EXPERIMENTAL RESULTS FROM A "DIAGNOSTIC" PULSE FOR SINGLE-PARTICLE-LIKE BEAM POSITION MEASUREMENTS DURING ACCUMULATION/PRODUCTION MODE IN THE LOS ALAMOS PROTON STORAGE RING*

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Abstract

Beam position monitors (BPMs) are the diagnostic most used in setting up and documenting the Los Alamos Proton Storage Ring (PSR). One-turn injection can be approximated as single-particle injection with initial betatron position and angle (x_0 and x_0'). The turn-by-turn beam position data from single-turn injection allows measurement of the betatron tune, closed orbit (CO), and injection offset (x_0 and x_0' at the injection point). In accumulation mode, many turns are injected into the ring, the transverse phase space is quickly filled, and there is no coherent betatron motion. The injection offset, which determines the accumulated beam size and is very sensitive to steering upstream of the ring, is not measurable during accumulation. We review our approach for measuring the injection offset during accumulation, focus discussion on recent experimental results, and compare measurements of the betatron tune, CO, and injection offset in single-turn injection mode and in a "diagnostic pulse" mode.

MOTIVATION

The PSR BPMs[1] are bi-directional, stripline-type with electrode length ~37 cm (a quarter 201.25 MHz wavelength). The 201.25 MHz longitudinal beam structure, to which the PSR BPMs are sensitive, is imposed during acceleration and decoheres after ~30 turns in the PSR due to momentum spread and synchrotron motion.

Single-turn injection mode is used to document the PSR. We measure 30 turns of beam position data before the longitudinal beam structure decoheres, which is sufficient to fit the betatron tunes, CO, and injection offset.

Normally, the PSR operates in production mode, where ~1800 turns are accumulated. With the filled phase space, there is no coherent betatron motion in production mode, so the betatron tunes and injection offset can not be measured, but does yield the CO.

Aside from beam energy, the CO and betatron tunes are independent of machine operation upstream of the ring. The injection offset is very sensitive to steering upstream of the PSR, and we cannot measure this important operational parameter in production mode.

We develop an operation mode we call LBEG+ that enables us to document the PSR by measuring the betatron tunes, CO, and injection offset without affecting delivery of production beam[2]. The scheme is to inject a single turn (diagnostic pulse) on the same machine cycle as the production mode ~50 μs after the accumulated beam is extracted, see Fig. 1. The 50 μs between production beam and the diagnostic pulse allows the linac RF to recover from the beam-off transient, the injection bump magnets to set to zero, and for residual field in the PSR buncher to dissipate. The diagnostic pulse coasts in the PSR and is lost.

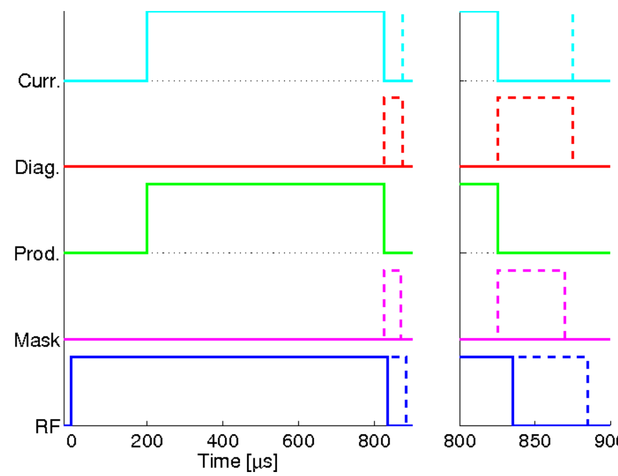

Figure 1: (Color) Timing scheme of one machine cycle for (from bottom to top) the linac RF gate (blue), RF system protect mask (magenta), production beam gate (green), diagnostic beam gate (red), and beam current in transport (cyan) for production (solid lines) and LBEG+ (dashed lines) modes. The right plot focuses on the end of the machine cycle.

LBEG+ AND SINGLE-SHOT MEASUREMENT COMPARISON

Operationally, the hope is for the LBEG+ scheme to replace the single-shot method for measurements of the CO, betatron tune, and injection offset during production. Thus, it is necessary for the CO, tune, and injection offset results measured via the LBEG+ scheme to be equal to the measurements taken in the single-shot scheme. We collected a set of BPM data in single-shot mode, and then collected another set of data in LBEG+ mode for comparison. In this section, we compare the LBEG+ and single-shot results for the CO, tune, and injection offset.

Thirty turns of betatron motion is digitized at each BPM.

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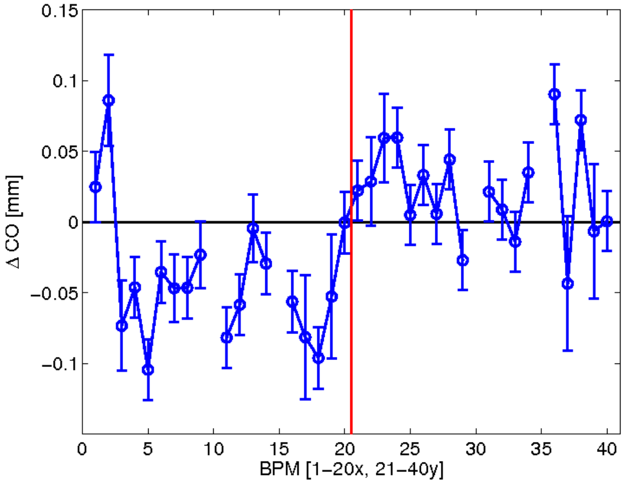

Figure 2: Difference in CO measurements using the single-shot and LBEG+ schemes with one rms uncertainty.

The beam position is fit with a cosine:

$$x_n = A\cos(2\pi\nu(n-1)+\phi) + O_{\text{ffset}} \tag{1}$$

where A, ν, n, ϕ, and O_{ffest} are the amplitude of betatron motion, tune, turn index, phase, and CO respectively. We also compare the fitted amplitude and phase from single-shot and LBEG+ measurement schemes.

In the comparison plots, we use an ORM BPM indexing convention where BPMs are 1-20 horizontal, BPMs 21-40 are vertical such that BPM 1 and 21 are the horizontal and vertical planes of the first BPM.

Closed Orbit Measurement

The CO describes the accumulated beam centroid position average. For minimum beam loss, we center the CO at all BPMs. The CO measurement results between single-shot and LBEG+ measurement schemes are very similar, Fig. 2, within three rms uncertainties with maximum deviation of 0.1 mm, which is within acceptable tolerance. We conclude the CO measurements yield the same result in both schemes.

Tune Measurement

The tune measurement describes the frequency of betatron oscillation. The tune measurements are very close, Tab. 1, within one rms standard deviation. We conclude that the tune measurement is the same in both single-shot and LBEG+ schemes.

Table 1: Comparison of the Measured Tunes from Single-Shot and LEBG+ Schemes with One RMS Standard Deviation

	ν_x	ν_y
Single-Shot	$0.1898 \pm 4\times10^{-4}$	$0.1870 \pm 2\times10^{-4}$
LBEG+	$0.1900 \pm 4\times10^{-4}$	$0.1870 \pm 2\times10^{-4}$
Difference	2.48×10^{-4}	-5.7×10^{-5}

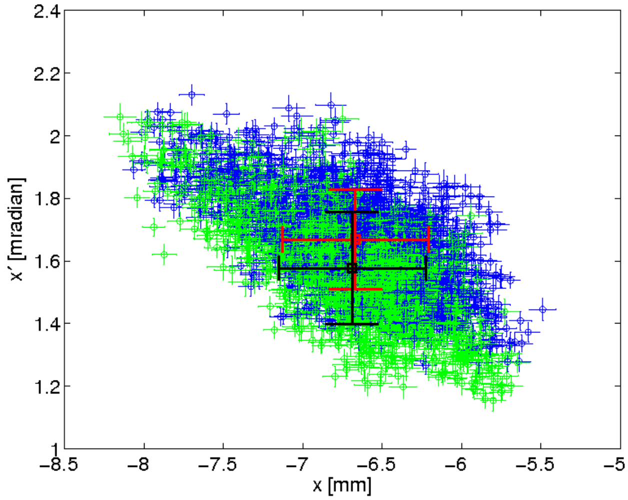

Figure 3: (Color) Horizontal injection offset measurement and the measurement distribution averages with one rms standard deviation from single-shot (blue, red) and LBEG+ (green, black) schemes.

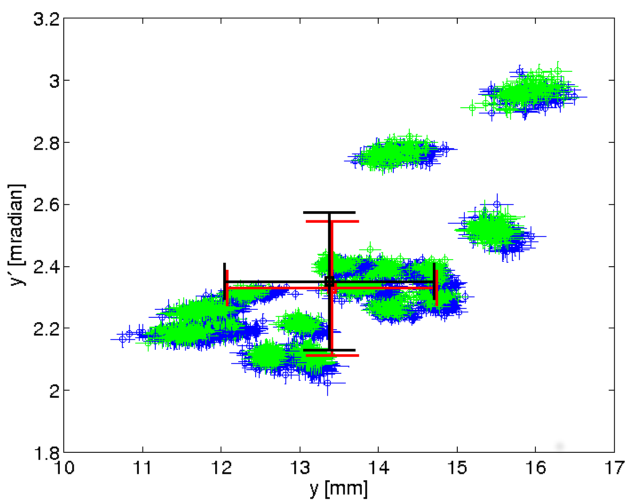

Figure 4: (Color) Vertical injection offset measurement and the measurement distribution averages with one rms standard deviation from single-shot (blue, red) and LBEG+ (green, black) schemes.

Injection Offset Measurement

The injection offset is fit to the turn-by-turn BPM data,

$$x_{i,n} = x_0\sqrt{\frac{\beta_i}{\beta_0}}(\sin\Theta + \alpha_0\cos\Theta) + x_0'\sqrt{\beta_i\beta_0}\sin\Theta - x_{CO_i}, \tag{2}$$

where $\Theta = 2\pi\nu(n-1)+\mu_{0\to i}$, the indices i, *0*, and n indicates values at the i^{th} BPM, the foil, or turn number re-

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Table 2: Comparison of the Measured Injection Offsets from Single-Shot and LEBG+ Schemes with One RMS Uncertainty on the Average

	x_0 [mm]	x'_0 [mradian]
Single-Shot	$-6.669 \pm 1.1{\times}10^{-2}$	$1.669 \pm 4{\times}10^{-3}$
LBEG+	$-6.689 \pm 1.2{\times}10^{-2}$	$1.577 \pm 5{\times}10^{-3}$
Difference	$2.0{\times}10^{-2}$	$-9.2{\times}10^{-2}$
	y_0 [mm]	y'_0 [mradian]
Single-Shot	$13.412 \pm 3.3{\times}10^{-2}$	$2.329 \pm 5{\times}10^{-3}$
LBEG+	$13.378 \pm 3.6{\times}10^{-2}$	$2.351 \pm 6{\times}10^{-3}$
Difference	$-3.4{\times}10^{-2}$	$2.2{\times}10^{-2}$

spectively, x and x' are the phase space position and angle, β, α, and μ are the beta function, its derivative, and the positive phase advance from the foil, and x_{CO} is the CO.

Figures 3 and 4 compare ∼100 measurements of the injection offset from each BPM. For typical operations, we set injection offset to $[x_0,\ x'_0,\ y_0,\ y'_0] = [-3.8\text{ mm},\ 0.85\text{ mradian},\ 16.5\text{ mm},\ 2.8\text{ mradian}]$. Table 2 compares the measurement distribution averages.

The measured injection offsets are quite different from our standard setup. This is an example of how the injection offset can change significantly with upstream tuning and why it is important to be able to measure the injection offset during production.

The islands in Fig. 4 are due to BPM measurement saturation for large beam positions. Each island is measurement from a different BPM, and each BPM has different degrees of measurement saturation depending on the type of BPM and the beam position. PSR BPM measurement saturation is the topic of a future paper.

We observe a statistically significant difference in the injection offset angles between the single-shot and LBEG+ measurements. The deviation is very small, $\sim 10^{-2}$ mradian and within tolerance. We conclude that the injection offset measurement from single-shot and LBEG+ schemes is the same.

Amplitude Measurement

The amplitude of betatron motion can be related to the beta function. Figure 5 compares the amplitude from single-shot and LBEG+ measurements. Note that the measurements agree within 3 rms uncertainties. We conclude the amplitude measurements from single-shot and LBEG+ schemes are the same.

Phase Measurement

The betatron phase can be related to the phase advance and is useful in model verification experiments. Figure 6 compares the phase measurements from single-shot and LBEG+ schemes. We observe a statistically significant and constant offset in the phase difference. The phase deviation is real and is due to the measured difference in injection offset angles discussed previously. Accounting for the very small change in injection offset, we conclude that the phase measurement from single-shot and LBEG+ schemes is the same.

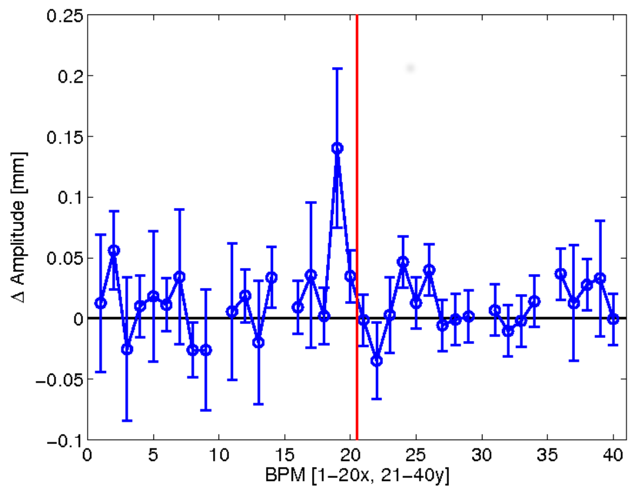

Figure 5: Difference in amplitude measurements using the single-shot and LBEG+ schemes with one rms uncertainty.

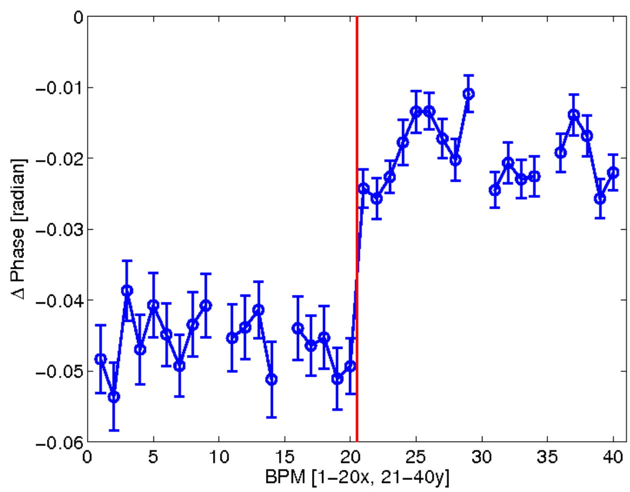

Figure 6: Difference in phase measurements using the single-shot and LBEG+ schemes with one rms uncertainty.

CONCLUSIONS

We demonstrate a proof of principle for the LBEG+ scheme to measure the CO, betatron tune, and injection offset during production. We compare measurements of the CO, tune, phase, amplitude, and injection offset from the single-shot and LBEG+ measurement schemes and show that both methods produce the same result.

REFERENCES

[1] J. Kolski, Ph.D. thesis, unpublished (Indiana University 2010).

[2] J. Kolski, et al. THPPP097, Proceedings of IPAC2012, New Orleans, Louisiana, USA.