FAST-GATED CAMERA MEASUREMENTS IN SPEAR3 [§]

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Abstract

A fast-gated, image-intensified CCD camera was recently commissioned on the visible diagnostic beam line in SPEAR3. Although the system does not produce high-resolution images, the 2ns electronic gate and ability to generate multiple-exposure images provides good diagnostic potential. Furthermore, the addition of a rotating mirror just upstream of the camera photocathode provides the ability to sweep multiple images across a single frame during a single dynamical event. In this paper, we report on several fast-gated camera studies including (1) imaging of the injected beam with and without emittance-spoiling windows in the BTS transfer line, (2) horzontal and vertical single-bunch beam dynamics, and (3) images of short-bunch 'bursting' in low momentum-compaction optics.

INTRODUCTION

The visible/UV diagnostic beam line at SPEAR3 [1] is equipped with a suite of beam-characterization systems including a standard CCD camera [2], a 'stellar interferometer' to measure vertical beam size [3], a streak camera with ~2.3ps rms time resolution [4] and a fast-gated, image-intensified PiMax camera [5]. With a minimum gating time of 2ns, the PiMax camera can selectively isolate individual bunches within the 476MHz pulse train on a single-pass basis. Although diffraction effects and low photon flux prohibit accurate profile imaging, gross beam blow-up and beam centroid motion can be resolved. Experiments at the Photon Factory [6], PEP-II [7] and CLS [8] provide recent examples of single-turn profile measurements.

At SPEAR3, the accelerator development program is presently focused on top-off operations [9]. To aid in the effort, the PiMax camera was configured to capture turn-by-turn images of the injected beam as a means to study errors in both transport line launch coordinates and optical match to the storage ring. The measurements are particularly important for top-off because previously a series of transport line 'windows' inadvertently scattered the injected beam resulting in loss of capture efficiency and bremsstrahlung. In this paper we discuss these measurements as well as observations of horizontal and vertical single-bunch beam dynamics, and 'bursting' activity under relatively high current, low–α conditions.

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EXPERIMENTAL SYSTEM

The diagnostic beam line accepts unfocused visible/UV light 17m from a dipole source. A 150mm-diameter, f=2m lens then re-condenses the beam for distribution to various measurement stations on the optical bench. Two interchangeable pick-off mirrors located ~1.5m after the f=2m lens can direct the converging beam back toward the PiMax camera through either a simple vertical periscope with 5x lens beam path, or through a second vertical periscope followed by a two cylindrical-lens optics system with rotating mirror.

With the 5x lens optics (not shown in Figure 1), the horizontal camera field of view is approximately ±8mm at the source plane (β_x=1.68m). The 5x lens configuration is useful to image evolution of the charge distribution of an injected pulse during early turns and for horizontal fast-kicker measurements. The effective 'emittance' of the injected beam centroid, for example, is ~22mm-mr, so the ±6mm horizontal betatron motion at the observation plane is readily observed. The 'first-pass' image, however, is under the injection kicker bump and therefore outside the camera field of view.

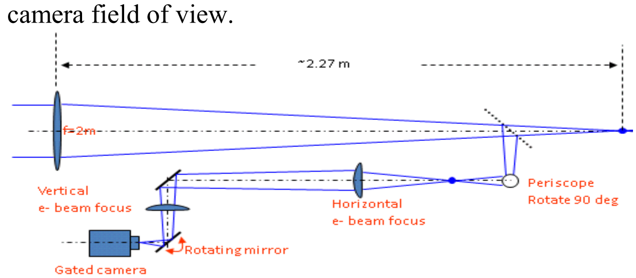

Figure 1: Plan view of gated-camera optics using cylindrical lens and rotating mirror configuration.

One drawback to the 5x lens system is that only a limited number of turns can be superimposed on a single exposure of the CCD without blurring images together. To capture many images in a single frame we used a cylindrical-lens optics with a rotating-mirror similar to the PEP-II system [7] (Figure 1). In this configuration, the photon beam is manipulated into a 'tall' image with a 'narrow' width. To produce the correct optics, the incoming beam is first rotated by 90° with a vertical periscope to orient the horizontal axis of the beam in the vertical plane. A *vertically-focusing* f=100mm cylindrical lens just after the periscope then focuses the horizontal beam axis onto the camera CCD for a net de-magnification M_x=0.7. A second, *horizontally-focusing* f=130mm cylindrical lens de-magnifies the vertical beam axis for a net value M_y=0.02 to produce a narrow stripe in the image plane. The rotating mirror then sweeps the resulting image across the CCD while the camera is gated in progressive steps to capture discrete, non-overlapping snapshots in time.

TIMING SYSTEM

The primary timing signals are the 1.28MHz ring revolution clock and the 10Hz injection trigger pulse train. A 10kHz, time-decimated version of the 1.28MHz ring clock is used to gate the camera in synchronism with bunch passage via the computer-controlled PiMax Pulse Trigger Generator (PTG). The PTG applies pre-programmed photocathode gate pulses with gate delay and gate width specified by GUI interface. Single bunch delay steps of 2.1ns, for example, are easily specified either by delaying the 10kHz gate trigger or in software. Both continuous 'repetition' and programmable 'sequence' photocathode gating modes are possible when acquiring multiple exposures in a given camera acquisition frame or over multiple acquisition frames.

Since the camera image can take up to 1s for readout, a 1Hz clock pulse is used to produce discrete bursts gate triggers for the PiMax PTG and to synchronously trigger the rotating mirror [7]. Figure 2 shows the trigger-inhibit arrangement using DG535 delay generators. Depending of the relative speed of the rotating mirror and the camera gate trigger rate, consecutive SR pulses will either appear as discrete images on the screen or overlap as the mirror sweeps the beam across the camera CCD. Figure 3, for example, shows the transient-decay of the injected-beam profile as seen by sweeping the image across the CCD with a total time interval of ~10ms. In this image the horizontal betatron motion is oriented top-to bottom and the images clearly overlap. As demonstrated below, with the rotating mirror operating at maximum angular velocity and the gate trigger rate set to 10kHz, discrete single-turn images can individually resolved (~every 130th turn).

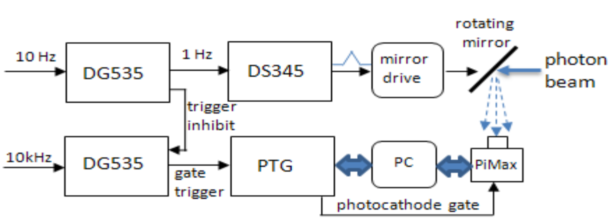

Figure 2: Timing system for rotating-mirror configuration. 1Hz trigger derived from 10Hz injection clock. 10 kHz derived from 1.28Hz revolution clock.

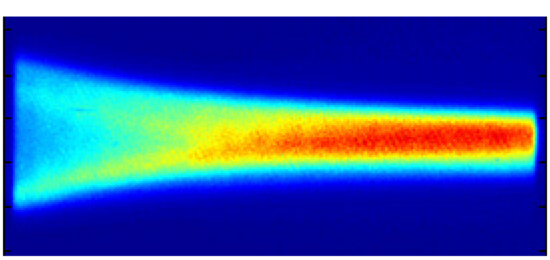

Figure 3: Injected-beam damping with rotating-mirror sweep across the camera CCD.

INJECTED BEAM DYNAMICS

As SPEAR3 moves toward top-off operation, beam injection efficiency and injected-beam dynamics become increasingly important [9]. Prior to removing a series of vacuum windows from the BTS and tuning the BTS optics, the injected beam was blurred by scattering at the windows and mismatch. Typically the first 12 turns appeared as in Figure 4a. Each image in the sequence is a superposition of 20 separate injected pulses photographed with the direct-imaging, 5x lens system (no rotating mirror). The composite picture was assembled from 14 consecutive images in software with horizontal betatron motion of the injected beam now in the horizontal plane. Due to the large oscillation amplitude and storage ring chromaticity the injected beam begins to filament after only a few turns. σy is artificially compressed in the figure. In order to avoid over-exposure from the 'stored' beam, the rf voltage was set just below the capture limit.

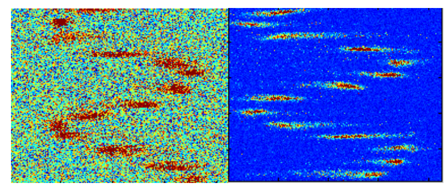

Figure 4: First 12 turns of injected beam (a) before, and (b) after BTS window removal and optics tuning. Time increases from top to bottom.

The transport line was then tuned and the BTS windows were removed during 2008 summer shutdown [10]. The repeat measurement of the turn-by-turn injected beam profile is shown in Figure 4b. The new data not only illustrates a more compact beam profile but also confirmed a reduction in vertical betatron motion and reduced vertical beam size oscillations due to the improved optical match. Images of a single turn profile with equal-scaled axes show the charge distribution is now more compact (Figure 5). Gaussian fits to the data are show below. Overall, the reduced beam size, optical match and reduction of vertical oscillation increases injection efficiency and minimizes loss at IDs.

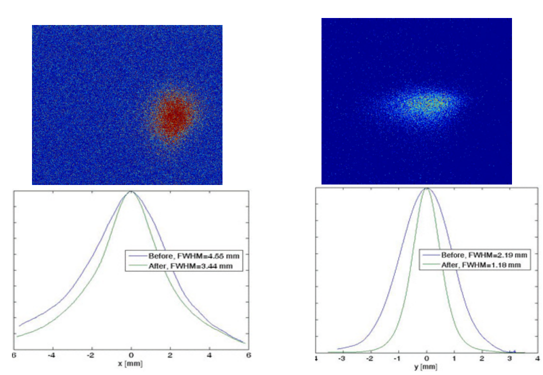

Figure 5: Top: First turn of injecting beam before (left) and after (right) BTS window removal and optics tuning. Bottom: Extracted horizontal profiles (left) and vertical profiles (right) for before and after upgrades.

KICK AND RESONANT EXCITATION

Nonlinear beam dynamics can be studied by measuring turn-by-turn oscillation data with beam position monitors and then extracting tune shift with amplitude. Since the BPMs detect beam centroid, it is also of interest to monitor the charge distribution with the fast-gated PiMax camera. In SPEAR3, for example, a horizontal kick can be generated by pulsing a single injection kicker. A sequence of images from the resulting motion for single stored bunch is shown in Figure 6. In this case, after evolving for 120µs (~150 turns), the beam clearly begins to filament.

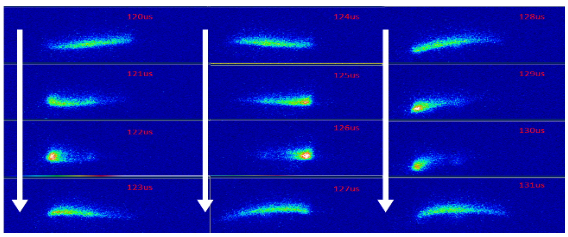

Figure 6: Turn-by-turn stored beam profile following a horizontal kick. Time proceeds top-to-bottom, left-to-right.

Although there is not a vertical 'kicker' in SPEAR3 the beam can be resonantly excited by driving a stripline near the vertical tune [11]. To lowest order the tune shift increases with the square of the oscillation amplitude so the drive signal frequency is chirped from below. Turn-by-turn centroid motion is measured with fast BPMs and betatron tune extracted accordingly. As shown in Figure 7 as the excitation progresses in time the charge distribution can also filament and thus blur centroid motion.

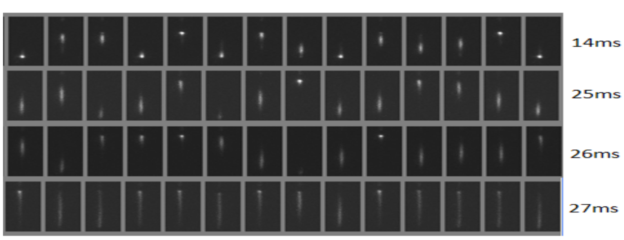

Figure 7: Resonant excitation in vertical plane using chirp signal near Q_y. Filamentation sets in a higher amplitudes.

BURSTING IN LOW-A OPTICS

As previously reported, short-bunch, high-current conditions in SPEAR3 can cause violent, quasi-periodic 'bursting' activity [12]. To further investigate transverse-plane dynamics during the burst phase, the cylindrical-lens/rotating-mirror configuration was used to capture a sequence of images in time. In this case, the rotating mirror was triggered at 1Hz to drive a 25ms duration sweep signal (~3 burst periods) and the ring revolution clock decimated to 10kHz to provide sufficient separation of images on the camera CCD. As shown in Figure 8, the 'bursting' phenomena manifests as periodic modulation of horizontal beam size in time.

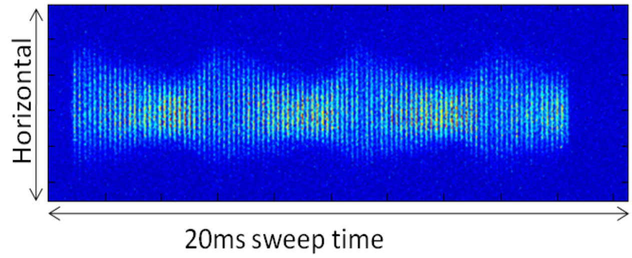

Figure 8: Horizontal bunch size modulation observed during quasi-periodic bursting in low-α optics mode. Images are spread across screen using rotating mirror.

SUMMARY

The fast-gated, image-intensified PiMax camera installed on the SPEAR3 visible/UV beamline has proved to be a useful diagnostic tool for a variety of applications. For top-off studies evolution of the beam profile evolution can be resolved on a single-turn basis and injected beam damping observed with aid of the rotating mirror. Non-linear single-bunch phenomena can also be studied in conjunction with horizontal kicks and resonant excitation in the vertical plane. For short bunch/low-α lattice studies the rotating mirror configuration yields time-resolved images of bursting in the horizontal plane.

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