ORBIT MEASUREMENTS AT THE BESSY II BOOSTER IN PREPARATION FOR QUASI-LOW ALPHA OPERATION

T. Atkinson*, E. Motuk, M. Ries, M. Ulrich,
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (HZB), Germany

Abstract

Diagnostic refurbishments are ongoing at the booster synchrotron in preparation for the near future Variable pulse Storage Ring (VSR) project at BESSY II. Essential orbit measurements have been re-installed after almost two decades of latency. This diagnostic will help assess the effectiveness of possible upgrade scenarios such as quasi-low alpha operation and extraction optimization. The contribution presents the preliminary Beam Position Monitor measurements from the continual global upgrade of the injector systems.

INJECTION REGIME BESSY VSR

A comprehensive description of the injection system at BESSY II was recently given in [1]. In a familiar fashion that characterized 3rd generation light sources across the world, injection into the Storage Ring is from a low energy LINAC followed by a Booster synchrotron. Although the present injection scheme is highly reliable, a global upgrade is foreseen for the BESSY VSR project [2]. The most prominent aspect with respect to the injector is the evidence that the bunch length on injection into the Storage Ring needs to be reduced from its present value, by at least a factor two in order to keep the high injection efficiencies. The problem arises from the large difference in the bunch lengths on injection and the reduced longitudinal acceptance due to the proposed VSR technique as pictorially shown in Fig. 1.

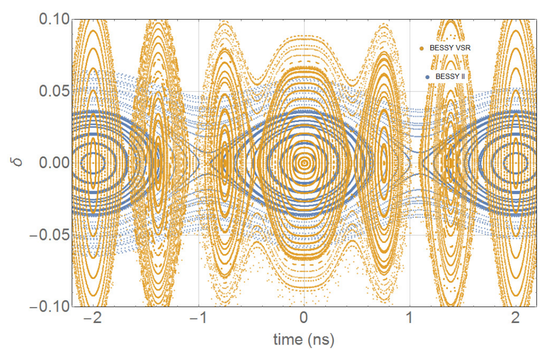

Figure 1: Longitudinal phase space comparison of BESSY II with BESSY VSR.

QUASI-LOW ALPHA IN THE BOOSTER

To complement an upgrade of the existing power capabilities of the accelerating structure in the Booster in order to produce a shorter bunch, a more flexible optic is envisaged. The present optic in the Booster is based on a simple FODO lattice with a 16-fold symmetry. The momentum compaction and hence optic to produce shorter bunch lengths is heavily restricted. Installing independent quadrupole power supplies and breaking the symmetry allows more tunable optic towards low alpha [1]. Such a large scale refurbishment of the existing power supplies requires considerable investment. Minor alterations to the present lattice to test the effectiveness of breaking the symmetry has led to the proposal of a quasi-low alpha lattice. Such a lattice in the BESSY II Booster is achieved by reversing the polarity of each 3rd quadrupole. This simple alteration transforms the original FODO lattice into a quasi-Double Bend Achromat with the quadrupole settings k1, k2, (-k1) and k2.

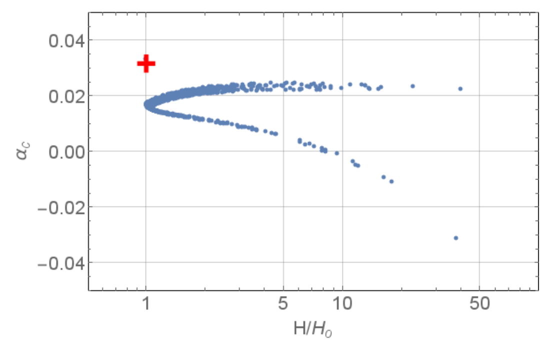

Figure 2: Momentum compaction as a function of transverse beam degradation for a quasi-low alpha optic in the Booster.

Each blue point shown in Fig. 2 represents a randomly generated stable lattice and the chromatic invariant $\mathcal{H}$ value of the horizontal axis portrays transverse beam degradation (emittance equilibrium) relative to the nominal optic. The transition from the present nominal setting depicted as a red cross to a quasi-low optic lattice is troublesome since no stable path therein exists. This notion was emphasized during the first attempts to find a stable optic after the polarity of each 3rd quadrupole was reversed during a 24 hour test. Every single stage such as the injection, the first turn and the compensation of over-steering magnetic elements were flawed by lack of allocated time and limited diagnostics. Driving the optic upgrade onwards is the refurbishment of the latter and is described in the following sections.

BOOSTER BPM SURVEY

All but one of the 32 quadrupoles in the Booster have an associated Beam Position Monitor (BPM). Almost two decades ago an orbit measurement system was in place. Multiplexers were used to switch between BPMs and measure the orbit over many injections. It was only used during the original bringing into service of the Booster and then

* terry.atkinson@helmholtz-berlin.de

remained latent until recently. Unfortunately the original diagnostics were found to be no longer operational; essential data taking components are missing and the software is not system integrated. The multiplexers are mostly irreparable due to defect circuitry. However, four of these RF-switches could be repaired and are now in service. Of course with such a long history of latency, some BPMs needed to be moderately refurbished but now all produce a reasonable signal for an orbit measurement.

COST EFFECTIVE DIAGNOSTICS

In order to test each BPM signal and with it the response of the multiplexers, a cost effective assembly was built around the data acquisition capabilities of the Red Pitaya [3]. The Red Pitaya is a low cost data acquisition platform consisting of two 14-bit 125 MS/s ADC and two 125 MS/s DAC chips. They are coupled to a Xilinx ZYNQ system-on-chip FPGA platform with a 512 MB DDR3 RAM capable of running a Linux operating system. The boards supports up to a 32 GB SD Card that holds the FPGA firmware, the Linux operating system and a free space for the user data. Fig. 3 shows a diagram of the assembly. The raw signal is analogue processed and sent to the RF inputs of the Red Pitaya. The trigger which starts the data acquisition comes from the Booster via the extension connector of the board. Likewise the multiplexers are controlled via the I^2C pins on the connector on the opposite edge of the board. The remote control data acquisition is undertaken by using python and other lower-level custom software that runs on Linux on the system's CPU which is an ARM Cortex A9+ core. The communication to the board is via a Gbit Ethernet port.

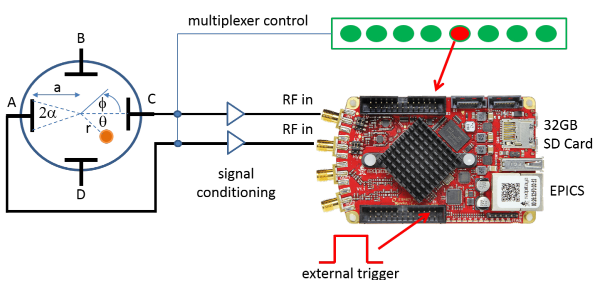

Figure 3: Diagnostic assembly for orbit measurements.

The bunches in the Booster have a 500 MHz time structure from the accelerator cavities and the 5 bunches common during TopUp are usually 12 ns apart, green in Fig. 4. These high frequency components cannot be readily acquired using the Red Pitaya due to its rather low 50 MHz analogue input bandwidth. Therefore each raw BPM signal passes through a bandpass filter, is amplified and mixed with the 500 MHz master clock. The resulting sinusoidal signal, blue in Fig. 4, is imprinted on the 3.125 MHz revolution frequency of the Booster and can be sampled on the Red Pitaya. Individual pulse resolution is lost due to the narrowband processing but the amplitude deviations of orbit motion can be detected.

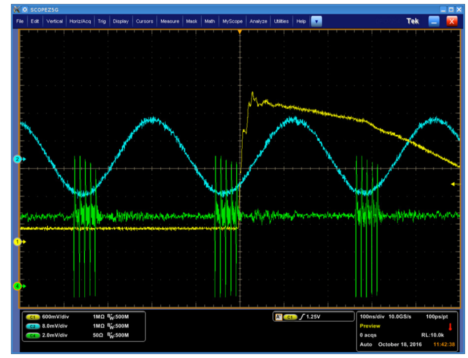

Figure 4: Raw BPM signal of 5 bunches in green, blue after signal processing and Booster ramp trigger in yellow.

FIRMWARE AND SOFTWARE MODIFICATIONS

The data acquisition application that comes with the Red Pitaya board only allows for 16 K 14-bit data points for each RF input upon a trigger. This restriction comes from the fact that after the digital processing (decimation, averaging and equalisation), the ADC data is stored in the Zynq chip's limited internal memory. In order to overcome this limitation we decided to store the digitally processed ADC data in the board's DDR3 RAM which is shared by the ARM processor. The FPGA firmware and the board support package of the system are modified such that a simple DMA scheme is used to store the data in a 128 MB continuous part of the DDR3 which the operating system would not have access to. With a relatively simple C program to configure and control the data acquisition that is initiated in response to an external trigger we were able to store up to 32 million samples for each input channel. This allowed us a full resolution with no decimation (125 MS/s) data acquisition over the entire 10 Hz Booster ramp. An additional Red Pitaya board was purchased and it was configured with the same firmware and software (with the same external trigger) in order to have simultaneous data acquisition in both the horizontal and vertical planes.

2D GEOMETRIC APPROXIMATION

The circular geometry of each 4 port button BPM was used to estimate the good field region [4] and the scaling constant k_x in a linear approximation. Here a thin "pencil" beam is located off-center by r at an angle θ as shown in Fig. 3, and the wall current density j_m is given as a function of the azimuthal angle ϕ.

$$j_m = \frac{I_{\text{beam}}}{2\pi a} \left(\frac{a^2 - r^2}{a^2 + r^2 - 2\,a\,r\cos(\phi - \theta)} \right) \tag{1}$$

The image current I_m can be found by integrating Eq. (1) over the angle α that each button covers in a beam pipe of radius a.

$$I_m = \int_{-\alpha/2}^{+\alpha/2} a \cdot j_m(\phi)\,\mathrm{d}\phi \tag{2}$$

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Figure 5 shows the normalized difference and the logarithmic ratio for a button BPM with an angular coverage of $\alpha = 24^\circ$ as function of on-axis $\theta = 0^\circ$ beam displacement.

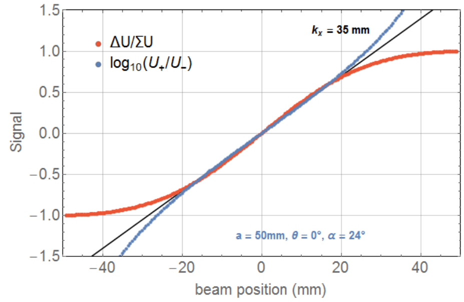

Figure 5: Electro-static approximation of the good field region in a button BPM.

The horizontal displacement X is expressed as the normalization of the image voltage U in each adjacent direction

$$X = k_x \frac{U_A - U_C}{U_A + U_C} = k_x \frac{\Delta U}{\sum U} \tag{3}$$

The good field region in a linear approximation suggests a scaling constant of k_x = 35 mm for the beam pipe of radius 50 mm as shown in Fig. 5 is ±20 mm. Not all of the BPMs have the same dimensions, so suggesting a good field region sightly less than the beam pipe radius is acceptable.

BPM START-TO-END

With the FPGA modifications in place over 6 million data points at 8 ns resolution were taken to measure the signal at each port of a given BPM during the acceleration cycle. Figure 6 shows that the beam is only in the Booster for approximately 35 ms on the acceleration side of the 10 Hz cycle before it is extracted.

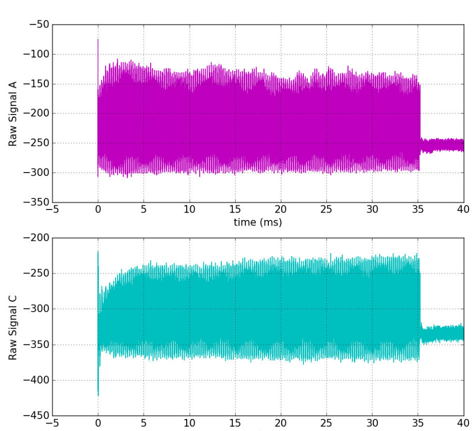

Figure 6: Raw signal over the Booster ramp (every 10^{th} point plotted).

The technique used to post process this large amount of data was based on scanning a moving FFT over the smaller section ~0.1 ms of the raw signal. In this case the turn-by-turn resolution is lost but an average orbit motion over the Booster ramp is attainable. The value of the peak signal at the Booster revolution frequency, where the signal-to-noise ratio is highest, represents U_i for each port. Together with the scaling constant k_x the offset was calculated throughout the acceleration cycle in the Booster.

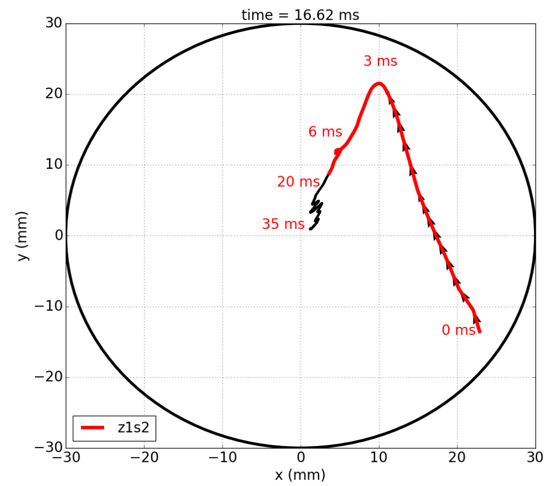

Figure 7: Snap shot of beam motion in a BPM over the ramp, black full path, red animation of data.

Figure 7 shows the beam position at a BPM in sector2 downstream from the injection point. The figure is a snap shot from an animation of the start-to-end orbit during post processing. The injected beam is initially observed off-axis and within the first few ms undergoes a large oscillation. The beam motion is adiabatically damped during the first 20 ms. At extraction the beam has moved towards being on-axis in both planes. Such beam motion is typical in the BPMs.

EXTRACTION OPTIMISATION

The rather slow bump ~0.2 ms applied during extraction from the Booster can be readily observed by further reducing the FFT window to observe turn-by-turn motion. This technique has been used to verify that the orbit bump about the extraction septum is not closed which causes unnecessary transverse beam motion and large synchrotron oscillations. Closing such a bump in a measurable manner using the surrounding BPMs will be a practical application for this diagnostic in order to help improve the overall extraction process to sustain high TopUp injection efficiencies at BESSY II.

REFERENCES

[1] T. Atkinson et al., "Status and prospects of the BESSY II injector systems", IPAC2016, paper WEPOW007.

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[4] P. Forck et al, "Beam Position Monitors", GSI, Germany.