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What is Time Correlated Single Photon Counting?

Introduction to

The Becker & Hickl SPC-series Module Family

PC Based Systems

intelligent measurement and control systems

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Time-Correlated Single Photon Counting

Time-Correlated Single Photon Counting (TCSPC) is a technique to record low level light signals with picosecond time resolution. Typical applications are

- **Ultra-Fast Recording of Optical Waveforms**
- **Fluorescence Lifetime Measurements**
- **Detection and Identification of Single Molecules**
- **DNA Sequencing**
- **Optical Tomography**
- **Fluorescence Lifetime Imaging**

The method has some striking benefits:

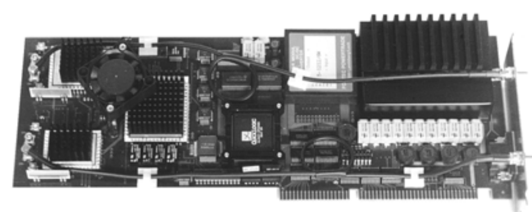
- **Ultra-High Time Resolution - 25 ps fwhm with the best detectors**
- **Ultra-High Sensitivity - down to the Single Photon Level**
- **Short Measurement Times**
- **High Dynamic Range - Limited by Photon Statistics only**
- **High Linearity**
- **Excellent Signal-to-Noise Ratio**
- **High Gain Stability**
- **Suppression of Detector Leakage Currents**

TCSPC works best for

- **High Repetition Rate Signals (MHz Range)**
- **Wavelengths from 160 nm to 1000 nm**

Measurement Principle

Time-Correlated Single Photon Counting 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. 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 of detecting 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 the figure below can be used:



Complete electronics on board - a TCSPC Module of Becker & Hickl

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 photon are very rare.

When a photon is detected, the time of the corresponding detector pulse is measured. The events are collected in memory by adding a ‘1’ in a memory location with an address proportional to the detection time. After many photons the histogram of the detection times, i.e. the waveform of the optical pulse, builds up in the memory.

Although this principle looks complicated at the first glimpse, it is very efficient and accurate for the following reasons:

The accuracy of the time measurement is not limited by the width of the detector pulse. Thus, the time resolution is much better then with the same detector used in front of an oscilloscope or another linear signal acquisition device. Furthermore, all detected photons contribute to the result of the measurement. There is no loss due to ‘gating’ as in ‘Boxcar’ devices or gated image intensified CCDs.

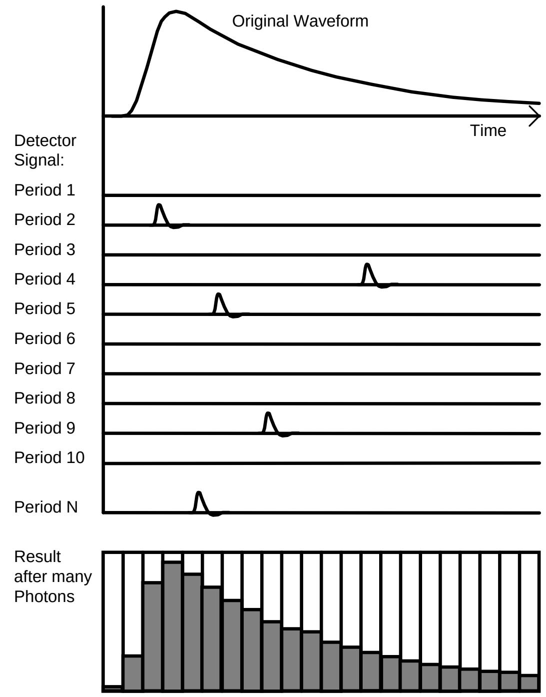


Fig. 1: TCSPC Measurement Principle

Sensitivity

The sensitivity of the SPC method is limited mainly by the dark count rate of the detector. Defining the sensitivity as the intensity at which the signal is equal to the noise of the dark signal the following equation applies:

$$S = \frac{(R_d * N/T)^{1/2}}{Q}$$

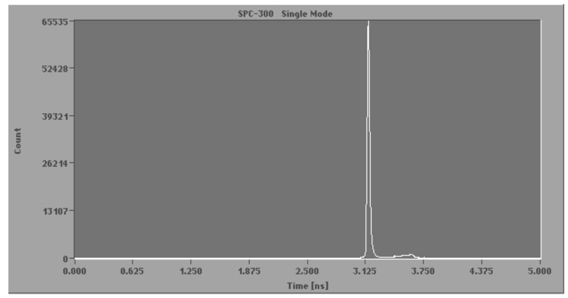
(R_d = dark count rate, N = number of time channels, Q = quantum efficiency of the detector, T = overall measurement time)

Typical values (uncooled PMT with multialkali cathode) are $R_d=300s^{-1}$, N=256, Q=0.1 and T=100s. This yields a sensitivity of S=280 photons/second. This value is by a factor of 10^{15} smaller than the intensity of a typical laser (10^{18} photons/second). Thus, when a sample is excited by the laser and the emitted light is measured, the emission is still detectable for a conversion efficiency of 10^{-15}.

Time resolution

The SPC method differs from methods with analog signal processing in that the time resolution is not limited by the width of the detector impulse response. For the SPC method only the timing accuracy in the detection channel is essential. This accuracy is determined by the transit time spread of the single photon pulses in the detector and the trigger accuracy in the electronic system. The timing accuracy can be up to 10 times better than the half width of the detector impulse response. Some typical values for different detector types are given below.

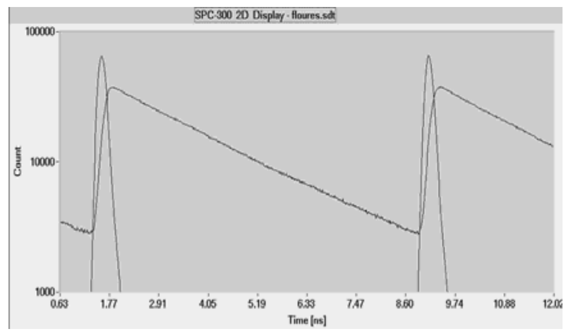
Conventional photomultipliers	
standard types	0.6 ... 1 ns
high speed (XP2020)	0.35 ns
Hamamatsu TO8 photomultipliers	
R5600, R5783	140 ... 220 ps
microchannel plate photomultipliers	
Hamamatsu R3809	25 ... 30 ps
avalanche photodiodes	60 ... 500 ps



A laser pulse recorded with 30 ps fwhm

Accuracy

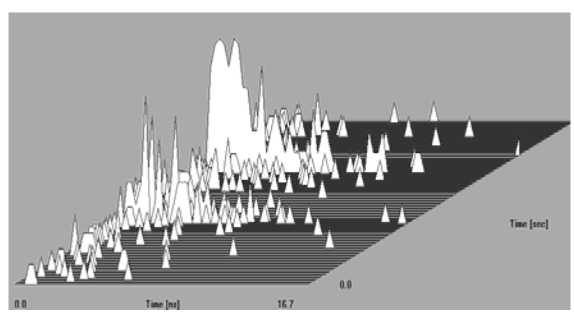
The accuracy of the measurement is given by the standard deviation of the number of collected photons in a particular time channel. For a given number of photons N the signal-to-noise ratio is $SNR = N^{-1/2}$. If the light intensity is not too high, nearly all detected photons contribute to the result. Therefore, the SPC yields a very good signal-to-noise ratio at a given intensity and measurement time. Furthermore, in the SPC method, noise due leakage currents, gain instabilities, and the stochastic gain mechanism of the detector does not appear in the result. This yields an additional SNR improvement compared to analog signal processing methods.



Fluorescence decay curves, excitation with Ar+ laser

Recording Speed

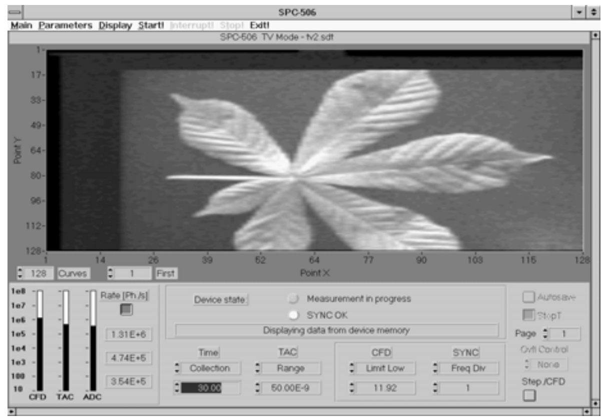
The TCSPC method is often thought to suffer from slow recording speed and long measurement times. This bad reputation comes from traditional TCSPC devices built up from nuclear instrumentation modules which had a maximum count rate of some 10^4 photons per second. State-of-the-art TCSPC devices from Becker & Hickl achieve count rates of some 10^6 photons per seconds. Thus, 1000 photons can be collected in less than 1 millisecond, and the devices can be used for such high speed applications as the detection of single molecules flowing through a capillary, for fast image scanning, for the investigation of unstable samples or simply as optical oscilloscopes.



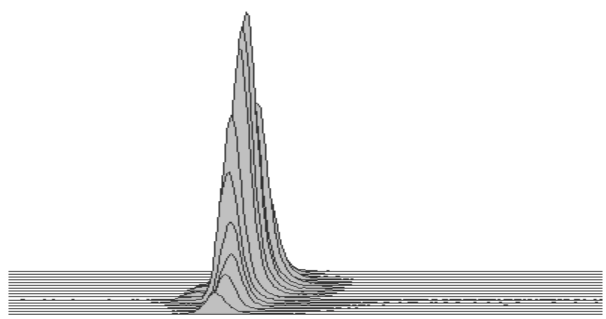
Fluorescence decay signals from single molecules running through a capillary. Collection time 1 ms per curve.

Multichannel and Multidetector Capability

Becker & Hickl has introduced multichannel and multidetector capabilities in their TCSPC modules. In the device memory space is provided for several waveforms, and the destination of each individual photon is controlled by an external signal. In conjunction with a fast scanning device, time resolved images are obtained with up to 128 x 128 pixels containing a complete waveform each. Furthermore, several detectors can be used with one TCSPC module. This technique makes use of the fact that the simultaneous detection of several photons in different detectors is very unlikely. Thus, the output pulses of several detectors are combined and an external 'Routing' device determines in which detector a particular photon was detected. This information is used to route the photons into different memory blocks containing the waveforms for the individual detectors.



A 128 x 128 pixel scan containing 16384 waveforms



16 signals measured simultaneously with a 16 channel PMT

PC Based Photon Counting Systems

Introduction

Based on a wide variety of photon counting modules Becker & Hickl delivers ready-to-use systems which contain one or more photon counting modules. Furthermore, combinations of different modules are available, and a step motor controller for experiment control can be added. Some examples for complex systems are described in this application note.
The following photon counting modules are available:

Time-Correlated Single Photon Counting Modules

- Recording of light pulses with a resolution down to 25 ps FWHM
- Time-Resolved Spectra with 25 ps Resolution
- Multi Detector Capability
- Short Measurement Times due to high Count Rates
- Optical Oscilloscope Capability
- Large Memory Versions for Image Scanning, Lifetime Imaging and Optical Tomography
- Versions for Fluorescence Lifetime Measurement of Single Molecules

Gated Photon Counting Counters and Multiscalers

- Up to 800 MHz Count Rate
- Multiscaling down to 250 ns / Channel
- Ultra-Low Background Count Rate by Gated Detection
- Steady State and Pulsed Emission Spectra
- Event Recording for Single Molecule Detection
- Bioluminescence Measurements

Multichannel Photon Counters

- Up to 32 Parallel Detector Channels with 100 MHz Count Rate

Fast Multiscalers down to 1 ns / Channel

- Luminescence Decay Measurements from ns to Seconds
- Ultra-Fast Acquisition, High Repetition Rates
- Time-of-Flight Measurements

Step Motor Controllers

- Monochromator Control and Sample Scanning

Detectors and Preamplifiers

- PMT-Modules with internal HV Supply
- Ultra-Fast MCPs for TCSPC
- Preamplifiers with Detector Overload Detection
- Photodiode Modules for Gating and TCSPC Triggering