TIME-SYNCHRONOUS MEASUREMENTS OF TRANSIENT BEAM DYNAMICS AT SPEAR3*

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Abstract

Multi-bunch beam instabilities can often be controlled with high-speed digital bunch-by-bunch feedback systems. The detected motion is based on charge centroid measurements that, for short bunches, cannot resolve intrabunch charge dynamics. To compliment the BxB data, we installed a fast-gated camera with a rotating mirror to sweep visible-light synchrotron radiation across the camera CCD. The SR measurements present a complimentary view of the motion. For this work we generated transient beam events in SPEAR3 using the BxB feedback system and synchronously observed the motion on the camera. Results are presented for a high-order multibunch beam instability and for single bunch drive-damp experiments.

INTRODUCTION

SPEAR3 routinely uses a transverse bunch-by-bunch (BxB) feedback system [1] for high current User operations and to study storage ring beam dynamics [2]. The BxB system detects the dipole moment q•Δx for each bunch on each turn where q is the bunch charge and Δx is the displacement of the bunch centroid. The data is digitally processed with sufficient bandwidth to control the motion of each bunch independently. To date, the SPEAR3 BxB feedback system has been used to control multibunch instabilities, study beam dynamics during resonant drive events and for bunch cleaning. Although BxB feedback systems measure every bunch on every turn, for short bunches the measurement system cannot resolve coherent intrabunch motion or charge decoherence.

To compliment the BxB feedback system we synchronized a fast-gated camera equipped with a rotating mirror to sweep an image of the visible light synchrotron radiation (SR) across the camera CCD. The original idea to "streak" the optical SR beam using a deflecting mirror was developed at KEK [3], applied at PEP-II to measure fast-beam dump dynamics [4], and then used at both SPEAR3 [5] and ANKA [6] to diagnose the bunch bursting in low-alpha mode. For the applications reported here, we time-synchronized the optical SR measurements with the BxB acquisition system to provide complimentary diagnostics during transient beam motion.

At SPEAR3, a high-order multibunch instability can develop in the vertical plane due to resonances in an in-vacuum insertion chamber (IVUN) chamber [7]. The instability occurs at discrete gap settings where electromagnetic "pillbox" modes in the vacuum chamber couple to transverse beam modes. On a shot-to-shot basis, the motion of individual bunches evolves differently in time, often with complex profiles. Using the rotating mirror to streak the optical SR beam image, an integrated time profile containing the motion of all bunches can be captured.

Similarly, to diagnose single bunch motion, the BxB system or a standard turn-by-turn BPM processor can record driven betatron oscillations for dynamic aperture studies, bunch cleaning or resonant excitation tests for short-pulse x-ray production. Since the bunch charge can decohere in phase space it is important to measure the transverse beam profile using visible-light synchrotron radiation to identify (a) the onset of charge decoherence, and (b) the impact of decoherence on the physical process under investigation.

EXPERIMENTAL CONFIGURATION

For normal User operations SPEAR3 stores 500 mA beam current with charge distributed in 4 discrete bunch trains plus an isolated timing bunch for pump/probe experiments. Top-up injection occurs every 5 minutes with charge deposited at a 10 Hz rate into single, targeted bunches. A 10 Hz TTL pulse train triggers the injection kickers and provides a convenient signal to use for synchronized diagnostics.

In order to study transient beam dynamics, the timing system was configured to select solitary injection pulses from the 10 Hz pulse train to initiate grow/damp or drive/damp events. The same pulse is used to trigger multiple, synchronous diagnostics. The synchronized diagnostic systems include BxB data acquisition, turn-by-turn BPM processors and visible SR diagnostics.

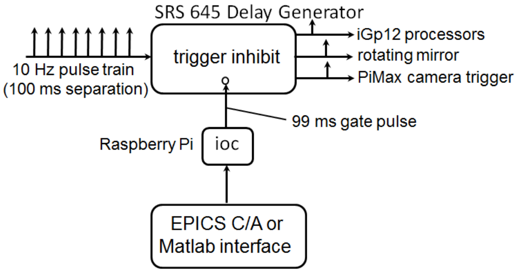

Figure 1: Schematic of the synchronous diagnostic timing system. A Raspberry Pi under EPICS control selects a single, time-isolated trigger.

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Timing Synchronization

Synchronized measurements using BPM processors and a Roper PiMax camera [8] require both timing accuracy and calibration. For synchronization, a single gate inhibit pulse to an SRS645 delay generator allows timing triggers to pass for parallel diagnostic systems [9]. Individual channel delay times take into account differences in transmission line propagation, electronic latency and photon beam time-of-flight. As illustrated in Fig. 1, the event sequence is initiated by using a trigger inhibit "gate" pulse from a Raspberry Pi configured with EPICS Channel Access [9]. The Raspberry Pi was selected for low cost, ease of implementation and independence from the main control system. At the top level, a Matlab-based graphical control interface [2] (or any C/A client) can instruct the Pi to issue the gate pulse.

Trigger to the iGp12 feedback processors can initiate transient beam events in the form of multibunch grow/damp instabilities or single-bunch drive/damp experiments. The BxB processors also save bunch-by-bunch, turn-by-turn data records in the SRAM memory. (Standard "turn by-turn" BPM processors integrate over all bunches for one revolution period [10]). The PiMax trigger is redistributed in the SR diagnostics room to initiate both the rotating mirror and the camera exposure. The exact PiMax camera exposure sequence is set in software [8]. Beam events of interest are then stored in timestamped files for post processing.

Currently only "single shot" events are captured by the BPM processors and PiMax camera for a given beam transient. It is also possible to trigger the PiMax with a pulse train to capture discrete segments of the beam transient by periodically gating the photocathode [4, 5]. An example of time-gating on a single bunch for a single pass is shown below.

Optical SR measurement system

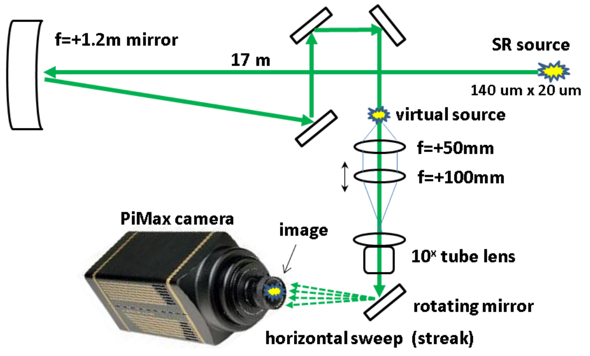

Figure 2: Optical transport line with10^x tube lens and rotating mirror.

At SPEAR3 the visible SR beam measurement systems use light extracted by a Rh-coated beam pick-off mirror under ring vacuum. The SR beam propagates unfocused to a dedicated optical bench. As shown in Fig. 2, the light travels approximately 17 m to an f=+1.2m concave focusing mirror which effectively forms the light-collecting objective of a Herschelian-type telescope [11]. The virtual source is de-magnified by a factor of 14 but is diffraction limited with a point spread function to about 75 µm rms [12].

To measure transient beam events, we need to project vertical electron beam motion at the SR source point from of order 100 µm to few mm onto the camera CCD. As seen in Fig. 2 the optical magnification system consists of a 2^x infinite conjugation lens system followed by a commercial 10^x infinity-corrected tube lens [13] yielding a net magnification of $M_{total} = 2*10/14\sim1.5$. Note that increasing the optical magnification does not improve the signal/noise ratio and tends to spread the photon flux over more pixels leading to a reduction in image brightness. The PiMax images are therefore plotted in log scale to enhance lower intensities. Beam rotation elements, colour filters and polarizers can be inserted between the 2^x telescope lenses. For the experiments reported here rotationally symmetric optics were used for equal magnification in both planes.

For practical reasons the 10^x tube lens was fixed at a stationary position to image the beam onto the camera CCD with fine focus adjustments made by moving the f=+100 mm lens under a micrometre control. After reflection from the rotating mirror, the "rest" position of the SR beam is to the left of the camera CCD to avoid saturating the sensor prior to the mirror sweep. Depending on the measurement, the trigger time and mirror sweep speed are adjusted to streak the SR beam image across the CCD at the desired rate [14] and the camera gain and exposure time set accordingly.

Camera Image Calibration

For transverse beam motion both the BxB and turn-by-turn BPM processors have known amplitude calibration factors in terms of mm/count. The PiMax calibration is more complicated because the calculation of optical magnification factors and mirror sweep speed are difficult to determine in terms of mm/pixel and ms/pixel, respectively. In order to measure the calibration factors empirically, we impulsively deflected the electron beam with the horizontal beam injection kickers to a known amplitude with known time intervals between kicks. Figure 3 illustrates how a Dove prism installed in the optical beam path is used to align the horizontal beam motion with the vertical camera axis.

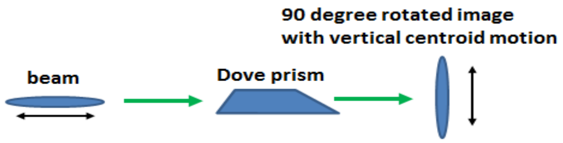

Figure 3: Dove prism rotates the horizontal SR beam axis into the vertical plane.

As shown in Fig. 4-a, the PiMax time axis was calibrated with the three injection kickers pulsed at 1 ms, 3 ms and 6 ms. The kick amplitudes were reduced by 50% to keep the beam within the dynamic aperture and the horizontal BxB feedback was ON to increase the betatron damping rate.

The injection kicker pulses were measured with a turn-by-turn BPM processor and then lined up with the PiMax image. Referring to Fig. 4, the calibration process yields a scale factor of 0.0083 ms/pixel. The 3 ms time interval between kicker K2 and K3, for instance, corresponds to about 360 pixels.

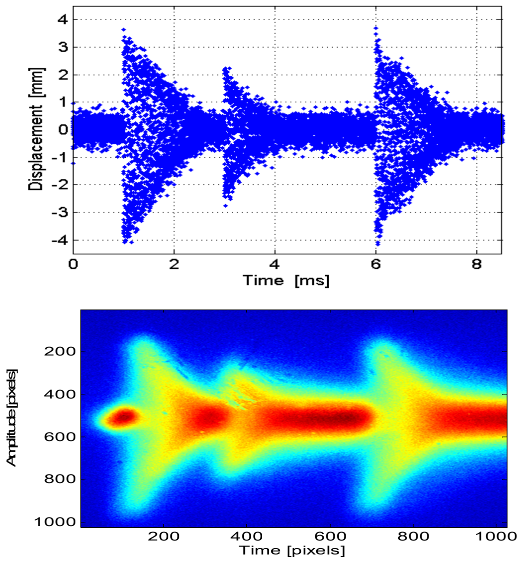

Figure 4: a) horizontal turn-by-turn BPM response and b) calibration image acquired by the PiMax.

As shown in Fig. 4-b, the ±4 mm beam displacement recorded by a turn-by-turn BPM processor was used to calibrate the vertical camera axis (amplitude). Scaling by the ratio of horizontal betafunctions between the BPM location and the PiMax SR source point, we have, $\Delta x = \pm 4\ \mathrm{mm} * \sqrt{1.86}/\sqrt{3.0} = \pm\ 3.15\ \mathrm{mm}$ on the camera [9]. The vertical span of the displacement on the PiMax camera is ±400 pixels leading to a calibration factor of 0.0079 mm/px. As a cross-check, the image of the stationary horizontal beam on the camera CCD is $1.5*140\mathrm{um}/7.9\mathrm{x}10^{-3}=26$ px rms which is consistent with Fig. 4.

For vertical beam measurements the Dove prism was removed and the same calibration factors applied. The action required to obtain an equivalent vertical amplitude must be scaled by the ratio of visible light source point betafunctions $f = \mathrm{sqrt}\left(\beta_x/\beta_y\right) = 2.8$ [9].

SYNCHRONOUS MEASURMENTS

Instabilities arise in storage rings when electromagnetic forces resulting from the overlap between the beam spectrum and the vacuum chamber impedance cause a positive feedback loop that grows faster than synchrotron radiation damping. The source and strength of the beam impedance can be studied using grow/damp measurements whereby the BxB feedback is momentarily switched off and on. Data stored in the BxB memory buffers yields the time evolution of each bunch centroid but cannot resolve charge decoherence. Instead, visible light images representing slices in phase space can be acquired simultaneously to complement the data. Drive/damp events can also be imaged to measure changes in transverse beam profile. This class of experiments is important for bunch cleaning and resonant crabbing research.

Multibunch Beam Instability

Similar to the mechanism for SASE build-up in an FEL, SPEAR3 is subject to a high-order vertical multibunch instability where the growth process is inherently startup-from-noise. In this case, the beam interacts with resonant pillbox modes trapped in a small-gap IVUN chamber [7]. The statistical nature of the process leads to small variances in the instability onset time and growth rate and rather large variances in the oscillation envelops for individual bunches. Figure 5-a, for example, shows turn-by-turn data recorded by the iGp12 processor for a single bunch as it executes complex envelop modulations during the damping phase of a grow/damp measurement. The modulations are believed to be caused by beating between different characteristic frequencies of the motion.

Figure 5-b shows the same grow/damp event synchronously measured on the PiMax camera. For this case the camera trigger was delayed by 7 ms to allow time for instability to startup from noise. Typical of most multibunch instability events in SPEAR3, the motion of individual bunches varies during a single measurement or from shot to shot whereas the shape of the envelop for the integrated SR camera image is more stable. For the event shown in Fig. 5, the camera image indicates a peak-to-peak amplitude of about ±4 mm at the SR source point. For this measurement the betatron amplitude of many bunches saturated the ADC's in the iGp12 BxB processor.

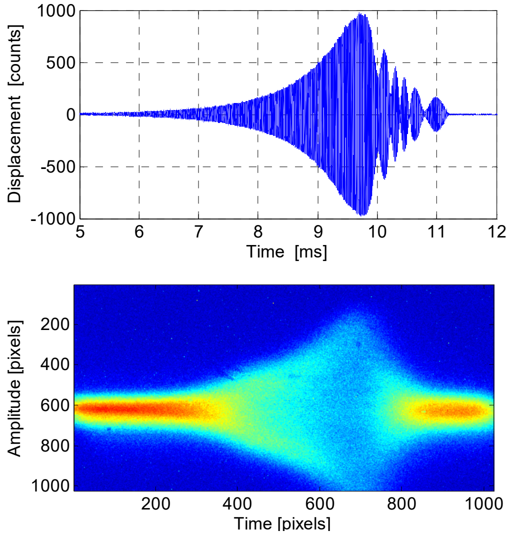

Figure 5: High-order multibunch instability showing a) oscillation envelop for bunch 1, and b) synchronous PiMax image with rotating mirror.

Single Bunch Drive Studies

For single bunch studies the BxB system or turn-by-turn BPM processors can again be used to measure bunch centroid data with the rotating mirror camera system recording the SR image in time.

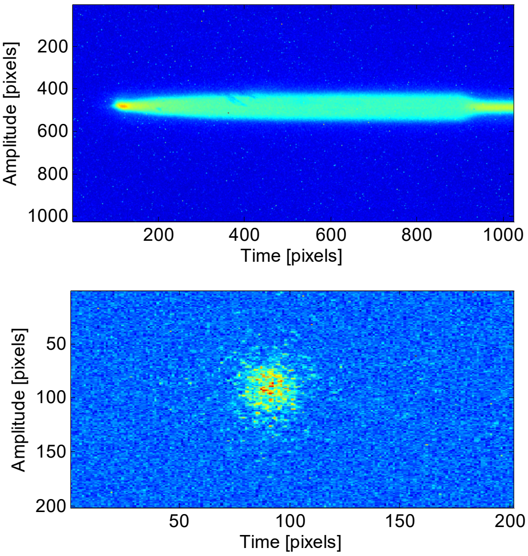

Figure 6: a) rotating mirror image of single-bunch drive-damp test with b) single turn cross-section.

As a preliminary test of resonant drive capability in SPEAR3, the iGp12 feedback processor was configured to excite a vertical betatron oscillation on a single bunch using a built-in phase-locked loop feature that tracks tune shift with amplitude. Both the drive signal and SRAM were synchronously triggered along with the PiMax camera and rotating mirror. As seen in Fig. 6-a, the SR image recorded on the PiMax shows the motion saturates to a sinusoidal steady state after about 3-4 ms.

Using the calibration factor of 0.008 mm/px, the measured amplitude is about 400 µm pk-pk. The one-turn image seen in Fig. 6-b was measured at time t = 4 ms and indicates no distortion in the x-y plane at low oscillation amplitude.

SPEAR3 will soon install high power BxB drive amplifiers that will excite the bunch in fewer turns or to higher amplitude for bunch cleaning. Synchronous SR imaging measurements will be continued to study decoherence with the new amplifiers. Since the bunch is executing driven betatron oscillations, multiple turns can be also captured in a single imaging frame.

SUMMARY

Synchronously triggered diagnostic systems in storage rings provide correlated data acquisition that helps to understand chamber impedance, beam dynamics and lattice non-linearities. In particular, by synchronizing a fast-gated camera with a rotating mirror with the BxB feedback processor we can study transient beam events from different perspectives. This paper gives preliminary measurements of both grow/damp and drive/damp beam transients that reveal different features of the motion. In the future we plan to further study multibunch instabilities caused by new IVUN chambers. For applications such as resonant crabbing it is important to measure charge decoherence of the bunch since the duration of the ultrashort x-ray pulse depends critically on the time evolution of charge distribution. Mechanisms leading to amplitude saturation and non-linear charge decoherence within the bunch will be investigated.

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