ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPAF042

MEASUREMENT OF THE BEAM YZ CRABBING TILT DUE TO WAKEFIELDS USING STREAK CAMERA AT CESR*

S. T. Wang†, D. L. Rubin, CLASSE, Cornell University, Ithaca, NY, 14853, USA

Abstract

Transverse vertical wakefields can increase the vertical emittance and distort the phase space of a bunch in a storage ring. Recently, we observed charge-dependent vertical beam size growth with a single scraper inserted through the top of the storage ring vacuum chamber. This apparent growth was due in large part to the yz coupling (vertical crabbing) induced by the wake field from the asymmetric scraper configuration. Here, we report a direct measurement of a small beam yz tilt (crabbing) using a streak camera. The recorded images (projected beam profiles in yz plane) are analyzed with three different methods, which yield consistent beam yz tilts. We found the directly-measured current-dependent beam tilts by the streak camera are consistent with the beam tilts calculated from a wakefield model.

INTRODUCTION

In storage rings, the charged particles in a bunch are normally Gaussian-distributed in all three dimensions (x, y, z). The charged bunch can be tilted in the three planes (xy, xz, yz) due to couplings. For example, horizontal dispersion in the rf cavity introduces horizontal-longitudinal coupling, contributing to beam tilt in the xz plane [1]. Similarly, vertical dispersion in the rf cavity will induce vertical-longitudinal coupling. Depending on the rf voltage, the dispersion, β functions, and phase advance from the rf cavity to the observation point, the beam tilt can be as large as 40 mrad [1]. At KEK, crab cavities were used to generate xz beam tilt at the collision point so as to increase luminosity [2]. The crabbing angle is about 40 mrad. Recently, we found the wakefields from asymmetric scrapers can induce a vertical-longitudinal coupling causing the beam to tilt in the yz plane with the “banana-shape" characteristic of a head-tail instability [3]. Unlike the head-tail instability, where the projected vertical beam size oscillates in time at synchrotron frequency, the beam tilt is fixed with an angle that depends on phase advance from the source of the wake. From simulations, we found the vertical crabbing angle to be 1~2 mrad at 4 mA in the asymmetric scraper configuration. Direct measurement of such small beam tilt was proposed.

To measure beam tilts, the most straightforward method is to image the Gaussian beam in three planes (xy, xz, yz) directly. Imaging the xy beam profile with a CCD camera is the basis of a visible-light beam size monitor (vBSM) [4]. The streak camera, a high-speed detector, normally used for longitudinal beam profile measurements, is a perfect tool to visualize xz or yz beam profile [5]. A dove prism which rotates the input light axis is used to switch between measurement of xz and yz profiles. From the xy, xz, and yz beam profiles, the beam xy, xz, and yz tilts can be extracted. The streak camera has been used to observe yz beam profiles at CERN [5] and NSLS2 [6], and measure the horizontal (xz) crabbing angle (~40 mrad) at KEK [7] successfully.

In this paper, we utilized the streak camera to record yz beam profiles and measure the beam yz tilt induced by the asymmetric scraper configurations for the first time. The beam yz profiles were analyzed with three different methods, which yield consistent beam yz tilts (<1 mrad). The extracted small beam yz tilt is also consistent with a theoretical model. In addition, the current-dependent beam tilts were measured, showing consistent results with the beam tilts calculated from a wakefield model.

SETUP AND CALIBRATION

The Cornell Electron-positron Storage Ring (CESR) is located on the University Campus. It has the capability to store electron or positron beam at different energies (1.5~5.3 GeV). The vBSM is located in the north area of CESR. The visible synchrotron light from a bending magnet is extracted by a Beryllium mirror as shown in Fig. 1. It is then directed by sets of mirrors, passed through two lens, a neutral density filter, and a bandpass filter and arrived at the streak camera in the experimental hall. The details of the optics setup can be found in [4].

Measurements were taken with a single positron bunch circulating in CESR at 5.3 GeV. The neutral density filter was necessary to attenuate input light to the streak camera when measuring the beam at a higher current (8 mA or 1.28×10^{11} particles). The streak camera (Hamamatsu C1587) is equipped with duel sweep module (M2887) [8]. The horizontal sweep was set to the fastest scan mode 0.1 µs/10 mm. The vertical sweep is in synchroscan mode with a frequency of 125 MHz, which is one fourth of CESR rf frequency. The recorded image covers ~0.1 µs horizontally and ~1 ns vertically.

The scrapers installed in CESR were used to scrape large vertically scattered particles during injection in order to reduce the radiation on the permanent magnets of narrow

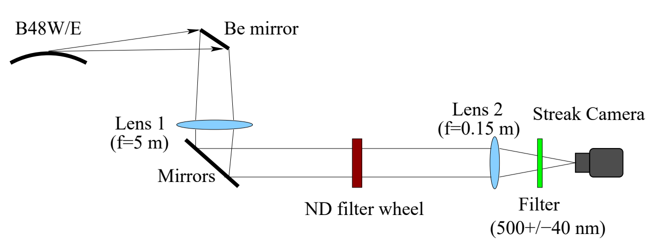

Figure 1: Schematic layout of the vBSM monitor.

* Work supported by NSF PHYS-1416318 and DMR-1332208.
† sw565@cornell.edu

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPAF042

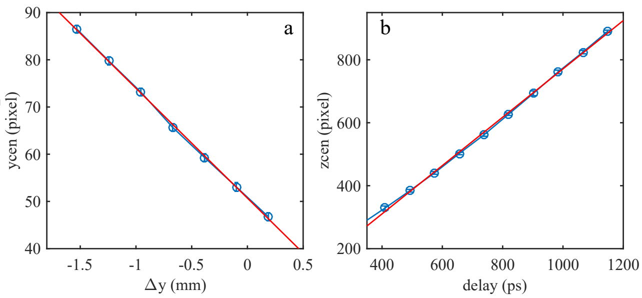

Figure 2: (a) The horizontal beam center on streak camera ($ycen$) vs vertical beam displacement. (b) The vertical beam center on camera ($zcen$) vs streak camera trigger delay. Symbols are the data and red lines are best fits.

gap undulators. The minimum gap between top and bottom scraper is ~6 mm. Since the wakefields from the asymmetric scrapers are generated in the vertical plane, the beam tilt induced by the wakefields will be in the yz plane.

In order to find the absolute beam tilt from streak camera images, we calibrated the scale factor of the streak camera both horizontally and vertically. A single positron bunch at 0.75 mA at 5.3 GeV was stored in CESR during the calibration process.

The horizontal axis in the streak camera corresponds to beam y axis. We created a four-element displacement bump at the vBSM source point to displace the beam vertically. At each beam position, the beam orbits around vBSM source point were measured using adjacent beam position monitors while the images on the streak camera were recorded. About ~30 images were recorded at each position. From fitting the Gaussian beam profile of an averaged image horizontally, the beam center $ycen$ can be found. The measured $ycen$ as a function of the beam displacement Δy are then plotted in Fig. 2a, showing a linear relationship. From fitting the linear $ycen$ vs Δy curve, we found the horizontal scale factor of the streak camera is 0.042 mm/pixel.

The vertical axis in the streak camera corresponds to the longitudinal (time) z axis of the beam. The calibration procedure is to record the streak camera images when changing the delay of the streak camera trigger with a fine step 82 ps. From Gaussian-fitting of the beam z profiles, the beam center $zcen$ at each trigger setting of the streak camera was obtained. Figure 2b shows the obtained $zcen$ as a function of the trigger delay, displaying a linear relationship. By fitting the $zcen$ vs delay curve, we found the vertical scale factor of the streak camera is 1.302 ps/pixel (0.39 mm/pixel).

EXPERIMENTS

A single positron bunch of 8.8 mA at rf bucket 1 was stored in CESR. The streak camera trigger delay was properly adjusted to visualize the bunch in the center of the streak camera. Figure 3a shows a typical single-shot image from the streak camera. About 30 images were recorded and then averaged to get the image displayed in Fig. 3b.

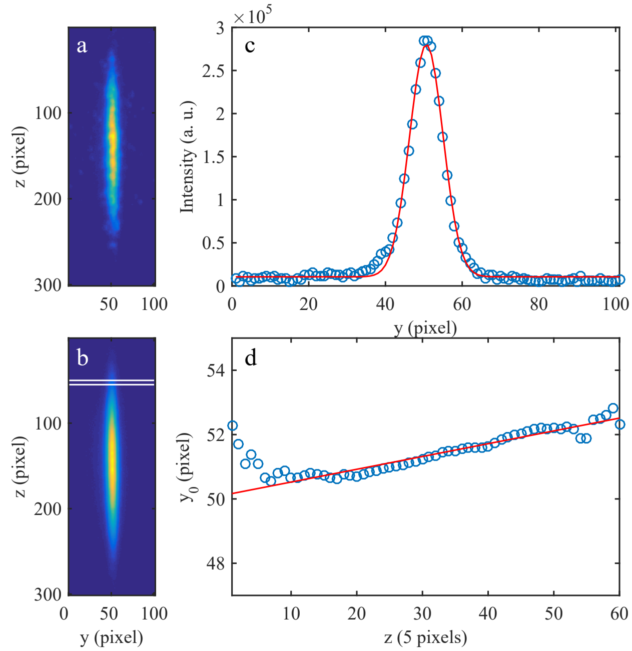

Figure 3: A single-shot (a) and the averaged (b) image from a single 8.8 mA bunch. (c) y profile averaged over 5 z pixels between two white lines in (b). (d) The obtained y centers vs z. Symbols are the data and red lines are best fits.

The variation of the centroid position (y_0) of the vertical distribution from head to tail of the bunch is a measure of the yz tilt. Thus, the first method to find the yz tilt is to obtain y_0 along the z axis. The beam is subdivided into vertical slices of 5-pixel width, for a total of 60 slices from head to tail. The vertical centroids of each slice is extracted from a Gaussian fit. Figure 3c shows a typical y profile of the 5-pixel slice indicated by two white lines in Fig. 3b. The 60 y_0 vertical beam centroids were obtained as shown in Fig. 3d. Fitting the y_0 vs z curve with a linear function yields the slope, from which the beam yz tilt was then calculated using the calibrated scale factors.

It is worth noting that the first and last 6 points in Fig. 3d are large outliers which were excluded in the linear fit. The fitting region still covers 250 pixels, which is ~ $5\sigma_z$. Without inserting the scrapers, the beam yz tilt was found to be 0.9 mrad. This residual beam yz tilt without scrapers inserted may be due to nonzero vertical dispersion at rf cavities. However, it could be an artificial effect due to the transport mirrors along the flight path or a slight rotation of the streak camera.

At the same current, the streak camera images were recorded for three additional cases: top scraper in, bottom scraper in, and both scrapers in. The images were then processed with the procedure discussed above. The acquired y_0 vs z profiles for all four cases were plotted in Fig. 4a. As indicated, the beam tilted more in the yz plane with the top scraper inserted and the bottom scraper out ("in-out") while the tilt was smaller with top scraper out and bottom scraper inserted ("out-in"). It can be more clearly seen in Fig. 4b that

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPAF042

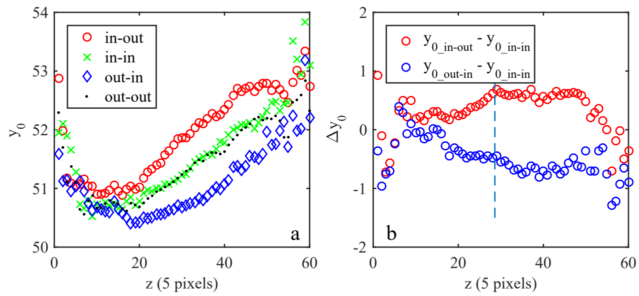

Figure 4: (a) Beam center profiles at different scraper configurations. (b) Subtracted beam center profiles for “in-out” and “out-in” configurations.

the beam yz tilt is positive with top scraper inserted while negative with bottom scraper inserted after subtracting the residual tilt without scrapers. This demonstrates the wakefields induced by the top scraper or the bottom have opposite signs. When both scrapers were inserted (“in-in”), the beam yz profile is the same as that of both scrapers out (“out-out”). This confirmed that no wakefields were induced from the symmetric scraper configuration when both scrapers were inserted.

The second method to evaluate the beam tilt is a matrix method, which is similar to the method we use to extract the tilt from tracking simulation [3]. The yz tilt is defined as

$$\theta_{yz} = \frac{1}{2}\arctan\frac{2\sigma_{yz}}{\sigma_{zz}-\sigma_{yy}}, \tag{1}$$

where σ_{yz}, σ_{yy}, and σ_{zz} are defined as follows:

$$\sigma_{yz} = \frac{\sum I_{ij} y_i z_j}{\sum I_{ij}}, \sigma_{yy} = \frac{\sum I_{ij} y_i y_i}{\sum I_{ij}}, \sigma_{zz} = \frac{\sum I_{ij} z_j z_j}{\sum I_{ij}}. \tag{2}$$

Here i and j are the horizontal and vertical pixel index in the image, respectively. I_{ij} is the intensity at the pixel (i, j). y_i and z_j are the relative horizontal and vertical distance of pixel (i, j) to the center of the beam (y_0, z_0), which are

$$y_0 = \frac{\sum I_{ij} i}{\sum I_{ij}}, z_0 = \frac{\sum I_{ij} j}{\sum I_{ij}}. \tag{3}$$

The third method is a linear regression method with the yz tilt defined as

$$\theta_{yz} = \arctan\frac{\sigma_{yz}}{\sigma_{zz}}. \tag{4}$$

Table 1: Beam yz Tilt at 8.8 mA

yz tilt	Gaussian fit (mrad)	Matrix method (mrad)	Linear reg (mrad)
$\theta_{\text{in-out}}$	1.046	1.044	1.035
$\theta_{\text{in-in}}$	0.903	0.819	0.811
$\theta_{\text{out-in}}$	0.572	0.483	0.478
$\Delta\theta$	0.237	0.281	0.279

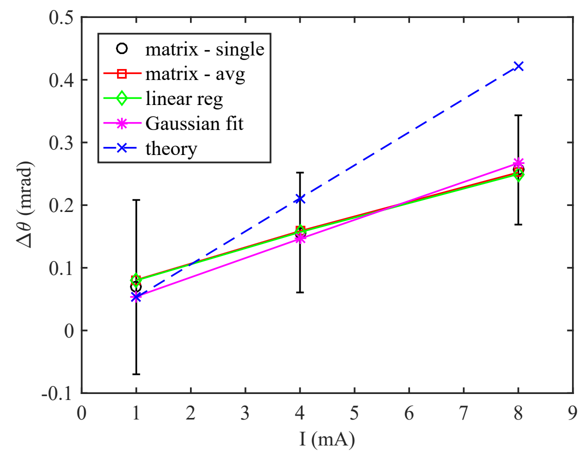

Figure 5: Current-dependent beam yz tilts calculated using different methods.

For our case here, since σ_{yy} is much less than σ_{zz}, the third method is equivalent to the second method. Table 1 shows the beam yz tilt calculated from three methods. The $\Delta\theta$ is the average beam yz tilt induced by the wakefield when inserting one scraper, which is calculated using the following equation:

$$\Delta\theta = \frac{\theta_{\text{in-out}} - \theta_{\text{out-in}}}{2}. \tag{5}$$

As shown in Table 1, the three methods yield similar beam yz tilt at 8.8 mA induced by inserting one scraper (~0.26 mrad).

To verify the current-dependent behavior, we studied the beam yz tilt at three currents: 1 mA, 4 mA, and 8 mA. The beam tilt extracted from the data by the three different analyses are plotted in Fig. 5. All three analysis methods consistently show linear dependence of beam tilt on bunch current, confirming that the beam yz tilt is indeed induced by the wakefields from asymmetric scraper configuration.

In Fig. 5, the tilt data displayed by symbols with error bars are the average value of the tilts obtained from analyzing the single-shot images at each current using matrix method. The error bar is the standard deviation of the tilts at each current. At higher current the error bar is smaller. The theoretical yz tilts are calculated using 1-turn matrix method when including the wake element in the lattice as described in Ref [3]. As Fig. 5 shows, there is a discrepancy between the measured beam tilt and the model, which could be due to a potential calibration error of the streak camera. Due to extreme small beam tilts we intend to measure, there may exist measurement errors (instrument, fitting, etc.) which will contribute to this discrepancy. Measuring larger beam tilts at lower beam energy could shed some light on this discrepancy.

CONCLUSION

Using a streak camrea, we successfully measured very small beam yz tilts (crabbing angle) at the vBSM source point induced by the wakefields from asymmetric scraper

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPAF042

configurations. The tilt angles are less than 1 mrad. From measuring the beam yz tilt at different currents, we found a linear relationship between the beam tilt and current, confirming that this beam yz tilt is indeed induced by the scrapers. The measured current-dependent beam tilt is also consistent with the theoretical calculation that includes a wakefield model.

ACKNOWLEDGMENT

We thank Walter Hartung, Robert Holtzapple, Jared Maxon, and Stephen Poprocki for valuable discussions.

REFERENCES

[1] M. P. Ehrlichman *et al.*, "Measurement and compensation of horizontal crabbing at the Cornell Electron Storage Ring Test Accelerator," *Phys. Rev. ST Accel. Beams* **17**, 044002 (Apr. 2014).

[2] Y. Funakoshi *et al.*, "Performance of KEKB with crab cavities," in *Proceedings of the 2008 European Particle Accelerator Conference, Genoa, Italy*, EPS-AG (2008), p. 1893–1896.

[3] S. T. Wang *et al.*, "Vertical-longitudinal coupling induced by wakefields at the Cornell Electron-Positron Storage Ring Test Accelerator," *Phys. Rev. ST Accel. Beams* **21**, 024401 (Feb. 2018).

[4] S. T. Wang *et al.*, "Visible-light beam-size monitors using synchrotron radiation at CESR," *Nucl. Instrum. Methods Phys. Res.* **A703**, p. 80–90 (Mar. 2013).

[5] E. Rossa *et al.*, "Real time measurement of bunch instabilities in LEP in three dimensions using a streak camera," in *Proceedings of the 1992 European Particle Accelerator Conference, Berlin, Germany*, EPS-AG (1992), p. 144.

[6] W. Cheng *et al.*, "Longitudinal bunch profile measurement at NSLS2 storage ring," in *IBIC 2015: Proceedings of the 4th International Beam Instrumentation Conference, Melbourne, Australia* (2015), p. 251–255.

[7] H. Ikeda *et al.*, "Crabbing angle measurement by streak camera at KEKB," in *Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, NM*, C. Petit-Jean-Genaz, Ed., IEEE (2007), p. 4018–4020.

[8] R. Holtzapple *et al.*, "Single bunch longitudinal measurements at the Cornell Electron-Positron Storage Ring," *Phys. Rev. ST Accel. Beams* **3**, 034401 (2000).