Measurement of Spontaneous Undulator Radiation Statistics Generated by a Single Electron (URSSE)

PERSONNEL

Fermilab:

- *Sergei Nagaitsev (spokesperson)*
- *Ihar Lobach (theory, design, data analysis, instrumentation)*
- *Alexander Valishev (beam dynamics)*
- *Aleksandr Romanov (beam dynamics)*
- *Giulio Stancari (optics, theory, design)*

SLAC:

- *Aliaksei Halavanau (theory, design, data analysis)*
- *Zhirong Huang (theory, design)*

PURPOSE AND METHODS

The purpose of the proposed experiment is to study the statistics of the undulator radiation produced by a single electron circulating in a storage ring. Additionally, the statistics of the undulator radiation generated by a bunch of electrons can be studied, if the intensity of radiation is reduced below one photon per turn via a monochromator and/or installing the detector at a rather large ($> 1/\gamma$) observation angle.

References [1, 2] report on an experiment where sub-Poisson statistics was observed in the seventh coherent spontaneous harmonic of a RF Linac free-electron laser (FEL) with a photomultiplier tube. This result cannot be explained by a quasi-classical model of synchrotron radiation, which predicts Poisson statistics. To the best of our knowledge, no further study was conducted in this area and the results of this experiment were neither confirmed nor invalidated by an independent experiment to this day.

In the proposed experiment we will attempt to experimentally study a system similar to [1, 2], i.e., second spontaneous harmonic of undulator radiation in a storage ring, with a detector based on a new technology that was not available during the experiment reported in [1, 2]. Namely, we will use a Single Photon Avalanche Diode (SPAD) Excelitas SPCM-AQRH-10 [3] which will provide unprecedented quantum efficiency for this kind of measurement ($\approx 60\,\%$). In [1, 2], quantum efficiency was $\approx 12\,\%$.

One possible explanation for the results from [1, 2] is instrumental error. Namely, it is shown in [4] that the dead time of the photomultiplier could result in observation of sub-Poisson statistics for the photocounts, even if the statistics for the emitted photons was Poissonian. In our experiment in IOTA, the effect of dead time will be virtually absent, since the dead time of Excelitas SPCM-AQRH-10 is $\approx 22\,$ns, which is considerably smaller than IOTA revolution 133 ns.

The main quantity that we want to measure in the experiment is the Fano factor [4] in the radiation statistics, which equals the ratio of photocount variance to photocount mean. Fano factor equals exactly 1 for Poisson statistics, it is less than 1 for sub-Poisson statistics, and greater than 1 for super-Poisson statistics . If the statistics of emitted radiation is sub- or super-Poisson, and a non-ideal detector (quantum efficiency less than 100 %) is used, Fano factor for the observable photocounts will be closer to 1, than Fano factor for the actual radiation. Therefore, higher quantum efficiency results in a more accurate measurement of Fano factor. Thus, a measurement with a SPAD detector will be more reliable than with a photomultiplier.

The signal of the SPAD detector will be collected with a Rohde&Schwarz RTO1044 4GHz 20 GSa/s oscilloscope. We are planning to collect one sample per 3 ns, because the SPAD's pulses are approximately 10 ns long. In addition, the signal from the IOTA clock will be collected in the second channel. The scope can collect 40 MSamples in each of the two channels. Thus, waveforms 120 ms long will be saved, and then analyzed offline. We will study the distribution of the number of photocounts in a certain time window, e.g., 100 IOTA revolutions.

The main source of uncertainty in Fano factor will be dark counts. There will be dark counts produced by the SPAD detector itself, as well as dark counts produced by poor isolation of the background light. The manufacturer guarantees dark count rate in the detector to be below 1500 cps. However, preliminary tests of one Excelitas SPCM-AQRH-10 which has already been received show that this specific SPAD's dark count rate is ~ 100 cps and the statistics of the dark counts is close to Poisson.

We estimate that we will be able to measure Fano factor for the undulator radiation in IOTA with $1-2\%$ error. We do not expect to see any deviations from Poisson statistics beyond experimental error. Rather, we want to make a precision measurement with unprecedented accuracy that will show that the deviation from Poisson statistics is not greater than $x\%$.

We will take some measurements with a bunch of electrons as in [1, 2]. However, we will focus on the measurements with a single electron in the storage ring, since it will let us gain necessary skills for further experiment regarding Mach-Zehnder interferometry of undulator radiation produced by a single electron, described in the LDRD proposal [5].

BEAM CONDITIONS

We request nominal lattice in the IOTA ring with the SLAC undulator in the "in" position (the perturbation in beta functions introduced by the undulator is not important in our experiment). Our studies will require the following two regimes:

- Single electron circulating in the ring.
- Variable injection current (from a few electrons to 2 mA)

The beam energy 100 MeV is acceptable for our studies, we can study the second harmonic of the undulator radiation at this energy. If 150 MeV beam is available at the time of experiment it would be even better, since it would let us study the fundamental.

APPARATUS

The layout of our proposed setup is shown in Fig. 1. The main parameters of the SPAD detector are given in Table I; its quantum efficiency curve is shown in Fig. 2. To focus the undulator radiation on the small sensitive area of the SPAD we will use one focusing lens with short focal distance (180 mm) and low dispersion. We have experience in focusing the undulator radiation on such a small area, see [6]. We will use a highpass and a lowpass filters to restrict the wavelength of radiation that is collected to the region where the SPAD has close to maximum quantum efficiency. The SPAD will be installed on a stage with 3 picomotors so that it can be positioned to collect the maximum possible amount of light. There will be a shutter with remote control, it will protect the SPAD from exposure to light of too high intensity. The SPAD's power supply will be connected through a relay, controlled by the Raspberry Pi. Most of the time the power will be off to protect the detector from overexposure as well. It will only be turned on for the measurements, when the intensity of the radiation is within acceptable limits.

To perform initial alignment, we can use bright beam produced by a bunch of electrons and shine the light onto the surface of the shutter. Then, the light spot can be observed with the camera. Thanks to the LED we will be able to see where approximately the undulator radiation light spot is located with respect to the center of the shutter. Then we can use the picomotors to adjust the position of the light spot on the surface of the shutter so that it is exactly in the center. After that, we should turn off the LED and inject a single electron. The shutter can be opened at this point. The alignment should be close to perfect. Final adjustment can be made by using the picomotors and looking at the count rate on the scope.

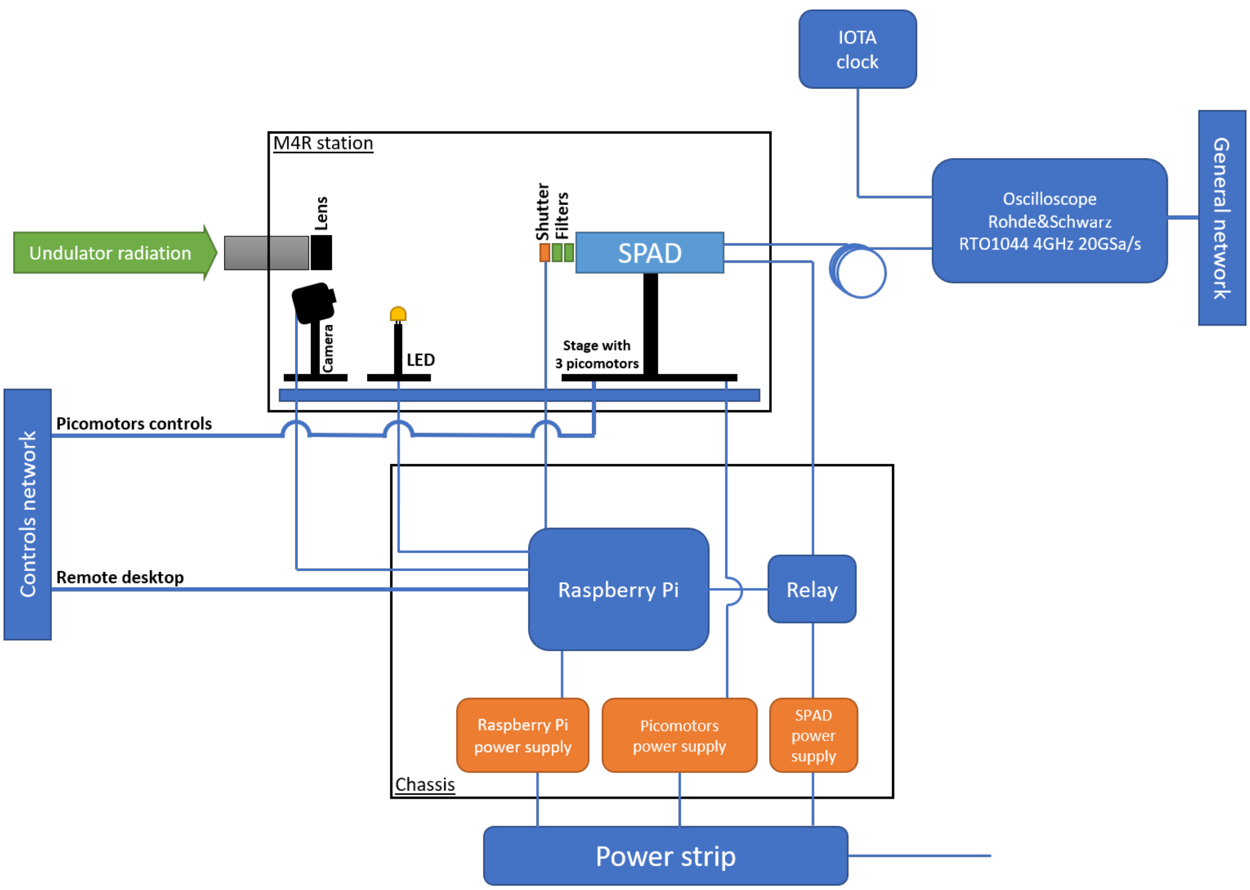

FIG. 1. Setup layout.

Using SRW [7] we calculated spectral density for the number of photons crossing the surface of the lens, see Fig. 3. In this figure we also show the total quantum efficiency curve, which includes the highpass and lowpass filters, the lens, the mirrors in the periscope, preceding the M4R station, and the SPAD detector. This simulation was performed for a 100 MeV beam. With a 100 MeV beam, we have to study the second harmonic of the undulator radiation, because this is where the peak of sensitivity of the SPAD detector is. We can study the fundamental if a 150 MeV beam is available at the time of the experiment.

TABLE I. Excelitas SPCM-AQRH-10 parameters.

Active area	⌀180 µm
Photodetection efficiency at 650 nm	65 %
Dark count rate	< 1500 cps
Output pulse width	10 ns
Dead time	22 ns

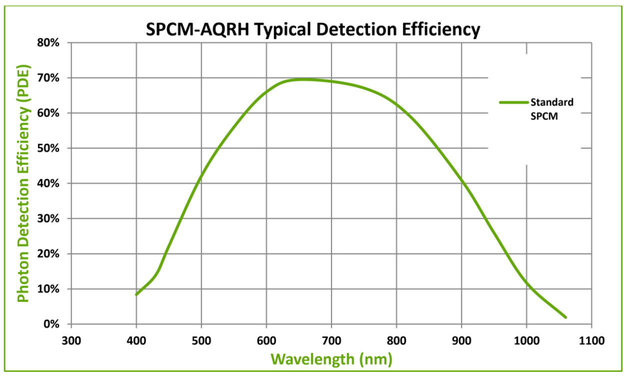

FIG. 2. Excelitas SPCM-AQRH-10 quantum efficiency.

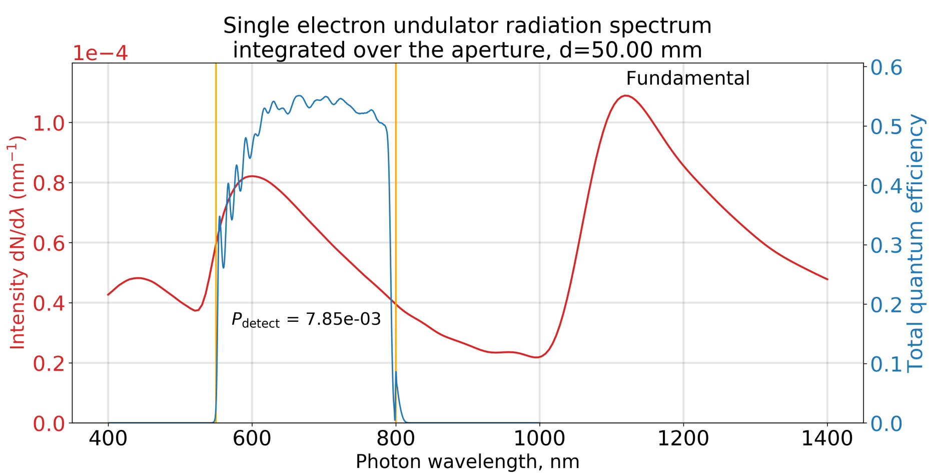

FIG. 3. The undulator radiation spectrum, integrated over the lens area.

According to the SRW simulation, we will observe ≈ 59 000 undulator photon counts per second. As was mentioned before, we will record 120 ms waveforms of the SPAD's signal (and also of the IOTA clock signal). Thus, we will have ≈ 7100 undulator photon counts per one waveform. The average number of detector dark counts for one waveform is ≈ 12. Moreover, we will be able to separate most of the dark counts from the undulator photon counts by looking at the time of arrival of each count, since the undulator photon counts will always arrive a certain fixed time after the pulse in the IOTA clock, as opposed to the dark counts that arrive at random times. This fact will reduce the contribution of the dark counts to a negligible level.

In the experiment with a bunch of electrons, the lens, the longpass and shortpass filters will be replaced by a monochromator, which will reduce the number of collected photons per turn. In order not to expose the detector to too high intensity, we will start from a very small value of beam current and we will gradually increase it until we see a satisfactory number of undulator photon counts per second. An estimate for the required value of beam current can always be calculated with SRW, the exact value depends on the specific choice of the monochromator. Another way to gradually increase the undulator photon count to a satisfactory value is to keep the lens in the setup and start from collecting the undulator radiation at a large ($> 1/\gamma$) observation angle, and then, slowly move the SPAD using the picomotors closer to the center of the undulator radiation cone.

Regardless of the number of electrons in the ring (single/bunch) we will study the distribution of the number of undulator photon counts in a certain time window, e.g., 100 IOTA revolutions. The collected scope waveforms will be first saved on the scope and then transferred via the general network to an office PC, where they will be analyzed offline. Additionally, the UChicago cluster [8] may be used in case that high computation power is necessary.

Optical components to purchase:

- 2 mirrors from Thorlabs: BB2-E02 - ⌀2" Broadband Dielectric Mirror, 400 - 750 nm
- 1 lens from Thorlabs: AC508-180-AB-ML - f = 180.0 mm, ⌀2" Achromatic Doublet, SM2-Threaded Mount, ARC: 400 - 1100 nm
- 1 longpass filter from Thorlabs: FEL0500 - ⌀1" Longpass Filter, Cut-On Wavelength: 500 nm
- 1 longpass filter from Thorlabs: FEL0550 - ⌀1" Longpass Filter, Cut-On Wavelength: 550 nm
- 1 shortpass filter from Thorlabs: FES0750 - ⌀1" Shortpass Filter, Cut-Off Wavelength: 750 nm
- 1 shortpass filter from Thorlabs: FES0800 - ⌀1" Shortpass Filter, Cut-Off Wavelength: 800 nm
- Maybe: 1 slider from Thorlabs: ELL9K - Four-Position Slider Bundle: Four-Position Slider, Interface Board, Cables
- 1 monochromator from Thorlabs: FL632.8-1 - ⌀1" Laser Line Filter, CWL = 632.8 $\pm$ 0.2 nm, FWHM = 1 $\pm$ 0.2 nm
- 1 monochromator from Thorlabs: FL632.8-3 - ⌀1" Laser Line Filter, CWL = 632.8 $\pm$ 0.6 nm, FWHM = 3 $\pm$ 0.6 nm
- 1 monochromator from Thorlabs: FL632.8-10 - ⌀1" Laser Line Filter, CWL = 632.8 $\pm$ 2 nm, FWHM = 10 $\pm$ 2 nm
- 2 LEDs from Hamamatsu: model L10762
- 2 C-mount optical shutters from Edmund Optics: Stock #87-208
- 1 flat C-mount adapter from Apogee: Apogee C-Mount Adapter for Apogee Ascent CCD Cameras. Apogee Instruments Product Number: 100163

RUN PLAN

The setup will be built and tested in a light-tight box outside of the IOTA cave. During the installation of the box at the M4R station it will be necessary to replace the mirrors in the periscope with new ones, designed for the visible wavelength range. A controlled access approximately 3 hr-long will be needed. Four network cables at M4R will be required for the picomotors and the Raspberry Pi. Also, one Heliax (preferably) or RG-58 cable will be required for the SPAD's signal. We will need 4-5 shifts, each about 4 hours long.

Shift 1. It will be necessary to establish a procedure to obtain 1,2,3,4,5 electrons circulating in IOTA by injecting dark current of the cathode into the ring. For this shift we will need Sasha Romanov. We will also make sure that we can reliably determine the number of electrons in the ring using the signals from PMTs and synclight cameras. Thus, we would like to have the signal from PMTs and synclight cameras available during this and following shifts. During this shift we will also estimate the dark counts rate coming from the detector, when it is installed in the enclosure. It may be different from what we observe in the lab.

Shift 2. We will observe single photon counts in the SPAD produced by undulator radiation from a bunch of electrons. It is safe for the detector if it is far from the "in focus" position. During this shift we will calibrate the delay between the pulses coming from the detector and IOTA clock. In addition, the statistical properties of the photon counts in this configuration are also an interesting subject for study.

Shift 3. The alignment of the setup will be performed. First, the light spot produced by a bunch of electrons will be observed on the surface of the optical shutter. The position of the detector will be adjusted with picomotors to make sure that the light spot is approximately in the center of the shutter. Then, only one electron will be left in the ring. We will open the shutter and fine-tune the position of the detector by looking at the counts on the scope. One measurement of photon statistics (a few scope waveforms) can be done during this shift. Then, the data will be analyzed offline, and it will be decided if additional adjustments or modifications are required for the next shift.

Shift 4. Data acquisition phase. Oscilloscope waveforms will be collected for 1,2,3,4,5 electrons circulating in the ring. For each number of electrons in the ring (1,2,3,4,5) a dataset about 30GB in size will be saved on the scope. Collecting each of these datasets will take about 15 minutes of beam time. If the number of electrons changes during that 15 minutes, we will have to obtain the same number of electrons again and keep collecting the waveforms, until the combined measurement time reaches 15 min. Then, the data will be analyzed offline.

Shift 5. If there is a possibility to have Shift 5, measurements for one electron in the ring with different neutral density filters can be made. It would be an additional verification of the value of the intrinsic Fano factor of the radiation obtained during Shift 4. The measurements with different neutral density filters could be more reliable and illustrative, since the intrinsic Fano factor in this case is represented by the slope of the measured Fano factor as a function of transmittance of the neutral density filter.

If by the time of the measurements we will be able to use the TDC at ESB to only record the timestamps of the pulses coming from the detector, instead of the entire waveforms, then this method of data acquisition will be used. This will reduce the time spent on collection of the data and its analyzis.

If some other setup needs to be installed at M4R station, the box with our setup can be removed as a whole during a 30 min controlled access. If the mirrors in the periscope need to be replaced too, it will add another 30 min to the controlled access. However, we would prefer to keep our setup at M4R during our entire study, because every time the box is removed and installed back, the alignment has to be performed from scratch.

If the SLAC undulator is motorized by the time of the experiment, it will be moved in and out remotely. Otherwise, additional controlled accesses (30 min) will be required each shift to move the undulator in and out.

FUNDING

The project is funded by a Fermilab LDRD grant [5] and supported by SLAC and UChicago.

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