qutools

quTAG – Time-to-Digital Converter

Time-Tagging Device with Picosecond Precision

The quTAG Family

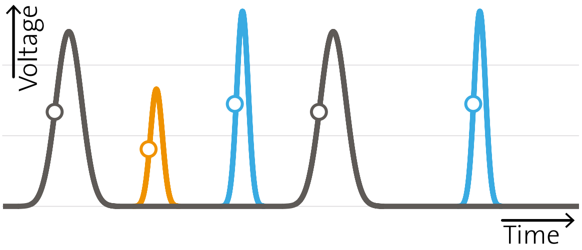
Down to 2.4 ps jitter | Up to 32 channels | Broad application variety

Time Tagging in the Picosecond Regime

Time tagging measurements determine the exact time of electrical events with picosecond precision. This universal method allows versatile setups and experiments with high timing resolution.

Every electrical event, e.g. from a single photon detector, is recognized and measured by the time tagging electronics. These events are marked with a timestamp and a list of events is created and sent to the computer for further evaluation.

The new generation of detectors are featuring a very low timing jitter and low dead times for more accurate and faster results. To use the full capacity of these detectors, the electronics have to match the requirements. We offer our time tagging systems with a jitter as low as 2.4 ps (RMS) and dead times less than 1 ns.



Channel	Timestamp
● 1	68 ps
● 2	192 ps
● 3	306 ps
● 1	417 ps
● 3	621 ps

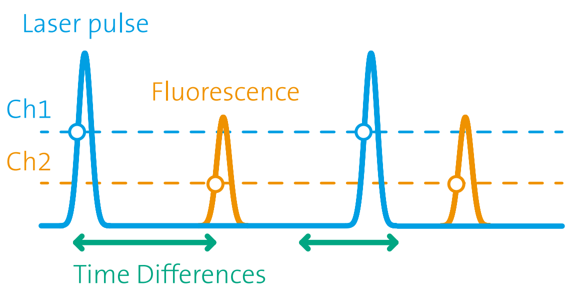
The electrical signals at the input channels are processed and a timestamp for each event is created. This list of timing events is sent to the PC.

Our universal approach allows various and versatile applications with time resolution from picoseconds up to days. The method allows correlation, coincidence and lifetime measurements within one experimental run. And even applications we did not think of yet! You can decide, even after the measurement, what kind of analysis will be performed since all information needed for any application is included in the time tag stream.

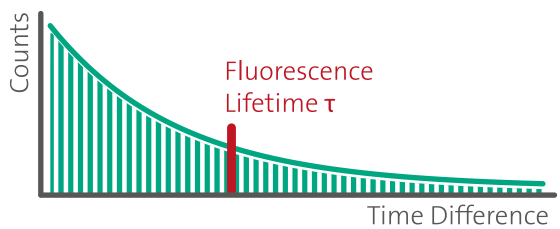
TCSPC

Together with the use of a single photon detector, like photomultipliers, single-photon avalanche diodes or superconducting nanowire detectors, the time tagging unit can be used to perform the well-known technique of time correlated single photon counting (TCSPC). TCSPC was introduced in the late 60s and was primarily used for recording fluorescence decay curves.

A typical TCSPC measurement involves a pulsed light source and a single photon detector. The trigger signal from the pulsed source and the detector signal is fed into the electronics and the time difference between the detector signal and the latest trigger signal is retrieved. These measurements are sorted into a histogram and the fluorescence lifetime can be determined. Our time tagging device in start-stop mode allows the direct output of the timing difference and easy calculation of the histogram.



A typical TCSPC measurement: electronics measure the timing difference at threshold voltages between the latest trigger pulse from the laser source and a photon event.



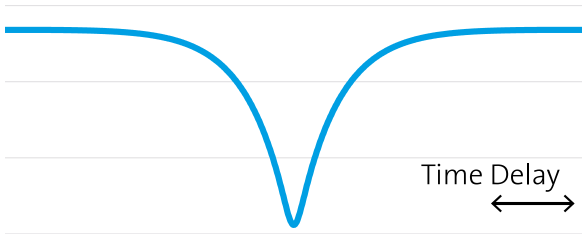
The TCSPC measurement is repeated many times and the timing difference is added to a start-stop histogram resulting in the original waveform of the fluorescent probe. The lifetime of the fluorophore can be extracted by fitting the data.

Time Tagging

The time tagging mode is the simplest but also the most versatile mode. All incoming events are time tagged relative to one starting point - normally the start of the device. This mode records all event data without even knowing what kind of evaluation is done. All measurement data is still available and the evaluation can be done on this raw data. On the other hand, the data stream can also be filtered already within the hardware to keep the recorded data as low as possible.

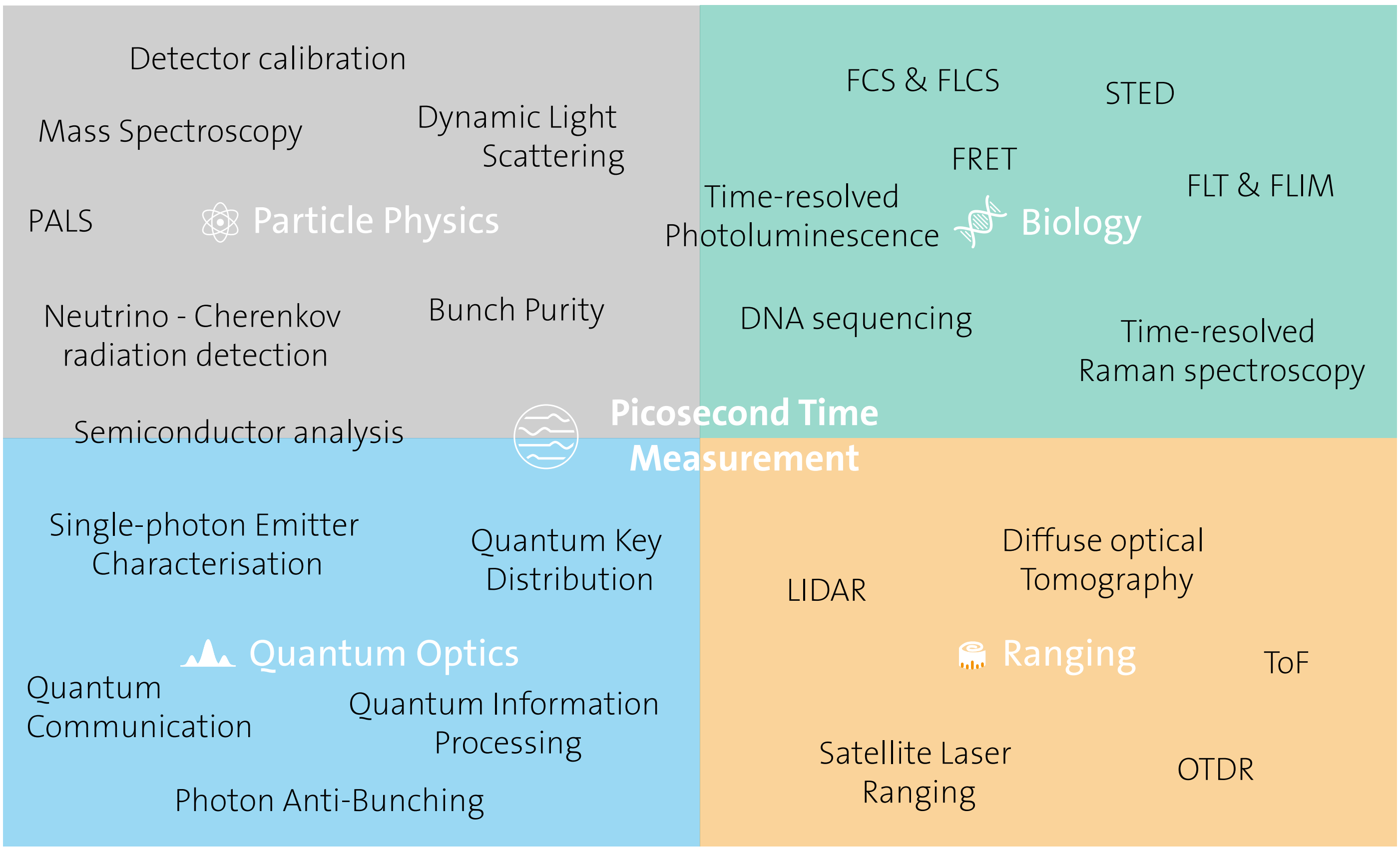
Correlation

The time-tagged event stream can be used to construct a correlation curve of the incoming data, as used in photon (anti-)bunching experiments or fluorescence correlation spectroscopy. Our time tagging electronic allows the calculation of the correlation function on-the-fly and records only the relevant histogram data without the need of recording all these timing events.



The measurement of the cross-correlation of two detector in a Hanbury Brown-Twiss setup. The data clearly shows the existence of a single photon emitter.

Application Area of Time Tagging



Picosecond measurements are used in many different kinds of experiments and applications.

Overview of the quTAG family

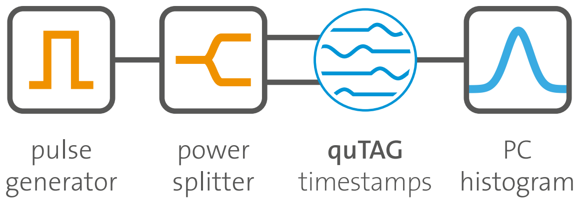
The quTAG is a versatile time-tagging device which comes in a high variety of input channels and timing jitter combinations to fulfill every requirement.

The quTAG family consists of high-end, easy-to-use time tagging devices, directly tailored to your needs. The members of the family differ in its timing resolution, number of input channels and counting rate, but have the core in common.

quTAG Family Members	Min. Jitter RMS	Number of Stop Channels	Mega Counts per Channel
quTAG Standard	3.0 ps	4-5	25 Mcps
quTAG MC series	< 20.0 ps	8, 16, 32	100 Mcps
quTAG HR series	2.4 ps	8, 16	25 Mcps

quTAG family with its three members. The variants of the members differ in the minimal jitter, number of input channels and maximal event rate per input channel. The maximum event rate per device is limited by USB 3.0 to 100 Mcps.

Jitter measurement



In order to measure the jitter, we generate an electrical pulse with steep edges. This pulse gets split into two pulses by a power splitter and sent into two different inputs of the quTAG (i.e. start and stop-X or stop-X and stop-Y). Then we use the quTAG software to generate a startstop-histogram. We fit a Gaussian function to this histogram and determine FWHM and RMS. This histogram now shows the jitter of the pulse generator and both input channels. The single channel jitter, assuming a Gaussian distribution, corresponds to $\sigma/\sqrt{2}$ from this two channel measurement.

Software

All quTAG variants include a software bundle with an easy-to-use GUI and a powerful API allowing all functions to be controlled via external software routines, like C, Python, LabView and Matlab. The timing events can easily be stored in a simple file format for postprocessing.

Use Cases

Stand-Alone Quantum-Dot Single-Photon Source for Quantum Key Distribution

Noiseless photonic non-reciprocity via optically-induced magnetization

Time-of-arrival detection for time-resolved scanning transmission X-ray microscopy imaging

Tools for the performance optimization of single-photon quantum key distribution

Hong-Ou-Mandel interference between independent III-V on silicon waveguide integrated lasers

Sub-ns timing accuracy for satellite quantum communications

quTAG Standard

State of the art time-to-digital converter

Overview

The quTAG Standard features 1 start and 4 stop input channels. A separate channel for external clock input is available on the front panel. The device allows synchronizing with up to four standard models with all 16 stop channels using the same timebase and clock input.

- 1 ps digital resolution
- Timing jitter **7.1 ps RMS** down to **3.0 ps RMS**
- **4 (+1) stop channels**
- Max. event rate per channel 25 MHz
- Sustained throughput rate 100 MHz

The timing jitter can be lowered by interconnecting input channels internally with a upgradeable feature.

Features

The quTAG Standard includes some features of the quTAG family and can also be upgraded with further ones.

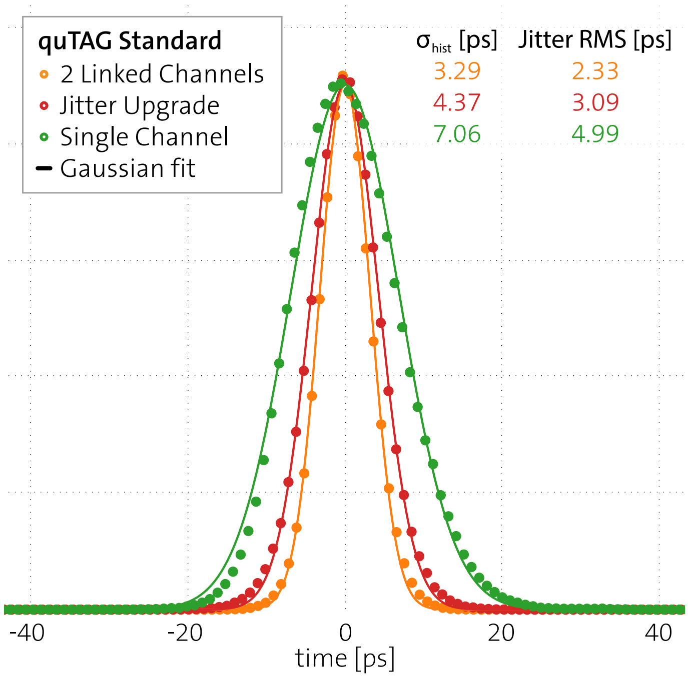
Included Features

- Software Lifetime & Correlation
- Clock input & User-defined Frequency
- Filters & Virtual Channels
- Synchronization between devices
- Divider for Start Channel

Available Upgrades

- Divider for Stop Channels
- Start as Stop Channel
- Jitter Upgrade
- Marker Input
- Single-Quantum-Input-Optimisator

Timing Jitter



Jitter determination of a quTAG Standard by histograms of two stop channels each. Jitter Upgrade and channel linking reduce the timing jitter. The histograms correspond to a jitter of a single channel with $\sigma/\sqrt{2}$.

The timing jitter can be lowered by the Jitter Upgrade feature for quTAG standard. Additional jitter reduction by linking input channels internally and measuring one single input signal by multiple channels is possible. The results are getting averaged automatically. Two channels can be linked internally to achieve the lowest timing jitter of 3.0 ps RMS. The external SMA plugs of the channels used for the linking are then disabled.

Variant	Stop Ch.	Jitter RMS [ps]
Standard	4	7.1
Jitter Upgrade	4	4.5
Jitter Upgrade & Linking	2	3.0

Internally linked stop channels reduce the timing jitter down to 3 ps RMS of a single channel.

quTAG MC Multi Channel

Multi channel time-to-digital converter

Overview

The quTAG MC has 1 start and 8, 16 or 32 stop input channels. An external clock input is also available. The device allows synchronizing multiple quTAGs by a clock output.

- 1 ps digital resolution
- Timing jitter **< 20 ps RMS**
- Up to **32 stop channels**
- Max. event rate per channel 100 MHz
- Sustained throughput rate 100 MHz

Variants

The quTAG MC comes in three different variants with a different number of input stop channels and the same timing jitter. The variants also differ in height (rack units U) and number of touch displays.

Variant	Stop Ch.	Jitter RMS [ps]	Display & Height
MC-20/08	8	< 20	5 displays, 1 U
MC-20/16	16	< 20	10 displays, 2 U
MC-20/32	*32*	< 20	10 displays, 2 U

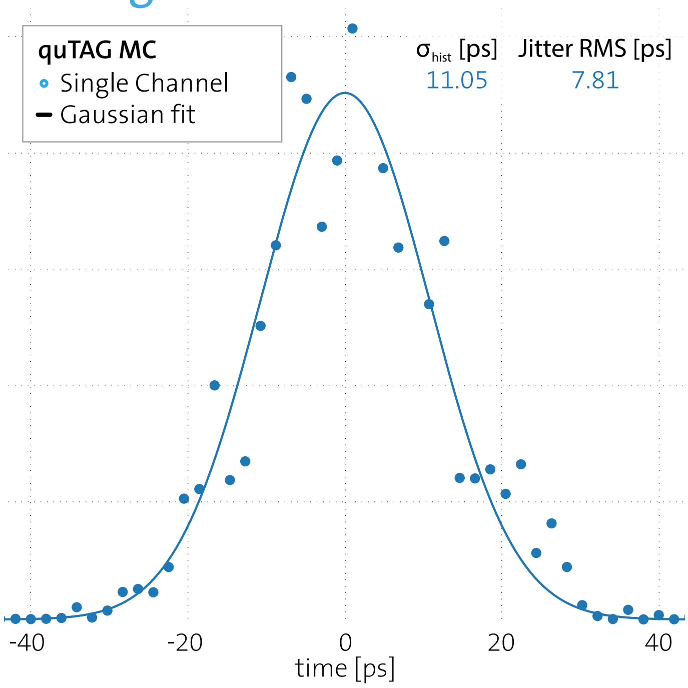
Features

The quTAG MC variants include some features of the quTAG family and can also be further upgraded.

Included Features
- Software Lifetime & Correlation
- Clock input & User-defined Frequency
- Filters & Virtual Channels

Available Upgrade
- Marker Input
- 2 Output Channels
- Synchronization of devices
- Single-Quantum-Input-Optimisator

Timing Jitter



Jitter determination of a MC-20/32 by a histogram of two stop channels measuring the same signal, split up by a power splitter. The MC comes with more input stop channels with higher jitter and a lower cost per channel ratio.

All quTAGs appear in a 19" rack with different numbers of input channels, displays and height in universal 1 or 2 rack units. At 32 channel devices, 16 channels are in front and the rest at the rear side of the device. The rear side also includes USB, Ethernet and a GPIO port.

quTAG HR High Resolution

High resolution time-to-digital converter

Overview

The quTAG HR has also 1 start and 8 or 16 stop input channels. An external clock input is also available. The device allows synchronizing multiple quTAGs by a clock output.

- 1 ps digital resolution
- Timing jitter **6.4 ps RMS** down to **2.4 ps RMS**
- Up to **16** high resolution **stop channels**
- Max. event rate per channel 25 MHz
- Sustained throughput rate 100 MHz

Variants

The quTAG HR comes in three different versions with a different number of input stop channels and different timing jitter. The variants also differ in height (rack units U) and number of touch displays.

Variant	Stop Ch.	Jitter RMS [ps]	Display & Height
HR-04/08	8	4.5	10 displays, 2 U
HR-06/08	8	6.4	5 displays, 1 U
HR-06/16	*16*	6.4	10 displays, 2 U

Features

The quTAG HR variants include some features of the quTAG family and can also be further upgraded.

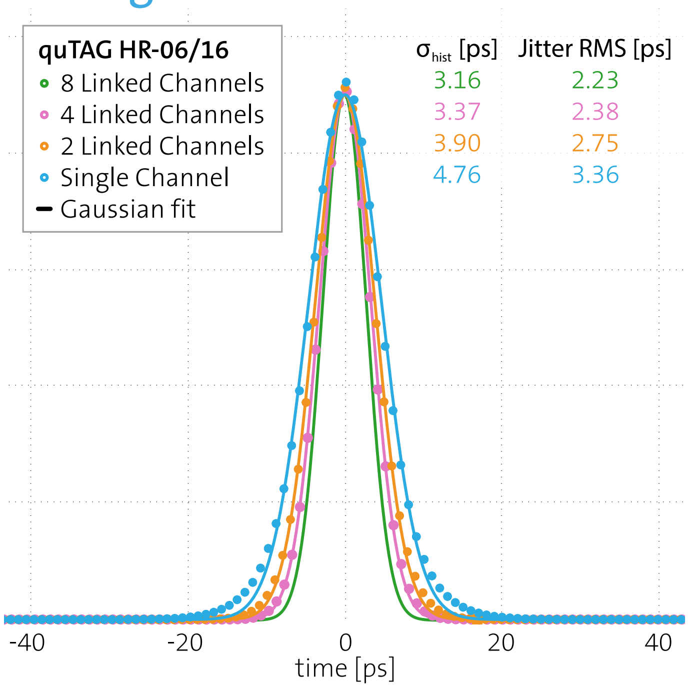
Included Features

- Software Lifetime & Correlation
- Clock input & User-defined Frequency
- Start as Stop Channel
- Filters & Virtual Channels
- Divider for Start and Stop Channels

Available Upgrade

- Marker Input
- 2 Output Channels
- Synchronization of devices
- Single-Quantum-Input-Optimisator

Timing Jitter



Jitter determination of a HR-06/16 by histograms of two stop channels each. Internally linking channels reduces the timing jitter. The histograms correspond with $\sigma/\sqrt{2}$ to a jitter of a single channel.

The timing jitter can be lowered by linking input channels internally by software and measuring one single input signal by multiple channels.

The linked channels are then averaging that one signal automatically. Two, four or up to eight channels can be linked internally to achieve the lowest timing jitter of 2.4 ps RMS. The external SMA plugs of the channels used for linking are then disabled.

Variant	16 Ch	8 Ch	4 Ch	2 Ch
HR-04/08		4.5	3.2_L	2.4_L
HR-06/08		6.4	4.5_L	3.2_L
HR-06/16	6.4	4.5_L	3.2_L	2.4_L

Linked stop channels reduce the timing jitter. The table shows the three quTAG HR variants and their single channel timing jitter RMS in picosecond with the resuming stop input channels without and with linked channels $_L$.

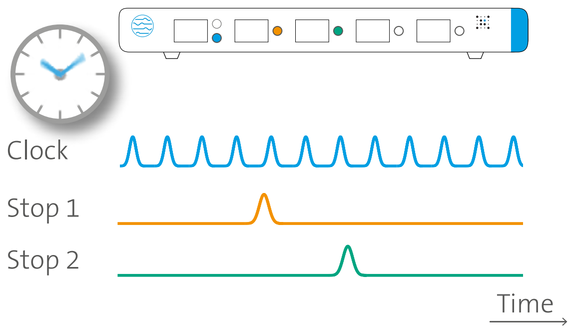
Options and Features

The quTAG offers a lot of optional features making it the most versatile device on the market. You can decide which features are essential for your experiments and choose to tailor the device specific to your needs.

Every experiment is different and so are the requirements for a time-to-digital converter. The quTAG is developed with your needs in the focus. It offers a lot of optional features that fit directly to your needs – you get your optimal solution with only the features you really need. And if your plans change, you can upgrade most of the features directly at your place – it is flexible and grows with your requirements.

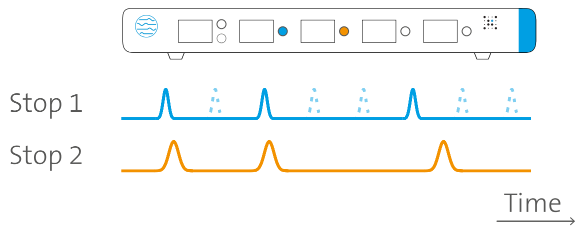
Clock Input & User-defined Frequency

The internal timing of the quTAG is crystal calibrated to provide very good timing accuracy. An external time base, e.g. from an atomic clock or a laser trigger, can be used to synchronize this internal clock to gain even better resolution. The external frequency can be adjusted to any frequency between 1 MHz and 100 MHz. quTAG MC and HR also have a clock output to synchronize clocks of multiple devices.



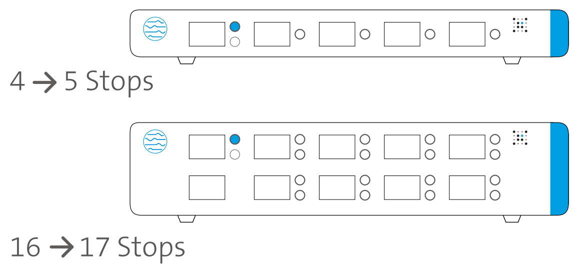
Filter & Virtual Channels

A lot of experiments produce data that are irrelevant for any evaluation. The quTAG has a built-in filter routine for the first five channels that already filters any signal you don't need. This can be unused trigger signals in one channel, coincidence measurements between two channels or gating filters. This filtering happens already inside the quTAG, so bandwidth on your USB connection and processing power on your PC also are saved.



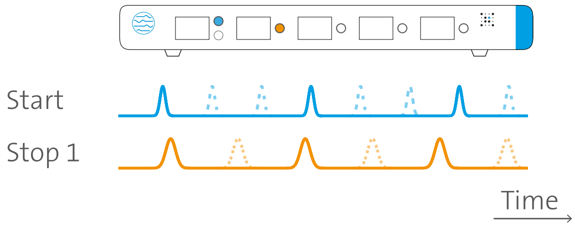
Start as Stop Channel

The quTAG can be configured with your needs of input channels. The start channel can be converted to a full stop channel and used in the time tagging mode with the full resolution of the other channels. All channels are completely independent but synchronized internally.



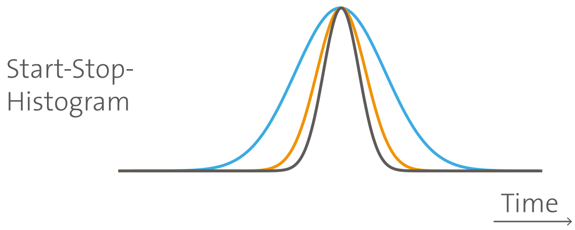
Input Divider Start and Stop

An input divider can be activated on the start and stop channels. This measures only every nth pulse, depending on the divider parameter 1, 2, 4 or 8. By dividing a periodic signal, higher frequencies can be measured. The “lost” time stamps can be reconstructed in the PC afterwards. *Available for quTAG Standard, HR.*



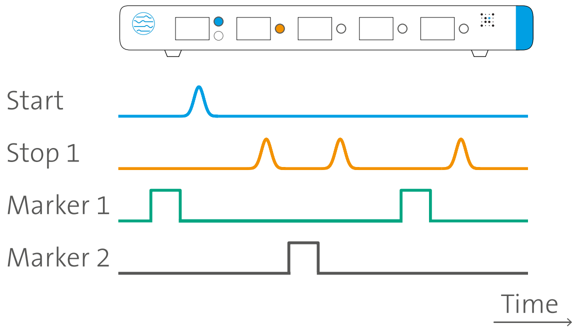
Jitter Upgrade Extension

This feature allows lower jitter at < 4.5 ps (RMS) on all four input channels of the quTAG Standard. For lowest jitter of < 3.0 ps, two channels can be combined, leaving two stop-channels of one device for measurements. For optimal jitter results, recalibration with external signals might be necessary. *Integrated in quTAG HR, available for quTAG Standard.*



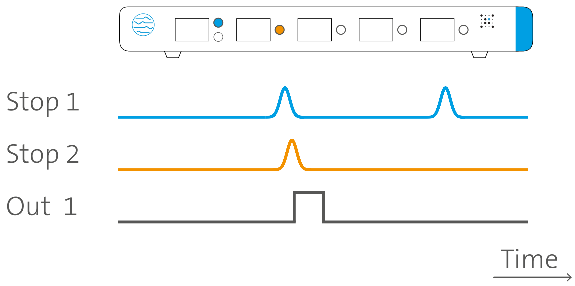
Marker Extension

Additionally to the stop channels with full resolution, marker inputs are added to the quTAG. These low-resolution inputs recognize (LV)TTL signals and insert them into the time tag stream. The marker inputs are used for any marker or trigger signals which sort the relevant part of your data, e.g. scanning trigger in microscopy.



2 Output Channels Extension

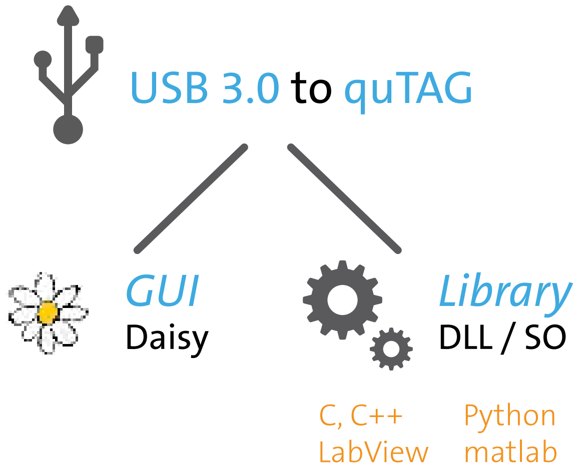
The quTAG can be enhanced with two output channels which generate TTL pulses as a function of the input channels. Several detection patterns like coincidences can trigger an output pulse train depending on your needs and exactly tailored to your experiments. *Available for quTAG MC, HR.*



Software

The quTAG comes with a huge and powerful software solution. The intuitive GUI allows control and setup of many experiments with a simple click. The included API easily integrates the device into your environment.

All quTAG variants include a software bundle with an easy-to-use GUI and a powerful API allowing all functions to be controlled via external software routines, like C, Python, LabView and Matlab. All functions are included in the packages, you can get the time-stamps directly or save it in a simple file format to your hard disc for later processing by your own analysis software. The software is available for Windows and Linux in 32bit and 64bit.



Daisy GUI

The Daisy - Data Acquisition and Imaging System - GUI is the simplest form to work with the quTAG. All functions can be used with a simple click. All parameter of all input channels can be assessed easily and adjusted with the graphical interface. No need for compensation cables, no need for voltage adaption.

Library and API

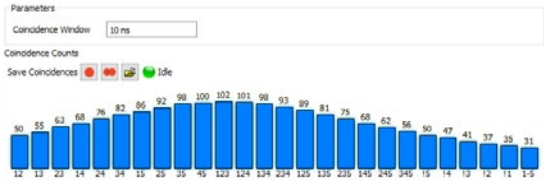
The quTAG API is a powerful library for complete control and handling measurement results from the quTAG hardware. The library is written in C/C++ and can be integrated in various programming environments like Python, Labview and Matlab. A wrapper for Python and Labview is available. The API allows easy integration into your environment, supported by various example codes.

```
# Import the python wrapper which wraps the DLL functions.
import QuTAG

#Initialize the quTAG device
qutag = QuTAG.QuTAG()
# Set the exposure time of the internal coincidence counters in milliseconds
qutag.setExposureTime(1000)
# Give some time to accumulate data
time.sleep(1)

# Now let’s retrieve the most recent channel and coincidence counters from quTAG.
data,updates = qutag.getCoincCounters()
print(‘Updates since last call: ‘, updates, ‘| latest Data: ‘, data)
# updates    Output: Number of data updates by the device since the last call.
# data       Output: Array counts and coincidences.
```

Short coding example in Python to retrieve count and coincidence rates of a quTAG.

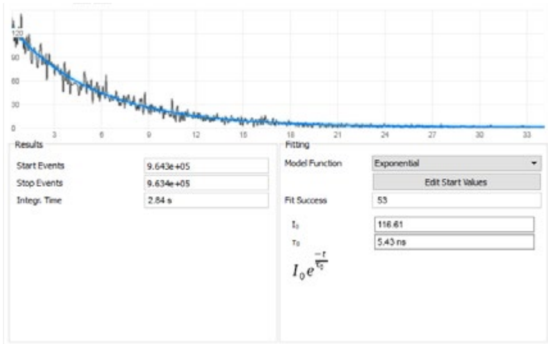
Coincidences & Counting

One of the most needed functions is the determination of count rates of each stop channel (singles) and the coincidence counting of two or more channels. The quTAG determines all of these count rates already in the device, so there is no need for evaluation of the time tags in the PC. The coincidence window can be freely adjusted by the user with the step size of the digital resolution.



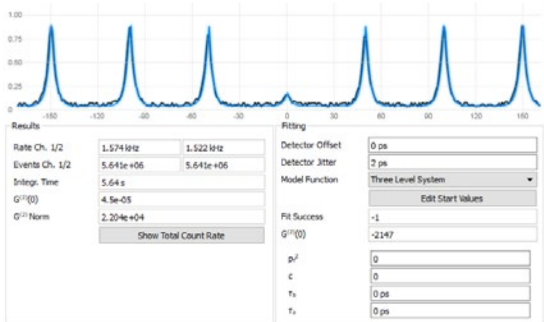
Histograms & Lifetime

The histogram and lifetime software of the quTAG easily analyzes a start-stop histogram or the lifetime of your probe. You just select the start and the stop channel and the width of your data. The software calculates the histogram (start-multistop) and fits the appropriate function to the data. The lifetime values are available with just one click in the software or can be called by one function in the API.



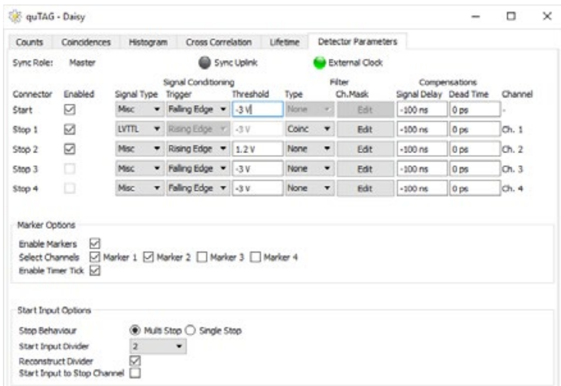
Correlations

The second-order correlation function - as used e.g. for the characterization of a single photon emitter in a Hanbury Brown-Twiss setup - can be generated easily with this software extension. You just have to set the two input channels and the width of your data and the software calculates the histogram including normalization and fits the appropriate function. This is also available as a function call in the API.



Settings

The delay, the threshold and an artificial dead time is adjustable with just one click in the GUI. The analysis of the data or just the storage of raw timestamps is possible and saved in a universal file format, either in ASCII or in a packed binary format that is completely described and accessible via your own software.

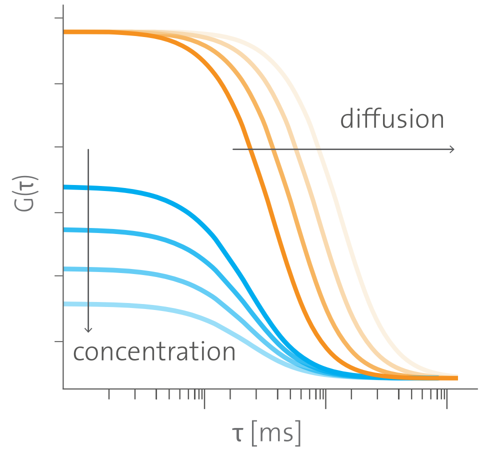


Applications

The quTAG is a versatile device that is used in a broad range of experiments. These examples give you an overview what is possible. Contact us with your application idea and together we will make that possible!

Fluorescence Correlation Spectroscopy

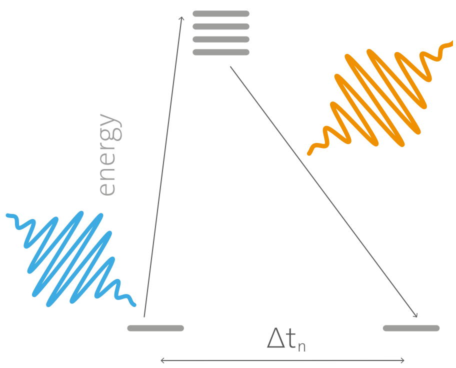
Information about the diffusion, concentration and binding properties of a biological sample can be acquired by the temporal fluctuations of fluorescence emission. The setup of this fluorescence correlation spectroscopy experiment is very similar to a FLIM setup. In a FCS measurement, a small volume of the sample is analyzed. The concentration of the fluorophores is typically so low that at most one fluorescent molecule is excited and its emission is recorded with single photon detectors.



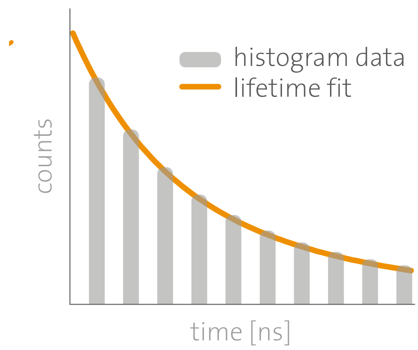
FCS can also be combined with lifetime measurements which allows a better assignment of photon arrivals to a specified fluorophore or measurements of protein-protein interactions. Therefore, a pulsed laser is needed and the relative time to the last pulse and beginning of the experiment is measured.

Fluorescence Life-Time

Fluorophores have beside a distinct excitation and emission spectra a specific lifetime. Measuring this lifetime allows to distinguish between two fluorophores with the same measured emission spectra. Fluorophores with a difference in lifetime can be imaged simultaneously with a much higher signal-to-noise ratio compared to conventional fluorescence microscopy.

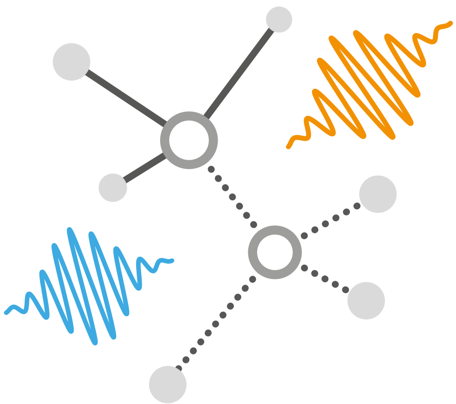


In the time-domain fluorescence lifetime imaging, a pulsed excitation source with short pulses is needed and the time between laser excitation and fluorescence emission is measured for each photon. Every arrival time is added to a histogram which provides the lifetime curve of the fluorophore. Analysis software fits an exponential curve to determine the lifetime – in many cases more than one lifetime is fitted giving rise to different pathways of decay.



NV Centre Microscope

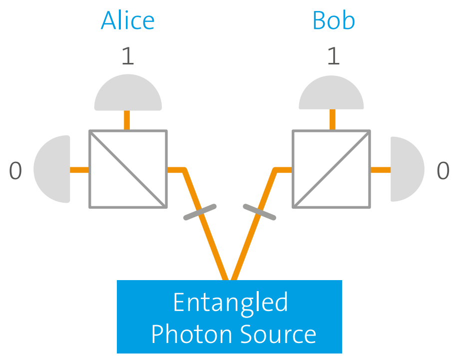
In one of its allotropes, carbon forms a cubic lattice, called diamond. Within the diamond lattice numerous types of defects can exist. One of these defects is the nitrogen-vacancy (NV) center. It is formed by a substitutional nitrogen atom associated with a neighboring vacancy.



The electron spins of the NV center can be manipulated at room temperature with microwave radiation or by applying magnetic or electric fields. Therefore, the NV center is suitable for quantum sensing applications and is also a promising candidate for quantum information processing.

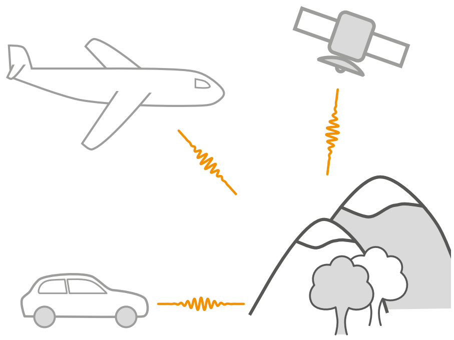
Quantum Key Distribution

Quantum Key Distribution (QKD) enables secure communication by sharing an encryption key based on quantum mechanical principles. The communication between two parties needs a shared secret key for encryption. By using QKD any attempt of eavesdropping of a third party is detected. The actual transmission of data is usually done by using the distributed key to encrypt the message to be sent. Most quantum cryptography protocols rely on single photons and its detection in a precise timing resolution.



LIDAR

Light detection and ranging - short LIDAR - is a method measuring the round-trip time of a light pulse to acquire the distance to an object. Combined with rotating mirrors - often referred as “3D laser scanning” - the measurement direction and the distance to the object assign coordinates in the room.



A special application of LIDAR is the satellite laser ranging where a laser beam is aligned to a satellite and its position is precisely determined to avoid collisions. This method is also be used to determine the tectonic drift on a global scale or map forest structures and characterize wildlife habitats.

Company portrait qutools

Highly individualized tasks can be mastered as we have flat hierarchy and a great spectrum which covers all competences.

We are convinced of all of our products – and our costumers rely on our long-term development competences, our understanding of science and honest consultation on highest level. All products can be customized as we always focus on optimizing the device for your application. We have special experience and know-how on the following fields:

Optics

In 2005 qutools started building demonstrators for entangled photons, fiber optics and single photon sources. Since then we gained further experience on many fields like interferometric length measurements, color centers in diamond, quantum dots or fluorescence spectroscopy.

Electronics

Our competence in analogue- and mixed-signal-electronics enables ultra-fast time measurements on the picosecond scale. Moreover, individual interfaces and ports for communication can be realized on demand.

Software

We provide and develop software for data collection and analysis as well as the GUI for all operating systems. Even atomic force microscopes can be controlled via tablet app.

Embedded Software

More than 15 years of experience in programming logic for algorithmic, control technology and analysis in ultra-fast time detection, microscopy and interferometry.

Construction

Our designers created designs ranging from simple mirror mounts up to complex mechanics of movable components. We use those for all of our products. An example is our Quantenkoffer, a science kit for quantum physics with more than 400 milled aluminum parts ensuring stability and all mechanical interactions.

Production

The production assembly of high-quality parts is also done by ourselves. Drilling and cutting of aluminum, steel, stainless steel, non-ferrous metals and plastics allows for realization all possible designs. The final assembly of all optical, electric and mechanical parts is also performed in-house.

Team

qutools and our partners can cover all desired abilities as physicists, developers, designers, electronics- and software-specialists are employed. Our own production completes the portfolio. Therefore, we can do everything from scratch, starting with patents and building prototypes and ending with serial production.

Company network for competency

qutools

Picometer or picosecond – high precision devices for research, teaching and industry.

N-Hands

Specialized in complex electronic- and embedded-systems, control engineering and software.

MiT - Made in Thüringen

CNC drilling, milling and assembly of high quality parts for prototypes, small and medium series.

qutools and nHands
Darmstadt, Idstein and Munich, Germany

MiT - Made in Thüringen
Meiningen, Germany

Further Products

Precision measurement devices for research and industry and quantum physics science kits for education

Quantum Physics in Teaching

The **Quantenkoffer** is a plug and play quantum science kit for schools and universities with single and entangled photon pairs. Multiple tokens with different optical abilities give a huge variety of experiments.

Our **quED** is a photon entanglement demonstrator with a source for single and entangled photon pairs. Multiple quantum experiments can be conducted with its add-ons.

The **quNV** is a setup for quantum sensing by a diamond magnetometer based on nitrogen-vacancy (NV) centers. Discover the world of quantum physics with spin manipulation or even single qubits!

Distance Measurement

Nondestructive interferometric distance measurement with the **quDIS** provides sub-nanometer resolution. The device is a confocal displacement sensor, by default based on a Fabry-Pérot interferometer, with highest signal stability of < 0.05 nm and without nonlinearities.

qutools GmbH

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