ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPM047

DIRECT DIODE DETECTION TUNE MEASUREMENT IN THE BESSY II BOOSTER*

M. McAteer†, G. Rehm, B. Schriefer
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany

Abstract

The Direct Diode Detection (3D) method for transverse tune measurement, which was developed at CERN, has been implemented in numerous hadron machines and has recently been tested in electron machines. This method can provide orders of magnitude greater sensitivity to betatron oscillations than conventional beam position measurement approaches, which is particularly useful in fast-ramping synchrotrons such as the Booster of the BESSY II light source. Typical systems used for tune measurement in an electron storage ring, which rely on the beam being in a relatively steady state, are not well-suited for fast-ramping machines; in order to measure the tune throughout the full acceleration ramp using conventional beam position approaches in the BESSY II Booster, it is necessary to use large external excitation which disturbs injection into the storage ring. Here we describe tune measurement in the BESSY II Booster using diode detectors, which allows for tune measurements during the full acceleration ramp with little to no external excitation and therefore no disturbance to user operation.

INTRODUCTION

The BESSY II Booster [1,2] is a fast-ramping (10 Hz) synchrotron with an RF frequency of 500 MHz and a revolution frequency of 3.125 MHz. Beam is injected into the Booster from a linac at 50 MeV and is accelerated to a maximum energy of 1.9 GeV. Each shot is either extracted to the storage ring at 1.7 GeV after 36 ms, or else ramped back down and lost at low energy after about 90 ms. The 96 m ring is filled with either 1 bunch (single-bunch mode, ~1 mA) or 5 bunches (multi-bunch mode, ~5 mA).

Measuring the betatron tunes in a fast-ramping machine presents particular challenges. The tune is generally not constant during the acceleration ramp due to effects such as eddy currents and hysteresis, which perturb the ratio of magnetic field in the dipoles and quadrupoles as they ramp from low to high energy. Small drifts or errors in magnet currents or magnet ramp timings can also produce large tune changes on a relatively short timescale during the acceleration ramp, so monitoring the tune is important for maintaining optimal performance. Since the tune can change on short timescales, the tune measurement from turn-by-turn beam position cannot be integrated over a large number of turns, so is necessary to apply a large external excitation so that the transverse oscillations are visible above the noise floor. Other techniques for tune measurement, such as phase tracking with a bunch-by-bunch feedback system, are also not well-suited for a fast-ramping machine.

The turn-by-turn position from Libera Spark ERXR processors [3], which are connected to button beam position monitors (BPMs) in the Booster, has been used to measure and correct the tune throughout the acceleration ramp [4]. However, in order to measure the tune in both planes throughout the full acceleration ramp using this approach, it is necessary to apply white noise excitation which is large enough that it reduces the efficiency of injection into the storage ring; this approach therefore cannot be used for monitoring the tune during top-up user operation. The increased sensitivity of the 3D tune measurement system allows for continuous tune measurement during the full acceleration cycle without disturbing user operation.

3D Principle

The Direct Diode Detection (3D) method of tune measurement [5,6] was developed for use in hadron accelerators at CERN and has recently been successfully tested in electron accelerators as well [7,8]. The 3D method increases the signal-to-noise ratio of tune measurements, relative to conventional BPM signal processing, by utilizing a larger portion of the power of the betatron motion contained in the signal from a pickup. The power in the signal induced on a pickup by a short particle bunch is spread over a large frequency range, and most of the power in the spectrum is contained in harmonics of the revolution frequency, with a small betatron modulation sidebands around each revolution harmonic. In conventional BPM processing, a band-pass filter selects a narrow band of the pickup signal around the RF frequency, thus collecting only a small portion of the total betatron content in the signal; the rest of the betatron content, which is spread among other revolution harmonics, is discarded.

By contrast, in the 3D approach, the signal from a pickup charges a capacitor through a diode and then the capacitor is slowly discharged, which in effect “stretches” the short beam pulse in the time domain. The power in the spectrum is thereby spread among a smaller number of revolution frequency harmonics in the frequency domain as a large portion of the betatron motion power is converted down to a sideband of the baseband revolution frequency. A larger portion of the total betatron oscillation content in the signal from the pickup can then be collected and digitized. This type of circuit, known as a diode detector or envelope detector, is commonly used for demodulating Amplitude Modulated (AM) radio signals.

In addition to increasing the total amount of betatron “signal” by converting higher harmonics down to the base band,

---

* Work supported by the German Bundesministerium für Bildung und Forschung, Land Berlin and grants of Helmholtz Association.

† meghan.mcateer@helmholtz-berlin.de

the diode detector also increases the signal-to-noise ratio by reducing the revolution harmonic content of the signal before digitization so that the smaller betatron component can fill the range of the analog-to-digital converter (ADC), rather than the digitized signal being dominated by the much larger revolution component. Careful choice of the parameters of the diode detector components, based on the beam properties and the size of transverse oscillations, is necessary in order to reduce the revolution content as much as possible while maximizing the betatron content [5]. The DC component of the diode detector output, which is proportional to the beam position, is also removed before digitizing, which essentially increases the sensitivity to small oscillations around the closed orbit at the expense of losing information about the position of the closed orbit.

While the diode detector itself removes a significant portion of the revolution harmonic content, maximizing sensitivity requires additional analog filtering to remove remaining revolution harmonic content before digitizing. The results discussed here for the BESSY II Booster do not yet include analog front-end processing.

DIODE DETECTORS

Detector Design

The schematic for the diode detectors built for the BESSY II Booster are shown in Fig. 1. They were built mostly following the design by M. Gasior for detectors used in Solaris [7], with small modifications. A single diode instead of two diodes in series was sufficient for this application, as the maximum peak voltages from the stripline in the Booster were much less than those in the Solaris system. A similar diode from a different manufacturer was substituted because the diode in the Solaris design was not readily available.

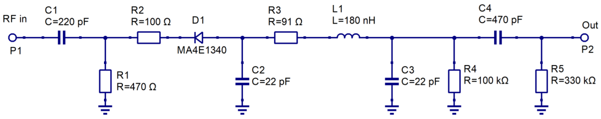


Figure 1: Schematic of the diode detector.

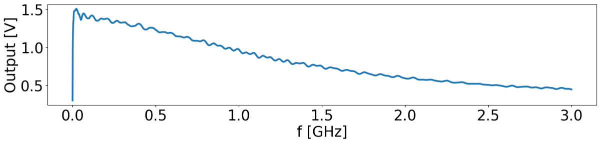


Figure 2: Frequency response of the detector measured on a test bench.

Capacitor C1 and resistor R1 form a 1 MHz high-pass filter to eliminate unwanted low frequency noise. Resistor R2 limits the current to ensure that the diode's maximum rating is not exceeded. Resistor R3 and inductor L1 form a low-pass filter together with the loading capacitors C2 and C3. Resistor R4 discharges the loading capacitors and is chosen to provide a discharge time constant which is long compared to the revolution time of the beam so that the capacitor discharges only slightly before it is charged again by the next beam pulse, which reduces the revolution frequency content of the detector output. Capacitor C4 and resistor R5 form a high-pass filter to remove the DC component of the output from the detector. The frequency response of the detector is shown in Fig. 2.

The input ports of four diode detectors are connected to the four pickups of a 30 cm stripline via one meter of coaxial cable, and the output ports of the detectors are connected directly to the inputs of the digitizer. The signals from the diode detectors were digitized using an 8-bit oscilloscope (in high input impedance mode) for initial testing, and later using a Picoscope 4262, a low-noise 16-bit digitizer with a 10 MS/s sampling rate. Currently, no further analog signal processing is done on the detector output before digitizing; an analog front-end consisting of amplification and a notch filter followed by a low-pass filter to remove remaining revolution harmonic content, similar to that described in [7], will later be added.

Detector Output

Several factors specific to fast-ramping machines complicate the design of the diode detectors. The parameters of detector components must be chosen taking into account the total amplitude of the signal on a pickup and also the depth of modulations due to transverse oscillations, but these parameters are not constant in the Booster. The position of the closed orbit changes during the course of the acceleration ramp, so the total amplitude of the signal on the pickup changes significantly. Also, the depth of betatron modulation changes dramatically during the acceleration ramp because, due to various sources of instability in the injector, the beam undergoes large oscillations around the closed orbit at injection which damp as the beam is accelerated. Beam-based measurements were therefore more useful than than simulations when choosing the best values for detector components.

Figure 3 shows the output of three prototype detectors, each with different values for the discharge resistor R4, from a horizontal pickup during the first few turns after injection with multi-bunch beam. In these measurements the DC component is not yet removed using a high-pass filter. The output of detector with the shortest discharge time (green) retained excessive revolution frequency content. The output of detector with the longest discharge time constant (blue) showed "drag" due to large changes in signal amplitude caused by large coherent synchrotron oscillations; in this case the signal amplitude sometimes changes too fast relative to the discharge time which distorts the output and reduces sensitivity to betatron oscillations. A 100 kΩ resistor was chosen as the best value, as it does not "drag" near injection and is still sensitive to the much smaller amplitude oscillations during most of the acceleration cycle.

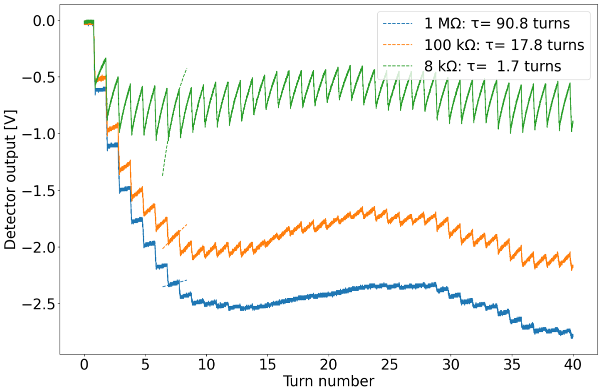
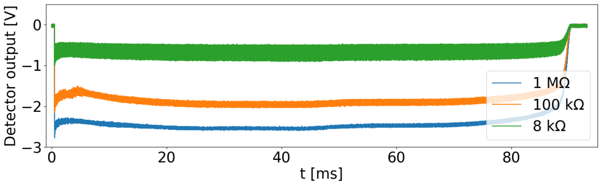
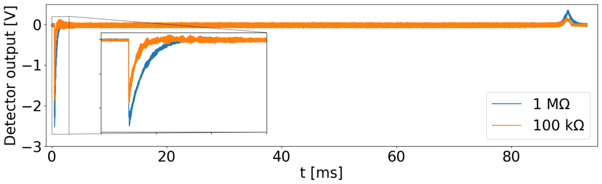


Figure 3: Output and discharge time constant of three prototype detectors, without DC offset filtered out, during the first turns after injection.

The removal of the DC component of the detector, which can be done simply using a series capacitor in the case of a steady-state machine, is not perfect in a ramped machine; there is inevitably some “overshoot” at the points of discontinuity in the signal when the beam abruptly enters or then leaves the machine. Figure 4 shows the output of the three prototype detectors during the full acceleration cycle, again with mult-bunch beam. In Fig. 4a the DC offset is not filtered out, and in Fig. 4b, a high-pass filter is used to remove the DC offset as described in the previous subsection. A large overshoot is present at injection and extraction, and this portion of the signal ends up being clipped when digitized.



(a) Output without DC offset filtered out.



(b) Output with DC offset filtered out.

Figure 4: Detector output from a horizontal pickup during the full acceleration ramp.

TUNE MEASUREMENTS

Here we show a comparison of tune measurements made using turn-by-turn position from the Libera Spark and using the diode detector, measured with single-bunch and with multi-bunch beam. A small, non-destructive white noise excitation was applied.

Figure 5 shows the spectra obtained from the Libera Spark. With full-current (~1 mA) single-bunch beam the tune is visible only briefly, immediately after injection, due to injection oscillations. With higher-current multi-bunch beam (~5 mA), the tune is somewhat visible in the horizontal plane but not in the vertical plane.

Figure 6 shows the spectra from the diode detector. The tune is clearly visible throughout the full acceleration cycle in both planes, even with single-bunch beam.

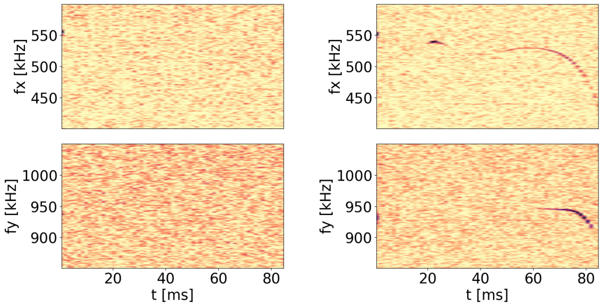


Figure 5: Spectra of Spark turn-by-turn beam position with single bunch beam (left) and multi-bunch beam (right).

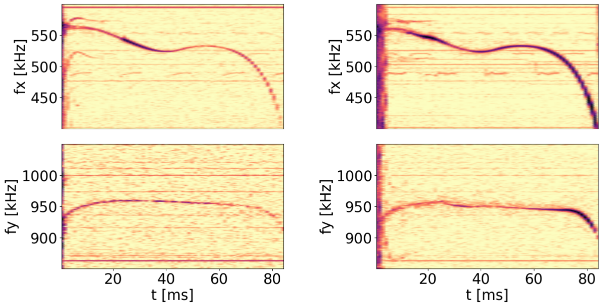


Figure 6: Spectra from diode detector with single bunch beam (left) and multi-bunch beam (right).

CONCLUSION AND OUTLOOK

This first test of tune measurement using a Direct Diode Detector in the BESSY II Booster shows that the increased sensitivity of this method allows for measurement of the tune throughout the fast acceleration ramp without the need for large external excitation. Next steps in the development of this system will include implementation of analog front-end processing to further improve the signal-to-noise ratio and increase the sensitivity of the measurement, and integration into the controls system for constant real-time monitoring of the ramped tune during operation.

ACKNOWLEDGEMENTS

Thanks to Marek Gasior for many helpful and interesting discussions and for providing schematics from previous implementations of this system.

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-THPM047

REFERENCES

[1] E. Weihreter *et al.*, “The BESSY II Booster synchrotron”, in *Proc. EPAC’96*, Sitges, Spain, Sep. 1996, paper TUP007G, pp. 527–529.

[2] M. Abo-Bakr *et al.*, “Commissioning of the BESSY II Booster synchrotron”, in *Proc. EPAC’98*, Stockholm, Sweden, Aug. 1998, paper WEP30G, pp. 436–438.

[3] Instrumentation Technologies, Libera Spark ERXR. `https://www.i-tech.si/products/libera-spark-erxr/`

[4] M. McAteer, G. Rehm, and M. Ries, “Optics corrections and performance improvements in the Bessy II Booster”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 3031–3034. `doi:10.18429/JACoW-IPAC2024-THPC24`

[5] M. Gasior and R. Jones, “The principle and first results of betatron tune measurement by direct diode detection”, CERN, Geneva, Switzerland, Rep. CERN-LHC-PROJECT-REPORT-853, Aug. 2005. `https://cds.cern.ch/record/883298`

[6] M. Gasior, “Faraday Cup Award: high sensitivity tune measurement using Direct Diode Detection”, in *Proc. BIW’12*, Newport News, VA, USA, Apr. 2012, paper MOAP02. `https://jacow.org/BIW2012/papers/MOAP02.pdf`

[7] M. Gasior *et al.*, “First results with a Base Band Tune (BBQ) measurement system at Solaris”, in *Proc. IBIC’24*, Beijing, China, Sep. 2024, pp. 607–611. `doi:10.18429/JACoW-IBIC2024-THP59`

[8] J. Lan, T. Zhou, B. Sun, C. Wang, and Y. Yang, “Development of a high-sensitivity tune measurement system based on diode-detection at HLS-II”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1039, p. 167017, 2022. `doi:10.1016/j.nima.2022.167017`