

# A TURN-BY-TURN BEAM PROFILE MONITOR USING VISIBLE SYNCHROTRON RADIATION AT CESR-TA\*

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## Abstract

A fast beam profile monitor using visible synchrotron radiation (SR) has been constructed and installed in the Cornell Electron Storage Ring. This monitor utilizes fast readout electronics based on the Hamamatsu H7260K multianode photomultiplier, which has a 32-channel linear array with 1 mm channel pitch and sub-nanosecond rise time. In a low emittance lattice at 2 GeV, a double-slit interferometer is employed to measure the horizontal beam size. After careful calibration of the interference pattern, the horizontal beam size within a range of 100 to 500  $\mu\text{m}$  can be measured. The small vertical beam size is measured by imaging the  $\pi$ -polarized component of the SR. The fast beam profile monitor is capable of measuring bunch-by-bunch turn-by-turn transverse beam sizes, which eliminates beam jitter inherent when imaging the average beam size with a CCD camera. Details of hardware and software controls are discussed.

## INTRODUCTION

Visible light from synchrotron radiation (SR) has been widely used to measure and monitor the transverse beam sizes in accelerators [1]. Because of the diffraction limit, depth of field, and etc., direct imaging cannot measure the transverse beam size accurately when the beam size is comparable to or smaller than the optical resolution. At CESR-TA [2], a visible-light beam size monitor (vBSM) utilizing the double-slit interferometry was constructed to measure the horizontal beam size as small as 150  $\mu\text{m}$ , well below the calculated optical resolution of 230  $\mu\text{m}$  [3]. A  $\pi$ -polarization method was also implemented to measure a small vertical beam size of 70  $\mu\text{m}$  [2]. A CCD camera was used in both methods.

A single CCD camera image records the intensity of SR light over a short period of time. Depending on the light intensity, the exposure time of CCD camera is typically 0.5-50 ms, during which the electrons circulate about 200-20000 turns (2.56  $\mu\text{s}$  per turn). In CESR, there can be a turn-by-turn beam motion of order 50  $\mu\text{m}$  in both horizontal and vertical planes. We have found the error due to the beam motion using the CCD camera to measure horizontal beam size is small but contributes significantly to the vertical beam size [2]. To eliminate sensitivity to beam jitter or vibration, a device with single bunch turn-by-turn capability is highly desired.

In order to study the electron cloud effect at CESR-TA, an x-ray beam size monitor was built [4], which is capable of measuring vertical beam size as small as 10

$\mu\text{m}$ . With the fast-readout electronics, it is able to perform turn-by-turn bunch-by-bunch measurements. However, the x-ray monitor was not designed for simultaneous measurement of both horizontal and vertical beam sizes. Therefore, an alternative fast beam size monitor using visible SR (vBSM) was constructed with a multianode photomultiplier (PMT) [5]. In this paper, we review the configuration of the vBSM and discuss its application to measure both horizontal and vertical beam sizes.

## VBSM SETUP

The beam profile monitors are located in the north area of CESR. The vBSMs are placed symmetrically at east and west ends of the L3 straight in order to image visible SR from the 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, which accepts light within a  $2.5 \times 2.2$  mrad ( $H \times V$ ) aperture. Through an adjustable iris, the SR photons reach the double slits and a focusing lens ( $f=5\text{m}$ ), 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 light is split into two paths. One goes through a lens ( $f=1\text{m}$ ), a polarizer, a 500-nm narrow bandpass filter and reaches the CCD camera at last. The second part passes through an image-expanding lens and reaches the PMT after a polarizer and a bandpass filter.

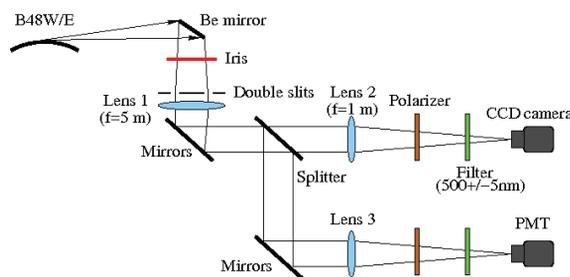


Figure 1: Layout of optics setup.

The iris opening is adjustable within the range 3.0~22 mm, which limits the acceptance of visible light down to 0.5 mrad and reduces the depth of field from 350 to 70 mm. Because the double slits are located inside the tunnel, adjustment of the slit separation is inconvenient during operation. Therefore, three vertically aligned double slits with fixed slit separation ( $D=2.0, 2.5, 3.0$  mm) were machined in one piece and mounted on a motorized translation stage. Different sets of slits can be

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chosen to measure the horizontal beam size over different ranges.

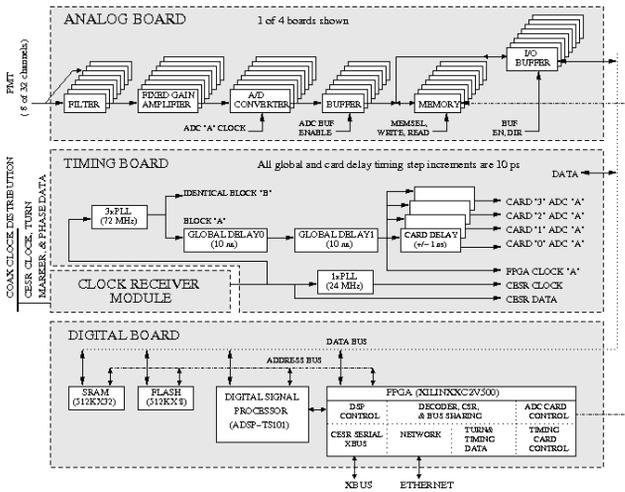


Figure 2: Electronic architecture overview.

## PMT READOUT ELECTRONICS

The multinode PMT consists of a 32-channel linear array with 1 mm channel pitch and 7 mm width. It has a high speed response with a sub-nanosecond rise time. Figure 2 shows the overview of the data acquisition hardware architecture [5]. It consists of a digital motherboard, on which a Xilinx field programmable gate array (FPGA) and a digital signal processor (DSP) are mounted. Four analog boards, a timing board, and an I/O board are plugged into the motherboard. The front end board connects to the PMT directly and monitors the channel-by-channel and total PMT current. It will switch off the high voltage supplied to PMT when the detected current is over the limit.

Each analog board has 8 channel inputs from PMT. Each input connects to a fixed gain amplifier, A/D converter, and 512K-words memory. The timing board receives the CESR 24 MHz clock signal and produces a 72 MHz clock, which allows capturing the signals of bunches with 14 ns spacing. The timing board also provides a global delay and 4 individual delays to the 72 MHz clock for each analog card for compensating variations in cable length or electronic delays.

The control software communicates with the device through either xbus serial port or ethernet interface. It is written in Matlab environment, in order to exploit the data analysis software package.

## ALIGNMENT AND TESTING

In order to obtain accurate beam sizes, the optics have to be properly set up and aligned. For the double-slit horizontal beam size measurement, the source image of the interference pattern is 3 mm long. In order to have enough sampling points of the interference pattern, the source image is magnified 10 times larger to cover the 32-

channel PMT detector (32 mm). To measure the vertical beam size, we have to magnify the  $\pi$ -polarized beam profile by 70 times. The magnification lenses are mounted on remotely controlled high precision translation stages to simplify precise identification of the image plane.

The timings for data acquisition channels need to be adjusted to synchronize with CESR to acquire bunch-to-bunch and turn-by-turn data. To check the fast read-out capability of the instrument, a train of 18 bunches with 14 ns bunch spacing was stored in the ring. The current in each bunch was 0.3 mA. The 1024-turn data of these 18 bunches were acquired. Figure 3a shows the measured horizontal beam profile of bunch 12 in a single turn. By fitting the beam profile with a Gaussian function, the centroid and sigma (beam size) were obtained. Figure 3b and 3c are the histograms of the sigma and center positions of the 1024-turn data of bunch 12. By applying a fast Fourier transform (FFT) on the center positions, the oscillation frequency of each bunch can be quantified. Figure 3d shows the FFT of the positions for all the 18 bunches. The dominant oscillation frequency is at the horizontal tune 223.5 kHz.

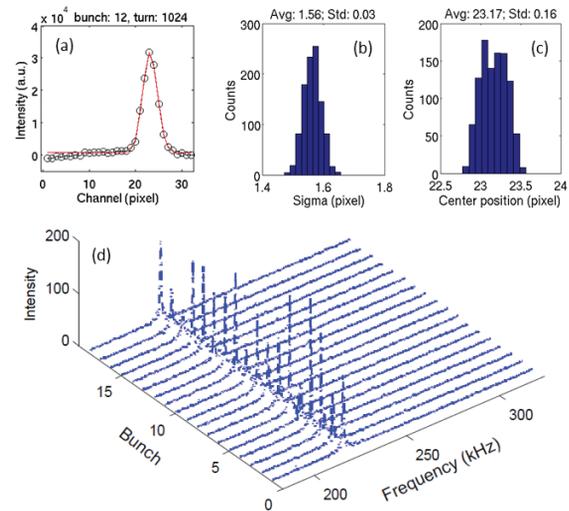


Figure 3: Turn-by-turn bunch-by-bunch measurement.

## HORIZONTAL BEAM SIZE

Once the optics are aligned using the Gaussian profile, a set of vertically aligned double slits was inserted to generate a horizontal interference pattern. A typical one-turn interference pattern acquired by the PMT is shown in Fig. 4a. By fitting the interference pattern with Eq. 1:

$$I(x) = I_0 \left[ \sin c \left( \frac{2\pi a}{\lambda R} x + \phi \right) \right]^2 \left( 1 + |\gamma| \cos \left( \frac{2\pi D}{\lambda R} x + \psi \right) \right) \quad (1)$$

we obtain the spatial coherence  $\gamma$  and then infer the beam size  $\sigma_x$  using Eq. 2 [6]:

$$\sigma_x = \frac{\lambda L}{\pi D} \sqrt{\frac{1}{2} \ln \frac{1}{\gamma}} \quad (2)$$

Figure 4b shows the histogram of 1024 horizontal beam sizes obtained from fitting the 1024-turn data of a single

electron bunch at 2.5 mA. The measured beam size variation from turn to turn is not small. To validate the function of the PMT, we measured the horizontal beam size using the PMT and CCD simultaneously of a single bunch as the current decayed from 6 to 1.5 mA (Fig. 4c). The horizontal beam size measured by the PMT shows similar decay behaviour as that from the CCD, which is consistent with intra-beam scattering theory [7]. However, the beam size measured by the PMT is consistently  $\sim 70 \mu\text{m}$  larger than that by CCD at all currents. Evidently there is some systematic error in the PMT measurement that needs to be investigated.

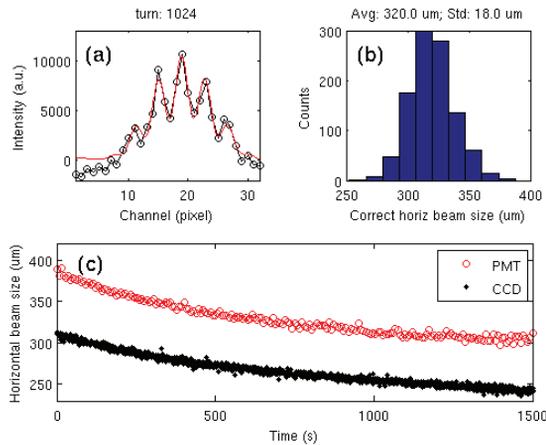


Figure 4: Horizontal beam size measurement.

### VERTICAL BEAM SIZE

In order to measure vertical beam size, the double slits were removed and the linear PMT array was oriented vertically to acquire the  $\pi$ -polarized vertical beam profile. Figure 5a displays a typical one-turn vertical beam profile for two different sizes. The vertical emittance is adjusted with coupling bumps that generate vertical dispersion in damping wigglers. From the valley-to-peak ratio of this profile, the vertical beam size can be determined [2, 8]. Figure 5a clearly shows the valley-to-peak ratio is larger for the large beam size data (red crosses). Figure 5b displays the histogram of 1024 beam sizes measured from 1024-turn profiles of a single electron bunch at 0.8 mA with minimum vertical size. The measured vertical beam size is  $31.6 \pm 6.9 \mu\text{m}$ , slightly larger than the size ( $25 \mu\text{m}$ ) measured with the xBSM [4].

For comparison, we measured the vertical beam sizes using the PMT and CCD simultaneously, while increasing the size in steps with the coupling bump. As shown in Fig. 5c, the measured vertical beam size increased as expected as the vertical emittance was increased. However, the vertical beam size measured with the PMT, which eliminates the beam jitter, was not smaller than that measured with the CCD. These measurements were consistent with each other within measurement uncertainty. The number of PMT pixels may be a limiting factor to measure even smaller vertical beam size.

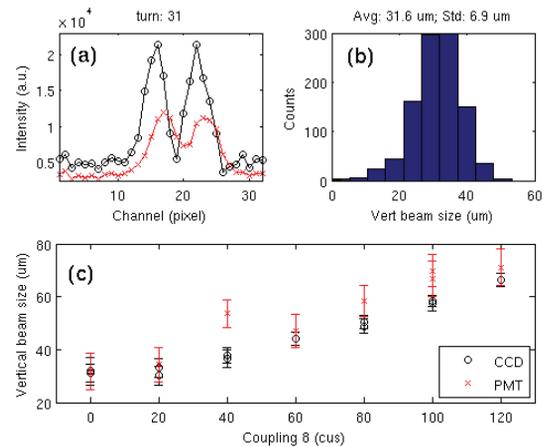


Figure 5: Vertical beam size measurement.

### CONCLUSION

We have demonstrated a beam profile monitor which is capable of measuring bunch-by-bunch and turn-by-turn transverse beam sizes. The horizontal beam size measured by the PMT is consistently larger than that with the CCD. This systematic error may be due to timing or electronic settings errors. On the other hand, the vertical beam size measured with the PMT is consistent with the CCD measurements, indicating that beam jitter may not be the dominant limiting factor for the  $\pi$ -polarization method to measure the small vertical beam size ( $< 20 \mu\text{m}$ ). Further investigation and calibration are needed.

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