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EXPERIMENTAL STUDY OF A SINGLE ELECTRON IN A STORAGE RING VIA UNDULATOR RADIATION

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Abstract

A single electron orbiting around a ring and emitting single quanta at the rate of about one event per hundred turns could produce a wealth of information about physical processes in large traps (i.e. storage rings) for charged particles. It should be noted that Paul and Penning traps in the 1980s led to the Nobel prize for studying state and motion of single quantum particles, and just recently the Penning trap technique has enabled the measurement of a single proton magnetic moment with an unprecedented precision of 10 decimal places. The information from the storage ring traps could also be used for characterization of a quantum system as well as the "trap" itself, i.e. measuring properties of the storage ring lattice and electron interaction with the laser fields. Although, the interest in single electron quantum processes today is mostly academic in nature, the diagnostics and methodology developed for single electron radiation studies could find subsequent applications in a variety of applied disciplines in quantum technology, including quantum communications and quantum computing.

INTRODUCTION

Recently, Fermilab has commissioned a 40-m long electron/proton storage ring, IOTA [1], for accelerator and beam physics experiments (see Fig. 1). Electrons can be stored at energies of 100-150 MeV and the IOTA ring can be used to trap and store a single electron to study its emission properties [2]. Figure 2 shows one of the photo-multiplier's photon counting rates from an IOTA dipole magnet. In addition, a $K \approx 1$ undulator with a 55-mm period and $N_u = 10$ was installed and commissioned in the IOTA ring.

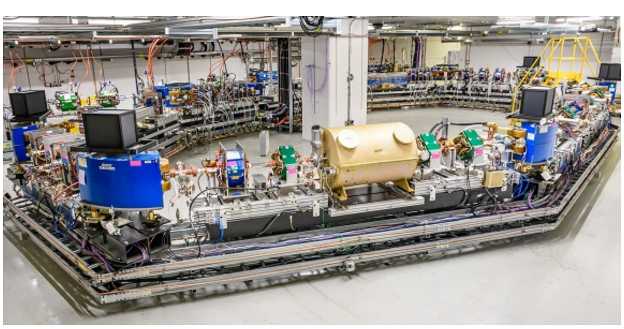

Figure 1: The IOTA storage ring at Fermilab.

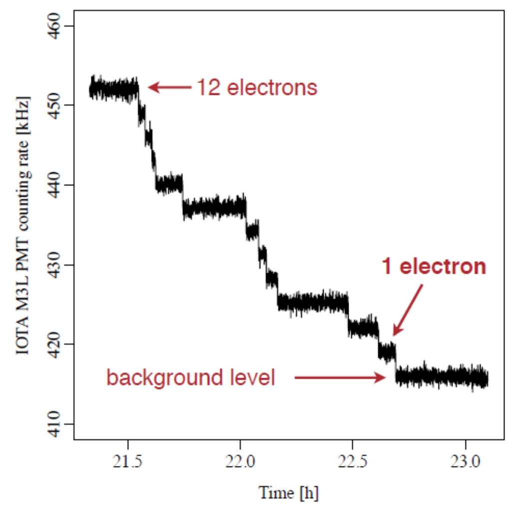

Figure 2: A measured photo-multiplier signal from a synchrotron radiation monitor after the bend magnet. One can clearly see finite jumps in the average proton count rate level as the number of trapped electrons becomes small, until a single electron is left in the IOTA storage ring.

In this paper we will describe experiments with a single electron and interacting with an undulator field.

SINGLE ELECTRON EXPERIMENTS

The initial experiment planned is to measure the two-photon emission events properties within a coherent angle, as a single electron passes through an undulator. The coherent angle θ_C, is defined as a maximum angle at which the off-axis red shift does not exceed the Fourier-limited linewidth $1/N_u$ of the on-axis undulator radiation at the fundamental wavelength, λ_r (460 nm in our case),

$$\theta_C = \frac{1}{\gamma}\sqrt{\frac{1+K^2/2}{N_u}}, \qquad (1)$$

where K is the dimensionless undulator parameter and γ is the usual Lorentz relativistic factor.

It is well known from a semi-classical theory of the undulator radiation that at the fundamental wavelength, and when K is not much larger than unity, the probability of a photon radiated by a single electron within the coherent angle in a single pass through the undulator is given by,

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$p \approx \pi\alpha K^2/(1+K^2/2)$, where α is the fine structure constant. In our case, a single-photon emission probability is estimated to be $p \approx 0.015$. Since the IOTA revolution frequency is 7.5 MHz, one would expect a single-photon emission rate of about 100 kHz.

It is important to note, that measuring such "one electron / one photon" (1e1p) emission properties is quite valuable for both metrology purposes, as well as for tracking the electron trajectory evolution in the ring. However, such measurements are not expected to yield any new results related to the photon emission itself, as compared to the semi-classical undulator radiation theory well corroborated with the experience at the existing synchrotron light sources. This is mostly because the recoil-related quantum corrections due to the photon emission in 1e1p events are insignificant, when compared to the thermal noise from the electron interacting with magnetic and RF field oscillators in a storage ring. In this scenario, we only expect to validate the semi-classical approximation of treating electron as a classical object, while the fields are in a quantum state. Therefore, we are more interested in studying 1e2p events, where an electron emits two photons in a single pass through the undulator.

It is expected that the 1e2p events will occur at a rate of p^2 or 1.5 kHz, and if the detector is designed to isolate and characterize such events, we can potentially get a better insight into basic quantum properties of a two-photon process.

Thus, we are planning to carry out a systematic theoretical and experimental study of two-photon and, eventually, three-photon undulator radiation (UR) with a single relativistic electron, circulating in a storage ring. In the proposed regime, we do not expect deviations from the well-established and well-tested QED theory, but we hypothesize that the behavior of multi-photon UR might deviate from the standard quasi-classical model of independent non-interacting photons. In particular, it is suggested that for long undulators ($N_u \gg 1$), photons, radiated at small angles $\theta < \theta_C$, are not formed locally, but rather through the entire length of an undulator [3]. This is the result of the constructive interference of photon emission probabilities by an electron from all undulator periods. Other researchers predict that the average number of undulator periods to "emit" a single photon (in long undulators) is approximately $1/(\pi\alpha K^2)$ [4].

The first dedicated two-photon UR experiments (at small angles) were performed at the Budker Institute of Nuclear Physics in Novosibirsk about two decades ago in the VEPP-3 storage ring (see Fig. 3) with a single circulating electron and an undulator [5, 6]. The quasi-classical UR theory predicts that both photons in a two-photon process are emitted independently and should arrive concurrently at a detector downstream of the undulator. To test the simultaneity of the two photons in VEPP-3 experiments, the standard Hanbury-Brown-Twiss intensity interferometer scheme with a splitter was employed to send the photons to two photomultipliers. The basic idea was to detect two photons by different photomultipliers during one passage of an electron through an undulator and to measure the rms time difference between photon arrivals. This experiment characterized the fourth-order correlation function of the radiation field, and quantum effects could be seen in it [7]. Unfortunately, the photomultipliers were slow, with a response time of around 160 ps. The signal time difference from two photomultipliers was well within this number. As for the three-photon UR processes, we have found no evidence of any experimental research.

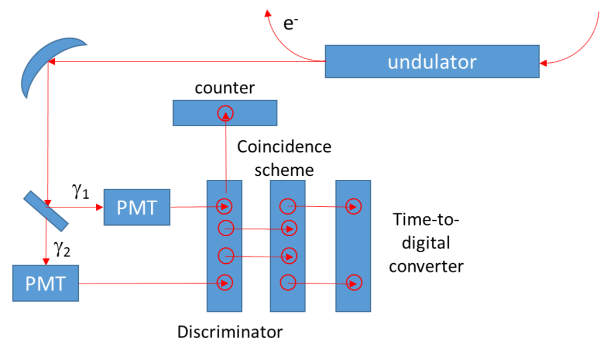

Figure 3: Measured photon counting rates for various number of stored electrons in the VEPP-3 experiment [6].

We are planning to repeat these measurements with modern faster instruments. It is important to note that we propose a "beam frame" version of an experiment, such as recently conducted in the laboratory frame [8] with the same goal of finding deviations from the point-emitter model of electrons. In that experiment, the direct measurements of the intense laser scattering from free electrons have not revealed any evidence of the radiation suppression due to the electron wave functions spreading effects, and the results came consistent with the classical point-emitters theory. In our case, the proposed experiment is carried out in a frame of the moving electron, with the undulator playing the role of the laser, and we expect data of much higher accuracy compared to the lab frame scenario, due to: (1) a better localization of the scattered photons (coherent angle), and (2) a much better repeatability and experimental statistics with 1.5 kHz rate of 1e2p events. An additional benefit from the beam frame configuration is an ability to study space-temporal correlations (if any) between the two photons.

Indeed, there is a theoretical evidence [9] of angular and energy correlations between the two photons in emitted photon pairs for some values of parameters, and the proposed research program can be readily extended to study these effects. In fact, a high intensity source of polarization-entangled photon pairs is in high demand for quantum information research, because a conventionally-used spontaneous parametric down-conversion has a very low efficiency. Therefore, in case of a positive outcome of these studies, the IOTA facility could become a source of polarization-entangled photons and attract applications in the area of quantum information and quantum cryptography.

To facilitate the entanglement or partial entanglement studies for the two photons in 1e2p events, we plan to deploy a diagnostics station based on the so-called Large Area Picosecond Photodetector (LAPPD). The LAPPD is being

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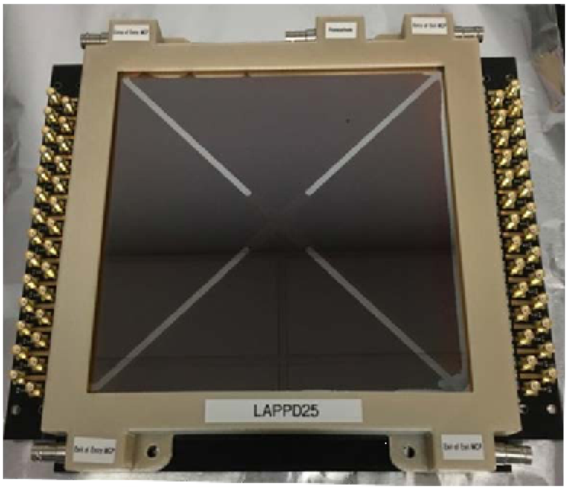

Figure 4: A photograph of the LAPPD detector, which features a 200×200 mm active area and 100 ps temporal resolution.

developed by the company Incom Inc. for high energy physics detector applications and is essentially a large-area, high-gain microchannel plate detector (Fig. 4). A real-time stripline readout enables single photon sensitivity, a large number of pixels, and a 100 ps temporal resolution in a single device [10]. In the most basic configuration (Fig. 5), the photons, generated by a single electron, circulating in the IOTA ring, will pass through the spectral filter and a collimator, to minimize the noise, and be subsequently magnified in a telescope enabling measurements of the photon flux angular distribution with a high resolution. Importantly, since the LAPPD has orders of magnitude better temporal resolution than IOTA revolution period, it will be possible to identify and isolate the 1e2p and even 1e3p events. Once the initial basic configuration is commissioned, we consider two additional measurements, where in one case the photons polarization is taken into account, and in the other, the telescope is augmented with the spectrometer along one axis, thus enabling double differential spectrum measurements.

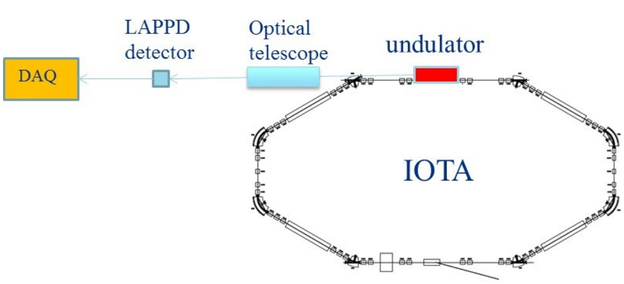

Figure 5: A schematic configuration of the basic set-up with the LAPPD diagnostics; a single electron passing through the undulator will generate photons which can be spectrally filtered to reduce noise, then magnified with an optical telescope, and detected with the LAPPD detector.

The system will be commissioned and calibrated in 1e1p mode, but the work will focus on the set of 1e2p experiments as envisioned above. A number of additional experiments with the same set up have also been considered, such as reconfiguring telescope and the collimator to study spatial correlations in the 1e2p events, which may shed some light on the transverse coherency and an extent of scale of the electron wavepacket. In addition, there is an interest in the precise measurements of the radiation reaction [11], which require a system that can trap a single electron for a very long time, and to which the proposed experimental set-up could be directly relevant. A higher order QED corrections effects, similar to those discussed in Ref. [12, 13], could also be investigated once the practical resolution limits at IOTA are fully understood.

SUMMARY

In summary, we have described a set of experiments, focused on studying various quantum aspects of undulator radiation, emitted by a single circulating electron in the IOTA ring at Fermilab. For the next generations of accelerator-based light sources and FELs it could be important to obtain insights into the quantum effects beyond first-order quasi-classical theory – it may lead researchers to an improved understanding of quantum properties of the undulator radiation and of future FELs that may operate in the quantum regime, light sources and single-photon instrumentation devices.

Finally, having well-defined initial conditions and time structure, single- and multi-photon radiation of a single electron in a storage ring may be a "standard candle" source for various kinds of quantum correlation and quantum optics experiments with the high-order field correlation function, such as, for example, quantum cryptography.

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