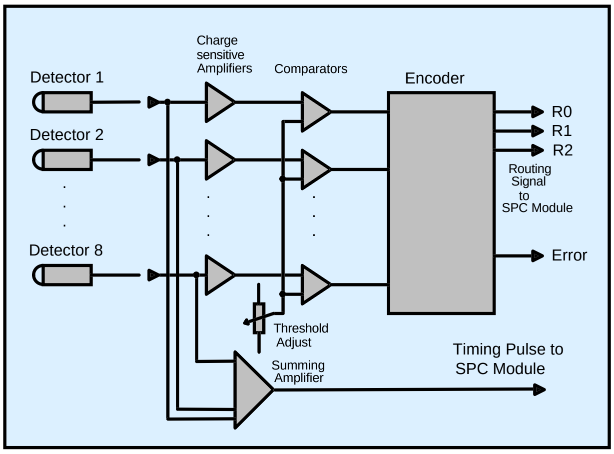
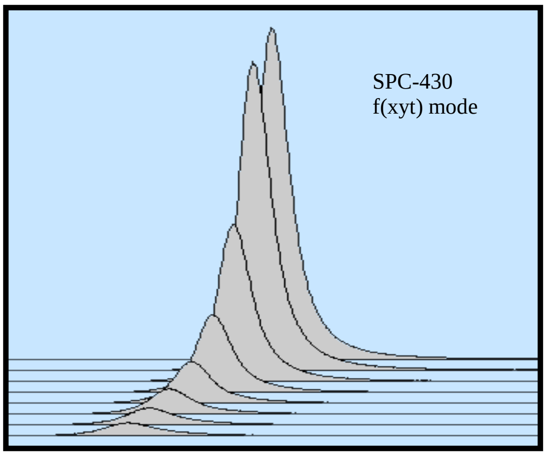
HRT-81

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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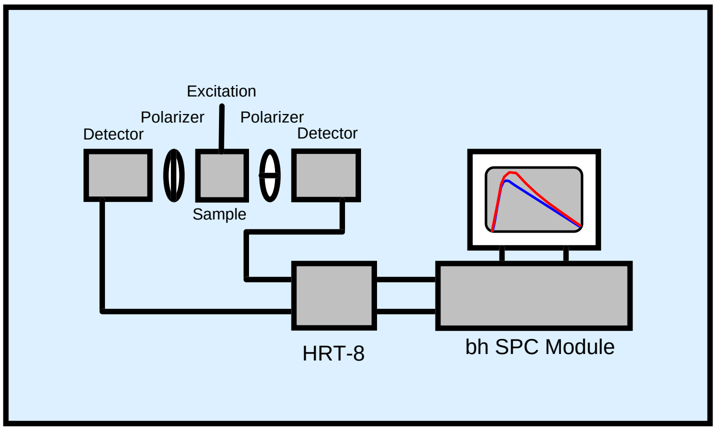
HRT-81

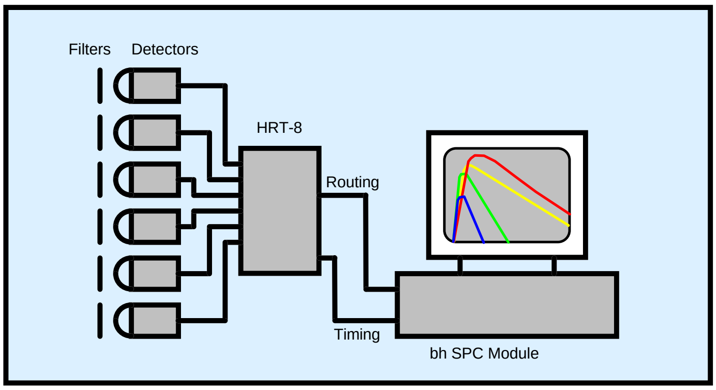
Specification

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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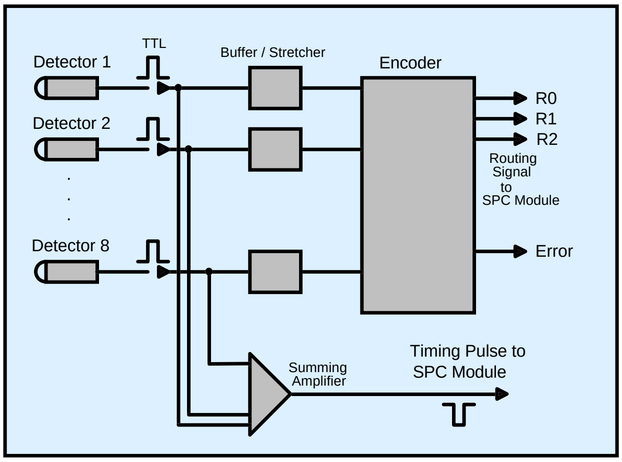
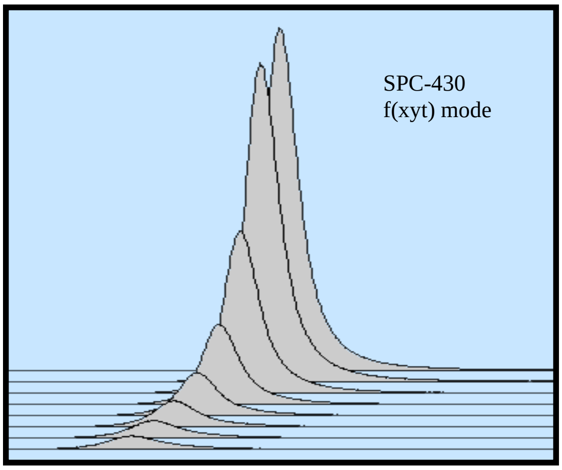
HRT-82

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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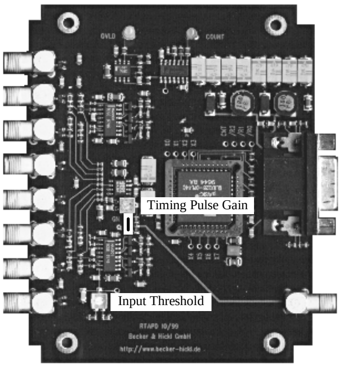
HRT-82

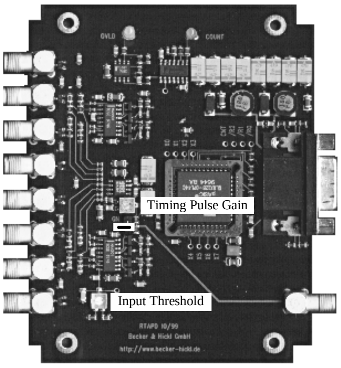
Specification

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

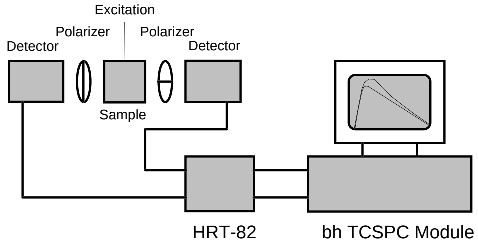


Vout = 120 ... 150 mV mV (SPC-x30)

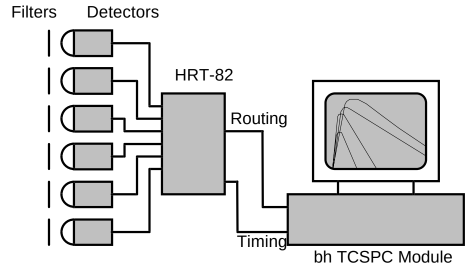


Vout = 50 ... 60 mV (SPC-x00)

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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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.

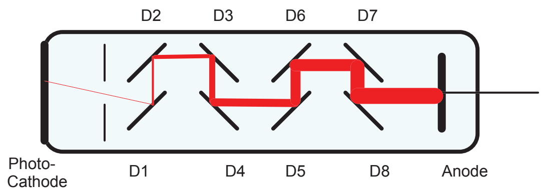


Fig. 1: Conventional PMT

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.

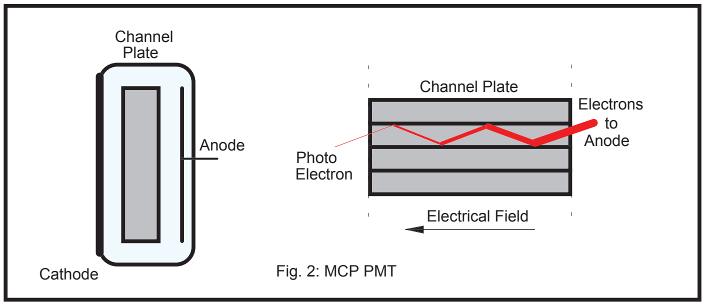


Fig. 2: MCP PMT

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.

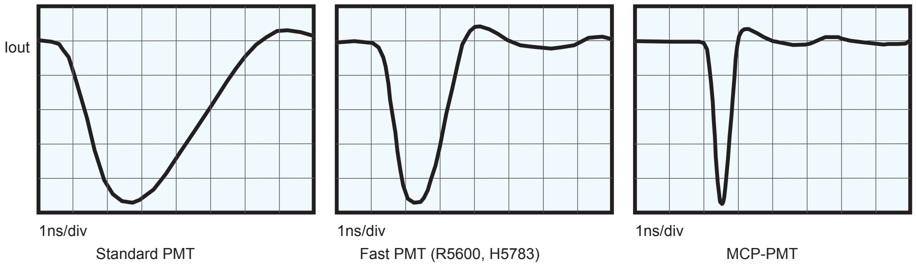


Fig. 3: Single Electron Response of Different PMTs

The peak current of the SER is approximately*

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

(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

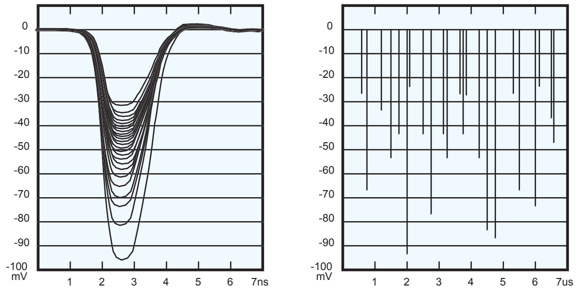
The conclusions from the table above are:

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.

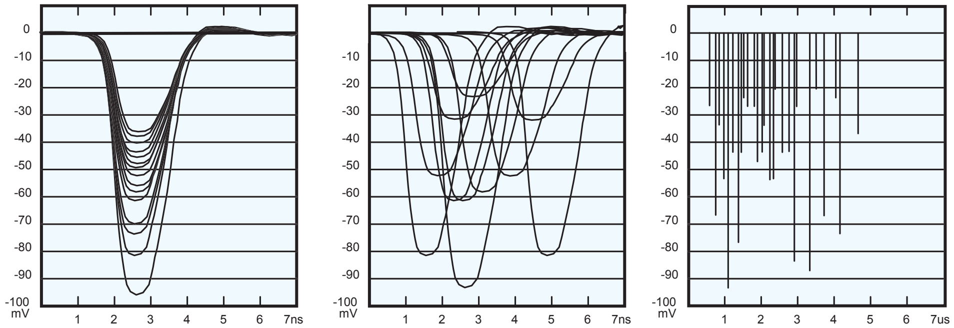
3. The peak current for a single photon , Iser, is only 1/20 to 1/100 of the maximum output pulse current, $I_{max(pulse)}$. Thus, even for light pulses no more than 20 to 100 photons can be detected at the same moment. This limits the SNR of the unprocessed PMT signal to less than 10. Actually the SNR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

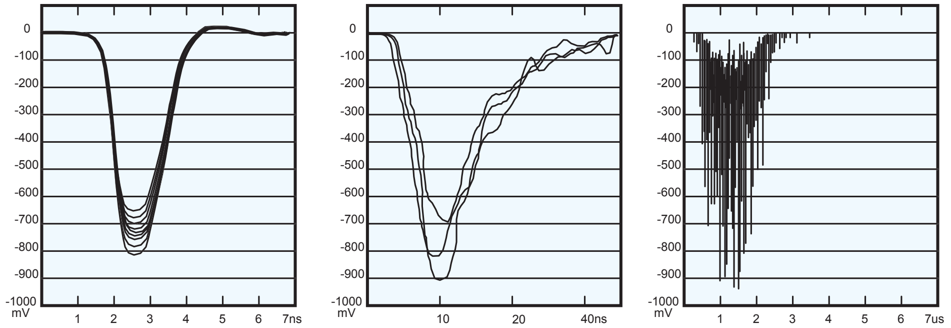
b
Continous Light, us Scale
Random SER Pulses



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.

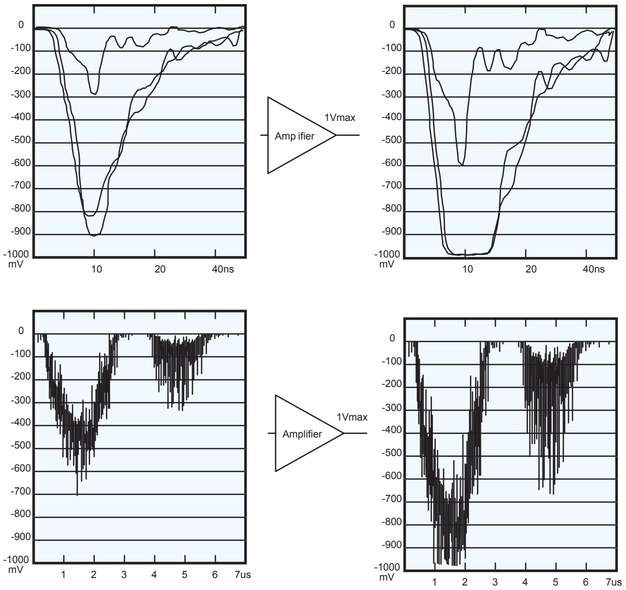


Fig. 5: Effect of an amplifier on a fast PMT signal

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.

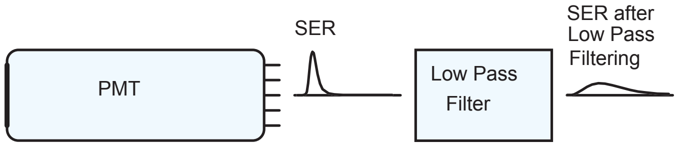


Fig. 6: Effect of Low Pass Filtering on the SER

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.

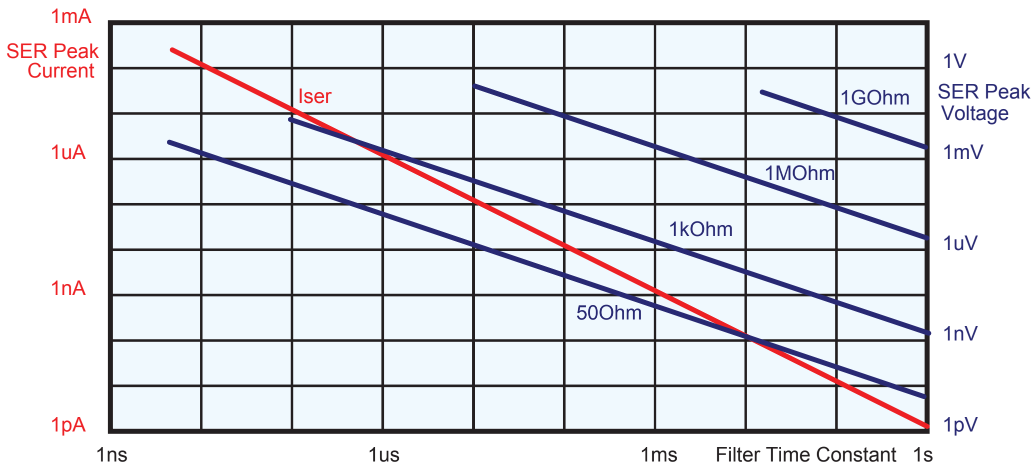


Fig. 7: Virtual SER peak current and SER peak voltage after low pass filtering

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.

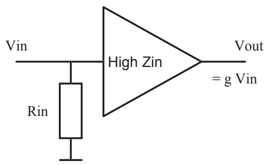


Fig 8 a: Voltage Amplifier
The voltage at the input is transferred
into a voltage at the output
The input has a high impedance

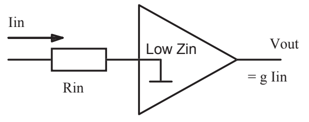


Fig 8 b: Current Amplifier
The current at the input is transferred
into a voltage at the output
The input has a low impedance

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.

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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

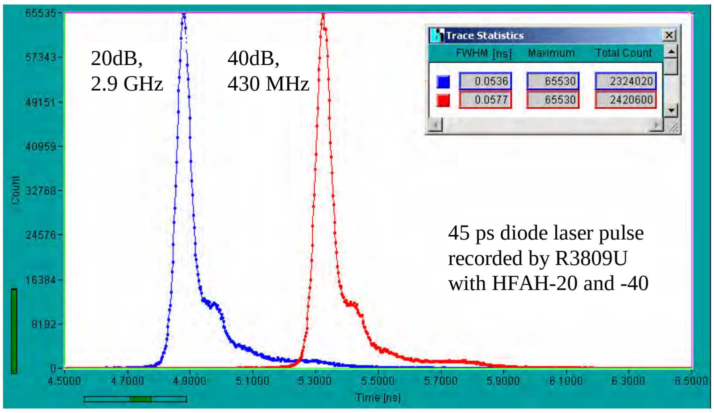
Low noise, high linearity

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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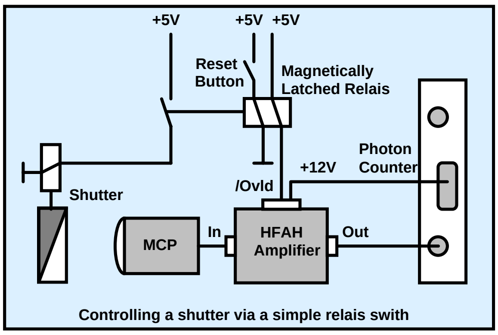
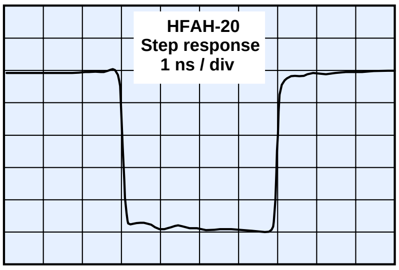
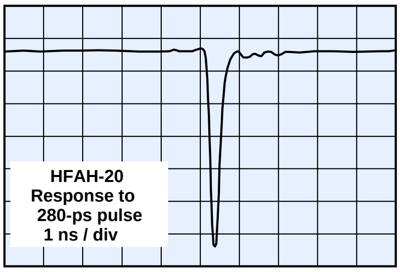


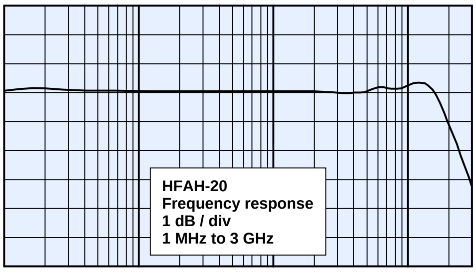
Controlling a shutter via a simple relais swith

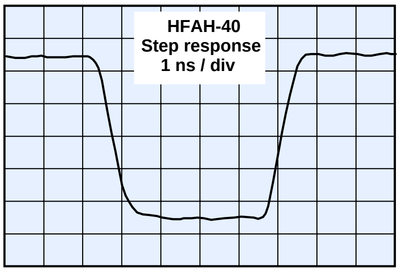
HFAH-20 HFAH-40

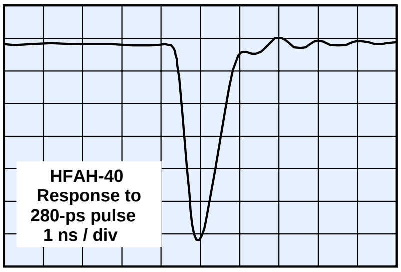
Input / output impedance	50 Ω	50 Ω
Singal Connectors	SMA	SMA
Gain	20 dB, non inverting	40 dB, non inverting
Bandwidth	2.9 GHz	430 MHz
Lower cutoff frequency	500 kHz	500 kHz
Max. linear output voltage	1V	1V
Noise Figure	4 dB	6 dB
Detector overload current threshold, I_{ovl}	0.1 1 2 or 10 µA	0.1 1 2 or 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	5 and 15: GND, 10: +12V 14: /overload (active low)	5 and 15: GND, 10: +12V 14: /overload (active low)

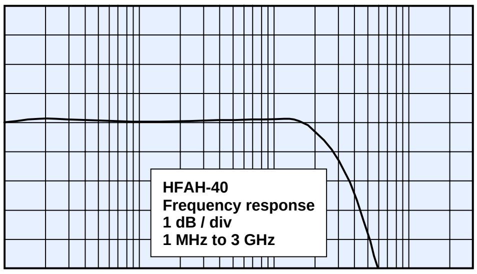


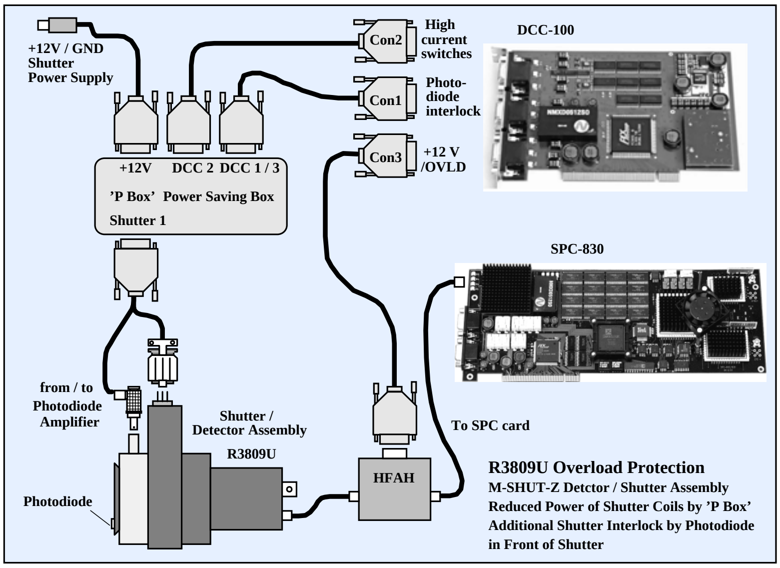












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HFAC - 26

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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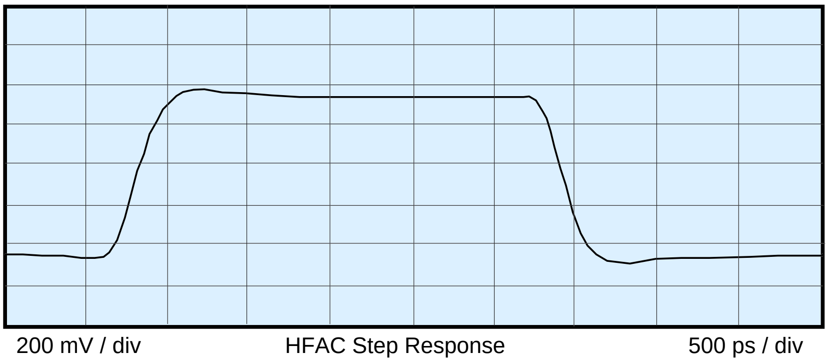
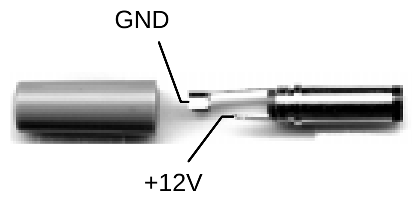
HFAC - 26

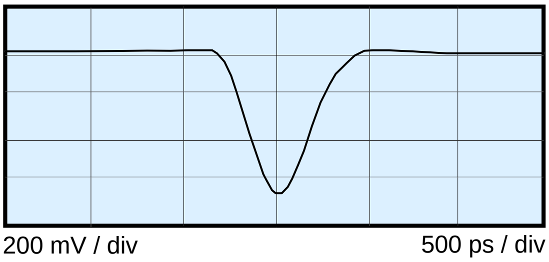
Input / Output Impedance	50 Ω
Connectors	SMA
Gain	26 dB non inverting
Bandwidth	1.6 GHz
Low Cutoff Frequency	5 kHz
Max. Output Voltage	1V
Noise Figure	5 dB
Detector Overload Current	0.1 µA, 1 µA or 10 µA (specified by extension HFAC-26-xx)
Detector Overload Warning	yellow LED at 0.5 I_{max} red LED at 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



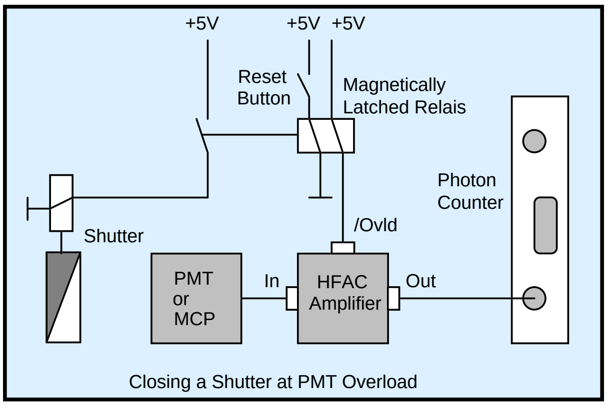
HFAC Step Response



Power Supply Connector Pin Assignment



HFAC Impulse Response



Closing a Shutter at PMT Overload

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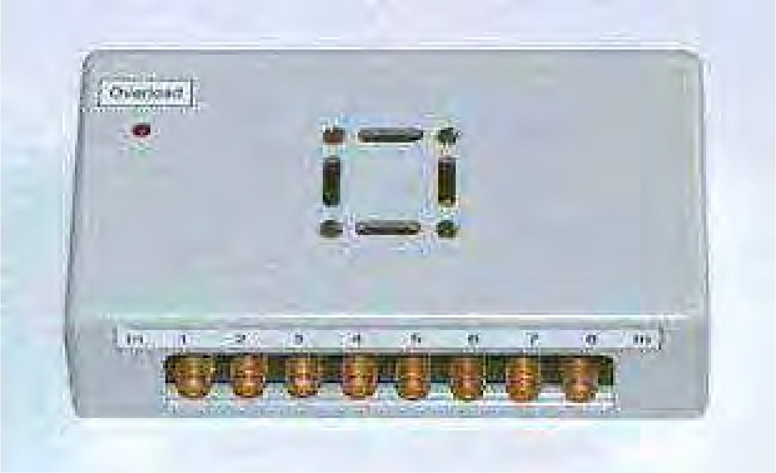
HFAM – 26

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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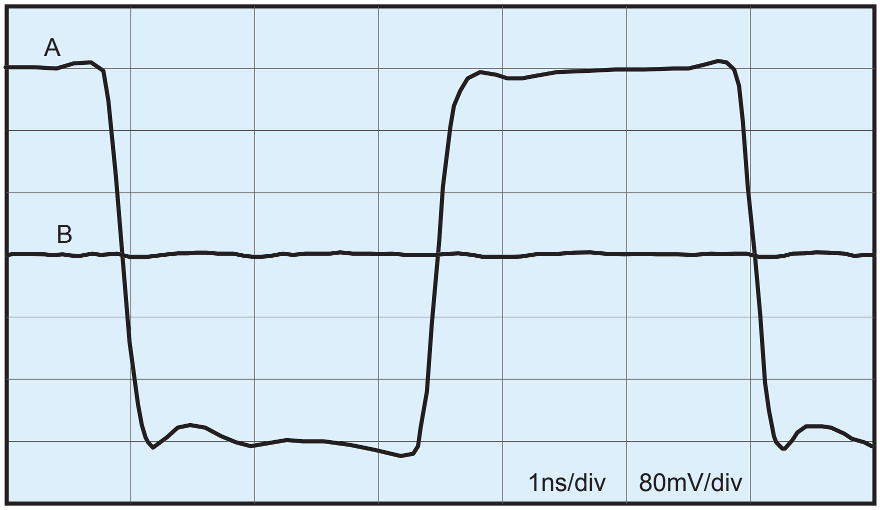
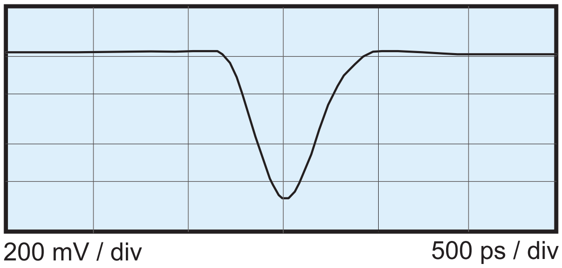
HFAM – 26

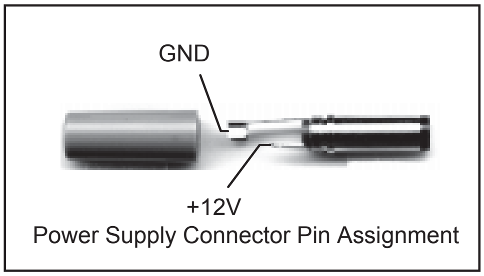
Input / Output Impedance	50 Ω
Connectors	SMA
Gain	26 dB, non inverting
Bandwidth	1.6 GHz
Low Cutoff Frequency	5 kHz
Max. Linear Output Voltage	1V
Noise Figure	5 dB
Detector Overload Current (I_{max}, please specify)	0.1 µA (for MCPs) or 10 µA (for PMTs)
Detector Overload Warning	red LED at I_{max}
Current 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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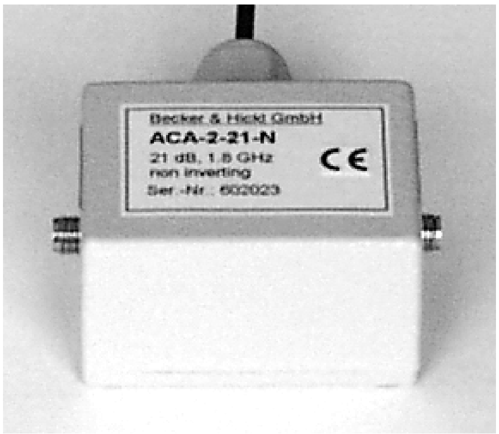
ACA - XX

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	+12 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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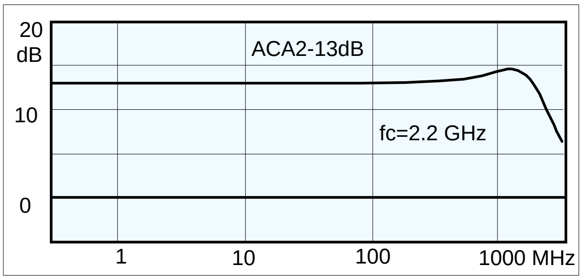
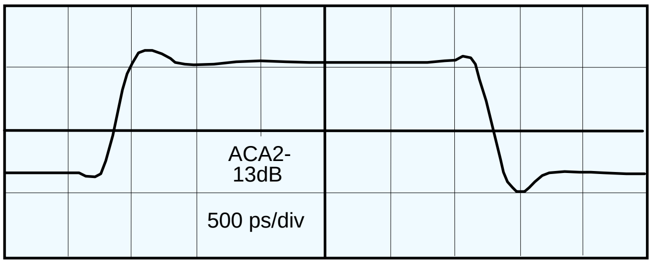
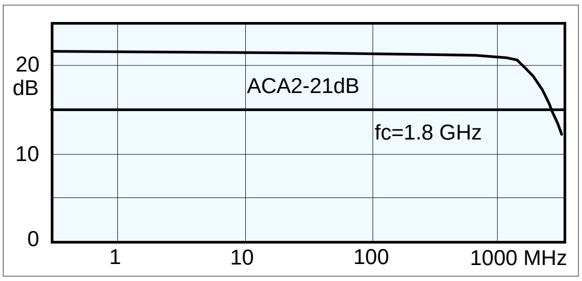
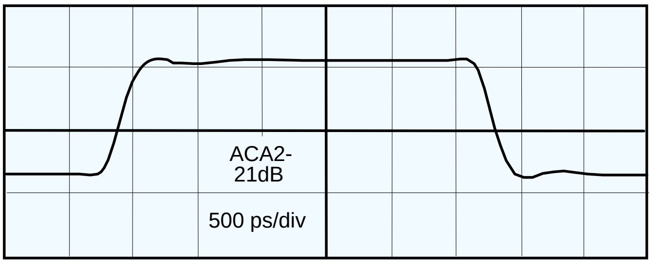
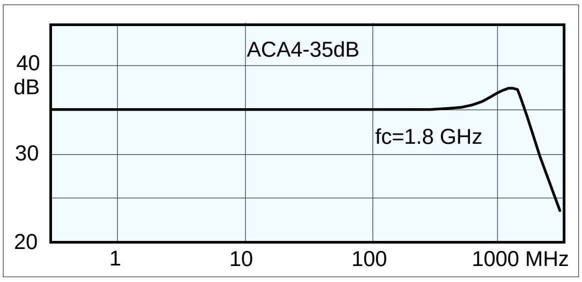
ACA Frequency and Step Response

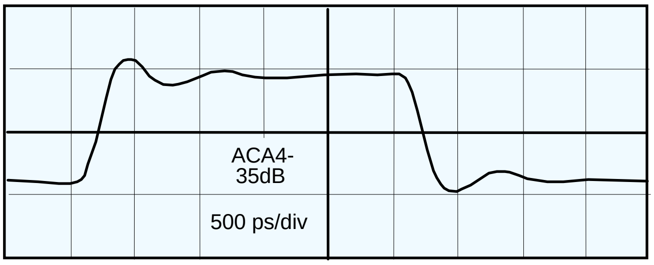


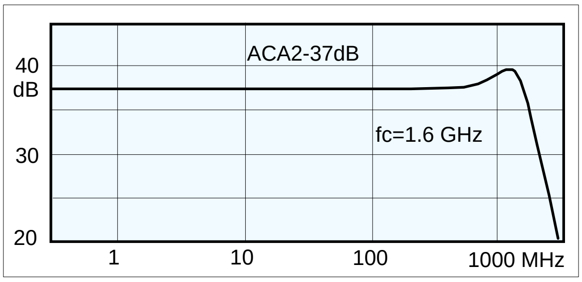


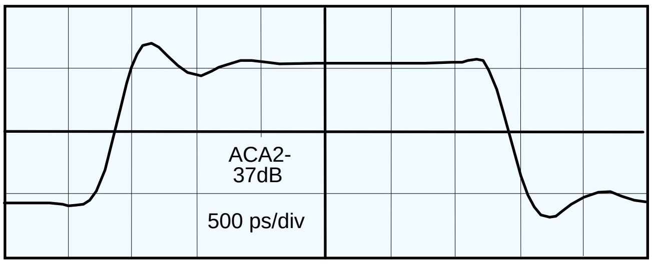












Other amplifier products: HFAC GHz Preamplifiers for PMTs and MCPs, DCA Series Low DC Drift Wideband Amplifiers, HFAM eight Channel GHz Preamplifier for PMTs and MCPs. Please see individual data sheets.

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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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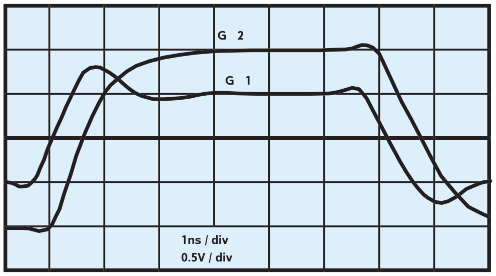
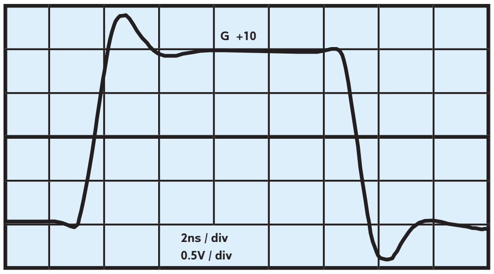
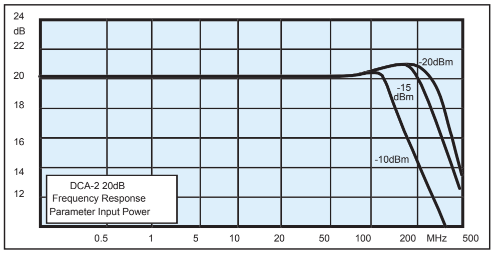
DCA –XX



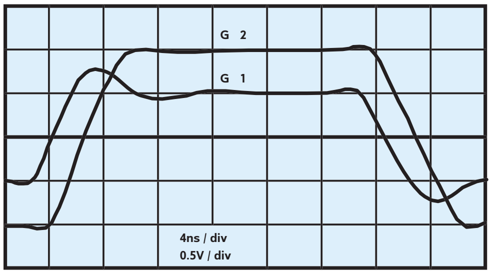
DCA-1-5V
Step Response (Gain = -1 and -2)



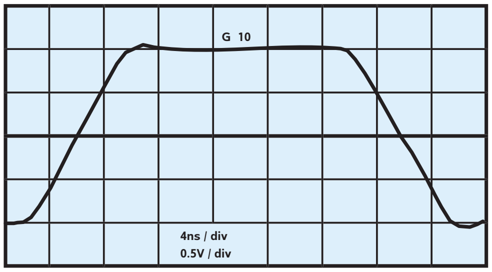
DCA-2-5V
Step Response (Gain = +10)



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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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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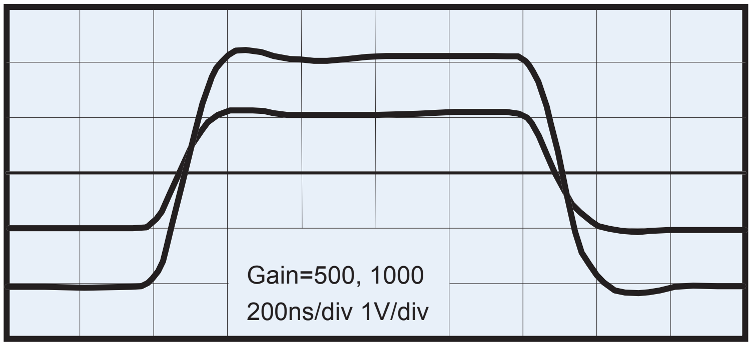
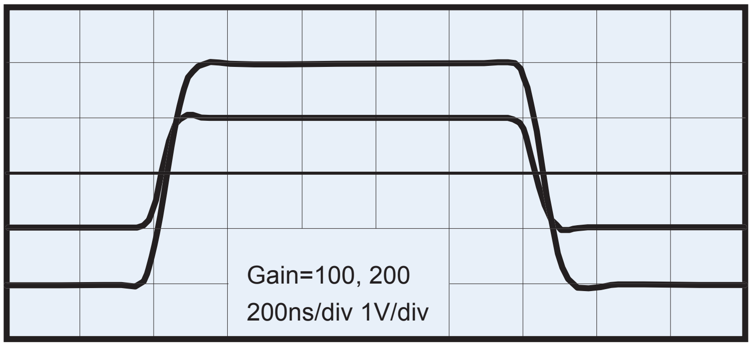
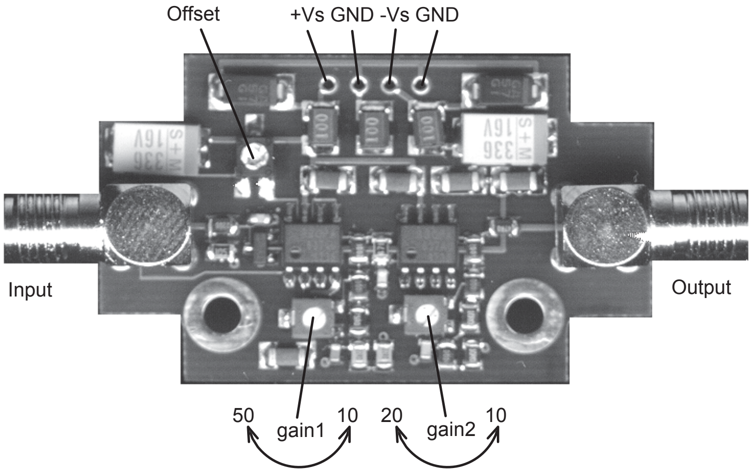
PPA – 100

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





PPA-100
Gain Setting Switches
and Offset Adjust



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