FERMILAB-POSTER-24-0051-AD
IPAC24 MOPG06
stancari@fnal.gov

Undulator Radiation of Single Electrons: Coherence Length and Quantum-Optical Properties

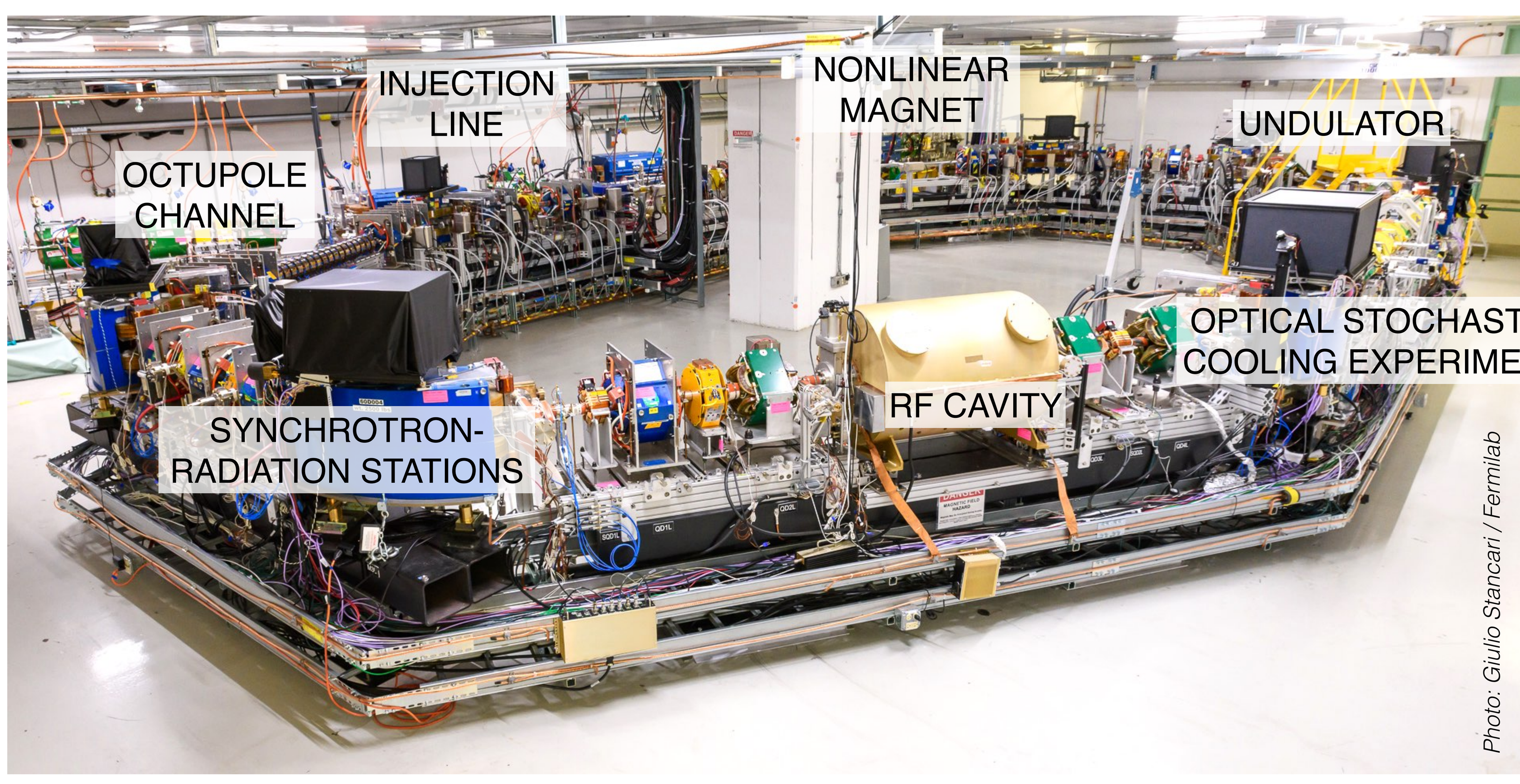
Giulio Stancari,[1,2] Jonathan Jarvis,[1] Aleksandr Romanov,[1] Alexander Shemyakin,[1] Alexander Valishev,[1] Ihar Lobach[3] and Sergei Nagaitsev[4]
[1]Fermi National Accelerator Laboratory [2]University of Chicago [3]Argonne National Laboratory [4]Brookhaven National Laboratory

Motivation

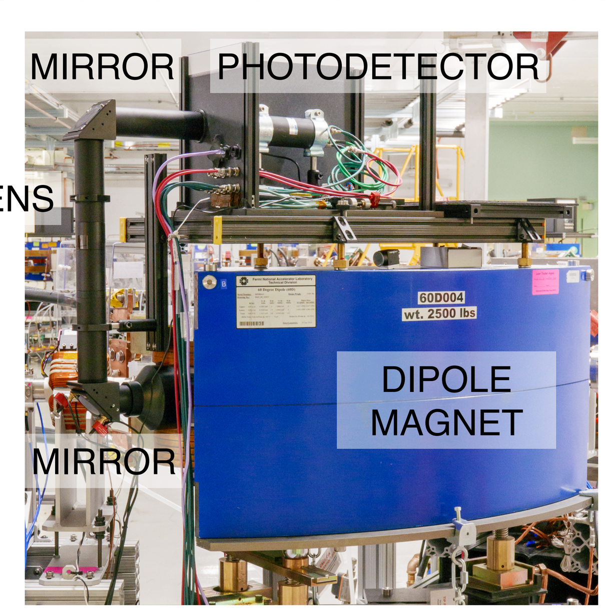
- What are the properties of radiation from single electrons?
- Can we directly observe the classical or quantum nature of undulator radiation?
- Are there new ways to generate quantum states of light?
- Are there novel applications of the techniques of quantum optics in accelerator physics and beam diagnostics?

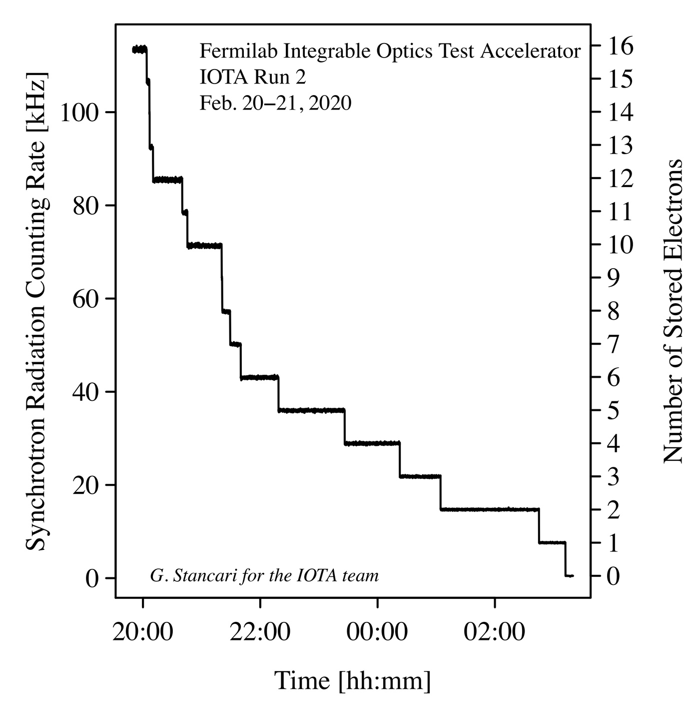
Single Electrons in the IOTA Storage Ring

The Fermilab Integrable Optics Test Accelerator (IOTA) is a 40-m-circumference storage ring dedicated to beam physics research in nonlinear dynamics, cooling, instabilities and other topics. It can store 150-MeV electrons or 2.5-MeV protons.



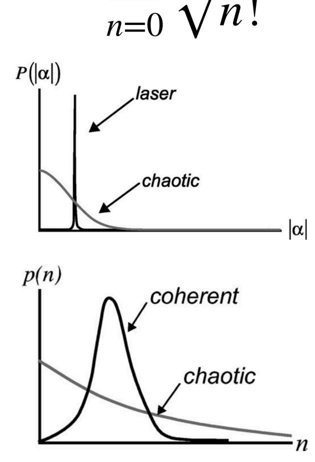
Single electrons can be stored by detuning injection or by lowering the rf voltage. Beam intensity and dynamics are recorded by synchrotron-radiation detectors.





Quantum States of Radiation

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

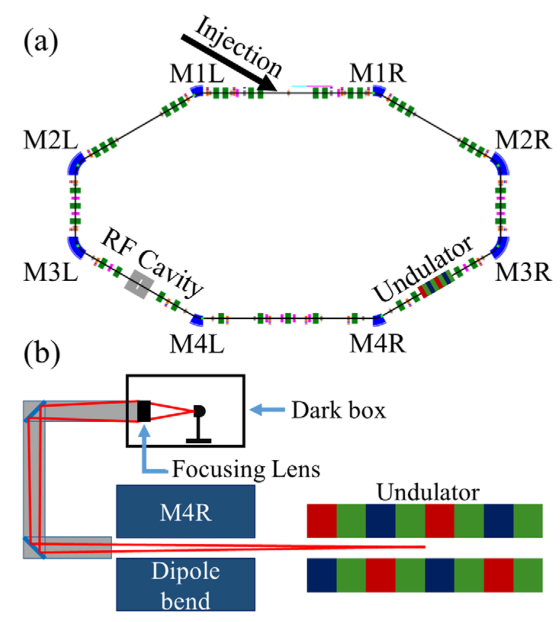


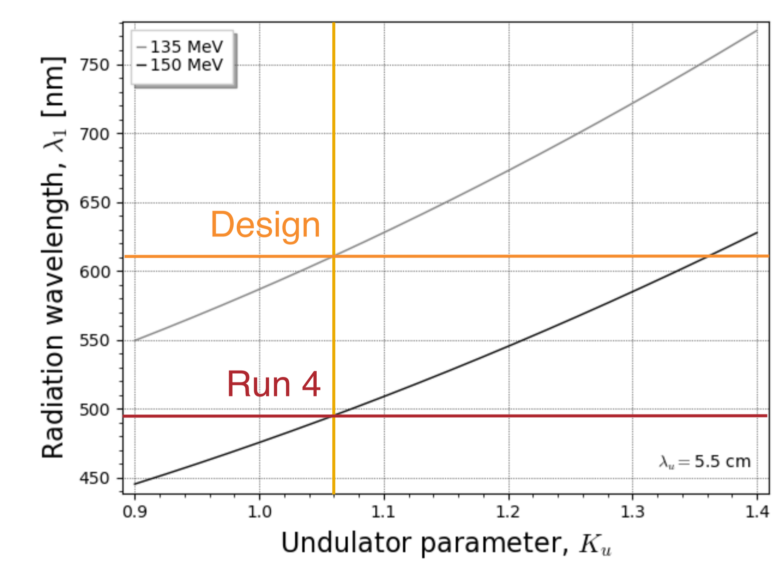
The radiation state can be identified by observing the statistics of photocounts and coincidences.

Low-energy radiation from high-energy electrons expected in a Glauber coherent state (classical wave).

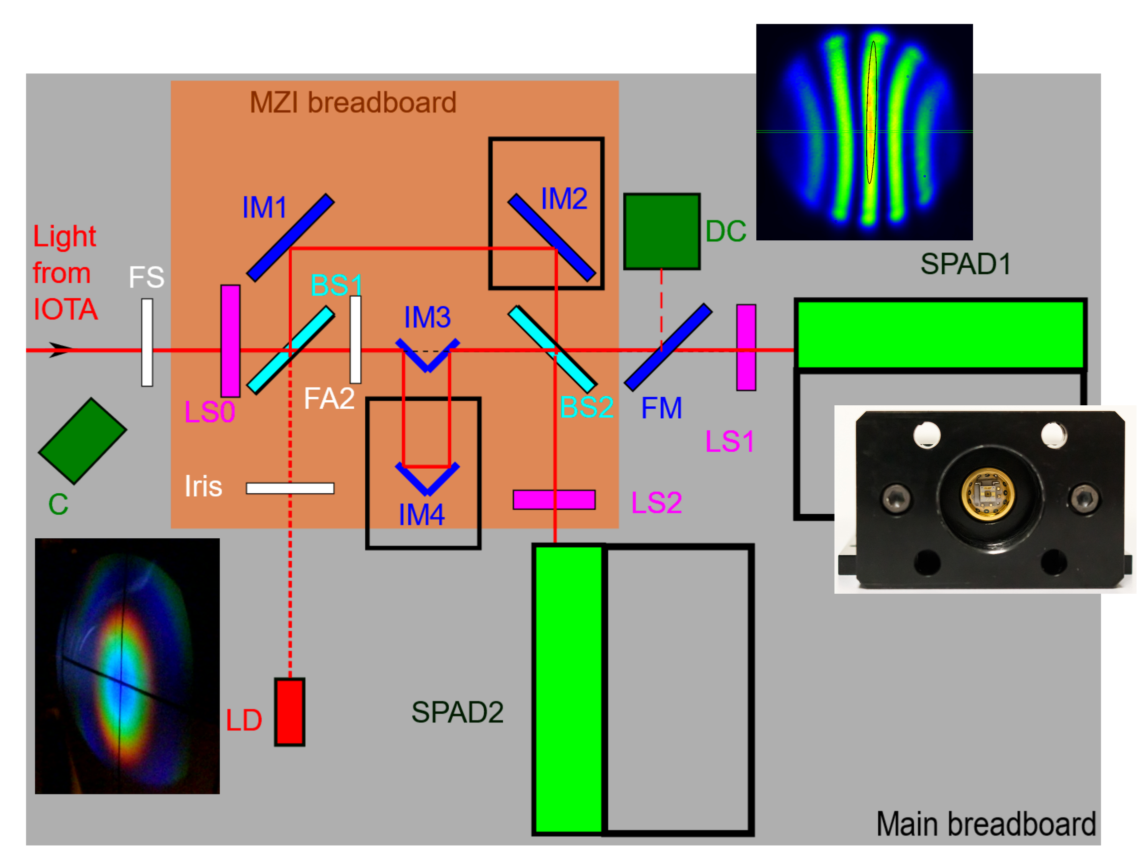
Experimental Methods

The CLARA experiment in IOTA Run 4 (2022—2023) studied the coherence length and statistical properties of undulator radiation with a Mach-Zehnder interferometer (MZI).





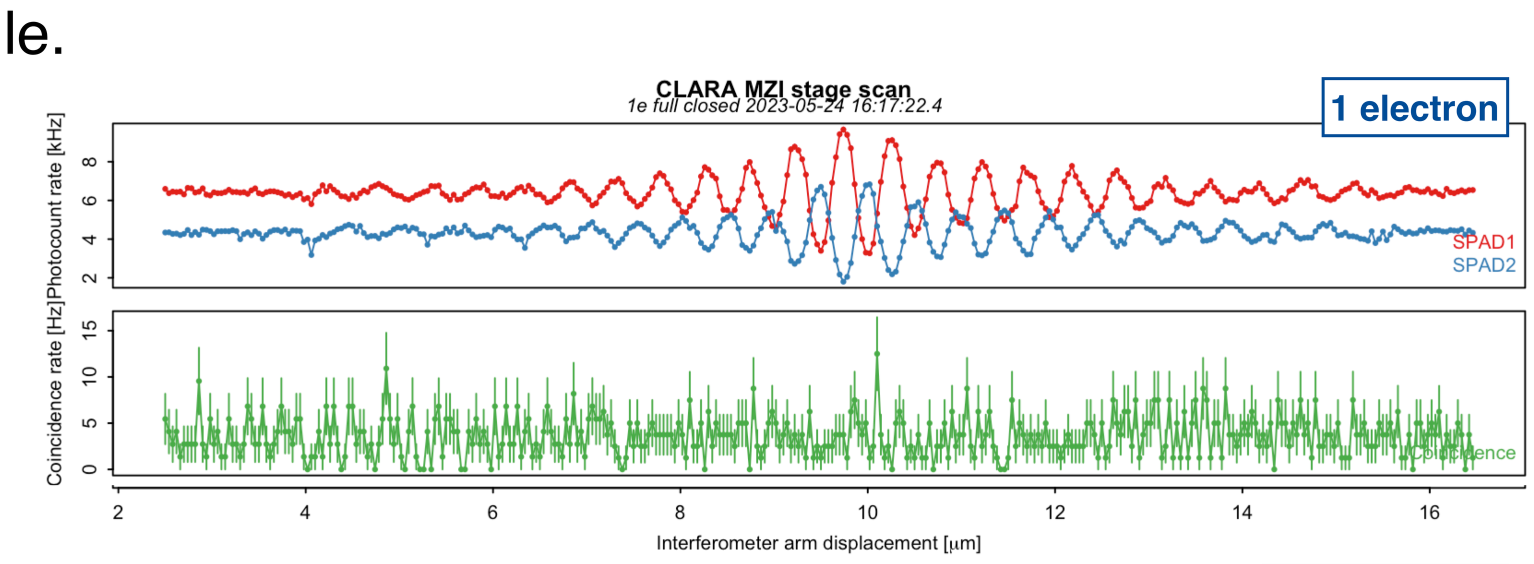
One interferometer arm was fixed. The length of the other arm was precisely controlled in 20-nm steps. Light was detected by digital cameras and by single-photon avalanche diodes (SPADs).

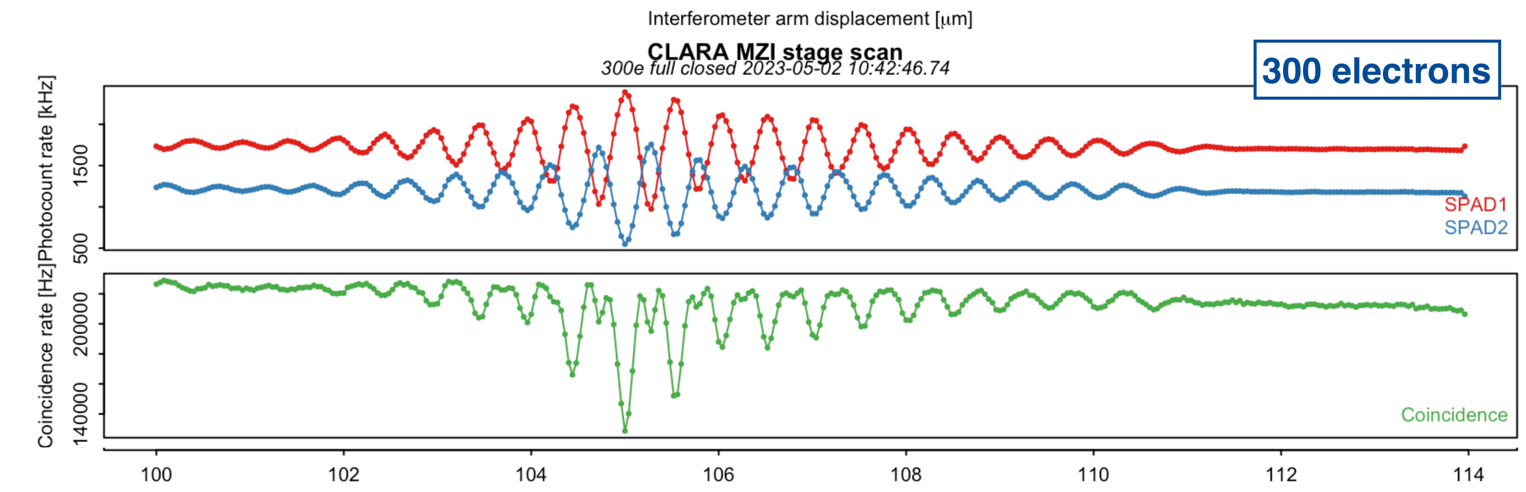


BS1, 2 — Beam splitters
C — Webcam
DC — Digital camera
FA2 — Arm-2 flipping screen
FM — Flipping mirror
FS — Flipping screen
IM1, 2 — Arm-1 mirrors
IM3 — Arm-2 right-angle mirror
IM4 — Arm-2 hollow-roof mirror
Iris — Laser collimator
LD — Laser diode
LS0 — Entrance lens
LS1, 2 — Detector lenses
SPAD1, 2 — Photodetectors

Results

Measured the individual and coincidence photocount rates and arrival times vs. arm length, number of electrons and acceptance angle.





Directly observed the temporal coherence of undulator radiation from single electrons at the femtosecond scale.

Preliminary results consistent with radiation in a coherent state.

Loudon, The Quantum Theory of Light (Oxford, 2000); Glauber, Rev. Mod. Phys. **78**, 1267 (2006)
Romanov et al., JINST **16**, P12009 (2021)
Lobach et al., Phys. Rev. Lett. **126**, 134802 (2021); Phys. Rev. Accel. Beams **23**, 090703 (2020) and **24**, 040701 (2021); JINST **17**, P02014 (2022)

Work authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. Partially supported by the University of Chicago Consortium for Advanced Science and Engineering (CASE).