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Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Interferometry of Undulator Radiation from Single Electrons (CLARA)

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Fermilab

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Scientific Motivation

What are the properties of radiation from single electrons?

Can we directly observe its classical or quantum nature?

Are there new ways to generate quantum states of light?

Are there novel applications of the experimental techniques of quantum optics in accelerator physics and beam diagnostics?

Bachor and Ralph, A Guide to Experiments in Quantum Optics (Wiley, 2019)
Couteau et al., Nature Rev. Phys. **5**, 354 (2023)

Theories of Light

Classical electromagnetism

Light as a field wave

Explains refraction, interference, diffraction, dispersion, synchrotron radiation, …

Semi-classical approach

Classical light, quantum matter

Explains most phenomena in atomic and molecular physics: spectroscopy, stimulated emission, lasers, Zeeman effect, magneto-optical traps, …

Quantum optics

The electromagnetic field is quantized with boson properties

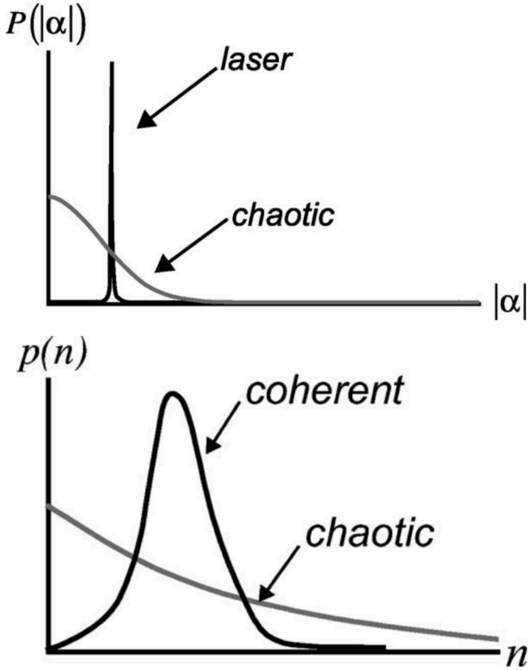
Explains spontaneous emission, Lamb shift, Hong-Ou-Mandel effect, …

Ambiguity of the word "photon:"
- photocounts
- energy quanta
- excitations of the field
- fuzzy balls of light
- …

Loudon, The Quantum Theory of Light (Oxford, 2000)
Grynberg, Aspect and Fabre, Introduction to Quantum Optics (Cambridge, 2010)
Bachor and Ralph, A Guide to Experiments in Quantum Optics (Wiley, 2019)

Quantum States of Radiation

Physical system	Corresponding quantum state
classical wave (dipole antenna, laser, …)	Glauber *coherent state* $\hat{a}\,\|\alpha\rangle = \alpha\,\|\alpha\rangle$ $\|\alpha\rangle = e^{-\|\alpha\|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}\,\|n\rangle$
thermal, “chaotic” source (light bulb, black body, star, …)	*incoherent mixture* (density matrix)
radiation from single atom, parametric down-conversion, quantum dot, …	Fock *number state* $\hat{n}\,\|1\rangle = 1\,\|1\rangle$ $\hat{n}\,\|2\rangle = 2\,\|2\rangle$ …



Glauber, RMP **78**, 1267 (2006)

How Can One Measure the Quantum State of Radiation?

Main observables

Photocount statistics: intensity fluctuations, arrival time distributions

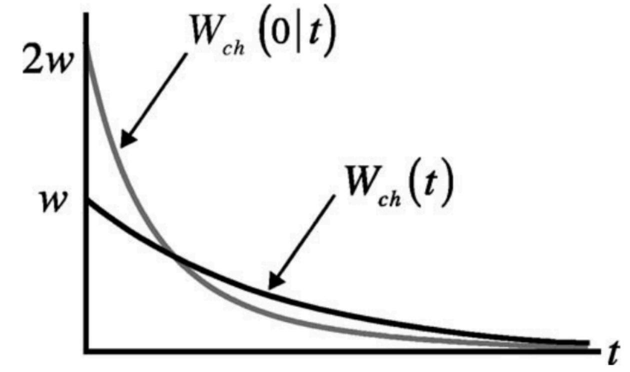
coherent state

$$W_{\mathrm{coh}}(t) = W_{\mathrm{coh}}(0\,|\,t) = we^{-wt}$$

chaotic state

$$W_{\mathrm{ch}}(t) = \frac{w}{(1+wt)^2}$$

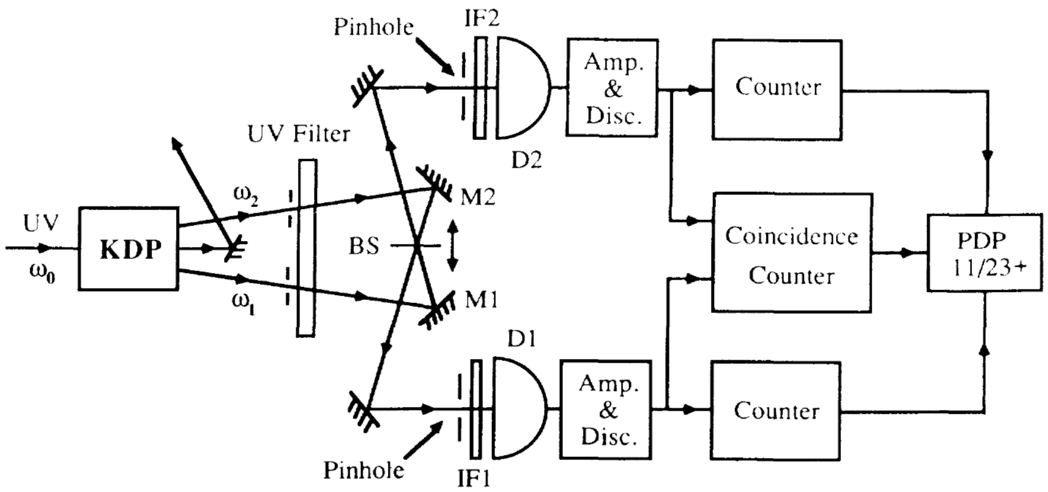
$$W_{\mathrm{ch}}(0\,|\,t) = \frac{2w}{(1+wt)^3}$$

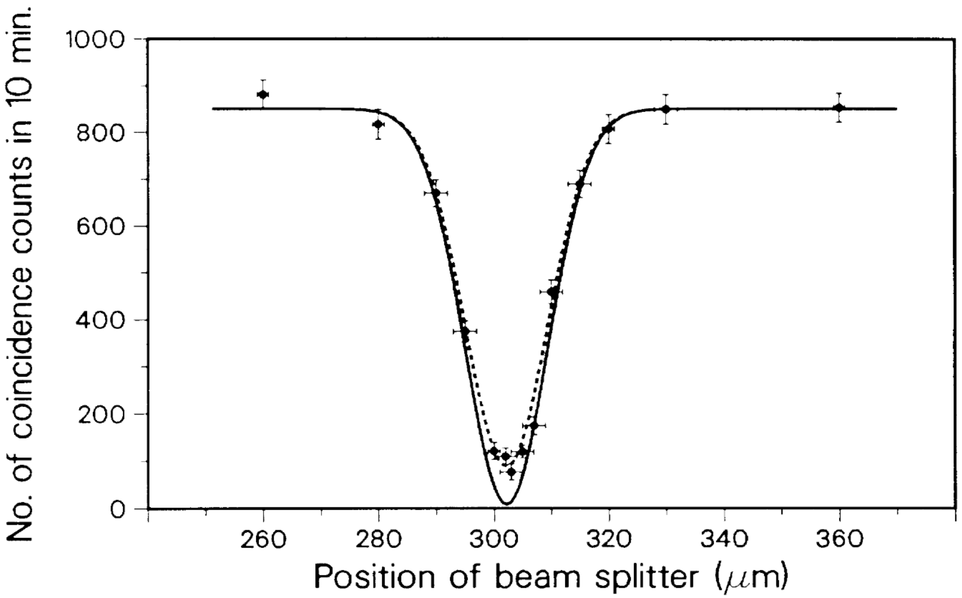


Coincidence rates vs delay: “bunching” and “anti-bunching”

The Hong-Ou-Mandel Effect

Radiation in a 2-photon state is observed in the same detector



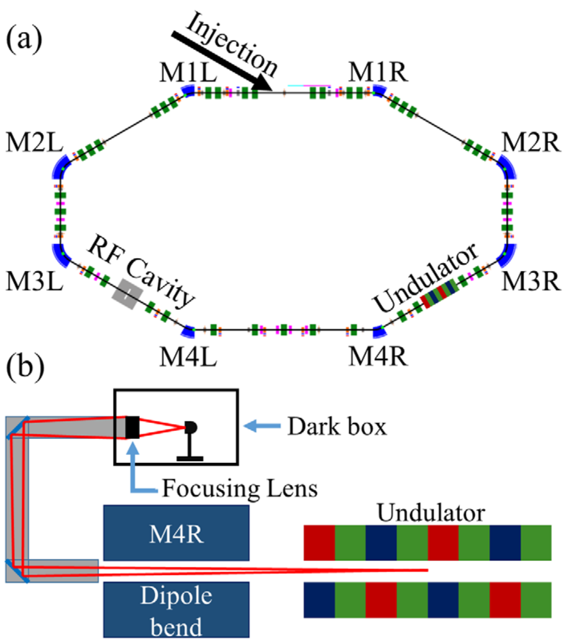


Coincidences are suppressed

Hong, Ou and Mandel, PRL **59**, 2044 (1987)

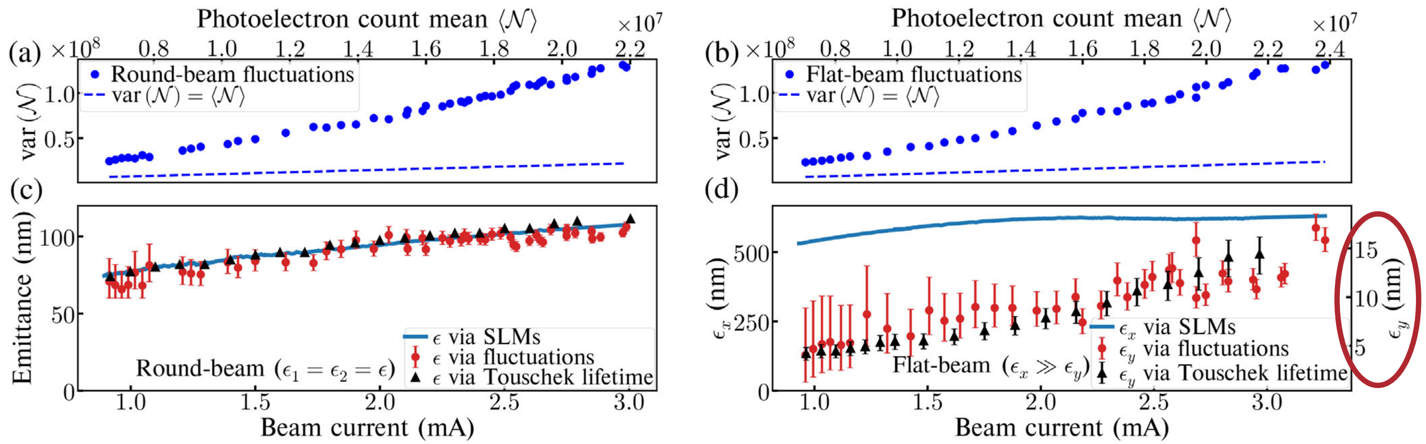
Previous Results in Runs 2 and 3 at IOTA

What are the statistical properties of undulator radiation from single or multiple electrons? Can they be used for beam diagnostics?

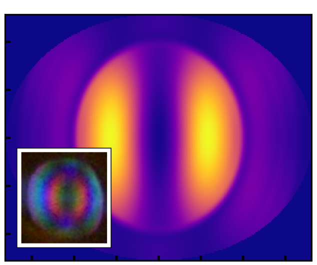


Verified that intensity fluctuations contain a calculable term that depends on beam sizes (interference)

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



Intensity fluctuations can be used to infer small beam emittances



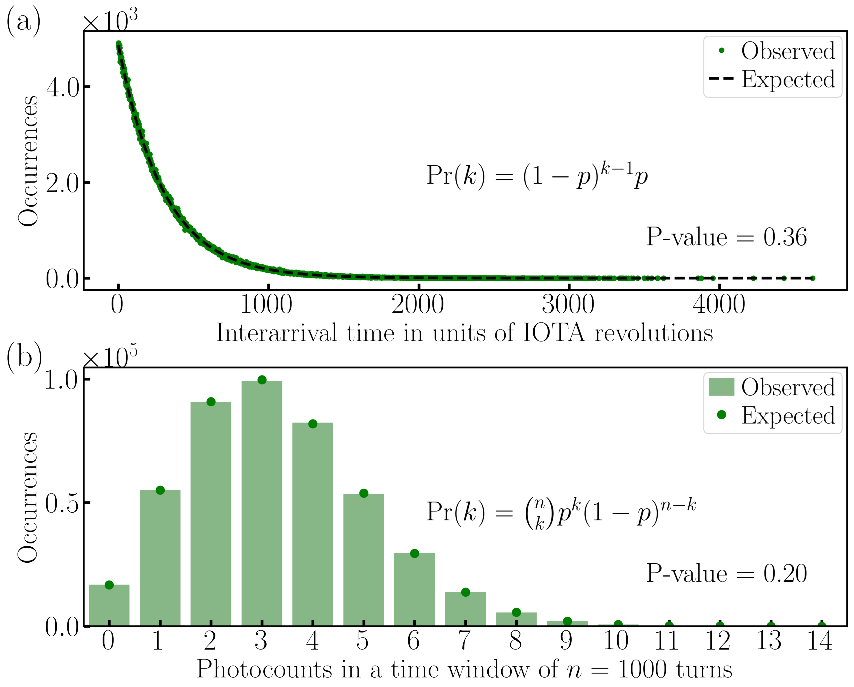
Editors' Suggestion, Featured in Physics

2022 APS DPB and IBIC Faraday Cup Awards

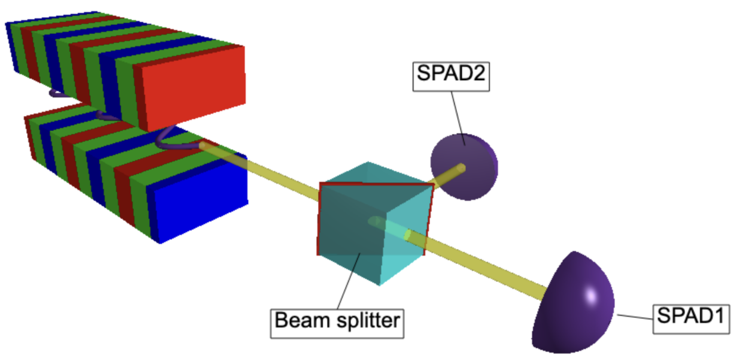
Lobach et al., PRAB **23**, 090703 (2020)
Lobach et al., PRAB **24**, 040701 (2021)
Lobach et al., PRL **126**, 134802 (2021)
Lobach, PhD Thesis (2021)

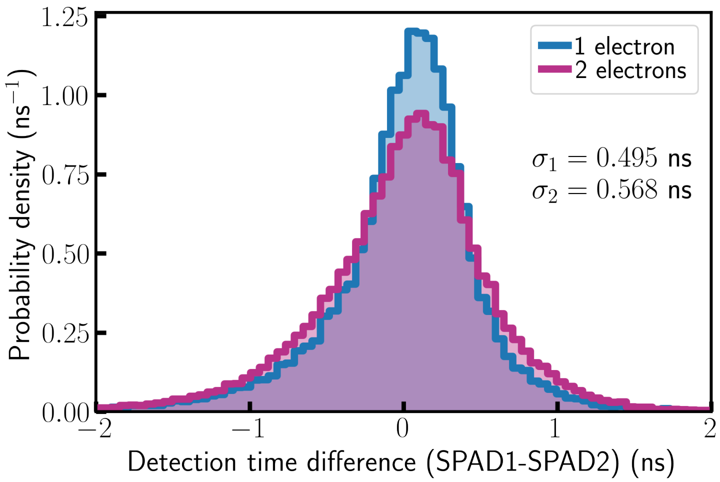
Previous Results in Runs 2 and 3 at IOTA

Photocount statistics with a single detector are consistent with a coherent state



First tests with beam splitter and 2 detectors





From arrival times, measured rf jitter and bunch length

Lobach, PhD Thesis (2021)
Lobach et al., JINST **17**, P02014 (2022)

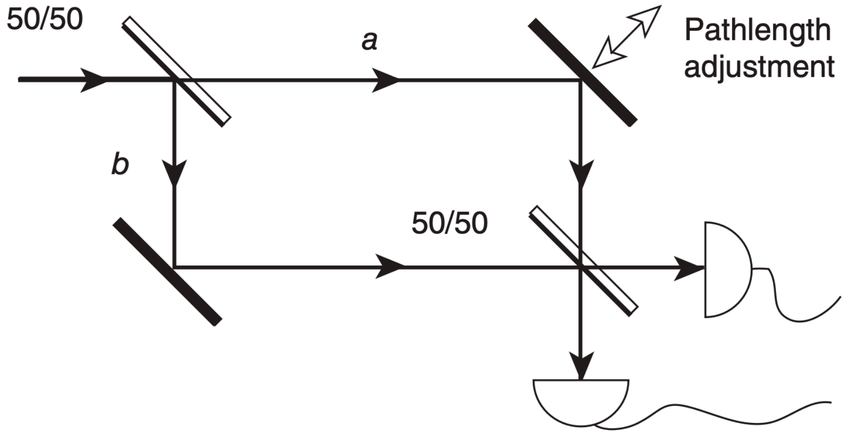
Goals of CLARA in Run 4

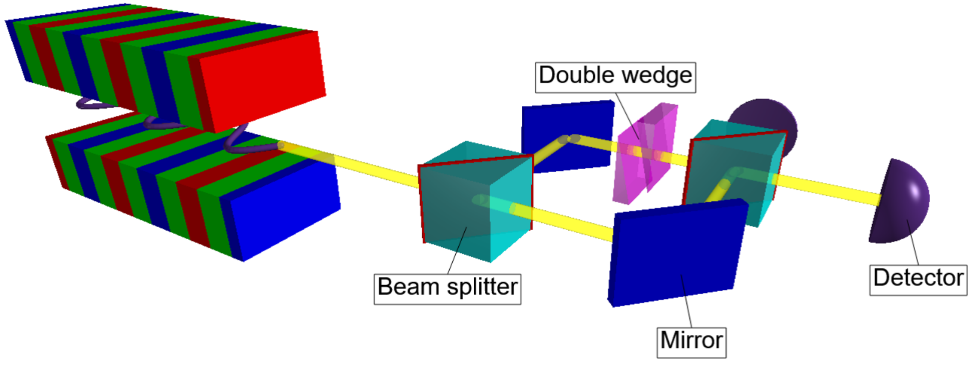
Measure the coherence length of undulator radiation vs. number of electrons

Study the statistics of coincidences

Gain experience with experimental techniques

Measurements based on a Mach-Zehnder interferometer (MZI)





Timeline of Activities

Nov 2021: Project start

Feb 2022 — Jan 2023: Interferometer assembly and commissioning at ESB

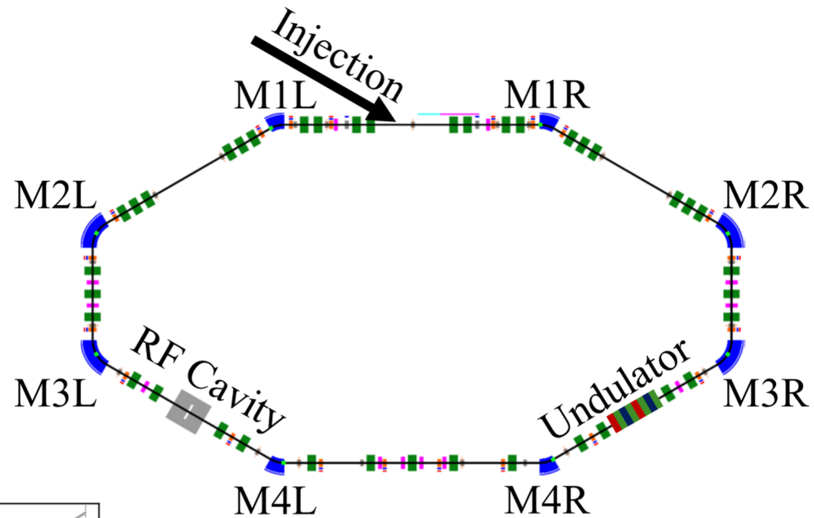
Jan 23, 2023: Apparatus moved from ESB to IOTA enclosure (M4R dipole)

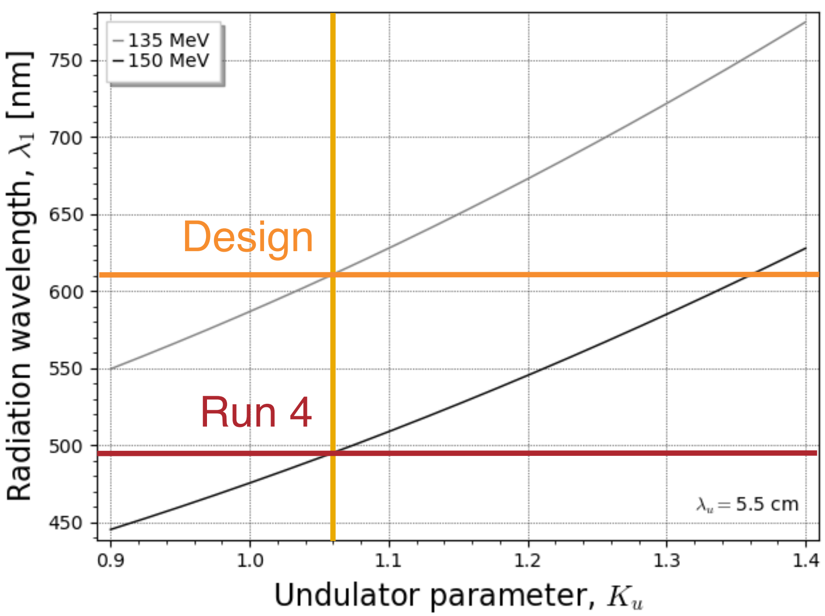
Feb 2023 — May 2023: Commissioning and experiments in IOTA

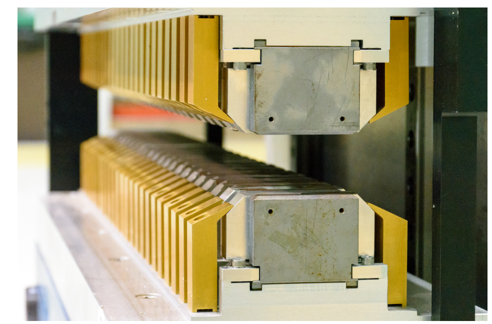
Beam Conditions and Apparatus

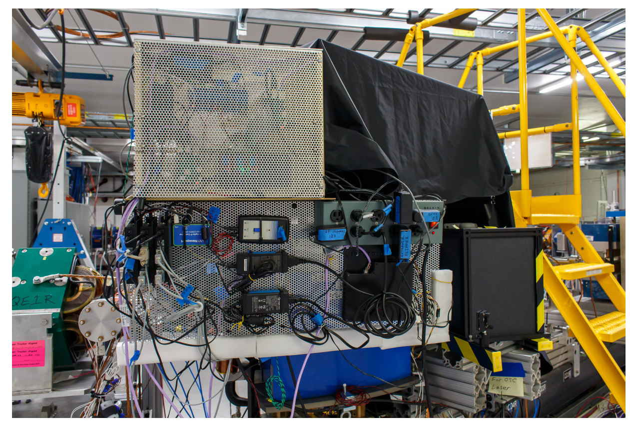
Electrons at 150 MeV
10^9 — 1 e^- per bunch
NIO lattice

[Designed to run at 135 MeV for max detection efficiency]



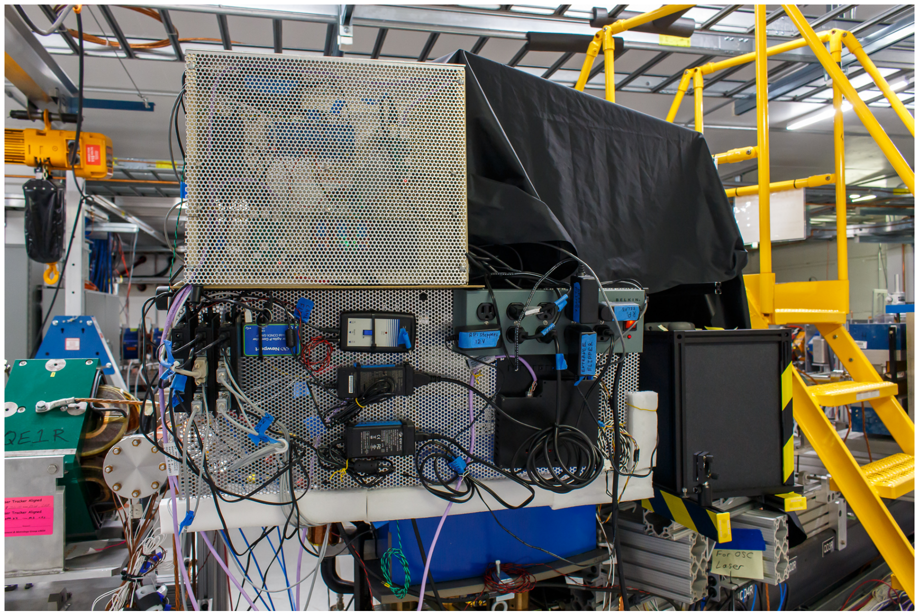




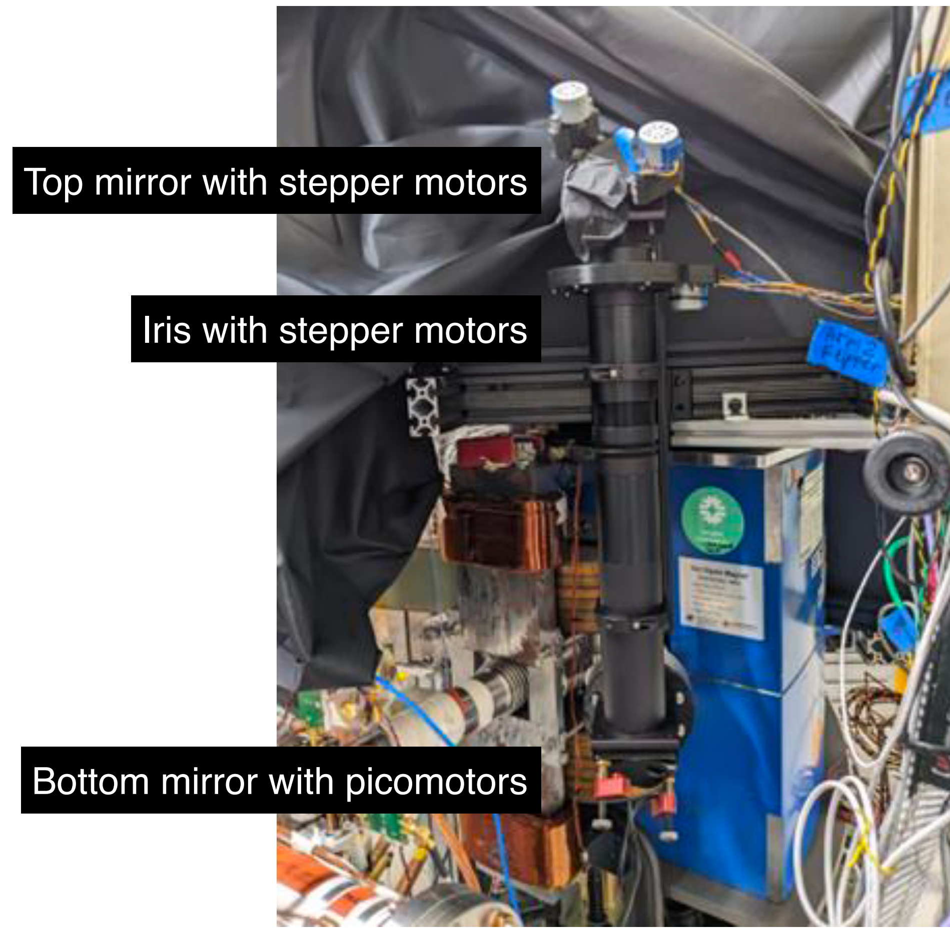


Apparatus

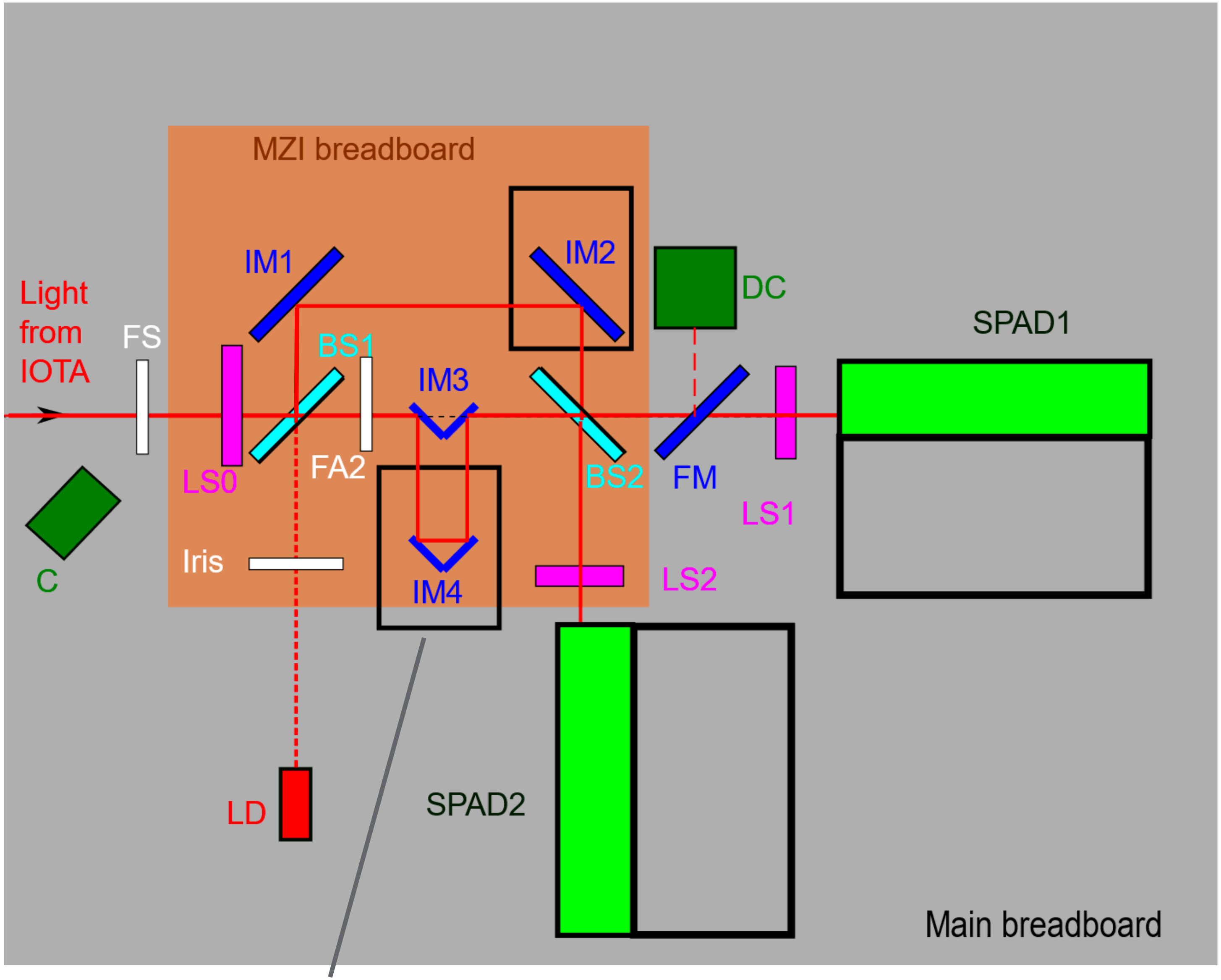
Interferometer on M4R dipole in IOTA



Light collection

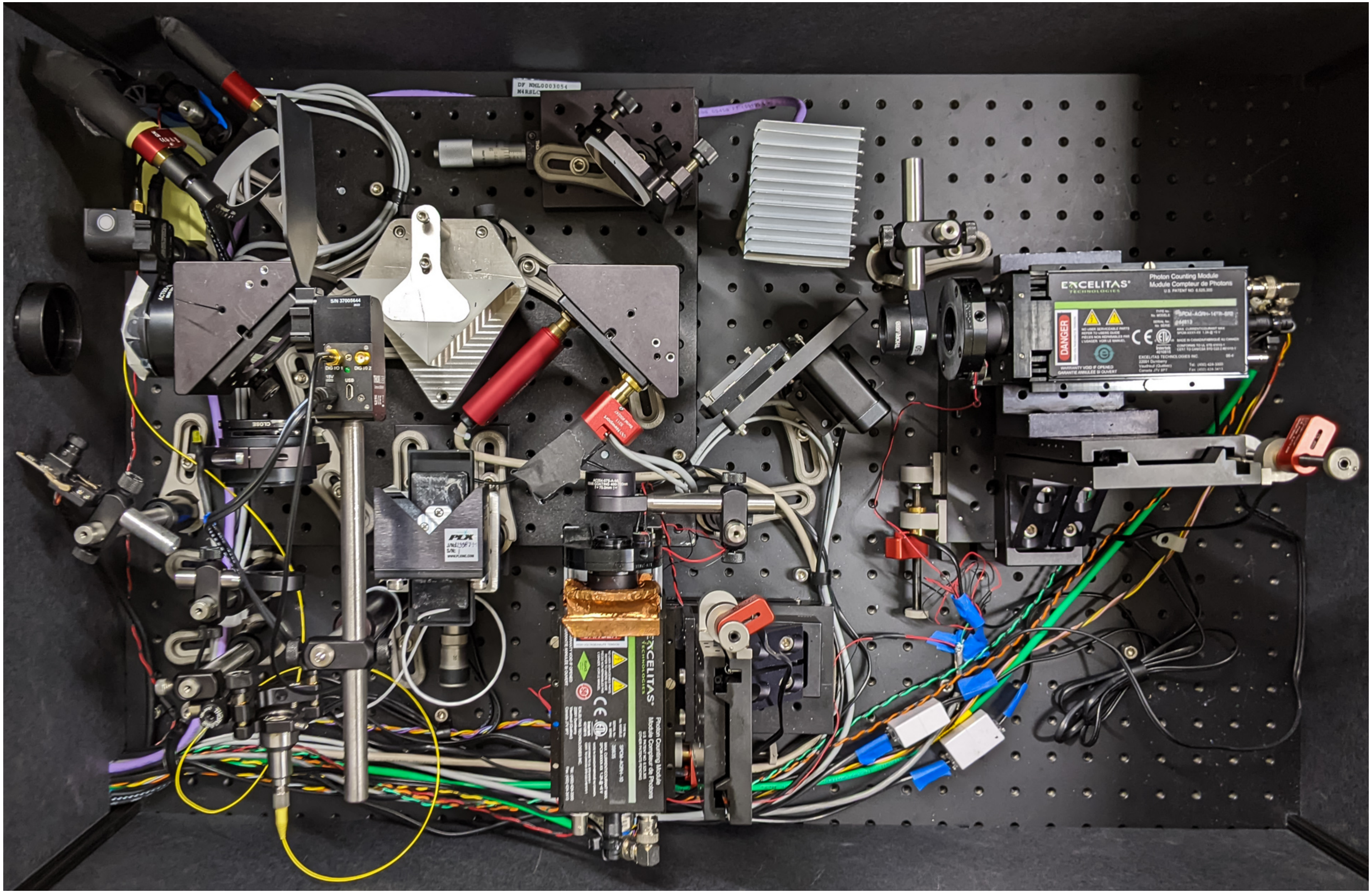


Mach-Zehnder Interferometer (MZI)

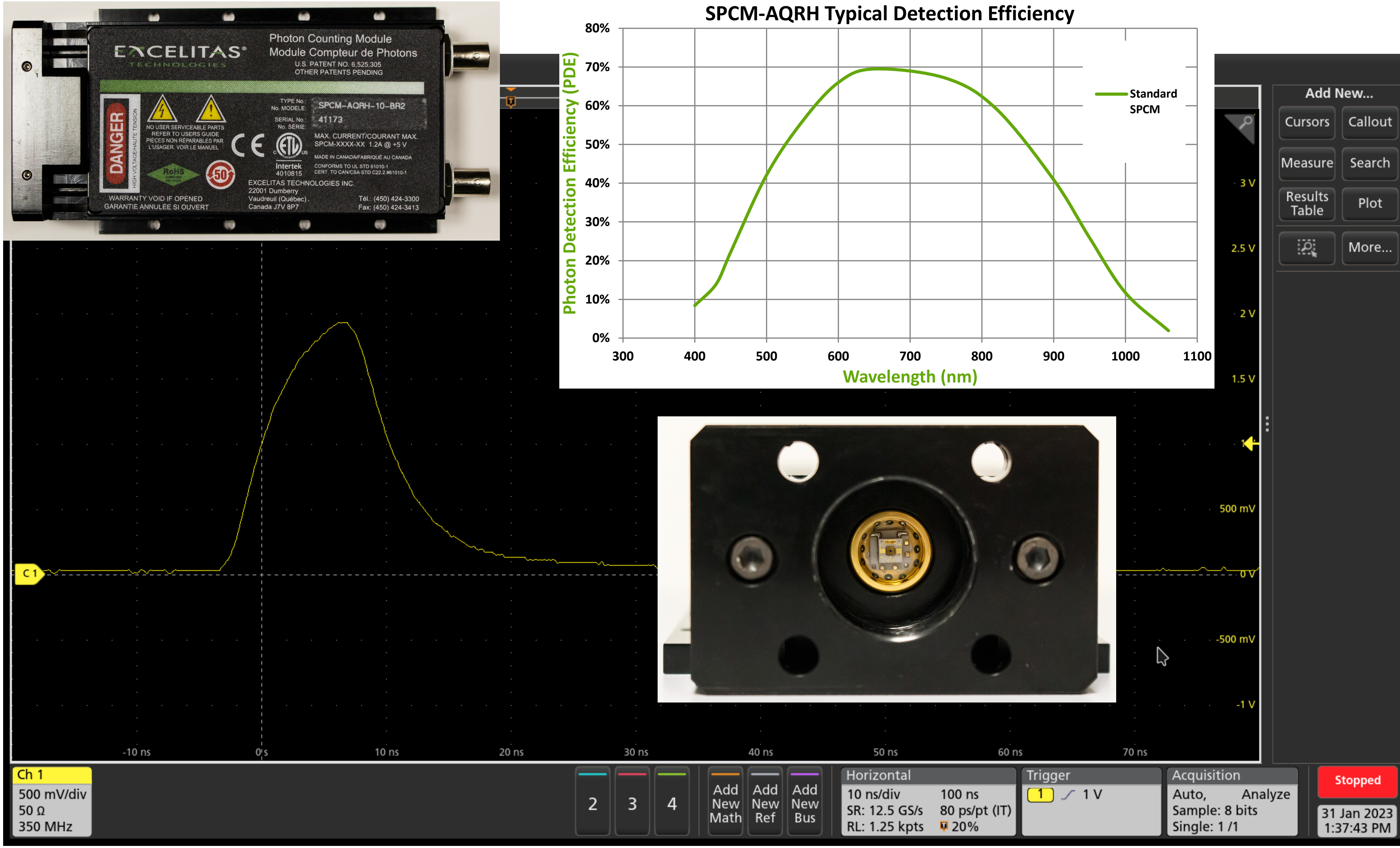


Minimum incremental motion of delay stage: 20 nm

Mach-Zehnder Interferometer (MZI)



Detectors — Single-Photon Avalanche Diodes (SPADs)



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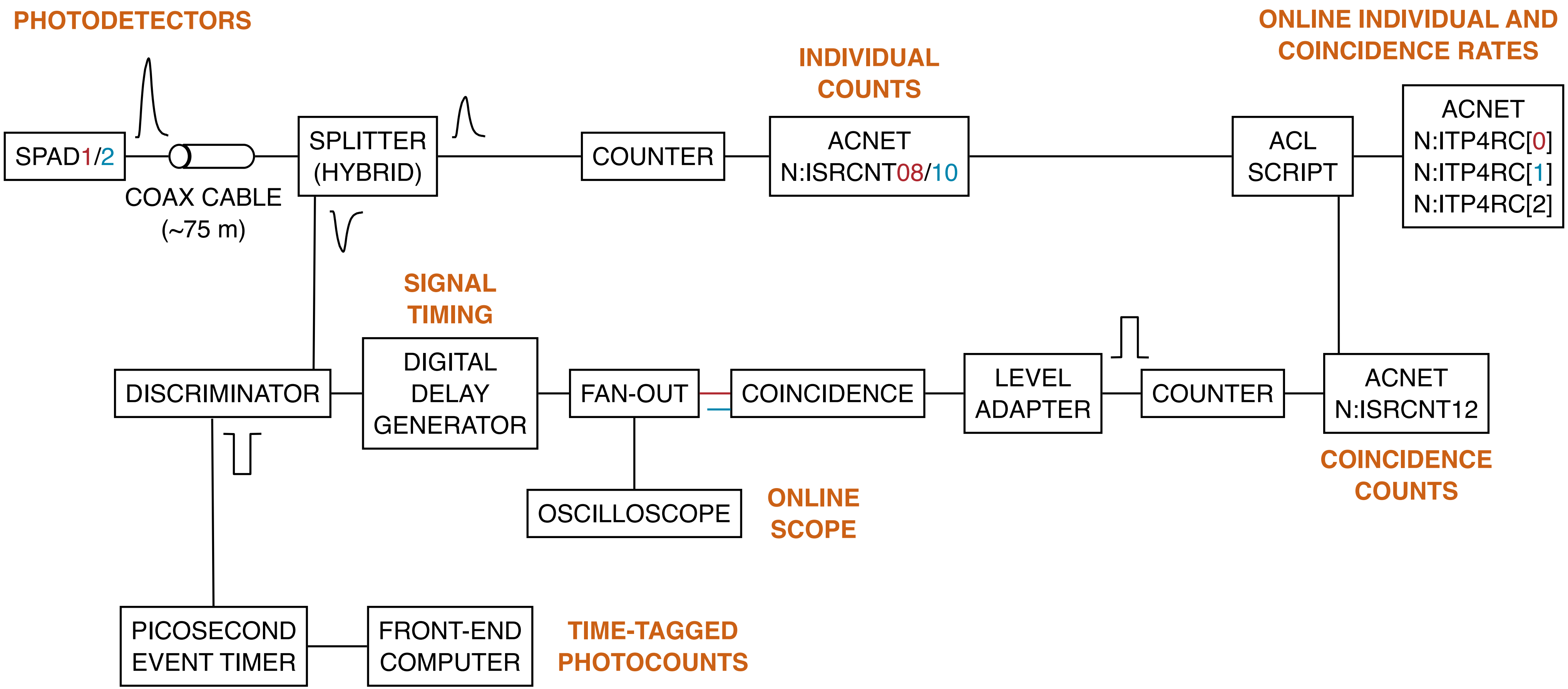
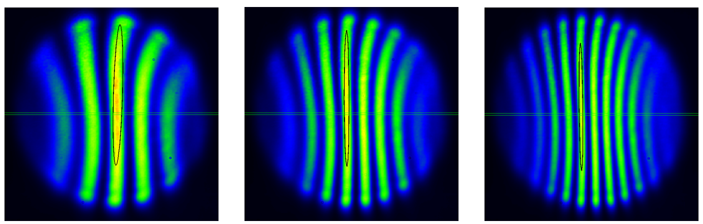
Data Acquisition System

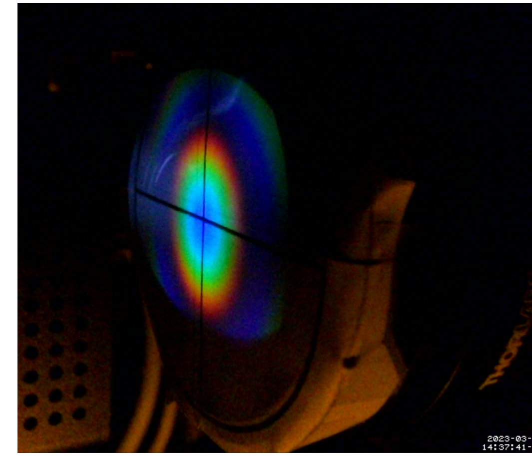


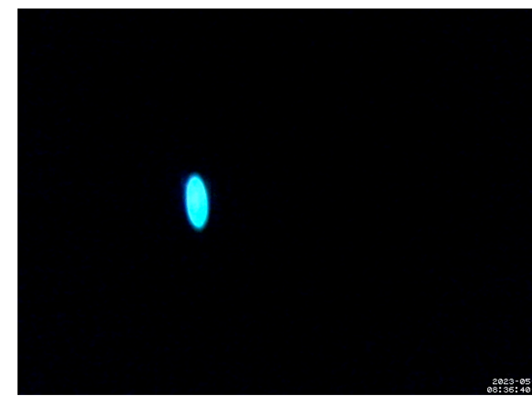
Gated counters, synchronized with the IOTA revolution marker, with similar setup

Experimental Procedure

- Inject full-intensity beam (~ 1 mA)
- Move beam from injection to central orbit
- Align periscope to center of iris and camera
- Establish interference conditions
- Measure alignment and fringe visibility with camera

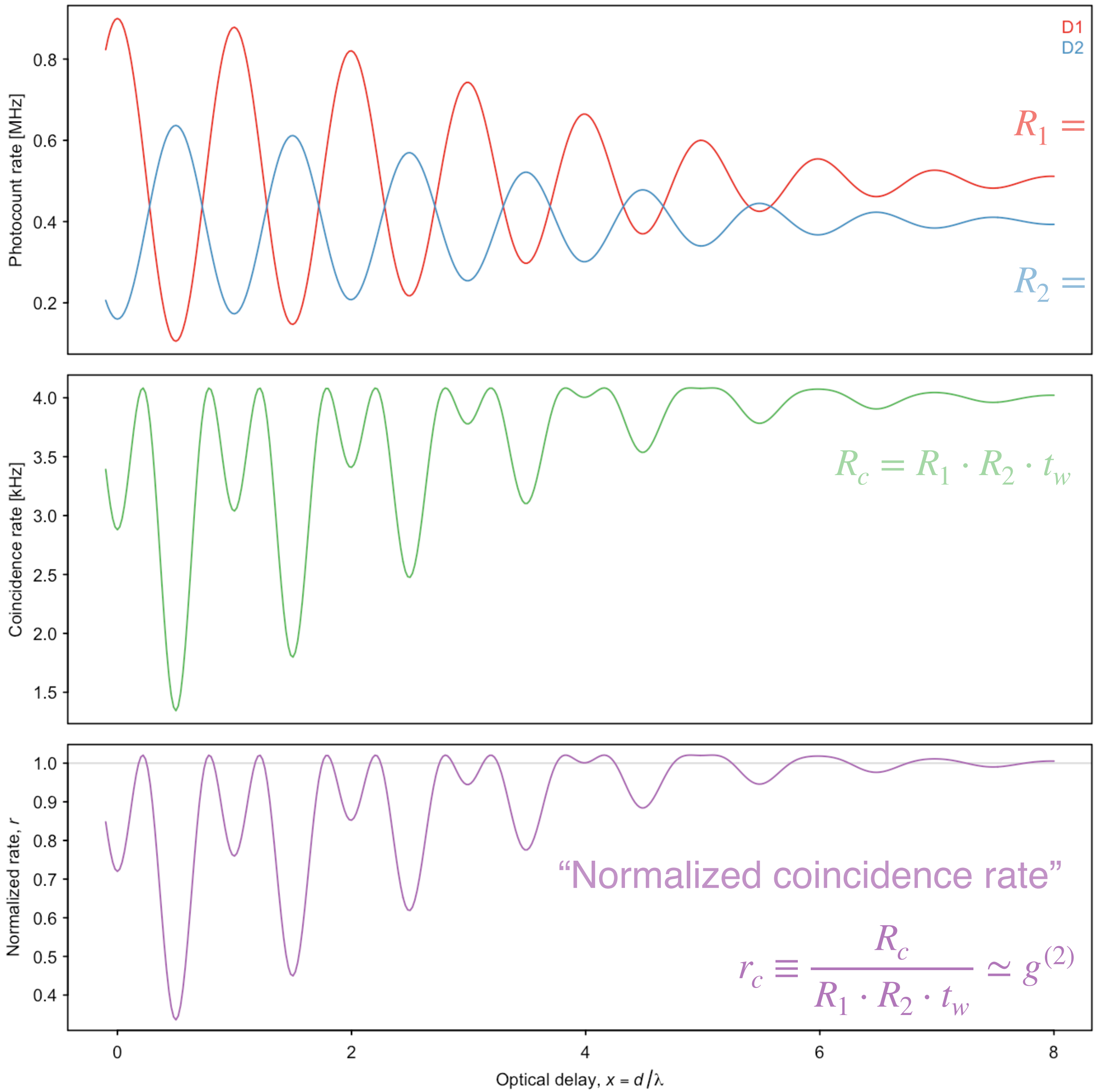






- Scrape beam to ~100s of electrons by reducing rf voltage
- Check beam intensity with camera and PMTs
- Turn on SPADs
- Align SPADs in 3 directions
- Collect SPAD rates and time-tagged photocounts under various conditions: number of electrons, MZI arm delay, iris opening

Model of Delay Scans



$$R_1 = C_1 \left[1 + V_1 \cdot \exp\left(-\frac{d^2}{2d_c^2} \right) \cdot \cos\left(\frac{2\pi}{\lambda} d \right) \right]$$

$$R_2 = C_2 \left[1 - V_2 \cdot \exp\left(-\frac{d^2}{2d_c^2} \right) \cdot \cos\left(\frac{2\pi}{\lambda} d \right) \right]$$

$$R_c = R_1 \cdot R_2 \cdot t_w$$

“Normalized coincidence rate”

$$r_c \equiv \frac{R_c}{R_1 \cdot R_2 \cdot t_w} \simeq g^{(2)}$$

“Normalized coincidence window”

$$W \equiv \frac{R_c}{R_1 \cdot R_2}$$

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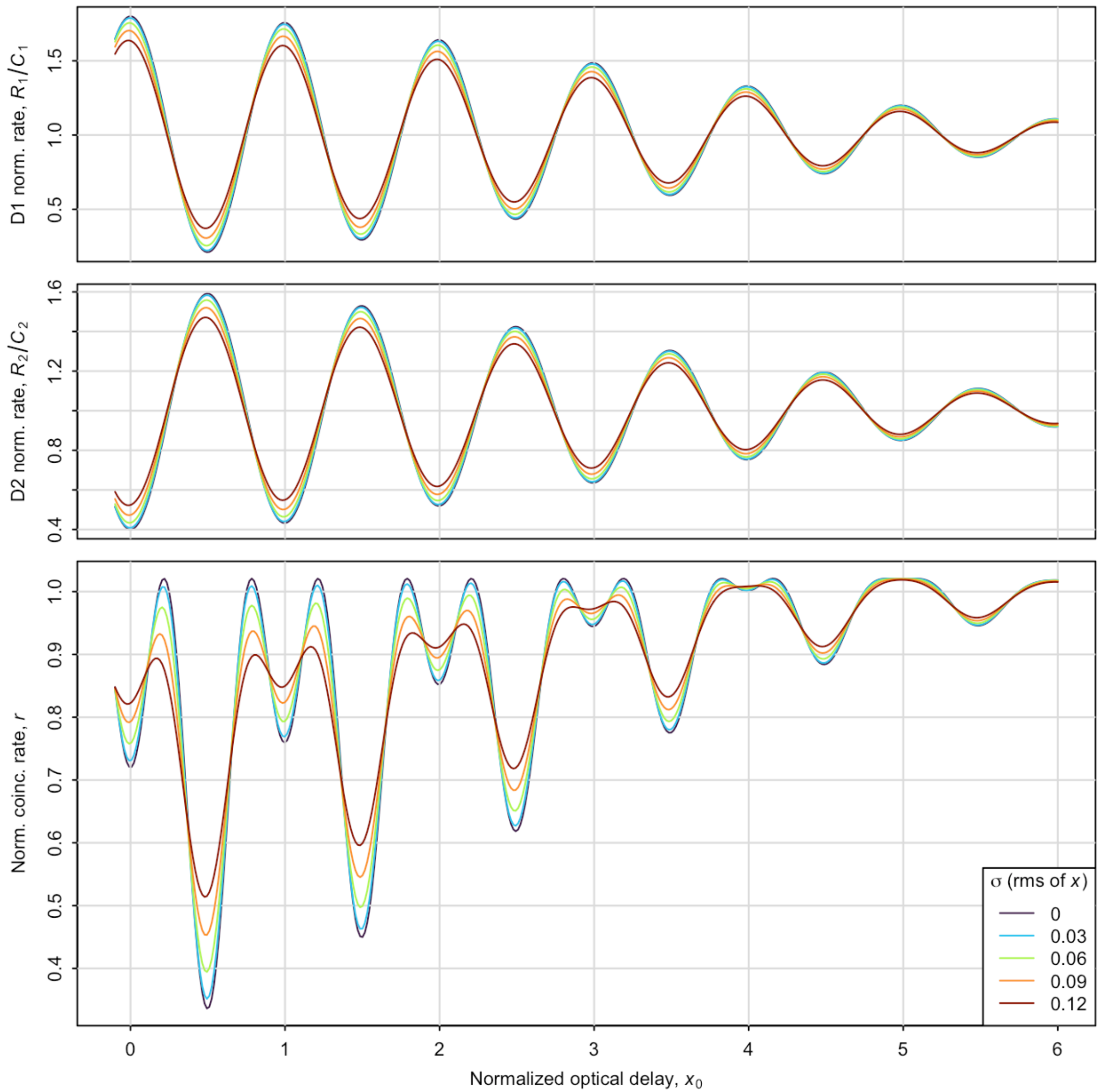
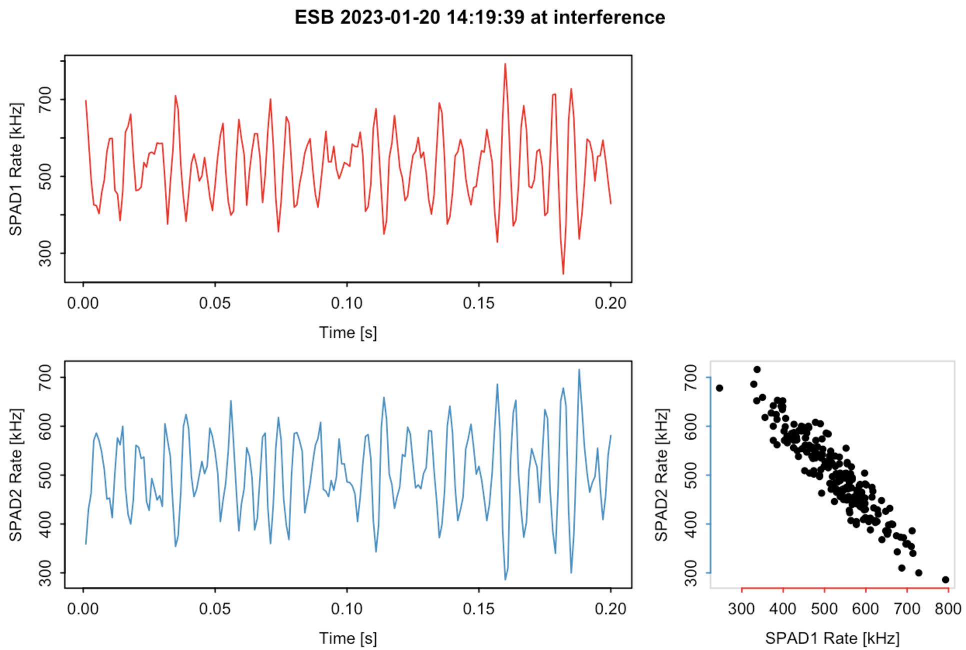
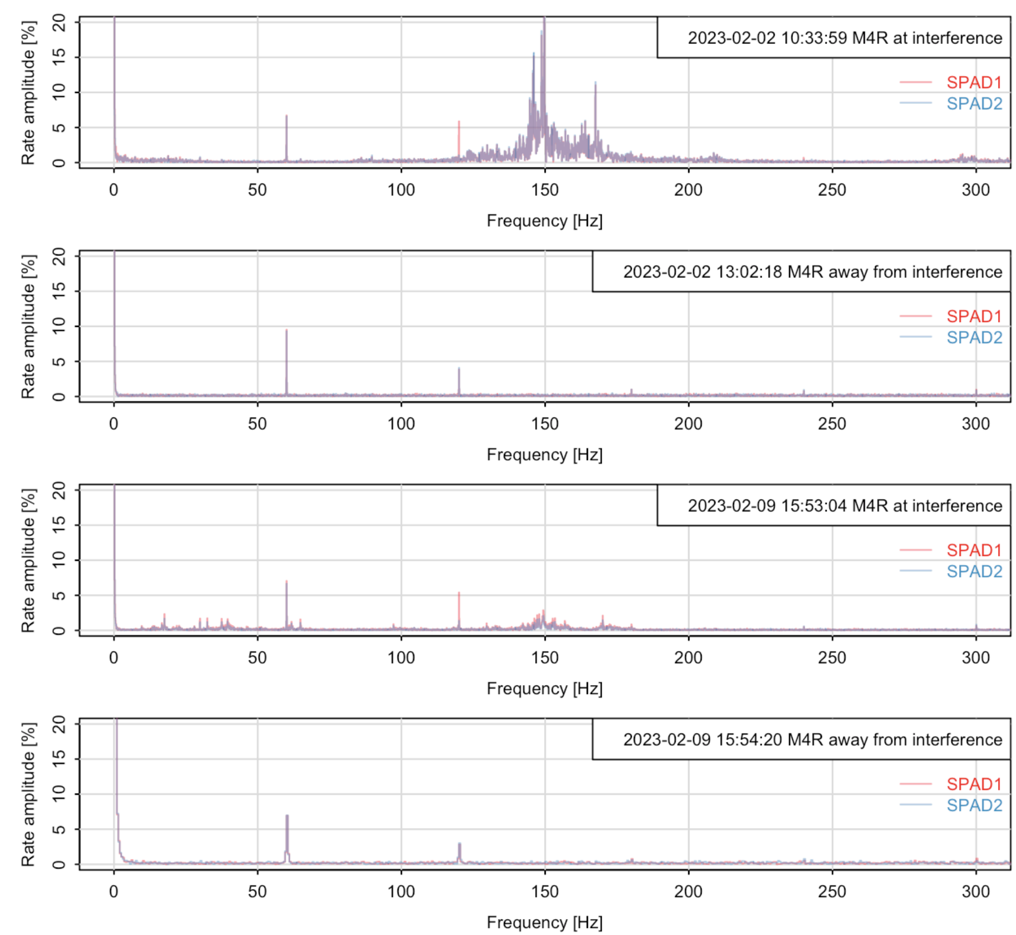
Effect of Vibrations

Fluctuations of arm length smear detector rates and mimic the HOM effect



Effect of Vibrations

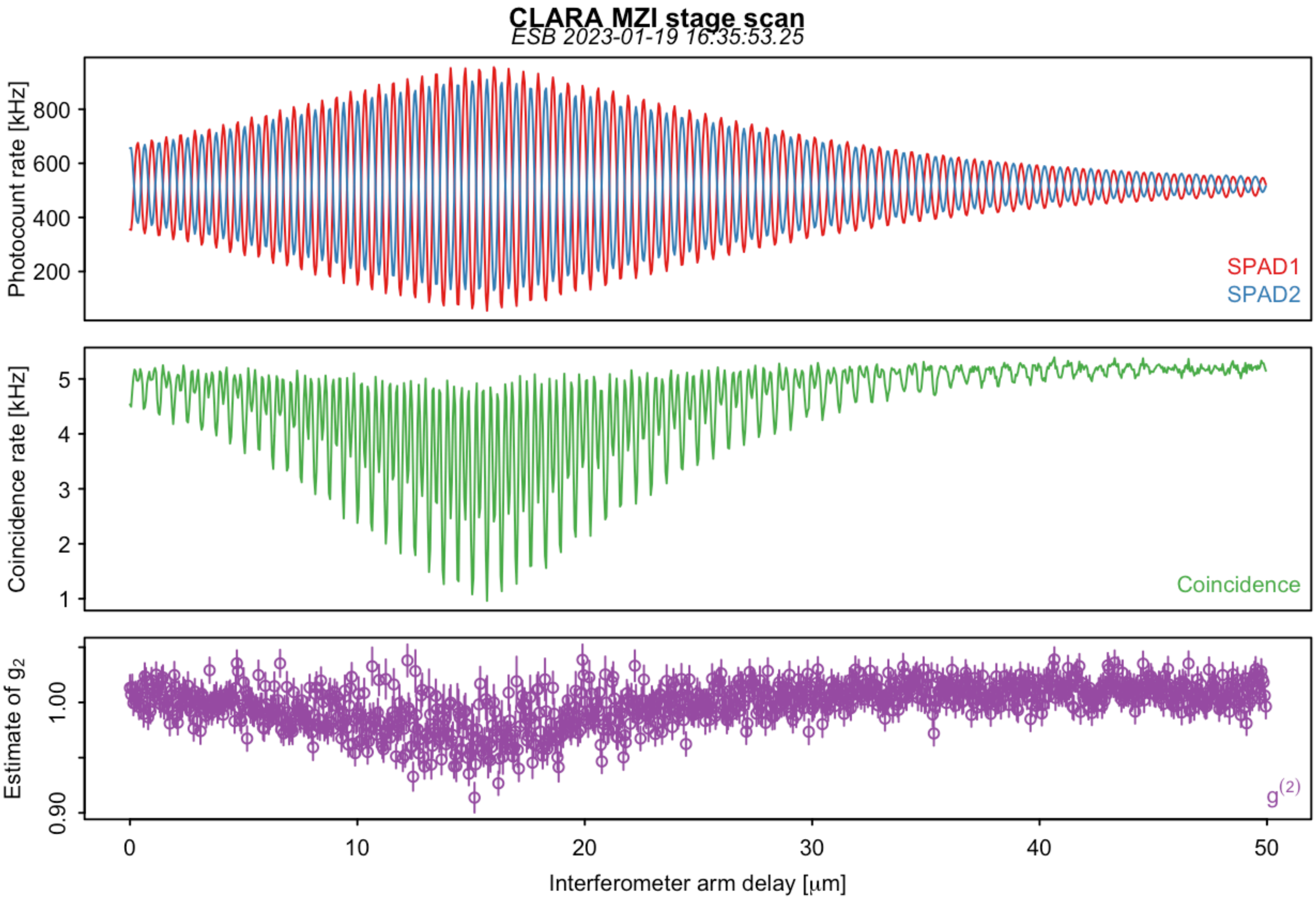




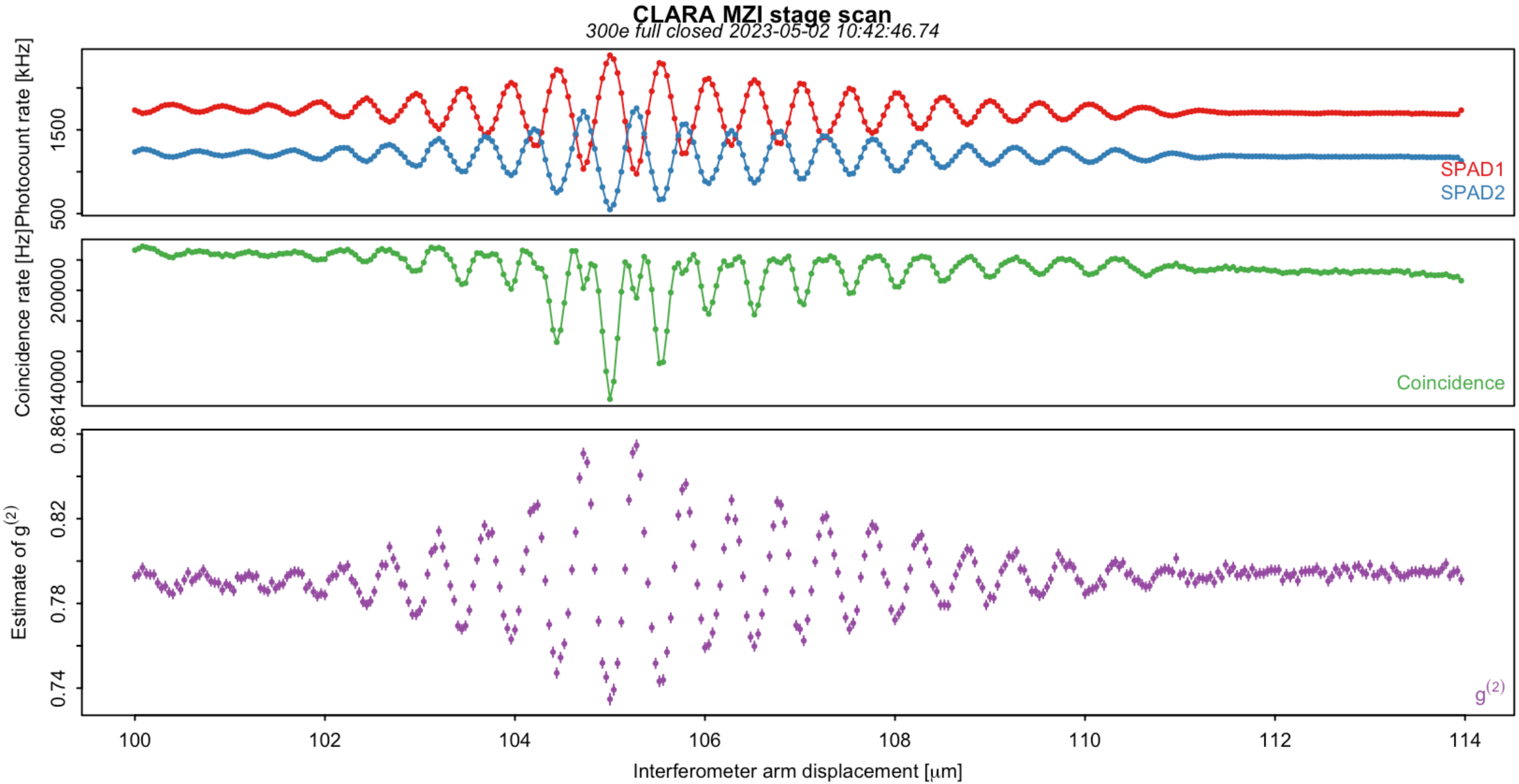
Fluctuations were measured and mitigated

Stancari et al., FERMILAB-FN-1246-AD (2024, in preparation)

Delay Scans with Laser Diode as Light Source

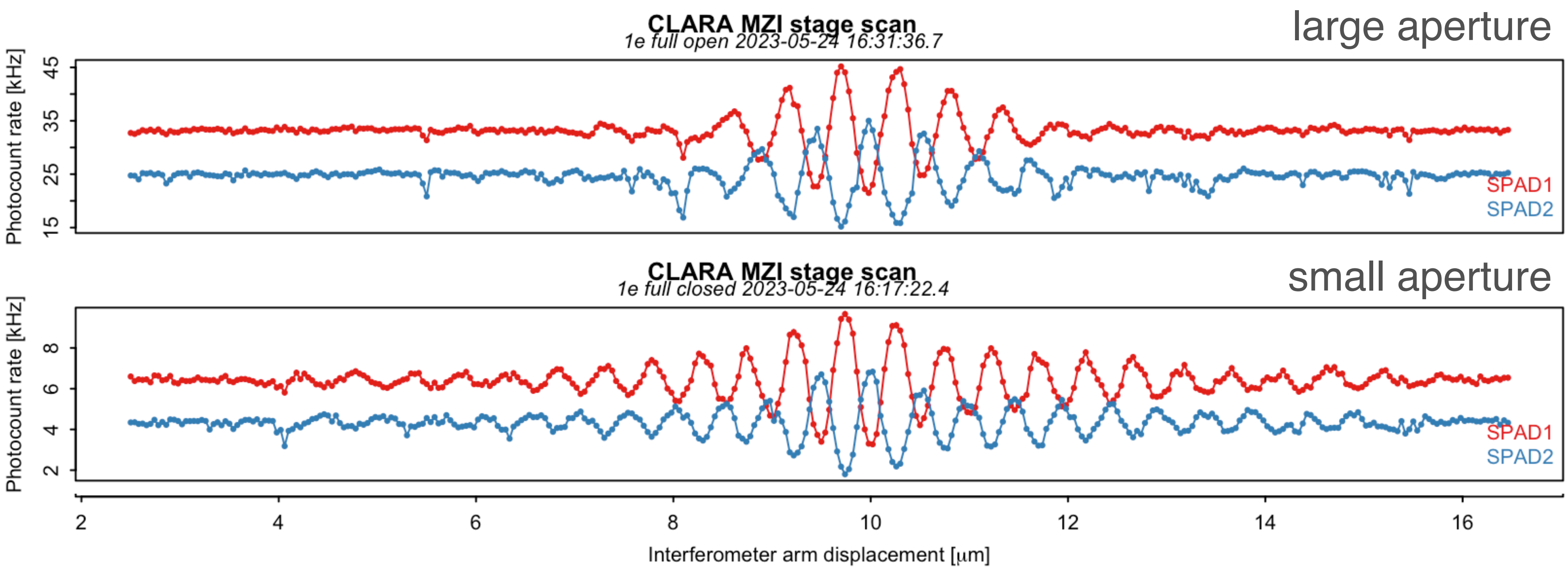


Delay Scan with ~300 Electrons in IOTA



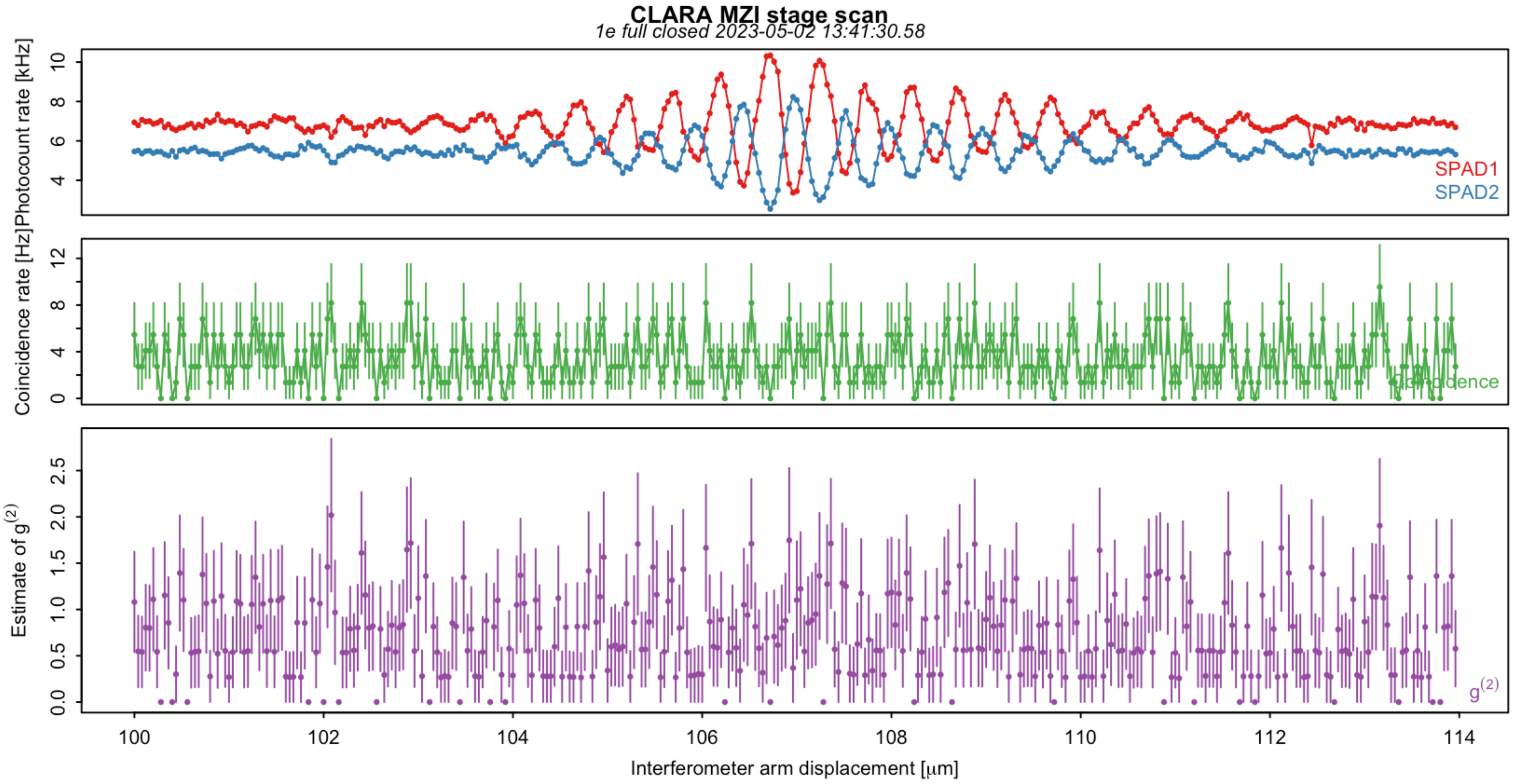
$$\tau = \frac{\lambda}{c} \simeq 2 \text{ fs}$$

Coherence Length from Single Electron! — Effect of Iris

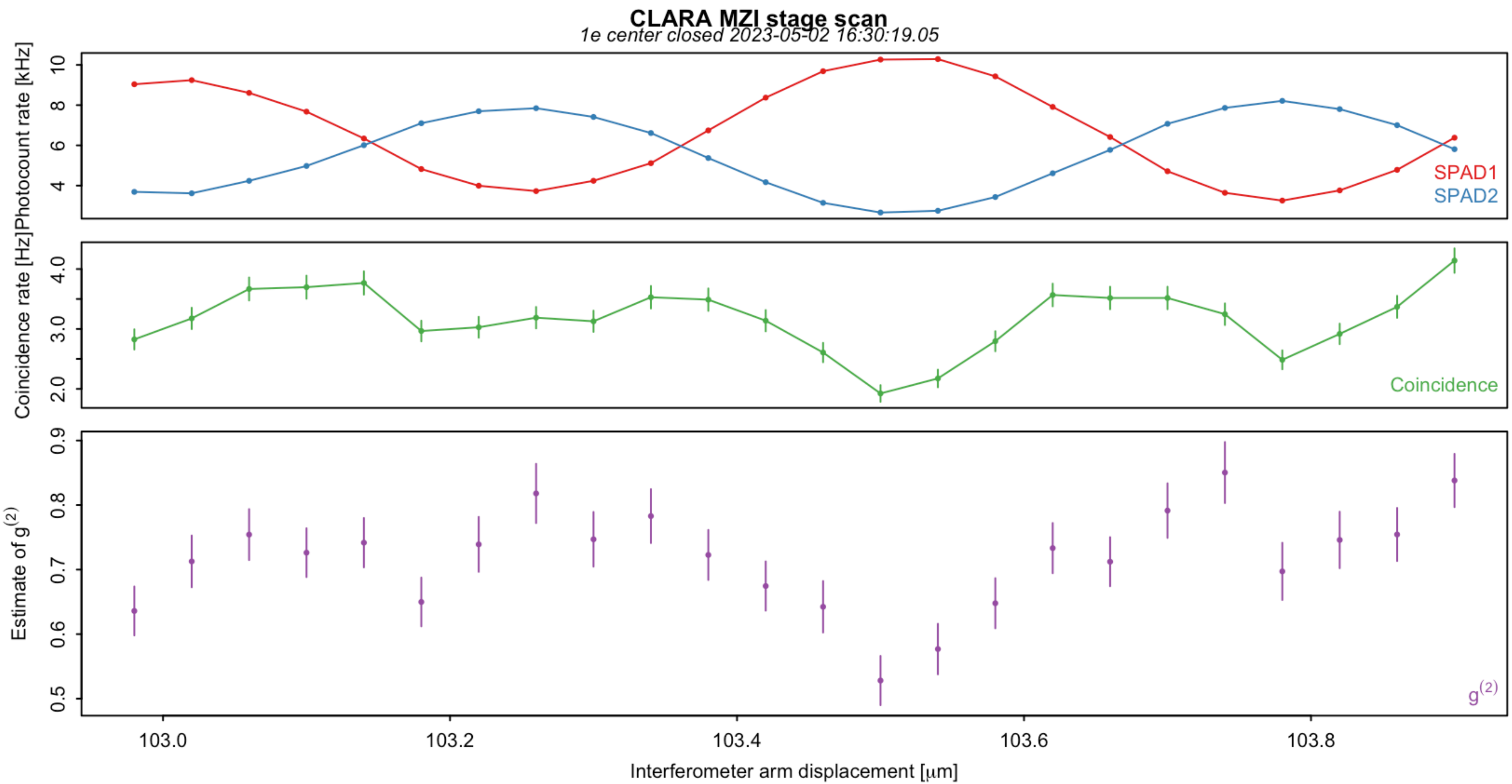


As expected, large apertures accept a wider range of frequencies, corresponding to a shorter coherence length

Delay Scan with Single Electron in IOTA



Delay Scan with Single Electron in IOTA — Central Fringes



High statistics scan, 100 s / point

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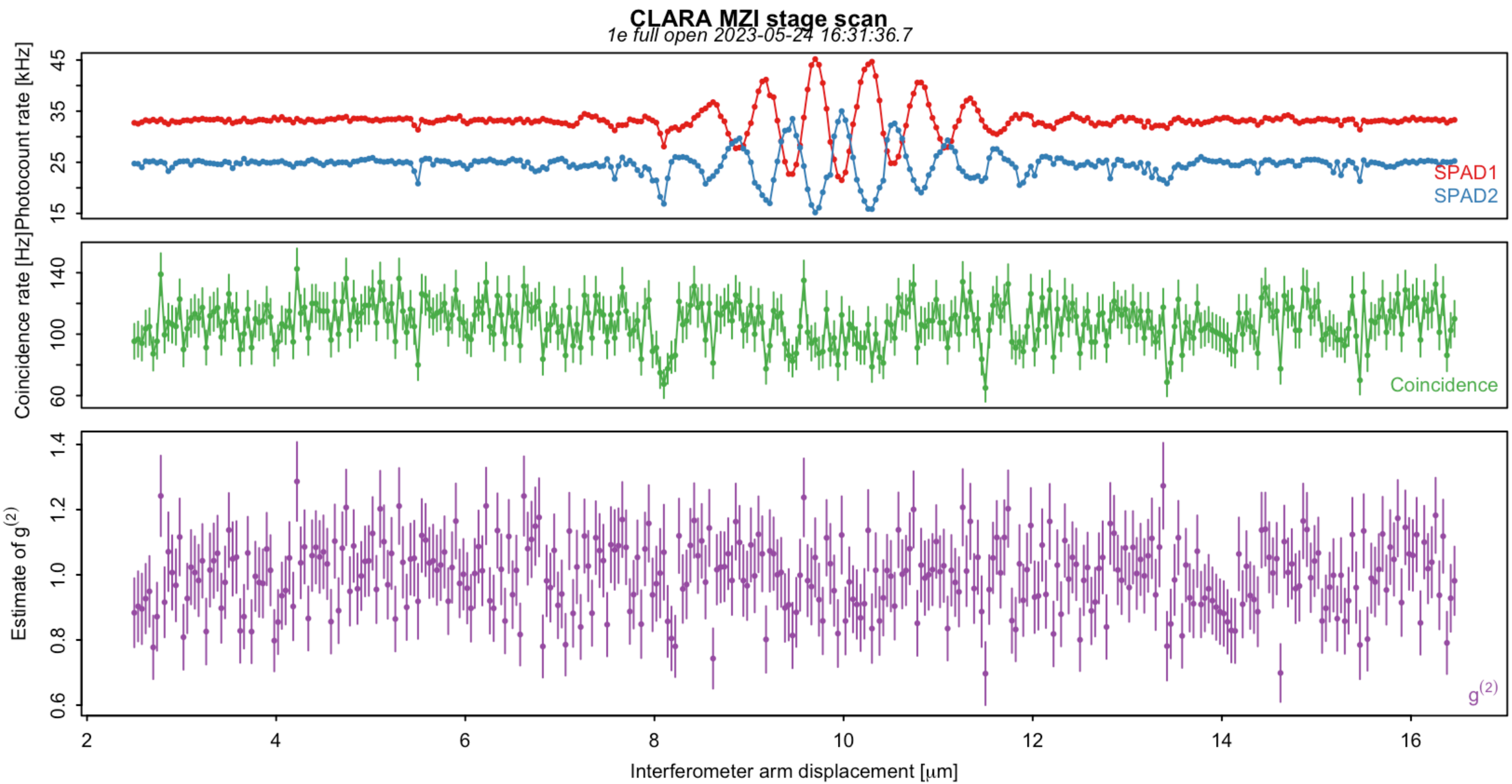
Delay Scan with Single Electron in IOTA — Gated Counters



Observations indicate that multi-photon undulator radiation from a single electron is mostly in a coherent state

Next Steps

Analysis
– quantify coherence lengths, compare with calculations and simulations
– quantify upper limit on Hong-Ou-Mandel dip
– photocount arrival times, fluctuations and correlations with different light sources: thermal, diode (below/above lasing threshold), electrons in IOTA

Publications
– technical memos and physics notes
– Run-4 report
– peer-reviewed journal

Interferometer still in place at M4R in IOTA

Scientific motivations for **continuation of the program** under discussion: beam diagnostics, generation of quantum radiation, improve experiment setup, …

Lessons Learned

- Interferometers are of course very sensitive to all kinds of noise: mechanical vibrations, power-line frequencies, etc.
- Lost detection efficiency at 150 MeV, but could work in parallel with NIO
- Lengthy alignment procedures of MZI and SPADs; undulator radiation alignment different from laser diode alignment
- If interference condition is lost, it may take a while to re-establish it
- Stage positions need to be in ACNET, synchronized with the rest of the data
- Acquisition of digital camera image data could be streamlined

Conclusions

Directly observed multi-photon radiation from a single electron at the femtosecond scale!

Fascinating physics

The techniques of quantum optics may provide novel tools for beam diagnostics

Contributors

Jonathan Jarvis (Fermilab): design, equipment, simulations
Ihar Lobach (Argonne): design, theory, equipment, controls
Sergei Nagaitsev (Brookhaven, PI): supervision, design, equipment, funding
Aleksandr Romanov (Fermilab): design, beam operations, MZI construction and controls, measurements
Alexander Shemyakin (Fermilab): design, MZI construction and commissioning, measurements, data analysis, documentation
Giulio Stancari (Fermilab / UChicago): design, data acquisition system, measurements, data analysis, documentation
Alexander Valishev (Fermilab): supervision, funding

Thanks to **the whole IOTA/FAST group** for making the experiment possible

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