IOTA Working Group 2 Discussion Start-up Paper for Single Electron Quantum Optics (SEQO): Dynamics of Radiation "Formation Length" and Single Electron Wave Function Size Measurements in IOTA Ring

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A single electron is a fascinating entity.

First of all it is born somewhere – either from a thermionic metallic cathode or from a semiconductor struck by a laser photon or stripped out of a carbon nanotube by extremely high lectromagnetic fields via field-emission or whatever. There must be memory in the electron wave-function of the nature of its birth…..an imprint of all the potential well and other huddles that it had to conquer to get to be a free classical wave-packet, described by an ever-dispersing and broadening free wave-packet propagating in space. But we in our field of accelerators, always subject the electron to various bending and focusing forces via magnets, so they are always in a magnetic field and what's more, we focus them longitudibally via time-dependent electromagnetic RF fields. So the fundamental "quantum" nature of a "trapped" single electron moving in an external time-varying electromagnetic field is of interest in its own right, that has only been studied in a very preliminary way in the past (see experiments in Novosibirsk referred to later later in this paper).

Second, we learn in graduate school that a charge has hidden inside it "trapped" Weissacker-Williams virtual quanta of photons, which can be released by violent shaking of the charge. At the point of disentanglement of these "trapped" photons from the charge, what is the nature of the quantum-mechanical wave-function of the electron? Surely it is an "entanglement" of the "about-to-be-emitted" photon field or wave-function and the left-over "classical" charged electron! At the instant one begins to "see" the emitted light, the electron probably loses identity as a classical charged particle and cannot be seen. One sees the ever emerging photon wave-packet. However, it takes only a fleeting moment and very short length of space, known as the "formation length", within which the electron dresses up again in its virtual cloud of photons, when it is perceived as a classical charged particle again but then we do not observe the radiation, which has far "disentangled" from the quantum classical wave-function of the electron. Can we study experimentally as a function of time, i.e. in a 'time-resolved' fashion, the details of this process? Unfortunately the theory of QED, which is great in giving us amplitiudes of scattering etc., is of no help, and the related time-scales are very short indeed, for experimental direct detection. However, can we invent sophisticated correlation methods of emission of single photons from undulating electrons in a storage ring, from fdifferent places of emission, to probe deeper into this process? Afterall, atomic physicists use various electromagnetic traps and laser-cooled atoms in these traps to study quantum entanglement and disentanglement processes of atomic wave-functions from "bound" states to "free" states. Here in the IOTA ring, we have a giant single-electron trap and it is a unique instrument to explore this area in a fundamental way.

Third, even semi-classically, the electron wave function size and its behavior in accelerators is a longstanding problem that does not yet have a solution yet. Simple quasi-classical estimates for the centroid motion were obtained long ago [1], but a theory for the wave function size has not been developed and it turned out to be too small to measure (see [2] and references therein). The reason for this could be that the electron wave function undergoes a continuous measurement process and its localization could be related to its collapse under acts of measurement. Or there are some other random processes that lead to the localization of the wave function. For next generations of electron machines it could be important to obtain insights into this problem—it may lead researchers to new physics of radiation, particle dynamics, etc.

The first dedicated experiments were started in Novosibirsk about two decades ago and described in [2, 3, 4, 5, 6]. The experiments showed that the wave function of an electron in a storage ring is much localized, and its motion is similar to the motion of a classical particle with random kicks without any sign of phase space dilution due to RF potential well nonlinearities.

The experiments were performed in the VEPP-3 storage ring with a single circulating electron [3] and the light from an undulator that was detected by photomultipliers. The standard Brown-Twiss intensity interferometer scheme used a splitter to send the photons to two photomultipliers. The basic idea to measure the longitudinal wave function size was to detect two photons by different photomultipliers during one passage of an electron through the undulator and the rms difference in time, multiplied by velocity of light, was supposed to give the wave function size. Unfortunately, the photomultipliers were slow—their response time (called the dispersion in [3]) was around 160 ps. The signal time difference from two photomultipliers was well within this number, therefore it was concluded that the wave function size is much shorter than that resolution. This experiment characterized the fourth-order correlation function of the radiation field, and quantum effects could be seen in it. Another high-order correlation experiment was the measurement of the photon arrival times during a long time interval. Fitting of amplitude and phase of synchrotron oscillation gave the electron trajectory in the longitudinal phase plane. The trajectory appeared to be continuous (with tens-picosecond precision) and chaotic, demonstrating the Brownian motion in a phase plane. In contrast to the classical Brownian motion, which may be predicted in principle by knowing the motion of molecules, surrounding the Brownian particle, the electron chaotic motion is fundamentally unpredictable (at least, according to the standard quantum theory), and gives us a rare example of the true random process.

The IOTA ring will have undulators for the optical stochastic cooling experiments [7]. It is straightforward to repeat similar experiments with the VEPP-3 setup but with a much faster and advanced detection system—systems with a ~psec resolution are under development by Fermilab, ANL, and the University of Chicago [8]. It corresponds to a 0.3-mm wave function size for electrons. If it is shorter than this we have to use or develop a different technique for the measurement. Several groups around the world are loking into single elecxtron and single photon detection in much fastrer time-scales [9, 10, 11, 12 and 13]. Having well-defined initial conditions and time structure, the radiation of a single electron may be a "standard candle" source for various kinds of "quantum optics" experiments with the high-order field correlation function, like, for example, quantum cryptography and teleportation. The experimental and theoretical investigation of the stationary state of the electron in a storage ring is useful for the development of non-perturbative methods of quantum electrodynamics, and, in general, the foundations of the quantum theory.

The IOTA facility will offer a unique opportunity to carry out the proposed measurement of the electron wave function size. That research requires a dedicated storage ring (IOTA) and its operation with 100-200 MeV electrons. It cannot be carried out anywhere else as there are no existing electron storage rings in that energy range which can afford installation of special insertions (wigglers, etc.), and which offer special instrumentation needed to perform such measurement. In addition, the high availability of IOTA for the experiment is extremely advantageous.

In summary, the proposed experiments with wave function measurements and possible experimental exploration of time-resolved 'formation length' process of the "disentanglement" of the radiation field wave-packet from the charge and subsequent "entanglement" again with trhe charge to form a quantum wave-function defined classically , is practically an unknown territory with possibilities of scientific breakthroughs and the IOTA ring would be well suited to do these measurements.

Fourth, while we often talk about ultra-low emittance, high brightness electron sources, etc., electrons being "Fermions" and not "Bosons", it is natural to ask the question: Can we ever have "electron condensate" [14] or a "frozen" electron beam in the quantum mechanical sense?

A.1.1.1 References

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