RESONANCE ISLAND EXPERIMENTS AT BESSY II FOR USER APPLICATIONS*

P. Goslawski†, J. Feikes, K. Holldack, A. Jankowiak, R. Ovsyannikov, M. Ries, M. Ruprecht, A. Schälicke, G. Wüstefeld, Helmholtz-Zentrum Berlin, Berlin, Germany

Abstract

Beam storage close to a tune resonance ($\Delta Q_x = 1/3, 1/4$) can generate resonance island buckets in the x, x' phase space providing a second stable island orbit winding around the standard orbit. Experiments with such an operation mode have been conducted at BESSY II and the Metrology Light Source (MLS) [1, 2]. The two orbits are well separated, with good life time and stability. Such operation mode will offer additional operation flexibility and allows users to choose their radiation source point from one or the other orbit. It has the potential to fulfill simultaneously conflicting user demands, e.g., high vs. low beam current and single or few bunch filling vs. multibunch filling. We discuss the required beam optics setup and present successful measurements taken at photon beamlines at BESSY II.

INTRODUCTION & MOTIVATION

The diverse user community of synchrotron light sources addresses different requirements on the radiation source, often difficult to fulfill simultaneously. X-ray scattering, spectroscopy, diffraction and microscopy users asking mainly for highest photon flux, not caring about the temporal photon pulse structure, whereas all kinds of timing experiments, such as time resolved, pump-probe and time-of-flight experiments rely on it.

One way to deliver optimized experimental conditions is to split up the user time in dedicated running periods, offering different electron bunch fill patterns, which define the photon pulse structure. For instance, BESSY II allocates three weeks per year for a high current single bunch mode with a repetition rate of 1.25 MHz. Recently, experiments additionally asked for repetition rates of 10 MHz, corresponding to 8 equidistant bunches [3] triggering an ongoing discussion about establishing a "few bunch" mode.

Using bunch separations schemes on a more advanced fill pattern is another way to satisfy user demands simultaneously and to increase the user time for timing experiments. Figure 1 shows the standard 300 mA "Multi Bunch Hybrid" fill pattern at BESSY II, consisting of a multi bunch train of 300 buckets, including 3 × 4 mA slicing bunches. In the 200 ns long filling gap a 4 mA camshaft bunch and a so called 3 mA PPRE bunch (Pulse Picking by Resonant Excitation) is stored for timing experiments.

By using a mechanical fast rotating chopper at photon beamlines [4] pulses can be locally separated and used for timing experiments as done with radiation of the camshaft

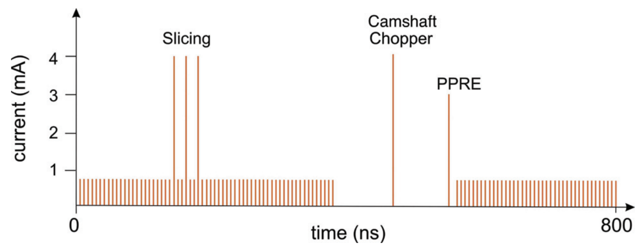

Figure 1: The standard 300 mA "Multi Bunch Hybrid" fill pattern at BESSY II.

bunch. Separating electron bunches in the transverse plane instead of photon pulses is a superior ansatz since all beamlines profit at once if earlier selection is possible. There are two methods available: The Advanced Photon Lightsource (ALS) developed a "vertical kick-and-cancel" scheme [5] using a fast vertical kicker and at BESSY II the PPRE has been recently established, based on a resonant incoherent excitation of one bunch increasing the horizontal emittance [6]. It achieves good signal ratios, i.e., purity of $\approx 10^3$, but the usable photon intensity is drastically reduced.

Except PPRE, these techniques share the necessity of a large gap in the order of 50 ns to 150 ns, since the technical realization of such a fast chopper or a sufficient kick within the bucket spacing of 2 ns, without disturbing further bunches is not feasible yet and arbitrary fill patterns with high intensity, such as a few bunch fill are not achievable.

The method described here uses resonance island buckets in the horizontal plane for separation and was triggered by the BESSY VSR project, which aims to provide short and long bunches simultaneously by upgrading BESSY II with superconducting (sc) cavities [7]. This separation method has the potential to store short and long bunches on different orbits and avoid strong transient beam loading effects by operating without filling gap.

STORAGE RING SETUP

Transverse resonance island buckets are well described in literature and have been studied long time ago, i.e. [8], but at lightsources mostly with the aim of avoiding the negative influence of the resonance on the beam quality. One application is the multi-turn extraction by trapping particles into islands as it is done at CERN-PS and ELSA [9, 10].

At BESSY II resonance islands are investigated as a bunch separation scheme and at MLS they have been used to increase the revolution frequency for a user experiment [11]. In order to achieve islands at BESSY II in the x, x' phase space the horizontal tune is slightly changed from 17.848 toward the 3rd order resonance $Q_x = 17, \bar{6}$. The chromaticities in both planes are set to small positive values by the

* Work supported by German Bundesministerium für Bildung und Forschung and Land Berlin

† paul.goslawski@helmholtz-berlin.de

ISBN 978-3-95450-147-2

two chromatic sextupole families whereas the four harmonic families are used to carefully adjust the amplitude dependent tune shift and generate island buckets. The island buckets provide a 2^{nd} stable closed "island orbit" winding around the standard core orbit and closing after n turns, whereby n is the order of the resonance. At a source point imaging system the island orbit appears as n radiation spots, see Figure 2. The core and island beam have different tunes, with a separation of up to 30 kHz in the tune spectrum, i.e., $\Delta Q_x^{\text{Core}} = 0.66$ and $\Delta Q_x^{\text{Island}} = 0.684$ at BESSY II. For the latest island setting the lifetime τ is reduced for the standard fill with 300 mA (see Figure 1), by a factor of 2 if all current is stored in the core orbit and by a factor of 1.2 for the island orbit. However, this setting was optimized to improve beam separation and not lifetime. Table 1 summarizes the machine settings.

Table 1: BESSYII Island Operation Settings

	Normal optics	**Island optics**	
		Core orbit	Island orbit
horz. Q_x	17.848	17.66	17.684
vert. Q_y	6.725	6.728	6.74
τ at 300 mA	6.8 h	3.5 h	5.5 h

Figure 2 shows a source point image from a bending magnet beamline when operating BESSY II at the 3^{rd} order resonance. Due to coupling the horizontal island buckets are shifted in the vertical plane. The displacement between island and core orbit at this beamline is in the horizontal plane 0.25 mm at a source size of 0.1 mm (rms).

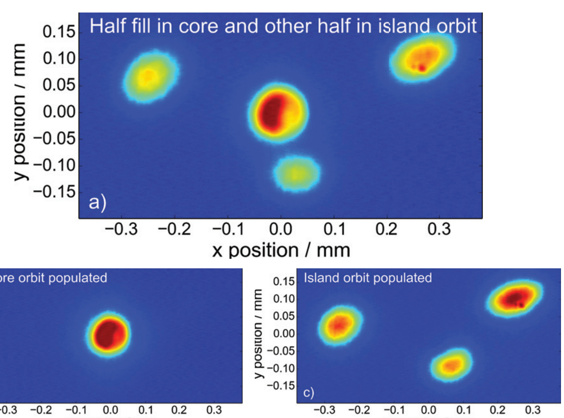

Figure 2: Source point image taken by a hard X-ray pinhole camera (8 keV) at a regular ring dipole at a 3^{rd} order resonance. a) Half of fill in core and other half in islands, b) all current in core and c) all current in island orbit.

The current can be distributed between the two orbits by manipulating the diffusion rates from one orbit to the other one by adjusting tune or the harmonic sextupole setting or by using an external excitation on the different horizontal tunes or their mirror tunes. In order to populate the island orbit, the excitation is applied on the tune of the core beam working as bunch cleaning and vice versa [2]. Using a bunch selective excitation as provided by bunch-by-bunch feedback systems, individual bunches can be manipulated and arbitrary fills can be delivered within seconds.

BESSY II is equipped with 14 insertion devices (IDs), 11 undulators, two sc 7 T wavelength shifters and one sc 7 T multipole wiggler. First tests negated concerns about negative impacts on the hardware or on beam stability because of the interplay of insertion devices and island bucket.

A main concern was that the hard X-ray sc multipole wiggler radiation from the island orbit with larger displacements and angles could be dumped inside the wiggler and damage the hardware. By increasing the separation of the two orbits it was verified that the beam gets lost due to other apertures outside the device and no radiation was dumped inside.

The influence on the tunes when changing the undulator gaps is compensated in the standard user optic at BESSY II by a tune feed forward to maintain a high lifetime and the transverse focusing, i.e., the source sizes at all beamlines. Although, there is no dedicated tune feed forward available for the island setting compensating the tune shift, the island operation and beam quality is preserved when closing nearly all ID gaps.

FIRST EXPERIMENTS AT PHOTON BEAMLINES

First experiments with in-house beamline scientists have been conducted to evaluate the island operation as a bunch separation scheme and if it is worth further developing this machine state, i.e., improving lifetime and injection efficiency for TopUp operation. Measurements have been made at one bending magnet as well as at undulator beamlines.

Bending Magnet Beamline PM4

The soft X-ray bending magnet beamline provides a horizontal intermediate focus at a slit and is therefore well suited for depicting and selecting the radiation source. The source point was mapped by a horizontal scan of the first beamline mirror when all current was stored in the island orbit and showed that the two outer island spots are mutually displaced by 0.5 mm at a source size of about 0.1 mm, corresponding to Figure 2. Once the slit is set to an island orbit spot, which is populated with the camshaft bunch only, the endstation (time-of-flight application) sees a clean 1.25 MHz pulsed source.

Undulator Beamline UE56/1-Apple II

Four undulator beamlines investigated the island operation mode, but only data from the UE56 will be discussed exemplarily. The beamline acceptance of most undulator beamlines at BESSY II is about 0.2 mrad. When all current is pushed to the island orbit, the photon flux vanishes completely at most beamlines, because the orbit separation is much larger than ≈ 0.3 mrad. At the undulator UE56 a orbit bump of 0.23 mrad and a displacement of 0.8 mm of the pinhole was introduced to align one of the island spots on the undulator axis. The photon pulses of the 3^{rd} undulator harmonic (831 eV, linear vertical polarized) have been measured with a fast avalanche photo diode (APD), which was able to resolve the bunch fill pattern. The APD signal

ISBN 978-3-95450-147-2

is shown in Figure 3 for different fills on the island orbit populated by a bunch selective excitation.

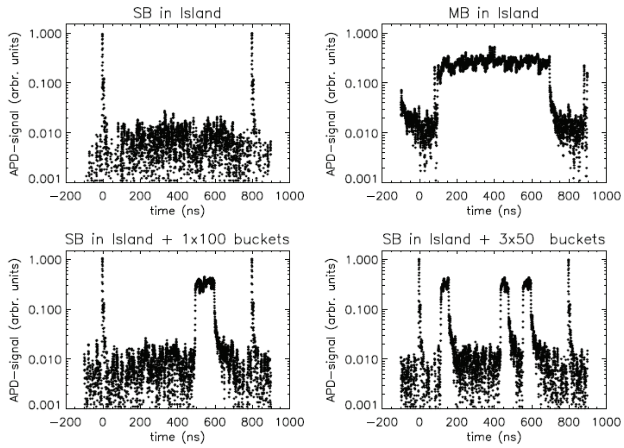

Figure 3: APD signal at the end of undulator beamline UE56 if island orbit adjusted on undulator axis. Different fill patterns have been stored on the island orbit.

In the upper left plot only the camshaft bunch is stored in the island orbit showing the revolution time of 800 ns and all other 350 bunches of the multibunch fill on the core orbit are not visible. The upper right plot shows the inverse situation, achieved by reversing the bunch selective excitation. The APD data reveal that the camshaft bunch on the island orbit can be well separated form the multibunch core beam with good purity (> 100) and further improvements of up to one order of magnitude are expected.

In a second shift the UE56 was operated in a elliptical mode, where the magnetic arrays of the undulator were longitudinal shifted. Again only the camshaft bunch was stored on the island orbit. As depicted in Figure 4, elliptically polarized X-rays of 1333 keV energy were recorded with an APD while the electrons from one of the islands were pointing along the undulator- and beamline axis using a local orbit bump of 0.28 mrad. Photons from the island spot (green) show a typical undulator spectrum while background from the core beam populated with the multibunch fill shows no harmonics since it appears far off-axis is blocked by the frontend aperture and cannot reach the experiment.

The purity ratio is highest (> 100) for the 5th harmonic, but improvable. Operating with this settings allows to measure time resolved X-ray magnetic circular dichrosim (XMCD) spectra with camshaft island bunch photons.

CONCLUSION AND OUTLOOK

The presented studies of island buckets at BESSY II demonstrated that the multi beam storage in island buckets is a very promising beam separation scheme using available hardware and static magnetic fields only. Different fill pattern have been stably stored in both orbits for several hours and photon beams could be separated at dipole and insertion device beamlines. Dipole and wiggler beamlines need at best intermediate foci or slits infront of the final focus to separate photons from islands and the core beam. In order to

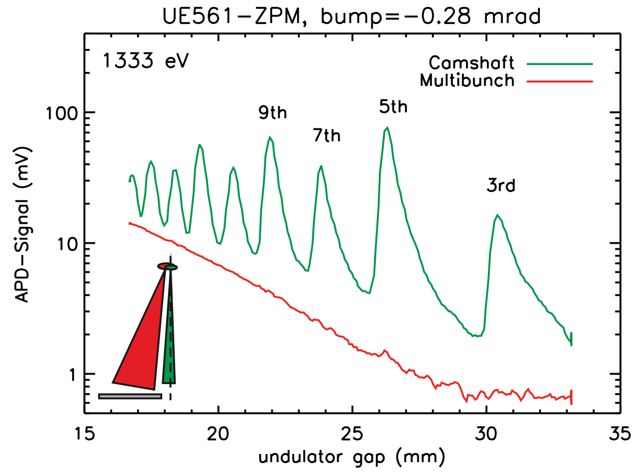

Figure 4: Gated X-ray APD signal recorded during a gap scan of the UE56-Apple II undulator at shift 25 (elliptical mode). The island orbit was aligned to the undulator and beamline axis while the standard orbit passes far off-axis blocked by apertures (insert). Light from the island (green) shows harmonics and from the core beam (red) does not.

point the island orbit along the undulator and beamline axis in the straight sections local bumps are required. Undulator gaps can be changed and their magnetic arrays can be shifted to produce elliptical radiation preserving the island and core beam. Studies of resolution, polarization and stability are ongoing. Currently, BESSY II is capable to offer such a operation mode with decaying beam. Further studies going on to combine the island operation with TopUp injection.

ACKNOWLEDGEMENT

The authors wish to express their thanks to in-house beamline scientists - in particular F. Kronast, F. Schäfers, E. Schierle, and G. Schiwietz, for participating in the first island operation shifts at BESSY II and providing us with helpful feedback.

REFERENCES

[1] P. Goslawski *et al.*, "Bunch Separation by Transverse Resonance Island Buckets", ESLS XXIII Workshop, 2015, Villigen, Switzerland.

[2] M. Ries *et al.*, "Transverse Resonance Islands for Simultaneous Multi Beam Storage at the MLS", in *Proc. IPAC 2015*, Richmond, USA, paper MOPWA021, p. 138.

[3] C. Tusche *et al.*, "Multi-MHz Time-of-Flight Electronic Bandstructure Imaging of Graphene on Ir(111)", *Appl. Phys. Lett.*, accepted and to be published, 2016.

[4] S. Plogmaker *et al.*, "Versatile high-repition-rate phase-locked camshaft system for fast timing experiments in the vacuum ultraviolet and x-ray spectral region." *Rev. Sci. Instruments* vol. 83, p. 013115, 2012.

[5] C. Sun *et al.*, "Pseudo-single-bunch with adjustable frequency: a new operation mode for synchrotron light sources" *Phys. Rev. Lett.* vol. 109, p. 264801, 2012.

[6] K. Holldack *et al.*, "Single bunch X-ray pulses on demand from a multi-bunch synchrotron radiation source" *Nat. Comms.* vol. 5, p. 4010, 2014.

[7] A. Jankowiak, J. Knobloch, P. Goslawski, N. Neumann, editors, “Technical Design Study BESSY VSR ”, Helmholtz-Zentrum Berlin, 2015, doi:10.5442/R0001

[8] E. Crosbie *et al.*, “Non-Linear Resonance Studies at the Synchrotron Radiation Center, Stoughton, Wisconsin” *in Proc. PAC 1991*, San Francisco, USA, p.1624.

[9] R. Cappi and M. Giovannozzi, “Multiturn extraction and injection by means of adiabatic capture in stable islands of phase space” *Phys. Rev. ST Accel. Beams.* vol. 7, p. 024001, 2004.

[10] W. Hillert, “The Bonn Electron Stretcher Accelerator ELSA: Past and future”, *Eur. Phys. J. A.*, vol 28, p. 139-148, 2006.

[11] J. Feikes *et al.*, “Specicific Operation Modes at the Metrology Light Source”, in *Proc. IPAC 2016*, Busan, South Korea, paper WEPOW008.