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TWO ORBIT OPERATION AT BESSY II - DURING A USER TEST WEEK*

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Abstract

Operating a storage ring close to a horizontal resonance and manipulating the transverse non-linear beam dynamics can generate stable Transverse Resonance Island Buckets (TRIBs), which give a 2nd stable orbit in the ring. Both orbits can be populated with different electron bunch filling patterns and provide two different radiation sources to the user community. Such a machine setting has been established at BESSY II and was tested under realistic user conditions in a first 'TRIBs/Two Orbit User Test Week' in February 2018. Results and user feedback will be discussed in this contribution.

INTRODUCTION & MOTIVATION

Fig. 1 shows the source point image when both orbits are populated with electron bunches. The main purpose of all TRIBs studies [1–4] at BESSY II is to carry out all the necessary proof-of-principle experiments to verify if a **realistic two orbit user operation mode with TopUp injection** is possible.

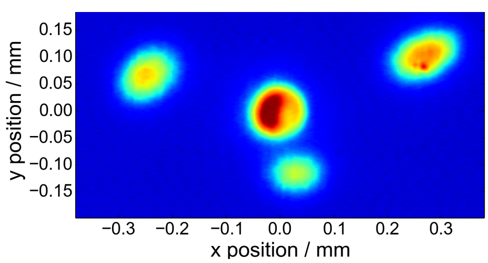

Figure 1: Source point image from a X-ray pinhole camera at a ring dipole at a 1/3 integer resonance. The central beam spot belongs to the main orbit and the three outer spots to the island orbit.

The diverse user community of a storage ring based synchrotron light source sets different and often even contradicting demands on the radiation source. High average brightness and photon flux-hungry experiments led to the development of Diffraction Limited Storage Rings using low emittance multi-bend-achromat (MBA) lattices in order to provide transverse coherent radiation. On the other hand time-resolved experiments focus on other parameters such as:

photon pulse length for high temporal resolution, which drives the BESSY VSR [5] upgrade project and

photon pulse repetition rate for coincidence, relaxation, time-of-flight and pump-probe experiments.

For the upcoming MBA light sources, so far, only very long bunches of a few hundred pico-seconds length in a homogeneous multi bunch (MB) filling are foreseen to avoid reduced lifetime, intra-beam scattering and collective instabilities. This will make time-resolved experiments more difficult at these facilities, which has already triggered an ongoing discussion and the request for timing modes with different pulse repetition rates [6].

The pulse repetition rate can be easily changed in a storage ring based light source by changing the stored filling pattern. The lowest repetition rate is achieved when only one electron bunch is stored in the ring in a so called Single Bunch (SB) operation mode. Since the bunch moves nearly with the velocity of light the lowest repetition rate is given by the circumference, i.e., the orbital period, of the ring. At BESSY II with 240 m, it is 1.25 MHz ($\hat{=}$ 0.8 µs). The highest repetition rate is provided when all buckets are filled. It is given by the frequency of the radio frequency system f_{rf}, which each turn restores the energy electrons lost during radiation. Many storage rings operate with f_{rf} = 500 MHz ($\hat{=}$ 2 ns bunch spacing) as BESSY II, others at 100 MHz ($\hat{=}$ 10 ns bunch spacing) as MAX IV.

Time-resolved experiments require repetition rates from 0.2 MHz to 20 MHz. Single bunch or few bunch fillings fulfill this requirement [7] to a large extent, but due to the lack of intensity needed for the average brightness experiments, they are offered only for a few weeks per year.

Photon pulse and electron bunch separation techniques are an other approach to fulfill the requirements for high average brightness and flexibility in repetition rate, simultaneously. Therefore, at some facilities an advanced electron fill-pattern is stored in the ring [8] and in the best case at each beamline the user can choose the desired radiation source for his experiment.

Temporal separation of photon pulses is realized locally at each beamline by blocking and passing photon pulses with mechanical choppers such as rotating discs with slits or with electro-acoustic choppers based on the grazing incidence x-ray diffraction on fast switching surface acoustic waves.

Spatial separation of electron bunches in the ring is a more efficient and elegant way to provide different repetition rates, since the radiation sources are already intrinsically spatial separated, in the best case available at all beamlines. Two different methods have been established so far: a) the vertical kicking of one bunch of the filling pattern on another vertical orbit with a fast kicker magnet and b) the PPRE, Pulse-Picking-Resonant-Excitation, method. Here, one bunch of the filling is blown up by quasi-resonant excitation in the horizontal plane. By blocking the central part of the radiation of all bunches and accepting only light from the bloated

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fringe area with larger divergence a pseudo single bunch signal is produced with significantly reduced intensity.

With TRIBs, spatial and angular separation of the electron beams comes for free as a consequence of the static magnetic optics resulting in high stability of the separated photon beams.

TRIBS BASICS

The tune working point of the transverse optics is usually chosen far away from resonances, due to the negative impact on the beam quality. In the vicinity of a resonance the dynamic aperture and hence the lifetime shrinks, the beam can blow up, or if the resonance is strong enough, beam storage becomes impossible. By counteracting these effects with non-linear elements such as harmonic sextupoles or octupoles, TRIBs can occur as additional stable fixed points in a transverse phase space. TRIBs are described in known textbooks and literature [9], have been seen in [10] and are used for multi-turn extraction at CERN [11].

The number of stable buckets is given by the order of the resonance. Fig. 2 shows the (x, x') phase space tracking of the BESSY II standard (Q_x=17.848) optics and the TRIBs (Q_x=17.656) optics at the 1/3 integer resonance. In contrast

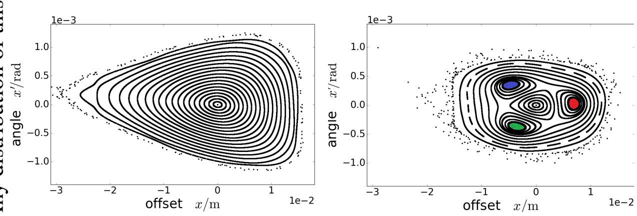

Figure 2: (x, x') phase space for the BESSY II standard (left) and for the TRIBs optics (right). The colors show the position of the orbit at $s = 0$ for the different turns in Fig 3.

to the standard setting, where the electron moves from turn to turn on its elliptical trajectory representing its tune, an electron captured in an island bucket jumps from turn to turn from one fixed point to the next one (red, blue, green, see also Fig. 3). At the 4^{th} turn, it is back on its initial fixed point, which represents a 2^{nd} stable orbit winding in the x-plane around the standard orbit, closing after three revolutions i.e., the order of the resonance. The orbit displacement and angle of the island orbit relative to the 'standard' orbit along the BESSY II ring is shown in Fig. 3. The maximum orbit displacement and angle is up to 7 mm and 6 mrad. There are high β (D)-straights, where the island orbit is displaced by 4 mm to 5 mm resulting in a separation $\geq 13\sigma$ at source sizes of $\leq$ 300 µm, whereas the angle deviation is small below 0.5 mrad. In low β (T)-straights the orbit displacement is small < 2 mm and the angle deviation is large up to 2 mrad.

The machine setting shown in Fig. 2 and Fig. 3 was used in the User Test Week and is a compromise between separation and fulfilling the demanding BESSY II TopUp injection conditions [12]. In principle the separation can be increased up to displacements far above 10 mm, but then the injection efficiency drops. Also the Dynamic Aperture has not been fully optimized (see Fig. 2) resulting in a reduced lifetime of 50%.

TRIBs AT MLS AND BESSY II

First TRIBs studies have been conducted at the Metrology Light Source (MLS - Circumference 48 m and only one ID) designed and operated by HZB and owned by Germany's National Metrology institute, the PTB. It has been shown that the two closed orbits have different horizontal tunes, which can be used by a resonant excitation (for example from the bunch by bunch feedback (BBFB)) to push the charge from standard bucket/orbit to the island buckets/orbit or vice versa [13]. The three island buckets can be populated equally from the bunch of the standard orbit/bucket, giving three island bunches with reduced bunch charge of 1/3. Or the bunch in the main bucket can be pushed into one island only [14]. This was used in a Time-Of-Flight user experiment to increase the revolution time of the small MLS ring from one to three turns, i.e., 160 ns to 480 ns when selecting only one island spot at the beamline [15].

In parallel TRIBs have been implemented at the larger user facility BESSY II with up to 15 insertion device (ID), 13 undulators and two 7 T wavelength shifters. First tests negated concerns about negative impacts on hardware or on beam stability cause by the interplay of insertion devices and island bucket. First common experiments with bending and undulator beamlines showed a good orbit separation. Most motivating was the fact, that the photon flux vanished nearly completely at all ID beamlines when the full current of 300 mA was stored in the island orbit. The achieved purity is also satisfying (> 100, > 1000 SB/MB ratio, depending on the beamline) and even elliptical operation of Apple II type undulator is possible [1].

Setting up TopUp injection into such an optics was the next important step. Therefore the classical 4 kicker injection was adapted to the TRIBs machine state [2]. In addition a Tune Shift With Amplitude measuring tool was developed in order to get better understanding of non-linear beam dynamics. From LOCO and improved simulations the island orbit has been characterized and optical functions were calculated. Emittance is only slightly increased for the TRIBs orbit (from 7 nm rad to 8 nm rad) and together with the separation in (x, x') phase space, it can be adjusted by the tune separation of both orbits using a tune bump. [2, 3].

TRIBS/TWO ORBIT USER TEST WEEK AT BESSY II

In order to verify if the TRIBs operation mode reaches the beam quality necessary for a user operation, in terms of
a.) electron orbit, i.e., photon signal stability
b.) injection efficiency and lifetime, i.e., TopUp conditions
c.) simultaneous use of multiple IDs and bends.
a complete Two Orbit/TRIBs User Test Week was carried out in February 2018. In the first 3 days common experiments with beamline scientists were conducted and afterwards a 'TRIBs User Run' as in a normal beam time has been offered.

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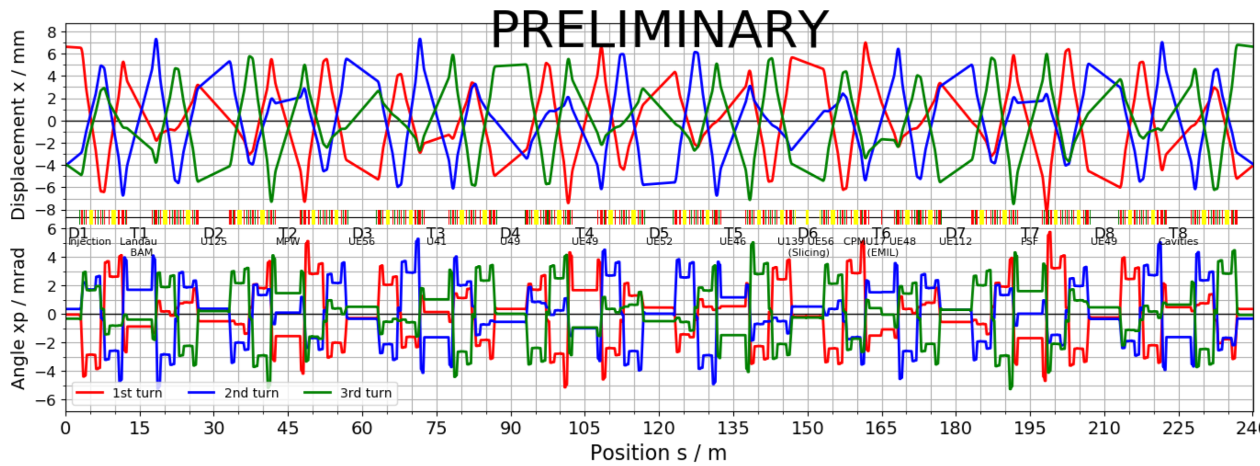

Figure 3: Orbit displacement and angle of the TRIBs orbit relative to the main orbit. The orbit closes after three revolutions, marked according to their sequence in red, blue and green. BESSY II has alternating high (D) and low (T) β-straights.

The storage ring reached an availability of about 99.7%, which is comparable to the standard user mode setting.

More than 20 beamlines participated in this test week, often with aggressive ID settings. The conclusions and response of 13 user feedback are summarized in [4]. In summary, the timing users are very positive and could harvest the SB signal from the island orbit with a repetition rate of 1.25 MHz. The beamlines focusing on the main orbit with the MB filling have not seen a degradation of the beam quality except during the injection. The **TRIBs TopUp injection procedure** is the last big conceptional challenge, which needs to be solved for a user operation.

In addition some technical issues could be improved to make TRIBs running more successful such as

- **additional apertures and X-ray optics** as well as
- **orbit bumps in more straights** are needed for good purity and separation at the beamlines and
- **adaption of the orbit feedback** to two orbits and some more ... .

The TRIBs TopUp injection is explained in Fig. 4 and shown in [16]. The TRIBs injection is based on the classical

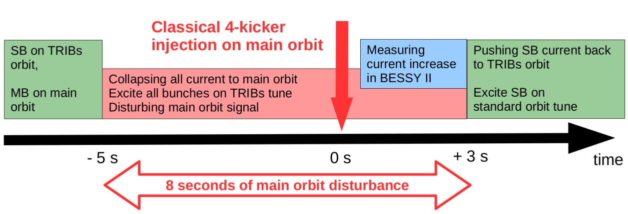

Figure 4: The TopUp injection for the TRIBs setting.

4-kicker injection scheme. That means that current on the off axis TRIBs orbit, will be immediately lost after the kickers fire. Therefore the bunch resolved excitation is used to push all current onto the main orbit 5 seconds before injection. During this time the excitation stays on and clears the island orbit, but it also slightly disturbs the main orbit, decreasing the S/N ratio of the photon signal. Three seconds after the injection the excitation is switched and pushes the SB out on the island orbit. So in total the SB signal on the TRIBs orbit disappears and the signal of the MB filling on the main orbit is disturbed for a time interval of 8 seconds, which is too long for user operation. In near future, we will try to reduce the signal disturbance following two approaches:

- **Reduce the distortion time** by optimizing all steps towards fastest procedure or by using more bunch resolved excitation for better diffusion control between buckets/orbits or
- **Develop independent injection on both orbits** so that no disturbance by the re-population process can occur.

CONCLUSION AND OUTLOOK

TRIBs are explored at BESSY II and MLS and user quality operation has been achieved. Even TopUp User operation at BESSY II has been realized, but still with a slightly disturbance of the photon signal during the injection process. The TopUp injection into a TRIBs/Two orbit setting is the last conceptional challenge towards user operation at BESSY II. However, a User Test week has been devoted to TRIBs and a 2$^{\text{nd}}$ one is planed for 2020. TRIBs as bunch separation scheme in DLSRs is being investigated and a first test at the MAX IV 3 GeV ring showed that TRIBs/Two Orbit is possible in a MBA lattice.

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