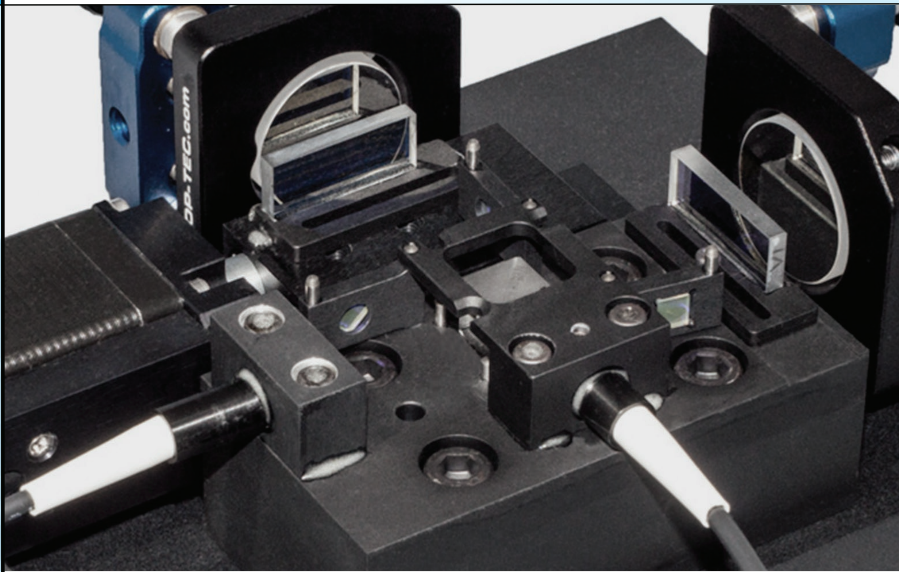
quED-MI

Michelson Interferometer



quED-MI Manual V1.0

quED-MI Manual V1.0 (January 16, 2019)

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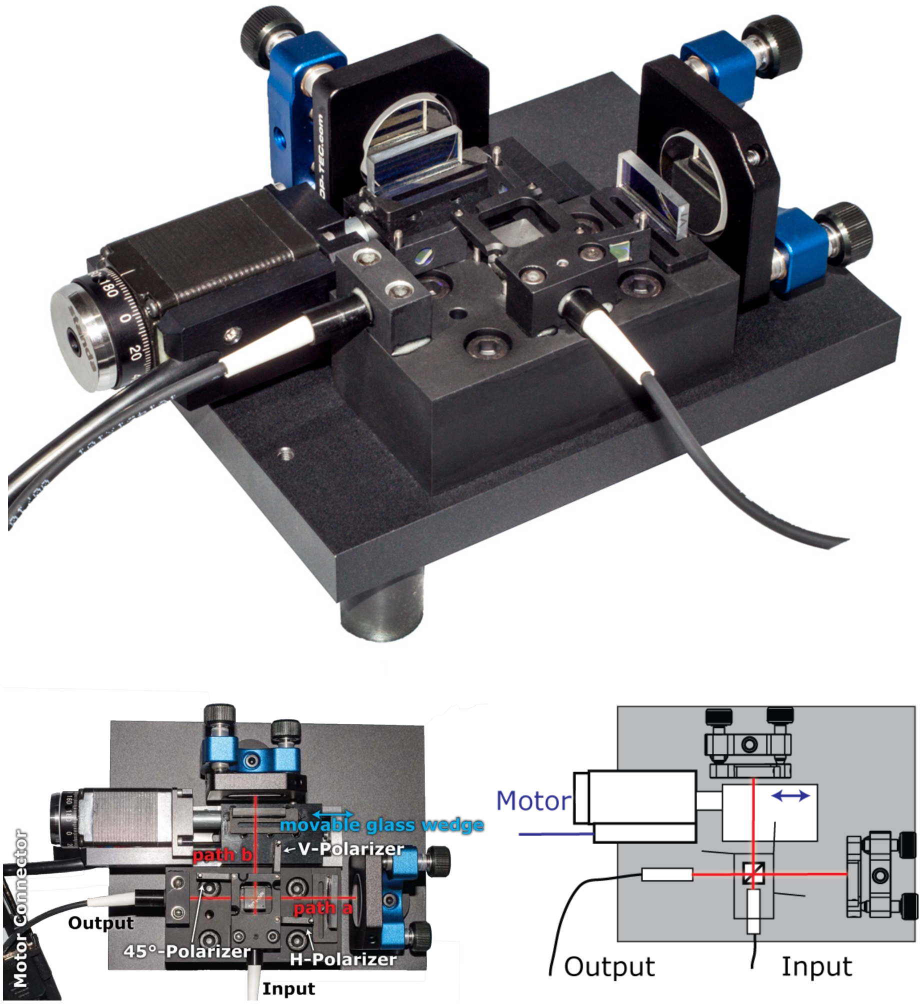

Figure 1.1: The quED-MI Michelson Interferometer and schematics.

1.1.1 Quickstart Manual

To put the Michelson Interferometer into operation, the two mirrors have to be aligned such that both arms of the interferometer are coupled into the output fiber. Thereby, a good overlap at the beamsplitter will be achieved automatically.

Aligning the mirrors

1. The polarizers in the small flaps of the interferometer have to be swung out of the beam path.
2. First, the visible red alignment laser is used as a light source and is connected to the input fiber.
3. Block one arm of the interferometer. On a piece of paper in front of the output fiber, the beam from the non-blocked arm can be observed.
4. With the two set screws of the mirror mount, align the red dot as central as possible with respect to the lens of the fiber coupler.
5. Maximize the intensity in the ouput fiber. This can be done by using the front camera of your cell phone: Just point the end of the fiber as straight as possible into the camera. A small red area should be visible in the center. If not, adjust the screws very carefully - if you still see nothing, return to the previous step and redo it even more exactly. Maximize the brightness of this red area.
6. The second mirror can be adjusted accordingly.
7. Connect one of the output fibers of the quED (instead of the red alignment laser) to the input of the interferometer. Connect the output fiber of the quED-MI to one of the APDs of the quCR.
8. Optimze the single count rates for each interferometer arm by again blocking the other one.

Coarse interference searching

The path lengths of the interferometer should be balanced when the movable glass wedge is aligned centrally in front of the mirror. To find out the actual position, a coarse search is helpful. Therefore, one can move the glass wedge over the middle position either manually by hand or (if motorized) using the quCR Tab *quCNT linear scanning* with the settings from Tab. 1.1. The *Target* has to be sepcified with the right sign (positive: the glass wedge moves away from the motor; negative: towards the motor). Interference can be observed on a distance of about $1,5\,\mathrm{mm}$ (with the single photons from the quED), the maximal visibility occurs at balanced interferometer path lengths.

With the quED-MI, the optical path lengths are controlled via a glass wedge and not via the mirror position (Fig. 1.2). The wedge angle α is related to its dimensions

Table 1.1: The settings for coarse searching.

chan	stage	Stepsize	Target	Integration
(12)	STANDA	200/12800	±6 mm	0.1 s

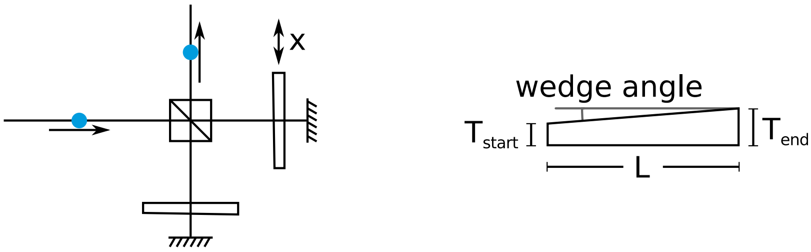

Figure 1.2: optical composition quED-MI

$$\tan\alpha = \frac{T_{\text{end}} - T_{\text{start}}}{L}. \tag{1.1}$$

In our setup, that is

$$\alpha = \arctan\left(\frac{0.44\,\text{mm}}{25\,\text{mm}}\right) \approx 1.0\,^\circ \approx 17.6\,\text{mrad} \tag{1.2}$$

The optical path length of light in the glass wedge is extended because of its higher refraction index in comparison with the distance in air. The thicker the wedge at position x of the beam, the bigger the delay

$$\Delta = 2x\tan\alpha \cdot (n_{br} - 1)\ . \tag{1.3}$$

It's important that the effect is applied double, because the beam passes through the wedge twice (thus the factor of 2). There is a slight change of beam angle due to the wedge, but it is constant with respect to the effective thickness and therefore does not disturb the coupling.

The retardation that stems from the minimal thickness of the wedge is constant and is neglected. Constant retardations are compensated by the mirror positions and the second, fixed wedge in this setup.

With the data from Tab. 1.2, equation (1.3) can be simplified

$$\Delta = \frac{x}{56.1} \tag{1.4}$$

The wedge therefore acts like an optical gear with a reduction of approximately $1:56$.

For the motorized Michelson interferometer, some important parameters can be found in Tab. 1.3. For a correct translation of motor steps to motor movement, "'Standa"' has to be selected in the quCR software.

A typical measurement of the interference signal with the qutools quED-MI is seen in Fig. 1.3.

Table 1.2: Relevant dimensions and specifications of the interferometer

length of the wedge	25 mm
wedge change of thickness	0.44 mm
wedge angle	1 °
refraction index of wedge (glass BK7)	
at 810 nm	1.511
at 630 nm	1.515

Table 1.3: Parameter for the motorized variant of the Michelson interferometer

motor type					Standa 8MT173
Full Step					1.25 µm
Steps per revolution					200
displacement per revolution					0.25 mm
Sub-steps qu3MD					16
Sub-steps per mm					12800
Path lengths dependent on wedge displacement:					
Sub-steps quCR n/12800	1	16	32	64	12800
wedge movement x	0.08 µm	1.25 µm	2.5 µm	5.0 µm	1000 µm
optical path lengths Δ	1.4 nm	22.5 nm	44.9 nm	89.9 nm	17973 nm

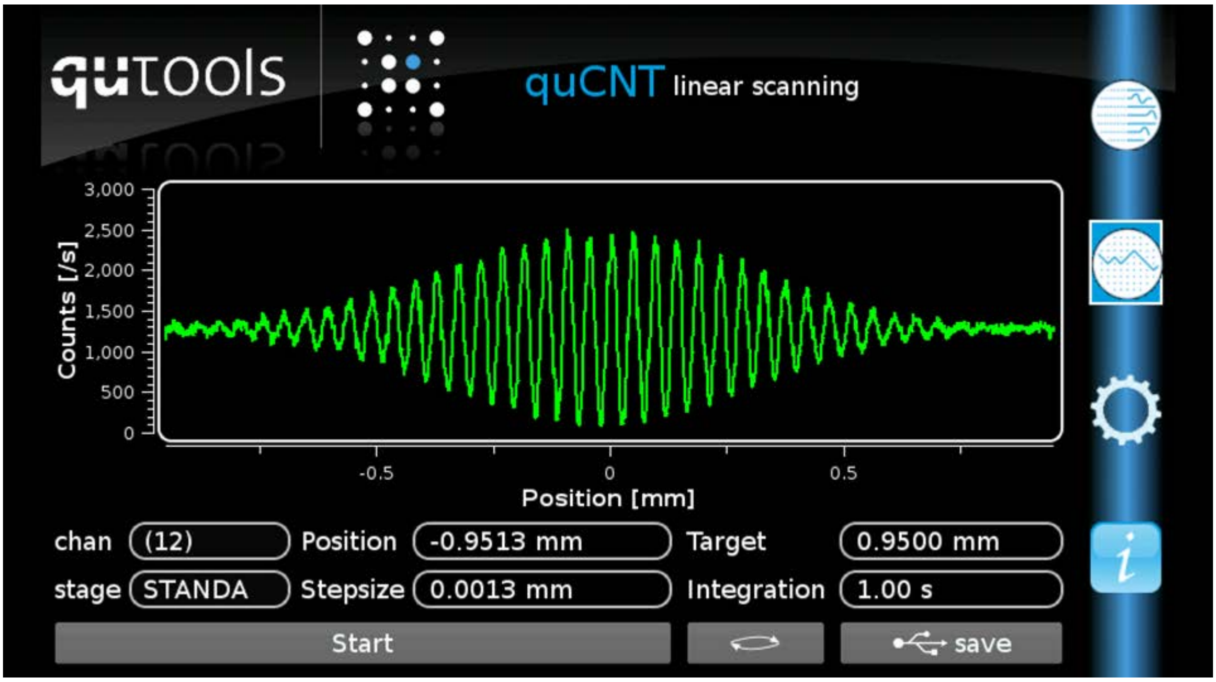

Figure 1.3: quCR-Screenshot of a typical measurement run with the motorized quED-MI. The green curve shows the coincidence count rate with respect to the wedge displacement and therefore the variation of the optical path length. One can nicely discern the envelope of the signal originating from the short coherence length of the used photons.

2 Experiments with the quED-MI

2.1 Single Photon Interference: Michelson Interferometer

The wave nature of light can be shown easily with an interferometric setup. The Michelson layout offers ideal conditions for this task.

2.1.1 Theoretical Background

Wave-Particle Duality

In classical physics there are the concepts of waves and particles. Waves, for example electromagnetic fields can interfere. The field of two waves add up and the intensity is the square of the sum. In a Michelson interferometer the optical path difference between two arms define if the waves interfere constructively or destructively in the output arm (fig. 2.1).
Classical particles are well localized at any time and the path of the particle is known (fig. 2.1). A particle can only take one of the two possible paths through the interferometer. Therefore the particle intensity in the output arm of the interferometer can not depend on the length difference of the two interferometer arms a and b.

A photon is the smallest energy packet of the electromagnetic field. Lots of experiments demonstrate interference of electromagnetic fields and therefore even weak electromagnetic fields should interfere. But photon anti-bunching and the anti-correlation of photon pairs anticipate a particle like behavior of photons. Grangier et al [2] showed that single photons can interfere. They demonstrated photon counting statistics which are "‘in contradiction

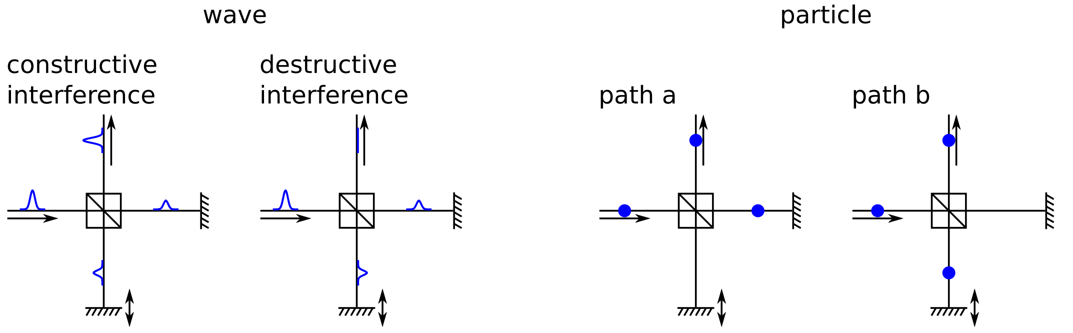

Figure 2.1: Michelson interferometer

with any classical wave model of light"' and interference of these photons in a Mach-Zehnder interferometer. Their experiment proved that a photon can not be described by the classical "'wave"' or "'particle"' concept.

Interference

The electric field of a plane wave propagating in z-direction can be represented by [1]

$$E_k(z,t) = \mathcal{R}\left\{A \cdot e^{ikz-i\omega t}\right\} = \frac{1}{2}(A \cdot e^{i(kz-\omega t)} + \bar{A} \cdot e^{-i(kz-\omega t)}) \tag{2.1}$$

Optical detectors like photodiodes are very slow compared to the frequency of light. The measured intensity is the time averaged squared field

$$I = \langle E^2 \rangle_t \ . \tag{2.2}$$

Two monochromatic waves

$$\begin{aligned} E_1 &= \mathcal{R}\left\{A_1 \cdot e^{ikz-i\omega t}\right\} \\ E_2 &= \mathcal{R}\left\{A_2 \cdot e^{i\Delta\phi}\, e^{ikz-i\omega t}\right\} \end{aligned} \tag{2.3}$$

can be superposed

$$E_{\text{sum}} = E_1 + E_2 \ . \tag{2.4}$$

After some calulation (see ?? ??), the sum intensity can be written as

$$I_{\text{sum}} = 2I_1 \cdot (1 + \cos(\Delta\phi)) = 4I_1 \cdot \cos^2 \frac{\Delta\phi}{2} \ . \tag{2.5}$$

The Michelson Interferometer

The beam splitter in a Michelson interferometer divides an incoming wave in two arms. The two waves are reflected by mirrors and overlap on the beam splitter. The phase difference $\Delta\phi = k \cdot d$ of the two waves depends on the optical path difference d and the wave number k.

The intensity in the output port of a monochromatic wave is

$$I_k = \frac{1}{2} I_0 \cdot (1 + \cos(k \cdot d)) \,. \tag{2.6}$$

Therefore the intensity signal of a monochromatic wave behind a Michelson interferometer is sinusoidal with zero minimum intensity and a visibility of one.

2.1.2 Quantum Mechanical description of the experiment

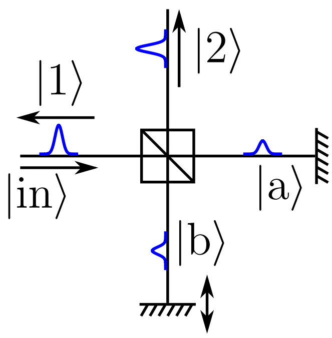

Figure 2.2: Schematic Michelson Interferometer with lables of the position states.

Using the action of a beam splitter on an impinging photon

$$|\mathrm{in}\rangle \rightarrow \frac{1}{\sqrt{2}} \left(|a\rangle - \mathrm{i}|b\rangle\right) \tag{2.7}$$

first for splitting the state of the photon into the two possible paths a and b and later for recombining them, the detection probability in output 2

$$P_2 = |\langle\, 2 \mid \mathrm{out}\,\rangle|^2 = \cos^2 \frac{\varphi}{2} \,, \tag{2.8}$$

can be calculated (see **?? ??**). Note that the result is the same as calculated with a classical wave (2.5).

2.1.3 Implementation with the quED

Necessary Components

- quED source with quCR control rack
- quED-MI Michelson-Interferometer AddOn

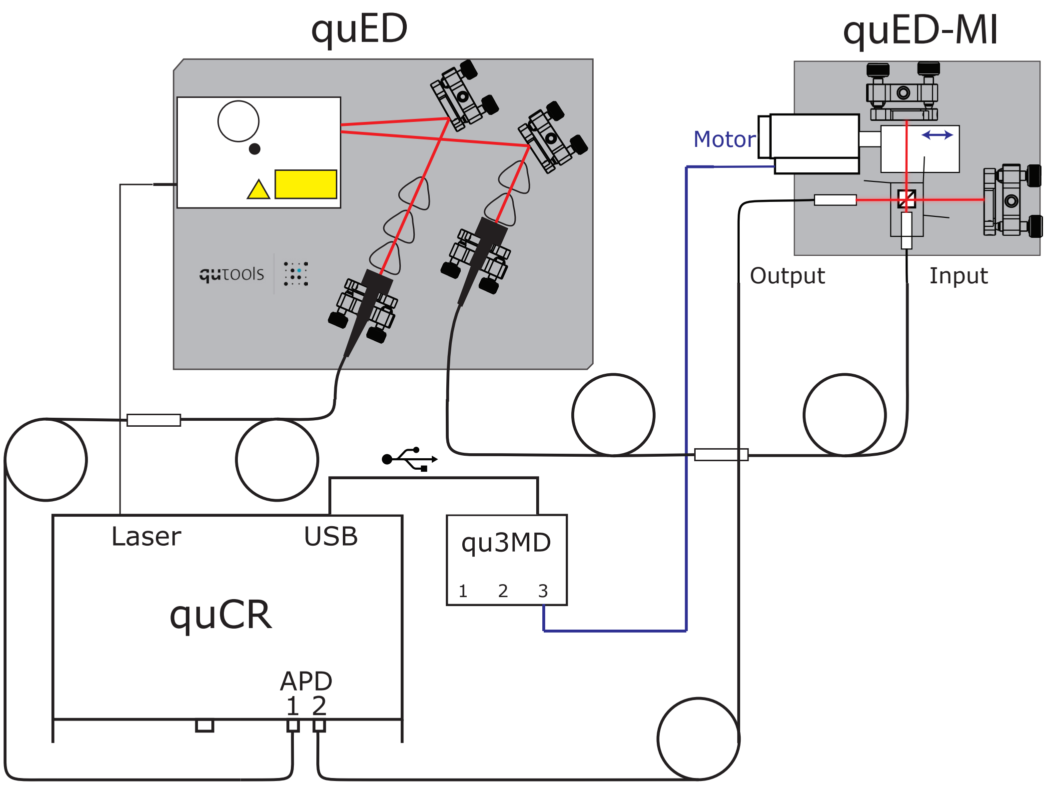

Figure 2.3: The setup of the single photon experiment with all necessary connections.

Experimental description

Setup A schematic view of the setup can be seen in Fig. 2.3.

To connect the Michelson interferometer (Fig. 2.4) with the quED, one of the output fibers of the quED is connected via a fiber adapter to the input fiber of the interferometer. The second output fiber of the quED has to be extended as well to balance out the path lengths (the quCR will not register any coincidences otherwise). The extended fiber and the output fiber of the interferometer is connected to the APD unit of the quCR. The polarizers in the interferometer are not necessary for this experiment and have to be swung out of the beam path.

Realigning the mirrors Before the experiment is performed, the alignment of the mirrors in the interferometer should be checked. For that, block one path of the interferometer with a business card. Adjust the set-screws of the mirror mount in the open path to reach the count rate maximum. Repeat for the other path to reach approximately the same count rate in both arms.

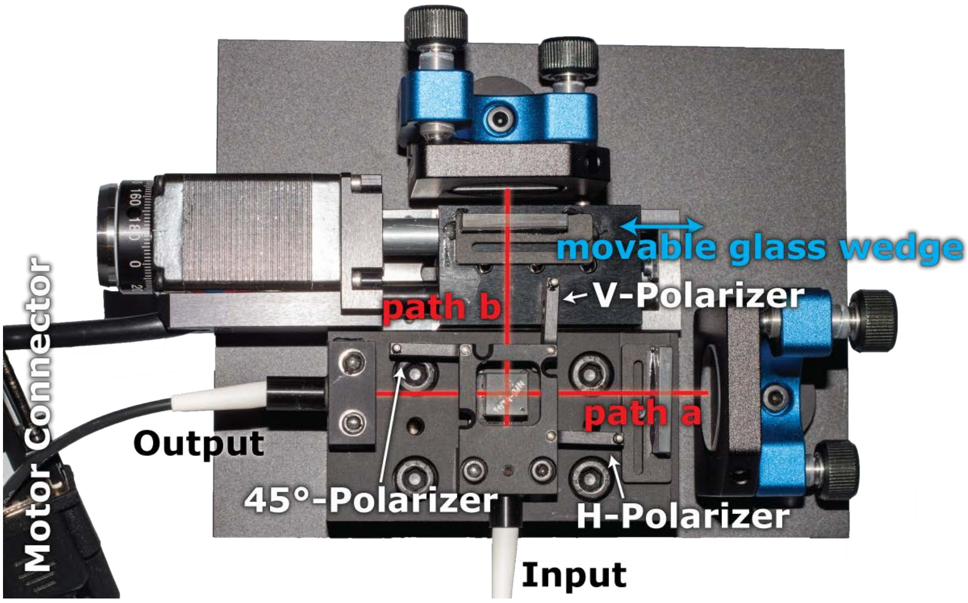

Figure 2.4: The quED-MI AddOn Michelson Interferometer. The flaps with the polarizers are not used in this expeiment and should be swung out of the beam path.

Coarse interference searching

The path lengths of the interferometer should be balanced when the movable glass wedge is aligned centrally in front of the mirror. To find out the actual position, a coarse search is helpful. Therefore, one can move the glass wedge over the middle position either manually by hand or using the quCR Tab *quCNT linear scanning* with the settings from Tab. 2.1. The *Target* has to be sepcified with the right sign (positive: the glass wedge moves away from the motor; negative: towards the motor). Interference can be observed on a distance of about 1, 5 mm (with the single photons from the quED), the maximal visibility occurs at balanced interferometer path lengths.

Table 2.1: The settings for coarse searching.

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(12)	STANDA	200/12800	± 6 mm	0.1 s

Recording interference To perform a good experimental run to record interference fringes, the integration time should be greater than 0.5 s. Also, the measurement points should lie closer together. Before the run, set the motor to a position away from the interference. The end of the measurement run is reached after a motor displacement of about 2 mm (Target=Position$\pm$2 mm). The measurement example Fig. 2.5 was recorded with the vallues from Tab. 2.2.

Table 2.2: The settings for a good measurement run. Before the measurement, set the motor to a position away from the interference; the target is then accordingly chosen on the opposite side.

chan	stage	Stepsize	Integration
(12)	STANDA	16/12800	1 s

Measurement example

The sample measurement of Fig. 2.5 was measured with the setting from Tab. 2.2 in a bright room on a conference table.

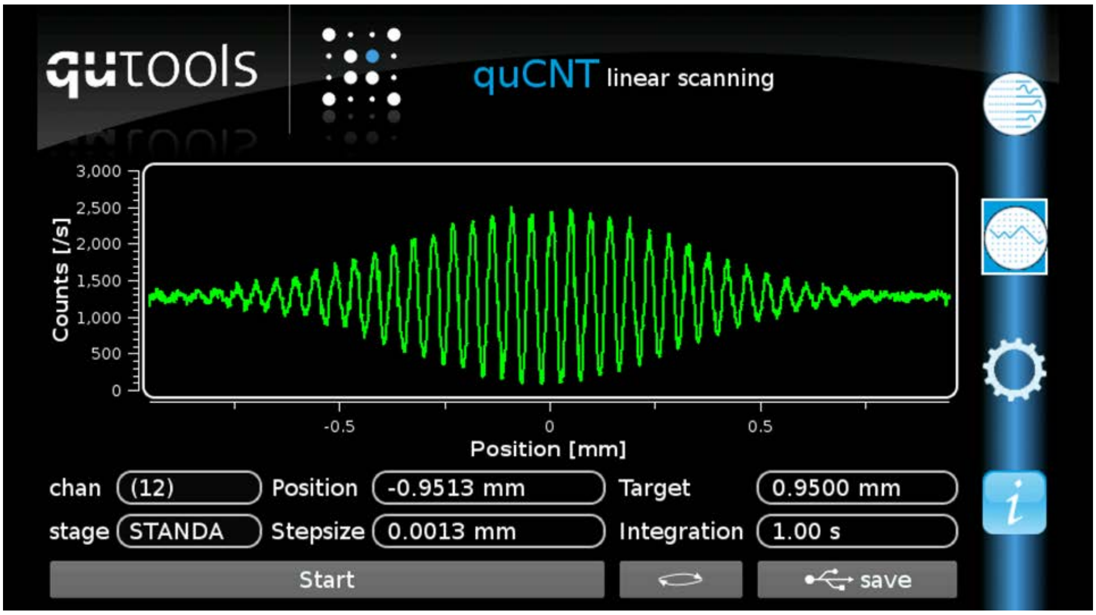

Figure 2.5: This measurement run was performed with the quED-MI Add-On in a bright room on a conference table.

2.1.4 Didactic Material

1. Calculate the intensity at the output of the Michelson Interferometer using the superposition of two classical plane waves

$$\begin{aligned} E_1 &= \mathcal{R}\left\{A_1 \cdot e^{ikz-i\omega t}\right\} \\ E_2 &= \mathcal{R}\left\{A_2 \cdot e^{i\Delta\phi}\, e^{ikz-i\omega t}\right\} \end{aligned} \tag{2.9}$$

2. How can one calculate the probability of the detection of a photon with the Dirac notation?
3. In which intervals are the maxima observed? Which quantity does this interval depend on?
4. Why is the visibility reduced for non-perfectly balanced optical path lengths?
5. Calculate the highest visibility of the interference fringes.

2.1.5 Sample Solution

For the sample solution please refer to the qutools quED-MI page `http://qutools.com/quED-MI`.

Bibliography

[1] Max Born and Emil Wolf. *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light.* CUP Archive, 2000.

[2] Philippe Grangier, Gerard Roger, and Alain Aspect. Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences. *EPL (Europhysics Letters)*, 1(4):173, 1986.