Two-Photon Interferometry of Undulator Radiation

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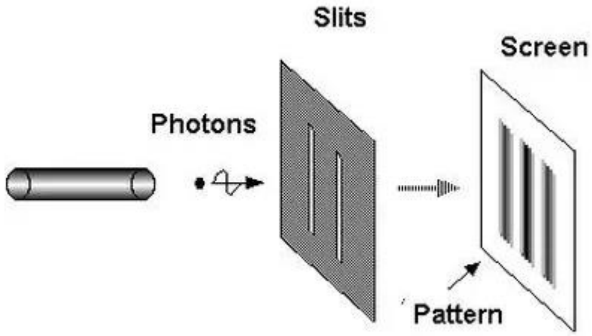
G. Stancari, A. Romanov, I. Lobach + interest from UC Berkeley and others

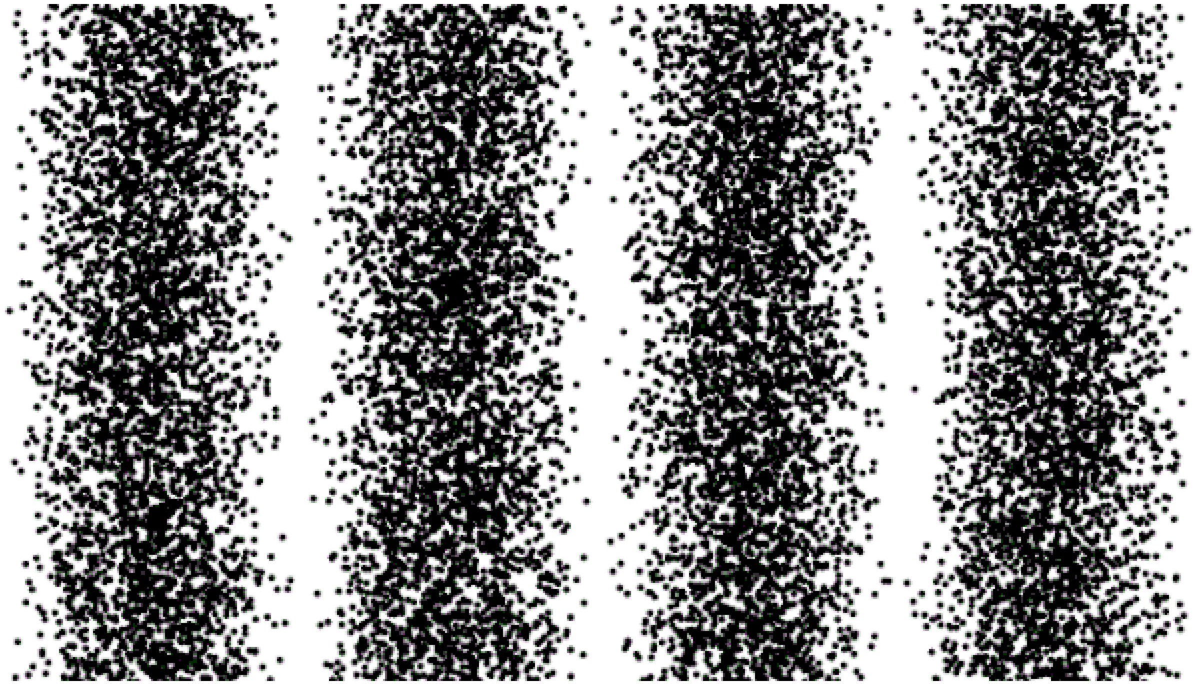
(project funded by Fermilab LDRD)

Oct. 28, 2021

Double-slit experiment with single photons



Thomas Young (1801)



Buildup of interference pattern from individual photon detections

Angular intensity distribution

Simulation:

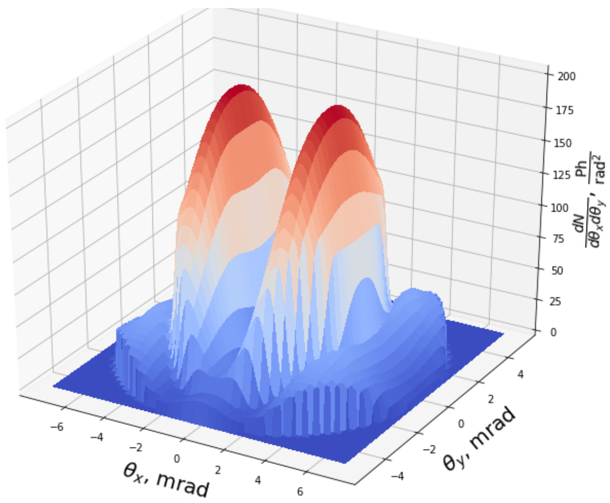
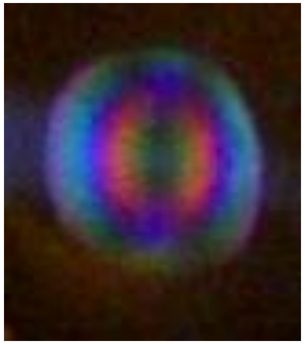
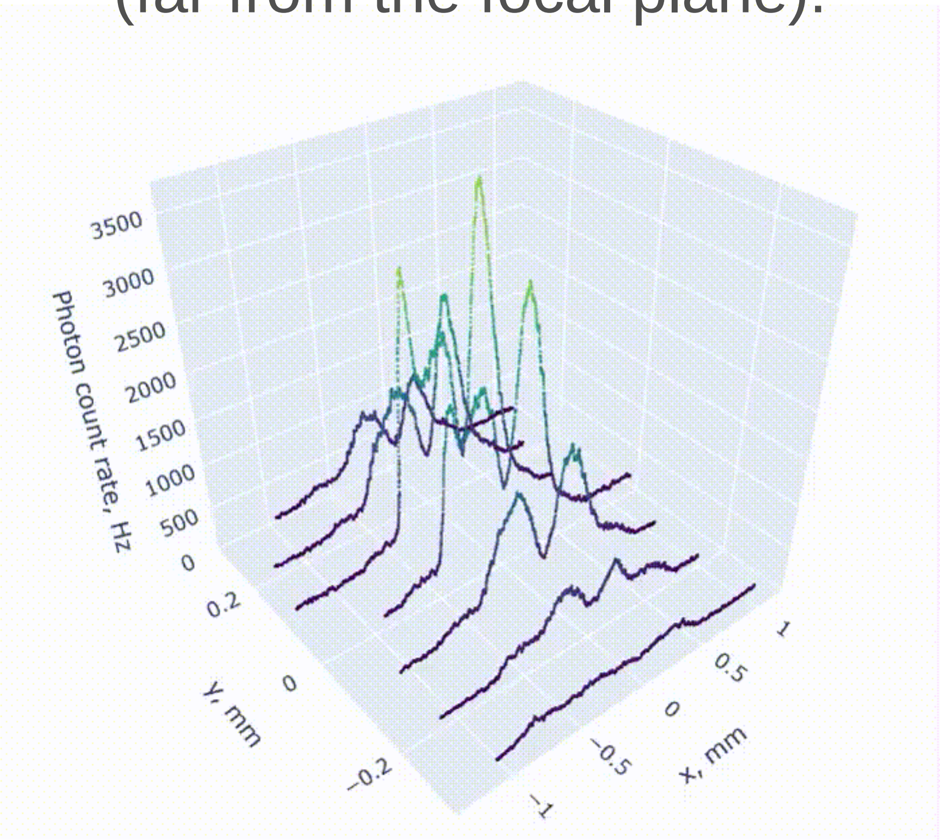


Photo:

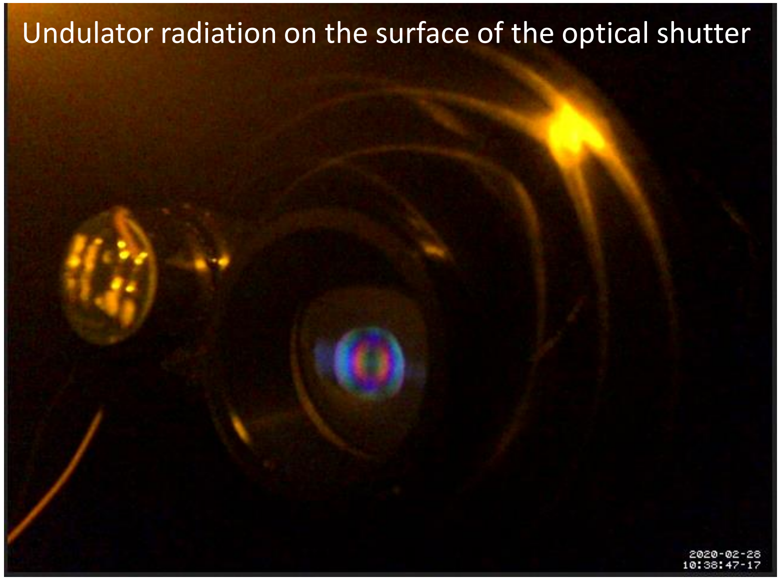


7 measured x-scans at different values of y (far from the focal plane):



Parameters of the undulator in IOTA

Many thanks to our collaborators from SLAC for providing the undulator



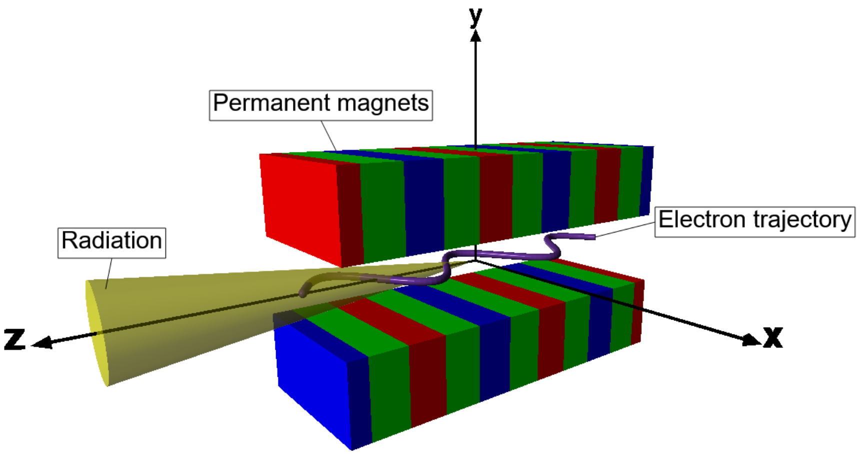
Undulator:

- Number of periods: $N_\mathrm{u} = 10.5$
- Undulator period length: $\lambda_\mathrm{u} = 55\ \mathrm{mm}$
- Undulator parameter (peak): $K_\mathrm{u} = 1$
- Fundamental of radiation: 1.1 um
- Second harmonic: visible light

} @100MeV

$$K_\mathrm{u} = \frac{eB\lambda_\mathrm{u}}{2\pi m_e c}$$

Motivation



Quantum effects in undulator radiation:

1) quantized radiation

(more than one photon can be emitted per pass)

2) quantum nature of an electron in a storage ring (the electron wavefunction's size may be measurable)

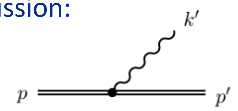
Single electron experiments in IOTA:

- **Photon statistics (number/temporal distribution) (2020-21)**
- The difference in arrival times of the photons emitted in one photon pair (tens of femtoseconds)
- Transverse correlation/entanglement can be tested with a 2D array of single photon detectors

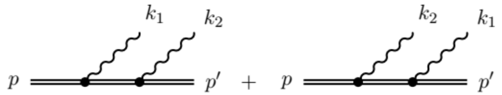
Description of single electron's undulator radiation in Quantum Electrodynamics

- Important parameter: electron recoil $\chi = \frac{E_{photon}}{E_{electron}}$ (in IOTA, $\chi \sim 10^{-8}$)
- $\chi \gtrsim 0.001$, Dirac-Volkov model
  (quantum electron + quantized radiation + classical undulator field)

Single-photon emission:



Two-photon emission:



Correlation, quantum entanglement between photons is possible:

PHYSICAL REVIEW A **80**, 053419 (2009)

Correlated two-photon emission by transitions of Dirac-Volkov states in intense laser fields: QED predictions

Erik Lötstedt*

Max-Planck-Institut für Kernphysik, Postfach 103980, 69029 Heidelberg, Germany

*would be observable at FACET-II with an optical undulator

- $\chi \lesssim 0.001$, Glauber's model (IOTA's case)
  (classical electron + quantized radiation)

PHYSICAL REVIEW VOLUME 131, NUMBER 6 15 SEPTEMBER 1963

Coherent and Incoherent States of the Radiation Field*

Roy J. Glauber

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts

(Received 29 April 1963)

Photons are not correlated

Poissonian photostatistics

$\mathrm{var}(N) = \langle N \rangle$

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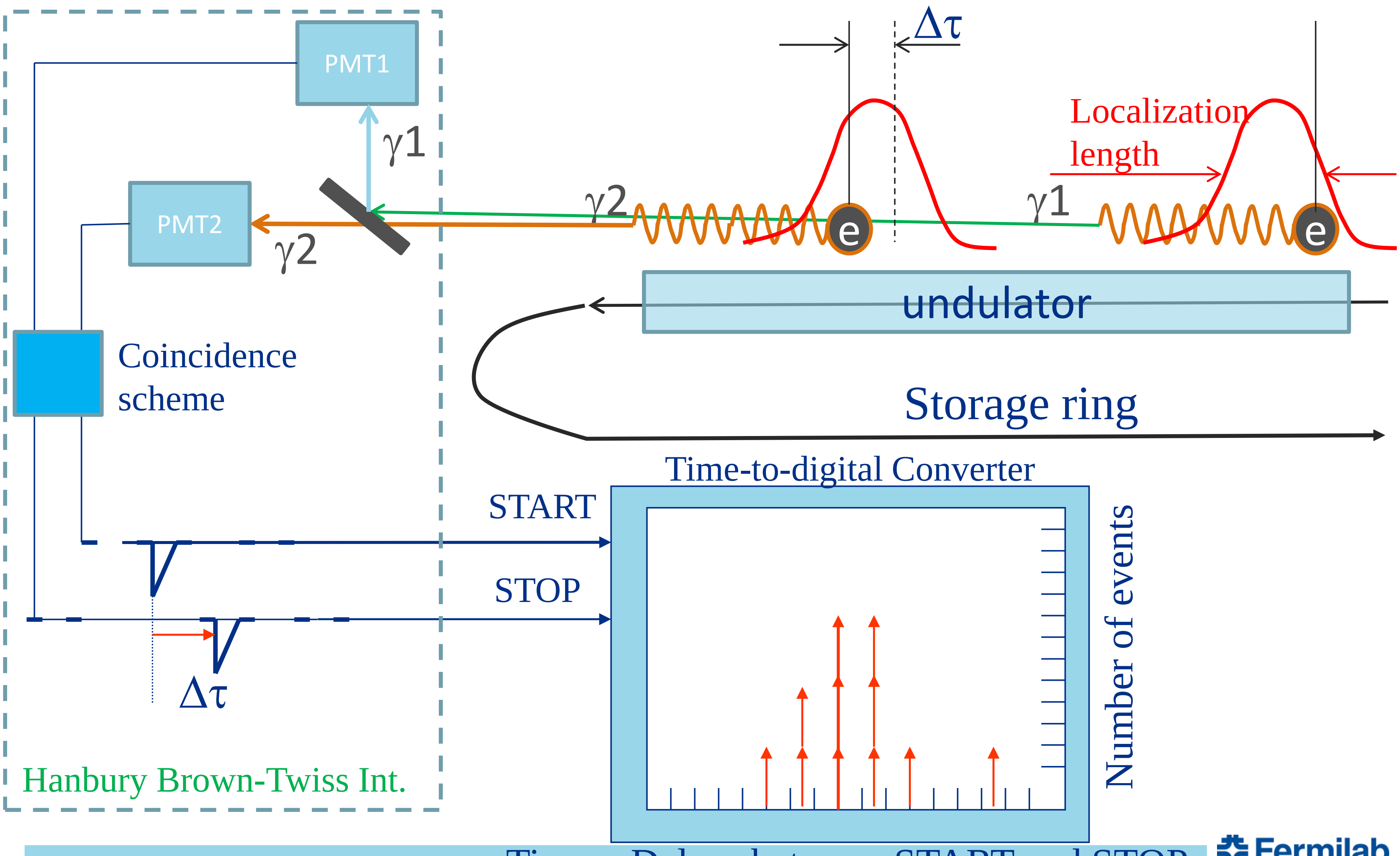
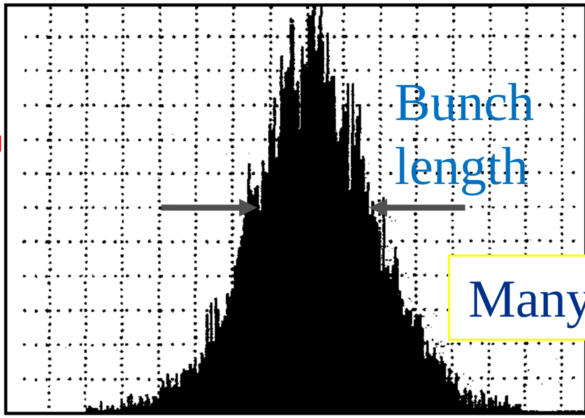
Experiments at VEPP-3 (BINP) – T. Shaftan at al. (1994-97)

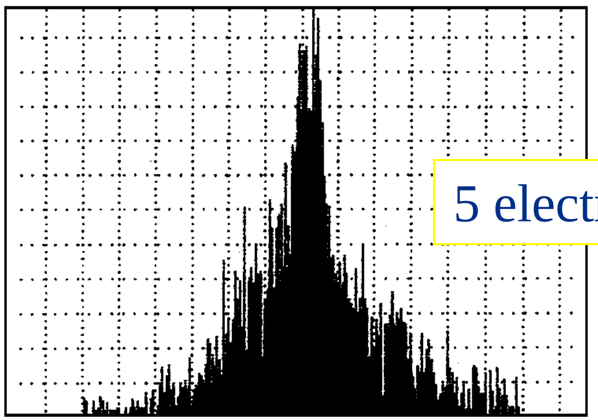


Results of experiments
(courtesy T. Shaftan)

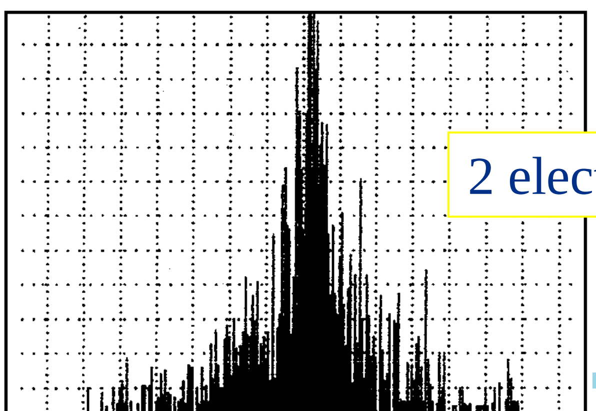
Distributions of intervals between photocounts from PMT A and PMT B for different number of electrons



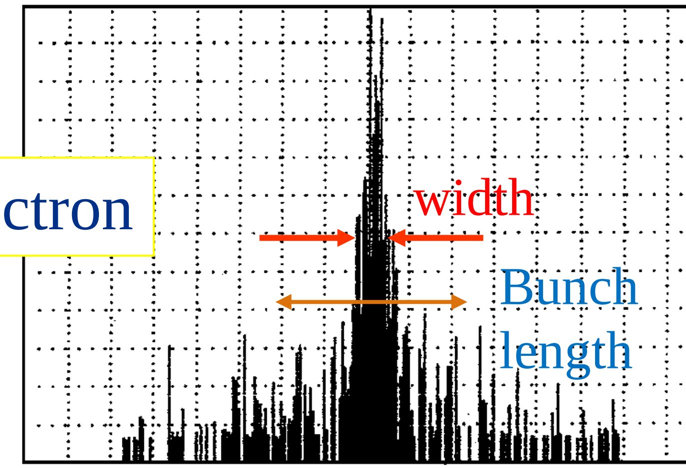
DELAY: 32NS / SCALE



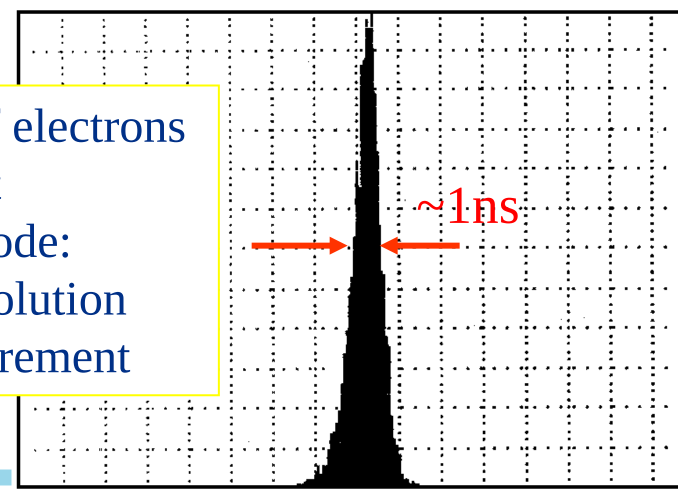
DELAY: 32NS / SCALE



DELAY: 32NS / SCALE



DELAY: 32NS / SCALE



DELAY: 32NS / SCALE

Conclusions (by T. Shaftan)

- For a large number of electrons we measure the density distribution in the bunch (e_A- e_B events)
- For a few electrons we measure the distribution, dominated by (e_A- e_A events)
- For a single electron the width of the distribution is equal to the time resolution (~1 ns rms) of the meas. system →
- Correlation length of UR intensity for a single electron is measured to be much shorter than the natural bunch length
- Interpretation: localization length of a single electron is much shorter than the bunch length
- How short is the localization length?

2018 workshop on Single Electron experiments in IOTA

- https://indico.fnal.gov/event/18395/

- We concluded that we need to detect 2 photons within the formation length
  - Time resolution needs to improve: 1 ns → <10 fs

- This resolution is possible with a two-photon interferometer
  - Resolution < optical wavelength is already achieved

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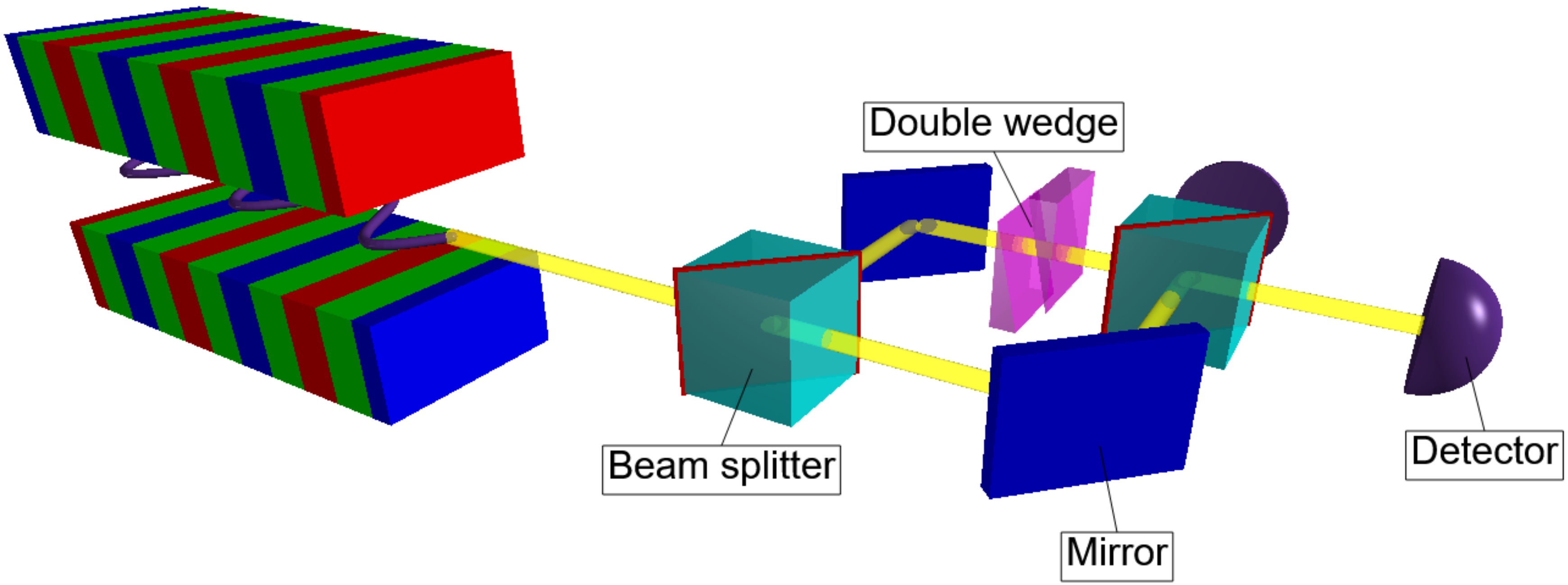
Mach-Zehnder interferometry of undulator radiation

- Interference of the photons in emitted photon pairs with two detectors
- IOTA Run 4 proposal



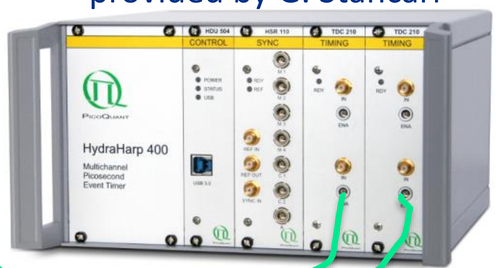
- **Mach–Zehnder interferometer:**
  - **Output 1:** $\boldsymbol{E(t) - E(t+\delta t)}$
  - **Output 2:** $\boldsymbol{E(t) + E(t+\delta t)}$

*light pulse length ≈ 30 fs

Measurement of the light pulse shape in time domain

Design of the experiment with a single electron

Picosecond event timer
(dead time < IOTA revolution period)
provided by G. Stancari

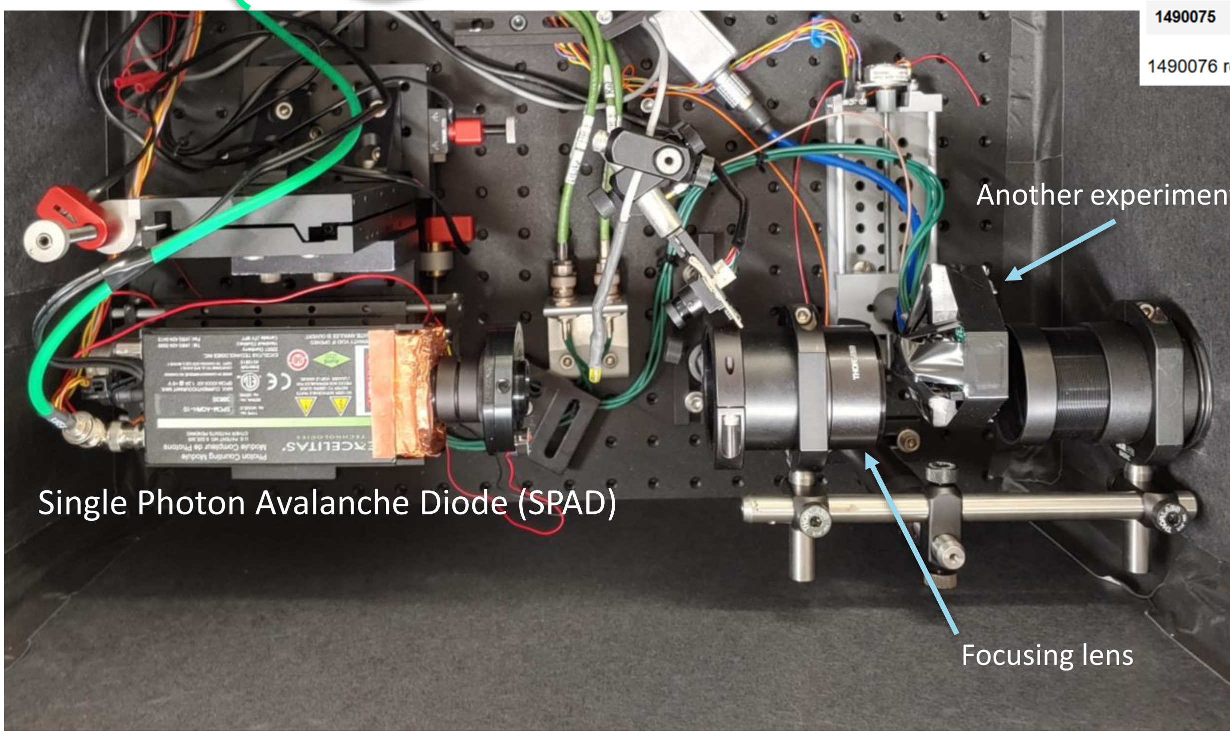


IOTA revolution marker

Record all events for 20 sec – 2 min

	Revolution number	Detection time relative to IOTA revolution marker, ps
0	51	62977.0
1	171	64337.0
2	239	62389.0
3	598	63454.0
4	999	64303.0
...	...	...
1490071	450123392	63592.0
1490072	450123677	62846.0
1490073	450123880	62373.0
1490074	450123931	62842.0
1490075	450124364	62746.0

1490076 rows × 2 columns



Undulator radiation

Single Photon Avalanche Diode (SPAD) detector (two in hand)

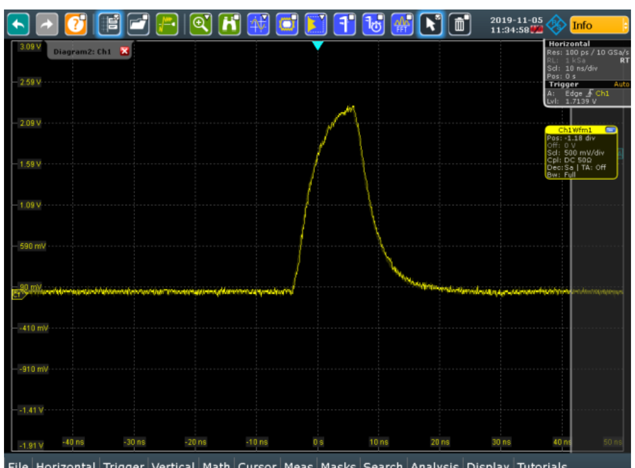
Excelitas SPCM-AQRH-10

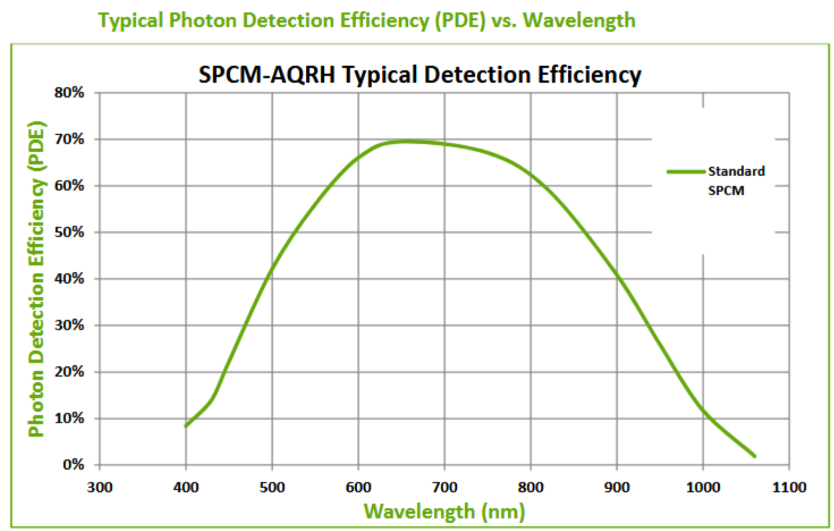
Active area (diameter)	180 μm
Detector efficiency at 650 nm	65%
Dark count	~100 Hz
Dead time	22 ns
Pulse height	2 V
Pulse length	10 ns
Transit time spread (TTS)	0.35 ns

*with gating <10 Hz

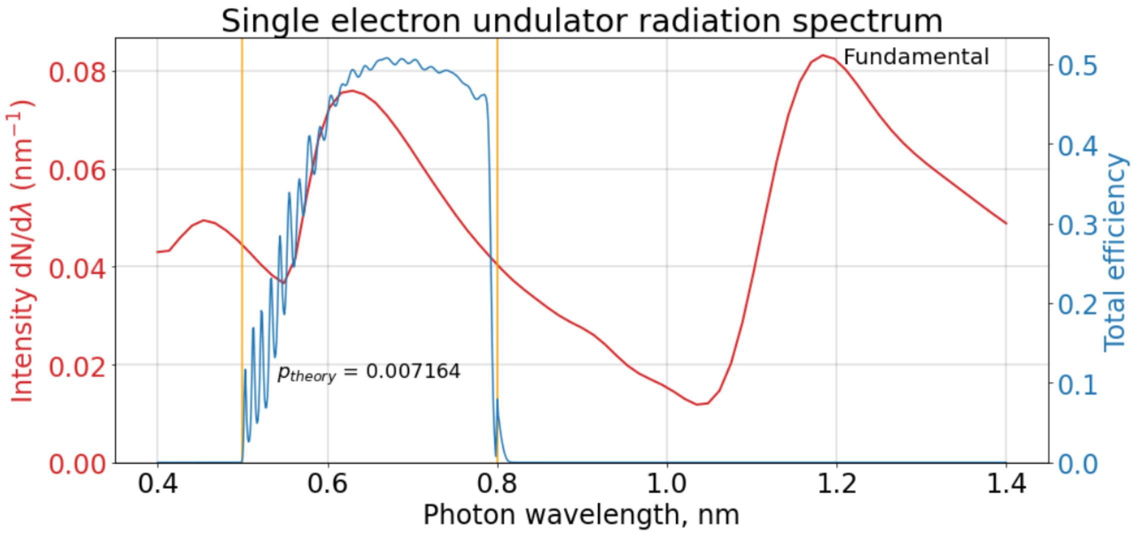
*IOTA period is 133 ns

Each detection event creates a pulse of the same height and width:





Photocount rate. Simulation vs. measurements (100 MeV)



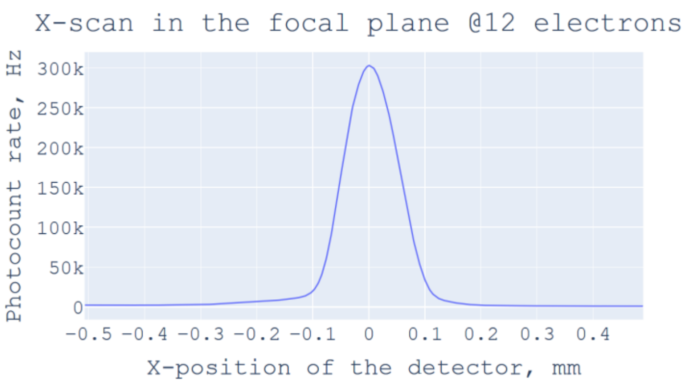
Total efficiency in the simulation takes into account:

- two mirrors,
- vacuum chamber window
- one lens
- low-pass filter
- high-pass filter
- quantum efficiency of the detector.

Simulated photocount rate for one electron: 53kHz

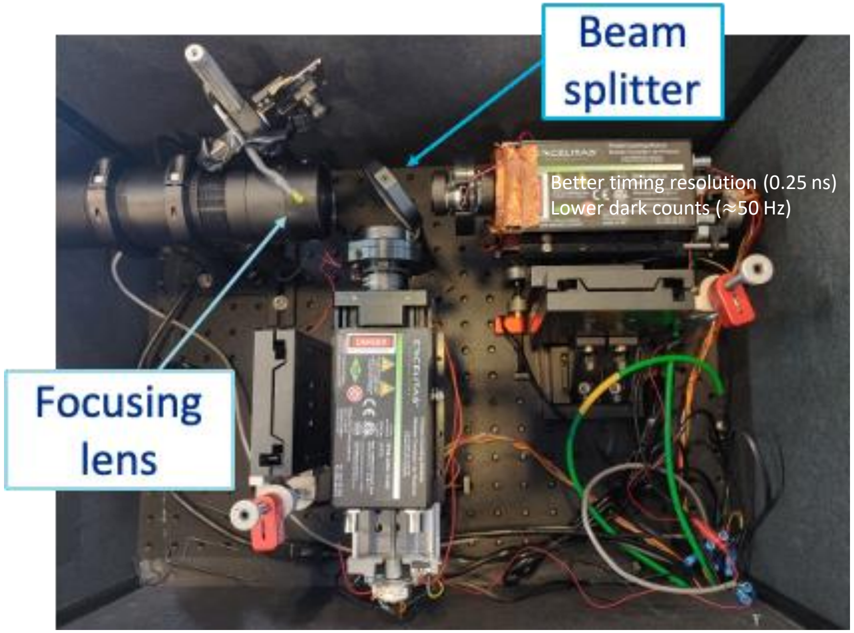
However, aberrations in the lens result in significant light spot size in the focal plane and not all the light is collected by the detector:

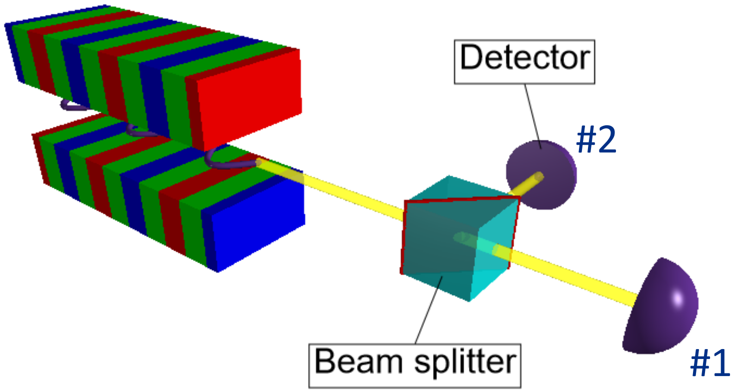
Measured rate for one electron: 25kHz, i.e., 1 detection per 304 IOTA revolutions



*dark counts: ~100Hz (with gating <10Hz)

Two SPAD detectors (June 2021) at 100 MeV





Collected data (up to 5-minutes-long):
00000100000110000000000200010000000112000000…

- So far, no deviations from our expectations

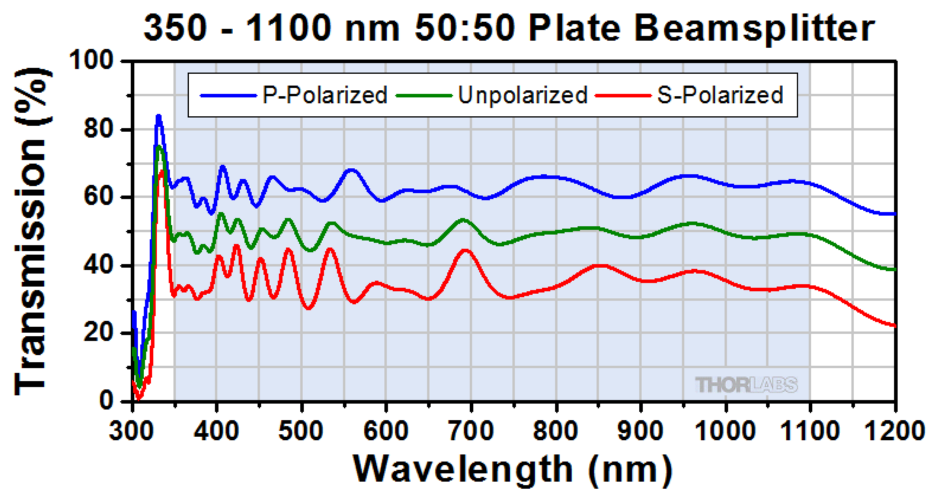
Detector #1: ~30 kHz

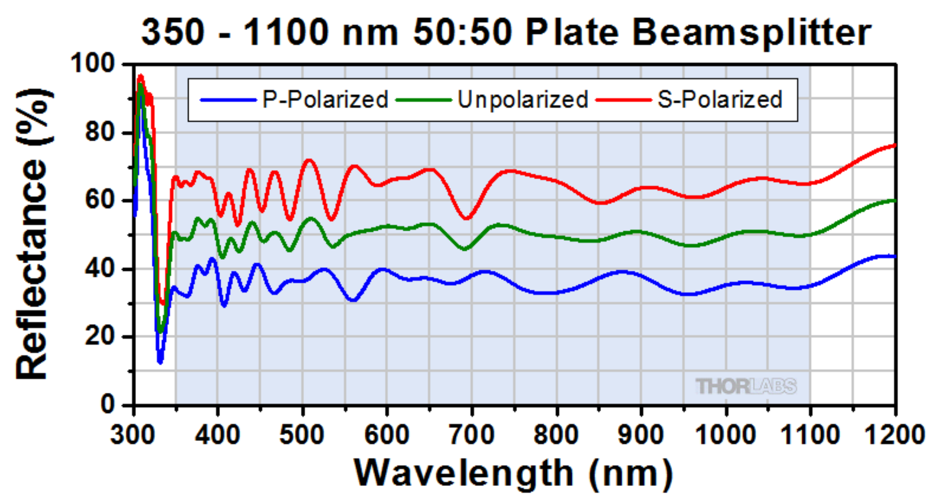
Detector #2: ~15 kHz

Detector #1 & Detector #2: ~70 Hz

Beamsplitter specifications

BSW27 - Ø2" 50:50 UVFS Plate Beamsplitter, Coating: 350 - 1100 nm, t = 8.0 mm





Detector #1: ~30 kHz

Detector #2: ~15 kHz

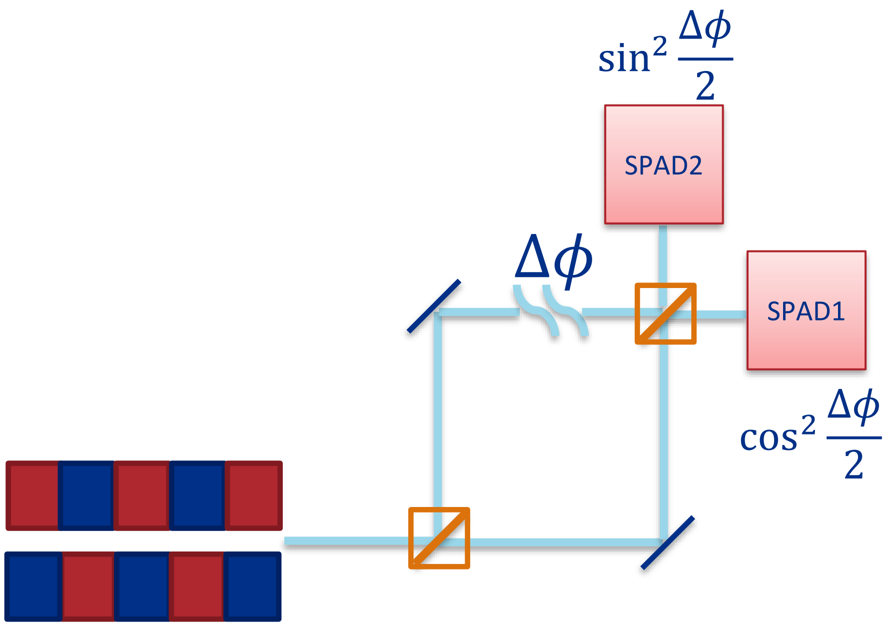
Detector #1 & Detector #2: ~70 Hz

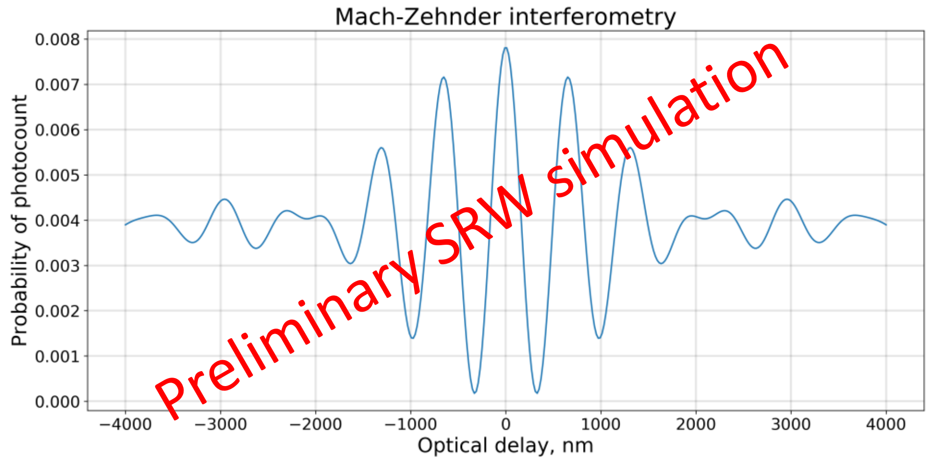
150-MeV beam tests

- The fundamental shifted from 1160 nm to 480 nm
- One SPAD configuration: 27 kHz
- Two-SPAD configuration:
  Detector #1: 8.9 kHz
  Detector #2: 4.6 kHz

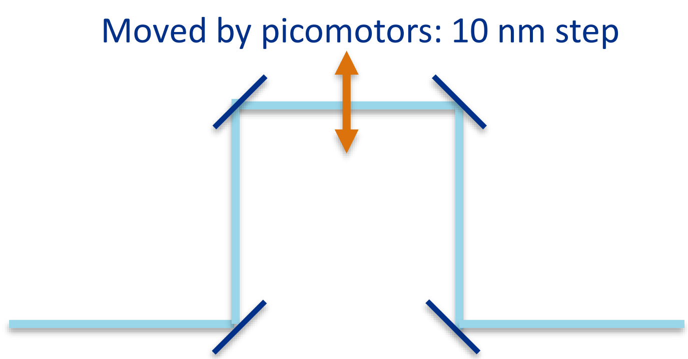
- We prefer to operate at the fundamental of undulator radiation in order to have non-zero intensity at zero-angle

Mach-Zehnder interferometry with a single electron





Very precise adjustable optical delay

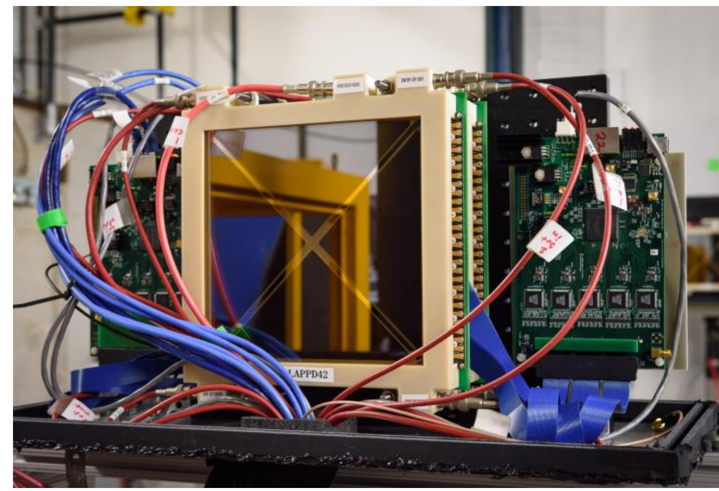


Future experiments. Angular correlation/entanglement of emitted photon pairs with an LAPPD detector

- Preliminary practice measurements have been carried out by Evan Angelico (UChicago) with a 2x2 MCP-PMT array
  - Evan's PhD thesis (May 2020)

2 cm Planacon MCP-PMT 2x2 array

20 cm LAPPD <1 mm spatial resolution



- LAPPD: Large Area Picosecond Photon Detector

Summary

- We are making steady progress towards first ever undulator radiation two-photon interference measurement.
- So far, good progress with preliminary measurements
- Prefer to operate with 150-MeV electrons in order to have non-zero intensity on axis.

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