EXPERIMENTAL STUDY OF VERTICAL-LONGITUDINAL COUPLING INDUCED BY WAKEFIELDS AT CESRTA*

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Abstract

Transverse vertical wakefields can cause vertical beam size growth in accelerators. Here we report recent measurements and simulations of wakefields from movable scrapers at the CesrTA. The charge dependent vertical beam size growth was observed while a single scraper was inserted through the top of the chamber. No change in the beam size was observed with top and bottom scrapers inserted symmetrically. The apparent growth in the vertical beam size was due in large part to the y-z coupling (vertical crabbing) induced by the monopole wake of the asymmetric scraper configuration. We explored this y-z coupling by varying vertical betatron phase advance between the vertical beam size monitor and the scrapers. In addition, we found that existing residual, current independent y-z coupling could be compensated by the scraper wake. Predictions of a tracking simulation are in good agreement with the measurements.

INTRODUCTION

The Cornell Electron-positron Storage Ring (CESR) stores counter-rotating beams of electrons and positrons. Positrons circulate in the clockwise direction in CESR and electrons in the counter-clockwise direction as shown in Fig. 1. Because ring energy can be easily configured in the range of 1.5 to 5.3 GeV, CESR has been used as a test accelerator (CESR-TA) for exploring the physics and technologies of low emittance rings since 2008 [1].

Wakefields induced by moving charged particles in vacuum chambers act back on the particles so as to affect the beam emittance and dynamics, and thus cause beam instability [2], which has been a long-standing topic in accelerator physics. During recent CesrTA runs, we observed a vertical beam size growth caused by inserting one set of vertical scrapers [3]. No change in the vertical beam size was observed with top and bottom scrapers inserted symmetrically. The monopole wake of the asymmetric scraper configuration was believed to cause the beam size growth. In this paper, we calculated the monopole wake of the asymmetric scraper configuration and incorporated it in a tracking simulation. The good agreement between the simulation and the measurements confirmed that the charge dependent vertical beam size growth was due to the y-z coupling induced by the monopole wake. We also found the y-z coupling depends on the vertical betatron phase advance between the vertical beam size monitor and the scrapers, and the existing residual y-z coupling could be compensated by the scraper wake.

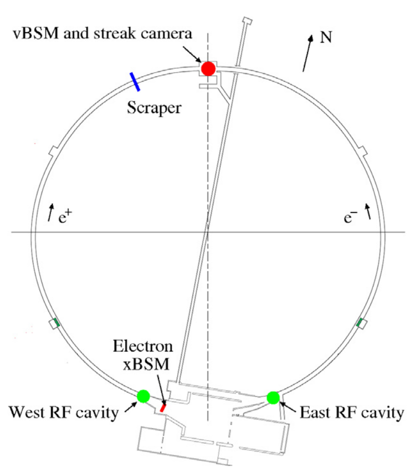

Figure 1: CESR layout.

EXPERIMENTAL RESULTS

Setup

The experiments were done with low emittance lattices (ε_x=2.6 nm) at 2.1 GeV. A tuning procedure was initially applied to achieve low vertical emittance (ε_y≈10 pm) in the accelerator [4]. The bunch dimensions (σ_x, σ_y, σ_z) were recorded concurrently as the beam current decayed from 4 mA to 1 mA. To avoid resonance effect on the beam size through entire current range, ring tunes were carefully set as Q_x=0.573, Q_y=0.629, Q_z=0.067 at low beam current (~1 mA).

The σ_y of an electron bunch was measured by the x-ray beam size monitor (xBSM) [5], located in the south of the ring as shown in Fig. 1. This instrument is capable of measuring bunch-by-bunch and turn-by-turn vertical beam size. The σ_x was monitored by the visible-light beam size monitor (vBSM) utilizing the interferometer method [6]. The σ_z was measured with a streak camera [7]. The instruments using visible light are located in the north region of CESR.

The vertical scrapers were located in the north region of the ring as well. The gap between top and bottom scrapers is 7 mm or 50 mm respectively when both scrapers are fully inserted or retracted. Before measurements, the electron beam was carefully centred between the two fully-inserted scrapers. The current decay data were collected with both scrapers retracted or with only the top scraper fully inserted. The bottom scraper remained retracted for the entire experiments.

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Beam Sizes vs Current

Figure 2 shows the measured beam sizes as a function of the beam current with top scraper inserted ("in-out") or retracted ("out-out"). With both scrapers retracted, the σ_x increased with the current from 1mA to 4mA while the σ_y remained constant (~21 µm). The observed current dependence of horizontal beam size is consistent with intra-beam scattering (IBS) [8]. Since both vertical dispersion and x-y coupling are small (after low emittance tuning [4]), the effect of IBS is most pronounced in the horizontal plane [8]. Thus, no apparent σ_y increase was observed. The longitudinal bunch lengthening was mainly due to the potential well distortion [7, 8].

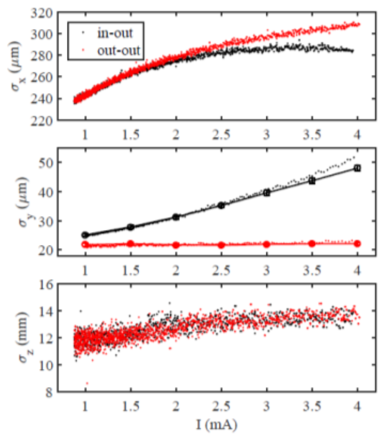

Figure 2: Beam sizes vs current for lattice 0.

When the top scraper was inserted, the measured σ_y increased dramatically with beam current (black dots in Fig.2). We attribute the current dependence of vertical bunch size to the monopole wake $W_\perp$ generated by the asymmetric scrapers. A simple explanation was discussed below. When a bunch travels through the scraper, each particle will experience a vertical kick Δy' induced by a transverse wakefield $W_\perp$ induced by the scraper from all of the leading particles:

$$\Delta y' = W_\perp \frac{eq}{E} \ , \qquad (1)$$

where q is the total bunch charge, e is the electron charge, and E is the beam energy. If the monopole wake $W_\perp$ is constant, the kick induced by the wake is similar to a dipole error which only distort the closed orbit without affecting the emittance. If $W_\perp(z)$ is a function of z, that is the particle distance relative to the bunch centre, the wakefield will then introduce a y-z coupling to the beam. The y-z tilt θ_{yz} of the beam can be estimated as follows. If the particle gets a vertical kick $\Delta y'$ at location s_0, the change in the closed orbit $y(s)$ at location s will be

$$y(s) = \frac{\Delta y' \sqrt{\beta_y(s)\beta_{y0}}}{2\sin \pi Q_y} \cos(\Delta\phi_y(s) - \pi Q_y) \ , \qquad (2)$$

where s is the location of the particle in the accelerator, $\Delta\phi_y(s)$ is the vertical phase advance from s_0 to s, and Q_y is the vertical tune. $\beta_y(s)$ and β_{y0} are the vertical Twiss parameter at s and s_0, respectively.

Since the particle at the head of the bunch gets a different vertical kick as that at the end, so will the $y(s)$ for the particle at the head differ from that at the tail. Thus, the bunch will tilt in the y-z plane. Assume $W_\perp(z)=Az$, the tilt angle θ_{yz} is approximately described as

$$\theta_{yz}(s) \approx \frac{y(s)}{z} \approx A\frac{eq\sqrt{\beta_y(s)\beta_{y0}}}{2E\sin \pi Q_y}\cos(\Delta\phi(s) - \pi Q_y) \ . \qquad (3)$$

The effect of the y-z tilt will be to increase the projected (and measured) vertical beam size according to

$$\sigma_y^{\ 2} = \sigma_{yn}^{\ 2} + (\sigma_z \theta_{yz})^2 \ , \qquad (4)$$

where σ_{yn} is the normal mode vertical beam size.

As Eq. (3) shows, the y-z tilt is proportional to the bunch charge q. The higher the bunch charge, the larger the tilt will be. This quantitatively explains the observed current dependent σ_y growth displayed in Fig. 2. In addition, the beam tilt depends on the phase advance $\Delta\phi_y(s)$ between the wake element (scraper) and the observation point (xBSM). Varying $\Delta\phi_y(s)$ will change the beam tilt so as to affect the measured σ_y. Therefore, a new phase=45 lattice was loaded into the accelerator, whose only difference from the phase=0 lattice is the vertical phase advance between the scraper and xBSM increased by π/4. The measured σ_y in this new lattice are shown in Fig. 3a.

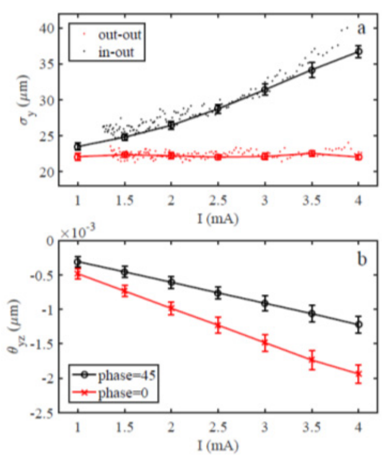

Figure 3: (a) σ_y vs current for phase=45 lattice. (b) y-z tilt calculated from tracking simulation for two lattices.

For the phase=45 lattice, the σ_y growth with top scraper inserted is much less than that in lattice 0 (Fig. 4b), indicating the dependence of the local tilt on phase advance with respect to the source of the wake. Indeed the y-z tilts calculated from tracking simulation (discussed in later section) for both lattices shown in Fig. 3b, which confirms weaker current dependent tilt in y-z tilt was phase=45 lattice than in the phase=0 lattice.

Pre-existing Tilt

If the beam had a y-z tilt at the xBSM with both scrapers out, the y-z tilt induced by the wakefield from

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inserting the top scraper could either reduce or increase the beam tilt. Since vertical dispersion in the RF could induce a y-z coupling [9], we created a closed coupling bump in the east RF region to generate a finite vertical dispersion (η_y) in the east RF cavity. Using this coupling bump (cp11), the pre-existing (current independent) y-z tilt at the xBSM can be varied. Measurement data of two cases cp11=+10k (η_y=+30 mm) and cp11=−10k (η_y=−30 mm) are shown in Fig. 4a.

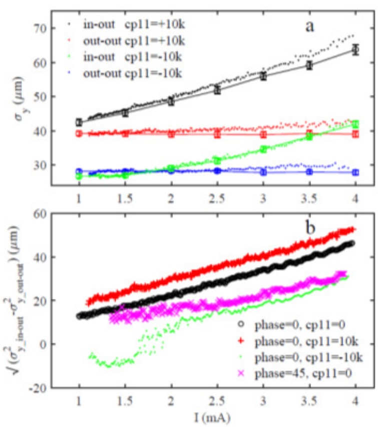

Figure 4: (a) σ_y with coup11 = +/−10k in lattice 0. (b) $\sqrt{(\sigma^2_{y\_in\text{-}out}-\sigma^2_{y\_out\text{-}out})}$ vs current.

With η_y=+30 mm in the RF, the y-z tilt generated by the dispersion has the same sign (−) as the tilt induced by the wake. Thus, the scraper wakefield tilted the beam more so that the increase of σ_y due to wake field ($\Delta\sigma_y=\sqrt{(\sigma^2_{y\_in\text{-}out}-\sigma^2_{y\_out\text{-}out})}$) is larger than that without pre-tilt (cp11=0) as shown in Fig. 4b. With η_y= −30 mm in the RF, the pre-tilt has opposite sign (+) as the tilt induced by the scraper wakefield. Thus, the pre-tilt from dispersion was compensated by the tilt induced by the wakefield so that the $\Delta\sigma_y$ is less than that without pre-tilt. These measurements demonstrate that beam tilt is the dominant effect induced by the monopole wake from the asymmetric scrapers.

SIMULATION

Transverse Monopole Wake

An electromagnetic simulation suite ACE3P was used to calculate the wakefields [10]. The three-dimensional structure of the asymmetric scraper as shown in Fig. 5a was constructed using the finite element mesh toolkit CUBIT [11]. This CUBIT model was imported to the time domain wakefield solver T3P to calculate the longitudinal wake. Three longitudinal wakes were obtained with the leading bunch at three y positions ($-\Delta y$, 0, Δy) where Δy=0.5 mm. Using the Panofsky-Wenzel theorem with three longitudinal wakes [12], the transverse monopole wake of asymmetric scrapers was calculated as shown in Fig. 5b. Although the monopole wake dependence on z is not linear, there is nevertheless an effective y-z beam tilt due to the z-dependence of the monopole wake. Dipole and quadrupole wakes were also obtained but found to be significantly weaker than the monopole wake so that they were ignored in the tracking simulation.

Tracking Simulation

The particle tracking codes made extensive use of BMAD, a subroutine library for relativistic charged-particle dynamics simulations [13]. The scraper was modelled as a wake element with a custom tracking routine, which applies the calculated vertical kick to the particle based on its z position. The bunch was modelled as a distribution of 1000 macroparticles and tracked through a lattice for 100K turns (~5 damping times). At every turn the particles 6-dimension coordinates (x, x', y, y', z, z') at the xBSM location were recorded to construct the sigma matrix, from which the y-z tilt and σ_y were calculated [14]. The simulated projected equilibrium σ_y, plotted as circles in Fig. 2, 3, and 4 are in very good agreement with the data. From the simulation, the pre-tilts with η_y=+30 and −30 mm in the east RF were obtained as -1.86 and +1.86 mrad, respectively.

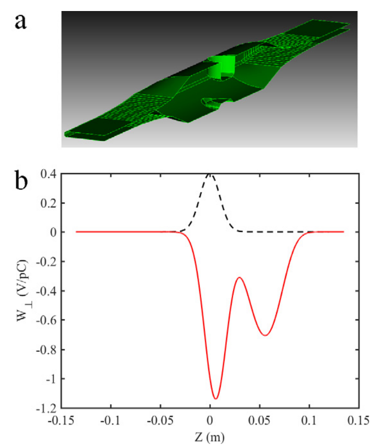

Figure 5: (a) CUBIT half model of the scrapers. Top scraper inserted and bottom scraper out. (b) Transverse monopole wake of the asymmetric scrapers. Dashed line is a10mm bunch distribution.

CONCLUSION

Current dependent vertical beam size growth was observed with top scraper inserted. We found this blowup was due to vertical-longitudinal coupling induced by the wakefields from asymmetric scraper configuration. The dominant transverse monopole wake was calculated using wake field solver T3P, and then incorporated into a tracking simulation. The simulated σ_y agrees very well with the measurements, confirming the σ_y growth are due to the y-z tilt of beam. In addition, the existing residual y-z coupling could be compensated by the scraper wake. We note that misalignment of the closed orbit through a narrow vertical aperture (a narrow gap undulator for example) will generate an effective monopole wake that can contribute to an increase in effective vertical beam size.

REFERENCES

[1] M.A. Palmer et al., "The Conversion and Operation of the Cornell Electron Storage Ring as a Test Accelerator (CesrTA) for Damping Rings Research and Development," in *Proc. PAC'09*, Vancouver, June 2009, p. 4200.

[2] A.W. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, (John Wiley & Sons, 1993).

[3] J. Calvey et al., "Measurement and Modeling of Single Bunch Wake Field Effects in CESR," in *Proc. IPAC'15*, Richmond, USA, May 2015, paper MOPMA056, pp. 681.

[4] J. Shanks, D. L. Rubin, and D. Sagan, "Low-Emittance Tuning at the Cornell Electron Storage Ring Test Accelerator," *Phys. Rev. ST Accel. Beams* 17, p. 044003, April 2014

[5] J. P. Alexander et al., "Vertical Beam Size Measurement in the CESR-TA e^+e^- Storage Ring Using X-rays from Synchrotron Radiation," *Nucl. Instrum. Methods Phys. Res. A* 748, p. 96, 2014.

[6] S.T. Wang et al., "Visible-light Beam Size Monitors Using Synchrotron Radiation at CESR," *Nucl. Instrum. Methods Phys. Res. A* 703, p. 80, 2013.

[7] R. Holtzapple and M. Billing, "Measurements of Bunch Motion due to the Longitudinal Dipole-coupled Bunch Instability at the Cornell Electron-Positron Storage Ring," *Phys. Rev. ST Accel. Beams* 5, p. 054401, 2002.

[8] M. P. Ehrlichman et al., "Intrabeam Scattering Studies at the Cornell Electron Storage Ring Test Accelerator," *Phys. Rev. ST Accel. Beams* 16, p. 104401, 2013.

[9] M.P. Ehrlichman et al.,"Measurement and Compensation of Horizontal Crabbing at the Cornell Electron Storage Rng Test Accelerator," *Phys. Rev. ST Accel. Beams* 17, p.044002, 2014.

[10] K. Ko, et al., "Advances in Parallel Electromagnetic Codes for Accelerator Science and Development", in *Proc. LINAC2010*, Tsukuba, Japan, September 2010, paper FR101, p 1028.

[11] CUBIT mesh generation program: cubit.sandia.gov

[12] W.K.H. Panofsky and W.A. Wenzel, "Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields," *Rev. Sci. Instr.* 27, p. 967, 1956.

[13] D. Sagan, The BMAD Reference Manual, http://www.lepp.cornell.edu/~dcs/bmad/

[14] A. Wolski, "Alternative Approach to General Coupled Linear Optics," *Phys. Rev. ST Accel. Beams* 9, p. 024001, 2006.

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