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OVERVIEW OF BUNCH-RESOLVED DIAGNOSTICS FOR THE FUTURE BESSY VSR ELECTRON-STORAGE RING*

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Abstract

The upgrade of the BESSY II light source in Berlin towards the Variable pulse-length Storage-Ring BESSY VSR leads to a complex fill pattern [1-3]. This involves co-existing electron bunches with significant variations of their properties. Among many other boundary conditions, this calls for bunch resolved measurements with sub-ps time resolution and micrometer spatial resolution.

Currently, we are constructing a diagnostic platform connected to new dipole beamlines for visible light as well as THz measurements. The mid-term aim is a 24/7 use of beam-diagnostic tools and the development of advanced methods for specific purposes. Recently, we have set-up a sub-ps streak camera [4] and we are investigating other innovative methods for bunch-length [5] as well as lateral size determination using visible light [6,7] at the first of our new diagnostic dipole beamlines. Preliminary results as well as our concepts for achieving high sensitivity, good signal-to-noise ratio and time resolution will be presented and discussed below.

TRANSITION FROM BESSY II TO BESSY-VSR OPERATION

The current BESSY II electron-storage ring of the Helmholtz-Zentrum Berlin (HZB) is operated at the electron energy of 1.7 GeV for a cavity frequency of 500 MHz. The typical ring current is 300 mA. Different optics modes are available and various bunch-filling patterns are distributed within the 400 buckets that are separated by approximately 2 ns.

The upgrade of the BESSY II light source towards the **V**ariable pulse-length **S**torage-**R**ing BESSY VSR [1-3] involves a triple-cavity structure at high mean electric field strengths. Thus, the bunch lengths may be significantly reduced at fixed bunch-charge values, see Fig. 1. This means that time-dependent X-ray experiments (coincidences, pump/probe measurements, etc., see ref. [8]) will gain time resolution, whereas precision spectroscopy and scattering experiments running in parallel profit from stable large mean currents for a matched bunch pattern.

Superposition of 0.5 GHz (BESSY II) and additionally 1.5 GHz and 1.75 GHz SRF (superconducting RF) at high voltages leads to a beating pattern of the field gradients and a corresponding formation of alternating short and long buckets every 2 ns. This will be the basis of an even more complex filling pattern with co-existing electron bunches that differ significantly regarding their bunch length, bunch charge as well as transverse profile and charge density. Thus, bunch resolved diagnostics of lateral size, position and bunch length with high sensitivity, good signal-to-noise ratio and high time resolution are demanded. This calls for new or at least improved properties of the future beam-diagnostics hardware.

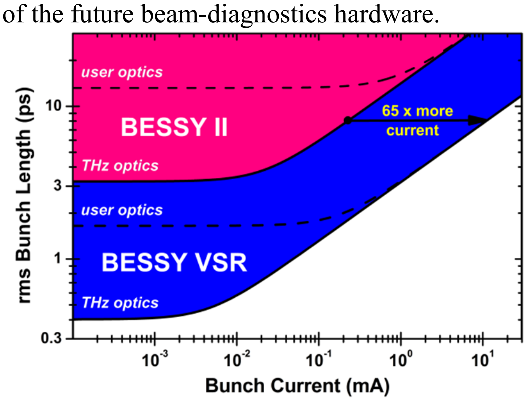

Figure 1: Comparison of standard user optics as well as THz optics for BESSY II with the future BESSY-VSR system, considering realistic SRF boundary conditions.

BUNCH-RESOLVED OPTICAL DIAGNOSTICS

New Platform and Beamlines

The diagnostic platform features visible-light output ports from two dipole beamlines (see Fig. 2) equipped with X-ray blocking baffles. Each outlet of the evacuated beamlines is fed through a radiation labyrinth and ends in a wedged glass window. The design target of the VSR diagnostic systems is 24/7 availability, robustness and sufficient space for future R&D.

One beamline (*Sector12-Dip1.2*) will be equipped with planar precision mirrors optimized for phase stability for the transverse size monitor (see next subsection). Another beamline (*Sector12-Dip1.1*) is optimized for high photon yields (opening angles of 20 x 5.6 mrad) and consists of precise ellipsoidal and toroidal focusing mirrors. This beamline is in operation since January 2019 and it is coupled to one optical table, mainly for bunch-length measurements (see further below). Both optical tables are air damped against the influence of ground vibrations and during the next few months they will be encased by an air-conditioned hutch against the influence of dust, external sound and unwanted stray light. Additional space is available outside the hutch for computer controls, work benches and storage.

A third beamline (*Sector12-Dip2.1*) will be used exclusively for THz intensity measurements and spectral THz

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investigations. This beamline will be placed inside the BESSY II ring tunnel far above the ring level for reducing radiation damage in the THz detector.

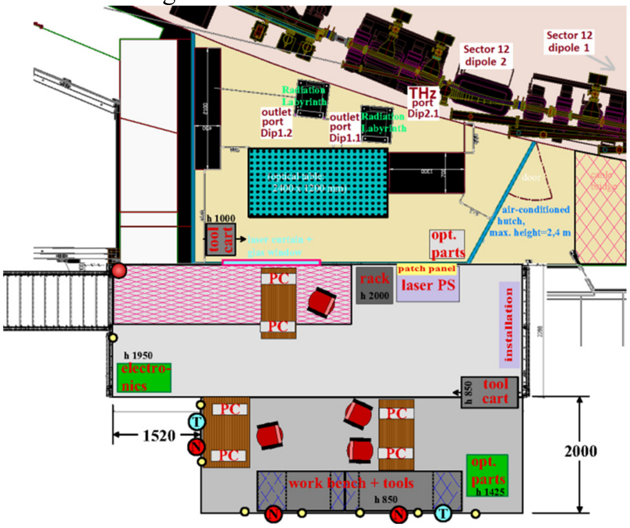

Figure 2: Scheme of the VSR Diagnostic Platform.

Transverse Beam Size: Interferometry

Double-slit interferometry using visible light in an optical Interferometric Beam-Size Monitor (IBSM) has already been proven at BESSY II [9-10] and will be installed permanently at the new diagnostic beamline *Sector12-Dip1.2*. The IBSM principle and accurate transverse beam-size determination with this method has been presented in detail elsewhere [4,9-11]. Typical raw data from our preparatory investigations of this method are shown in Fig. 3.

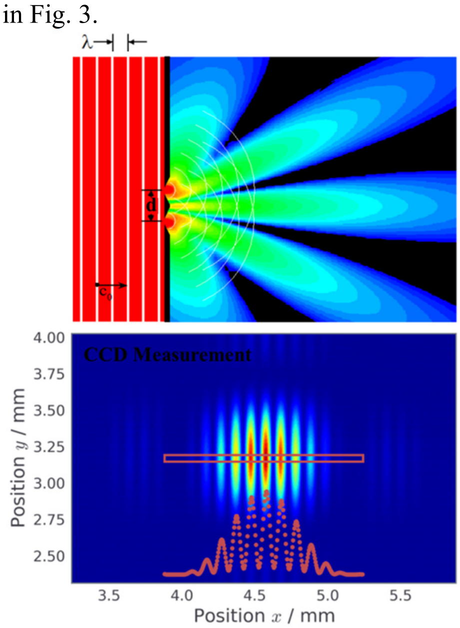

Figure 3: Transverse Interferometry: calculated double-slit interference pattern (upper plot) and CCD pattern taken at a diagnostics test beamline (lower plot).

A slit separation large compared to the selected photon wavelength yields a narrow interference pattern, where the intensity at the destructive minima is very sensitive to the beam size for incoherent photons. Compared to the existing BESSY X-ray pinhole systems [12], our tested IBSM leads to a significantly improved size resolution (11 vs. 27 µm) [13].

The new beamline shall start operation during the year 2020. It will involve an advanced optical system with high quality adjustable mirrors and an X-ray blocking baffle, less sensitivity to vibrations as well as an additional interference stage. This stage will be at reduced distance from the dipole source, enabling improved resolution at small beam sizes. All these measures should further improve the position resolution and robustness of the method. Finally, a fast gated intensified CCD camera (ICCD camera type XXRapidFrame by Stanford Computer Optics) will enable bunch-resolved interferometry for transverse beam-profiling with minimum exposure times of 200 ps. However, the low ICCD timing jitter of 10 ps rms (including adjustable delay) calls for an improved accuracy of the BESSY revolution trigger, see further below.

Bunch Length: High Time-Resolution and 2D Streak Camera Modes

One of the new diagnostic beamlines (*Sector12-Dip1.1*) is already in operation. The transfer optics after the evacuated part enables selection of polarization direction, wavelength, bandwidth, as well as an exchange of the transversal directions on the optical table. Measurements with a fast streak-camera (FSC) and also geometrical beam imaging of larger profiles as well as interferometry of the vertical beam size by using the X-Ray baffle method [6,14] are possible. This beamline is currently being optimized (installation of an improved toroidal mirror M2, new RF divider, further motorization, etc.) and thus, the results discussed here are preliminary to a certain extend.

The FSC (type HAMAMATSU C10910) involves a high synchro-scan-repetition rate of 1 kHz and the estimated time resolution is 0.9±0.2 ps FWHM (σ≈0.37 ps rms), after consideration of external sources of timing jitter [4]. It involves a vertical scanning frequency of 125 MHz derived from the 500-MHz ring RF (divided by 4). Thus, only every second bunch can be detected directly (say the even bunch positions of the filling pattern). Using a beam splitter and a delay stage in a Michelson configuration, pulses from the other fraction (e.g., odd bunch positions) may be delayed by 2 ns to become visible in the FSC.

Results of this FSC double-pulse mode are displayed in Fig. 4, for the BESSY II low-α mode at a ring current slightly below 15 mA. At the horizontal time axis (slow sweep) below 50 ns and above 150 ns, one may see four rows with the multi-bunch train, where each consecutive bunch is filled (real time difference is 2 ns). Some bunches [8] appear only in the lower row. Two of the four rows represent a signal from the upward sweep plus the downward sweep of the (fast) vertical FSC time axis (bunch number $1{+}4n$ and $3{+}4n$). The FSC double-pulse method leads to the other two rows for bunch numbers $2{+}4n$ and

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4+4n. Thus, we are able to investigate all bunches in parallel and the distance between neighboring bunches inside each FSC row is 8 ns, allowing for encoding of additional information along the slow-scan axis.

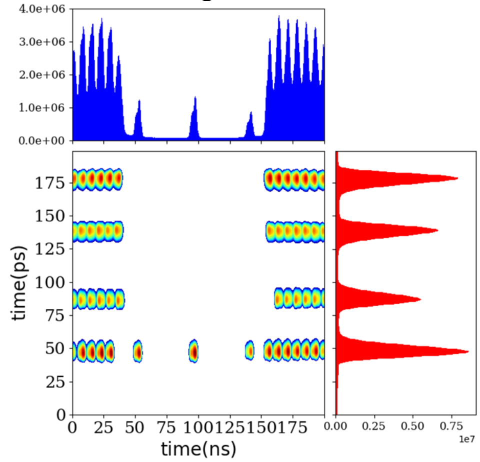

Figure 4: FSC data of the BESSY II low-α mode for the central 200 ns out of 800 ns bunch-fill pattern.

The FSC beamline and transfer optics is optimized for high quality image reproduction at a light-path length of about 18 m from the dipole source. The horizontal entrance slit of the FSC (at a typical slit opening of 13 µm) cuts a horizontal slice out of the focal spot and determines also the time resolution. When a small time range is selected for the horizontal scan axis (100 ns in Fig. 5) and the vertical FSC collimation is wide open, horizontal position and size information are encoded in the horizontal bunch shapes (along the slow-scan axis). As the vertical bunch shape contains the time information of each bunch, we are able to measure bunch-resolved 2D spots. Dependent on the chosen configuration of transfer-line mirrors, we may acquire horizontal or vertical beam shapes vs. the time distribution of each spot. The third parameter (the other transversal direction) may in principle be scanned sequentially. Even a correlated three parameter-detection is in principle possible for single-bunch operation [15], but not intended at the moment.

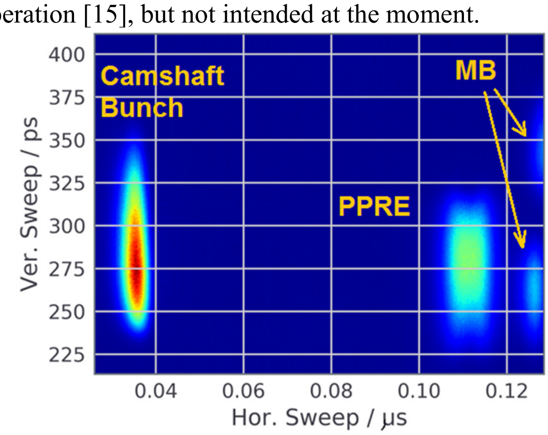

Figure 5: FSC measurement, showing the 2D time- and horizontal-size- variation for different bunch types.

One 2D example is shown in Fig. 5, for the standard BESSY-II user fill-pattern at top-up conditions. The plot shows the camshaft bunch (with 4mA partial ring current) at the center of the pseudo-single-bunch gap, the PPRE bunch (3mA) for pulse picking by resonant excitation [16,17] and two bunches of the Multi-Bunch train (MB with 0.8 mA per bunch). One can see that each vertical bunch size (the bunch length) depends significantly on the bunch charge. The PPRE bunch, however, is much wider than all other bunches. The reason is an excitation by a resonant horizontal electrical-field oscillation giving rise to a horizontal broadening of a specific bunch. Several types of bunch-resolved 2D measurements of size or position dependencies at specifically excited electron buckets or also Transverse Resonance Island Buckets (TRIBs, see [18]) have been tested successfully in the meanwhile [13].

Accurate Trigger Signals

Both, the FSC as well as the ICCD operation are strongly dependent on the quality of the trigger signals. Thus, we have determined the timing jitter of a variety of different timing signals using a Signal-Source Analyser (SSA, for the partial jitter frequency range from 1 Hz to 20 MHz) and a fast Mixed-Signal Oscilloscope of type Tektronix MSO 71254C (effective bandwidth of 1 kHz to 12.5 GHz at 100GS/s). For the SSA we extrapolate the differential phase-noise signal to the specific investigated frequency and for the MSO we restrict the bandwidth correspondingly (using the digital band-path filter), perform a more accurate offline analysis and subtract the internal trigger/acquisition jitter of 270/100 fs.

The 500-MHz RF transmitted from the master oscillator via an optical line to the diagnostic platform yields an rms timing jitter of σ=640 fs. The FSC needs a 125-MHz signal derived from the cavity RF after division by 4. Here we have tested two low-jitter frequency converters

- HAMAMATSU FSC device yields σ= 1.55 ps (measured with SSA and MSO).
- Optronis LJFD/H4 yields σ~ 0.5 ps (measured with the SSA only).

Thus, we are going to use an Optronis 500-MHz divider for the FSC synchronization in the future.

The standard BESSY 1.25-MHz revolution trigger (via optical transmission line) shows a short-time jitter of ~200 ps during some minutes of data-acquisition time and temperature drifts above 1 ns during 24 hours. These values are neither acceptable for FSC-2D measurement nor for the planed ICCD experiments. Thus, we have tested two solutions for producing a local 1.25-MHz revolution trigger signal from the 500-MHz reference.

We have used an Optronis divider chain consisting of LJFD/H4, LJFD/H2, and LJFD/N, with σ = 2.2±0.2 ps plus an additional long-time drift of 4.1 ps during 24 hours. Synchronization to the BESSY revolution trigger is possible only for the last divider of the chain.

We have also started an internal development in our center by using divider-evaluation boards of the type AD9513 by Analog Devices. Here, we have measured σ=2.6 ±0.3 ps. The long-time temperature drift is currently 30 ps and re-synchronization is still missing, but both

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will be improved soon. Thus, already now we have two acceptable solutions for a precise revolution trigger. The final decision for one of the systems will depend on the achieved performance of the ongoing in-house development, as this system has some advantages over the commercial one.

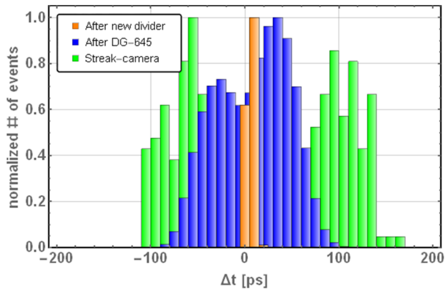

Figure 6: Long-time investigation (over about 24 hours) of the jitter in the horizontal FSC trigger systems.

Fig. 6 displays the measured jitters at three different points of the FSC trigger system for the slow axis. The orange bars represent one of the revolution-trigger divider chains (the peak width is dominated by the binning size of 10 ps). The blue bars represent the output jitter of the DG-645 digital delay generator from Stanford Research Systems. Without steady re-synchronization, this distribution becomes narrower (σ= 25 ps instead of 45 ps, as in the plot). The green bars display the drift of the analysed FSC peak positions in the horizontal direction. This bi-modal distribution corresponds to about ±1 pixels on the camera chip. It is related to a temperature drift over 24 hours and the green distribution would be very close to the blue one for measurements below 1 hour.

FURTHER DEVELOPMENTS

Button BPM Design and Signal Shaping

The BESSY II fill-pattern monitor and also the feedback system based on Beam-Position Monitors (BPMs) feature bunch-sensitive operation already now. For constant bunch filling the BPMs deliver high quality data. An observed signal ringing in the BPM output, however, causes different problems. There are changes of the signal shape along the bunch train due to long-time interferences of the unwanted ringing. Furthermore, misreading of the beam position of low-charge bunches following a high-charge bunch during BESSY VSR operation seems to be unavoidable. In order to mitigate signal-ringing effects, three distinct methodologies are investigated.

1. Development of new button-type BPMs [19] with optimized structure, increased cutoff frequency, and reduced reflection coefficient.
2. Analog signal mixing with passive self-compensation [4]. This reduces long-time disturbances at a fixed frequency.
3. Use of (additional) linear-phase response low-pass filters (Bessel type), as typical Butterworth type LC filters produce long oscillations due to logarithmic phase variation at the upper stopband.

Trigger-Free Bunch-Length Measurements

All FSC timing results are related directly to the fast 125-MHz trigger signal. Technically, the device performance is strongly relying on the stability of the electronic trigger signal provided by a timing system. It is noted that the same holds true for all other time-critical elements of the electron ring. Physically, each bunch may oscillate longitudinally within its bucket, being not stable w.r.t. a trigger signal. Particularly for low-α or low-current operation, long integration times are required to obtain a reasonable number of photons. Under this condition, the long-term jitter of the trigger can limit the accuracy and also there is no way to distinguish between a broad bunch and an oscillating one. Therefore, we are going to investigate two additional methods for trigger-free bunch-lengths determination that are appropriate for the quantitative investigation of short bunches.

1. Our timing beam line has a high radiation power (~4 mW for visible light). Thus, second-harmonic autocorrelation with a nonlinear BBO (β-Barium Borate) crystal for type-I phase-matching [5] and a single-photon camera is envisaged.
2. For weak photon sources, coincident two-photon detection enables intensity interferometry via 4th-order amplitude correlations using two arms of an optical interferometer [20]. Similar as for method 1, a variation of the 2-photon yield is measured as a function of the optical delay [5].

CONCLUSION

Many developments are running in parallel for improving the electron-beam diagnostics at BESSY II in order to reach robust bunch-selective monitoring of beam-position, beam size and timing for the BESSY-VSR project. Already now we have high-resolution bunch-length and even 2D measurements in operation. The interferometric beam-size determination has passed many tests successfully and other methods are still in the evaluation phase.

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