Measurement of Coherence Length in UndulAtor RAdiation (CLARA) – status update

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Quantum effects in undulator radiation
LDRD Project L2019.025

- A 3-year project
- The goal of the proposed experimental research is to investigate the quantum nature of "a particle in a ring" by studying a single 150-MeV electron, circulating in the IOTA storage ring and interacting with an undulator through single- and multi-photon emissions. The focus of this proposal will be two-photon undulator emissions. We will use a two-photon interferometer for the first time for the undulator radiation.
  – Note: since then we found a couple of prior publications, similar but not identical
- This beam run is the final (Year 3) run

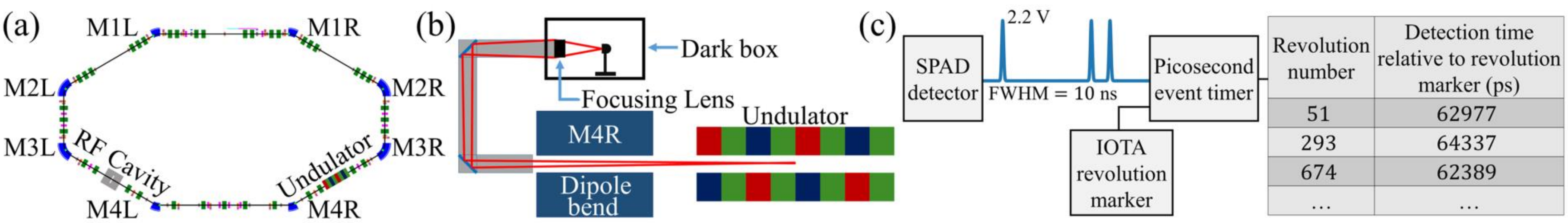
Project status

- Project started in May 2019
- Year 1 Progress:
  - Installed and commissioned undulator (from SLAC)
  - Procured, tested and commissioned 2 SPADs and electronics
  - Measured photon statistics with a single SPAD (100 MeV).
- Year 2 Progress:
  - Measured two-photon statistics with 2 SPADs
  - Commissioned IOTA ring at 150 MeV (needed for this experiment)
- Year 3 Goals:
  - Procure, assemble and test a two-photon interferometer
  - Perform interference measurements with single and many electrons

Year 1: single-electron single-photon at 100 MeV

- Results published in JINST (Feb 2022): https://iopscience.iop.org/article/10.1088/1748-0221/17/02/P02014/pdf

On average one detection per 304 revolutions



Detector: Single Photon Avalanche Diode (SPAD)

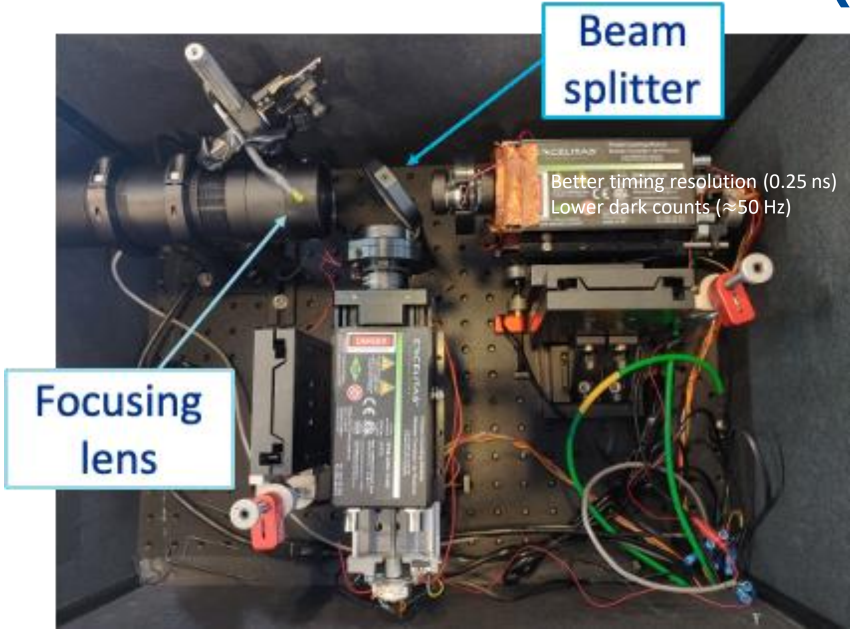
Excelitas SPCM-AQRH-10

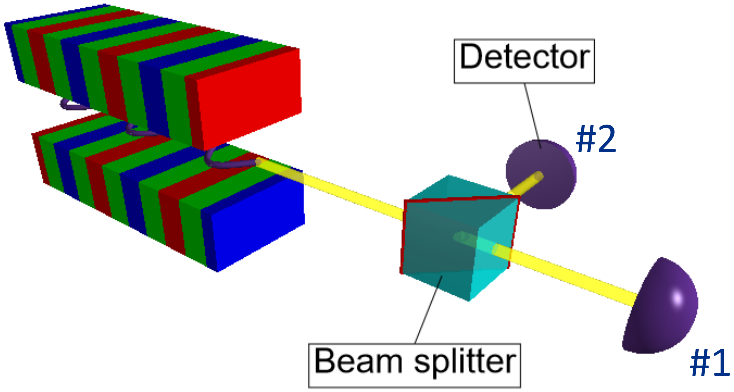
Active area (diameter)	**180** μm
Photon detection efficiency at 650 nm	65%
Dark count	~100 cps
Dead time	22 ns
Pulse height	2 V
Pulse length	10 ns

*can be reduced by using a gate (~ 5 ns)

*IOTA revolution: 133 ns

Year 2: Two SPAD detectors (June 2021) at 100 MeV





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

000001000000110000000000200010000000112000000...

- So far, no deviations from our expectations

Detector #1: ~30 kHz

Detector #2: ~15 kHz

Detector #1 & Detector #2: ~70 Hz

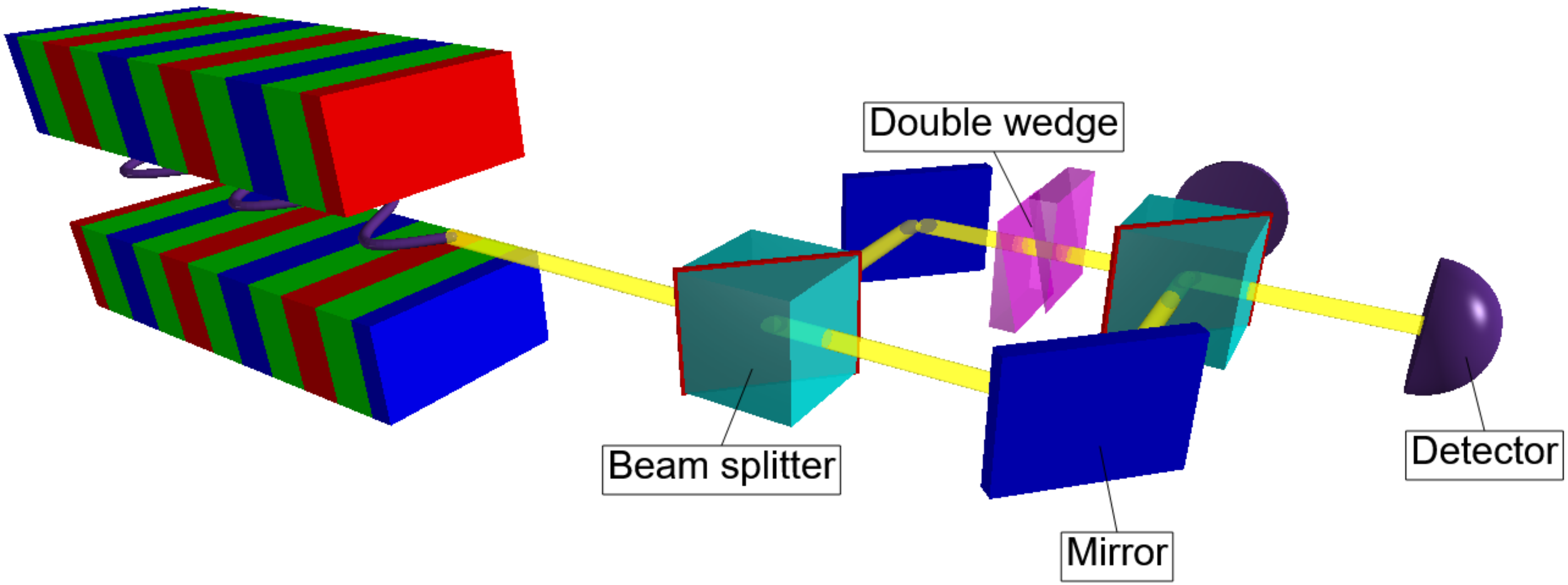
We did not observe any deviations from a random memoryless process

Goal of CLARA experiment (present run)

- Measure the undulator radiation coherence length for a single electron in a ring and two-photon emissions.
  - An electron in IOTA is believed to be a classical object, so no deviation from classical radiation is expected. Undulator radiation is in a "coherent" state. The opposite case is a Fock state (purely quantum) of radiation, e.g. photon emission from a single atomic transition.
- Potentially, we might be able to see if the undulator radiation is in a "mixed" state.

Mach-Zehnder interferometry of undulator radiation

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



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

*light pulse length ≈ 30 fs

Measurement of the light pulse shape in time domain

HOM dip: Fock state

Rep. Prog. Phys. **84** (2021) 012402 Key Issues Review

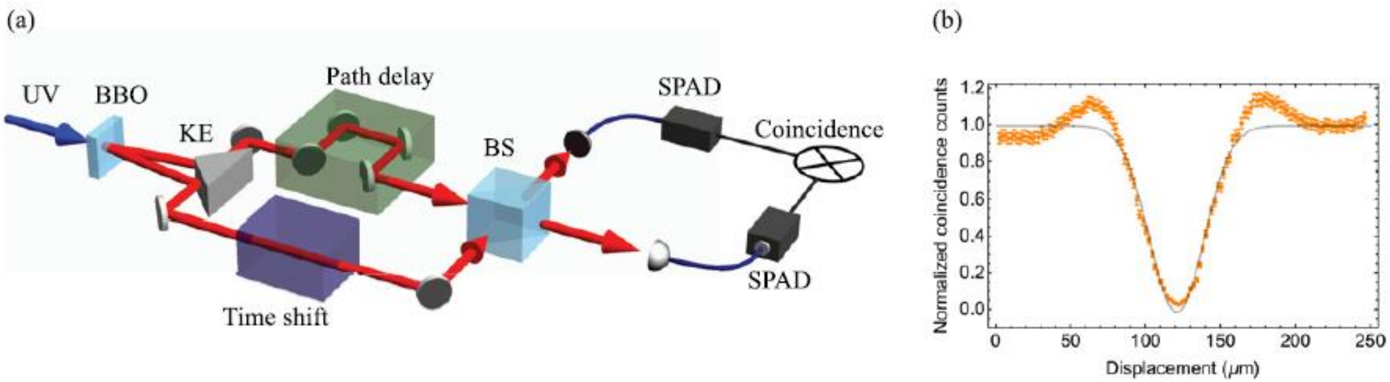


Figure 2. Simplified experimental setup to observe the Hong–Ou–Mandel dip. (a) We present an experimental setup similar to that presented by Hong, Ou and Mandel. An ultraviolet (UV) laser pumps a nonlinear crystal, e.g. KDP, BBO or ppKTP. Pairs of photons are generated with anti-correlated linear momentum and separated using a knife-edge (KE) mirror. The photons are brought back together at a 50:50 BS, where a variable path delay is scanned to control the arrival time of one of the photons. The photons exiting the output ports of the BS are detected using single-photon avalanche diode (SPAD) detectors and coincidence counts are recorded. (b) Example of experimental results showing the two-photon interference dip, dropping to zero when the two photons enter the BS simultaneously. Solid line indicated expected theoretical coincidence counts, and dots indicate experimental measurements. The peak in counts on either side of the dip is caused by the use of a rectangular bandpass filter in experiment, as compared to a Gaussian filter in theory. Figure legends: UV, ultraviolet beam; BBO, Beta barium borate nonlinear crystal; KE, knife edge; BS, 50:50 beam splitter; SPAD, single photon avalanche diode.

HOM dip: weak coherent state

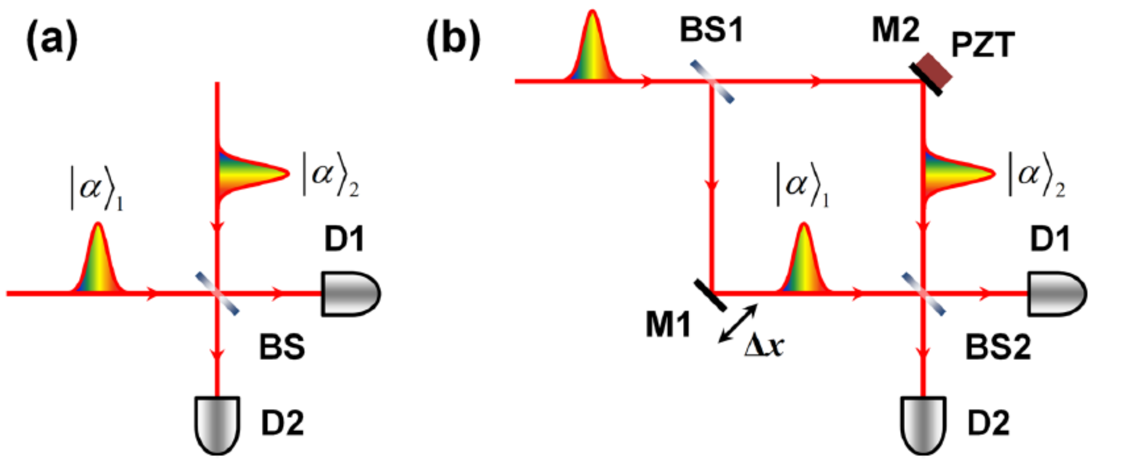


Figure 1. Two types of experimental schemes for realizing the two-photon interference of weak coherent pulses. The two photons contributing to the interference originate from (**a**) two *independent* sources or (**b**) a *common* source. BS, beam splitter; M, mirror; PZT, piezoelectric transducer; D, single-photon detector.

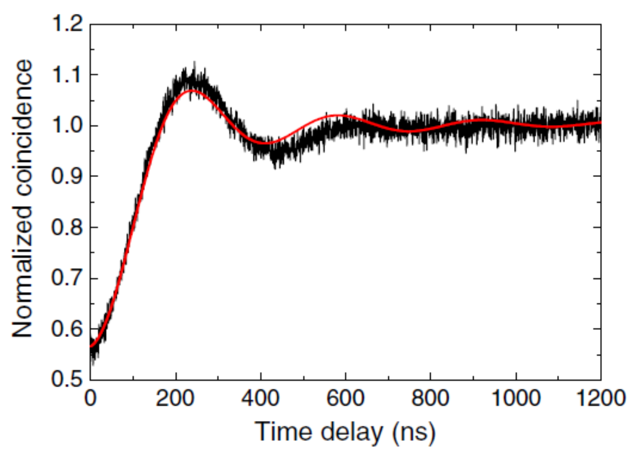


Fig. 3. Hong–Ou–Mandel interference fringe with two independent continuous-wave coherent photons. Experimental result and theoretical curve fitting under the conditions of a bandwidth of 3.3 MHz and $\Delta\omega = 0$.

Beam Conditions

- Beam energy: 135 MeV
  - To match our test set-up at 630 nm with a laser diode
- Beam lifetime: > 30 min
- Bunch length: ~30 cm (rms)
- Transverse beam size in the undulator: 1 – 1.5 mm
- Three types of beams:
  - Single electron
  - Small number of electrons (1 – 1,000) in one bucket
  - Nominal bunch current (~ 1mA)

Beam request (presented on Sep 9, 2022)

- Installation
  - Installation in IOTA tunnel at M4R. Mounting, connecting and initial testing. (access) 2×8 h
- Experiments at high bunch intensity
  - Commissioning with laser diode. (no beam) 3×4 h
  - Next step: Commissioning of 135-MeV beam. Optional energy scan to maximize signal. 2×8 h
  - MZI measurements. 4×8 h
- Transition to few electrons
  - Alignment of camera and SPADs with laser diode and delay scans. (no beam) 4×8 h
- Experiments with few and single electrons
  - Re-establish procedures for injection, scraping, electron counting. 2×8 h
  - MZI data collection with 0, 1 and 2 electrons. 4×8 h