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OBSERVATION OF OPTICAL SYNCHROTRON RADIATION FROM ULTRA-LOW CHARGES STORED IN A RING OPERATING AT 425 MeV*

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Abstract

The initial observations of optical synchrotron radiation (OSR) emitted over millions of passes from a few electrons circulating in the Particle Accumulator Ring (PAR) at the Advanced Photon Source have been done with a digital CMOS camera and a synchroscan streak camera operating at 117.3 MHz. The discrete changes of integrated counts in the CMOS image region of interest are ascribed to single electron steps at ~3500 counts per e^-. Circulations of a single electron at 375 MeV and at 425 MeV were demonstrated in the 12 bit digital FLIR USB3 camera images. The Hamamatsu C5680 streak camera operating at the 12th harmonic of the fundamental revolution frequency at 9.77 MHz was used to measure the bunch length from 0.5 nC circulating charge down to tens of electrons or < 10 aC. The latter cases were performed with 6 ps temporal resolution for the first time anywhere, to our knowledge. We report a preliminary effective bunch length of 276 ± 36 ps for 57 electrons (9.1 aC) stored based on a fit to a single Gaussian peak. The results will be compared to the standard zero-current model for the ring.

INTRODUCTION

Investigations into the probability of photon emission via the optical synchrotron radiation (OSR) mechanism from single electrons circulating in small storage rings have been done with spatially-integrating and light-intensity-monitoring photo multiplier tubes (PMTs) or photodiodes in the past [1, 2] and more recently with PMTs and digital CCD cameras [3]. These gave the intensity effect vs stored electron number and transverse size. However, mapping of the longitudinal distribution of photons emitted by a few electrons circulating in a ring has only been done at the 10 ns level [1–4].

We employ for the first time a synchroscan streak camera that is phase locked to 117.3 MHz, the 12th harmonic of the fundamental revolution frequency at 9.77 MHz of the Particle Accumulator Ring (PAR) at the Advanced Photon Source (APS). This provided temporal resolution of about 6 ps on the slowest streak range. In this case electrons circulate at 1/12th the streak camera vertical deflection frequency so no turns are missed, and the phase locking of the instrument to the radiofrequency (rf) means the camera phase is nearly the same to a few ps over hundreds of seconds. The streak camera sees every turn, and its phosphor screen integrates the arrival times of the photo-electron events on the deflection axis (one photon is emitted per electron per 137 turns, the reciprocal of the fine structure constant α). The readout CCD sensor accumulates the phosphor image over 33 ms, and the analogue image is then readout at 30 Hz and digitized.

We also obtained digital CMOS camera images for the single electron emissions averaged over the acquisition range of 0.1–10 s on the chip, as demonstrated by the discrete or quantized steps in the integrated intensity of the OSR-based beam image over 97.7 million turns. These data provided the critical online assessment of the number of stored electrons in the ring in parallel with the streak camera studies.

EXPERIMENTAL ASPECTS

The APS Accelerators

The schematic of the linac and PAR is shown in Fig. 1 [5]. The small ring is designed to accumulate charges injected from the S-band linac which can operate at up to 30 Hz macropulse rate. Usually, the thermionic cathode rf gun is used to generate a short ~10 ns pulse train of 28 micropulses at 2.86 GHz. Operations at a 30 Hz rate allow the generation of 1–1.8 nC per macropulse. This is far more than we need, so for the low-charge studies up to 5 beam profile screens were inserted in the beam line to attenuate the number of electrons actually captured in the PAR. As we stepped in the screens, we compensated for the input signal loss in the digital camera with increased exposure times from 100 µs up to 10 s. We roughly demonstrated an ultra-low charge monitor operating at 6 orders of magnitude below the rf BPM sum signal monitor used normally as a beam intensity monitor. These experiments were done at 375 MeV in the July 2019 injector studies period and 425 MeV in the November 2019 studies period.

The Optical Diagnostics

The OSR was transported from the PAR West dipole magnet source through a quartz window and via Al mirrors out of the accelerator enclosure up to a shrouded optics table on the mezzanine above [6]. This configuration (Fig. 2) provided access to the detectors in use, the digital CMOS camera and the Hamamatsu C5680 streak camera. (The PMT on the East dipole source was not optimized for these tests, but it did provide some medium-intensity level data.) The OSR signal was split by a mirror that was inserted halfway into the light path. Approximately half of the signal went to the digital camera and half to the Hamamatsu C5680 streak camera with an UV-IR transmitting input optics and S20 photocathode. This camera's vertical sweep unit was phase

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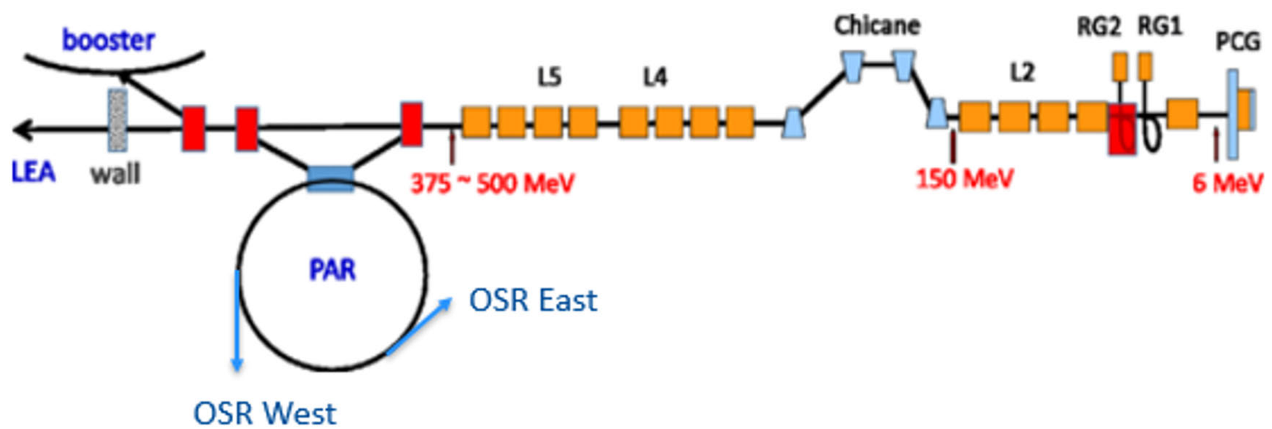

Figure 1: Schematic layout of the APS linac and PAR injector chain. (Adapted under Creative Commons license CC-BY 4.0 from Ref. [5]).

locked to the 117.3 MHz sine wave input that was amplified in the synchroscan unit to generate the sinusoidal sweep voltage. Arrival times of the different photons from the different turns were synchronously summed, giving the time-averaged x-t images. The image shape and projections of these two planes provide the unique information on several-electron OSR emission.

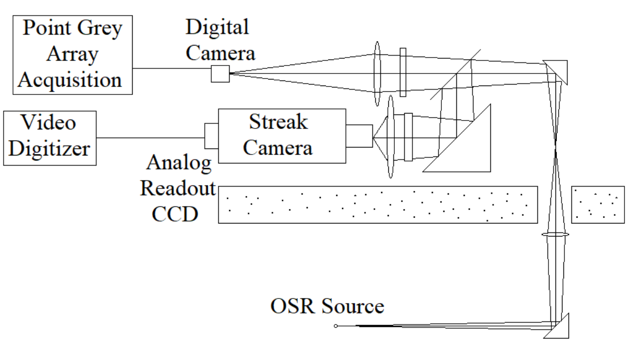

Figure 2: Schematic illustration of the PAR West optics table with the CMOS camera and the streak camera.

The 12-bit digital CMOS camera was a FLIR Grasshopper3 USB3 camera. It allowed designations of a region of interest (ROI) and output of the integrated counts. This was very useful in tracking the intensity changes with electron number and establishing the 3500 counts per e- steps in the ROI online. The high quantum efficiency (~58% at 500 nm) for visible wavelengths was advantageous for these studies. The calibration factor was 31.8 µm per pixel (in both x and y axes).

EXPERIMENTAL RESULTS

Initially, we considered a PMT to look for OSR intensity changes at low charge. This proved to be problematic at about 100 fC. The digital camera, however, was able to track the average ROI intensity signals down to the few-electron range ($Q \approx 1$ aC) and even to a single electron stored. The streak camera data in focus mode and streak mode also showed results at the 10 electron level for the first time, to our knowledge.

Digital Camera Data

The experimental CMOS results were exemplified by the recognition of the discrete steps in the intensity as we lost individual electrons as shown in Fig. 3. This plot shows the intensity changes in the ROI in the 4 to 1 electron (s) stored cases. Insertion of ND 5.0 filters at selected times including at 03:57 and 04:19 checked the baseline which did drift over time. The 1 e$^-$ intensity level at 04:25 is bracketed by the ND test at 04:19 and the purposeful dump of the single electron at 04:28. The single electron was stored for ~15 minutes, or 8.7 billion turns at 375 MeV.

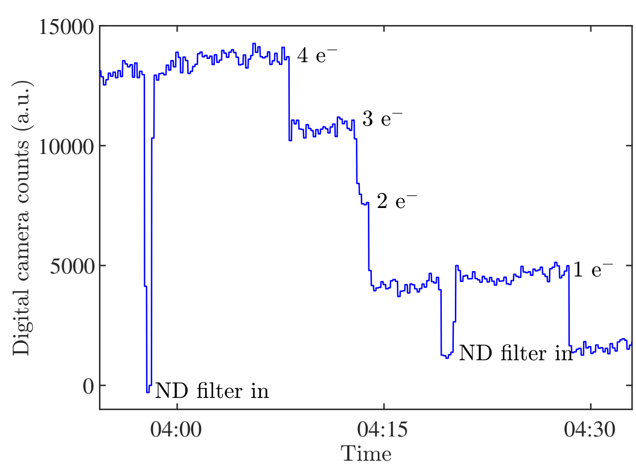

Figure 3: OSR intensity in the west synchrotron light monitor (PAR:SLM1) versus run time. The discrete intensity steps are at 3,500 counts/e$^-$. At 04:19, the ND filters were inserted briefly to show the background level while a single electron was stored. This electron was purposely lost at 04:28.

Another way to assess the digital CMOS data involved using the images obtained during the run for different electron numbers and subtracting the background image obtained

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with zero electrons. Examples are shown in Fig. 4 where the background subtracted images for 4, 3, 2, and 1 electron are shown. The 2D image is shown in all four cases.

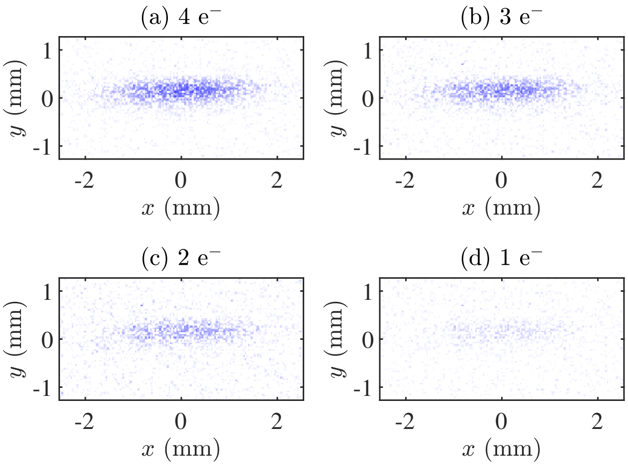

Figure 4: A set of 4 CMOS camera 2D images. These are background subtracted for the four stored-electron-number cases indicated, 4 to 1. This is at 375 MeV.

Streak Camera Results

The streak camera results are partly constrained by the Hamamatsu fiber-optically-coupled analogue readout CCD camera that was Peltier cooled to 0°C to reduce dark current and used with an 8-bit video digitizer running at 30 Hz. We acquired a reference nominal-charge streak image with 0.32 nC stored using the streak range 4 (R4) with ~1.5 ns time coverage and 3.0 ps per pixel temporal calibration factor. The calibration factor was from the data sheet for this synchroscan unit. Figure 5 shows an example focus mode image (a) with a focus y-size of σ = 1.7 pixels in Fig. 5b. The entrance slit was opened so the small vertical beam size set the streak axis resolution limit. Fig. 6 shows the streak camera image and a measured bunch length of 124 ± 4 pixels or 372 ± 12 ps based on a fit to a single Gaussian peak, respectively. These are screen captures from the ImageTool MATLAB program [7]. This latter bunch length value is consistent with the zero-current bunch length for the PAR model at 425 MeV with the 12$^{\text{th}}$ harmonic rf powered on [8–10] and recent photodiode bunch length data [11].

We reduced the stored charge controllably by using the PAR injection kickers down to the single electron circulating. On the way, we obtained 100s of streak camera images at different charge levels. In Fig. 7 we show the accumulated image for 57 e$^-$ (< 9 aC) circulating. The fitted value to the projected time profile is 276 ± 36 ps, 25% lower than the observed 0.32 nC case in Fig. 6 and ~17% lower than the calculated equilibrium bunch length of 331 ps at 1 aC using the impedance model for the PAR at 425 MeV [12].

The high frequency noise in the images was addressed with a sliding 9-channel average routine available in the MATLAB processing program [7]. In Fig. 8a we show the raw temporal profile for 57 e$^-$ data compared to the smoothed

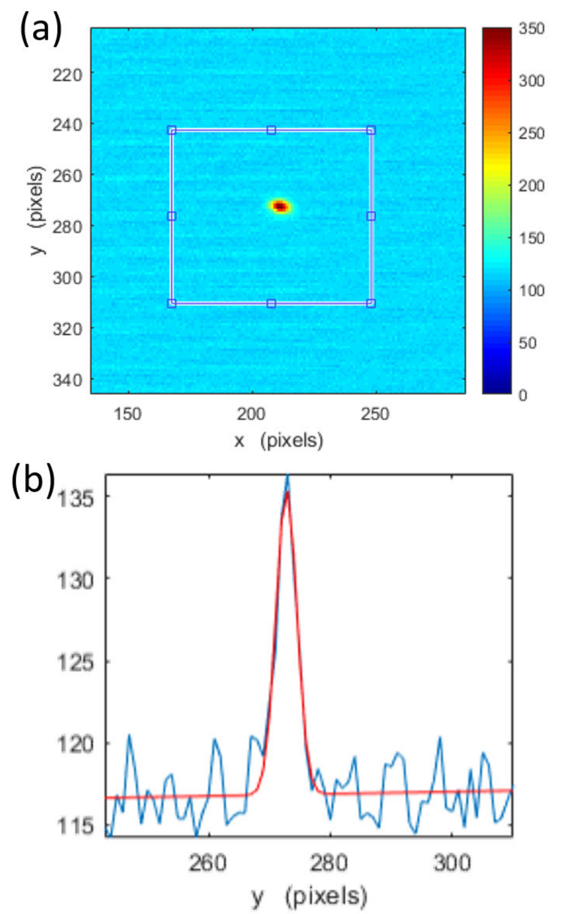

Figure 5: (a) Focus mode image and (b) projected time-axis profile with σ = 1.7 pixels at 0.32 nC.

background. This smoothing then was applied to both the data profile and the summed background image (200 images) as shown in Fig. 8b. It is clear the OSR data are far above the background, and there appear to be some residual localized structures. The interpretation of these is still to be done, although weak background noise bands are a candidate. This temporal profile is in principle the probability distribution of the emission of OSR photons over ~65 million turns. Localizations might occur in statistically starved conditions. This will be explored in the future using onboard averaging in the digitizer board to reduce the digitizing readout noise role. Improved noise filtering algorithms will also be considered.

SUMMARY

In summary, we performed initial investigations of OSR emissions from a few electrons stored in the PAR at 375 and 425 MeV with a digital CMOS camera and with a synchroscan streak camera. We measured a bunch length of 285 ps at 0.5 nC stored charge as a reference at 325 MeV and 372 ps at 425 MeV. We were able to identify OSR from a single electron stored using the CMOS camera and OSR from 10s of electrons stored using a streak camera for the first time. The latter bunch length for 57 e$^-$ stored was observed

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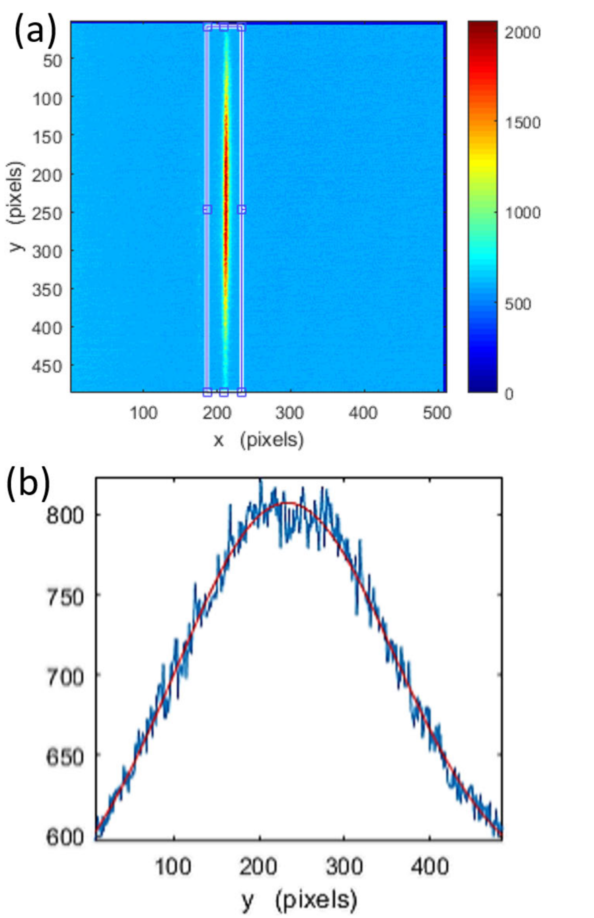

Figure 6: (a) Streak mode Range 4 image and (b) time profile with bunch length of 372 ± 12 ps at 0.32 nC. The vertical scale time range is 1500 ps.

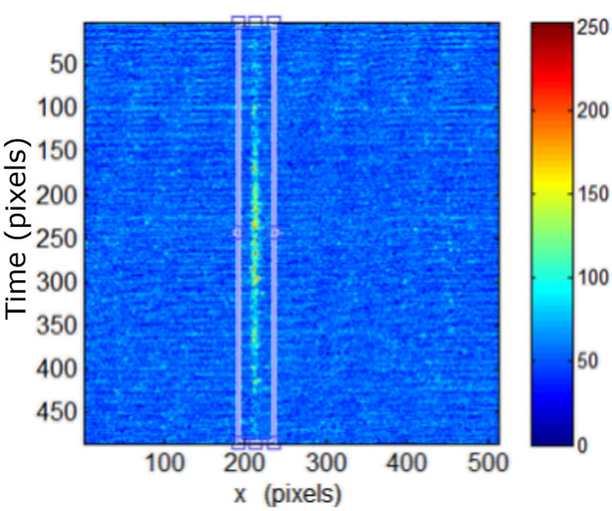

Figure 7: Streak camera sum image (200 images) at 425 MeV for 57 e⁻ circulating in the ring. The vertical scale time range is 1500 ps. The projected time profile with the single Gaussian peak fit gives the bunch length σ_t = 276 ± 36 ps. The digitizer background noise adds to the variance.

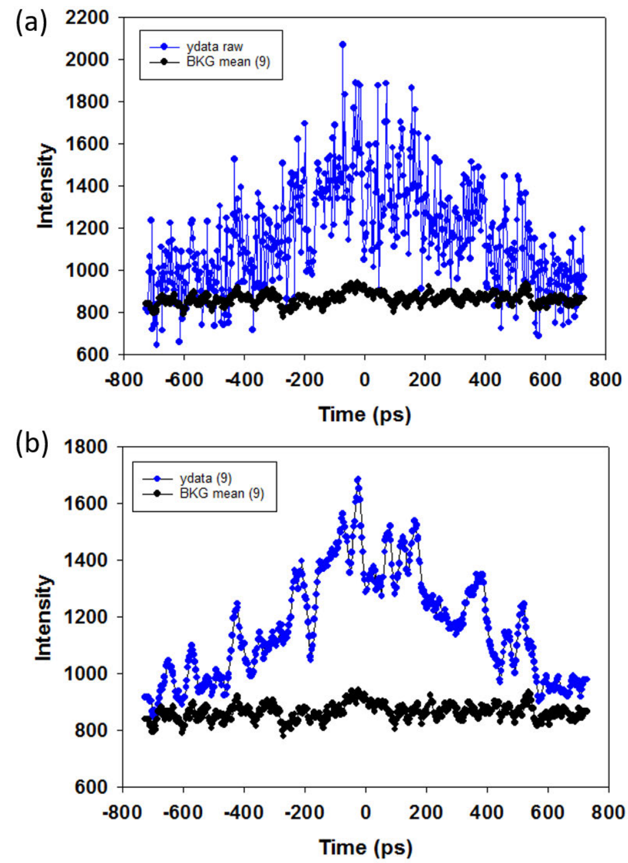

Figure 8: Comparisons of the 57 e⁻ data (a) y raw data vs. smoothed background and (b) smoothed data (blue) profile from Fig. 7 and the smoothed, independently summed background profile. A sliding 9-channel smoothing routine for the mean in MATLAB was used to reduce the fluctuations in both.

to be 25% shorter than the reference at 425 MeV. We are reviewing our results in the context of existing models on the PAR [12], OSR, and streak tubes. Further investigations and data processing are planned to elucidate the effect.

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