ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRO104

LOW-ENERGY INTRABEAM SCATTERING MEASUREMENTS AT THE SPEAR3 STORAGE RING *

K. Tian#, J. Corbett, X. Huang, J. Safranek, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

Intrabeam scattering (IBS) can cause emittance growth in diffraction limited light sources. At lower beam energy, the IBS effect is expected to be more pronounced. To study these effects we have developed a series of low energy lattices in SPEAR3 with beam energy ranging from 3GeV to 700MeV. The horizontal beam size and bunch length are measured as a function of beam energy and compared with theoretic calculations.

INTRODUCTION

Recent developments in multibend achromat (MBA) lattices allow electron storage rings to reach transverse emittance substantially below 1 nm rad and show a feasible path to diffraction limited storage rings [1]. To operate a storage ring light source with such low emittance, it is important to understand various collective effects [2, 3]. One of these effects is Intrabeam Scattering (IBS), whereby a small angle multiple Coulomb scattering causes the beam size to grow in all directions. IBS is counteracted by radiation damping in an electron storage ring and results in a new, larger, equilibrium beam emittance. In current third generation storage ring based light sources, the growth rate of IBS is much smaller than that of radiation damping. As a result, normally the IBS effect can be neglected. However, by ramping down the beam energy of the storage ring, we can deliberately produce strong IBS even at low current. This enables us to experimentally explore extreme effects of IBS. There have been efforts in various facilities to study IBS effects with lower energy operation [4, 5], in this paper, we will present results in SPEAR3.

THEORY

Let us represent the radiation damping time and IBS growth time by τ_i and T_i, respectively, where subscript i stands for p, x, or y. The horizontal and vertical equilibrium beam emittance (ε_x and ε_y) and energy spread σ_p of a storage ring can be expressed as:

$$\varepsilon_x = \frac{\varepsilon_{x0}}{1-\frac{\tau_x}{T_x}}, \varepsilon_y = \frac{\varepsilon_{y0}}{1-\frac{\tau_y}{T_y}}, \sigma_p^2 = \frac{\sigma_{p0}^2}{1-\frac{\tau_p}{T_p}}, \quad (1)$$

where subscript 0 represents the 'natural' beam property due to synchrotron radiation without IBS. The damping times can be calculated using the following expression [6]:

$$\tau_i = \frac{4\pi R\rho}{cC_\gamma J_i E^3}, \quad (2)$$

where R is the average radius of the ring, ρ is the local radius of curvature, C_γ is a constant, J_i is the damping partition number, and E is the particle energy. Eq. (2) implies that for a storage ring with fixed lattice and radius, the radiation damping time is inversely proportional to the cubic power of energy.

Following the Bjorken and Mtingwa formalism, the growth rates due to IBS can be expressed as [7]:

$$\frac{1}{T_i} = 4\pi A(log) < L_i >, \quad (3)$$

where (log) is the Coulomb logarithm, and $<L_i>$ is a lattice dependent integration around the whole ring. The factor A is defined by:

$$A = \frac{r_0^2 cN}{64\pi^2\beta^3\gamma^4\varepsilon_x\varepsilon_y\sigma_s\sigma_p}, \quad (4)$$

where $r_0$is the classical radius of the charged particle, c the speed of light in vacuum, N the number of particle in a bunch, β particle speed divided by c, γ the Lorentz factor, and σ_s is the rms bunch length. The factor A is directly related to the fourth power of beam energy. In addition, the natural emittance is approximately proportional the quadratic power of beam energy. Thus, when the emittance is relatively high, the IBS growth time is roughly proportional to the eighth power of beam energy.

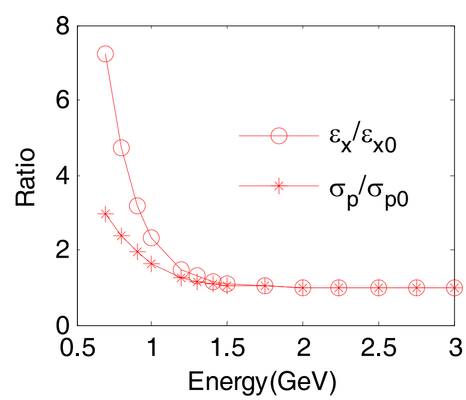

Figure 1: Calculated emittance and energy spread growth vs beam energy in SPEAR3.

At the nominal 3GeV working energy, the IBS effect in SPEAR3 is negligible. For example, with 0.05nC per bunch in SPEAR3, the IBS growth time for horizontal emittance is over 45 seconds while the radiation damping time is about 4 ms. However, as discussed above, when we ramp down the energy of SPEAR3, the increased radiation damping time and reduced of IBS growth time will both contribute to the enhancement of IBS effects. Thus, the IBS effect can be significant at lower beam energies. In Figure 1, we show simulation results for the

*Work supported by U.S. Department of Energy Contract No. DE-AC02-76SF00515
#ktian@slac.stanford.edu

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRO104

growth of horizontal emittance and energy spread in SPEAR3 for the experimental conditions described in the next section of this paper. The beam energy ranges from nominal 3GeV to 698.3 MeV. The IBS effect is calculated with ibsEmittance [8] using the normal operating lattice parameters. The bunch charge ranges from 50 pC at 3GeV to 41 pC at 698.3 MeV. In the simulations the transverse coupling at higher energy is about 0.1% then gradually increases to 0.66% at the minimum energy.

EXPERIMENT SETUP

Lattice Development

We first filled the storage ring with 280 bunches at 3GeV and total current of 18mA (the orbit interlock limit). The beam energy was then ramped down by reducing all ring magnets except the dipole correctors. To minimize the effect from the Insertion Devices, we opened all ID gaps before the ramping process. At several beam energies, we corrected the lattice by fitting the measured response matrix to the model, i.e. LOCO correction [9]. After optics correction, we take LOCO data again to calculate the transverse coupling factor. The RF gap voltage was also ramped down to keep the synchrotron tune constant, which in turn keeps a constant aspect ratio of the longitudinal phase space ellipse.

Beam Size Measurement

The SPEAR3 diagnostic beam line receives visible/UV Synchrotron Radiation (SR) from a standard dipole magnet. During the experiment, the SR light is split to a two-slit interferometer [10] for horizontal beam size measurement and a dual-axis Hamamatsu C5680 streak camera for the bunch length measurements.

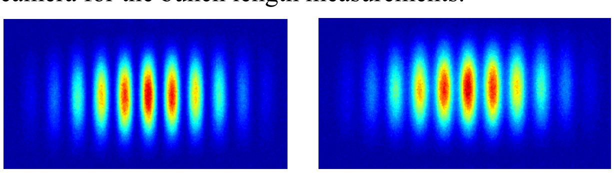

Figure 2: Interference fringe images for 1.2GeV beam (left) and 3 GeV beam (right).

For a Gaussian beam profile, the slit separation of the interferometer can be set to a fixed value to infer beam size; however, the slit separation should accommodate various beam sizes at different energies. The chosen slit separation of 10.5mm in the experiment allows us to have a visibility ranging from 0.61 to 0.87 during the ramping process. For each beam size measurement, 10 interference images were saved and analyzed for statistical calculation of the error bars. Errors in slit separation reading are not taken into account in the beam size calculation. The interference patterns for 1.2 GeV (minimum beam size) and 3 GeV are shown in Fig. 2.

Bunch Length Measurement

The streak camera can conduct single or dual axis scan (fast [ps] vertical, slow[100ns to 100ms] horizontal) with a time resolution of about 2 ps FWHM. The streak camera was operated in synchroscan mode, in which every other bunch can be captured. For beams with longitudinal motion dominated by synchrotron oscillations, the single scan or dual scan with relatively long horizontal sweep time is suitable for measuring bunch length because the synchrotron tune is usually small.

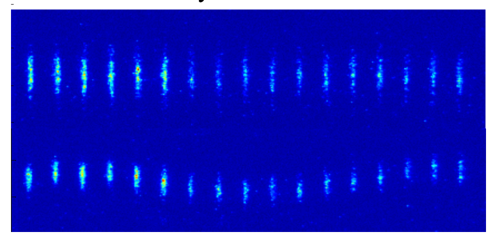

Figure 3: 200 ns horizontal range dual-scan for 3GeV (top) and 1.3GeV (bottom) beam.

However, during the experiment, we observed longitudinal oscillations at about 10 MHz when the beam energy is at or below 1.3 GeV. Figure 3 shows longitudinal oscillations at 1.3 GeV but not at 3 GeV. The oscillations appear to be current and energy dependent and can introduce large errors for bunch length measurements. As a result we had to reduce the horizontal sweep time to resolve individual bunches.

EXPERIMENT RESULTS

Energy Ramping

In Fig. 4, we compare the measured horizontal beam size and bunch length with calculation results including

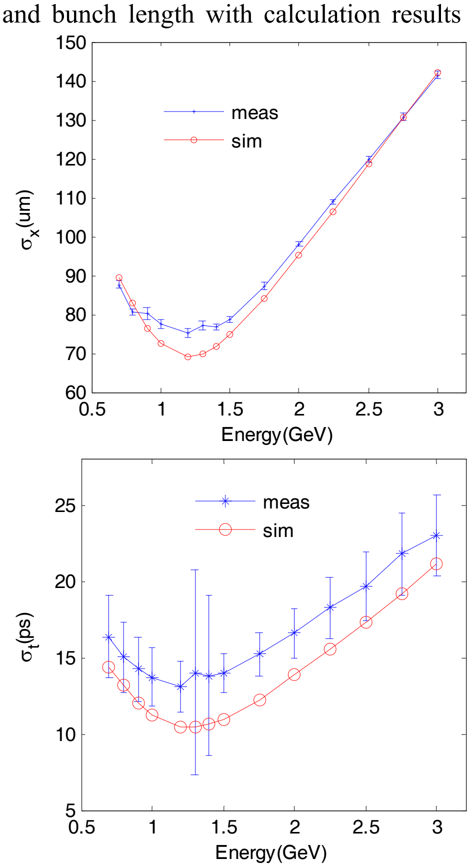

Figure 4: Horizontal beam size vs. beam energy (top) and bunch length vs. beam energy (bottom).

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRO104

IBS as a function of beam energy. As predicted by simulation, the horizontal beam size and bunch length reach the minimum at ~1.2 GeV. The horizontal beam size agrees with the simulation better when it is over 80µm, i.e. when the beam energy above 1.5 GeV or below 900 MeV. It is unclear what causes the larger discrepancy when the beam size is smaller but could be related to the 10MHz longitudinal oscillations on the low energy beam. One should also note both the measured bunch length and beam size 'jump' above the smooth trend line by a small amount at 1.3 GeV. As discussed earlier, we derive the bunch length from images of individual bunches, but the visible SR from a single passage of a bunch is weak, producing an image dominated by shot noise that degrades the Gaussian fit. To reduce the fitting error, we took multiple images to capture around 300 bunches in total and calculated the bunch length of each using Gaussian fit. The statistical mean and standard deviation are used for the measured bunch length and error bar respectively. The error bars are clearly larger at 1.3 GeV.

RF Gap Voltage Scan at Low Energy

At beam energies above 1.5 GeV, varying the RF gap voltage has only a small effect on beam size. At lower energies, when IBS is strong, a reduction in bunch length by increasing RF voltage starts to impact the transverse beam size. Calculation and measured results of horizontal beam size and bunch length at different RF gap voltage are shown in Fig. 5 for a 0.7 GeV and 0.9 GeV beam. At 0.9 GeV, the measured horizontal beam size increases with the RF gap voltage which agrees with the calculation results. However, at 0.7 GeV, the horizontal beam size blows up at an RF gap voltage of 1.56 MV. Then the beam size decreases with RF voltage until the voltage was set to 2.76 MV. When ramping the RF gap voltage from 2.16 to 2.46 MV, we observed a step loss of beam current by about 20% (from 14.24 mA to 11.5 mA). One can also note from Fig. 5 that the measured beam size is larger than the calculation result when the gap voltage is smaller than1.86 MV, but it becomes larger than the calculation result when the RF voltage was higher than 2.16 MV. We cannot theoretically explain the inconsistency between calculation and measurement at 0.7 GeV, but it is likely to be related to the longitudinal oscillation we observed at lower beam energy.

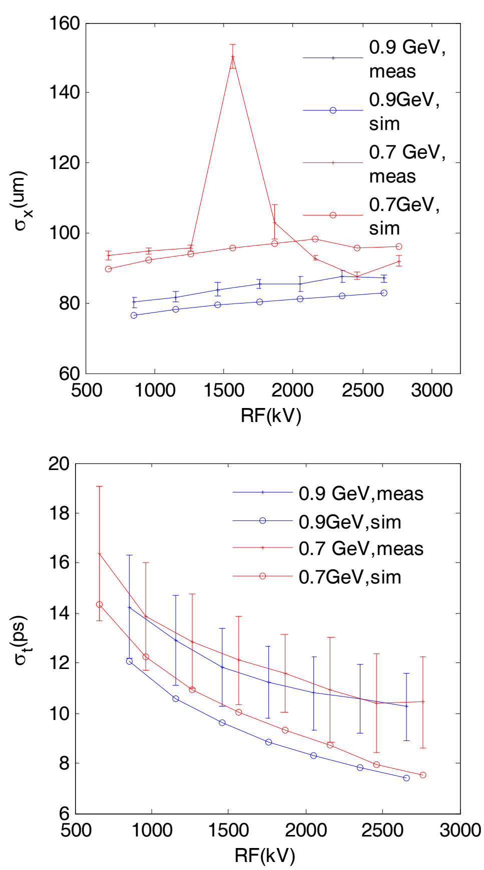

Figure 5: Horizontal beam size vs. RF gap voltage (top) and bunch length vs. RF gap voltage (bottom).

CONCLUSION

A study of IBS effects has been made in SPEAR3 by ramping down the beam energy. Using a horizontal interferometer and streak camera, we were able to simultaneously measure both horizontal beam size and bunch length demonstrating a strong IBS effect at low beam energy. The measurements indicate good agreement with calculation in most cases. Some discrepancy between measurement and simulation remains unexplained and requires further study.

ACKNOWLEDGMENT

We wish to acknowledge J. Sebek for valuable discussions and SPEAR3 operators for assisting in the experiment. We also appreciate T. Mitsuhashi and S. Park for helping in the interferometer and streak camera.

REFERENCES

[1] R. Hettel and M. Borland, Proceedings of PAC 2013, p. 19 (2013)
[2] K. Bane, “Review of Collective Effects for Low Emittance Rings”, LER 2013 workshop, Oxford, England (2013)
[3] S.C. Leemann, Phys. Rev. ST Accel. Beams 17, 050705 (2014).
[4] F. Antoniou et al., Proceedings of IPAC 2012, P. 1951(2012)
[5] M. P. Ehrlichman et al., Phys. Rev. ST Accel. Beams 16, 104401 (2013).
[6] S. Y. Lee, *Accelerator Physics*, World Scientific,2004
[7] K. Kubo et al., Phys. Rev. ST Accel. Beams 8, 081001 (2005).
[8] A. Xiao and M. Borland, Proceeding. of PAC 2009, p.3821 (2009)
[9] J. Safranek, NIMA 388(21), 1997
[10] J. Corbett et al, Proceeding of PAC 2009, p. 4018 (2009)