SINGLE-SHOT BUNCH-BY-BUNCH HORIZONTAL BEAM SIZE MEASUREMENTS USING A GATED CAMERA AT CESR-TA*

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Abstract

A visible-light beam size monitor has been built and commissioned to measure transverse beam profiles at CESR-TA [1]. In order to eliminate beam jitter and to study bunch-by-bunch beam dynamics, a fast-gating camera has been utilized to measure single bunch transverse beam profiles. The minimum camera gate width is ~ 3ns which allows us to resolve single bunch beam dynamics along a CesrTA bunch train. Using single bunch interferometry, we found that the horizontal beam sizes measured by gated camera are consistently less than those measured by a conventional CCD camera, demonstrating the elimination of turn-by-turn beam jitter with single shot capability. By stepping the camera trigger delay, we collected transverse beam profile images from each bunch in a 14ns-spacing 30-bunch train. The horizontal motion of each bunch as well as the horizontal beam size increases dramatically along an electron train but not along positron bunch trains under the same machine condition. The difference in single bunch horizontal dynamics may be a signature for the difference between electron cloud build-up for positron bunch trains versus ions present for electron bunch trains.

INTRODUCTION

Synchrotron radiation (SR) from bending magnets, mainly visible light or x-rays, in accelerators have been widely used to monitor the beam profiles transversely and longitudinally. Most transverse beam profile monitors use conventional CCD cameras to measure beam dimensions, regardless of the direct imaging or interfereometer methods. CCD cameras are intensity-integrated devices collecting the light intensity over a short of period (10 to 1000 ms). Thus, the collected signals are integrated light from all bunches in the storage ring over many turns. When the beam has transverse jitter, either turn-by-turn or bunch-by-bunch, the profile measurements using conventional CCD camera will certainly be affected.

To eliminate the beams transverse jitter effect or to study beam dynamics along a bunch train, detectors with response time less than a few ns are required. Recently, an x-ray beam size monitor is built to measure vertical beam size blow-up along a positron train due to electron cloud effect [2]. This monitor is constructed with a fast-response diode array and fast read-out electronics, which can resolve turn-by-turn beam sizes in a 4ns spaced bunch train. In addition, a fast response Photomultiplier Tube (PMT) array is also used in a visible-light beam size monitor (vBSM), which has bunch-by-bunch and turn-by-turn capability to measure horizontal beam size [3]. These two devices utilize one-dimensional array detectors.

Fast-gated cameras have been utilized to record turn-by-turn beam profiles from injected beam [4-6] and stored beam [7-8]. The bunch-by-bunch capability has also been demonstrated at KEK [9]. All these measurements were direct imaging profiles, not interferometric measurements. In this paper, we utilized a fast-gated camera to record bunch-by-bunch interferometry along a train to quantify the horizontal beam sizes under various operating conditions. From these measurements, we determined the beam dynamics is quite different between a positron and electron bunch trains.

SETUP

vBSMs are located in the north area of CESR. They are placed symmetrically at east and west ends of the L3 straight in order to image visible SR from counter rotating electron and positron beams respectively. Figure 1 shows the schematic layout of the instrument. The visible SR from a soft bending magnet is reflected by a Beryllium mirror in the vacuum chamber. In order to reduce diffraction effect, the mirror was upgraded to provide a larger vertical aperture that accepts light within a 2.5×4.4 mrad (H×V) aperture. Through an adjustable iris, SR photons reach the double slits and a focusing lens (f=5m), which is 6 m from the source. Passing through many reflection mirrors, the SR light arrives at an optical table located 27 m from the source. On the optical table, the SR goes through a lens (f=1m), a polarizer, a 500-nm narrow bandpass filter and reaches the location of the cameras, where either a conventional CCD or a fast-gated camera is housed.

The double-slits set is mounted on a translation stage so it can be moved in or out of the light path to allow direct imaging or interferometry of the beam. For interferometry of the horizontal beam size, one set of vertically aligned double slits with fixed slit separation (e.g. D=2.0 mm) are moved into beam path. More details of our vBSM setup can be found in [1].

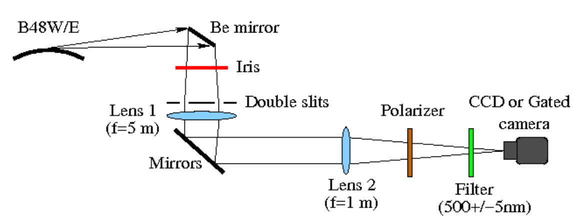

Figure 1: Schematic layout of the setup.

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The gated camera is a PI-MAX4 camera from Princeton Instruments [10]. Its minimum gate width is ~ 3ns which allows to resolve single bunch beam dynamics along a CesrTA bunch train (4 ns or 14 ns spaced). A 60-Hz timing trigger is derived from machine clock synchronized with machine turn clock. The trigger delay could be fine adjusted with a step size of 80 ps. In order to measure beam size of a specific bunch in a bunch train, the trigger delay needs to be changed accordingly. Stepping the trigger delay along a bunch train and taking images in sequence are automatically managed by a custom LabVIEW program through EPICS interface.

SINGLE BUNCH

Before setting up the gated camera, a CCD camera was staged to align the light optics. Once aligned, the CCD camera took a reference interference image. A double slits set of D=2.0 mm is inserted for both CCD and gated camera measurements. Figure 2(a) shows the reference image taken with a single positron bunch of 0.7 mA stored in CESR. The extracted horizontal profile from the interference image is displayed in Fig. 2(b). By fitting the interference pattern to interference equation [1], a visibility of γ of 0.575 is obtained, which, according to our set-up gives a horizontal beam size of 252.4 µm. The measured beam size is consistent with our design CESR optics.

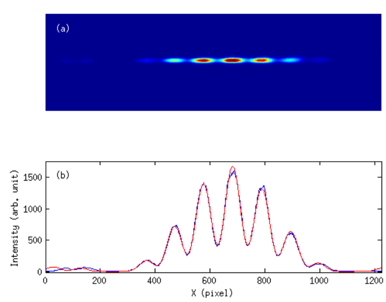

Figure 2: CCD image and horizontal intensity profile.

The gated camera was positioned at image focusing plane to replace CCD camera. The camera trigger delay was then changed to select correct single bunch signal. The gating width was set to 3 ns. The camera MCP (Multi Channel Plate) gain has a range of 0 to 100. For a single bunch of 0.75 mA in CESR, a gain of 20 was selected to avoid saturation effects. One hundred frames were captured and stored in one image file. Figure 3(a) displays a single image which demonstrates that turn-by-turn single bunch measurements at 0.75mA produce an interference pattern, although the extracted profile (Fig. 3c) is a little noisy. Fitting to the profile yields a visibility of γ=0.62. Figure 3(b) is a single bunch image averaged over 100 frames, which provides a much cleaner image but with a visibility that is less γ=0.54 (Fig. 3d). This reduction in visibility is expected because the averaged image includes transverse beam jitter effect that smears the visibility. We also processed 100 frames individually. The frame-by-frame fitting can be seen in a movie [11]. The averaged visibility over 100 frames fitting is γ=0.58±0.03, which is slightly higher than that obtained from CCD camera.

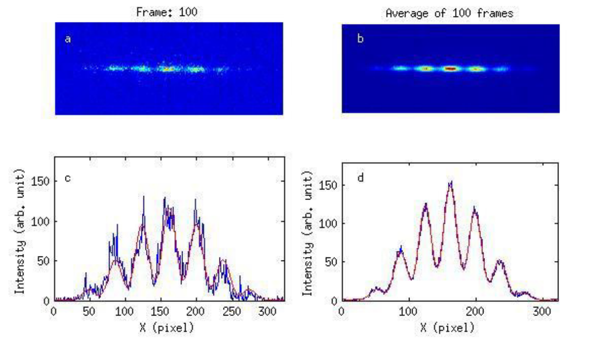

Figure 3: A single-shot image and its horizontal profile (left) and the averaged image over 100 frames (right).

To quantify transverse beam jitter in CesrTA, 100 single-shot image frames of the Gaussian beam are recorded in a movie [12]. The x and y movement of the beam is partially due to actual beam jitter and partially due to system vibration. The images are fit to a horizontal and vertical Gaussian beam profiles, as shown in Fig. 4, where the blue circles are either the vertical/horizontal beam size ($\sigma_{x,y}$) or the bunch centroid (x_{center},y_{center}) for 100 frames. The standard deviation of x and y centroids are 0.97 and 0.63 pixels, respectively. Because the pixel size of gated camera is 13.3 µm and the image magnification is 0.2, we estimate the maximum horizontal and vertical beam jitter at the vBSM source point would be 65 and 42 µm, respectively.

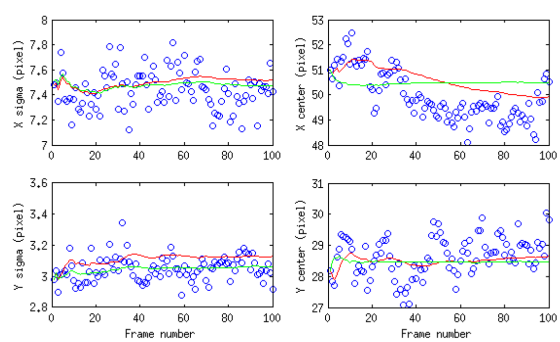

Figure 4: Circles: fit to each frame. Lines: fit to direct (red) or center-shifted (green) sum images.

Due to the transverse beam jitter, σ_x and σ_y determined by fitting the 100 frames average image is 7.52 and 3.13 pixels, respectively, which are both larger than the mean value σ_x and σ_y from fitting 100 single frames (σ_x =7.44, σ_y =3.05 pixels). To eliminate transverse jitter when image averaging, we sum the 100 frames based on the center of beam profile. Before image summing, each image is shifted to the same beam center which eliminates beam jitter in the summed image. The effect can be seen in the third row of movie [13]. Now fitting the shifted average beam profile, both the horizontal and vertical beam sizes ($\sigma_{x,y}$) (green lines in Fig. 4) are reduced compared to the direct summation (red lines in Fig. 4).

The same center-shift-sum method is also applied to the interference patterns. The visibility obtained from center-shifted-sum image is similar to that from direct sum image. This is understandable because the beam jitter in horizontal plane cause a phase shift in the interference pattern but not change the centroid [14]. Shifting the centroid does not eliminate the smear-out effect by from a phase shift.

MULTIPLE BUNCHES

During an electron cloud study shift, a train of 30 positron bunches with 14-ns spacing was stored in CESR at 2.1 GeV. To measure the horizontal beam size of each bunch, the gated camera trigger delay was changed in step of 14 ns. For each bunch, 100 single-shot frames were recorded and stored in one image file. The measurement of a 30 bunch train took about 2 to 3 minutes.

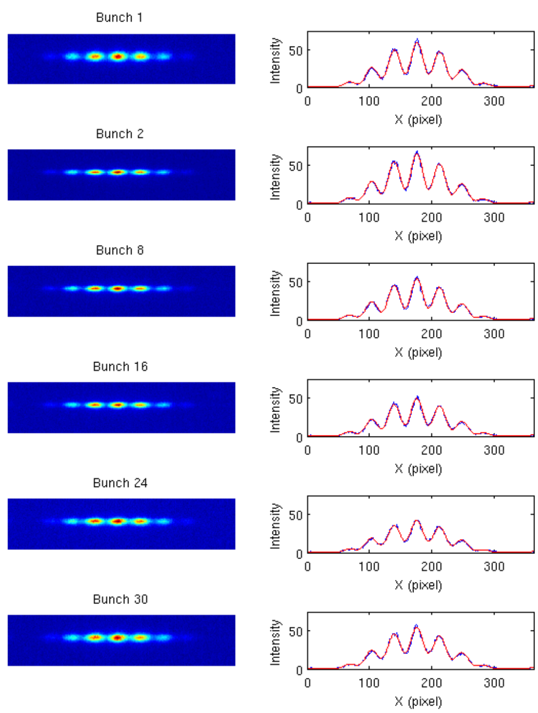

Figure 5: Interference pattern of 6 different bunches in a 30 bunch positron bunch train.

Figure 5 displays the average of 100 interferometer images for bunches 1, 2, 8, 16, 24, and 30 in a 30 bunch train of 0.75mA per bunch. Fitting the interference profiles gives the horizontal beam sizes. From the results shown in Fig. 6, it is evident that the horizontal beam size (σ_x) starts to increase after bunch 16 and continues toward the train end. In addition, we see a similar behavior in the vertical beam size along the train as well. Bunch-by-bunch vertical beam size (σ_y) measurements from x-ray Beam Size Monitor confirms our observations [15]. The increase of both σ_x and σ_y are likely due to the electron cloud build-up along the train [15].

For comparison, a train of 30 electron bunches were studied under the same accelerator conditions for both electron and position bunches. In both cases, only the horizontal feedback was turned on. Interestingly, we find the horizontal motion of electron beam is larger than positron beam [16] such that the fits to the averaged interference pattern is inconclusive. Instead, the beam size are obtained by fitting 100 frames interference individually. We found that σ_x did not change along the bunch (Fig. 6). Under different machine conditions, such as different vertical chromaticity, we did observe slightly increase of σ_x as long with the beam motion. Further studies of beam dynamics using the gated camera are underway.

The electron beam motion is likely due to the presence of ions in the vacuum chamber [17]. At a good vacuum level (~1 nTr), the beam size along the bunch train was not affected by the ions. However, when the vacuum level is degraded, we observed a beam size increase and motion attributed to ions [17]. In contrast, under similar machine conditions, the positron beam motion along the train is much smaller while the beam size increased. These experiments demonstrate the difference in beam dynamics for bunch trains for positrons, due to the electron cloud, and electrons due to ions.

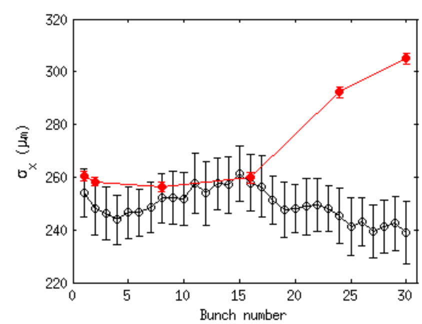

Figure 6: Horizontal beam size of a 30 bunch train of positrons (red) and electrons (black).

CONCLUSION

A fast-gating camera was utilized to acquire single-shot images from single and multiple bunches in CESR to quantify horizontal beam dynamics. Using interferometry techniques, a method has been established to determine the horizontal beam size of each bunch in a 30-bunch train that eliminates transverse beam jitter. Comparing the beam dynamics between positron and electron trains, we found the electron cloud build-up along a positron train increases the beam size but not affect the beam motion, while the beam motion and beam size increase along the bunch train of electrons train in the presence of ions.

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