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SINGLE-ELECTRON EXPERIMENTS AT THE DELTA STORAGE RING*

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Abstract

Scraping the beam in an electron storage ring while counting photons of synchrotron radiation is a well-known technique to produce a beam of a single or a few electrons which enables new experimental opportunities compared to standard accelerator physics. Synchrotron radiation is usually described as an electromagnetic wave in the frame of electrodynamics. The emission of photons by a single electron, on the other hand, reveals the quantum nature of synchrotron light. The statistical properties of photons contain additional information, which can be used for beam diagnostics purposes. The paper describes the experimental setup and first single-electron measurements at the 1.5-GeV synchrotron radiation source DELTA at TU Dortmund University.

INTRODUCTION

Single-electron operation of storage rings has been performed at several facilities in the past. Already in the 1960s, visitors of AdA in Frascati/Italy, the worldwide first e^+e^- collider, were shown synchrotron light from one electron, which was visible to the naked eye [1]. The stochastic nature of photons from a single electron was studied at VEPP-2 and VEPP-3 in Novosibirsk/Russia [2]. At BESSY and MLS in Berlin/Germany, radiation from a single electron is used by the Physikalisch-Technische Bundesanstalt (PTB) for metrology purposes [3], and recently, the motion of single electrons was tracked at the experimental storage ring IOTA of Fermilab in Batavia/USA [4]. Experiments with a single electron were also conducted at UVSOR in Okazaki/Japan [5].

Compared to traditional accelerator physics studies, single-electron operation opens up new opportunities in beam diagnostics and to study the quantum nature of synchrotron light. The knowledge of beam properties, such as the beam size or energy distribution, is usually deduced from the assumed dynamics of single particles under the influence of electromagnetic fields in a storage ring as well as the interaction of these particles with the residual gas and among themselves. These assumptions are rarely tested by observing a single particle directly. While a non-invasive study of single hadrons would be difficult, photons emitted by electrons in a dipole magnet or undulator can be easily detected using, e.g., a photomultiplier (PMT) or an avalanche photodiode. Classical electrodynamics describes synchrotron radiation quantitatively rather well as an electromagnetic wave [6], but does not explain the stochastic emission of quanta by individual electrons. Thus, the statistical properties of photons provide additional information beyond the classical treatment.

SINGLE-ELECTRON BEAM PREPARATION

The 1.5-GeV electron storage ring DELTA is operated by the TU Dortmund University as a synchrotron light source and for accelerator physics studies [7]. Starting February 2023, a new operation mode with a single or a small number of electrons was tested. With a revolution time of 384 ns, the current of one electron is 0.42 pA, while a typical beam current of 100 mA corresponds to 240 billion electrons circulating in the ring. The mean lifetime of a single electron cannot be determined in practice, but with radiation desorption and collective effects being absent, it is far beyond the typical beam lifetime, which is presently around 30 hours.

At beamline BL 4, single photons from the undulator U250 are directed via three flat Al-coated mirrors onto a PMT [8] in a dark box (Fig. 1). A circular aperture defines the off-axis angles over which the radiation is integrated (typically > 0.4 mrad). Filters and an additional aperture protect the PMT against excessive radiation. The PMT produces a 4-V signal sampled by a digital oscilloscope [9] every 10 ns over a period of 1 s, and the determined pulse rate is transmitted to the EPICS-based control system. The signal neither depends on the photon energy nor on the number of emitted photons.

To produce a single-electron beam, a low single-bunch current is first injected into the storage ring. Given the usual

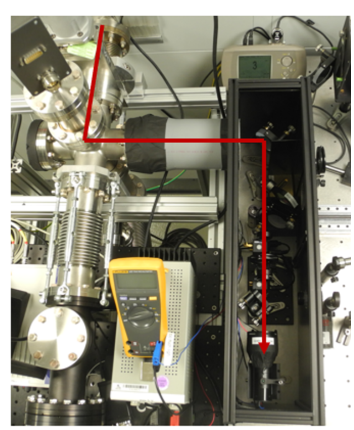

Figure 1: Photon beam path at beamline BL 4 with a PMT in a dark box (lid open). The first deflecting mirror near the storage ring is not shown.

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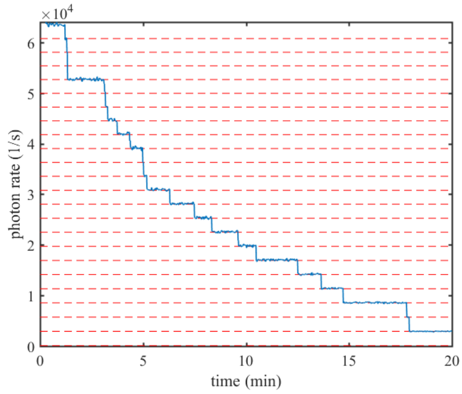

Figure 2: Evolution of the rate of synchrotron radiation photons from a single electron passing the undulator U250 while the electron beam is scraped. Each step corresponds to the loss of one electron.

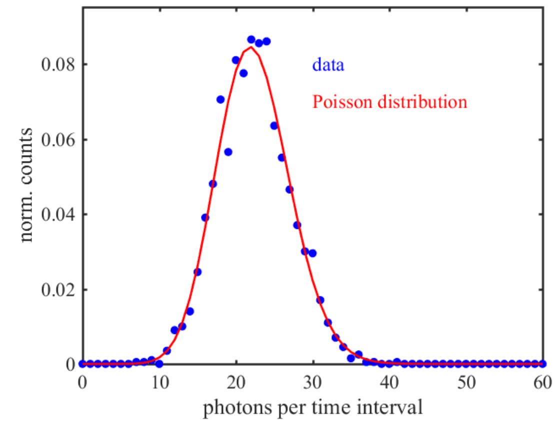

Figure 3: Distribution of the count rate of synchrotron radiation photons in equal time intervals (red line: Poisson distribution).

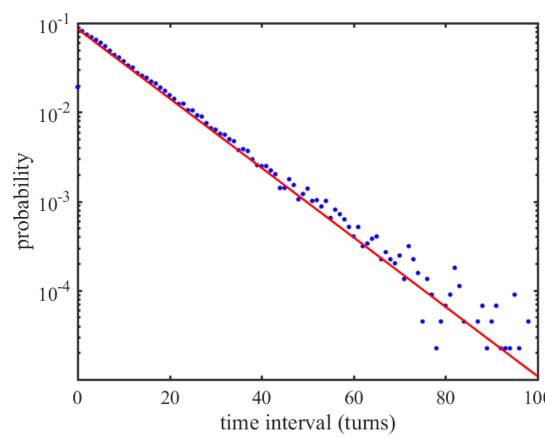

Figure 4: Observed probability of detecting two successive photons as function of the time interval between them (red line: expectation for independent events).

beam lifetime, it would take several weeks until only a single electron is left. Thus, an obstacle (a so-called scraper) is moved close to the beam in order to drastically increase the loss rate. At very low beam current, which is no longer detected by the usual current transformer, the PMT count rate is observed while successively removing filters. As shown in Fig. 2, the loss of each electron corresponds to a step in the photon rate. Retracting the obstacle at the right moment leaves the desired number of electrons in the ring. The steps in Fig. 2 are not equal. While the photon rate difference between 21 and 20 electrons amounts to 2700 photons/s, more than 2800 photons/s are detected from the last electron. This is because the PMT signal does not depend on the number of simultaneous photons, the probability of which reduces when decreasing the number of electrons. The background from dark counts and residual light is a few 10 photons/s.

The setup was first tested with a moderate single-bunch current and a strongly attenuated beam of synchrotron radiation. Figures 3 and 4 demonstrate the good agreement of the measured data with the statistical expectation for independent events.

UNDULATOR RADIATION

Extending the classical Larmor formula to the relativistic regime [10], the spectrum of undulator radiation is usually described by integrating the retarded Liénard-Wiechert potentials continuously generated by an electric charge along its trajectory [6, 11, 12]. Differences between the classical and quantum mechanical treatment are subtle and hard to observe experimentally. The emission of a photon by a single electron at approximately every 100th passage through an undulator is completely different from the classical description. Yet, the properties of the spectrum integrated over an extended period of time are expected to be the same, since each emitted photon "interferes with itself" [13]. This is a quantum mechanical phenomenon analogous to a diffraction experiment with low photon rate, in which the trajectory of the individual photon is not determined.

At DELTA, the spectral properties of undulator radiation using an electromagnetic undulator (U250 with 25 cm period length). were studied at wavelengths around 400 nm. Radiation from an electron beam of a few mA was detected using a conventional grating spectrometer, while photons from a single electron were accumulated with a PMT over 45 minutes. As expected, the spectral distributions agree within the experimental accuracy. In addition to the much larger statistical uncertainty in the single-electron case, systematic errors cannot be ruled out. For example, the orbit correction system requires a certain beam current and an unwanted shift of the trajectory in single-electron operation influences the observation angle and thus the shape of the spectrum.

It is remarkable that, unlike typical objects to study quantum mechanical phenomena, an undulator usually extends over several meters. This may allow to use standard accelerator techniques like radiofrequency and magnetic fields to manipulate non-classical properties. Once the data analysis

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is finalized, more details on single-electron results will be presented in a forthcoming paper.

SUMMARY

At the electron storage ring DELTA, several experiments with a single electron were performed. The scraper parameters and the photon count rate from a PMT are integrated in the control system. Thus, it will be easy to generate a single-electron beam with an automated procedure, if this mode of operation is employed more often in the future.

ACKNOWLEDGEMENTS

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