UNDULATOR RADIATION FROM A SINGLE ELECTRON IN A STORAGE RING*

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Abstract

Low-intensity interference experiments in the time domain have been undertaken by measuring the spectral distribution of synchrotron light from a single relativistic electron in a storage ring. In an undulator, an electron emits light from different magnetic poles leading to a spectral interference pattern - in close analogy to the angular distribution of light behind spatially separated slits. Experiments at the electron storage rings DELTA in Dortmund, Germany, and UVSOR-III in Okazaki, Japan, show directly that the spectral distribution of accumulated synchrotron light from a single electron is essentially the same as the spectrum from a beam of many electrons. While the latter is usually explained by interference between light waves emitted at different undulator poles, the single-electron experiments demonstrate that the photon source point is delocalized over several meters.

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 world's 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 routinely used by the Physikalisch-Technische Bundesanstalt (PTB) for metrology purposes [3]. The motion of single electrons was tracked at the experimental storage ring IOTA of Fermilab in Batavia, USA [4].

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 tube (PMT).

Classical electrodynamics describes synchrotron radiation with a high degree of precision as an electromagnetic wave [5], 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. A conceptional difficulty arises when a single electron emits only one photon after passing an undulator ~ 100 times. Radiation from a particular magnetic pole would result in a broad spectrum, while a source point delocalized over the whole undulator would lead to a spectrum described by $\sin^2 x/x^2$, a squared sinc function with $x \equiv \pi N_\mathrm{U}(\lambda_0/\lambda - 1)$, where λ_0/λ is ratio of central undulator wavelength and observed wavelength, and N_U is the number of undulator periods [6, 7]. The latter case is a temporal analogy to a photon passing multiple spatial slits with interfering probability amplitudes. To make the analogy to a classical double-slit experiment [8] even more apparent, consider two undulators in an optical-klystron configuration, i.e., tuned to the same wavelength λ_0 with a magnetic chicane between them [9, 10]. Here, two consecutive radiation pulses with longitudinal separation $R_{56}/2$ are produced, and their spectrum with interference fringes reads

$$P_\mathrm{OK}(\lambda) = 2P_1(\lambda)\left\{1 + f\cos\left[2\pi\left(N_\mathrm{U} + N_\mathrm{D}\right)\frac{\lambda_0}{\lambda}\right]\right\}, \quad (1)$$

where $P_1(\lambda)$ is the power spectrum of a single undulator, $N_\mathrm{D} = R_{56}/(2\lambda)$, and a factor $f < 1$ reduces the fringe visibility due to nonzero electron energy spread and emittance.

This paper presents results from two synchrotron light sources, UVSOR in Okazaki, Japan [11], and DELTA in Dortmund, Germany [12], where spectral information from single electrons was obtained using two different methods.

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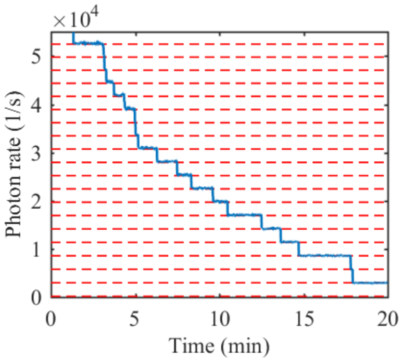

Figure 1: Photon rate (blue) while scraping the beam down to a single electron in the DELTA storage ring. Each step (red dashed lines) corresponds to the loss of one electron.

SINGLE-ELECTRON BEAMS

Producing a single-electron beam typically starts by injecting a low single-bunch current into the storage ring. Given the usual beam lifetime, it would take several weeks until a single electron is left. Thus, an obstacle, a so-called scraper, is moved close to the beam which drastically increases the loss rate. At a beam current too low to be detected by a current transformer, the photon rate can be observed while successively removing filters. As shown in Fig. 1, the loss of each electron corresponds to a step in the photon rate measured by a PMT. Retracting the scraper at the right moment leaves the desired number of electrons in the ring. Since the PMT signal does not depend on the number of simultaneous photons, the steps in Fig. 1 are not equal but slightly increase with decreasing number of electrons. The background from dark counts and residual light is a few 10 photons/s. 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 usual beam lifetime.

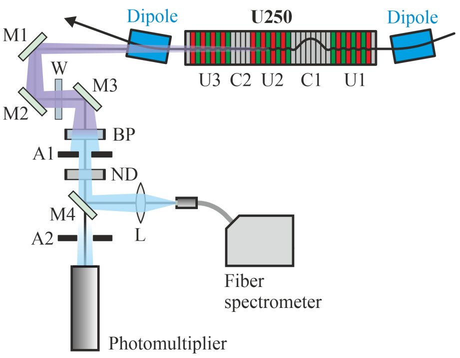

Figure 2: Experimental setup at DELTA. Synchrotron radiation from undulators (U1, U2, U3) passes a vacuum windows (W), mirrors (M), apertures (A), a bandpass (BP) and a neutral-density filter (ND). A fiber spectrometer records data from a 2-mA electron beam while photons from a single electron are counted using a PMT (ND, M4, A2 removed).

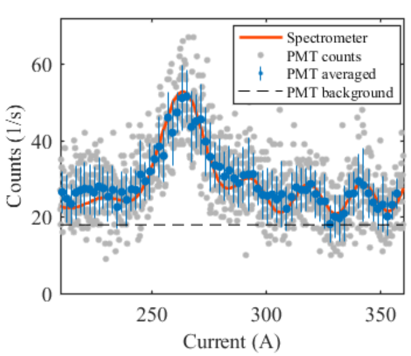

Figure 3: Synchrotron radiation intensity after passing a 400-nm bandpass filter while scanning the coil current of an electromagnetic undulator at the DELTA storage ring. Gray: PMT count rate from a single electron. Blue: Average PMT rate and standard deviation within current intervals of 2 A. Dashed line: Average PMT background rate. Red: Spectrometer data with 2 mA electron current normalized to the PMT counts above the background.

EXPERIMENT AT DELTA

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 [13]. Operation with a single or a small number of electrons was tested since 2023 [12]. With a revolution time of 384 ns, the current of one electron is 0.42 pA while a beam current of 2 mA corresponds to $4.8 \cdot 10^9$ electrons circulating in the ring.

At beamline BL 4, radiation from the electromagnetic undulator U250 is reflected by a water-cooled Al-coated copper block (M1), passes a vacuum window, and is directed by further mirrors (M2-M4) either to a fiber spectrometer [14] or onto a PMT [15] in a dark box (Fig. 2). A circular aperture defines the angles over which the radiation is integrated (±0.4 mrad). Neutral-density filters and an additional aperture protect the PMT against excessive radiation. A digital oscilloscope [16] samples the 4-V PMT signal, which neither depends on the photon energy nor on the number of simultaneous photons.

Since the PMT yields no spectral information, an indirect method was employed. Radiation passing a 400-nm bandpass filter (BP in Fig. 2) was detected while varying the current of the undulator coils, thus shifting the spectrum relative to the 10 nm wide filter window. This procedure was first applied to a 2-mA beam recording data with the fiber spectrometer, and then repeated for a single electron using the PMT with mirror M4 removed. Even though the spectral shape changes slightly during the scan, a comparison between the two measurements demonstrates that there is no significant difference in spectral content. This is true for a single undulator (Fig. 3) as well as for the case of an optical-klystron. Minor deviations can be attributed to experimental shortcomings such as variations of the beam orbit (which cannot be controlled in the single-electron case) or hysteresis of the undulator magnets when repeating the measurement.

EXPERIMENT AT UVSOR-III

UVSOR-III at the Institute of Molecular Science in Okazaki, Japan, is a 750-MeV synchrotron light source. Single-electron experiments were performed at beamline BL1U [17, 18] using one or two permanent-magnet APPLE-II undulators with 10 periods, each tuned to 355 nm in horizontal linear polarization, and a 3-magnet chicane between them. After a 90-degree deflection in vacuum and passing a window into air and an aperture (acceptance ± 0.3 mrad), undulator radiation reaches a grating (830 grooves/mm) and first-order diffraction is captured by a cooled CCD camera [19] with a (355 ± 30) nm bandpass filter to reduce background light. Zero-order radiation was detected by a PMT, as shown in Fig. 4, in order to prepare the single-electron beam. In another measurement, the fundamental undulator wavelength was varied and zero-order radiation was recorded by a fiber spectrometer [20] while CCD images were taken. By a linear fit to the spectral maximum, a calibration of horizontal CCD pixels in terms of wavelength was obtained. For a 0.1-mA beam (10^8 electrons), spectra were recorded by the CCD camera with an exposure time of 1 ms without significant background. In the case of a single electron, radiation was collected over 3600 s with an extremely small signal-to-background ratio. However, subtracting a dark image with the same exposure time resulted in spectra with only a small residual background, which was empirically determined. Figure 5 shows an undulator spectrum after subtracting the dark image, integrated over vertical CCD pixels (gray dots) and averaged over 1-nm intervals (blue dots with root-mean-square variation). On top of a fitted residual background (dashed line), the 0.1-mA spectrum (red) is normalized to the single-electron data. As shown in Fig. 6, the signal-to-background ratio is 0.007 for the case of a single undulator. Again, there is an excellent agreement between the spectra from a single electron and a beam of many electrons.

CONCLUSIONS

Independent measurements at two synchrotron light sources using different methods show that the radiation spectrum from a single electron accumulated over typically one hour shows no significant deviation from spectra obtained with mA beams, as expected for undulator radiation consistent with coherent states [21]. Thus, the emission point of single photons is delocated over the whole length of the undulator or optical klystron. This result is a temporal analogy to an interference experiment with feeble light [22], where the path taken by each photon is uncertain. Remarkable features of the experiments presented here are (i) a delocalization over several meters, which is unusual for a quantum mechanical process, and (ii) the relativistic transformation converting the meter scale to a very wide range of wavelengths accessible by synchrotron radiation, from infrared light to the X-ray regime. Thus, there is a potential to study quantum phenomena like delayed choice, decoherence, and entanglement [23] using standard accelerator technology.

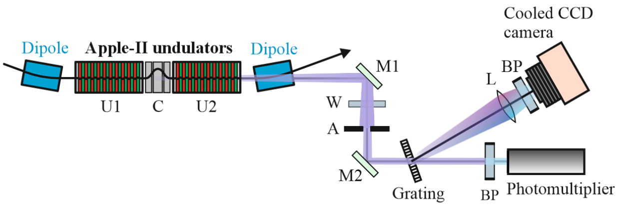

Figure 4: Experimental setup at UVSOR-III. Synchrotron radiation from undulators (U1,U2) passes a vacuum window (W), mirrors (M), an aperture (A), and bandpass filter (BP). Spectra were recorded by a cooled CCD camera. The PMT was employed to prepare the single-electron beam.

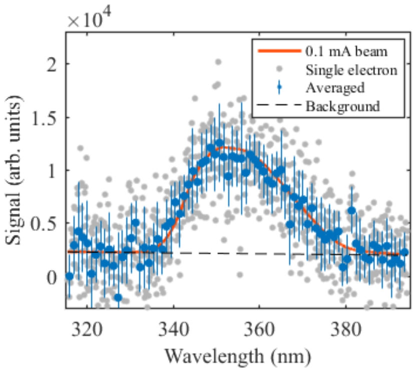

Figure 5: Spectrum of an undulator at UVSOR-III. Gray: Single-electron data averaged over vertical CCD pixels as function of wavelength after subtracting a dark image. Blue: Average of single-electron data and standard deviation within wavelength intervals of 1 nm. Red: Spectrometer data for a 0.1-mA beam normalized to the single-electron spectrum above background (dashed line).

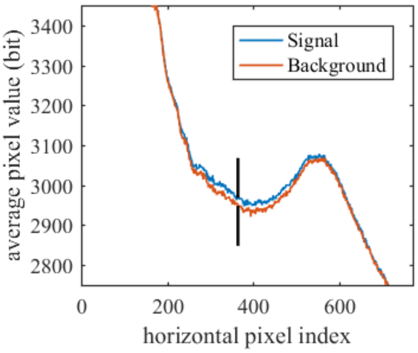

Figure 6: Blue: Average of vertical CCD pixel values as function of the horizontal pixel index (representing the wavelength axis) integrated over one hour for a single electron. Red: Background from a dark image with the same exposure time. At the marker, the signal-to-background ratio is 0.007.

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