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OPTICS CORRECTIONS AND PERFORMANCE IMPROVEMENTS IN THE BESSY II BOOSTER*

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Abstract

The BESSY II Booster has been reliably delivering beam to the storage ring for several decades. As part of an effort to better understand and control beam dynamics in the Booster, new instrumentation, including Libera Spark ERXR beam position processors, has recently been installed and commissioned. These instrumentation upgrades have enabled measurements and corrections of optics parameters throughout the acceleration ramp which were not previously possible, leading to understanding and mitigation of mechanisms for beam loss and instabilities. Here we describe the beam position measurement system, corrections to the tune and chromaticity, and the resulting improvements to the top-up operation of BESSY II.

INTRODUCTION

The BESSY II Booster is a fast-ramping synchrotron which has been reliably delivering beam to BESSY II for over 25 years [1–3]. During that time the light source has undergone numerous upgrades to meet the evolving needs of users, such as a switch to top-up operation and implementation of a fill pattern which contains several high-current bunches in addition to a lower-current bunch train. These upgrades required the Booster to perform well beyond its design parameters, particularly in terms of emittance and charge per bunch. The Booster had few diagnostics available for much of that time, and despite that limitation, an empirical approach to tuning the machine had ensured reliable operation with sufficient beam current and good injection efficiency into the storage ring.

Beam is injected into the Booster from a linac at 50 MeV and accelerated to a maximum energy of 1.9 GeV. Each shot is either extracted to the storage ring at 1.7 GeV, or else decelerated and lost at low energy. Between one and five of the Booster's 499.6 MHz RF buckets is filled on each shot, with bunches spaced 8 ns apart. A new gun driver board will provide a more flexible fill pattern for more uniform top-up of the storage ring with less injection distortion [4].

The focusing quadrupoles, defocusing quadrupoles, and main dipoles in the Booster [5] are powered by three 10 Hz resonant White circuits [6] following the function

$$I(t) = I_{DC} - I_{AC} \cdot \cos 2\pi f t, \tag{1}$$

where $f = 10$ Hz. AC current amplitude, DC current amplitudes, and a time offset are set independently for each of the three magnet types. There are no independent trim coils on the magnets powered by the White circuits, so neither beta beating corrections nor beam-based alignment procedures are possible. Due to the factor of ~40 in energy range, field errors in the dipole magnets are significant at low energy.

In recent years, plans were made for further development of BESSY II which would require significant changes to the beam dynamics in the Booster, and new instrumentation was commissioned as part of this effort [7, 8]. These recent instrumentation upgrades included Libera Spark ERXR processors for the button beam position monitors (BPMs) which had been installed since the machine was commissioned but lacked individual electronics for much of that time. As a result of these diagnostics upgrades, it has become possible to understand and control the optics and beam dynamics to a greater extent than was previously possible. This has resulted in an increase of about 50% in the maximum current in the Booster, approaching the administrative limit established for radiation protection, with no loss of injection efficiency into the storage ring.

BPM SYSTEM

The Booster is equipped with a set of 31 button BPMs, with one at each end of almost every drift section. These BPMs have orthogonal pickups and most have a radius of 30 mm. Libera Spark ERXR [9] electronics have recently been installed and commissioned for all of the button BPMs in the Booster, which can provide turn-by-turn position measurement over the full 100 ms acceleration ramp (almost 320000 turns) or a decimated measurement averaged over 64 turns each. The decimated orbit measurement is acquired on each Booster cycle, and the full turn-by-turn data is set to be acquired only on request.

Due to leakage from RF structures, significant ambient 499.6 MHz RF power is present in the area where the Spark front-ends are located. This ambient RF power is detected by the Sparks, causing an apparent 'ghost' orbit with measured position offsets of up to ± 10 mm when no beam is present in the machine. Thanks to the uneven fill pattern in the booster, it was possible to detune the internal filter of the Sparks by adjusting the frequency of the Numerically-Controlled Oscillator (NCO) so that it receives not the main RF frequency, but a sideband one revolution harmonic higher. This modification effectively suppresses the detection of stray RF power, but it results in a reduction of the beam signal amplitude by about 3 dB because this frequency is outside of the range which the internal filter is designed to receive. Figure 1 shows the 'ghost' signal which follows the shape of the Booster's RF ramp when the Spark is tuned to the main RF

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frequency, and which disappears when the Spark is detuned to a revolution harmonic of the RF frequency.

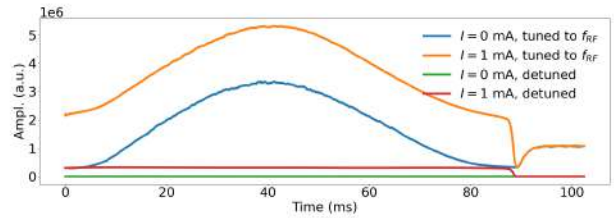


Figure 1: Measured amplitude on one channel of a Booster Spark when tuned to the RF frequency (blue, orange) and when it is detuned to a revolution harmonic of the RF frequency (green, red).

Boundary Element Method Position Calculation

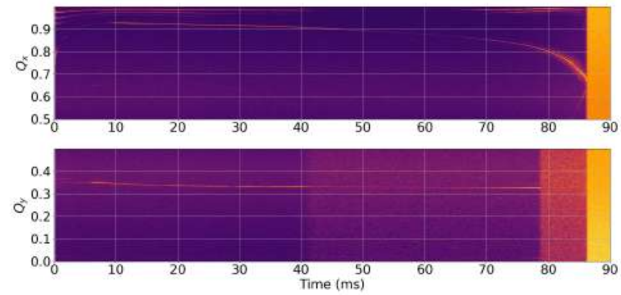
The closed orbit distortion in the Booster is large enough that, in many cases, the beam position lies well outside of the approximately-linear region of the BPM response. Rather than trying to fit the BPM response to a polynomial, an approach which can be highly sensitive to noise and offset errors, we used the Boundary Element Method (BEM) approach to determine the beam position based on the measured voltage on each pickup [10, 11]. This method involves numerically calculating the expected charge density on each pickup from a beam at a given position from the Laplace equation, and then iteratively finding the “best fit” beam position which minimizes the difference between the expected charge densities and measured voltages on each pickup.

The BEM fitting algorithm was implemented in Python, and this implementation is not fast enough to allow for real-time position calculations for the full the acceleration ramp at 1 Hz. The BEM calculations are done offline in cases where a more precise calculation is necessary, such as when measuring orbit response. Possible future improvements may include development of an algorithm which delivers similar result and could be implemented in real time directly on the Sparks’ FPGAs.

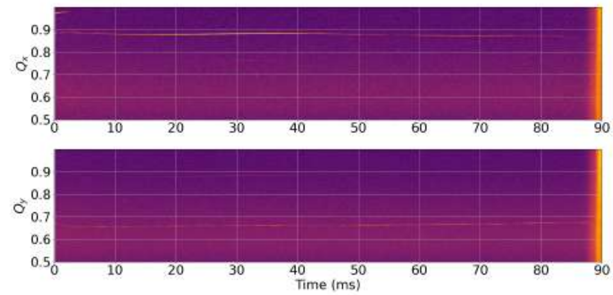
TUNE CORRECTION

The quadrupoles and dipoles are powered by sinusoidal resonant circuits (see Eq. 1), and due to eddy current effects in the dipole magnets, the ratio of field strengths in the dipoles and quadrupoles is not identical to the ratio of their currents; the field strength ratios, and therefore the betatron tunes, change during the acceleration ramp. In the Booster’s previous ‘empirically tuned’ operational state, the tunes swung through a range of 0.15 during the first several milliseconds after injection, crossing through potentially dangerous resonances (see Fig. 2a). With a careful choice of the free parameters of the White circuits (AC current amplitude, DC offset, and time offset), it was possible to keep the tunes nearly constant throughout the acceleration ramp.

In addition to flattening the tune throughout the acceleration ramp, the working point was changed from the lower



(a)



(b)

Figure 2: Measured transverse tunes throughout the acceleration ramp, before (a) and after (b) tune correction.

right quadrant ($Q_x = 5.88, Q_y = 3.35$) to a symmetric point in the upper right quadrant ($Q_x = 5.88, Q_y = 3.68$). The motivation for this change was to avoid unstable sum resonance lines near the initial working point, and instead be near stable difference resonance lines at the symmetric new working point in a different quadrant. Figure 2 shows the tunes after correcting the tune flatness and changing the working point.

At the original working point, about 20% of the beam current was lost during the first milliseconds after injection (see Fig. 3a). After changing the working point, those losses were eliminated, increasing the accelerated beam current by about 20%. This change in working point also resulting in a broader region of stability during injection into the booster, making the machine more robust against small fluctuations from the injector and decreasing the amount of effort needed to tune the injector for high booster current.

CHROMATICITY CORRECTION

Sextupole errors in the bending magnets have a significant impact on the chromaticity, especially at lower energy when magnet field errors are large. The booster contains a set of 8 focusing and 8 defocusing sextupole correctors, in alternating sections around the ring. The magnets are powered in pairs, and the power supplies for each type of sextupole are all driven by a single ramp card which can produce an arbitrary waveform.

When correcting chromaticity, the aim was to keep the chromaticity constant throughout the acceleration ramp, with a slightly positive value in order to reduce headtail instabilities. Figure 4a shows the measured chromaticity in the

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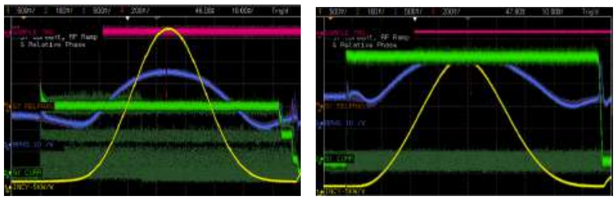
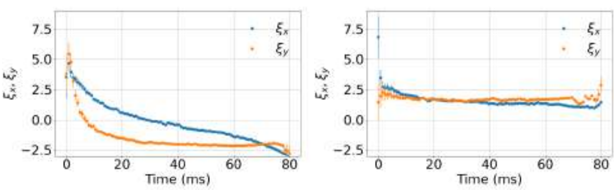
previous typical operational state, in which the corrector sextupoles had been empirically tuned to maximize beam capture during injection into the booster. In this state the chromaticity crossed through zero in both planes, leading to instabilities and beam loss above a certain current threshold. Figure 4b shows the measured chromaticity with new corrections applied. With corrected chromaticity, it became possible to accelerate nearly 50% more current (see Fig. 3b).



(a) (b)

Figure 3: Beam current (green curve) in the original state (a) and after tune and chromaticity corrections, with higher current and beamloss at lower energy on the downramp (b).



(a) (b)

Figure 4: Measured chromaticity during the acceleration ramp in the original operational state (a) and after correcting to a nearly-constant, slightly positive value (b).

Figure 3 shows the beam current in the previous operational state (right), and with corrected tune, new working point, and corrected chromaticity (left). In addition to increasing the total accelerated current, these changes also result in beam loss at lower energy on the downramp, which is beneficial from a radiation protection.

CLOSED ORBIT DISTORTION

Figure 5 shows the 64-turn decimated orbit measurement at each BPM with no orbit correction. Steering errors in the ring include a time-varying component from dipole field errors at low energy and a constant component from quadrupole misalignments. Without correction, a closed orbit distortion of almost 25 mm peak-to-peak is measured in the horizontal plane near injection.

The Booster contains 7 horizontal orbit correctors and 8 vertical orbit correctors, each of which has a bipolar power supply. Previously all orbit correctors had been driven by a single ramp card which can produce an arbitrary waveform, and recently five additional ramp cards have been introduced, providing some flexibility to implement time-varying corrections. Still, the number of correctors and the number of ramp cards has not been sufficient to fully correct the closed orbit distortion throughout the full acceleration ramp. Figure 6 shows a comparison of the uncorrected orbit and the best correction achieved so far.

It should be noted that a flat orbit doesn't produce the best performance during top-up operation. Due to the alignment of elements in the extraction region, a vertical orbit offset is required in order to prevent the beam from passing through nonlinear fields in the septum which would introduce coupling between the transverse planes. Also, the definition of an "ideal" orbit in the Booster is somewhat arbitrary because the quadrupoles lack independent trim power supplies needed for beam-based alignment procedures; some of the measured orbit deviations may simply reflect misalignment of the BPMs. It is not clear that the significant hardware upgrades which would be necessary for properly defining and fully correcting the orbit would bring further performance improvement.

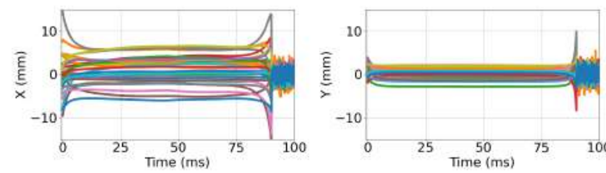


Figure 5: Uncorrected orbit distortion at all 31 BPMs.

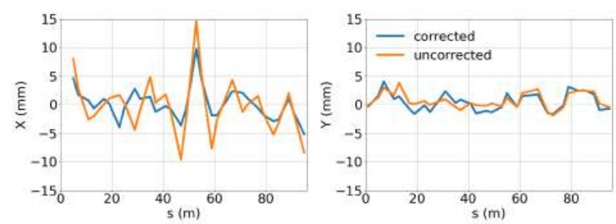


Figure 6: Closed orbit distortion at injection energy.

SUMMARY

The commissioning of Libera Spark ERXR beam position processors in the BESSY II Booster has allowed for improved understanding and control of the optics and beam dynamics in this fast-ramping machine. Chromaticity has been corrected to a small positive value, the working point has been moved to a more stable region, and variations in tune and chromaticity during the acceleration ramp have been reduced or eliminated. With these corrections, the Booster is more stable and less sensitive to small fluctuations from the linac, reducing the time needed to tune the machine to maintain optimum performance. Beam losses during capture, acceleration, and deceleration are reduced, and the current delivered to the storage ring increased by almost 50%. As a result, the time between shots during top-up operation have also increased by almost 50%, reducing perturbations in the beam delivered to users of the light source.

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REFERENCES

[1] E. Weihreter *et al.*, "The BESSY II Booster synchrotron," in *Proc. EPAC'96*, Sitges, Spain, 1996, pp. 527–529.

[2] M. Abo-Bakr *et al.*, "Commissioning of the BESSY II Booster synchrotron," in *Proc. EPAC'98*, Stockholm, Sweden, 1998, pp. 436–438.

[3] E. Weihreter, "Booster synchrotron for BESSY II: Optical considerations," Helmholtz-Zentrum Berlin, Tech. Rep. BESSY-TB-174, 1993.

[4] D. Schueler *et al.*, "Flexi-Gun research and development project at BESSY II," in *Proc. IPAC'23*, Venice, Italy, 2023, pp. 2013–2015. doi:10.18429/JACoW-IPAC2023-TUPL123

[5] T. Knuth, D. Krämer, E. Weihreter, I. Chertok, S. Michailov, and B. Sukhina, "The magnet system for the BESSY II injector synchrotron," in *Proc. PAC'95*, Dallas, TX, USA, May 1995, pp. 1316–1318.

[6] K. Buerkmann, G. Schindhelm, and T. Schneegans, "Performance of the White circuits of the BESSY II Booster synchrotron," in *Proc. EPAC'98*, Stockholm, Sweden, 1998, pp. 2062–2064.

[7] T. Atkinson *et al.*, "Status and prospects of the BESSY II injector system," in *Proc. IPAC'16*, Busan, Korea, 2016, pp. 2826–2828. doi:10.18429/JACoW-IPAC2016-WEPOW007

[8] T. Atkinson, P. Goslawski, J. G. Hwang, M. Ries, T. Flisgen, and T. Mertens, "VSR injector upgrade at BESSY II," in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4110–4113. doi:10.18429/JACoW-IPAC2018-THPMF030

[9] Libera Spark ERXR, https://www.i-tech.si/products/libera-spark-erxr/.

[10] R. W. Helms and G. H. Hoffstaetter, "Orbit and optics improvement by evaluating the nonlinear beam position monitor response in the cornell electron storage ring," *Phys. Rev. ST Accel. Beams*, vol. 8, p. 062 802, 6 2005. doi:10.1103/PhysRevSTAB.8.062802

[11] T. Shintake, M. Tejima, H. Ishii, and J.-i. Kishiro, "Sensitivity calculation of beam position monitor using boundary element method," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 254, no. 1, pp. 146–150, 1987. doi:10.1016/0168-9002(87)90496-7