STATUS OF TRANSVERSE RESONANCE ISLAND BUCKETS AS BUNCH SEPARATION SCHEME*

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Abstract

Beam storage close to a tune resonance (e.g. $\Delta Q_x = 1/3$) can generate **T**ransverse **R**esonance **I**sland **B**uckets (TRIBs) in the x, x' phase space providing a second stable island orbit winding around the standard orbit. For users this mode is offered as the "Twin Orbit Mode". The two orbits can be well separated, with good life time and stability. The bunch fill pattern of the second orbit can, to some extent, be chosen independently of the first orbit. Successful user experiments with such an operation mode have been conducted at the **M**etrology **L**ight **S**ource (MLS) and proof-of-concept experiments at **BESSY II** [1,2]. Motivated by the promising results from first common experiments between beamline scientists and accelerator group, a lot of effort was put into combination of the TRIBs operation mode with the TopUp injection scheme during the last year at BESSY II . In order to get a deeper understanding for the experimental conditions a measurement setup for the **T**une **S**hift **W**ith **A**mplitude (TSWA) is under development. In this paper a current status report of TRIBs as bunch separtion scheme at HZB is given and the TSWA measurement is presented.

MOTIVATION AND OVERVIEW

The diverse user community of synchrotron light sources addresses different requirements on the radiation source, often difficult to fulfill simultaneously. In the course of fulfilling most user needs a very specific fill pattern and some special operation modes are offered only for a few weeks per year, e.g. at BESSY II the low-α, a single bunch and since 2017 also a few bunch mode [3,4]. The planned upgrade BESSY VSR [5] will offer short and long bunches in one storage ring, giving strong motivation for a superior separation scheme in addition to the established methods (MHz chopper for the X-ray pulses, fast kicking of the electron bunches to another orbit or pulse picking resonant excitation of one bunch, see [1,6]). We propose an approach using a special setting of the magnetic lattice generating a second stable orbit in the machine using TRIBS. As described in [1,2] and shown here [7] the two closed orbits can be populated at will by using a bunch selective excitation as provided by a **B**unch-by-**B**unch **F**eed**B**ack system (BBFB).

At the MLS first investigations were made and as a first use case the TRIBs mode was used to increase the single bunch repetition time by a factor of three from 160 ns to 480 ns for a first time of flight user experiment [2].

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In contrast to the MLS the implementation of TRIBs as user mode at BESSY II has to fulfill some more stringent requirements, e.g. multi **I**nsertion **D**evice (ID) operation; there are 14 straights equipped with three superconducting IDs and other 12 "normal" undulators. The more restrictive requirement is to fulfill the TopUp injection conditions.

TOPUP INJECTION INTO TRIBS

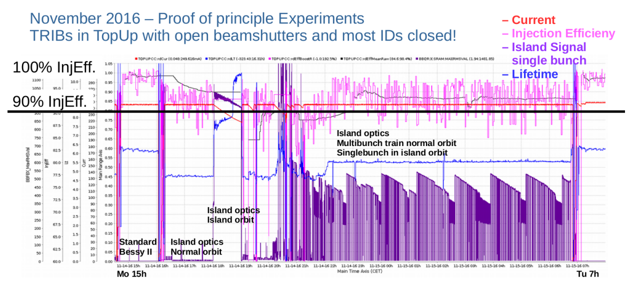

Figure 1: The overall machine performance in the first "TRIBs-with-TopUp-injection" user night. This setting fulfilled the TopUp conditions.

In order to provide the most stable conditions for the user community nearly all 3rd generation synchrotron radiation storage rings provide TopUp injection. This is a full energy injection adding a small amount of charge every few minutes with open beam shutters to refill the decaying current in the storage ring. By this the stored current in the storage ring is kept constant within a ~ 1% level during the whole experimental user time, which provides many advantages compared to a decaying beam. The demands from radiation protection for the TopUp injection process at BESSY II are very challenging:

- The shot-by-shot injection efficiency must be above 60%. A single shot below this threshold automatically stops TopUp. An injection with over 60% with closed beam shutters is required to reactivate TopUp.
- The 4h-average injection efficiency has to be above 90%. If this can not be guaranteed, a decaying beam period will follow.
- The lifetime has to be above a lower limit depending on the current, e.g. 5 h for 300 mA or 4.2 h for 250 mA.

Currently the BESSY II ring is operated with 250 mA, as the Landau cavities [8] are not available due to vacuum issues.

The injection process in the TRIBs differs slightly from the standard procedure. Since two closed orbits are available, it should be possible to inject into both of them. For a fast

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implementation we decided to use the standard four kicker-bump-injection scheme and adapt it as little as possible [9]:

- For the injection process population of the island orbit is avoided. The excitation by the BBFB system is switched on pushing the electrons to the standard orbit. It seems that this excitation has an impact on the standard orbit, which has to be further investigated.
- The harmonic sextupoles in the injection straight are used to improve and guarantee high injection efficiency, whereas the other harmonic sextupole families are adjusted to establish the second orbit.
- Also the skew quadrupoles have a very strong and localized impact on the injection efficiency, which has to be further studied.

The injection process is shown in this short video [10].

This setting has enabled us to run the BESSY II storage ring in the TRIBs mode with TopUp injection and open beam shutters as well as nearly all IDs for one overnight shift. The overall machine performance in this night and the preparing studies are summarized in Fig.1.

We operated the machine with 250 mA current, consisting of a multibunch train and a single bunch in the ion clearing gap, which was the only one pushed to the second orbit. The average injection efficiency was reduced by $\sim 3\%$ compared to the normal BESSY II user mode, but still above 90% (pink). The lifetime was nearly 5 h, shown in blue and the single bunch signal from the other orbit at a bending magnet beamline is shown in purple.

In order to investigate this setting in more detail a complete week in July (03.07.-09.07.2017) was declared as Twin-Orbit-User-Test week. Over the day we will study dedicated questions with our beamline scientists and in the night we will provide normal user time with a single bunch or few bunch fill pattern on the island orbit and a multibunch train on the standard orbit.

In order to get a deeper understanding of the TRIBs operation mode and its injection process, we are working on a Tune Shift With Amplitude measuring setup.

TUNE SHIFT WITH AMPLITUDE

Since January 2013 digital BBFB systems are in use at BESSY II [11, 12]. Besides suppressing transverse and longitudinal beam instabilities in a wide range of machine parameters the fast 12-bit ADC offers excellent diagnostic capabilities. Bunch positions for all 400 bunches over 32k turns and for one specific bunch over 80k turns can be measured. To get the TSWA, the bunch tune is measured as a function of the amplitude. When performed in both transverse planes frequency maps are found [13]. The effect of decoherence and head-tail damping effects [14, 15] on the measured amplitude should be considered when calculating the TSWA. The measurement is realized by exciting a bunch to high amplitudes with a kick that also triggers a BBFB measurement. Figure 2 shows the calibration of ADC counts to mm

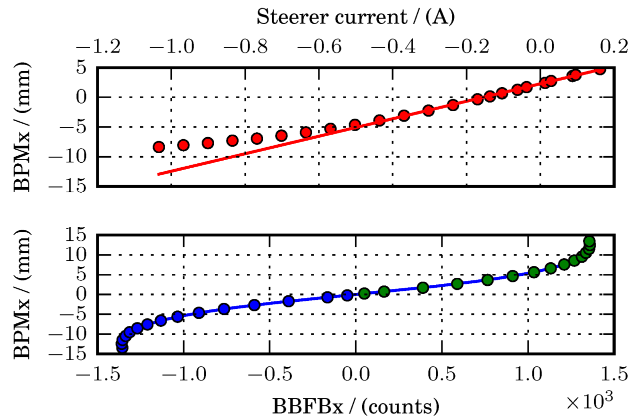

Figure 2: A steerer was used to deflect the beam giving an asymmetric measurement due to aperture (septum). Calibration of the BBFB was found by comparison of current normalized ADC counts (blue) and BPM values (red). Assuming symmetric behaviour the measured counts are extended (green). The interpolation (blue line) is further on used to calibrate current normalized BBFB counts to an offset in mm.

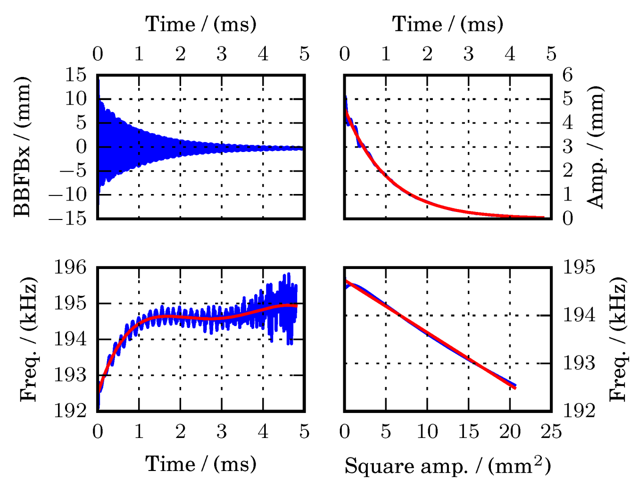

Figure 3: Here a TSWA measurement in standard user mode is shown. The current normalized and calibrated BBFB ADC delivers the oscillation of the excited bunch over many turns (top left). A Hilbert transformation delivers the instantaneous amplitude (top right) and frequency (bottom left) of the betatron oscillation over time. The TSWA is given by the dependence of the instantaneous frequency of the associated amplitude (bottom right). In Standard user mode the TSWA is on the order of $-100\,\mathrm{Hz\,mm^{-2}}$

with the **B**eam **P**osition **M**onitor (BPM) system. The calibration measurement was limited to small amplitudes in one direction due to particle loss but was extended assuming linearity to the kick strength and symmetry in general. Future calibrations can be improved by using local orbit bumps instead of a single steerer. The presented measurement in Fig. 3 shows the TSWA at BESSY II in standard user mode. Since diagnostic kickers were not available the slower

(5 - 6 turns) injection kicker was used to excite the beam. It was tuned to maximum amplitude with reasonable lifetime and for standard optics the subsequent kicks summed up. A tool for online measurement of the TSWA has been developed [16] and provides the possibility to monitor the TSWA using the diangostic or injection kickers for excitation. First measurements for different sextupole settings showed the expected impact on the TSWA.

SIMULATION OF BBFB DATA

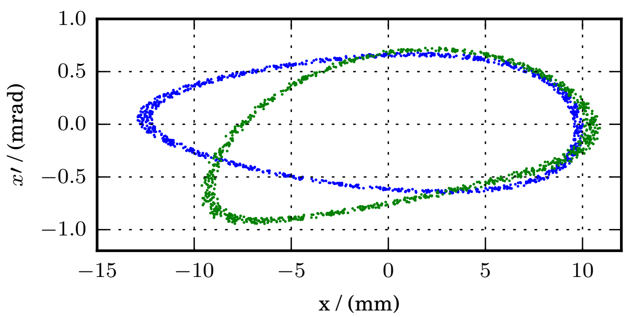

Figure 4: Phasespace plot at injection point (blue) and BBFB measuring point (green) from tracking simulation with elegant illustrating the different amplitudes in x.

For direct comparison of measured data to simulation, the BBFB data is simulated by tracking with elegant. Figure 4 shows the positional dependence of the oscillation amplitude. Therefore the watch point in elegant must be positioned accordingly with the real BBFB system for comparison if the TSWA is not normalized to the twiss functions at the measured position. The tracking results are then evaluated with the same tool as the measurement. The linear optics from closed orbits (LOCO) method is used to generate the linear optics for the used lattice file. The sextupole settings are taken from current conversion factors and for the chromatic sextupoles corrected to give the measured chromaticities. The obtained TSWA for the BESSY II standard optics also lies in the order of $-100\,\mathrm{Hz\,mm^{-2}}$ giving confidence that the tools and methods used can be used to get better knowledge of the non-linear optics of BESSY II .

TSWA SIMULATION FOR TRIBS

The simulation and measurement of the TSWA has two major applications for TRIBs:

- The measurement of global non-linear observables such as the TSWA and chromaticity can be used to verify the non-linear optics which are crucial for the stable operation of TRIBs.
- The simulated TSWA for island optics as seen in Fig. 5 shows the separation of the island tune from those of the core and enclosing buckets. The correlation between tune separation in frequency space and diffusion rates between the different buckets is one of the main aspects of future investigations on TRIBs.

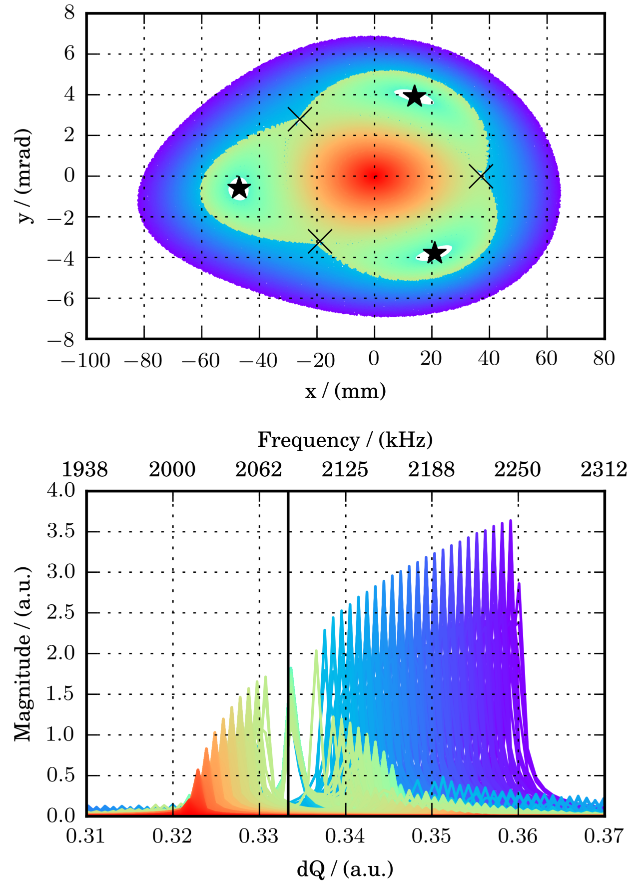

Figure 5: Tracking results for many particles starting at different offsets in x (colors) for the island optics of the MLS. The phase space plot nicely illustrates the core (red), island (★) and enclosing bucket (blue) as well as the instable fix points (×). Below the corresponding frequencies are shown.

CONCLUSION AND OUTLOOK

The TSWA from measurement and tracking simulation are in fair agreement for standard user mode. The developed tool and utilized measuring scheme provide reliable results and a basis for the ongoing studies on TRIBs.
The well established scheme for the LOCO at BESSY II delivers reliable linear optics for use in simulations. A coequal measurement for the nonlinear optics is not yet established at BESSY II . In principle the measurement of the sextupole response matrix with the differential change in TSWA and chromaticity as a function of the different sextupole currents should provide the possibility to gain such a method.

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