SPEAR3 BOOSTER RESPONSE MATRIX MEASUREMENT*

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Abstract

In this paper, we present the orbit response matrix (ORM) measurements for the SPEAR3 booster obtained using a set of Libera Spark ERXR beam-position processors. The turn-by-turn acquisition capability of these processors enables continuous tracking of the beam trajectory throughout the full energy ramp prior to injection into SPEAR3. This dataset provides sufficient resolution to extract the booster's optical functions and measure the orbit response matrix. The resulting refinements to the booster machine model have contributed to improved understanding of beam-loss mechanisms, thereby enabling future development of algorithms to improve beam capture from the linac-to-booster (LTB) transport line and injection efficiency into SPEAR3.

INTRODUCTION

The SPEAR3 injector complex consists of a 120 MeV linac, a 3 GeV booster synchrotron, and the associated transport lines used to deliver beam into the SPEAR3 storage ring [1]. The booster synchrotron operates at a 10 Hz repetition rate with a resonant-driven White circuit that accelerates the beam from 120 MeV to 3 GeV in approximately 37 ms. During each top-up cycle, approximately 50 single-bunch injections are transferred through the injector chain and accumulated in the storage ring.

Accurate diagnostics of the booster orbit are essential for understanding injection efficiency, beam capture dynamics, and beam losses during the acceleration cycle. The original booster beam-position monitor (BPM) system at SPEAR3 was based on a multiplexed analog architecture developed in the early 1990s [2]. While adequate for routine operations, the system provided limited temporal resolution and was capable of orbit measurements only every 1.5 ms during the ramp cycle.

To address these limitations, Libera Spark-ERXR BPM processors were installed and evaluated in the SPEAR3 booster [3, 4]. The processors provide high-resolution turn-by-turn acquisition throughout the full energy ramp and allow continuous monitoring of the beam orbit from injection through extraction (~ 85k turns). In addition to operational diagnostics, the improved BPM performance enables detailed accelerator physics studies, including optics characterization and orbit response matrix analysis.

The work presented here builds upon previous studies demonstrating the suitability of Libera Spark systems for booster diagnostics [5–8]. By measuring the dispersion at injection energy, the tune evolution along the acceleration cycle, and finally, the ORM we are able to more comprehensively characterize the booster, enabling the future development of advanced optics and correction algorithms for operation.

BOOSTER BPM SYSTEM

The SPEAR3 booster synchrotron uses stripline BPMs distributed around the ring. In the current configuration, several booster BPMs were connected directly to Libera Spark-ERXR processors through RG223 coaxial cables though a future upgrade to LM240, or even LM400, is planned. The Spark processors were configured for the booster RF frequency near 358 MHz. Signals from the stripline pickups were filtered and sampled using PLL-controlled analog-to-digital converters operating at 109.8 MHz.

The Libera Spark processors sampled the beam signals 49 times per revolution during the 446 ns booster revolution period. This configuration enables turn-by-turn measurements throughout the entire acceleration cycle, including the beam capture process immediately following injection, longitudinal damping during acceleration, and the extraction phase. The processors demonstrated sufficient sensitivity to resolve single-bunch motion during the full ramp even when operated using the existing lossy coaxial infrastructure [2].

TURN-BY-TURN BOOSTER MEASUREMENTS

Orbit And Sum Signal

The upgraded BPM system provides detailed observation of beam dynamics during the booster cycle. Figure 1 shows representative turn-by-turn beam motion measured from a booster BPM immediately following injection.

Continuous acquisition over the 37 ms acceleration ramp revealed modulation structures in both beam position and beam intensity during the low-energy portion of the cycle. These oscillations are associated with the longitudinal capture dynamics of the injected beam. Approximately five to seven S-band bunches from the linac are injected into a single booster RF bucket, and the bunches subsequently damp into a single equilibrium bunch through synchrotron radiation and longitudinal phase-space evolution. The measurements indicate that the damping process is largely complete after approximately 17 ms into the acceleration cycle. Prior to this point, the observed orbit oscillations reflect complex synchrotron motion and capture dynamics.

There exists a vertical orbit distortion near the top of the energy ramp associated with the extraction septum magnet pulse. Measurements show an approximately 1 mm vertical orbit shift during extraction magnet excitation and can provide important information for minimizing beam loss during transfer into the Booster-to-SPEAR3 (BTS) transport line.

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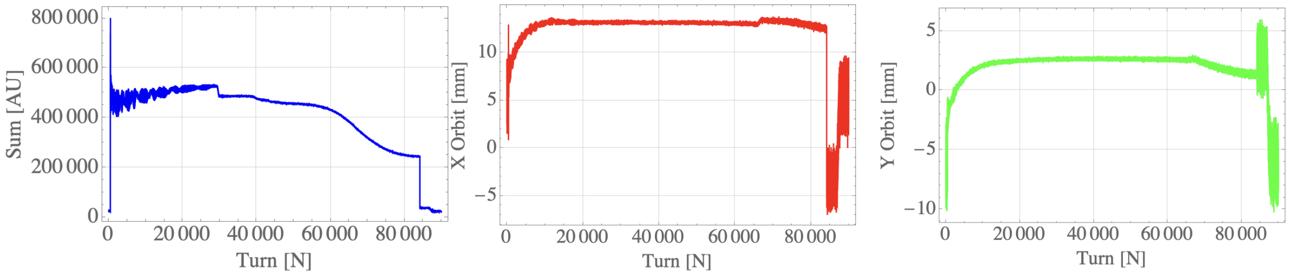

Figure 1: Turn-by-turn sum signal and transverse orbit evolution during the booster acceleration cycle for a single BPM. The left panel shows the BPM sum signal proportional to stored beam intensity, while the center and right panels show the horizontal and vertical centroid motion, respectively.

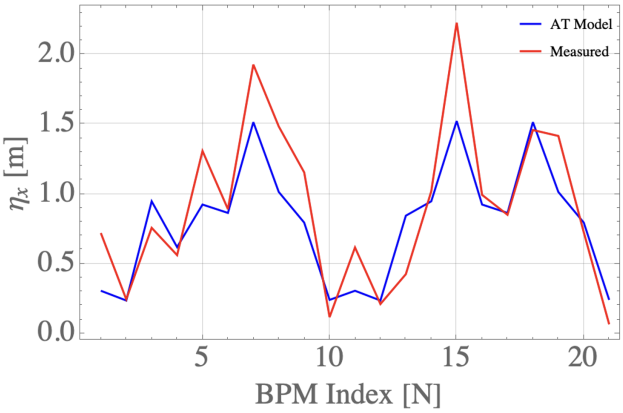

Figure 2: Comparison of the measured horizontal dispersion function with the lattice model (AT) at the BPM locations around the booster ring. The agreement validates the linear optics model and the dispersion response predicted by the lattice configuration.

Additionally, there is a notable reduction in the BPM sum signal observed between 60-80k turns. This has been attributed to operation of the solid-state amplifier (SSA) under reduced RF gap voltage conditions.

In addition to single-cycle measurements, the BPM system enabled long-term monitoring of booster orbit reproducibility across repeated top-up cycles. The horizontal and vertical orbit trajectories were found to be repeatable under normal conditions, potentially providing a stable baseline for identifying machine drifts and operational deviations [9].

Dispersion

The horizontal dispersion function at the booster injection energy ($\sim 120 MeV$) was measured by introducing controlled RF frequency offsets and recording the resulting closed-orbit distortions at the BPM locations (Fig. 2). Since the booster RF system is phase-locked to the SPEAR3 master oscillator, the booster RF frequency was varied indirectly through adjustments to the SPEAR3 RF frequency. A change in RF frequency modifies the equilibrium energy of the circulating beam according to the momentum compaction relation ($\delta_p = -\frac{1}{\alpha_c}\frac{\Delta f}{f_o}$), producing an off-momentum closed orbit proportional to the local horizontal dispersion. For each applied RF frequency shift, the corresponding horizontal orbit displacement was measured turn-by-turn using the BPM system. The horizontal dispersion at each BPM location was then extracted from the slope of the measured orbit offset as a function of relative momentum deviation, obtained from the applied RF frequency perturbation.

The AT model shows good agreement with the measured dispersion, reproducing the overall profile along the BPMs. The dominant orbit features and extrema are captured at the correct BPM locations, confirming reasonable consistency between the lattice model and machine optics. Residual discrepancies are primarily amplitude-related, suggesting possible optics mismatch, BPM calibration errors, or unmodeled higher-order effects, which may be further diagnosed and corrected using LOCO (Linear Optics from Closed Orbits) analysis [10].

Tune Evolution

The turn-by-turn BPM data was used to measure the evolution of the transverse betatron tunes throughout the booster's energy ramp (approximately 120 MeV to 3 GeV). For each time window along the ramp, the transverse centroid motion recorded by the BPM system was Fourier transformed to obtain the corresponding horizontal and vertical tune spectra. Repeating this analysis sequentially over the acceleration cycle produced the tune waterfall spectrograms shown in Fig. 3, providing time-resolved tracking of the betatron tune evolution during energy ramping. At low-energy, the spectra exhibit coupling between the horizontal and vertical planes as indicated by a strong spectral component near a tune of approximately 0.15–0.20 in both plots during the initial portion of the ramp. The coupling at injection energy is consistent with the increased sensitivity of the low-rigidity beam to skew quadrupole field components, alignment errors, and residual transverse coupling sources. As the beam energy increases during acceleration, the coupling signature becomes substantially weaker, reflecting the reduced influence of magnetic field imperfections at higher beam rigidity and the corresponding stabilization of the transverse optics throughout the remainder of the ramp.

ORBIT RESPONSE MATRIX MEASUREMENTS

The augmented orbit response matrix (Fig. 4) for the booster was measured by sequentially exciting horizontal and vertical corrector magnets while recording the resulting

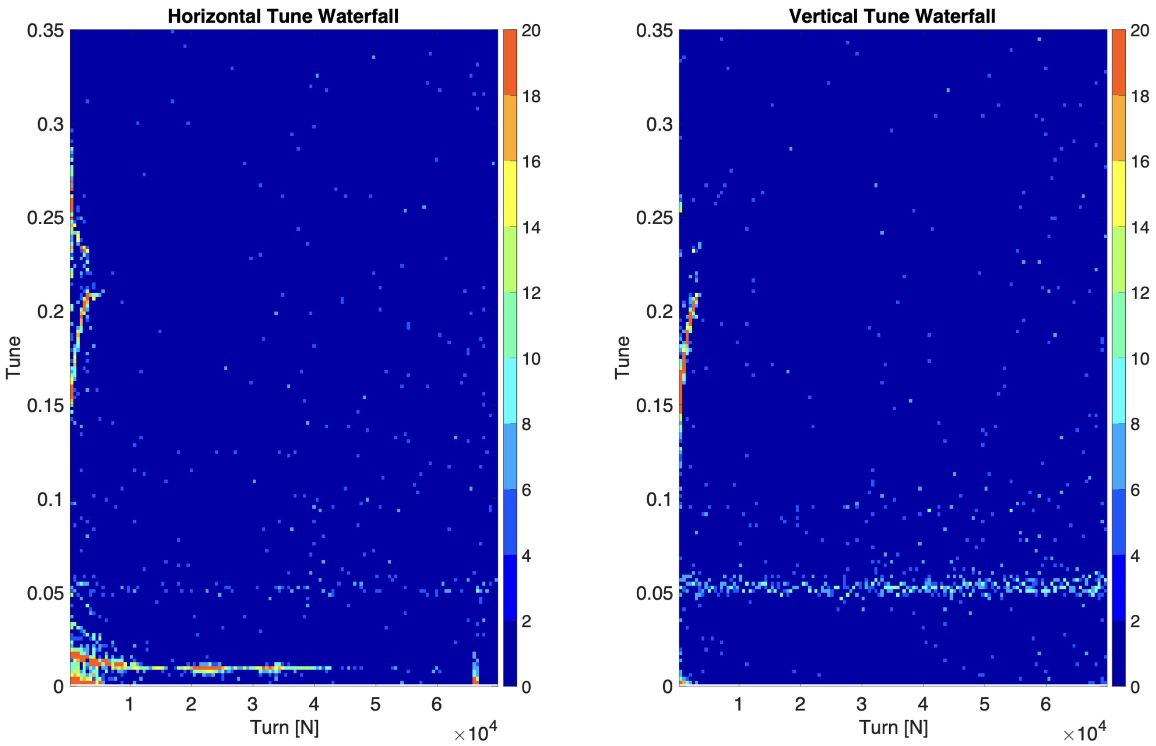

Figure 3: Horizontal and vertical tune waterfall spectra obtained from turn-by-turn BPM data during the energy ramp. The plots show the evolution of the betatron tunes as a function of turn number.

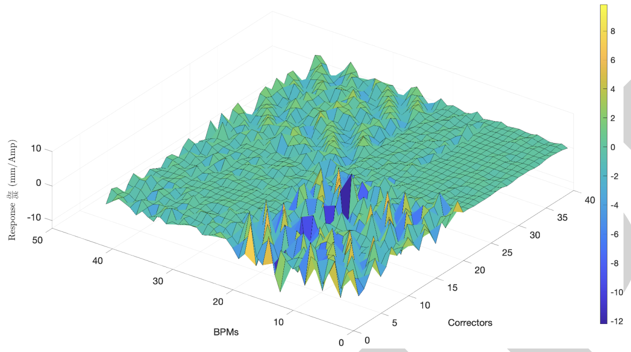

Figure 4: Measured augmented orbit response matrix for the booster lattice. The matrix elements characterize the linear optics coupling between steering magnets and BPM locations and provide the basis for optics correction and lattice model calibration.

orbit perturbations at the BPM locations. Note the presence of finite off-diagonal matrix elements indicates residual coupling between the horizontal and vertical planes. These non-zero cross-plane responses correspond to orbit motion generated in one transverse plane due to corrector excitations applied in the orthogonal plane. The observed coupling is relatively weak compared to the primary diagonal response, indicating modest but measurable linear betatron coupling in the machine.

CONCLUSION

The upgraded BPM diagnostics and ORM analysis have provided several operational benefits for the SPEAR3 injector complex. The ability to continuously monitor the beam orbit throughout the energy ramp can be developed into a general diagnostics tool. Future work will include extension of the ORM measurements to energy-dependent optics characterization across the full booster ramp, incorporation of additional BPM locations, and integration of automated trajectory and lattice correction procedures into routine machine operations.

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