BESSY II SUPPORTS AN EXTENSIVE SUITE OF TIMING EXPERIMENTS*

R. Müller[†], T. Birke, F. Falkenstern, H. Glass, P. Kuske,
R. Ovsyannikov A. Schälicke, D. Schüler, and K. Holldack, HZB, Berlin, Germany

Abstract

The synchrotron light source facility BESSY II has put top-up and a fast orbit feedback (FOFB) into operation in 2013. Both operational improvements have matured and turned out to be especially beneficial for the advanced timing opportunities supported at BESSY. In combination with very tight injection efficiency requirements a thorough understanding of top-up injections under all operational conditions has been developed. Consequently arbitrary bunch currents can be dialed in and maintained on demand [1]. In standard mode, a very pure camshaft bunch is available both in general for laser pump/X-ray probe and for pseudo single bunch experiments at the MHz chopper beamline. 3 constant high current bunches support the FEMTOSPEX slicing facility [2]. An additional bunch can be resonantly excited and pulse picked via custom orbit bumps at 3 different undulator beamlines (PPRE) [3]. Due to the FOFB the classical timing modes "single bunch" and "low alpha" feature an attractive pointing stability.

OVERVIEW

Capabilities of synchrotron radiation light sources to fulfill experimental user requirements depend on many factors. The most fundamental constraints are based on primary accelerator design and installation decisions: total size, beam energy, intensity, distribution of length and specific beam optics characteristic into segments around the ring. Achievable flux and spot sizes depend on details of photon generating units, the insertion device tuning ranges, the beamline performance and accessibility, etc. Available pulse duration and repetition rates depend on RF frequency, circumference, filling pattern and longitudinal focussing. These are relatively fixed properties of the storage ring.

Resolution of conflicting requirements within the user community of a specific synchrotron radiation (SR) facility by large adjustments of the accelerator tuning is nearly impossible, since this can potentially affect all experiments. Most SR facilities attempt to combine the quasi continuous high brilliance photon flux of even MB fillings with the timing options of the bunched beam into some hybrid mode.

As an additional option the tuning of the BESSY II optics to the nearly isochronous case at very low momentum compaction (low α) matured to an unique and in various aspects attractive short bunch operation mode. Today's viable compromise for the majority of the BESSY experimental community consists of a well defined suite of three base operation modes and a sophisticated beam time distribution fixed for any semester beamtime application block.

The shares of BESSY II beamtime modes try to match demand and supply, resulting in weeks per year (w/y) distributions: 2–3 w/y single bunch top up (SB); 24–36 w/y multi bunch top up (MB); 2–3 w/y short bunch decaying beam (low α); 7–8 w/y machine/beamline development (M/C).

At BESSY it is even more complicated to find common denominators due to the specific inventory on the experimental floor: split mirror units (SMU) allow to sequentially steer the insertion device (ID) photon beam into one or up to 5 beamlines in a time sharing manner. In summary, dipoles and 14 ID straights serve some 50 beamlines, some with accessible open ports for flexible usage. In consequence of this extensive utilization of the SR and the growing demands for time-resolved applications, a specific quest for hybrid variants of the main operation modes result.

Thus at BESSY sophisticated filling patterns as well as manipulation and separation techniques of custom bunches have been developed for the MB and low alpha modes. These tailored configurations allow for a new class of time resolved experiments along with the underlying MB majority user mode. Use cases of the minority modes as well as accelerator specifics involved are subject of this paper.

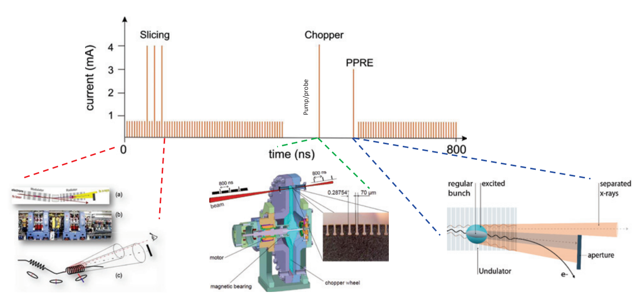

Figure 1: Specific bunches and their bunch currents (Top Up) in BESSY II standard fill pattern, illustrated by their use cases and separation schemes, respectively.

TIME TUNING RANGES

The variation scope in sample sensitivity, system times, excitation and detection methods is huge. Excitation techniques for pump pulses in combination with the triggered sample properties can be very fast and frequent (up to a few GHz electrical, MHz laser etc.). Options to match parameters on the accelerator side are quite limited. On the SR probe

* Work supported by the German Bundesministerium für Bildung und Forschung, Land Berlin and grants of Helmholtz Association
† Roland.Mueller@helmholtz-berlin.de

side (X-ray, THz), pulse intensity, duration and separation are very much linked to bunch charges, length and separation. Finally, at the detection side, there are other specific constraints. Here sample relaxation characteristics, signal arrival time, max allowed event time matter (space charge, TOF geometries, detector dead time, damping times).

At the light source BESSY II available pulse durations range from 100 ps (13 mA SB), 30 ps (300 mA MB) 5 ps–2 ps (100 mA–5 mA low α) to 100 fs (slicing [2]). The light pulse temporal separations cover 2 ns (RF bucket separation), 800 ns (circumference) and possible multiples.

Within the limits of standard user- and low alpha optics the effective bunch length can be tweaked by the bunch charge and the longitudinal focussing, adjustable by the 4 HOM damped 500 MHz fundamental cavities and the 4 passive 3^{rd} harmonic copper cavities, the latter set to shortening or lengthening mode. The BESSY VSR project [4] promises an order of magnitude improved pulse duration variation by the proper combinations of strong longitudinal focussing and bunch charge variations.

BUNCH SEPARATION

The simple plain SB mode with a high current singular bunch and a full 800 ns dark gap is still well suited for classical time of flight (TOF) experiments, conventional X-ray choppers can be used to further downscale the pulse repetition frequency to some kHz. Developments for SB mode at BESSY benefit from stabilities of top up and FOFB, and the well controlled purity ($> 10^4$).

For fast detecting experiments like the scanning X-ray microscopy (STXM, MAXYMUS beamline) the 2 ns MB bunch separation is already very well suited. Time resolution of STXM can be improved by an efficient damping of the longitudinal bunch motion and a small phase transient, induced by the dark gap.

Other experiments depend on the separation of usable photons from unwanted beam. This can be either the gating of the detector or selection of photons by blocking of the unwanted *background* beam (chopper, scraper).

For the majority of pump-probe experiments a purity controlled camshaft bunch in the middle of an 5 ns – 120 ns ion clearing gap (camshaft bunch) is adequate, e.g. for static gate box car averager data acquisition or for a gated PILATUS area detector. At BESSY a gating module for the delay line detector of the Scienta ARTOF [5] is studied. Photoelectrons are deflected by a potential pulse to a gold mesh close to the detector, here a 150 ns dark gap is sufficient to improve detection efficiency by a factor of 20.

True turn-by-turn isolation of the camshaft X-ray pulses by a mechanical 1.25 MHz pulse selector [6], based on a (2 ns precision) synchronization with the RF clock and an extended dark gap of 184 ns, make the full 4 mA camshaft intensity available as pseudo-SB during standard BESSY user service.

Opposite to gap and camshaft three 4 mA bunches are maintained to be sliced by a 6 kHz high power 20 fs laser. The short energy modulated X-ray pulses are separated from the undulator core beam by a horizontal bump of the electron beam and a slit [2]. The fs THz pulses emitted from the slicing hole in the bunch is guided to the THz end station at the downstream dipole.

A bunch near the end of the gap is filled to 3 mA and horizontally excited at the tune resonance. Radiation from this enlarged bunch bypasses the core beam and can be simultaneously used in 3 undulator straights, following the horizontal photon separation principle by proper bump and slit settings there (PPRE [3]).

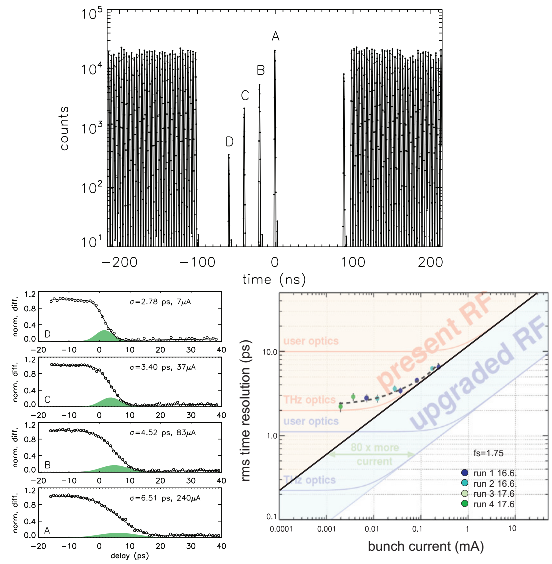

Figure 2: Tuning bunch lenght (lower right) and X-ray pulse length (lower left) by bunch charges in low α mode employing a staircase pattern (upper) in the dark gap [4, 7, 8].

Another option is the orbit separation of specific bunches, e.g. the kicking of the camshaft bunch (ALS kick/cancel [9]). Or the simultaneous filling of a core beam and well separated resonant island buckets [10]: tests at BESSY have shown a clean 0.3 mrad beam pointing separation.

Optical beam choppers using the reflective properties of mirrors, the diffractive properties of rotating crystals, or surface acoustic waves (SAW) have been proposed in many configurations at synchrotron light sources. The fast bunch isolation by a several ns pulsed SAW has been characterized using the BESSY camshaft bunch and intense work on this X-ray separation technique is in progress at the HZB [11]. Today micro electro mechanical systems are under development that promise, at least for hard X-rays, dynamic and miniature X-ray optics for focussing, wavefront manipulation, multicolour dispersion, and even pulse slicing [12].

ACCELERATOR ADAPTATIONS

Primary key to the various timing options is a custom tailored stable but flexible bunch current fill pattern. During BESSY top up user mode a very robust control program maintains the requested bunch charges, obeying the allowed range of charges and repetition rates, by singular shots varying from 1 to 6 bunch injections [1].

ISBN 978-3-95450-147-2

Unwanted charges, e.g. the purity of the gap, is controlled by a vertically acting knock out amplifier, that is triggered at the injection shot. Other charge reduction or cleaning can be done with the bunch-by-bunch feedback (BBFB) system.

In low α mode injection efficiencies < 60% do not allow for top-up. Thus in low α weeks 12 h/12 h operational blocks offer a half day of high current decaying from initial 100 mA. After scraping to <15 mA the following half day features non-bursting, steady CSR THz.

Testing BESSY VSR ideas [4] the usability of the short bunch length in the very low current regime, below the bursting threshold have been explored. A custom stair case fill pattern in the dark gap covered 240 μA down to 7 μA (Fig. 2). Precise bunch currents have been set up by aperture scraping with selective BBFB bunch excitations. The expected transition from turbulent bunch lengthening to the zero current limit could be verified. Even the shortest 2.8 ps low current bunch could be used for experiments (Fig. 1) [7].

In order not to ruin the purity relevant region around the camshaft bunch, today only the shortest bunch is provided as low current bunch (LC in fig. 3) at the beginning of the gap, together with the PPRE bunch at the end.

DIAGNOSTICS

Bunch length and phase can be measured at BESSY with a Hamamatsu C5860 Streak camera. Trombone sweep delay scans of the bunch charge profile is routinely performed with the fs slicing laser at 300 fs precision and sensitivity [13]. The fast bunch resolved digital data of the BBFB and the STXM time machine provide valuable additional timing informations.

Chromaticity and beam spectral measurements help to adjust momentum compaction and the longitudinal focussing of fundamental and harmonic cavities. Selective longitudinal damping of the BBFB can provide an effective shortening of the PPRE excited bunch, from an undamped 55 ps down to 41 ps.

For quality control of beam details, i.e. absolute and relative bunch currents (purity) time correlated single photon counting devices (TCSPC, APD, picoharp) are available. Ultra-sensitive analysis of strip line signals enable fast and precise fill pattern analysis, bunch resolved orbit measurement and surveillance of the synchronous phase.

LIMITATIONS, CONFLICT OF INTERESTS

Being a multi user, multi installation facility imposes serious limitations, even to small details of the base operation modes. Shielding and cooling specifics of the recently refurbished 7 T super conducting multi pole wiggler (SC MPW) can stand only a certain heat load induced by the beam. At full SR current of 300 mA this requires *long* bunches, limiting the longitudinal focussing. Otherwise the LHe inventory of the vessel boils away within a few hours.

The present version of the mechanical MHz chopper requires 184 ns gap in the bunch train, the second generation device will improve this to only 100 ns already this year. Generally, a *long* gap increases the charge within the remaining bunch train, reduces the lengthening capability of the 3^{rd} harmonic cavities and can cost operational head-room of about 0.5 h lifetime. Both long bunches and long gap increased bunch phase transient have a strong adverse effect on today's STXM DAQ time resolution.

Some minor effects might not be noticeable: the increased energy spread of the sliced bunches is probably only visible by the beam diagnostic systems. The brilliance is slightly reduced by the excitation of the PPRE bunch, this might affect e.g. the contrast of lens less imaging. In low alpha mode the lifetime of the PPRE excited bunch can become very small, even at moderate amplitudes, this can require a smart selection of excitation/experimental times, or negotiations on the still filled camshaft bunch.

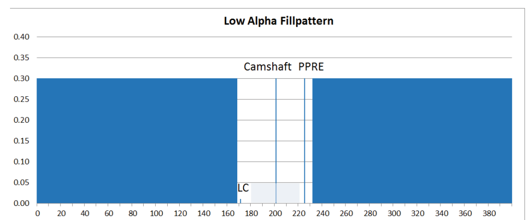

Figure 3: MB Hybrid filling in low α mode.

Other conflicts of interest are easily solved: the bunch separation of PPRE and slicing happen both in the horizontal wings, but at easily gated frequencies (1.25 MHz and 6 kHz, 400 ns apart). Purity requirements and the opposing stair case filling(s. fig 2) could be resolved by choosing a specific bunch at a fixed position (s. fig 3).

SUMMARY

Key to the enhanced usability of BESSY II for timing experiments with special requirements is a combination of: (1) The robust and stable pulses from the LINAC and booster chain, injectable with constant high efficiency (2) filling, manipulation and steering of individual bunches at specific beamline locations. (3) stability increase provided by the FOFB, which made a *parasitic* use of the low α mode attractive, giving more weight to the development of this short pulse mode.

The pulse shaping made feasible by the BESSY VSR project [4] and the orbit separation of specific sub-fillings of resonant island buckets [10] promise to open a new branch of synchrotron based timing experiments.

ACKNOWLEDGEMENTS

The authors appreciate many elucidating discussions with M. Ries and M. Ruprecht. Support of G. Schiwietz, F. Sorgenfrei and D. Kühn in establishing a robust PPRE operation mode is gratefully acknowledged.

REFERENCES

[1] T. Birke, et.al. *Comprehensive Fill Pattern Control Engine: Key to Top-Up Operation Quality*, Proc. ICALEPCS 2015, Melbourne, Australia, 2015, `http://icalepcs2015.vrws.de/papers/moc3o01.pdf`

[2] K. Holldack, et.al. *FemtoSpeX: a versatile optical pump-soft X-ray probe facility with 100 fs X-ray pulses of variable polarization.* Journal of Synchrotron Radiation 21 (2014), p. 1090-1104 `http://dx.doi.org/10.1107/S1600577514012247`

[3] K. Holldack, et.al. *Single bunch X-ray pulses on demand from a multi-bunch synchrotron radiation source*, Nature Communications 5 (2014), p. 4010/1-7 `http://dx.doi.org/10.1038/ncomms5010`

[4] A. Jankowiak, J. Knobloch, P. Goslawski, N. Neumann, editors, *Technical Design Study BESSY VSR*, Helmholtz-Zentrum Berlin, 2015, `http://dx.doi.org/10.5442/R0001`

[5] Scienta ARTOF–2 10k, `http://www.scientaomicron.com/en/products/358/1215`

[6] D. Förster et al., *Phase-locked MHz pulse selector for x-ray sources*, `https://www.osapublishing.org/ol/abstract.cfm?uri=ol-40-10-2265`

[7] Karsten Holldack, HZB, in preparation, `karsten.holldack@helmholtz-berlin.de`

[8] J. Feikes et al., *Sub-Picosecond Electron Bunches in the BESSY Storage Ring*, Proc. EPAC 2004, Lucerne, Switzerland (2004).

[9] C. Sun, et al., PRL 109, 264801 (2012).

[10] P. Goslawski et al., *Resonance Island Experiments at Bessy II for User Applications*, presented at IPAC'16, Busan, Korea, 2016.

[11] Ivo Zizak, HZB, private communicaiton, `zizak@helmholtz-berlin.de`

[12] D. Mukhopadhyay et al., *X-ray photonic microsystems for the manipulation of synchrotron light*, `http://www.nature.com/ncomms/2015/150505/ncomms8057/full/ncomms8057.html`

[13] K. Holldack et al., *Bunch Shape Diagnostics using Femtoslicing*, Proc. EPAC 2006, Edinburgh, Scotland, THPLS016 (2006).

ISBN 978-3-95450-147-2