Electron Wave Function Localization in Accelerators - S. Nagaitsev (University of Chicago/FNAL), Kwang-Je Kim (University of Chicago/ANL), Henry Frisch (University of Chicago) and Young-Kee Kim (University of Chicago)

One of the most fundamental questions of the 21st century is still unanswered: what is the quantum measurement process and its associated localization of the particle's wavepacket? The first answer to this question came from Bohr, who stated that the apparatus should be classical. This separation between classical world from quantum world (apparatus versus test system) was felt to be unnatural. Von Neumann considered an apparatus as macroscopic and postulated that it induces a collapse of the wave function (reduction/localization of the wavepacket), so his complete quantum mechanics consists of Schroedinger dynamics plus the collapse postulate. Modern experimental physics has very few relevant experiments to shed light on this subject. One such example is a single electron, trapped is a quadrupole Paul trap [1]. Similarly, we propose that a single electron in a storage ring presents a model of a single particle interacting with its environment and being registered via the quantum measurement process. Unlike the Paul trap with its electron in a close-to-ground energy state, an electron in a storage ring is never in a ground state, and in fact, has a very well-defined momentum (~100 MeV/c in our case), which would indicate that its wavepacket should be close to a plane wave and far from being well-localized.

The electron quantum wave function size and its behavior in accelerators is a longstanding problem that does not have a comprehensive solution yet [2]. Simple quasiclassical estimates for the centroid motion were obtained long ago [3], but a complete theory for the wave function size has not been developed yet and it turned out to be too small to measure experimentally (see [4] and references therein). The reason for this could be that the electron wave function undergoes a continuous "measurement" process via photon emission 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 (VEPP-3 ring) about two decades ago and described in [4, 5]. The experiments showed that the wave function of an electron in a storage ring is very 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 potential (rf) well nonlinearities.

These experiments were performed in a storage ring with a single circulating electron [4] and the light (single photons) from an undulator that was detected by photomultipliers. The standard Hanbury Brown-Twiss (HBT) intensity interferometer scheme used a splitter to send the photons to two separate 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 the speed of light, was supposed to give the wave function size. Unfortunately, the photomultipliers were slow – their response time was around 1 ns. 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, under construction at Fermilab, will have an undulator for various experiments. A ~100 MeV electron and an undulator with a ~cm period would produce visible-light photons. Modern methods of light detection enable detection of photons with high sensitivity, picosecond resolution and large event count. It is fairly straightforward to repeat similar experiments but with a much faster and more advanced detection system. Systems with a ~psec resolution are under development by Fermilab, ANL and Univ. of Chicago now. It would correspond to a 0.3-mm wave function size resolution for relativistic electrons. If it is shorter than this we have to use or develop a different technique for the measurement. 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 an 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.

As a follow-up, there up a number of opportunities to extend this research. For example, one can consider two physically different undulators with drastically different wave lengths and a study of time-domain correlations between the two photons of different energies. Also, one can imagine creating a double-well rf bucket for the longitudinal particle confinement, where one can study tunneling of a single electron. One can also study the entangled electron-photon pair by manipulating the photon and then forcing the electron to absorb this manipulated photon.

The FAST/IOTA facility at Fermilab 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 100-150 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 experiment with wave function measurements is practically an unknown territory in experimental accelerator physics. It offers many topics for graduate and under-graduate student research with possibilities of scientific breakthroughs.

References

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