MEASUREMENTS OF BUNCH LENGTH IN THE ADVANCED PHOTON SOURCE BOOSTER SYNCHROTRON*

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Abstract

A bunch duration monitor (BDM) was installed at the end of a synchrotron light monitor (SLM) port in the Advanced Photon Source (APS) booster synchrotron. The BDM is based on a fast Hamamatsu metal-semiconductor-metal detector with nominal rise and fall times of 30 ps. Bunch length data is especially important as the bunch charge will be raised from 3 nC, used in the existing machine, to as much as 18 nC for APS-Upgrade operation. During preliminary high-charge studies, the SLM image is observed to move over a period of minutes, while the BDM signal intensity varies; the motion is likely due to thermal loading of the in-tunnel synchrotron light mirror. Work is underway to stabilize the position using a simple feedback system and motorized mirror mount, as well as a new synchrotron light mirror assembly with improved thermal load handling capability. The feedback system will maintain optical alignment on the BDM at an optimum position based on the SLM centroid location. The optical layout will be presented along with preliminary bunch length data.

INTRODUCTION

A second bunch length diagnostic, referred to as a bunch duration monitor (BDM), has been installed in the Advanced Photon Source (APS) booster synchrotron. The initial BDM diagnostic was installed in the APS particle accumulator ring (PAR) [1]. The new BDM detector and electronics are located outside of the booster radiation shield wall at the end of a synchrotron light monitor (SLM) optics line. Bunch length is important as we plan to raise the charge per bunch from 3 nC to 18 nC for the APS upgrade (APS-U) [2]. The BDM has been used to measure bunch length over the full cycle of the booster [3].

Recent measurements indicated growth in bunch length with charge were not in line with expectations. Further investigation showed the apparent growth in pulse duration was correlated with the input signal (light) levels rather than charge. In addition, during studies with high charge (>6 nC) and continuous injection (at 1 or 2 Hz) a loss of BDM signal with time was observed. This latter behavior is likely due to misalignment of the synchrotron light spot on the BDM caused by thermal effects from heating of the in-tunnel mirror.

EXPERIMENTAL ARRANGEMENT

The detection system is based on a Hamamatsu metal-semiconductor-metal (MSM) G4176-03 photodetector with quoted rise and fall times of 30 ps. The device can be biased with either positive or negative DC voltage. Peak power must be kept under 50 mW, otherwise, the device output begins to saturate and the bunch duration will appear to increase. The schematic in Fig. 1 shows the arrangement of the BDM detector-amplifier and SLM camera. A motorized mirror mount is used to adjust position on both the SLM and BDM with a picomotor hand pad; this will be converted to EPICS control.

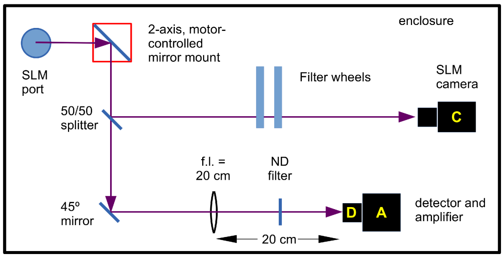

Figure 1: Schematic of the SLM and BDM optical paths.

BUNCH LENGTH MEASUREMENTS

Saturation Effects

BDM data were collected during high-charge studies in November 2021. Bunch charge was varied from approximately 7 to 12 nC. A plot of bunch duration versus charge is presented in Fig. 2. The data was collected 180 ms after injection corresponding to a beam energy of 5.6 GeV; the full acceleration interval in the booster is 225 ms. For normal APS operations, beam is extracted from the booster at an energy of 7 GeV. For APS-U the storage-ring energy is 6 GeV.

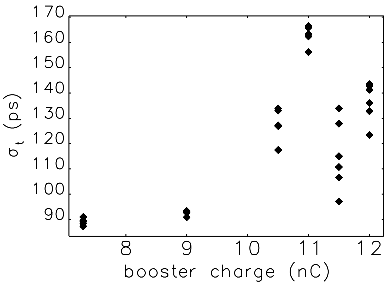

Figure 2: Booster bunch duration vs. charge.

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The measured duration did not behave as predicted nor as observed previously [3]. An rms bunch duration of 90-100 ps is expected at this time in the booster cycle over this range of charge. In Fig. 3, we plot the same duration data, this time versus the deconvolved peak voltage. In this case, a more coherent picture emerges. Saturation appears above a deconvolved amplitude of 8 V; this likely represents an instantaneous input power level of 50 mW. At the time of this study, the neutral density filter shown in Fig. 1 had an attenuation factor of 10 (ND 1.0).

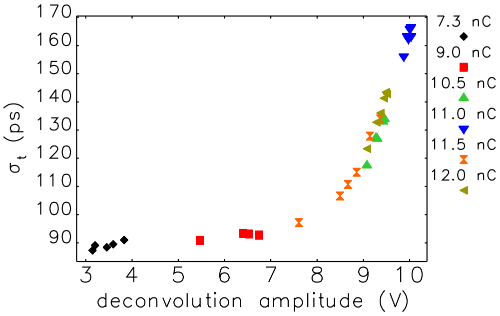

Figure 3: Booster bunch duration vs. deconvolved peak voltage (high charge).

During a subsequent study conducted in December 2021, additional attenuation was added, and charge in the booster was kept below 6 nC. An example of a raw BDM waveform at 2 nC in the booster and t=180 ms is presented in Fig. 4. A total of eight turns are captured in the 10-μs-long record; the turn period in the booster is 1.2275 μs. Each pulse is deconvolved; an average of the 8 deconvolved pulses is given in Fig. 5. Surprisingly, saturation behavior appeared in this data set as well. Figure 6 shows a similar pattern to that of Fig. 3; i.e., the bunch duration rapidly rises for deconvolution amplitudes above 8 V. Because of the lower charge, thermal effects are expected to be reduced. Saturation effects set in at 3 nC and above likely due to tighter focusing on the BDM chip. After this data set was acquired, neutral density filtering in the BDM line was increased to ND1.5 (x30 attenuation). The fact that Fig. 2 shows bunch lengths increasing and then decreasing with charge is most likely due to thermal misalignment as higher charge delivers more synchrotron energy to the in-tunnel mirror. The slightly misaligned photon beam reduces the peak light power level on the BDM chip to less than 50 mW, allowing a more linear response.

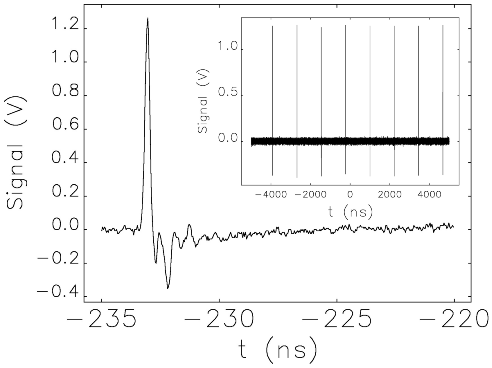

Figure 4: Single, raw BDM waveform at 2 nC and 180 ms and (inset) the full waveform.

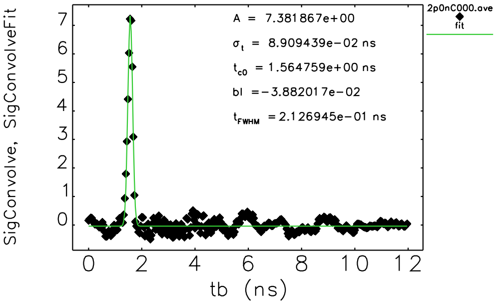

Figure 5: Averaged deconvolved pulse from the waveform presented in Fig. 4 along with Gaussian fit parameters. Ripples after the pulse are artifacts of the deconvolution.

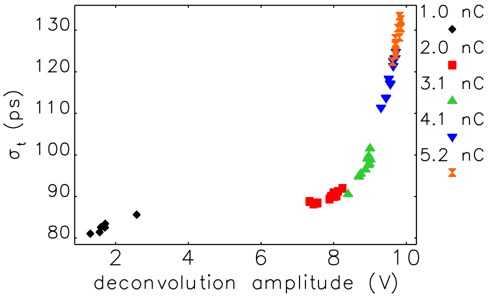

Figure 6: Booster bunch duration vs. deconvolved peak voltage (normal charge).

Signal Loss

Drifting of the SLM image centroid was observed, mainly in the vertical direction. The synchrotron light was manually aligned on the BDM during low-charge operation and the centroid location was recorded on the SLM camera. At higher charge, as the SLM image drifted and BDM signals levels dropped, we demonstrated that signals could be recovered when the SLM centroid was returned to the aligned origin coordinates using the motorized mirror.

The beam centroid was tracked over time with the SLM camera during continuous 2-Hz booster injection with 1.8 nC. The x- and y-drifts on a normalized pixel scale are presented in Fig. 7 to compare relative amplitudes. The motorized mirror was activated at approximately 11h48m to restore the BDM signal. The pixel size for this camera is 5.86 μm, with x and y array dimensions of 1920x1200.

Prior to using the SLM camera image to determine position, background noise must be subtracted. As shown in Fig. 8, the noise is substantial relative to the peak signal; the

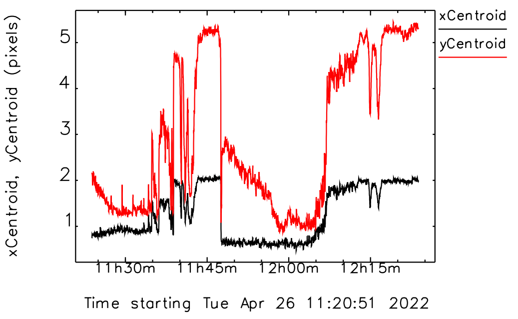

Figure 7: Beam centroid drift observed on the SLM camera during 2-Hz continuous injection with 1.8 nC. At approximately 11h48m, the motorized mirror was used to recover BDM signal levels.

image was obtained at a charge of 1.8 nC, 180 ms after injection. The inset shows the same data set with background noise subtracted. Gaussian fits to centerline x- and y-profiles of the background-subtracted image data set presented in Fig. 8 are plotted in Fig. 9.

The x-centroid of a 2-D, Cartesian distribution with light level, $I_{i,j}$ and background noise, $B_{i,j}$ may be calculated as,

$$< x + x_b >= \frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(I_{i,j}+B_{i,j})x_i}{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(I_{i,j}+B_{i,j})} \tag{1}$$

and similarly for y-centroid.

$$< y + y_b >= \frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(I_{i,j}+B_{i,j})y_j}{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}(I_{i,j}+B_{i,j})} \tag{2}$$

We wish to compare the centroid values calculated for the image data files with ($B_{i,j} = 0$) and without background subtraction so the centroid drift data in Fig. 7 can be corrected. The image data used to calculate the centroids were not saved, only the centroid values. The background noise levels essentially remained constant over the data acquisition period. In the extreme case where the noise dominates the signal ($B_{i,j} >> I_{i,j}$) over x- and y-regions of a detector defined by lengths L_x and L_y, $< x > \rightarrow L_x/2$ and $< y > \rightarrow L_y/2$.

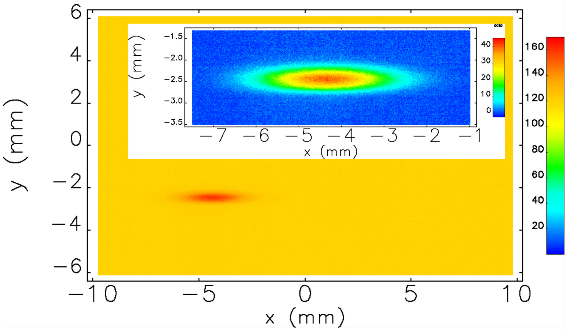

Figure 8: SLM image for 1.8 nC, 180 ns after injection; (inset) same data set with background subtracted.

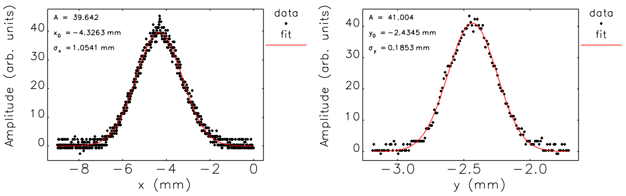

Figure 9: Gaussian fits to the background-subtracted centerline x-profile [left] and y-profile [right] shown in Fig 8.

DISCUSSION AND SUMMARY

We are addressing two issues: 1) saturation of the BDM detector from large synchrotron light levels and 2) motion of the focused spot on the detector's photosensitive area. The focused spot of synchrotron light on the BDM is small as is the active area of the detector itself (0.2 mm × 0.2 mm); this makes the BDM sensitive to fluctuations in spot position. We want to measure the position and size of the beam at the source point, but we also need to determine the location and spot size on the BDM chip. The distance from the BDM chip to the source point is 7.8 m and 5 m to the in-tunnel mirror. With a 0.2-m lens-to-detector distance (see Fig. 1), the magnification is approximately 39. The distance from source point to the SLM camera is 8.6 m. A vertical deviation of 2 pixels as seen from the SLM was enough to completely extinguish the BDM signal. This represents a position shift of approximately 400 µm, more than sufficient to misalign the BDM. The apparent beam drift seen in Fig. 7 is dominated by vertical motion. This observation is consistent with the way the in-tunnel mirror was designed and built. Thermal loading on the in-tunnel mirror is expected to yield beam vertical deflection.

We continue to develop the BDM diagnostic for the APS booster synchrotron. The diagnostic provides a straightforward method to measure bunch length. The BDM's sensitivity to large signal intensity and apparent beam centroid motion have been examined. Neutral density filtering has been used to address the former issue including use of a remotely-controlled filter wheel. With respect to beam motion, we demonstrated that alignment can be recovered using motorized mirror mount. We plan to incorporate this mirror into a feedback system based on centroid data from the SLM. In addition, steps are underway to test an improved in-tunnel mirror design that will be much less sensitive to thermal effects from synchrotron radiation.

ACKNOWLEDGEMENTS

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