Recent Results from CesrTA Intrabeam Scattering Investigations [*]

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Abstract

Manifestation of intrabeam scattering (IBS) in an electron/positron storage ring depends on the radiation damping time in two ways. First, the beam size is the equilibrium of the IBS growth rate in each of the three degrees of freedom and corresponding damping rates. Second, scattering events that occur less frequently than order once per damping time contribute to non-Gaussian tails that are invisible to our beam size monitors. The tail cut procedure excludes these relatively rare events in the calculation of equilibrium beam size. In machines with short damping times, the tail cut significantly reduces the effective IBS growth rate. At CesrTA, we measure the dependence of beam size on bunch charge in IBS-dominated beams. We vary the vertical emittance using a closed optics bump that increases the vertical dispersion and transverse coupling in the wiggler regions. Measurements are taken at 2.1, 2.3, and 2.5 GeV. Here we report the results of these experiments and compare those results to theory.

INTRODUCTION

For about two months per year, CESR is operated as a dedicated test faclity (CesrTA) where the physics of stored e^+/e^- beams are studied[1]. CesrTA is aimed at improving our understanding of beam dynamics and developing technoligies that will enable us to build the next generation of accelerators. Documented here are detailed measurements of the current dependence of the emittance of single-bunch beams.

The current dependence of the horizontal beam size in these studies is dominated by intrabeam scattering (IBS). IBS describes how collisions between the particles that compose a beam transfer momentum between the three beam dimensions [2]. This transfer of momemtum drives the emittances away from their design values, and in machines with dispersion can result in an increase of the total emittance of the beam.

Understanding IBS is important for the design of future light sources and collider damping rings, which are are designed for low emittance and high charge per bunch. An important target parameter for colliders is the luminosity and for light sources the peak brilliance. High bunch charge and low emittance is important for maximizing these performance parameters.

IBS has been explored experimentally in hadron machines, such as the Tevatron [3], and in ion machines, such as RHIC [4]. In these machines, IBS manifests itself as a dilution of the beam emittance on a time scale of several 10s of minutes or many hours.

The presence of strong damping in e^+/e^- machines makes IBS a different phenomenon. These machines typically have short bunch lengths, which increases particle density and results in a fast IBS rise time. They also have a short damping time. In such machines, IBS counteracts radiation damping, leading to a current dependent equilibrium beam size.

Here we report measurements of IBS versus two key parameters, namely, beam energy and particle density. Beam energies explored are 2.1, 2.3, and 2.5 GeV. Particle density is varied by adjusting the zero-current vertical emittance. Measurements are taken with both e^+ and e^-. Measurements of the dependence of beam size on RF voltage can be found in IPAC13 contribution `TUPME065` [5].

THEORY

We model IBS using the theory developed by Kubo and Oide [6, 2]. Their theory is a generalization of the formalism developed by Bjorken & Mtingwa [7] and uses the eigen-decomposition of the beam Σ-matrix, rather than Twiss parameters. The theory naturally handles arbitrary coupling conditions. The implementation of this IBS model at CesrTA is discussed in detail in [8].

The theory by Kubo and Oide includes the tail-cut procedure. The tail-cut is a modification to IBS theory that takes into account the fact that large angle scattering events are very rare. The distribution of momenta among the particles that compose a beam are sums over a history of momentum kicks due to stochastic photon emission events. The mean and variance of these kicks are finite. The central limit theorem predicts that the resulting distribution will assume a Gaussian profile. Similarly, there are frequent small-angle IBS events and these contribute to the Gaussian core of the bunch. Large-angle IBS events, however, do not occur frequently enough for the central limit theorem to apply. These events generate lightly populated tails. It is the Gaussian core that we measure and that is relevant to luminosity in a collider or peak brilliance in a light source. The tail-cut procedure consists of removing from the calculation of the IBS rise time those scattering events which occur less frequently than once per damping time. The result is a smaller IBS growth rate. With the tail cut, the IBS theory is in good agreement with the CesrTA measurements [8].

In additional to IBS, potential well distortion (PWD) is observed at CesrTA. It is seen as a growth in bunch length without a corresponding growth in energy spread. The PWD model we use is based on a formalism by Billing [9].

Transverse coupling is well-corrected in CesrTA and is measured to be less than 0.2%. However, the lattice has significant horizontal-longitudinal coupling due to horizontal dispersion in the RF cavities. This coupling is handled in simulation by calculating the beam sizes using the beam Σ-matrix. The Σ-matrix is generated from the normal mode emittances and the eigen-decomposition of the 1-turn transfer matrix as described in [10]. The 11 and 33 elements of the Σ-matrix are taken as the horizontal and vertical beam sizes. These are the projections of the beam into lab coordinates and are what the instrumentation measures.

Our model of IBS emittance growth has 3 free parameters, the zero current horizontal and vertical beam sizes, and the inductive impedance for the PWD model. Bunch length and energy spread are set by the radiation integrals calculation. The model lattice is an element-by-element representation of CesrTA. The transfer matrices are modified to incorporate the 10 mm residual vertical dispersion that remains after low emittance tuning. With input of zero current emittances, our model of IBS returns the current dependence of the beam sizes.

EXPERIMENT

CesrTA is a 768 wiggler-dominated e^+/e^- storage ring. Energies explored for single-bunch studies are 2.1, 2.3, and 2.5 GeV.

CesrTA has independently powered quadrupole magnets. This allows for precise control of the optics. Our IBS experiments begin with the application of correction procedures to minimize vertical dispersion and coupling. To explore higher emittance beams, optics are adjusted to create localized coupling and vertical dispersion bumps in the wiggler regions.

Data is taken by charging a single bunch to more than 10^{11} particles and recording beam sizes as it decays naturally due to Touschek scattering. At low current, the lifetime becomes very long and a pulsed bump is used to scrape current out of the beam in 0.25 mA increments.

Horizontal measurements are taken with a visible synchrotron light interferometer. Vertical size measurements are made by imaging x-rays from a hard bend through a pinhole onto a vertical diode detector array. Bunch length measurements are done with a visible light streak camera.

DATA

The data presented here were taken December 2012 and April 2013.

IBS theory is species-independent. However, electron and positron data is gathered with separate instrumentation. Data is gathered for both electron and positron bunches as a check for instrumentation systematics and species-dependent beam physics. We find that e^+ and e^- beams have similar behavior during single-bunch studies.

Shown in Fig. 1 are measurements and simulation results for electron bunches at 2.1 GeV. Three data sets are shown. The Low ϵ_{y0} result is in conditions tuned for min-
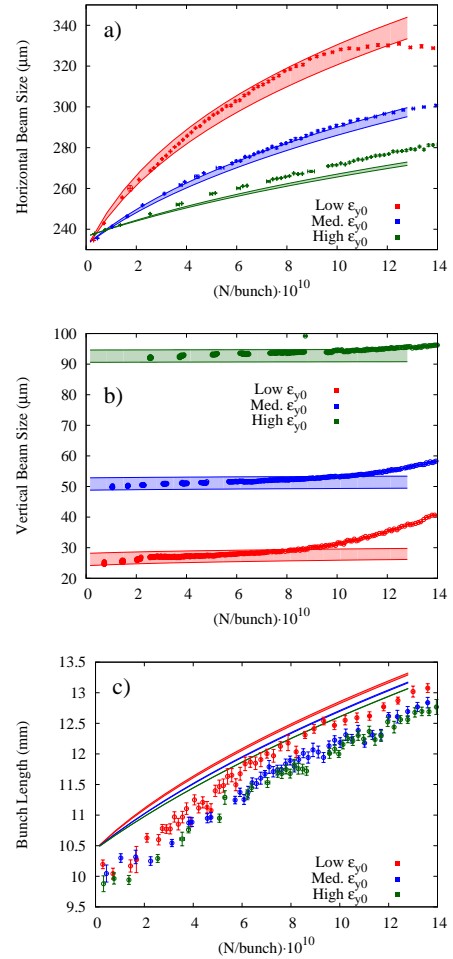

Figure 1: Measured and computed (a) horizontal size, (b) vertical size, and (c) bunch length for a 2.1 GeV bunch of electrons. Points are data, shaded bands are calculated beam sizes reflecting the uncertainty in the zero current vertical emittance.

imum emittance. The other two results are in conditions where the zero-current vertical emittance was increased using closed coupling and dispersion bumps.

The zero current vertical size measurements that are an input to the simulation have a ± 2 micron systematic uncertainty. The colored bands reflect the impact of that uncertainty in the simulation of current dependent emittance growth.

Table 1 shows the simulation parameters, and also the horizontal emittance at 7.5×10^{10} particles.

Figures 2 and 3 show measurements at 2.3 GeV and 2.5 GeV, respectively. Note that IBS growth rates have a γ^{-4} dependence.

CONCLUSION

The measured current dependence of horizontal beam size is in good agreement with IBS theory over a broad range of the parameter space, including beam energy, and zero current vertical and horizontal emittance. However,
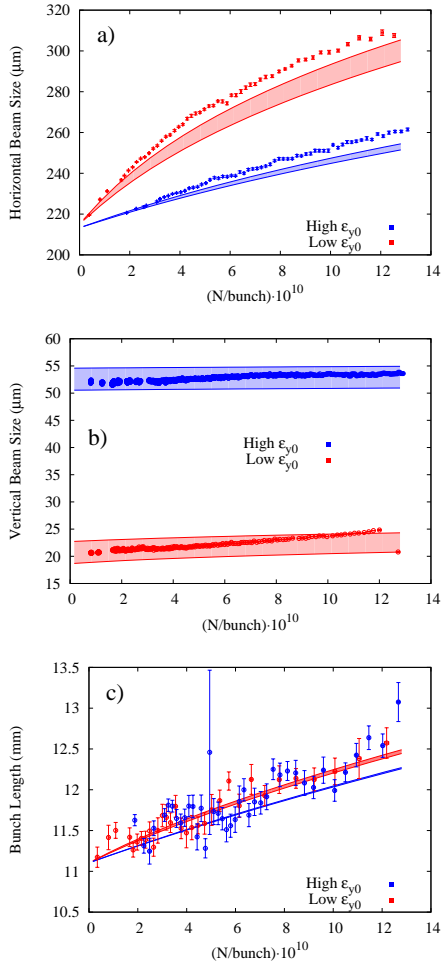
Figure 2: Measured and computed (a) horizontal size, (b) vertical size, and (c) bunch length for a 2.3 GeV bunch of positrons. The 2.3 GeV lattice has distinctly different horizontal optics than the 2.1 and 2.5 GeV lattices.

Figure 3: (a) horizontal, (b) vertical and (c) bunch length measurements and simulation results from 2.5 GeV e^+ bunch.

Table 1: Simulation parameters

Energy (GeV)	ϵ_{y0} (pm)	ϵ_{x0} (nm)	$\epsilon_x \left(7.5 \times 10^{10} \text{ parts.}\right)$ (nm)
2.1	$12.7 - 17.9$	3.1	7.83
2.1	$57.1 - 67.2$	3.2	5.73
2.1	$200.8 - 219.2$	3.4	4.69
2.3	$7.01 - 11.2$	5.7	9.41
2.3	$62.0 - 72.6$	5.6	7.06
2.5	$9.0 - 14.6$	4.4	6.65
2.5	$47.6 - 56.9$	4.5	5.57

the vertical beam size grows anomolously with increasing beam current and with positive curvature inconsistent with IBS theory. The result of the blowup of the vertical emittance is reduced growth of the horizontal. This effect is evident especially in the 2.1GeV data in Figure 1.

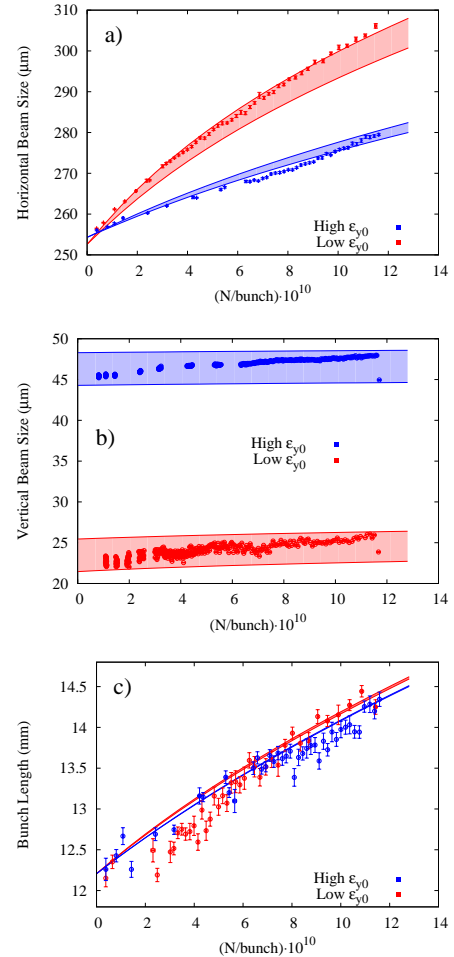The current-dependence of the vertical beam size data is not well-understood. Above some threshold, typically $2 - 3$ mA, the vertical beam size increases with positive curvature. The blow up is dependent on betatron and synchrotron tunes, but a model for the tune dependence has yet to be formulated. The blow up is species-independent. The vertical behavior appears to be due to multiple effects. The effects we have considered include IBS, direct space charge, current-dependent coupling, and head-tail instability, but we have not yet found a robust model consistent with the measured current dependence of the vertical beam size.

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