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# Experiments With Undulator Radiation, Emitted by a Single Electron

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I. Lobach, E. Angelico, UChicago, S. Nagaitsev, G. Stancari, V. Lebedev, A. Romanov, A. Valishev, J. Santucci, Fermilab, A. Halavanau, Z. Huang, V. Yakimenko, SLAC, A. Murokh, Radiabeam, K. J. Kim, ANL, T. Shaftan, BNL

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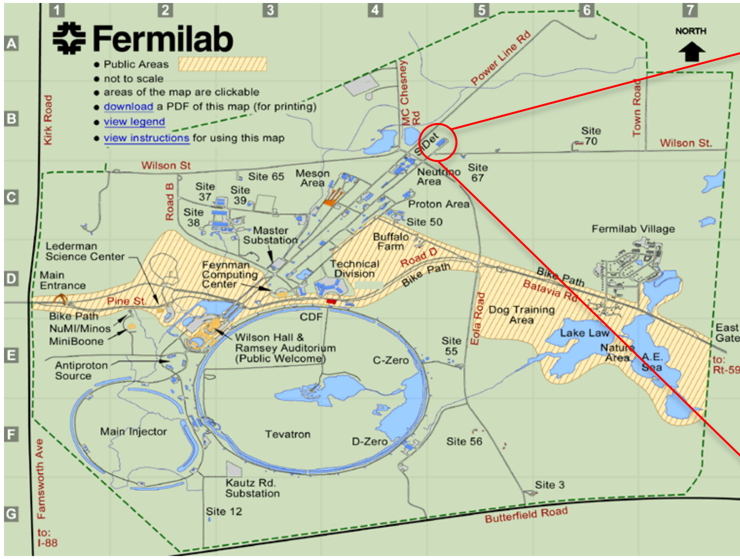
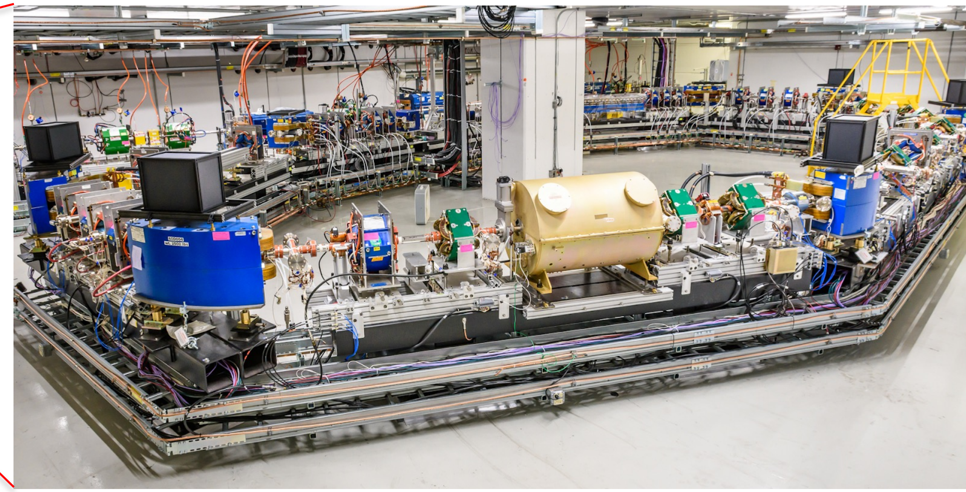
# Fermilab's Integrable Optics Test Accelerator (IOTA)

- First beam Aug 21, 2018



**Primary purpose: accelerator science and technology research (not production of radiation for users)**

- Particles: electrons/protons
- Main experiments:
  - Nonlinear beam optics
  - Optical stochastic cooling

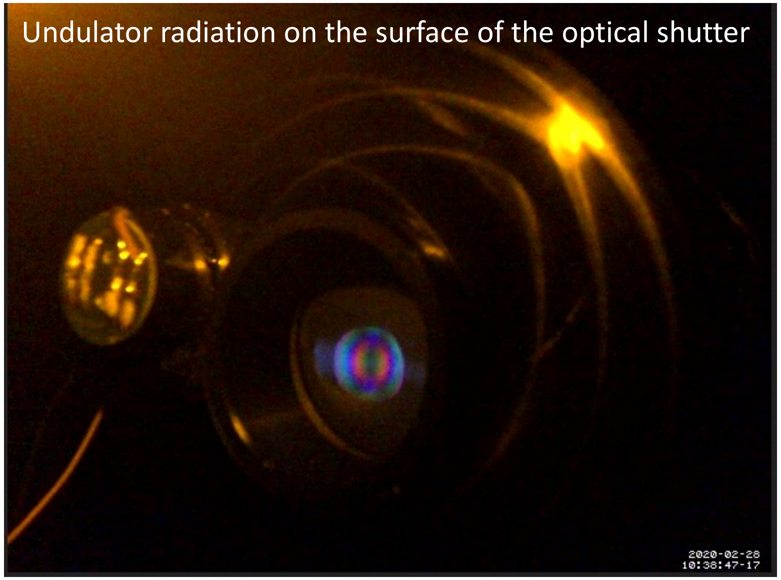
Circumference: 40 m (133 ns)

Electron energy: 100 MeV

*plus some measurements at 150 MeV

# 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

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

@100MeV

# Layout of the undulator section in IOTA

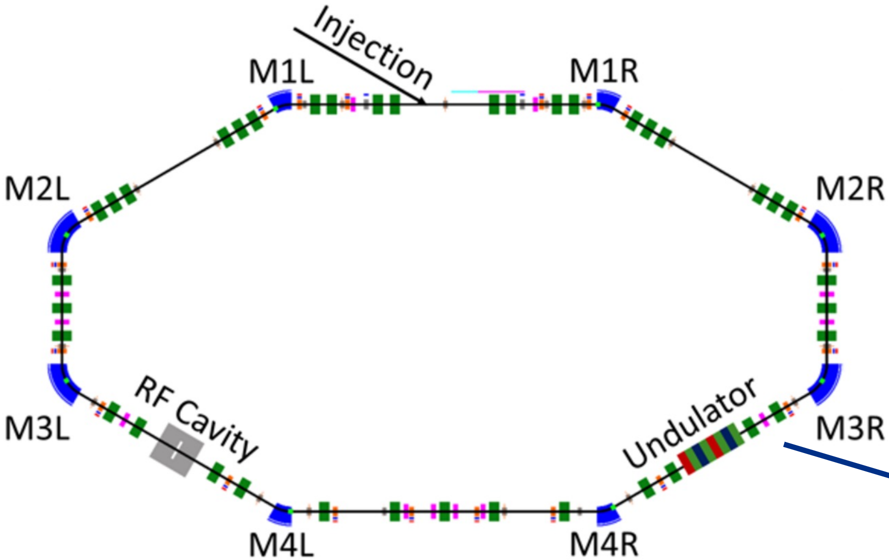
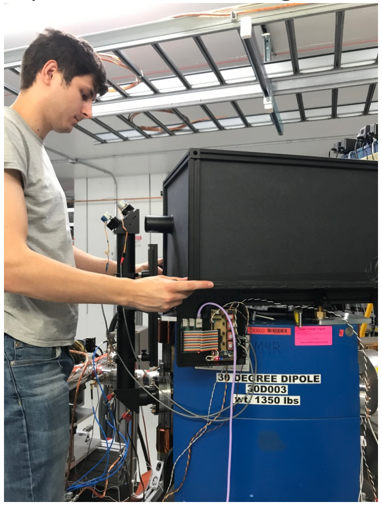
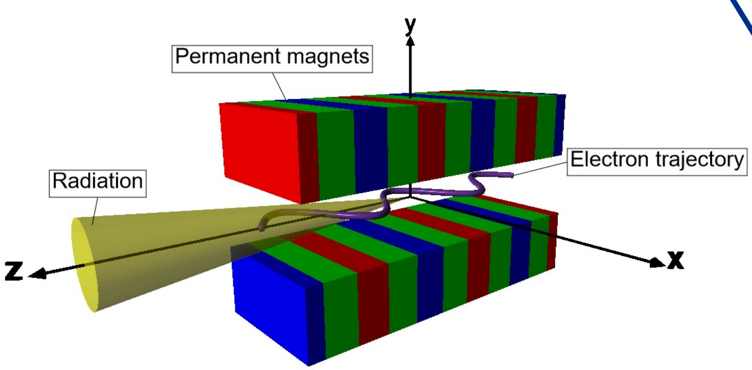
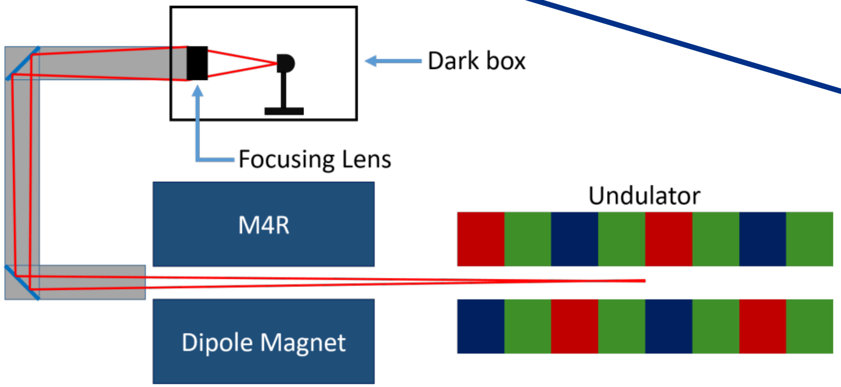



photo credit Evan Angelico



# Previous research about statistical properties of synchrotron radiation

## Both theoretical and experimental results:


[1] M. C. Teich, T. Tanabe, T. C. Marshall, and J. Galayda, Statistical properties of wiggler and bending-magnet radiation from the Brookhaven Vacuum-Ultraviolet electron storage ring, Phys. Rev. Lett. **65**, 3393 (1990).

[2] V. Sajaev, *Determination of longitudinal bunch profile using spectral fluctuations of incoherent radiation*, Report No ANL/ASD/CP-100935 (Argonne National Laboratory, 2000).

[3] V. Sajaev, Measurement of bunch length using spectral analysis of incoherent radiation fluctuations, in *AIP Conf. Proc.*, Vol. 732 (AIP, 2004) pp. 73–87.

[4] F. Sannibale, G. Stupakov, M. Zolotorev, D. Filippetto, and L. Jägerhofer, Absolute bunch length measurements by incoherent radiation fluctuation analysis, Phys. Rev. ST Accel. Beams **12**, 032801 (2009).

[5] P. Catravas, W. Leemans, J. Wurtele, M. Zolotorev, M. Babzien, I. Ben-Zvi, Z. Segalov, X.-J. Wang, and V. Yakimenko, Measurement of electron-beam bunch length and emittance using shot-noise-driven fluctuations in incoherent radiation, Phys. Rev. Lett. **82**, 5261 (1999).

[6] K.-J. Kim, Start-up noise in 3-D self-amplified spontaneous emission, Nucl. Instrum. Methods Phys. Res., Sect. A **393**, 167 (1997).

[7] S. Benson and J. M. Madey, Shot and quantum noise in free electron lasers, Nucl. Instrum. Methods Phys. Res., Sect. A **237**, 55 (1985).

[8] E. L. Saldin, E. Schneidmiller, and M. V. Yurkov, *The physics of free electron lasers* (Springer Science & Business Media, 2013).

[9] C. Pellegrini, A. Marinelli, and S. Reiche, The physics of x-ray free-electron lasers, Rev. Mod. Phys. **88**, 015006 (2016).

[10] W. Becker and M. S. Zubairy, Photon statistics of a free-electron laser, Phys. Rev. A **25**, 2200 (1982).

[11] W. Becker and J. McIver, Fully quantized many-particle theory of a free-electron laser, Phys. Rev. A **27**, 1030 (1983).

[12] W. Becker and J. McIver, Photon statistics of the free-electron-laser startup, Phys. Rev. A **28**, 1838 (1983).

[13] T. Chen and J. M. Madey, Observation of sub-Poisson fluctuations in the intensity of the seventh coherent spontaneous harmonic emitted by a RF linac free-electron laser, Phys. Rev. Lett. **86**, 5906 (2001).

[14] J.-W. Park, *An Investigation of Possible Non-Standard Photon Statistics in a Free-Electron Laser*, Ph.D. thesis, University of Hawaii at Manoa (2019).

# Two experiments to study statistical properties of undulator radiation in IOTA

- Experiment #1 with **many electrons** $(\sim 10^9)$
  - Fundamental harmonic, $\approx 1.16\ \mu\text{m}$
  - InGaAs p-i-n photodiode
  - Feb-Apr 2019, Feb-Mar 2020

| Revolution number | Number of photocounts, N |
|---|---|
| 0 | 9994352 |
| 1 | 9997379 |
| 2 | 10002465 |
| 3 | 9999482 |
| 4 | 9996153 |
| ... | ... |
| 11273 | 10000362 |

1.5 ms

$$\mathrm{var}(\mathcal{N}) = \langle \mathcal{N}^2 \rangle - \langle \mathcal{N} \rangle^2$$

Focus of this presentation:

- Experiment #2 with a **single electron**
  - Second harmonic, $450 - 800\ \text{nm}$
  - Single Photon Avalanche Diode (SPAD)
  - Feb-Mar 2020 + Summer 2021

| Revolution number | Number of photocounts, N |
|---|---|
| 0 | 1 |
| 1 | 0 |
| 2 | 0 |
| 3 | 1 |
| 4 | 2 |
| ... | ... |
| 150375934 | 0 |

60 s

$$\mathrm{var}(\mathcal{N})$$

+ arrival time for each detection

# Our previous experiment with <u>many electrons</u> ($\sim 10^9$)

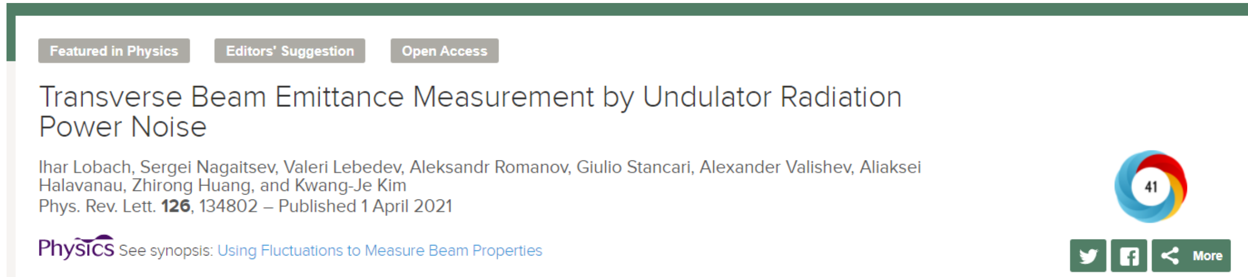
This research resulted in:

**Phys. Rev. Lett., 126, 134802 (2021)**

**Phys. Rev. Accel. Beams, 24, 040701 (2021)**

**Phys. Rev. Accel. Beams, 23, 090703 (2020)**

All are authored by Lobach, I., Nagaitsev, S., Lebedev, V., Romanov, A., Stancari, G., Valishev, A., Halavanau, A., Huang, Z., & Kim, K.-J.


Featured in Physics | Editors' Suggestion | Open Access

Transverse Beam Emittance Measurement by Undulator Radiation Power Noise

Ihar Lobach, Sergei Nagaitsev, Valeri Lebedev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim

Phys. Rev. Lett. **126**, 134802 – Published 1 April 2021

Physics See synopsis: Using Fluctuations to Measure Beam Properties

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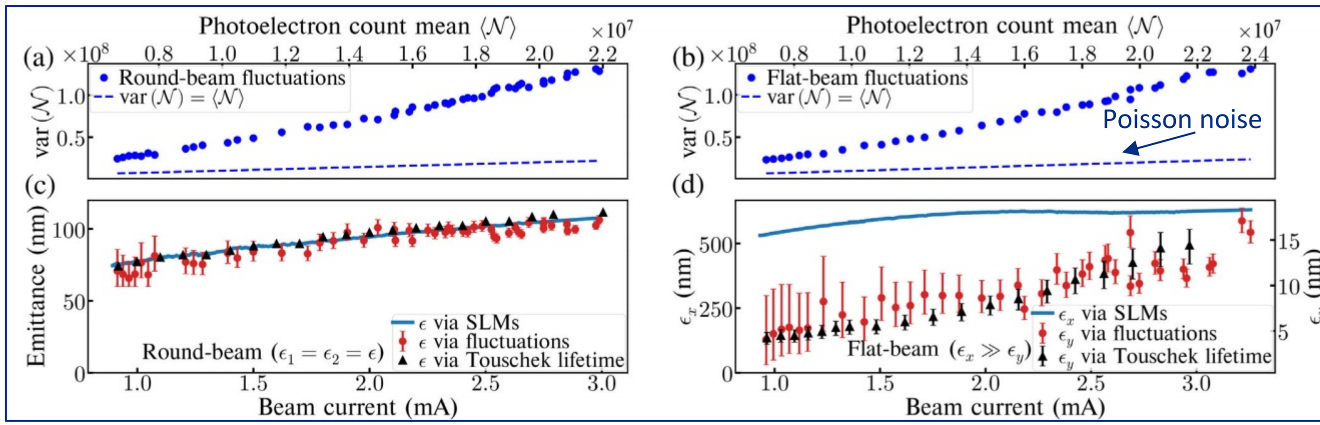
More




<u>We observed a deviation from Poissonian statistics (quantum + classical fluctuations):</u>

$$\mathrm{var}(\mathcal{N}) = \langle\mathcal{N}\rangle + \frac{1}{M}\langle\mathcal{N}\rangle^2$$

$\mathcal{N}$ – number of detected photons per turn

$M$ is the number of coherent modes. It depends on the electron bunch's transverse emittances, longitudinal density distribution and momentum spread. Thus, it may be possible to reconstruct these properties from the measured value of $M$.

# Experiment #2 --- a single electron in the ring

Next step is a single electron because it is free from any collective effects. It is a very repeatable and well controlled system to study possible deviations from Poisson statistics.

**Goal #1** Verify that the photostatistics in the single-electron case is Poissonian:

$$\mathrm{var}(\mathcal{N}) = \langle\mathcal{N}\rangle + \frac{1}{M}\langle\mathcal{N}\rangle^2$$

$$\frac{1}{M} \propto (n_e - 1)$$

Super-Poissonian light:

$$\mathrm{var}(\mathcal{N}) > \langle\mathcal{N}\rangle$$

Sub-Poissonian light:

$$\mathrm{var}(\mathcal{N}) < \langle\mathcal{N}\rangle$$

unusual – non-classical state of the radiated field

**Goal #2** Use the photocount arrival time information to study the synchrotron motion of the single electron



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# Kinds of photon statistics

- The **Fano factor** is a measure of photon statistics:

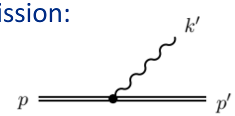
$$F = \frac{\mathrm{var}(\mathcal{N})}{\langle \mathcal{N} \rangle}$$

- $\boldsymbol{F = 1}$ – Poissonian light (very common)
  - laser radiation
  - radioactive decay
- $\boldsymbol{F > 1}$ – Super-Poissonian light (very common as well)
  - thermal light
  - any classical fluctuations of intensity
  - incoherent radiation by an electron bunch (Experiment #1)
- $\boldsymbol{F < 1}$ – Sub-Poissonian light (unusual! non-classical light)
  - Fock state (number state)
  - Parametric down-conversion

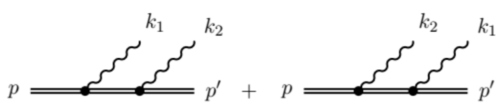
# Description of single electron's undulator radiation in Quantum Electrodynamics

- 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
  (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

**However, it does not explain this paper:**

VOLUME 86, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 2001

**Observation of Sub-Poisson Fluctuations in the Intensity of the Seventh Coherent Spontaneous Harmonic Emitted by a rf Linac Free-Electron Laser**

Teng Chen and John M. J. Madey
*Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822*
(Received 18 April 2000)

Poissonian photostatistics

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

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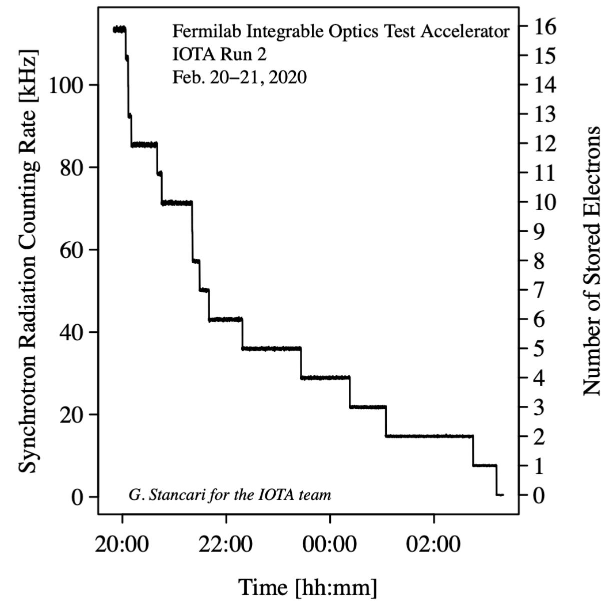
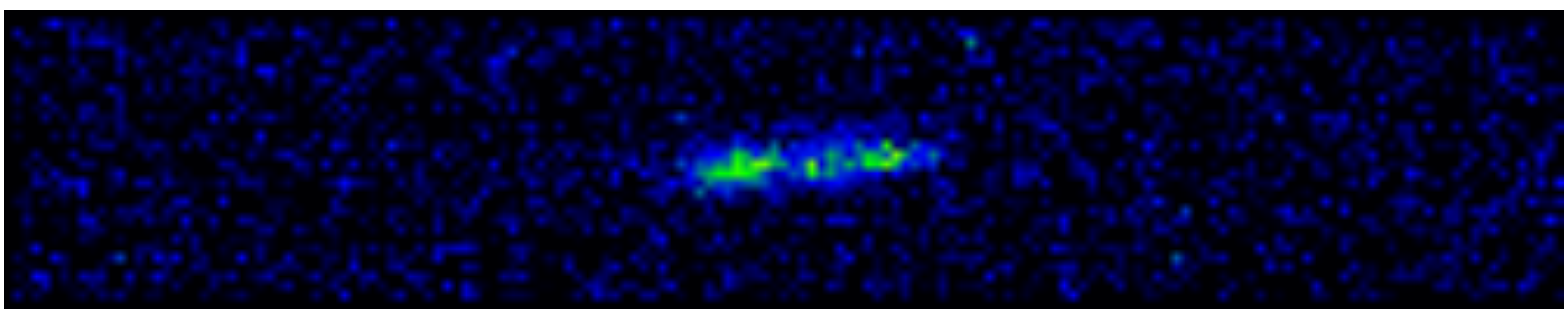
# Obtaining a single electron in the ring

- Injecting very low current from linac
- Changing RF voltage quickly to scrape electrons
- The number of electrons is easily determined by looking at photocounts rate
- Lifetime ≈1-2 hours



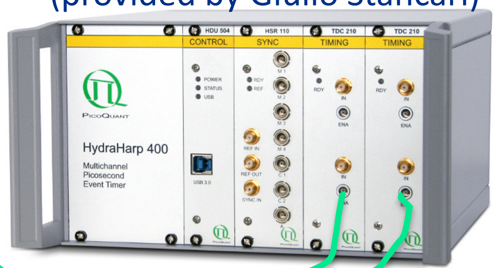

- Real time footage of **one electron** from M2R camera after specially developed noise cancellation algorithms (bending magnet radiation)
  - Clearly visible "stopping" points are due to integration time of less than damping time



*video borrowed from Sasha Romanov's presentation at the workshop "Single-electron experiments in IOTA"

# Design of the experiment with a single electron

Picosecond event timer
(provided by Giulio Stancari)



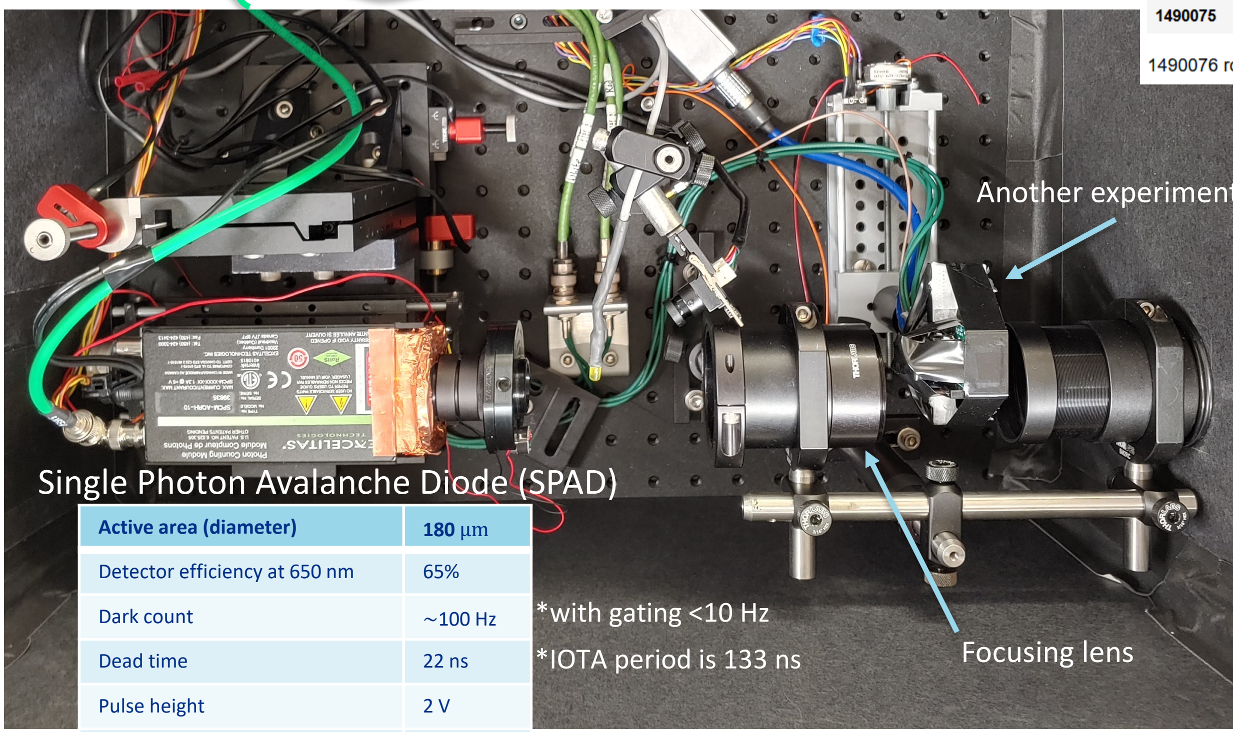

IOTA revolution marker

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

*on average one detection per 304 revolutions

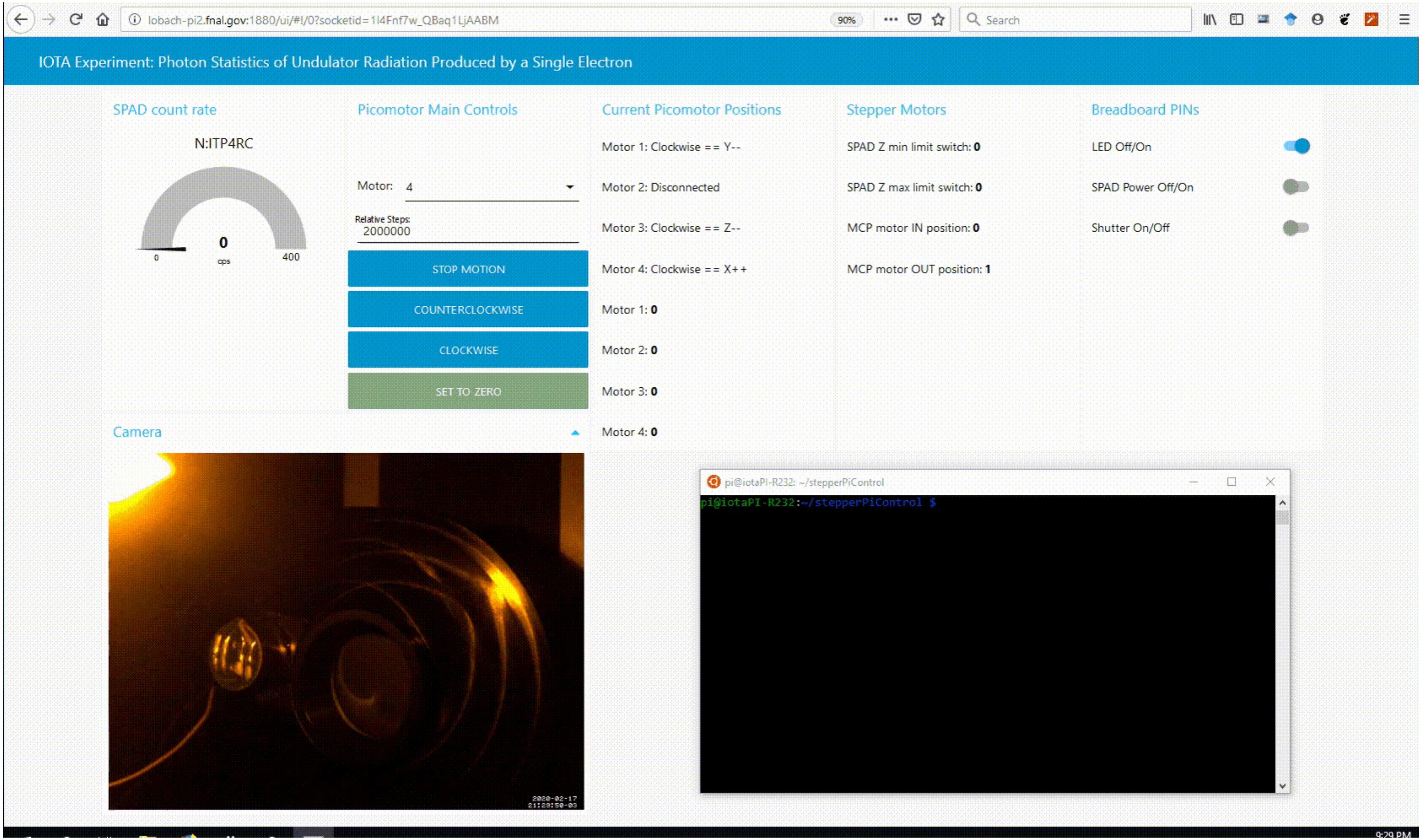



| Active area (diameter) | 180 μm |
|---|---|
| Detector efficiency at 650 nm | 65% |
| Dark count | ~100 Hz |
| Dead time | 22 ns |
| Pulse height | 2 V |
| Pulse length | 10 ns |

Undulator radiation

*the stepper motor translation stages were provided by Sasha Romanov

# Controls




- Live camera video
- x, y, z motors
- Photocount rate
- Optical shutter
- Detector power switch
- LED power switch

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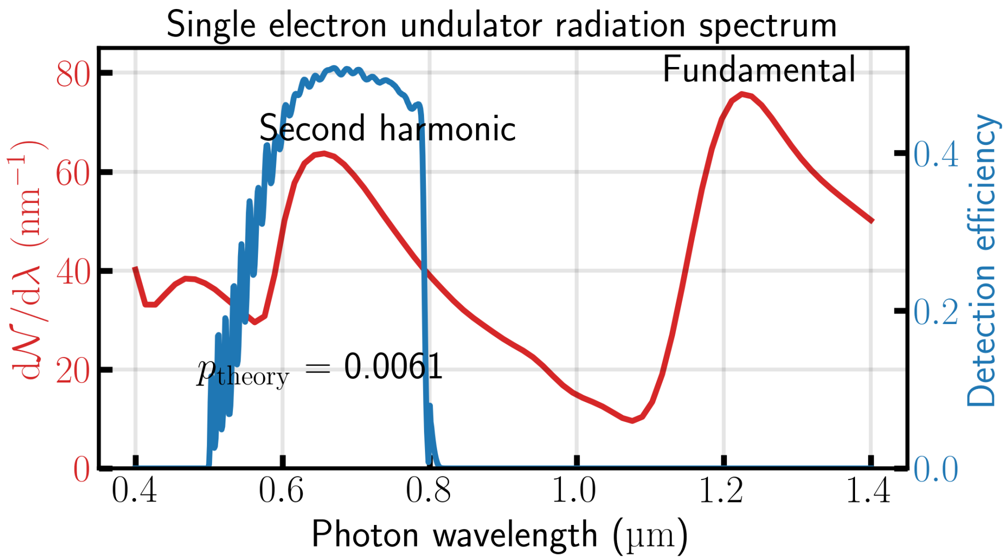
# Photocount rate. Simulation vs. measurements




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 (assuming focusing to a point): 46kHz

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

*dark counts: ≈ 100Hz (with gating ≈ 4Hz)

**Measured rate for one electron: 25kHz, i.e., 1 detection per 304 IOTA revolutions**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# Angular intensity distribution

Simulation:

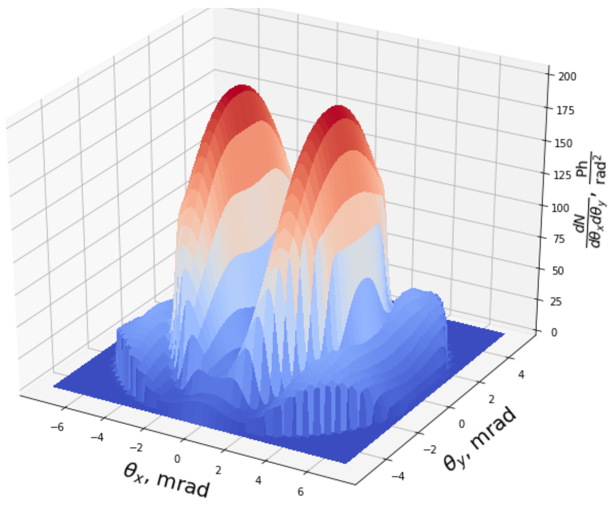
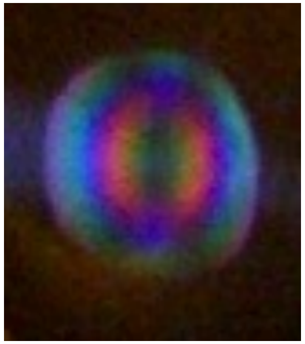
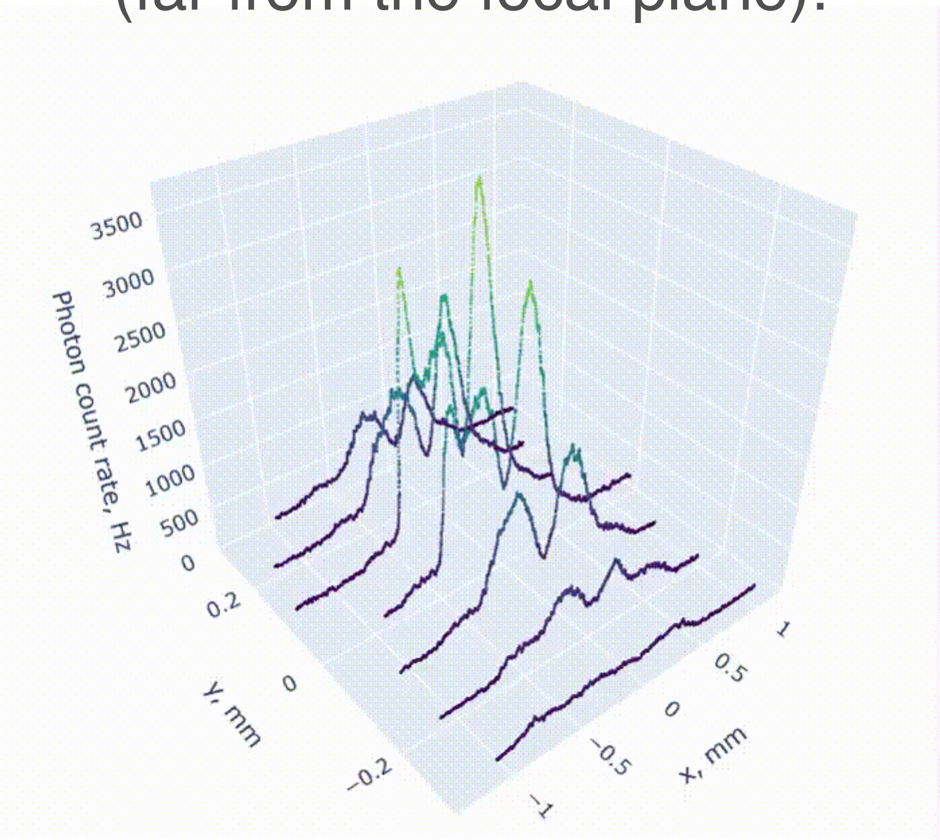



Photo:



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



# Analysis of the statistical properties

*on average one detection per 304 revolutions
*Probability to detect a photon(s) in one revolution: $p = 0.0033$

- Our detector (SPAD) is binary:
  000001000000110000000000001000100000000111000000…
- If our detector could see 0,1,2,3,… photons:
  000001000000110000000000002000100000000131000000…
  0 - no detection, 1,2.. - photon(s) detected

- Poisson distribution

$$\Pr(k) = \frac{\lambda^k}{k!} e^{-\lambda}$$

- Bernoulli distribution

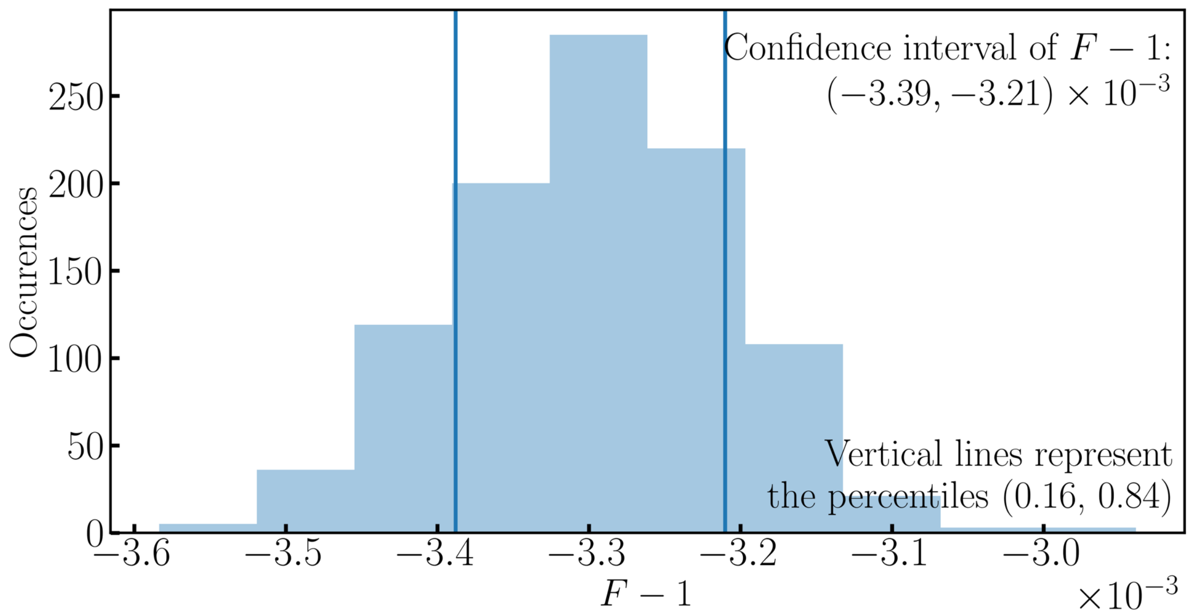
$$\Pr(k) = \begin{cases} 1-p, \text{if } k=0 \\ p, \text{if } k=1 \end{cases}$$

$$\lambda e^{-\lambda} + \frac{\lambda^2}{2} e^{-\lambda} + \frac{\lambda^3}{6} e^{-\lambda} + .. = 1 - e^{-\lambda} = p$$

- $F = \frac{\text{variance}}{\text{mean}} = \frac{\lambda}{\lambda} = 1$
- $F = \frac{\text{variance}}{\text{mean}} = \frac{p(1-p)}{p} = \boxed{1-p}$

# Measurement of the Fano factor in our experiment

- A 60-seconds long data set. The number of photon detections = 1484118
- To determine the confidence interval for the Fano factor:
- Divide the full data into 1000 sub-samples, and calculate the Fano factor in each of them
- Plot the histogram for the obtained 1000 values of the Fano factor:




For Bernoulli trials:

$$F = \frac{\text{variance}}{\text{mean}} = \frac{p(1-p)}{p} = 1 - p$$

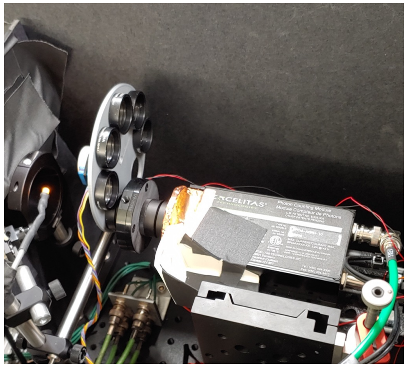
In our experiment, $p = 0.0033$

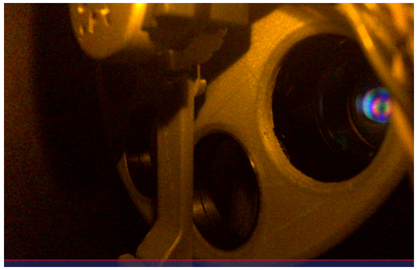
The measured Fano factor is less than 1! Sub-Poissonian light?

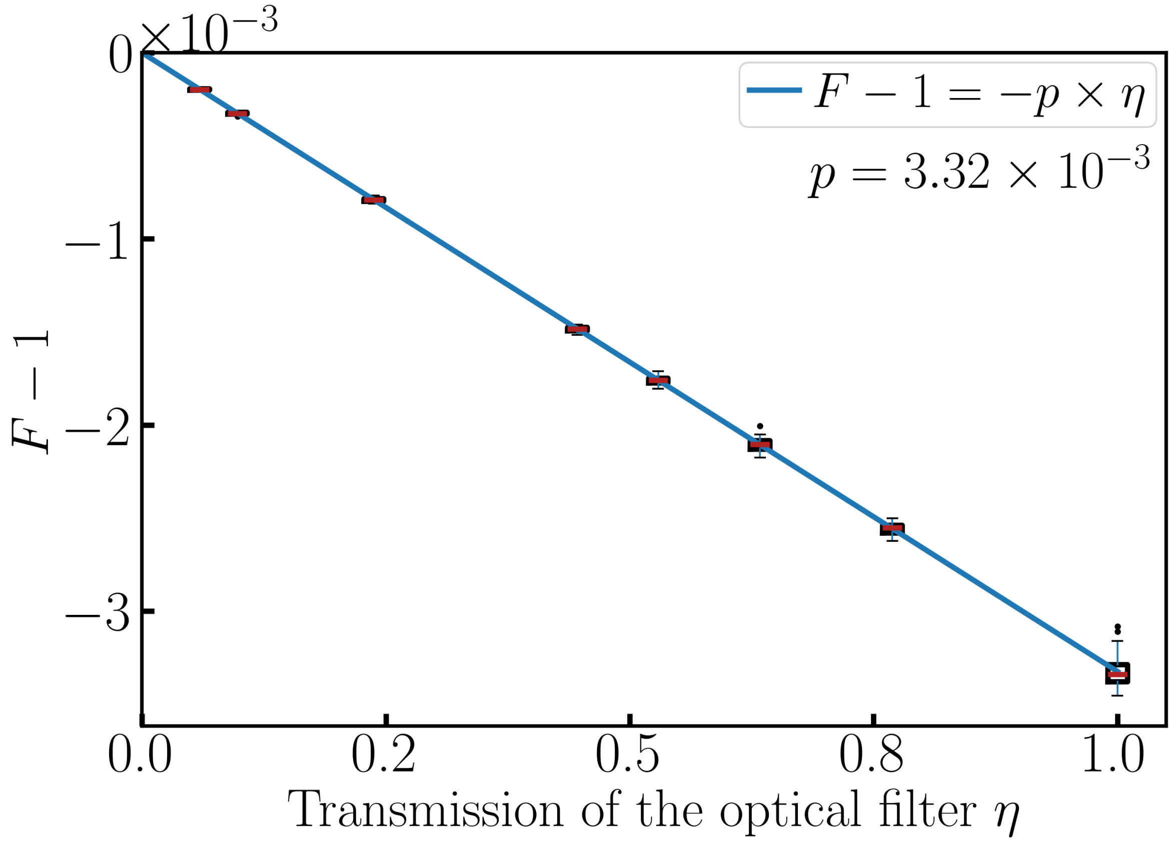
# Fano factors with different neutral density filters

Filter wheel:

(made by Sasha Romanov)







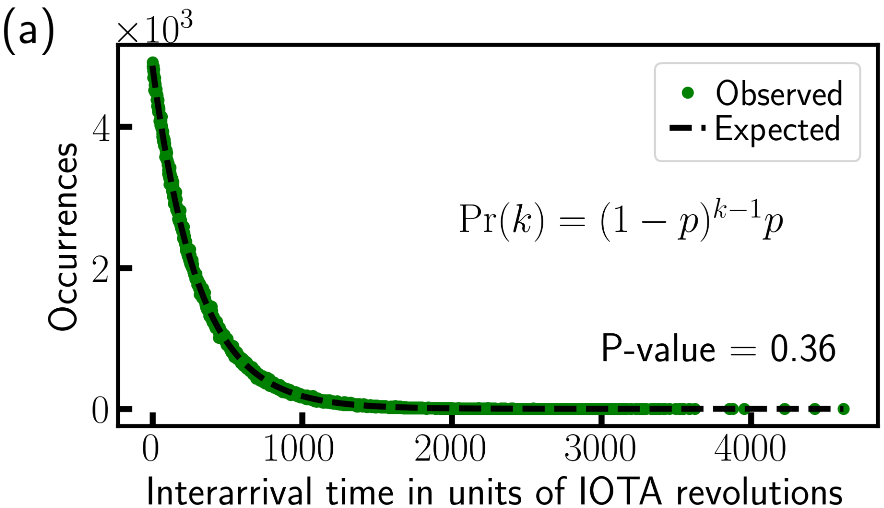

$$F_{\text{measured}} - 1 = \eta(F_{\text{source}} - 1)$$

$\eta$ is the detection efficiency

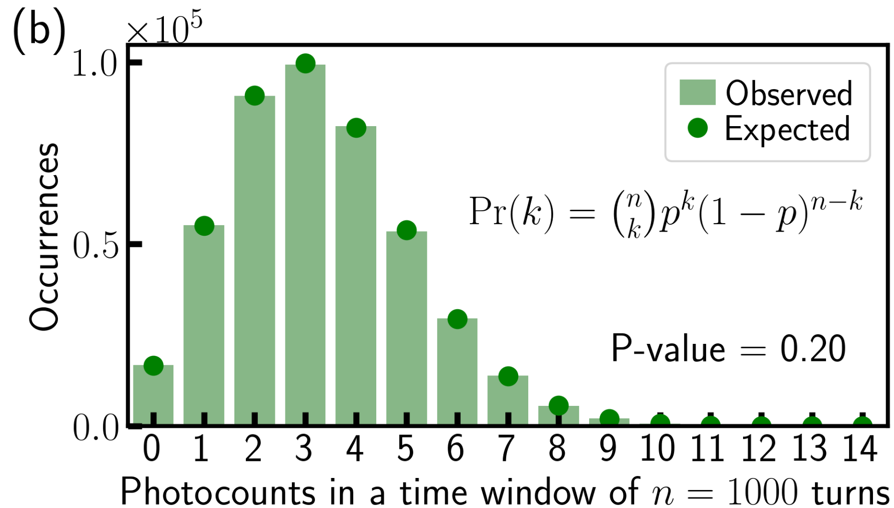
# Analysis of the statistical properties: continued

~~Poisson distribution~~ → **Bernoulli trials**: $\mathrm{var}(\mathcal{N}) = (1-p)\langle\mathcal{N}\rangle$

Distribution of interarrival times: geometric

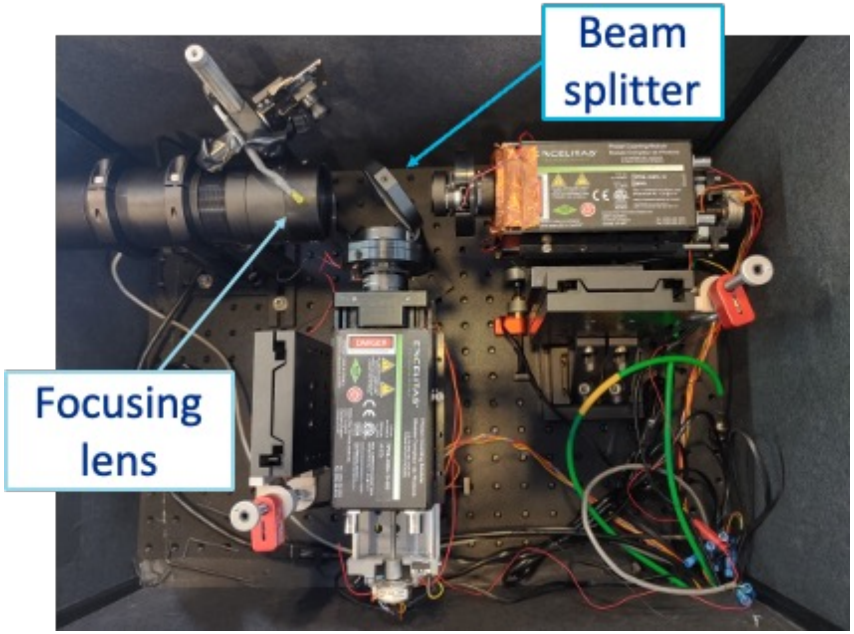


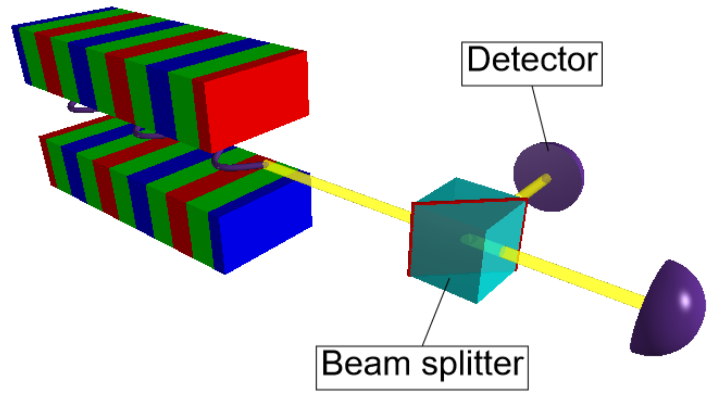

Distribution of photocounts in a time window: binomial




P-value – for hypotheses testing ($\chi^2$ goodness of fit test)

# Measurements with two SPAD detectors




Collected data:

00000100000110000000000200010000000112 0000000...

- So far, no deviations from our expectations

  Detector #1: ~30 kHz

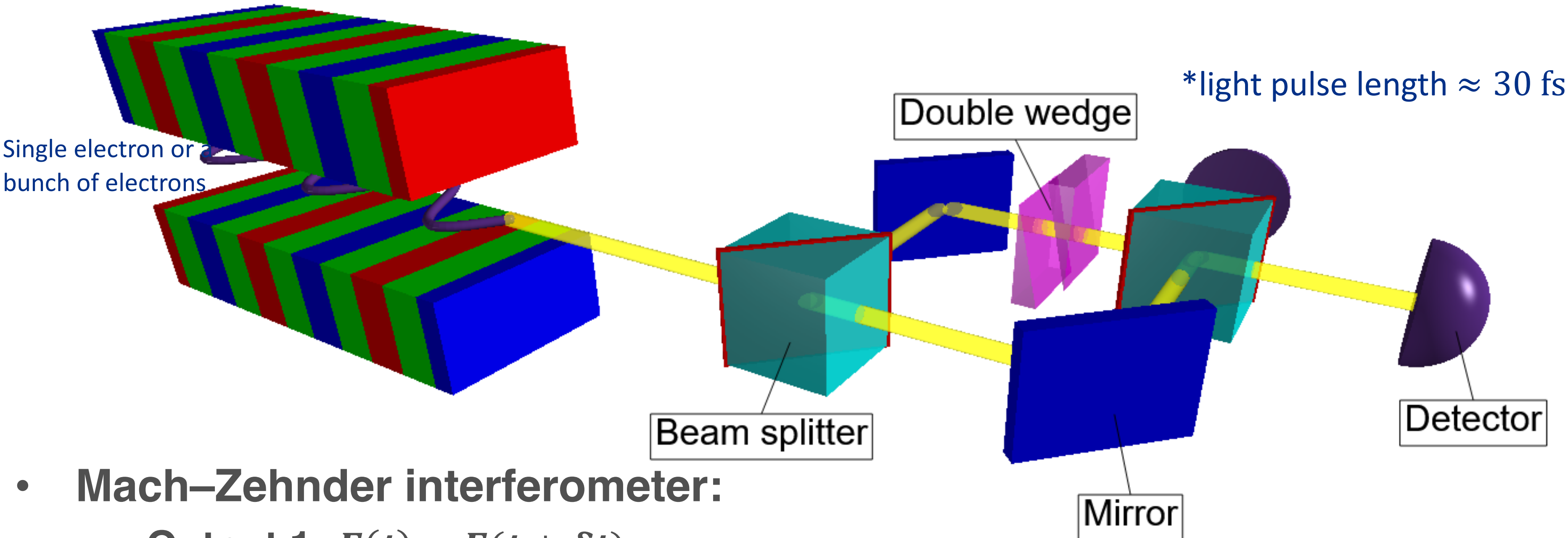
  Detector #2: ~15 kHz

  Detector #1 & Detector #2: ~70 Hz

No correlation or anticorrelation between the two detectors

# Future experiments: Mach-Zehnder interferometry

- Interference of the photons in emitted photon pairs with two detectors:

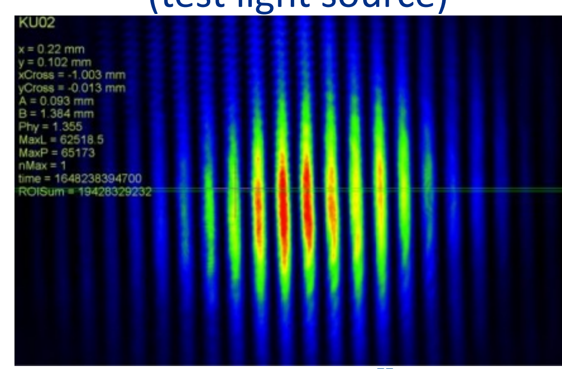



- **Mach–Zehnder interferometer:**
  - **Output 1:** $E(t) - E(t + \delta t)$
  - **Output 2:** $E(t) + E(t + \delta t)$

In some sense, this is a measurement of the light pulse shape in time domain

This experiment is currently under preparation by Alexander Shemyakin, Aleksandr Romanov, Sergei Nagaitsev, Jonathan Jarvis, and Giulio Stancari

MZ fringes with a HeNe laser (test light source)

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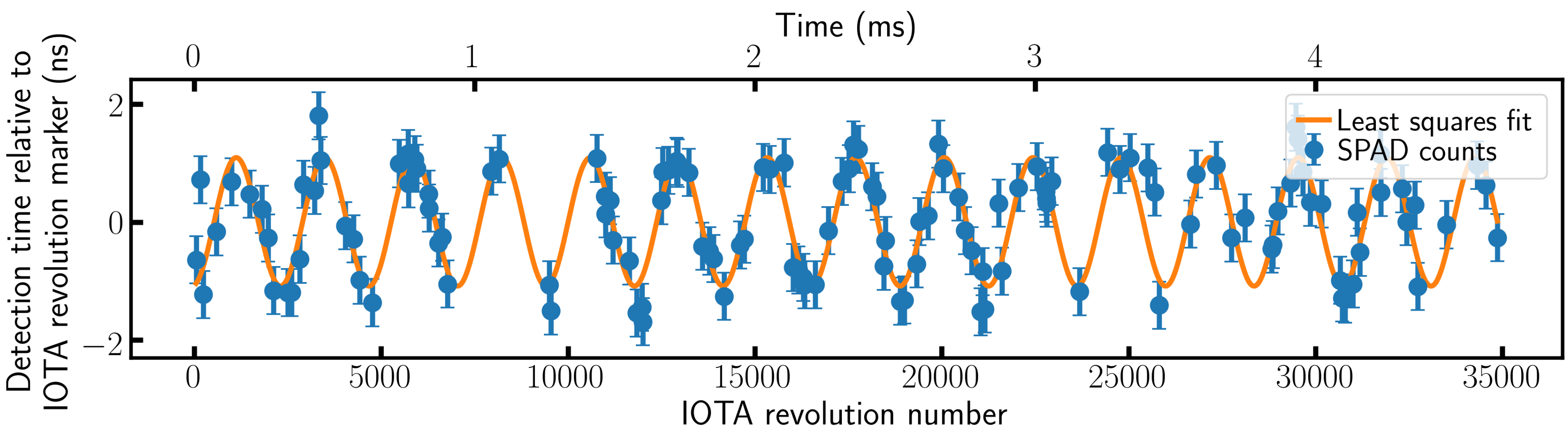
# A possible diagnostic tool: Synchrotron motion of a single electron




- The SPAD's timing resolution is ≈ 0.4 ns (the error bars)
- The outliers could also be the dark counts

# Simulation of the single electron's synchrotron motion

Turn-by-turn map equations:

Radiation damping — Quantum excitation

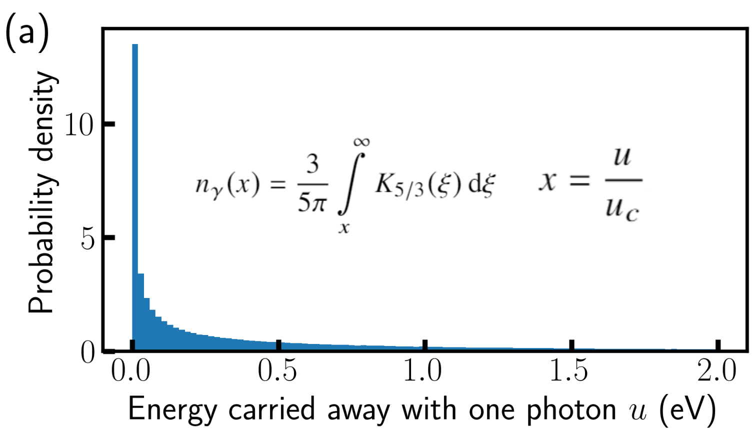
$$\begin{cases} \delta_{i+1} = \delta_i + \dfrac{eV_0}{\beta^2 E_0}(\sin\phi_i - \sin\phi_s) - \dfrac{\langle U\rangle \mathcal{J}_E}{E_0}\delta_i - \dfrac{U_i - \langle U\rangle}{\beta^2 E_0} \\ \phi_{i+1} = \phi_i + 2\pi q \eta_s \delta_{i+1} + \xi_i \end{cases}$$

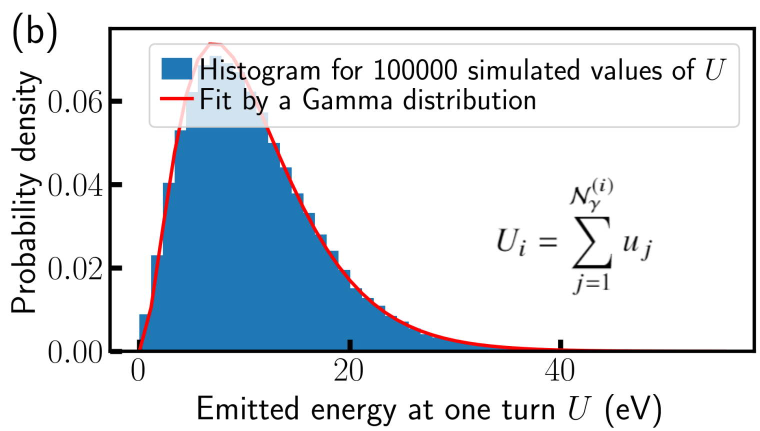
rf phase jitter (Gaussian)

$\eta_s = \alpha_c - 1/\gamma^2$,
$\alpha_c = 0.070\,86$,
$\eta_s = 0.070\,83$,
$V_0 = 380$ V,
$\gamma = 188.6$,
$E_0 = 96.4$ MeV,
$\phi_s = 0.0287$ rad,
$\mathcal{J}_E = 2.64$,
$h = 4$

Average number of photons emitted per turn: $\langle \mathcal{N}_\gamma \rangle = \dfrac{5\pi\alpha}{\sqrt{3}}\gamma = 12.5$ (mostly in bending magnets)

H. Burkhardt, "Monte Carlo generation of the energy spectrum of synchrotron radiation." `http://cds.cern.ch/record/1038899/files/open-2007-018.pdf` (2007)





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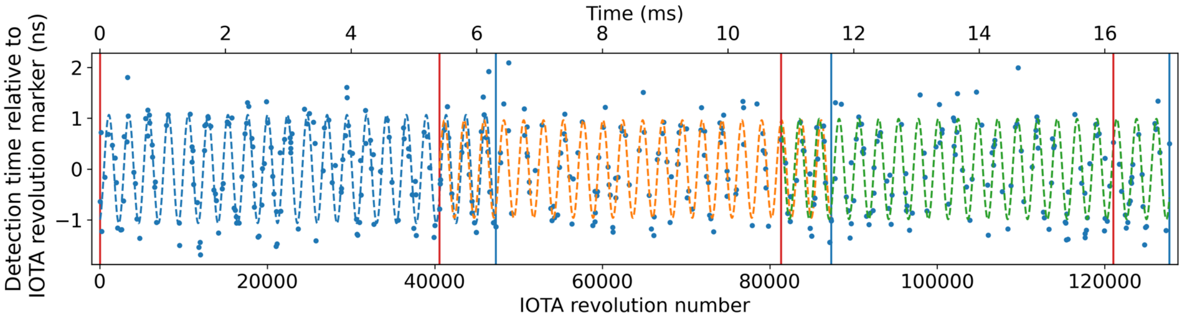
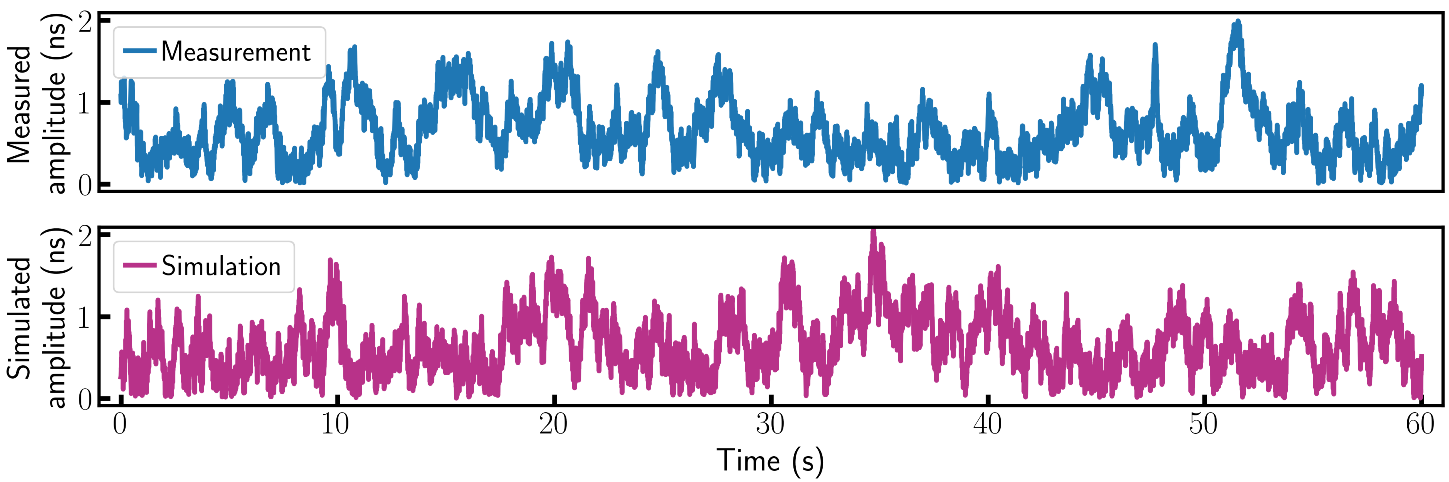
# Synchrotron motion amplitude as a function of time




$A_1, A_2, A_3 \ldots$

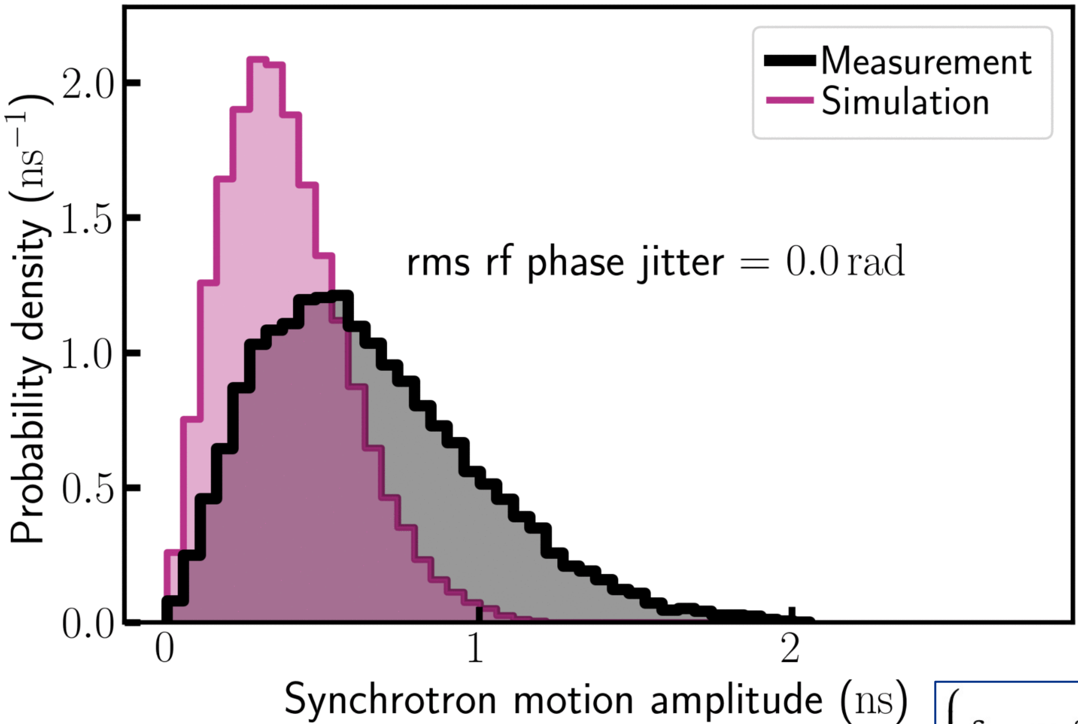
## The measurement and the simulation have similar behavior:




In this simulation, the rms phase jitter is

$$\sigma_\xi = 6 \times 10^{-5} \text{ rad}$$

# Inference of the rms rf phase jitter

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Single electron in a storage ring: a probe into the fundamental properties of synchrotron radiation and a powerful diagnostic tool

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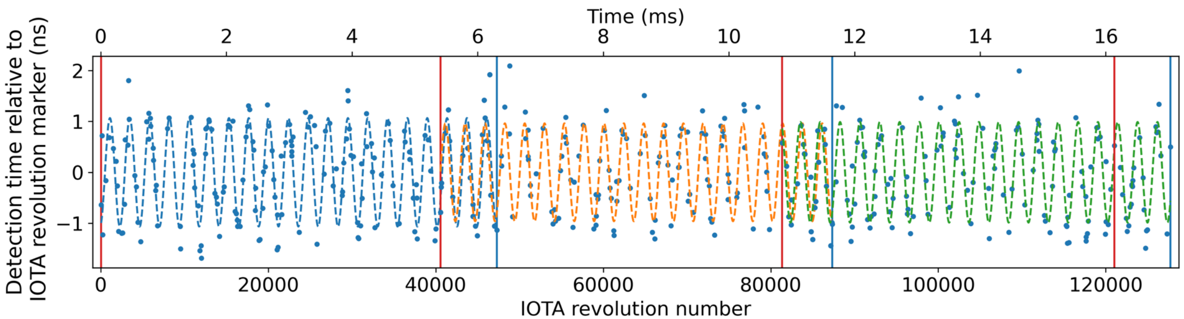
rms rf phase jitter $\sigma_\xi \approx 6\times10^{-5}$ rad

$$\begin{cases} \delta_{i+1} = \delta_i + \dfrac{eV_0}{\beta^2 E_0}(\sin\phi_i - \sin\phi_s) - \dfrac{\langle U\rangle \mathcal{J}_E}{E_0}\delta_i - \dfrac{U_i - \langle U\rangle}{\beta^2 E_0} \\ \phi_{i+1} = \phi_i + 2\pi q \eta_s \delta_{i+1} + \xi_i \end{cases}$$

rf phase jitter

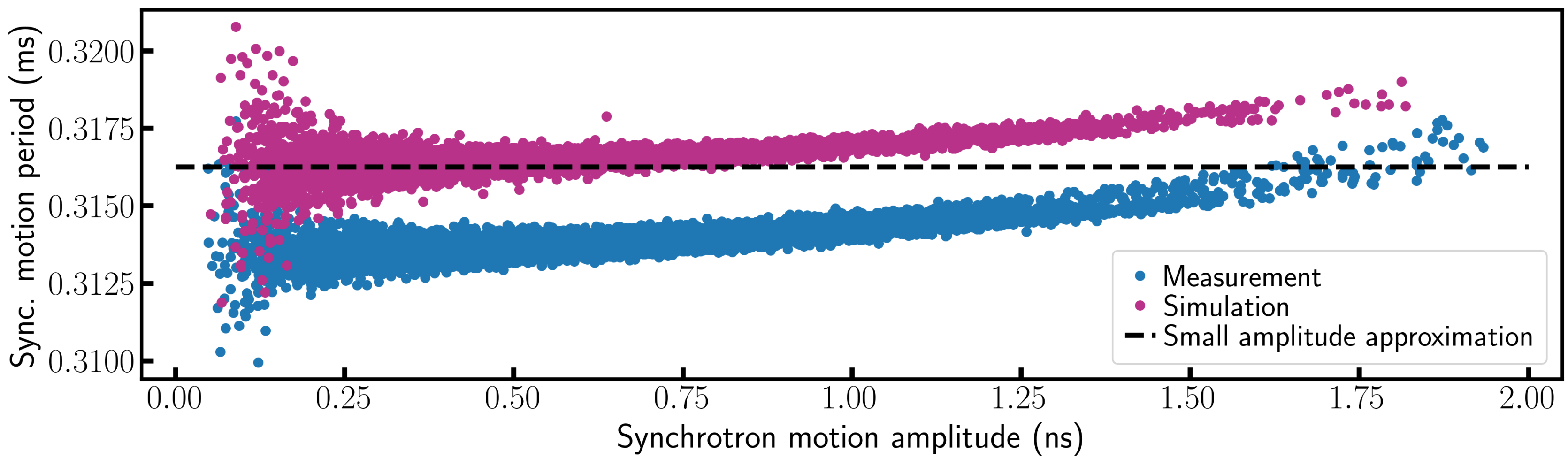
Here we use several data sets, the combined length is 150 seconds.

# Synchrotron motion period as a function of amplitude




We can count the exact number of full synchrotron motion oscillations in a time interval

Thus, we can investigate sync. motion period as a function of amplitude:

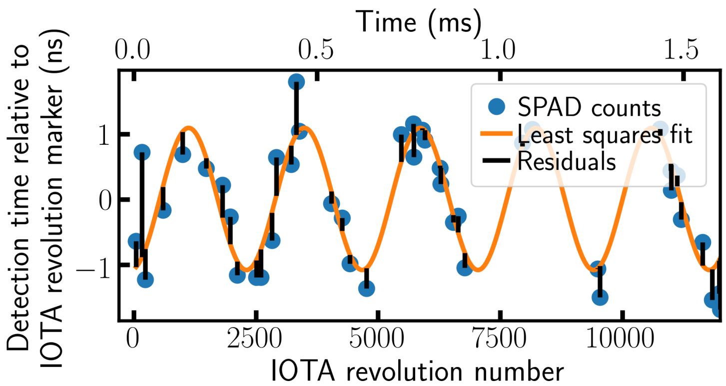


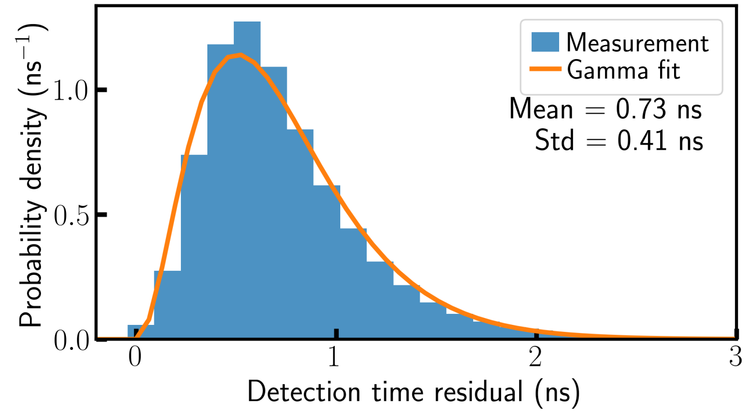

$$T_s = T_0\sqrt{\frac{2\pi E_0}{h\eta_s eV_0 \cos\phi_s}} = 0.3163\,\text{ms}$$

Each point corresponds to an estimation of the period in a time interval of **25 ms**

# Effect of the detector's timing resolution

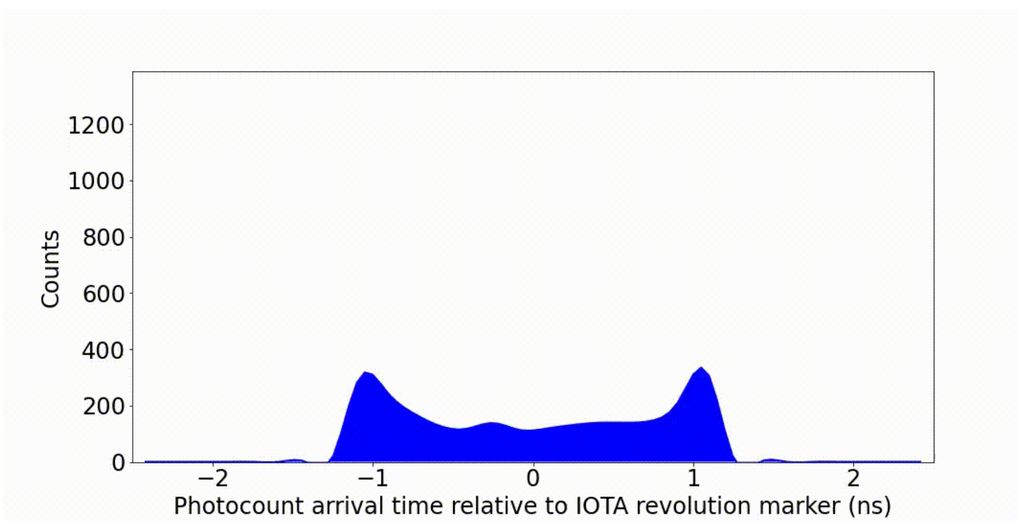
The distribution of residuals describes the random delay introduced by the SPAD detector:




A real time video of the electron's longitudinal position with 0.1 sec-long "exposure":

(the residuals were removed)





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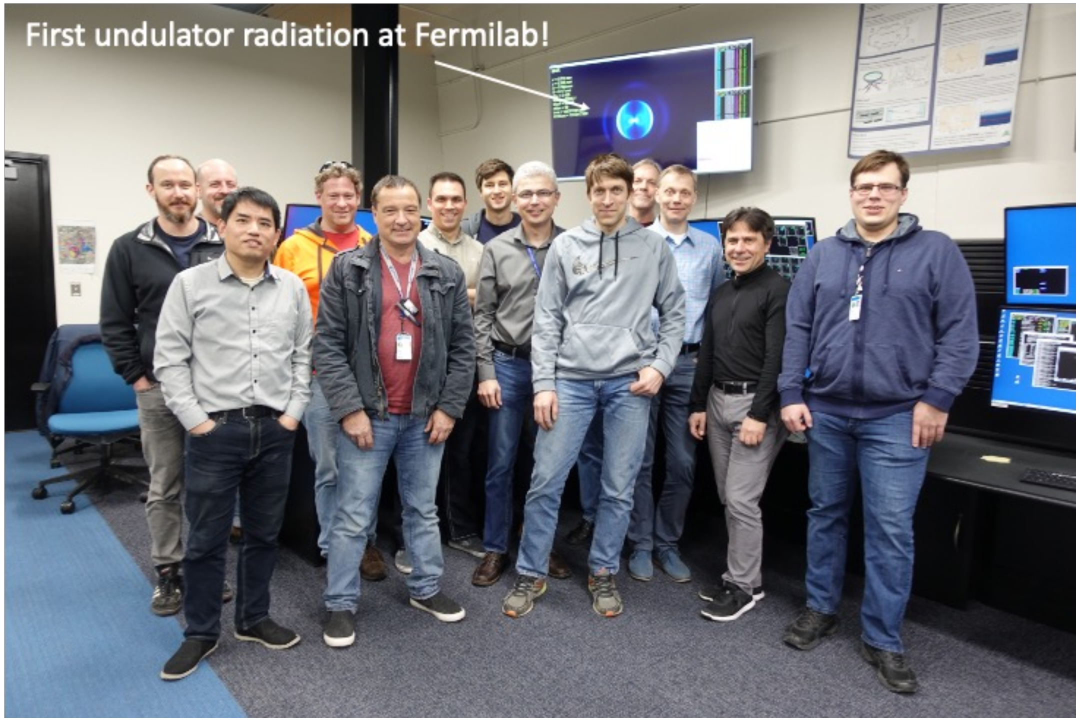
## FAST/IOTA team:




Aleksandr Romanov and Alexander Valishev tuned the ring and the beam. Mark Obrycki, James Santucci, Wayne Johnson, Dean Edstrom, and Kermit Carlson helped build the apparatus. Greg Saewert constructed the photodiode detection circuit and provided the test light source. Brian Fellenz, Daniil Frolov, David Johnson, and Todd Johnson provided some equipment and assisted during our detector tests. We had useful discussions about theoretical description with Valeri Lebedev and our collaborators from SLAC --- Aliaksei Halavanau and Zhirong Huang --- who also kindly provided the undulator.

# Thank you for your attention!