Universität Hamburg
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ZOQ
Zentrum für Optische Quantentechnologien

ILP
INSTITUT FÜR LASERPHYSIK

ILP9 - Single Photon Sources

An Introduction to Quantum Optics

F-Praktikum Review Day

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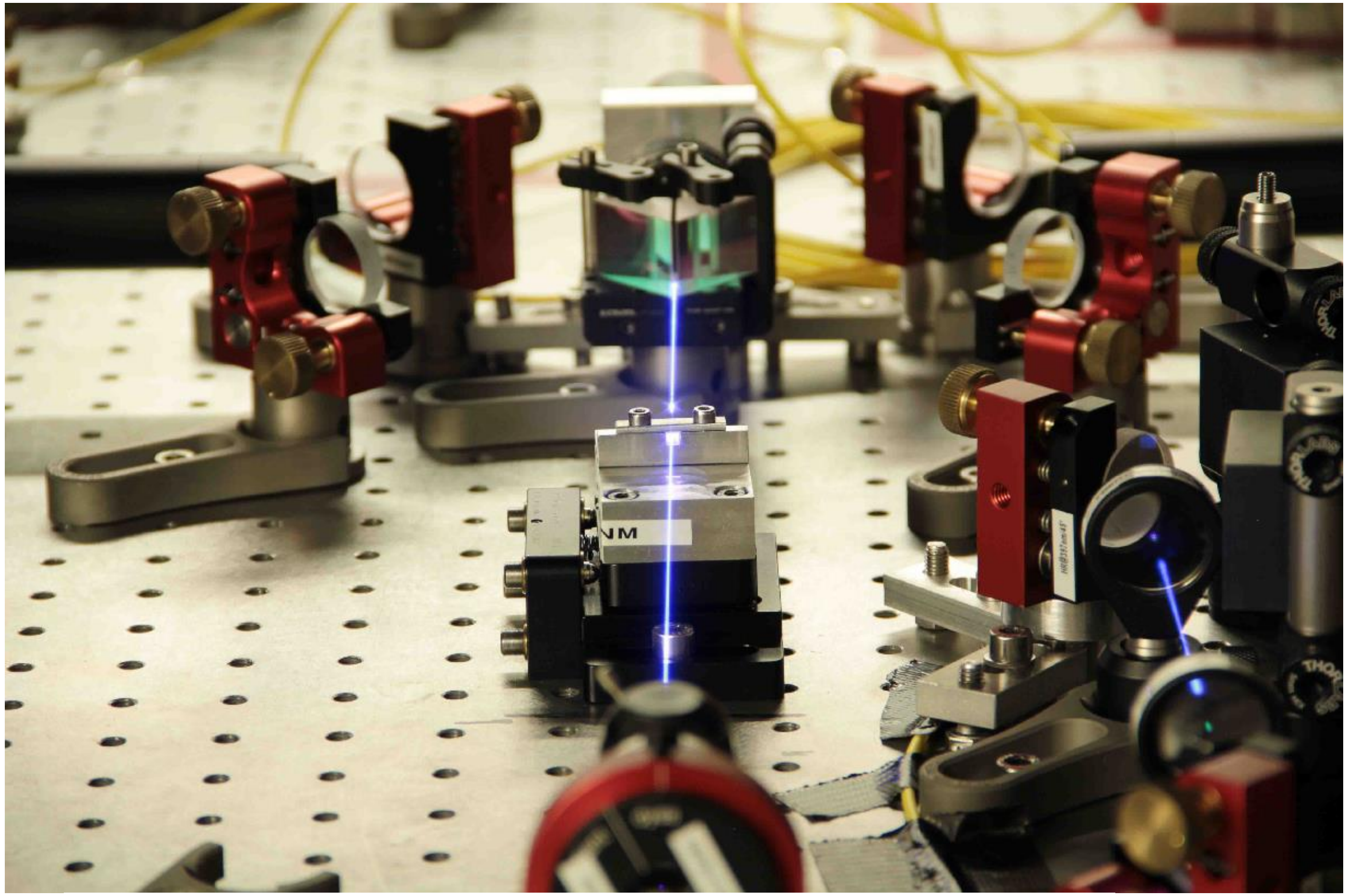
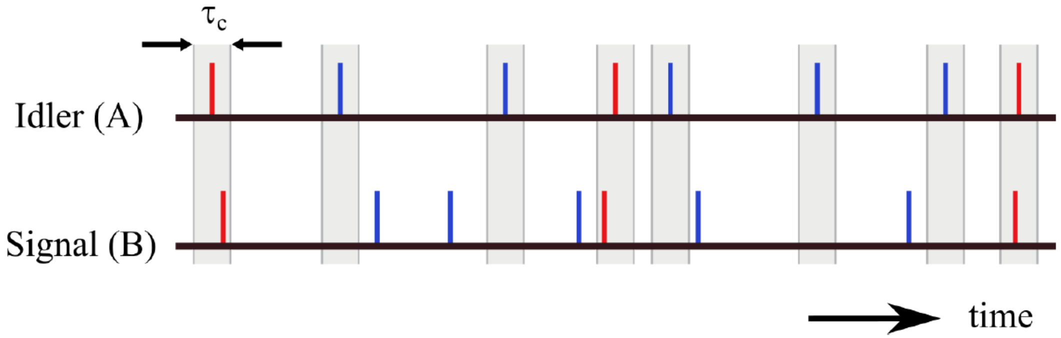
Overview
Laser pumps non-linear crystal, creating entangled single photon pairs. Charactise setup, first and second-order correlations

Scientific Context
Quantum optics & technologies





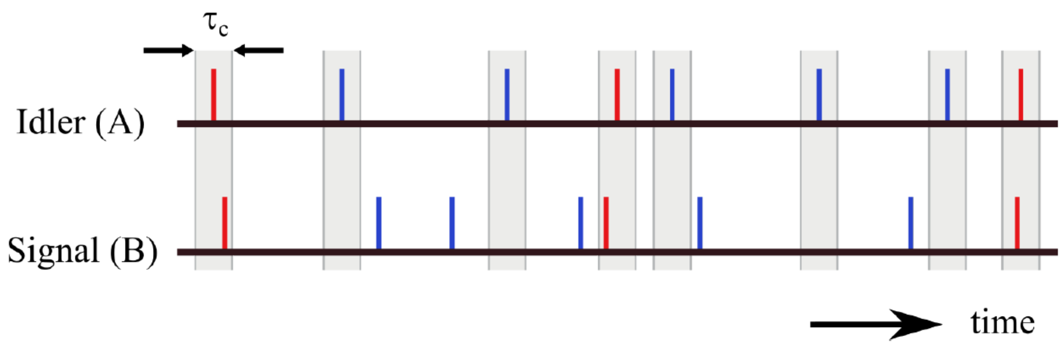
Goals
1. **Quantum character of light**
2. **Work in a laser lab** (fundamental optics measurements, align interferometer, fibre coupling, polarisation control)
3. Correlation functions
4. Coincidence measurements
5. Minor: non-linear optics

Day 1: Characterise the single-photon source

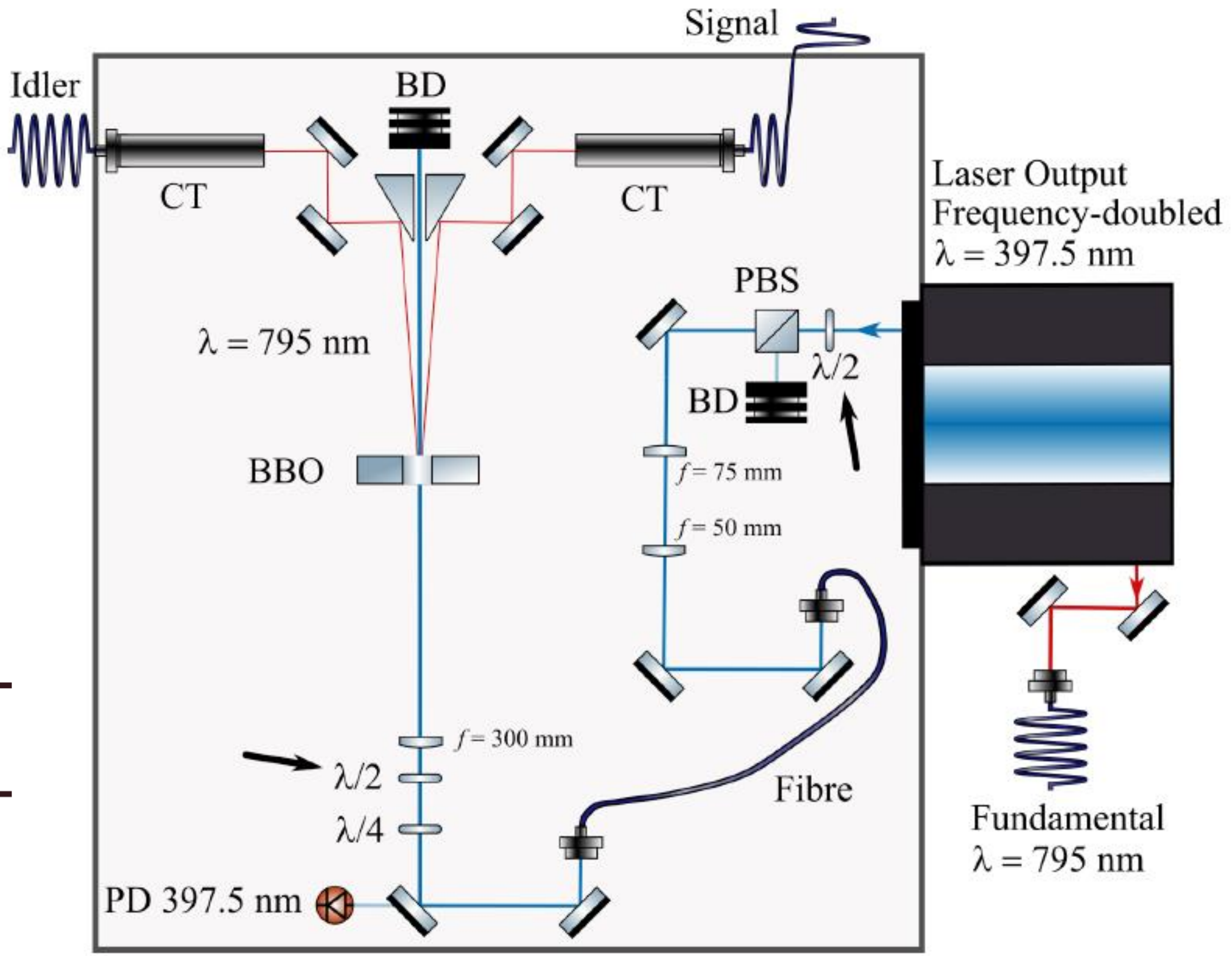
Laser at 397.5 nm pumps a non-linear crystal (BBO), type 1 phase-matching

Exercises:

1. Coincidence window
2. Coincidences as a function of pump power
3. Coincidences as a function of polarisation



1.5 hours: colloquium
0.5 hour: showing the lab
1-2 hours: measurements
Rest: time for analysis



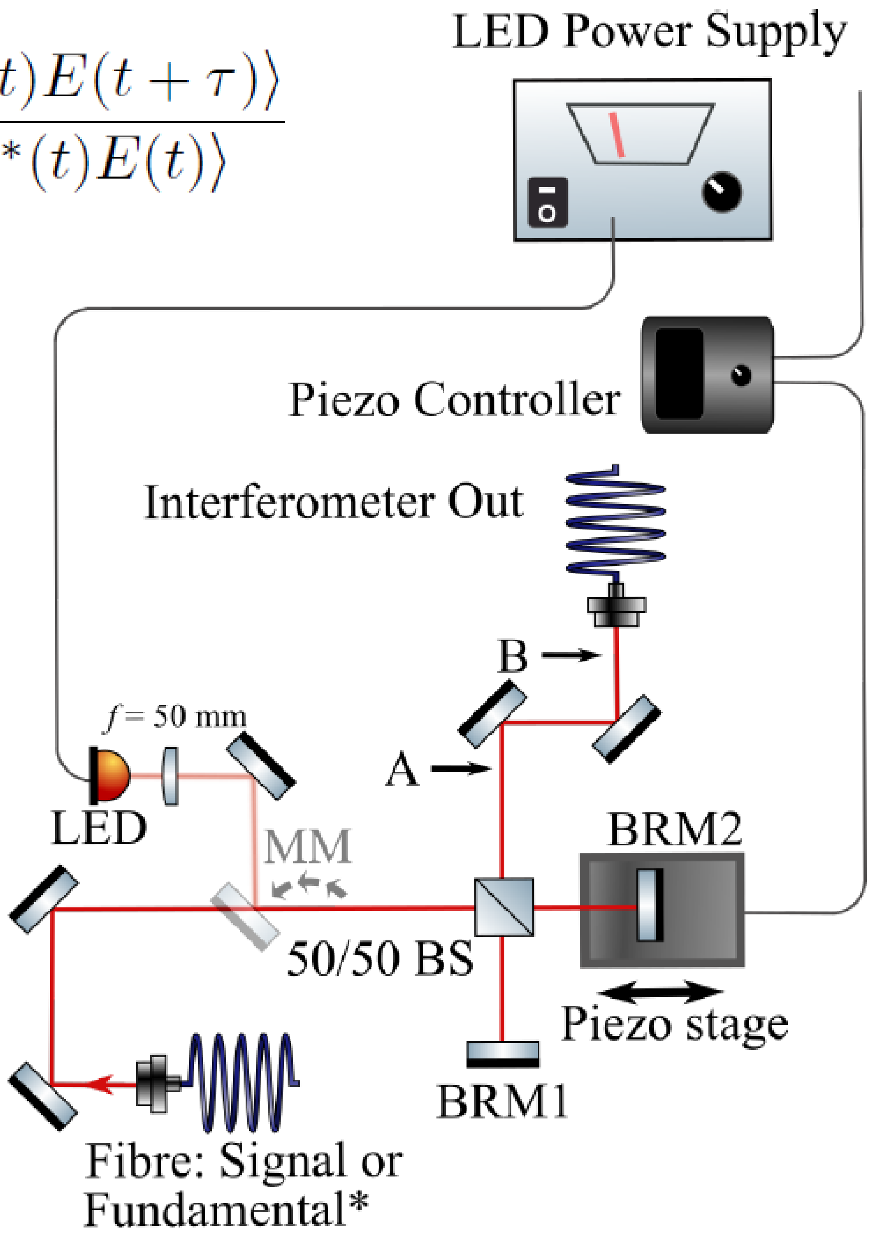
Experimental Setup

Day 2: first-order correlations

$$g_1(\tau) \equiv \frac{\langle E^*(t)E(t+\tau)\rangle}{\langle E^*(t)E(t)\rangle}$$

- Twyman-Green interferometer
- Measure g_1 of coherent light and single photons

- For single photons: determine l_c
- Challenges:
  - Align interferometer (sensitive!)
  - Fibre coupling
  - Make a small measurement plan
- Conclusion: single photons also show interference effects



2-3 hours: alignment
3-4 hours: measurement

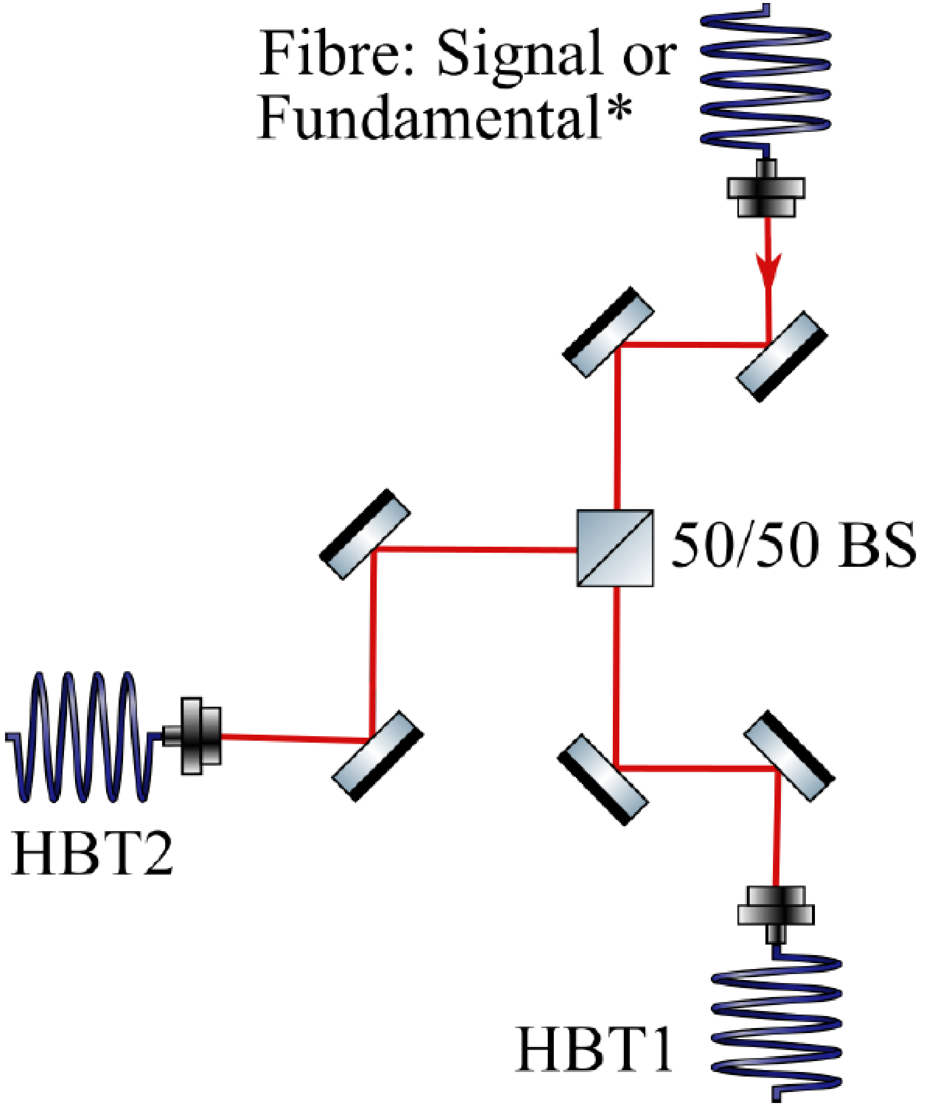
Experimental Setup

Day 3: second-order correlations

$$g_2(\tau) = \frac{\bar{I}(t)\bar{I}(t+\tau)}{\bar{I}^2}$$

- Hanbury Brown Twiss setup
- Measure g_2 of coherent light and single photons

- $0 < g_2 < 1$ is non-classical, quantum description needed
- Conclusion: Single photons need a quantum description of light



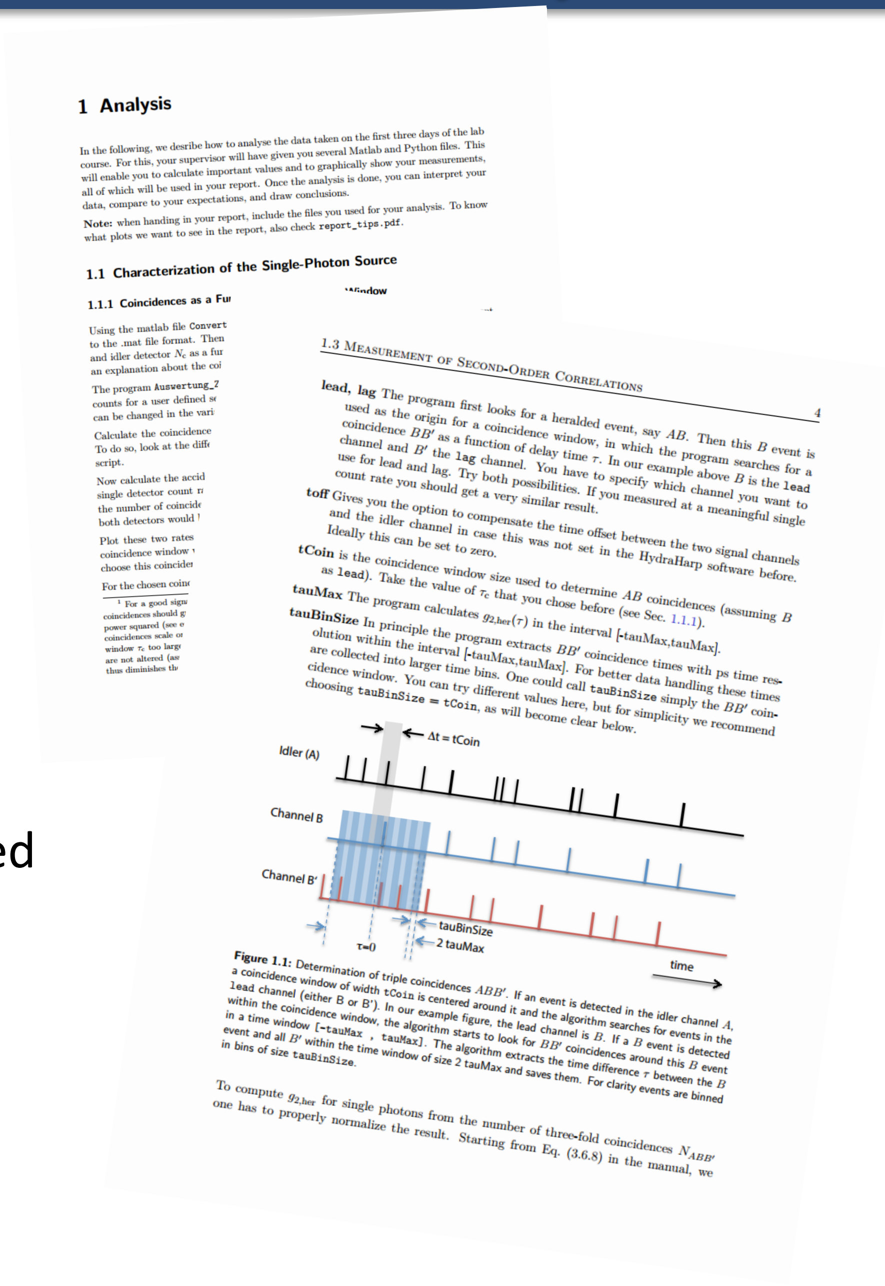
0.5 hour: discussion
0.5-1 hour: alignment
0.5 hour: measurement
Rest: time for analysis

Data Analysis

Day 4-5

- PC in lab can be used for analysis
- Python code provided up to and including plotting
- Students have to do fitting and error propagation themselves
  - Day 2: correlated error propagation is needed

- Analysis tips document provided (shortens main manual)



1 Analysis

In the following, we describe how to analyse the data taken on the first three days of the lab course. For this, your supervisor will have given you several Matlab and Python files. This will enable you to calculate important values and to graphically show your measurements, all of which will be used in your report. Once the analysis is done, you can interpret your data, compare to your expectations, and draw conclusions.

Note: when handing in your report, include the files you used for your analysis. To know what plots we want to see in the report, also check report_tips.pdf.

1.1 Characterization of the Single-Photon Source

1.1.1 Coincidences as a Fu

Using the matlab file Convert to the .mat file format. Then and idler detector N_c as a fu an explanation about the coi

The program Auswertung_2 counts for a user defined s can be changed in the vari

Calculate the coincidence To do so, look at the diffe script.

Now calculate the accid single detector count ra the number of coincide both detectors would

Plot these two rates coincidence window choose this coincide

For the chosen coinc

[1] For a good signa coincidences should g power squared (see e coincidences scale or window τ_c too large are not altered (as thus diminishes th

1.3 MEASUREMENT OF SECOND-ORDER CORRELATIONS 4

lead, lag The program first looks for a heralded event, say AB. Then this B event is used as the origin for a coincidence window, in which the program searches for a coincidence BB' as a function of delay time τ. In our example above B is the lead channel and B' the lag channel. You have to specify which channel you want to use for lead and lag. Try both possibilities. If you measured at a meaningful single count rate you should get a very similar result.

toff Gives you the option to compensate the time offset between the two signal channels and the idler channel in case this was not set in the HydraHarp software before. Ideally this can be set to zero.

tCoin is the coincidence window size used to determine AB coincidences (assuming B as lead). Take the value of τ_c that you chose before (see Sec. 1.1.1).

tauMax The program calculates $g_{2,\mathrm{her}}(\tau)$ in the interval [-tauMax,tauMax].

tauBinSize In principle the program extracts BB' coincidence times with ps time resolution within the interval [-tauMax,tauMax]. For better data handling these times are collected into larger time bins. One could call tauBinSize simply the BB' coincidence window. You can try different values here, but for simplicity we recommend choosing tauBinSize = tCoin, as will become clear below.

Figure 1.1: Determination of triple coincidences ABB'. If an event is detected in the idler channel A, a coincidence window of width tCoin is centered around it and the algorithm searches for events in the lead channel (either B or B'). In our example figure, the lead channel is B. If a B event is detected within the coincidence window, the algorithm starts to look for BB' coincidences around this B event in a time window [-tauMax , tauMax]. The algorithm extracts the time difference τ between the B event and all B' within the time window of size 2 tauMax and saves them. For clarity events are binned in bins of size tauBinSize.

To compute $g_{2,\mathrm{her}}$ for single photons from the number of three-fold coincidences $N_{ABB'}$ one has to properly normalize the result. Starting from Eq. (3.6.8) in the manual, we

```python
[1]:
import numpy as np
import numba
from numba import jit

[15]:
# Read in the data
time = np.loadtxt('times_th_10min.txt', unpack=True,delimiter=',')
sync = np.loadtxt('sync_th_10min.txt', unpack=True,delimiter=',')

[16]:
# Find the total time
total_time = time[time > 0][-1]

# Define which channel is the lead (B) or lag (B') channel. These must be 2 or 3
lead_id = 2
lag_id = 3

# Make boolean lists of the
lead_events = np.where(sync == lead_id, 1, 0)
lag_events = np.where(sync == lag_id, 1, 0)

# At the end of the lists, there are many zeroes. Remove these.
lead_events = lead_events[time>0]
lag_events = lag_events[time>0]
time = time[time>0]

# Find the total number of lead and lag counts
N_lead = float(sum(lead_events==1))
N_lag = float(sum(lag_events==1))

# Choose the bin size of tau. Recommended tau_Bin_Size = tau_coincidence
tau_Bin_Size = 10000.0 # in ps

[17]:
# Initialise g2
g2_unh = [];

# Copy the (lead) times in a separate array such that one does not overwrite them later
all_times = time
lead_times = all_times[lead_events==1]

# Loop over all taus
for i_tau in range(-15,15):

    tau = i_tau*tau_Bin_Size # i_tau is an integer, tau_Bin_Size is in ps

    # Initialise coincidence counts Nc (as per Sec. 3.6.2.2. of the manual)
    Nc = 0

    # Shift the lead times with tau, put back into all times
    all_times[lead_events==1] = all_times[lead_events==1] + tau

    # Make a list with all times where either the lead (B) or lag (B') channel has a count
    all_times_with_events = all_times[np.logical_or(lead_events==1, lag_events==1)]

    for ind in range(len(all_times_with_events)-1):
        # Check if two consequetive events are within one bin time/2 with each other. If so, there
        if all_times_with_events[ind+1]-all_times_with_events[ind] < tau_Bin_Size/2. and all_times_
            Nc += 1

    # Calculate the unheralded g2 according to Eq. (3.6.10) of the manual
    g2_unh_i = Nc*total_time/(N_lead*N_lag*tau_Bin_Size)

    g2_unh.append(g2_unh_i)

    # Shift the lead times back with tau, for the next run
    all_times[lead_events==1] = all_times[lead_events==1] - tau
```

Improvements

Changes made over last few years:

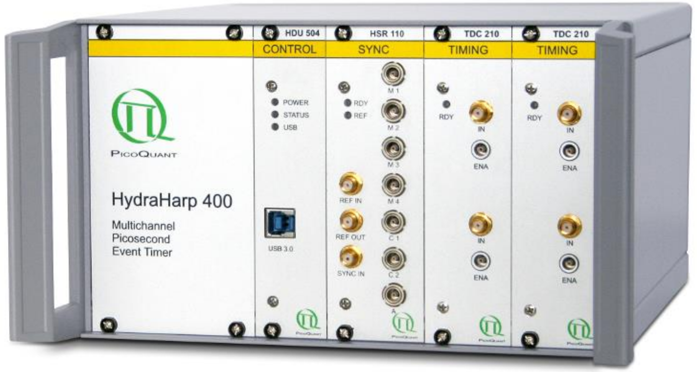
- Switched Matlab → Python
- Less recipe-like, more self-critical thinking
  1) Answer questions
  2) Discuss with supervisor
  3) Measure
- Separate documents with analysis and protocol tips (shortens manual)
- Students have to hand in their scripts (easier to see if analysis is correct)

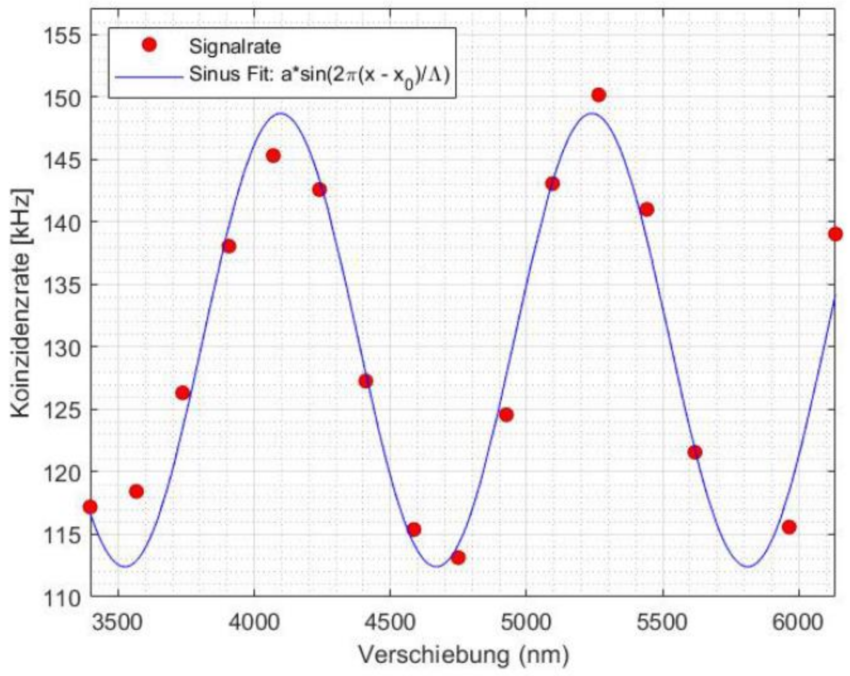
- In progress:
  - Supervisor document with answers on questions
  - Supervisor analysis with correct statistics

Results & Relevance

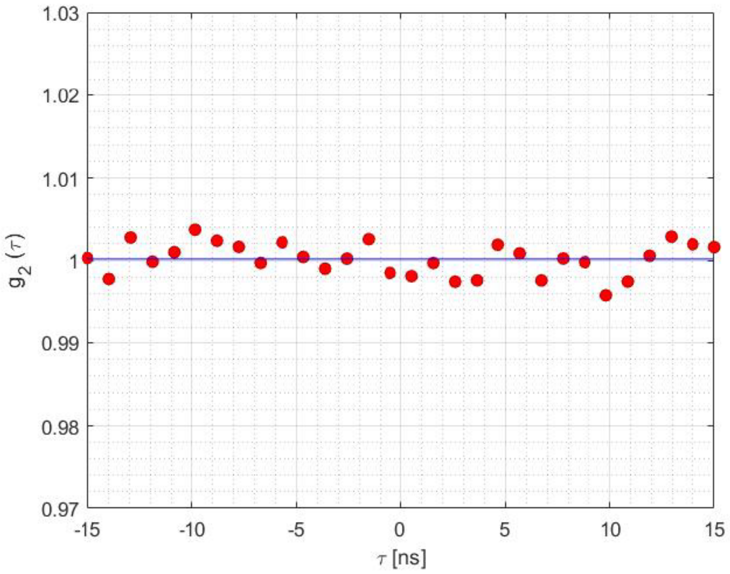
Results

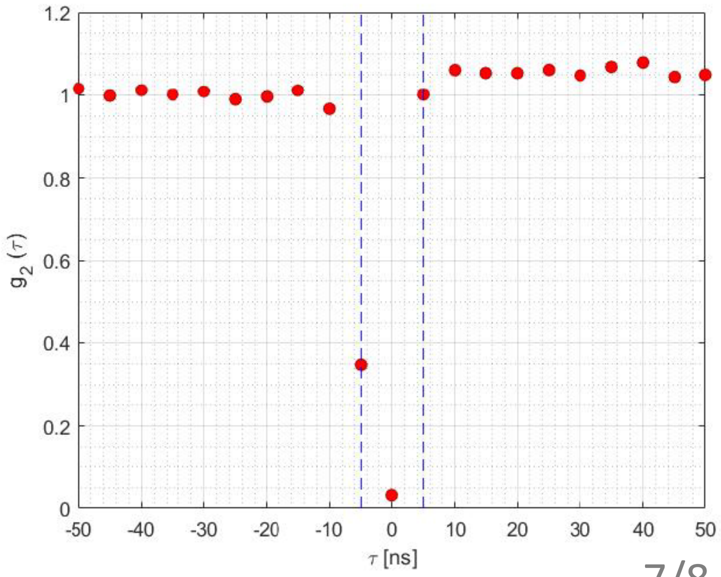
- Characterisation: optimal settings found
- g_1: single photons interference, coherence length $l_c = 20\ \mu m$
- g_2: coherent light has $g_2 = 1$, single photons $g_2(\tau = 0) = 0$ → non-classical!





- Equipment state-of-the-art





Relevance

Essential building block for photon-based quantum technologies, quantum computing & communications

Our Observations

General

No one…

- … cites correctly
- … knows writing conventions (units, equations in sentences, etc)
- … makes good plots
- … makes a paper-like outline (order: all theory, then all experiments, then all results, then all discussions)

Example

$$l_c = 14160,09 \pm 10653,36nm = 14,16 \pm 10,65\mu m$$
$$\tau_c = 4,72 * 10^{-14} \pm 3,55 * 10^{-14}s$$
$$\Delta\lambda_c = 44,63 \pm 33,58nm$$
$$g_1(\tau = 0) = 0,0964(-0.02463, 0.2175)$$

Statistics

No one…

- … can round correctly
- … can quantitatively check if two values are significantly different
- … can do error propagation with correlations (without correlations 50/50)

Physik6 Requirement & F-Praktikum

- P6 is required for ILP9
- Many people sign up for P6, but do not come to P6 at all
- Makes planning very hard