Angular Measurement of Photons from Undulator Radiation (AMPUR) in IOTA's Single Electron Mode

I. PERSONNEL

- *Principal Investigator*: Evan Angelico, University of Chicago, PhD Student: experiment design, detector testing and setup, data acquisition, data analysis
- *Co-Principal Investigator*: Sergei Nagaitsev, Fermilab, Head of Accelerator Science Programs: experiment design, funding
- Ihar Lobach, University of Chicago, PhD Student: theory and modeling, apparatus design, data taking, data analysis
- Giulio Stancari, Fermilab, Senior Scientist: experiment design, detector setup, signal processing, data analysis

II. PURPOSE AND METHODS

A. Background and scientific motivation

Technological improvements in electron storage rings are beginning to put pressure on the assumption that interactions with background fields are classical [1]. One scenario where a full quantum treatment of the electron wave-function becomes relevant is when high current densities traverse short wavelength undulators with large K parameter [1].

A single electron circulating in the IOTA storage ring can be used as a standard candle for studying the differences between classical and quantum effects of radiation produced in an undulator. One phenomenon of interest is multi-photon emission from a single electron passing through the undulator [1]. By studying the properties of the two photons emitted by one electron, one learns about the spatial and temporal extent of the electron wavefunction in the undulator during its interaction with the background field. Some of the measured properties of this interaction may be extended to systems with many electrons.

Classical and quantum perspectives do not entirely agree on the angle at which each photon is emitted in a one-pass, two-photon emission event. With quantum electrodynamics, the electron wavefunction may be approximated in the limit where the electron receives negligible recoil energy from the undulator field ($\chi \ll 1$) and emits two-photons sequentially within the undulator [2]. This calculation suggests that the two photons are statistically uncorrelated and are emitted at any angle and wavelength, mostly within a cone of $\theta = 1/\gamma$. In the classical picture, photon emission occurs over the entire length of the macroscopic undulator. Emission is not sequential but occurs over the entire traversal period. Having two photons of different modes (angle and wavelength) form over the entire extent of the undulator is non-intuitive and would suggest that the observed angular distribution of two-photon events could contain correlations.

The goal of this project is to measure the rates and angular distribution of photons emitted from a single electron circulating in the IOTA storage ring. The output data from the first phase of the experiment will be used to inform a follow-up experiment with much higher precision on the angular distribution of two-photon events.

B. Methods

The main goal of this project is to observe the angular distribution of two-photon emission events of a single electron traversing an undulator. The sensitivity to angular correlations will depend on the position resolution of the detectors used. In the first phase, a Mini Planacon XPM85112 micro-channel plate based photo-detector (MCP-PMT) will provide coverage and position resolution to make a coarse angular measurement, confirm calculated emission rates, and commission the triggering and DAQ (see Section IV for details on the detector). In the next phase, a Large Area Picosecond Photodetector (LAPPD) MCP-PMT along with optics to expand the emission cone will be used to measure photon angles at 1-2 orders of magnitude higher precision. A new proposal will be written for the follow-up experiment, but some of the methods and sensitivity estimates are considered here for comparison.

The photo-detector with planar surface will be situated in a dark-box enclosure 3.5 m from the center of the undulator. The photo-detector will record events in coincidence with the passing of an electron through the undulator. The position and number photons will be recorded.

C. Expected results and sources of uncertainty

Consider a detector situated 3.5 m from the center of the SLAC STI Optronics undulator with $K = 1$ and 10 periods of 55 mm wavelength [3]. Assume this photo-detector has peak quantum efficiency of about 18% at 365 nm optical wavelength (see Section IV and Figure 2). The number of photons emitted by a single 100-MeV electron per unit wavelength through a circular disk of diameter 50 mm at 3.5 m from the center of the undulator is shown in Figure 1 (for references to the calculation, see [4, 5]).

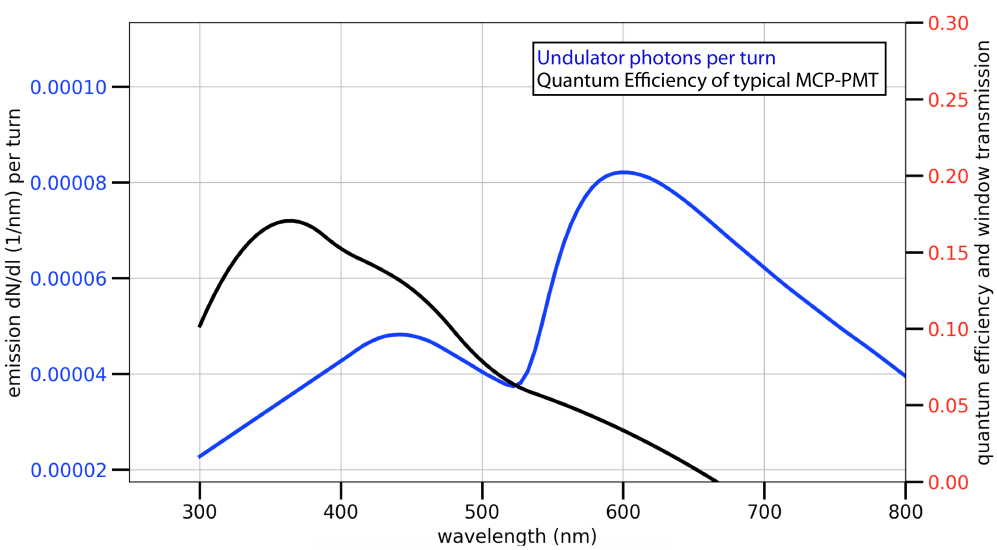

FIG. 1. In blue (axis left), number of photons emitted by a single 100-MeV electron per unit wavelength per turn through a disk of 50 mm diameter situated 3.5 m from the center of the SLAC STI Optronics undulator [4, 5]. In black (axis right), typical quantum efficiency spectrum for bi-alkali photocathode (LAPPD and Planacon) scaled to typical peak quantum efficiency of Photonis Planacon photo-detectors. Emission rates are calculated by multiplying and integrating these two spectra.

A total detection rate of about 1 photon per 5600 turns results from integrating these spectra. This does not account for transmission losses in lenses and mirrors used to transport the photons to the detector; however,

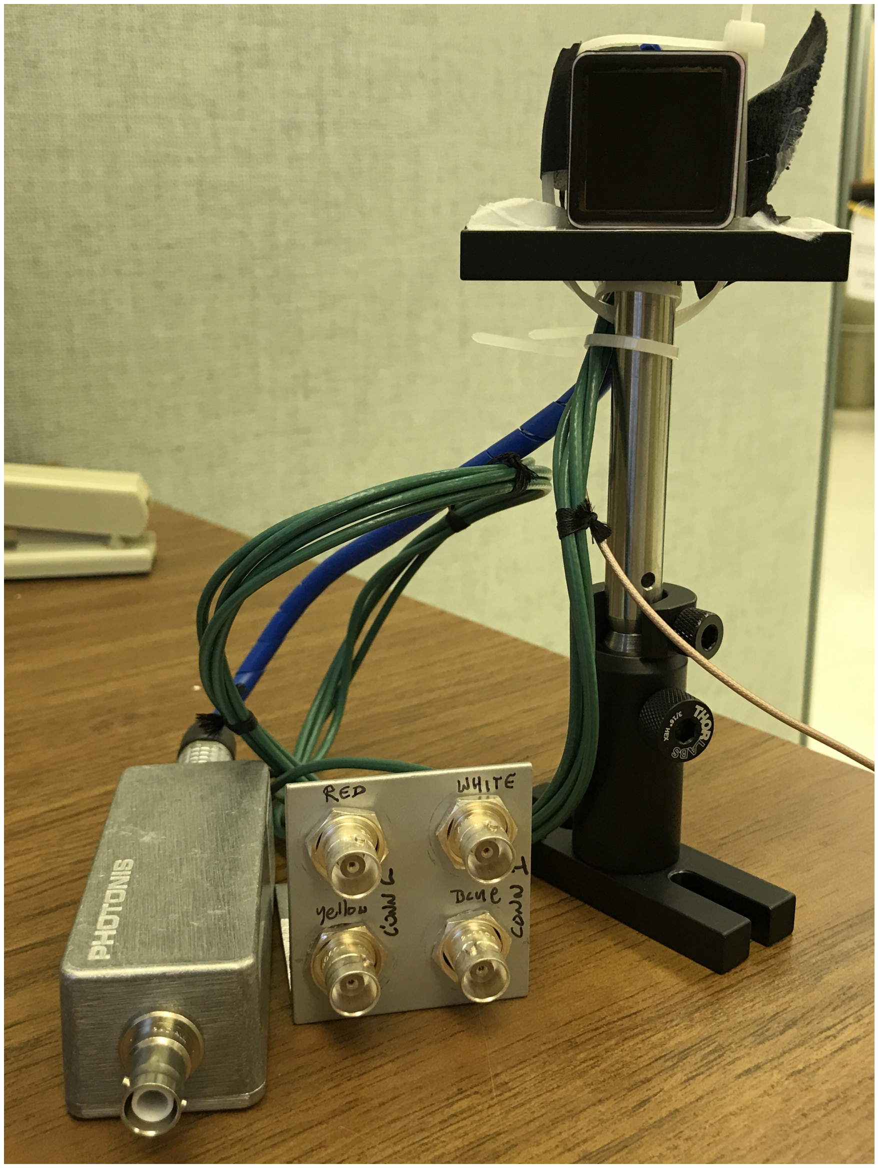

FIG. 2. Photograph of the Planacon XPM85112 photo-detector instrumented with HV and signal electronics and mounted on an optical post. The detector has an 4 x 4 array of square anode-pixels that have been joined externally to be 2 x 2. The detector sensitive area is 4 cm^2. Charge showers inside the detector will be shared between multiple pixels. Therefore, by sampling the amplitudes on each pixel, a charge centroid may be calculated to infer the position of a photon hit. This detector has been instrumented with readout cabling and Photonis-supplied HV divider during previous use in the IOTA diagnostic system. It was taken from M3L on 9-3-2019.

it does account for transmission losses in the photocathode window of the photo-detector. Two-photon events have about a factor of 300 lower rate, making the signal detection rate about 4 Hz. In this phase we will observe the contribution of the lenses and mirrors to rate loss.

These rates become lower when taking into account trigger and electronics inefficiencies. This phase of the experiment will quantify the DAQ dependent inefficiencies. The requested run-time has taken into consideration an estimate of the statistics needed to measure rates and angular distributions (see Section V for proposed time).

One requirement is to be able to separate single photo-electron and double photo-electron pulses outputted by the photo-detector. If the two photons emitted are completely correlated, they may land directly on top of eachother on the photo-detector surface. This must be recognized as a two-photon event. Photodetectors with high gain have better charge discrimination. Typicall Planacon single-photoelectron amplitudes on a 50 Ω terminated line are 5–10 mV. We plan to amplify each channel by a factor of 4 or so to improve discrimination between single and double photon emission events. Discrimination power will be characterized by performing a calibration on single-photoelectron integrated charge.

Expected observables for this run include total emission rate per turn (integrated with the detector quantum efficiency), rate per Planacon quadrant/pixel, rate of two-photon emission in a single pass, detector gain, and detector separation power between single and two photo-electrons. Efficiency of the various DAQ and readout options will be quantified. With the waveform sampling DAQ system expected observables include position resolution as a function of photon position, timing resolution, and properties of the raw waveforms like pulse-height distribution.

A significant source of noise to the angular distribution measurement comes from radiation from the upstream dipoles [6]. Simulated combined undulator and dipole intensity distribution at the undulator viewport are shown in Figure 3. These photons can be filtered out by optics and restricted optical apertures. At this phase of the experiment, the aperture of the viewport window can be restricted from 50 mm to 3–10 mm which will reduce the background from dipole radiation by a factor of 100 while allowing the undulator radiation cone to persist [7].

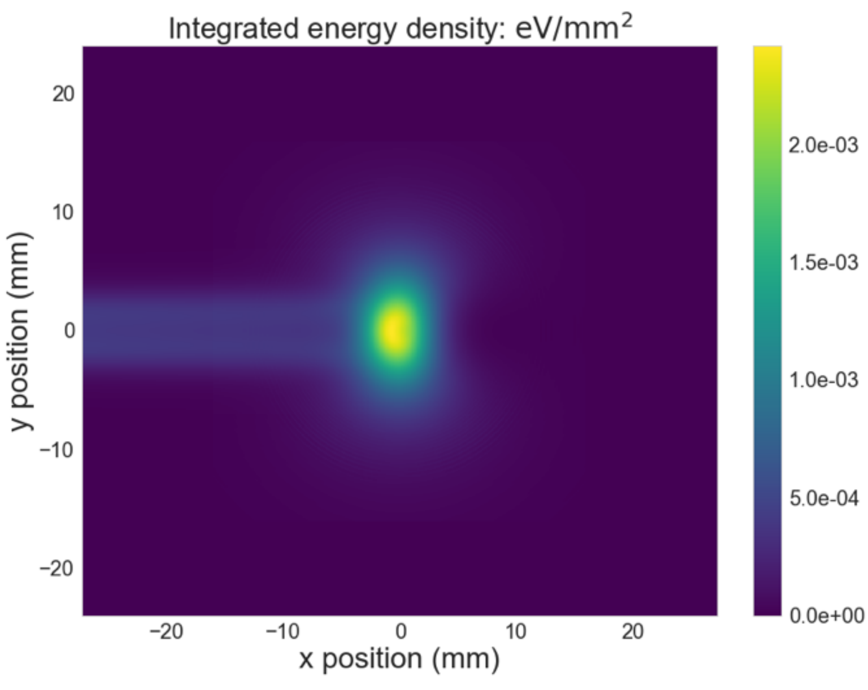

FIG. 3. Calculated undulator and dipole radiation intensity distribution at the undulator viewport over a broad photon wavelength range from 460 nm to long infrared. The dipole radiation is confined to a stripe in the *x* coordinate with a vertical extent of a few millimeters.

The position resolution of the Planacon photo-detector proposed in this phase is likely too coarse (> a few mm) to observe subtle angular correlations in the set of two-photon emission events. In upgrading to the LAPPD, the position resolution will likely be < 1 mm and could be as low as 40 μm. Additional sensitivity to angle will come from expanding the spot size of the undulator radiation (cone of $\sim$3 mrad angle) to the size of the LAPPD, about 10 cm radius, using optics.

III. BEAM CONDITIONS

- **Species:** electron
- **Energy:** any energy between 70 - 150 MeV
- **Intensity:** Main operating mode is single electron. Every 3–4 shifts, we request a low intensity operating mode for trigger alignment and calibration, about 10^4–10^6 electrons per bunch (see Run Plan V). If the number of electrons per bunch exceeds 10^{10} the detector may undergo damage. Please notify our experiment if this happens on shift and we will remove bias on the detector. If this is a foreseeable and common event, an interlocked shutter could be implemented.
- **Number of bunches, transverse emittance, beam size, bunch length, momentum spread:** Transverse beam size can be comfortably large for this phase, say < 3 mm. Information on the average spot size (from BPMs or otherwise) would help characterize errors in the angular distribution analysis. Other parameters are not critical/relevant.
- **Injection time structure:** maximize time with single electron, e.g. 30 minutes of circulation then re-inject
- **Orbit:** central orbit to maximize circulation time
- **Lattice parameters:** not critical, can be compatible with non-linear optics experiments.

IV. APPARATUS

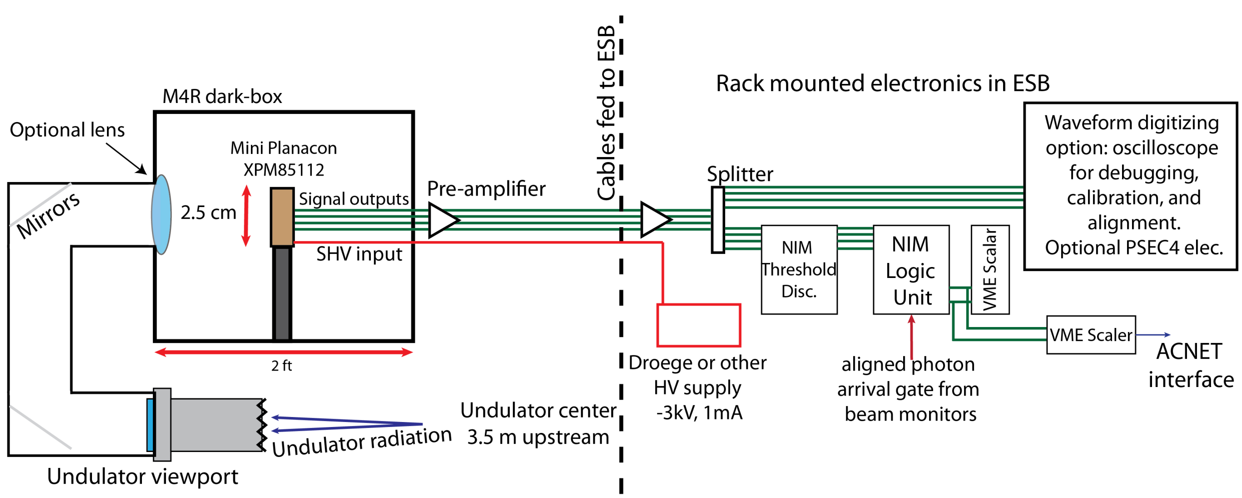

FIG. 4. Left of the dashed black line, a diagram of the detector hardware located in the M4R dark-box station in the IOTA cavern. The undulator radiation exits a viewport and hits mirrors that direct it to a dark-box that is mounted to the accelerator structure. The mirrors, light tube, and dark-box are constructed and already installed. The four channel Planacon photo-detector is mounted inside the dark box with a single SHV input and four signal outputs that lead to ESB. Right of the dashed black line, a diagram of the data acquisition system contained in a rack in ESB. See the text for detailed discussion.

A viewport and dark-box setup exists in the M4R section of IOTA, previously used to measure undulator radiation emission in many electron mode with the study of undulator radiation fluctuations experiment by

Ihar Lobach [3]. A light pipe directs undulator radiation from the viewport to a detector apparatus inside the dark-box.

The detector chosen for this phase of the experiment is a Mini Planacon XPM85112, previously installed in IOTA at the M3L sync-light station (see Figure 2). This Planacon is a micro-channel plate (MCP) based photo-detector with 2.5 cm $\times$ 2.5 cm square active area. The present readout is four channels, one for each 1 cm^2 area on the detector surface. It was chosen for the following reasons:

- Photo-coverage: the area of the photo-cathode completely contains the beam of photons from the undulator at this distance after mirrors and optics.

- Position resolution: charge showers from the MCPs cause signals to be shared among neighboring pixel channels. If waveforms are digitized, a charge centroid can be made in offline analysis to allow for position receonstruction on the surface of the Planacon at resolutions better than the pixel width.

- Low channel count: at this stage of the experiment, we can simplify the DAQ by having a low number of channels going into NIM logic units for making a coarse rate and angular correlation measurement.

- Simplicity: this detector has recently been used and only has one high-voltage input. Therefore cabling and calibration is simplified. Also, its size makes it easy to mount and remove in a consistent manner.

Figure 4 shows a schematic diagram of the experimental layout in the IOTA cavern as well as the data acquisition system contained in ESB. There are no infrastructural needs for this experiment other than space in a NIM rack in ESB. The cables, signal and SHV, needed for this experiment are already routed from ESB to M4R.

A. Electronics, data acquisition, and computing

We plan to occupy space in a rack in ESB with the following equipment:

- High voltage supply: Droege or equivalent supply with the ability to supply up to -3 kV and up to 1 mA.

- NIM threshold discriminator: LRS:420I or equivalent module from PREP or already in ESB

- 2x NIM logic unit: LRS:364 or equivalent from PREP or existing in ESB

- Digital display scaler: JORWAY:1880B or equivalent for visual sanity checks and monitoring

- VME scaler unit: this is a VME based scaler unit existing in a crate in ESB that can count logic signals from NIM units and send them to ACNET. It takes a ribbon cable input and has 16 channels, 5 of which are currently in use. This is provided by IOTA.

- LEMO to ribbon cable adapter: for interfacing NIM units with VME scaler unit

- Oscilloscope: for calibration of cable lengths, amplitudes, and sanity checks. Will use intermittently to digitize full waveforms for use in data analysis. This is provided by UChicago.

- PSEC4 electronics: another optional waveform digitizing electronics system, used for digitizing LAPPD and Planacon signals at 10.24 GSPS and 1.6 GHz bandwidth. This electronics system will likely be used in the LAPPD version of this experiment; some debugging could be performed at this stage

Our computing needs include support from AD Controls / Front-End Group (Rich Neswold) to interface new channels of the VME scaler into ACNET for monitoring and storage of data.

During the alignment and trigger calibration phase (first and fourth shift) we will ask assistance from James Santucci (optics) and Dean Edstrom (trigger timing). They have agreed to be somewhat available for help in the IOTA cavern.

The project has a Fermi Redmine page to store information, files, data, documents and papers [10].

Data will be backed-up on an external hard drive provided by UChicago and also stored on a Fermilab Linux machine (`thudpucker.fnal.gov` on the Cartoon Cluster).

Off-line analysis will be performed on existing computers at UChicago and Fermilab. Analysis scripts will be saved and versioned on Fermi Redmine.

V. RUN PLAN

A. Proposed installation plan

Installation of detector and calibration of the detector will be performed before IOTA turns on for run 2. A gain calibration is being performed in a dark-box in Lab 6 presently. Installation into IOTA will take one hour, as cables already exist and are routed to the dark-box station, M4R.

B. Requested running period and approximate duration

We request 1–2 8-hour shifts per week for 4–8 weeks, depending on availability. This setup will be as compatible with other experiments as possible. Spacing shifts by a few days allows feedback and quality control of data.

Plan for individual shifts:

- **Shift 1:** Beam in low intensity mode to start. Oscilloscope based DAQ. Calibrate trigger alignment and expected arrival time of photons. Switch to single electron mode. Adjust post-amplification, pre-amplification, and NIM discrimination thresholds based on amplitudes measured by the oscilloscope. Record a small dataset with oscilloscope.

- Interim or just before shift 2: adjust position of Planacon to maximize spot size based on data analyzed from shift 1. Adjust amplifiers if needed.

- **Shift 2:** Single electron mode. Take one hour of oscilloscope data and one hour of NIM discriminated data. Compare rates and efficiencies to make sure that thresholds and logic is in agreement with oscilloscope data.

- **Shift 3:** Briefly start in low intensity mode to confirm consistency. Then 7 hours of single electron mode data recording rates with the NIM and scaler DAQ. One hour at the end of oscilloscope recorded data.

- **Shift 4:** Single electron mode. 7 hours of data recording rates with the NIM and scaler DAQ. One hour at the end of oscilloscope recorded data.
- If allotted additional shifts, repeat the plans for shifts 2-4.

C. Proposed decommissioning plan

Removal of detector from M4R dark-box can be done intermittently throughout the 4–8 week shift period as needed by other experiments. Consistent positioning of the detector will be taken into account. Preference is to leave the detector and M4R dark-box unchanged from shift to shift.

Removal of DAQ system from ESB can be completed in an hour or so if the space is needed.

VI. FUNDING

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