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LONGITUDINAL PROFILE MEASUREMENTS OF PARTICLE BEAMS WITH DECONVOLUTION IN THE APS-U STORAGE-RING*

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Abstract

Accurate measurement of the longitudinal profile (bunch length) of particle beams is essential for evaluating and optimizing beam quality in the Advanced Photon Source Upgrade (APS-U) storage ring. Although Beam Position Monitor (BPM) are designed for position measurements, their signals also contain information about the longitudinal bunch distribution convolved with the BPM system transfer function. To recover the true bunch profile, we compute the BPM transfer function with CST Studio by driving the BPM model with a short Gaussian pulse that approximates a Dirac delta function, then combine measured transfer functions of accessories to form an end-to-end system response. This composite response is used as the deconvolution kernel to reconstruct time-domain bunch profile from measured BPM signals. BPM signals from the tuned Bunch Lengthening System (BLS) are analyzed in both time and frequency domains. Deconvolution yields longitudinal profiles and bunch lengths that will be compared with streak camera measurements for validation.

INSTRUCTION

Measuring bunch length or longitudinal profile of particle beam is essential for assessing and controlling beam quality in APS-U and helps interpret the measured beam lifetime. A near-term goal is to demonstrate bunch lengthening produced by the BLS [1, 2]. A streak camera provides direct profiles [3], but the optical transport line at APS-U was not fully ready.

The APS-U storage ring has 560 RF BPMs in 40 sectors (14 per sector) for position measurements. Raw broadband BPM button signals are available at selected locations which can be used for various developments. The broadband button signals, as measured at the end of long-haul cable on the mezzanine, contain beam longitudinal profile information filtered by the feedthrough, the cables and other components in the signal path. The transfer function of those components can be measured and simulated. By deconvolving measured BPM signals with this transfer function, the time-domain bunch profile can be reconstructed, and the bunch lengths can be evaluated.

Direct measurement of the APS-U RF BPM short-pulse response is difficult, so we obtain the BPM transfer function from CST Studio simulations and combine it with measured accessory responses to form the end-to-end system response [4].

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LONGITUDINAL PROFILE FROM DECONVOLUTION

By the convolution theorem, r(t) = h(t) * g(t) implies R(f) = H(f) G(f), so H(f) = R(f) / G(f), where g(t) is a short Gaussian bunch and r(t) is the simulated BPM response; h(t) is the end-to-end impulse response and H(f) = FFT[h(t)] is the transfer function. Figure 1 summarizes the workflow: simulation of the APS-U BPM transfer function (top), and deconvolution of measured BPM signals using that transfer function (bottom).

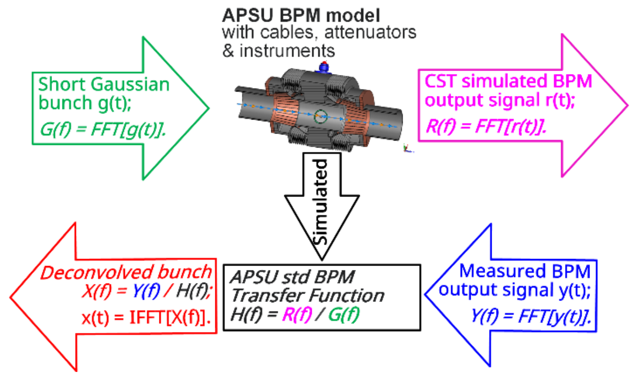

Figure 1: Workflow: simulate the APS-U BPM transfer function and deconvolve measured BPM signals to recover the input bunch profile.

Given a measured BPM waveform y(t) with Y(f) = FFT[y(t)] and known H(f), the input spectrum is X(f) = Y(f) / H(f), and the time-domain bunch profile follows from x(t) = IFFT[X(f)].

APS-U BPM SIMULATION AND END-TO-END TRANSFER FUNCTIONS

The APS-U transfer function was simulated with different wake lengths, e.g., s = 300 mm and s = 600 mm. Finite wake length introduces spectral ripple. A longer wake window reduces ripple at the cost of runtime. We use s = 600 mm as a tradeoff. Figure 2 shows the simulated transfer functions for a $\sigma_z = 2$ mm Gaussian bunch.

Composite end-to-end transfer functions were built for specific locations by combining the simulated BPM response with measured responses of cables, connectors, attenuators, and the instrument. Figure 3 compares S37CP1:BO [standard (std) BPM, 11.5 m SPF250 cable, 15 dB attenuator, oscilloscope, connectors] and S39AP0:TO (P0 BPM, 26 m SPF250 cable connectors), capturing location-dependent differences.

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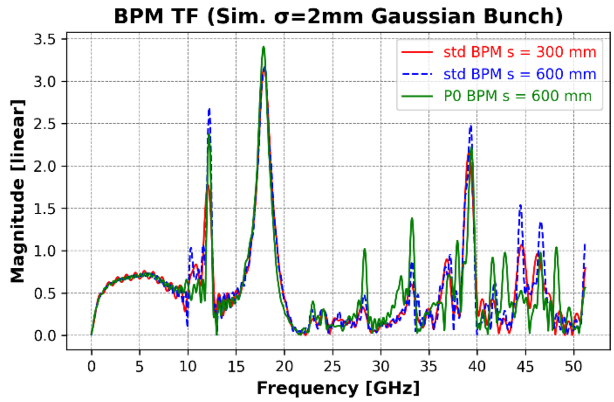

Figure 2: Transfer functions of APS-U std and P0 BPMs simulated for a Gaussian bunch with $\sigma_z = 2$ mm.

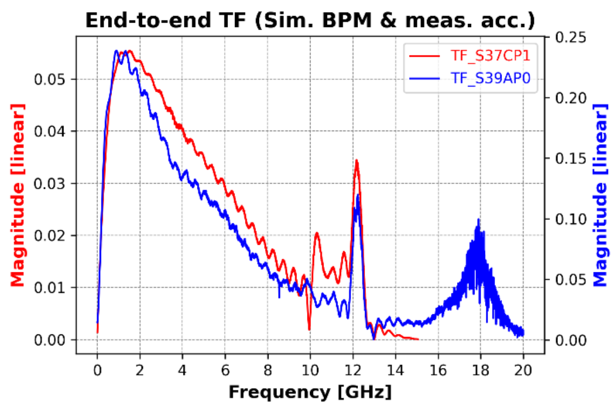

Figure 3: End-to-end transfer functions at S37CP1:BO and S39AP0:TO.

MENSUREMENTS AND RESULTS

BPM signals were recorded in the time domain at S37CP1:BO with a Tektronix DPO1254B oscilloscope (12.5 GHz bandwidth, 50 GS/s real-time sampling rate) and in the frequency domain at S39AP0:TO with an Aeroflex 3283 spectrum analyzer.

Deconvolution from Oscilloscope Time-Domain Measurements

Figure 4 shows single-bunch waveforms at 200 mA beam for several fill patterns at S37CP1:BO. Applying the S37CP1:BO transfer function to the Fig. 4 waveforms, the deconvolved longitudinal profiles in Fig. 5 show BLS-induced bunch lengthening [2].

Additional data were also acquired for the 324-bunch fill at 198 mA using a longer record, enabling turn-by-turn evolution to be visualized: Fig. 6 shows single-bunch waveforms plotted every 5 turns (interpolated by a factor of 100), and Fig. 7 the corresponding deconvolved profiles.

Deconvolution from Spectrum Analyzer Frequency-Domain Measurements

During the time-domain measurements at S37CP1:BO, simultaneous spectra were acquired at S39AP0:TO. Figure 8 shows broadband spectra envelopes from 0-10 GHz used for deconvolution with the S39AP0:TO transfer function; Fig. 9 shows the corresponding profiles.

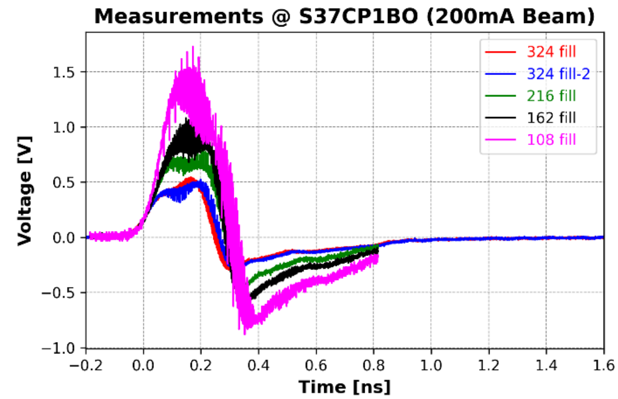

Figure 4: 200 mA beam waveforms for several fill patterns at S37CP1:BO (DPO1254B, equivalent-time sampling rate 2.5 TS/s; record length 5k points for 324-fill, 2.5k for others).

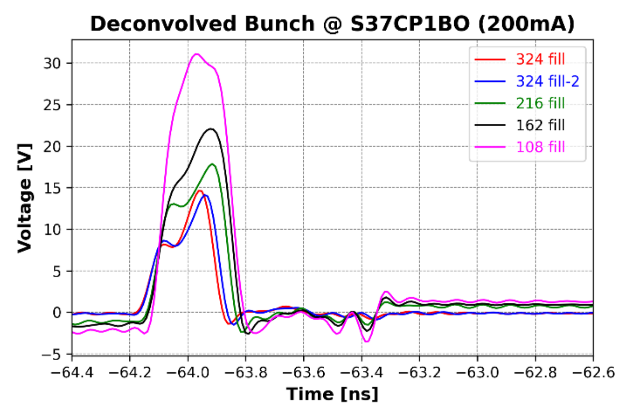

Figure 5: Deconvolved longitudinal profiles from the Fig. 4 waveforms using the S37CP1:BO transfer function.

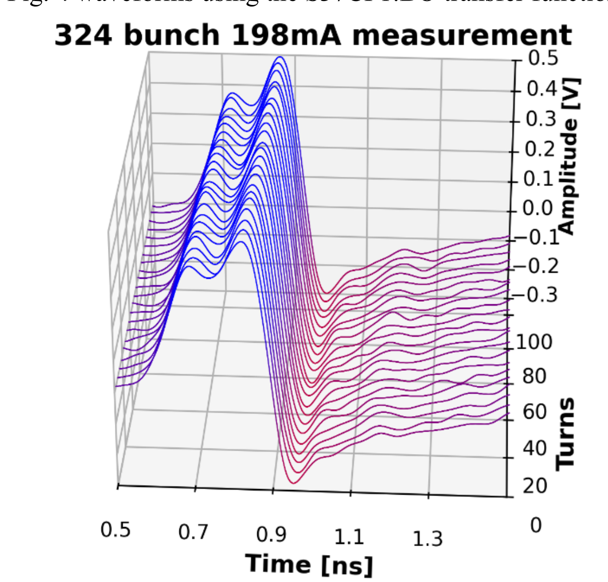

Figure 6: 324-fill 198 mA waveforms at S37CP1:BO measured at 25 GS/s with a 10 M-point record (~108 turns), interpolated by 100 and plotted every 5 turns.

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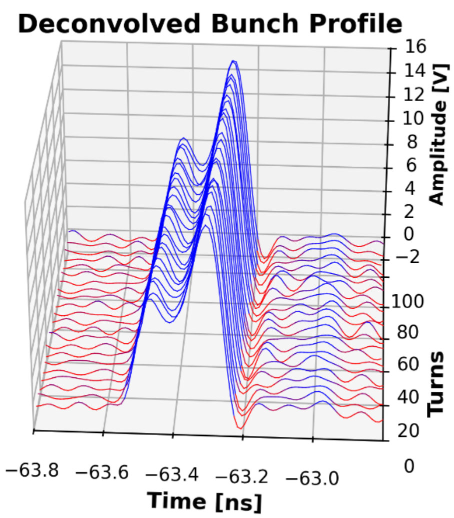

Figure 7: Deconvolved longitudinal profiles from the Fig. 6 waveforms using the S37CP1:BO transfer function.

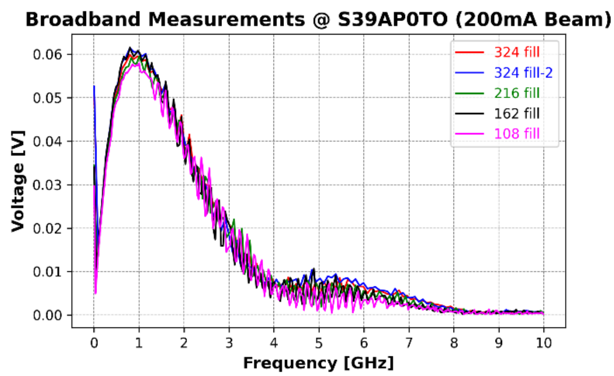

Figure 8: Broadband spectra envelopes (0 - 10 GHz) at S39AP0:TO (Aeroflex 3283) for several fill patterns.

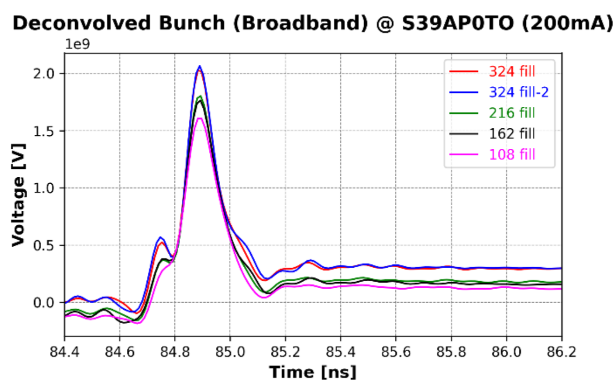

Figure 9: Deconvolved longitudinal profiles from the Fig. 8 spectra using the S39AP0:TO transfer function.

Narrowband spectra sampled at integer RF harmonics (Fig. 10) produce similar deconvolved profiles (Fig. 11).

The spectrum-derived profiles (broadband and narrowband) are mutually consistent but differ slightly from the time-domain results. The S37CP1:BO oscilloscope path offers higher usable bandwidth (12.5 GHz) and a shorter cable (~11.5 m) than the S39AP0:TO spectrum-analyzer path (7 or 10 GHz with an ~26 m cable), so time-domain deconvolution at S37CP1:BO is more reliable for the bunch profile.

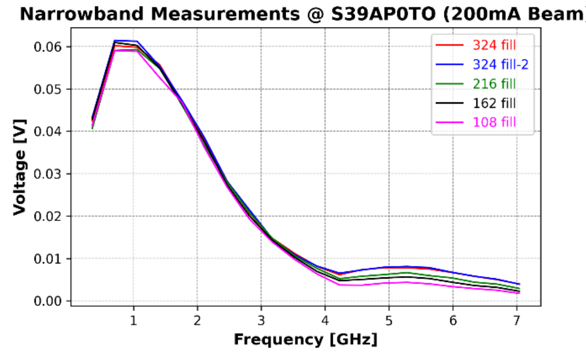

Figure 10: Narrowband spectra sampled at integer RF harmonics at S39AP0:TO (Aeroflex 3283).

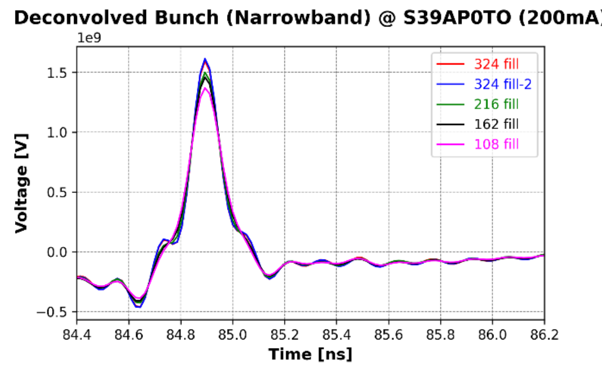

Figure 11: Deconvolved longitudinal profiles from the Fig. 10 spectra using the S39AP0:TO transfer function.

CONCLUSION

We reconstructed the electron-bunch longitudinal profile from BPM waveforms by deconvolving a composite transfer function that combines a CST-derived APS-U BPMs response with measured responses of accessories. The method is effective when the bunch spectrum lies mainly below ~12.5 GHz and reveals bunch lengthening produced by the BLS. Accuracy is limited by model fidelity, instrument bandwidth, cable loss and length, and trigger stability; to reduce loss an 8 m SPF250 cable has been installed at S37CP1. Validation includes comparison with streak camera measurements.

REFERENCES

[1] M. P. Kelly *et al.*, "Installation and commissioning of the APS-U bunch lengthening system", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2713-2716. `doi:10.18429/JACoW-IPAC2024-WEPS10`

[2] E. Louis, private communication, Mar. 2025.

[3] W. X. Cheng, B. Bacha, A. Blednykh, Y. Li, and O. Singh, "Longitudinal bunch profile measurement at NSLS2 storage ring", in *Proc. IBIC'15*, Melbourne, Australia, Sep. 2015, pp. 251-255. `doi:10.18429/JACoW-IBIC2015-MOPB083`

[4] CST Studio Suite, `https://www.3ds.com/productsservices/simulia/products/cst-studio-suite/ solvers/`