MACHINE STUDIES WITH LIBERA INSTRUMENTS AT THE SLAC SPEAR3 ACCELERATORS

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Abstract

Turn-by-turn BPM readout electronics were tested on the SPEAR3 booster synchrotron and storage ring to identify possible improvements in data acquisition. For this purpose, Libera Spark [1] and Libera Brilliance+ [2] instruments were customized for the booster (358.4 MHz) and SPEAR3 storage ring (476.3 MHz) radio-frequencies, and tested during machine studies. Even at low single-bunch booster beam current, the dynamic range of the Libera Spark provided excellent transverse position resolution during the linac-to-booster beam capture process, the energy ramp phase and during beam extraction. Booster injection efficiency was analyzed as a function of linac S-band bunch train arrival time. In SPEAR3, turn-by-turn Libera Brilliance+ measurement capability was evaluated for single and multi-bunch fill patterns as a function of beam current. The single-turn measurement resolution was found to be better than 15 microns for a single 1.5 mA bunch. The horizontal single-bunch damping time was then observed with the 238 MHz bunch-by-bunch feedback system ON and OFF, and the multibunch fill pattern stability evaluated as a function of total beam current.

INTRODUCTION

SPEAR3 is a 3rd generation, 3 GeV synchrotron light source with 234 m circumference. The storage ring nominally operates with 500 mA circulating beam current and approximately 1.8 mA/bunch (1.4nC). Topup occurs every 5 minutes using about 50 pulses of single-bunch charge at a 10 Hz rate. The booster synchrotron features a 10 Hz resonant-driven White circuit with a 100 MeV to 3 GeV energy ramp in ~37 ms. Of significance, injection into the booster consists of about 7 S-band bunches selected from a 1 μs S-band bunch train produced in a thermionic RF electron gun. The S-band bunches are not phase-locked to the booster and the arrival time can vary due to thermal and electronic drift over time.

Libera BPM processor electronics were installed in the booster ring and in the SPEAR3 storage ring to study measurement performance under different beam conditions. The Libera Spark was configured for highest sensitivity and was able to accurately measure single bunch position during the 37 ms booster ramp phase. Analog signals from four booster BPM striplines were connected to the Libera Spark front end processor equipped with 352 MHz bandpass filters. The filters stretch the response which is then sampled by PLL-controlled ADCs clocked at 109.8 MHz. The baseband signals were sampled 49 times each revolution (1 turn=466 ns).

For SPEAR3 a Libera Brilliance+ module was installed to monitor beam position from a set of four botton-style BPM electrodes. In this case the sampling clock was 112.7 MHz and the baseband signal was sampled 88 times during the 781 ns revolution period. At this sampling rate the Brilliance+ module can resolve two diametrically opposite bunches separated by 390 ns in SPEAR3.

BOOSTER BPM MEASUREMENTS

The SPEAR3 charge transfer sequence starts in a 100 MeV linac followed by a 3 GeV booster and finally injected into SPEAR3 at a 10 Hz repetition rate every 5 minute topup cycle. At each 10 Hz injection event, the single-bunch booster beam is accelerated and extracted in about 37 ms.

The original 1990's-era booster BPM system consists of a commercial multiplexor that switches individual BPM button signals through an electronic peak detector followed by a sample-hold-digitization circuit chain. As a result, the measurement resolution for the electron beam position is sub-optimal and can only read the beam orbit every 1.5 ms during the energy ramp.

By introducing the Libera Spark module, it is now possible to measure the single bunch beam position turn-by-turn and with much higher resolution throughout the ramp. Figure 1 for example shows raw turn-by-turn data over three turns from one booster ring BPM pickup.

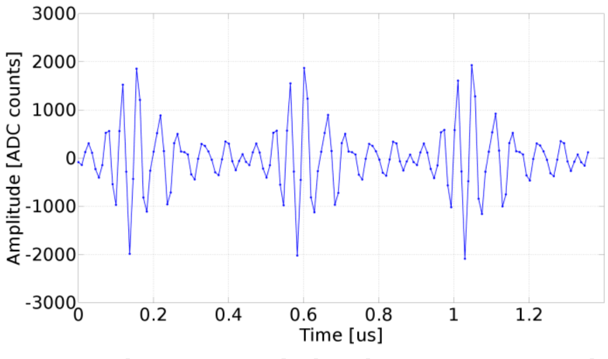

Figure 1: Three-turn single bunch measurement in the SPEAR3 booster ring.

Figure 2 shows the beam position and charge (SUM) throughout the full booster acceleration cycle. The turn-by-turn data was clocked using the injection timing trigger and processed in the time domain.

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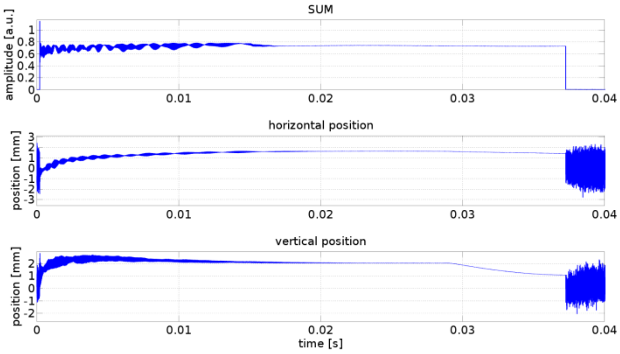

Figure 2: Single acceleration cycle in the SPEAR3 booster ring as measured with Libera Spark.

Of interest, modulations are evident in both the position and amplitude data out to about 17 ms. The modulations are believed originate in the beam capture process. At each injection cycle about 7 S-band bunches are injected from the linac into a single booster RF bucket. The S-band bunches are separated by 250 ps and radiation-damp into a single booster bunch during the energy ramp. By 17 ms the radiation damping process is complete. The modulations seen in Figure 2 are due to complex longitudinal phase oscillations during the ramp.

In practice, the overall charge capture efficiency depends on the S-band bunch train arrival time. To test this dependence we manually varied the arrival time and monitored the injection dynamics with the Libera Spark. The nominal arrival time setpoint was 2.5 V where each 0.1 V corresponds to a delay of 40 ps. Figure 3 shows the SUM (charge) for series of different S-band bunch train arrival times. The injection efficiency went down by over 50% for a setpoint of 2.8 V (-120 ps delay) with a smaller decrease when the timing was advanced. Amplitude SUM values in plot were normalized to the tail of the 2.7 V setting for comparison. Based on the scan results the optimum injection efficiency was found near the original setting of 2.5 V as indicated by the upper magenta line.

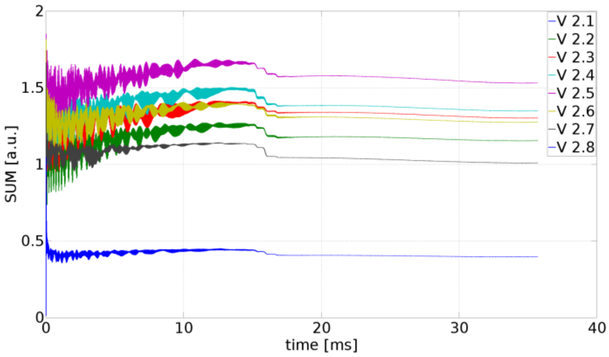

Figure 3: Booster injection efficiency scanning.

Another significant effect detected by the Libera Spark processor occurs at the at the top of the energy ramp. Referring to Figure 4, we see a -1 mm vertical orbit shift when the extraction septum magnet is activated. The 'half-sinewave' character of the field profile in time is evident just prior to beam extraction and the beam steering into the transfer line must be adjusted to compensated for this effect.

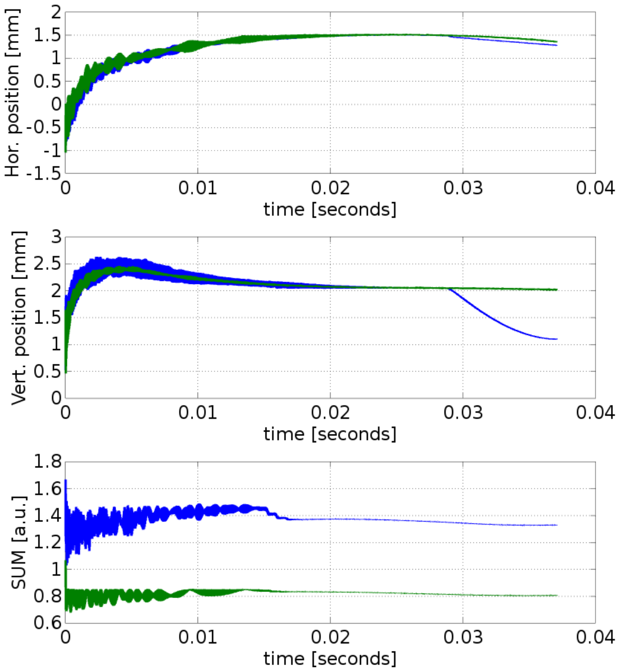

Figure 4: Injection cycle with septum magnet ON (blue line) and OFF (green line).

SPEAR3 BPM MEASUREMENTS

The SPEAR3 storage ring contains 18 magnet girders with 3 operational BPM's per girder. The original BPM processors are Bergoz type with custom built-in electronics to provide both x/y and individual button signals a-b-c-d which are digitized at a 4 kHz rate for the beam interlock and fast orbit feedback systems, respectively. In addition, the storage ring is equipped with several Echotek BPM processor modules to provide turn-by-turn orbit information. To evaluate the potential for a hardware upgrade, turn-by-turn beam measurements were made with a Libera Brilliance+ processor demonstrating accurate, single-bunch, single-pass measurements down to a bunch current of about 250 μA (200 pC charge).

For these measurements the Brilliance+ was not optimized for gain or phase compensation rather simply provided turn-by-turn data at each current level. As seen in Figure 5, above low-charge single bunch values of 30-50 nA, the beam position measurements stabilized to approximately 10 μm pk-pk between 0.2 to 3.7 mA. After 2 mA, the automatic gain control in Brilliance+ increased channel attenuation two times. Since the gain compensation circuit was not activated, a position deviation is observed in the vertical direction between 2 and 3 mA.

Turn-by-turn noise performance was then evaluated for single bunch currents ranging from 0.5 to 5 mA. For these measurements, the K_x and K_y scaling coefficients were set to 15 mm (default 10 mm). The results listed in Table 1 indicate the RMS noise figures are satisfactory providing reliable readout of the electron beam orbit position in single bunch mode. Since the BPM buttons are located in a region of non-zero dispersion, significant contributions from ~11 kHz synchrotron oscillations were found above

1.5 mA bunch current and add between 3-5 µm systematic RMS noise. The vertical turn-by-turn noise figures are also listed in Table 1.

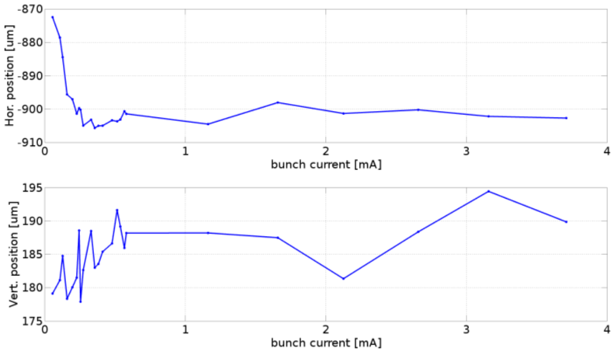

Figure 5: Single bunch, single turn measurement capability as a function of electron beam current.

Table 1: Single bunch, turn-by-turn noise performance in a bandwidth of 0 – 0.6 MHz.

Beam current	Horizontal plane (RMS)	Vertical plane (RMS)
0.5 mA	39 µm	38 µm
1 mA	20 µm	19 µm
1.5 mA	15 µm	14 µm
2 mA	14 µm	12 µm
2.5 mA	12 µm	9 µm
3 mA	10 µm	8 µm
3.5 mA	11 µm	9 µm
4 mA	10 µm	8 µm
4.5 mA	10 µm	8 µm
5 mA	9 µm	7 µm

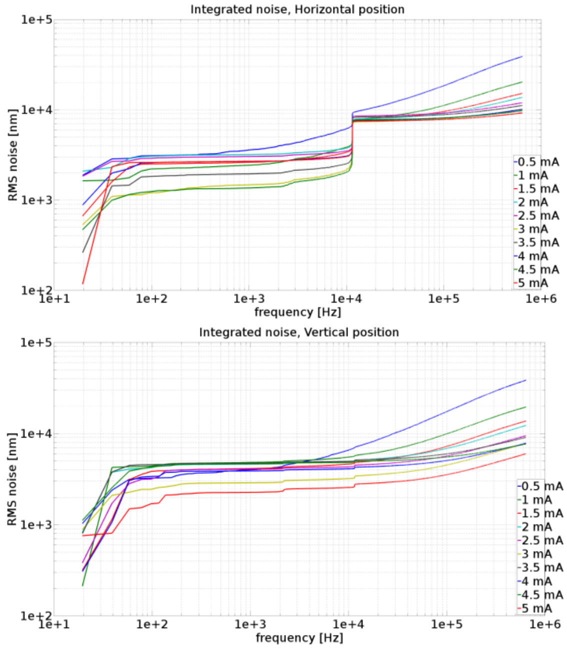

Figure 6: Integrated FFT plot for horizontal and vertical planes.

Using the same single-bunch data from Table 1, the FFT algorithm was applied to the raw turn-by-turn data. The resulting frequency content is plotted in Figure 6 over a ~650 kHz measurement bandwidth. Other than a noticeable 'jump' in horizontal RMS noise content at 11 kHz, the noise figure grows monotonically with frequency and as expected improves with higher bunch charge for both planes.

Figure 7 shows the same horizontal data where we 'zoom-in' on the low frequency band near the 11 kHz synchrotron oscillation frequency. Above the low 500 µA current level, the step seen at the synchrotron frequency is approximately equal for all bunch charges.

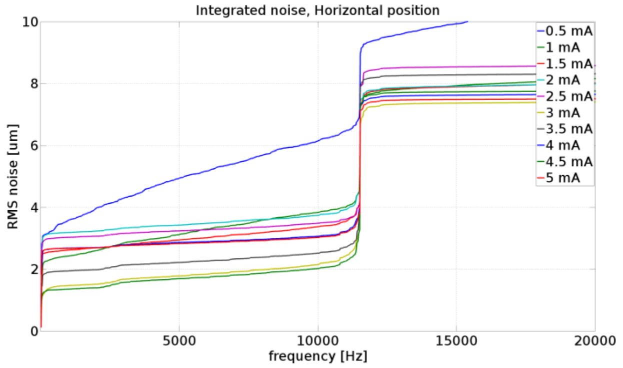

Figure 7: Noise contribution from synchrotron oscillations detected at a position of nonzero dispersion.

The power spectra calculated from the turn-by-turn data are plotted as a function of single bunch current in Figure 8.

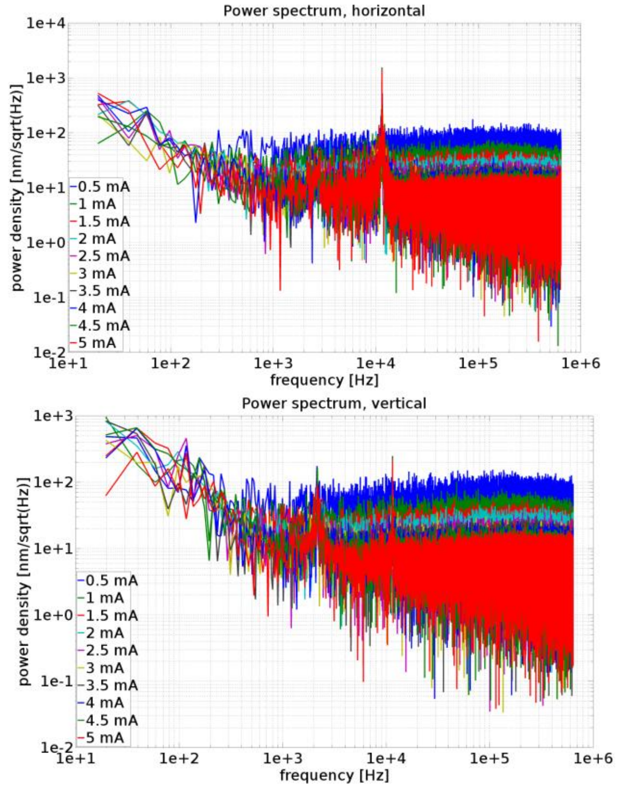

Figure 8: Power spectrum for horizontal and vertical planes.

To test the Brilliance+ module in a 'dynamic' beam motion environment, we pulsed a single horizontal injection kicker to instantaneously ping the beam in the horizontal plane. Tests were performed with the 235 MHz bunch-by-bunch (BxB) feedback system OFF and ON and the Brilliance+ module triggered synchronously with the 10 Hz injection kicker. With feedback OFF, the horizontal betatron oscillations damp with the characteristic few msec exponential damping time for the SPEAR3 magnet lattice (Figure 9, blue). The 'scalloping' pattern seen on the beam envelop is again due to synchrotron oscillations. When the BxB feedback is switched ON, the betatron oscillations decay in about 1 ms (1,300 turns). In this case the characteristic linear amplitude reduction is due to the BxB feedback system driving the BxB kicker as hard as possible each turn. The lower plot shows coupling into the vertical plane is relatively small.

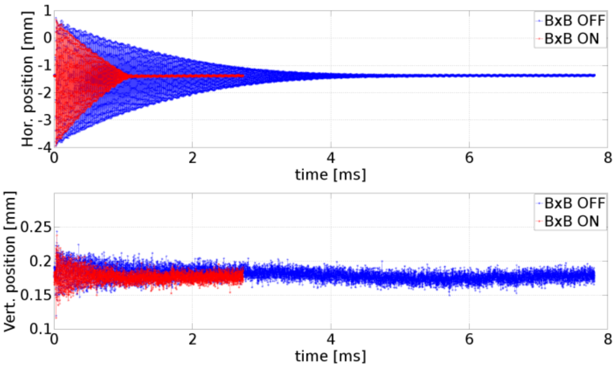

Figure 9: Damping time with BxB feedback ON / OFF.

We can further characterize the effect of BxB feedback by zooming in on the betatron oscillation motion embedded in the turn-by-turn BPM data. Figure 10 shows horizontal oscillation data across two different time intervals. The top plot shows data for the first 75 turns where the effect of feedback is still relatively small. The bottom plot starts at 800 µsec and shows 100 turns after the initial injection kicker event. In this case we see both the damping action of the BxB feedback system and a phase shift due to an effective change the reactive impedance seen by the beam with the feedback loop closed.

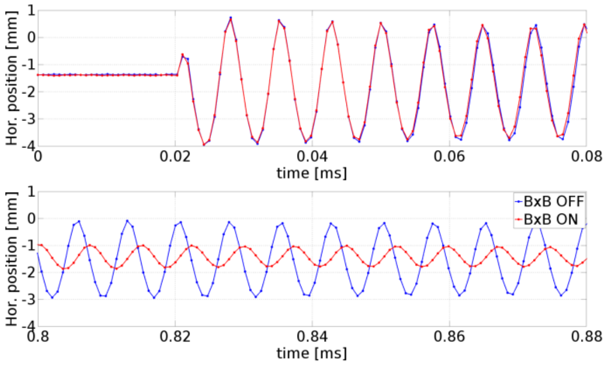

Figure 10: Horizontal oscillation data with BxB switched OFF and ON.

To test the Brilliance+ performance in multi-bunch mode, beam was injected into the standard bunch fill pattern with the total beam current increasing from 0.1 mA to 500 mA. The resulting beam position measurements are shown in Figure 11. Based on the data, we suspect the observed drift in beam position is due to current-dependence of the SPEAR3 fast orbit feedback system. The Brilliance+ was operating in the fully-automatic mode with the cross-bar switch enabled [3]. In this state the anticipated dependence on beam current is typically under 1 µm across the full dynamic range.

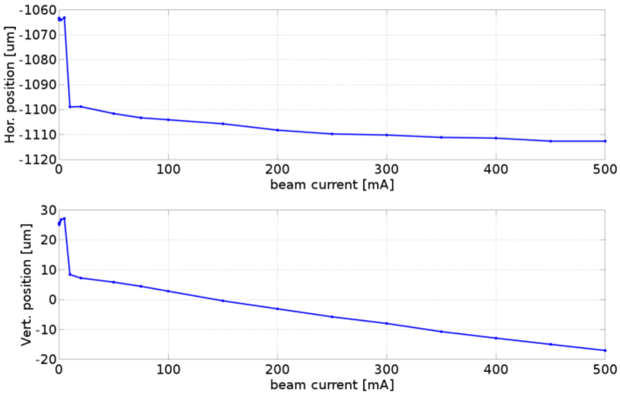

Figure 11: Beam position recorded over full current range.

SUMMARY

In this paper we report preliminary tests of Libera Spark and Libera Brilliance+ BPM processors operating on the SPEAR3 booster and main ring, respectively. At the booster, the Spark processor provides more accurate transverse beam position data with much better time resolution than previously available. An important effect involving vertical beam orbit shift induced by the pulsed extraction septum at the top of the energy ramp was discovered.

The Libera Brilliance+ processor also provided accurate turn-by-turn beam position measurements over a wide range of single-bunch and multi-bunch operating conditions in SPEAR3. Since the physical BPM buttons were located at a region of horizontal dispersion, an FFT of the data clearly indicated the presence of synchrotron oscillations. Of interest the Brilliance+ turn-by-turn data provides an accurate beam diagnostic tool for dynamic BxB feedback events including the ability to resolve phase shift in the oscillation data. In the near future SSRL will install a Libera Spark processor on the Booster and is in the process of testing a Spark processor on the SPEAR3 ring to upgrade turn-by-turn diagnostic capabilities.

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REFERENCES

[1] P.Leban, “Libera Spark User Manual”, Instrumentation Technologies d.d., 2017, Slovenia

[2] P.Leban, “Libera Brilliance+ Specifications 2.0”, Instrumentation Technologies d.d., 2016, Slovenia

[3] U. Mavric “Innovative RF Design Unites Benefits of Multiplexed and Multi-channel System”, 11th Beam Instrumentation Workshop 2004, Knoxville, USA.